REPUBLIC OF TÜRKİYE
BURSA TECHNICAL UNIVERSITY
GRADUATE SCHOOL

USING GIS-BASED NETWORK ANALYSIS METHOD FOR SAFER FOREST TRANSPORTATION PLANNING

MASTER OF SCIENCE THESIS

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Department ofForest Engineering

Forest EngineeringMaster's (with Thesis) Programme

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FOREWORD

First of all, I would like to thank Allah and praise Him for granting me success, and I ask Him to make this knowledge useful.I extend my huge appreciation to Prof. Dr. Abdullah Emin AKAY, whose outstanding supervision has formed the foundation of this research endeavor. His experience, passion, and continuous support have helped shape this thesis, and I am grateful for his guidance. Additionally, I am thankful to my esteemed jury members, Prof. Dr. Temel SARIYILDIZ and Assoc.Prof. Dr. Sercan GÜLCİ, for their insightful guidance and unwavering encouragement throughout this academic pursuit.

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June 2024 Abdifitah Mohamed ABDULLAHI

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ABBREVIATIONS

BTU	**:**Bursa Technical University
FED	**:**Forest Enterprise Directorate
FEC	**:**Forest Enterprise Chief
GIS	**:** Geographical Information System
Ha	**:** Hector
Hr	**:** Hour
Km	**:**Kilometer
Load	**:**Capacity
MR	**:**Machine rate

SYMBOLS

$\mathbf{C_i}$	: Transportation cost
$\mathbf{l_i}$	: Length of road segment*i*
t	:Time
$\mathbf{m^3}$	: Cubic Meters
$\mathbf{v_i}$	: Vehicle speed on section *i*
$\mathbf{t_i}$	: Travel time on road section *i*

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USING GIS-BASED ON NETWORK ANALYSIS METHOD FOR SAFER FOREST TRANSPORTATION PLANNING SUMMARY

SUMMARY

Forest transportation, performed by using logging trucks, is one of the costly stage of producing forest products. Driving a logging truck is regarded as one of the most dangerous tasks in forestry, especially in areas where forest lands are mostly located in mountains. In recent decades, large size logging trucks have been preferred during hauling of forest products to minimize the transportation costs. The forest roads with inadequate technical standards (i.e. platform width, curve radius, curve width, etc.) and the lack of engineering structures and superstructure limit the movement and maneuverability of large logging trucks which negatively effects the safety of truck drivers. In this study, it was aimed to develop transportation plan with safety constraint using GIS-based network analysis method and compute the additional transportation cost that would be faced when driver safety is the priority. The study area consisted ofthree Forest Enterprise Chiefs (FECs) including Paşalar, Sarnıç, and TurfalFECs located in the city of Bursa in Turkiye. Two scenarios considered in the study 1) transportation plan that minimized the transportation costs and 2) transportation plan that maximized the safety of the truck drivers. The difference between transportation plan of two scenarios were evaluated in terms of optimum routes, destination depots and additional transportation cost spent for safety of the truck drivers. Total forest products transported to landing areas in Paşalar, Sarnıç, and TurfalFECswere 8852.50 m^3, 10327.11 m^3, 6,352.73 m^3, respectively The results indicated that forest products from landings in Sarnıç FEC and Turfal FEC were transported to their own depots, while forest products from landings in Paşalar FEC were transported to both its own depots and to depots in other FECs in the first scenario. In the second scenario, the forest products from landings in Turfal FEC were transported to its own depot while forest products from landings in Paşalar and Sarnıç FECs were transported to both its own depots and to depots in other FECs. It was found that the total transportation cost increased in the second scenario of considering safety by 58.23% (12874.70 €). In was also found that the transportation cost increased in the second scenario by 36.14%, 93.33%, and 32.54% inPaşalar, Sarnıç, and Turfal FECs, respectively. GIS-based network analysis method can be effectively used to plan transportation of forest products considering safety of logging truck drivers. The results from the sample transportation plan example suggested that the decision-makers should be willing to pay over 50% additional transportation cost for transportation of forest products in forest areas with high safety risks associated with driving logging trucks.

Keywords: Forest transportation, Transportation costs, Transportation safety, GIS.

GÜVENLİORMAN TRANSPORTU PLANLAMASIİÇİN CBS-TABANLI AĞANALİZİYÖNTEMİNİN KULLANILMASI

ÖZET

Tomruk kamyonları kullanılarak yapılan orman transportu, orman ürünleri üretiminin maliyetli aşamalarından biridir. Tomruk kamyonu kullanmak, özellikle orman alanlarının çoğunlukla dağlık alalarda yer aldığı bölgelerde, ormancılık çok tehlikeli mesleklerden biri olarak kabul edilmektedir. Son yıllarda orman ürünlerinin taşınması sırasında nakliye maliyetlerini en aza indirmek için büyük tonajlı tomruk kamyonları tercih edilmektedir. Teknik standartların yetersiz olduğu (platform genişliği, kurp yarıçapı, kurpgenişliği vb.) orman yollarının yanı sıra sanat yapıları ve üstyapı eksikliği, büyük tonajlı tomruk kamyonlarının hareket ve manevra kabiliyetini sınırlandırmakta ve bu durum kamyon sürücülerinin güvenliğini olumsuz etkilemektedir. Bu çalışmada, CBS tabanlı ağ analizi yöntemi kullanılarak güvenlik kısıtlamalı ulaşım planının geliştirilmesi ve sürücü güvenliğinin ön planda olduğu durumlarda karşılaşılacak ek ulaşım maliyetinin hesaplanması amaçlanmıştır. Çalışma alanı, Türkiye'nin Bursa şehrinde bulunan Paşalar, Sarnıç ve TurfalOrman İşletme Şefliklerinden (OİŞ) oluşmaktadır. Çalışmada iki senaryo ele alınmıştır: 1) nakliye maliyetlerini en aza indiren transportplanı ve 2) kamyon sürücülerinin güvenliğini maksimuma çıkaran transport planı. İki senaryonun transportplanı arasındaki fark, optimum güzergahlar, nihai orman depoları ve kamyon sürücülerinin güvenliği için harcanan ek transport maliyetleri açısından değerlendirilmiştir. Paşalar, Sarnıç ve TurfalOİŞ'detaşınan orman ürünlerinin hacmi sırasıyla 8852,50 m^3, 10327,11 m^3 ve 6.352,73 m^3bulunmuştur. Birinci senaryo sonuçları, Sarnıç ve TurfalOİŞ'dekirampalardan taşınan orman ürünlerinin kendi depolarına, Paşalar OİŞ'dekiorman ürünlerinin ise hem kendi deposuna hem de diğer OİŞ'lerdeki depolara nakledildiğini göstermiştir. İkinci senaryoda ise TurfalOİŞ'deki orman ürünlerinin kendi deposuna, Paşalar ve Sarnıç OİŞ'lerdeki orman ürünlerinin ise hem kendi depolarına hem de diğerOİŞ'dekidepolara taşındığı bulunmuştur. Güvenliğin dikkate alındığı ikinci senaryoda toplam transport maliyetinin %58,23 (12874,70 €) arttığı tespit edilmiştir. Ayrıca ikinci senaryoda Paşalar, Sarnıç ve TurfalOİŞ'lerdekitransportmaliyetinin sırasıyla %36,14, %93,33 ve %32,54 oranında arttığı belirlenmiştir. CBS tabanlı ağ analizi yöntemi, tomruk kamyonu sürücülerinin güvenliği dikkate alınarak orman ürünleri nakliyatının planlanmasında etkin bir şekilde kullanılabilmektedir. Örnek taşıma planı sonucunda elde edilen çıktılar, karar vericilerin, tomruk kamyonlarının kullanılmasıyla ilgili yüksek güvenlik riskleri bulunan orman alanlarında orman ürünlerinin taşınması için %50'nin üzerinde ek nakliye maliyeti ödemeye gönüllü olması gerektiğini ortaya koymuştur.

Anahtar Kelimeler: Orman transportu, Transport maliyetleri, Transport güvenliği, CBS.

1. INTRODUCTION

Transporting timber from designated landing zones to forest depots is a vital stage in the production of wood-based forest commodities. This phase ensures that the harvested timber reaches processing locations, where it can be further refined and distributed. Poorly planned forest transportation can become the most financially burdensome part of timber production, potentially impacting the overall profitability and efficiency of the operation (Acar and Eroğlu, 2001). To mitigate these costs, it is crucial to develop and implement effective transportation strategies. This requires evaluating multiple potential routes to identify the most efficient and cost-effective options. In recent years, the adoption of computerized methodologies has become widespread in this assessment process. These advanced technologies facilitate the analysis of various alternative transportation strategies, making it easier to determine the most economical and efficient plan (Aruga et al., 2005; Akay et al., 2012). Thus, incorporating sophisticated computational tools into the planning process can significantly enhance the efficiency and cost-effectiveness of timber transportation.

Forest transportation predominantly relies on the use of logging trucks, a task that is considered hazardous within the forestry sector. This is especially true in Turkiye, where most forested areas are located in rugged and challenging terrain. The safety risks associated with operating logging trucks are largely dependent on the quality of the road infrastructure. In Turkiye, a significant portion (66%) of forest roads are classified as Type-B secondary forest roads, which often require substantial repairs annually due to their substandard construction (GDF, 2012). These inadequate road conditions naturally restrict the operational flexibility of forestry trucks, especially those with large cargo capacities (Buğday and Menemencioğlu, 2014). As a result, effective forest transportation planning must consider not only transportation costs but also the safety concerns associated with driving logging trucks on these challenging roads. This dual focus on cost and safety is essential for ensuring efficient and secure timber transportation within the forestry sector.

Effective planning of forest transportation activities is essential for minimizing organizational risks and reducing transportation costs. Efficient planning ensures that the logistics of moving timber from forests to processing locations are optimized, thereby avoiding unnecessary expenses (Akay and Erdaş, 2007). The adoption of computer-based network analysis methodologies plays a pivotal role in overcoming transportation challenges. These advanced methodologies provide precise and timely solutions by calculating critical logistics parameters such as the shortest path and maximum flow, which significantly enhances the efficiency and reliability of forest transportation operations (Akay et al., 2012).

During the optimization phase of forest transportation planning, which primarily aims at cost reduction, several critical factors need to be considered. These include the length of the road, travel time, and the unit cost of transportation. By assigning these variables to the respective road links within the transportation network, planners can systematically evaluate different routing options. This involves a thorough exploration of alternative paths to identify the optimal route that balances cost efficiency and operational effectiveness. This detailed planning ensures that the chosen route minimizes expenses while maximizing productivity (Chung and Sessions, 2002).

Furthermore, when incorporating safety constraints into forest transportation planning, it is crucial to account for specific parameters such as road standards and road conditions. These parameters are vital in ensuring that the selected transportation routes are safe for both vehicles and drivers. Higher-standard and well-maintained roads reduce the risk of accidents, vehicle damage, and delays, which can otherwise result in significant financial and operational setbacks. Ensuring that transportation routes adhere to safety standards is crucial for mitigating risks associated with navigating through challenging and often hazardous forest terrain (Dijkstra et al., 2007).

By integrating these considerations into the planning process, forest transportation activities can be effectively managed to optimize both economic efficiency and safety. This approach not only helps in reducing costs and risks but also enhances the overall sustainability and productivity of forest transportation operations.

The integration of network analysis tools with Geographic Information System (GIS) capabilities enables a rapid and accurate examination of alternative paths for forest transportation. The Network Analyst tool within ArcGIS software is particularly effective in addressing transportation issues by allowing for detailed analysis of various routes. Bonazountas et al. (2007) presented a decision support system aimed at managing forest fire casualties, where the approach time of vehicles to a fire is calculated using GIS network analysis techniques. This system employs a raster-based road network with impedance values to determine access times, taking into consideration factors such as water recharge cycles

1.1 Forest Roads

Forest roads are essential for providing access to forest resources, ensuring that timber and other forest products can be transported efficiently. Proper planning of the road network is crucial to facilitate the safe and comfortable transportation of these products, while also prioritizing the safety and comfort of drivers (Murray, 1998; Abeli et al., 2000). These roads typically exhibit three distinct characteristics: they have low traffic volumes, are designed for one-directional traffic, and accommodate heavy traffic loads. The specific features of each road section depend on its function within the overall road system, ensuring that the transportation needs are met while maintaining safety and efficiency.

1.1.1 Forest roads standards

The construction of forest roads involves several fundamental components commonly referred to by specific terms. These components include the roadway, shoulder, subgrade, base course, surface course, ditch, and cross slope. Each part plays a critical role in the overall structure and functionality of the road. The roadway forms the main path for vehicle travel, while the shoulder provides additional support and space for emergency stops. The subgrade is the foundational layer that supports the base and surface courses, ensuring the road's stability and durability. The base course provides a supportive layer above the subgrade, and the surface course constitutes the top layer that comes into direct contact with vehicles. Ditches are implemented for drainage purposes, and the cross slope ensures proper water runoff to prevent erosion and road damage. A cross-section of a typical forest road is shown in Figure 1.1, highlighting these essential components and their arrangement within the road's structure.

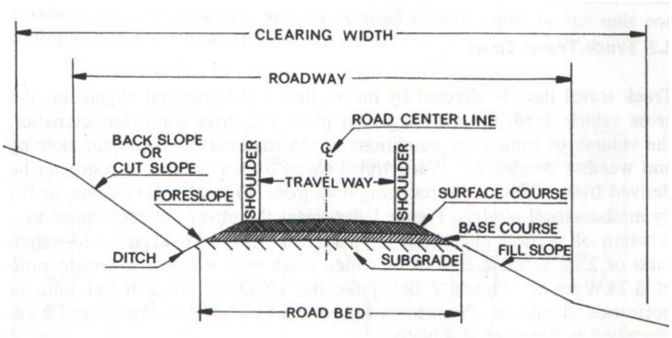

Figure 1.1: Forest road cross-section structures (Sessions and Heinrich, 1993).

The travel way is the designated width of the road surface reserved for vehicle passage. For double lane roads, it encompasses each travel lane, while for single lane roads, it represents the width of the single lane. On the other hand, the shoulder refers to the defined width of the road shoulder in the design, as well as any excess width beyond the travel way width that functions as a useful shoulder adjacent to the travel way (Sessions and Heinrich, 1993).

The subgrade serves as the foundational layer for road surfacing, providing essential support for all other road components. Above the subgrade lies the base course, a crucial layer of material designed to support traffic loads and ensure the road's structural integrity. The surface course, which is the topmost layer of the roadway, provides a smooth and durable running surface for vehicles, facilitating safe and efficient transportation (Sessions and Heinrich, 1993).

Ditches in forest road construction are typically classified into two types: roadside ditches and intercept ditches. A roadside ditch is located at the base of a back slope and runs parallel to the road subgrade. Its primary function is to collect runoff water from both the road surface and the cut bank, preventing water accumulation on the roadway. On the other hand, an intercept ditch is positioned above a cut bank and is designed to capture runoff water before it can reach erosion-prone areas, thereby redirecting it to prevent soil erosion and road damage. The term "cross slopes" refers to the crown or superheight of traffic routes and/or shoulders, which are designed to facilitate proper drainage by directing water away from the road surface (Sessions and Heinrich, 1993).

1.1.2 Forest road classifications

Access roads serve as permanent connections between forests and public roads, facilitating the transportation of resources from forests to wood processing sites, as depicted in Figure 1.2. These roads are constructed to withstand various weather conditions, ensuring reliable access throughout the year. In addition to their primary role in forestry, access roads often function as permanent public thoroughfares, supporting the movement of goods and people. In some instances, rural access roads handle the transportation of significant volumes of wood, with annual quantities reaching up to 100,000 cubic meters or more (Sessions and Heinrich, 1993).

Figure 1.2: Access roads (Kakol, 2014).

Main forest roads, which include branch roads and forest truck roads, are critical components of the fundamental forest road network. Figure 1.3 illustrates how these roads enable the year-round delivery of wood by truck. When their use is projected to span several years, main forest roads often require construction to higher standards to ensure durability and reliability over time (Sessions and Heinrich, 1993).

Figure 1.3: Main forest roads(Kakol, 2014).

Secondary forest roads, also referred to as feeder roads or subsidiary roads, serve as crucial connecting pathways within the forest, linking landing spots to main highways, as depicted in Figure 1.4. These roads generally lack developed surfacing, making them accessible to trucks primarily during the dry season.

Figure 1.4: Secondary forest roads(Kakol, 2014).

However, they are often closed during wet weather due to poor road conditions. Additionally, secondary forest roads are typically abandoned once logging activities conclude, reflecting their temporary nature in the forest transportation network (Sessions and Heinrich, 1993).

Skid roads, also known as temporary dirt roads within forest stands, function as skidding or forwarding paths from the fall location to the predetermined landing spot, as illustrated in Figure 1.5. In steep terrain, the construction of skid roads often involves earth-moving activities, which can be performed manually or with small bulldozers or loaders. Conversely, in flat and easily passable terrain, such construction activities are typically unnecessary. Notably, in automated logging operations, logging residues may be intentionally left on skid roads to protect the soil from damage (Sessions and Heinrich, 1993)

Figure 1.5: Skid roads(Kakol, 2014).

Figure 1.6 depicts skid trails, which are paths used to transport timber from the stump area to the boundary of the skid road. Unlike skid roads, skid trails do not involve any earth-moving activities. However, trees and underbrush along these trails can be cleared, and stumps are typically cut as close to the ground as possible to facilitate timber movement. In automated logging operations, logging residues may be left on skid trails to protect the soil from compaction and erosion (Sessions and Heinrich, 1993).

Figure 1.6: Skid trails (Solgi et al., 2019).

1.2 Forest Transportation

Forest product transportation typically involves two distinct phases: primary transport and secondary transport (Aykut, 1985). In the primary transportation phase, forest products are moved from the stump to landing sites, where they are temporarily consolidated. This stage is crucial for gathering and organizing the timber before it is moved to its next destination. Following this, during the secondary transport phase, the consolidated forest products are transported from landing sites to forest depots, as illustrated in Figure 1.7. This stage involves moving the timber over longer distances to central storage locations. It is important to note that secondary transportation costs can be significant, accounting for up to 40% of the total costs associated with forest product production (Acar, 1998).

In forest transportation planning, the application of computer technology and advanced mathematical algorithms plays a crucial role in aiding decision-makers to select the most cost-effective hauling routes. By systematically analyzing various possibilities, these tools help identify the routes with the lowest transportation costs.

Figure 1.7 : Transportation of logs to forest depots by a logging truck(Kakol, 2014).

The network analysis method, frequently used to solve shortest path problems, has proven to be particularly valuable for several tasks. These tasks include optimal project planning, determining maximum value streams, and efficiently allocating tasks. This method provides a structured approach to decision-making in forest transportation, ensuring that resources are utilized in the most effective manner possible (Başkent, 2004).

1.3 GIS in Forest Transportation

Geographical Information System (GIS) technology has seen growing utilization across various forestry applications, including forest operations, transportation, management, and fire management (Sivrikaya et al., 2007; Yuksel et al., 2008; Akay et al., 2008; Gumusay and Sahin, 2009; Wing et al., 2010). A modern GIS system typically comprises four fundamental components: hardware, software, data, and human resources. Hardware refers to the physical devices needed to run GIS applications, such as computers and GPS devices. Software includes the programs and applications used to analyze and visualize geographic data. Data encompasses the geographic information and datasets that are input into the system. Human resources are the skilled personnel who operate and interpret the GIS tools and data (Davis, 1996).

Geographical Information System (GIS) technology enables users to explore, analyze, query, interpret, and visualize data in various formats. This capability allows for the discovery of relationships, patterns, and trends through the use of maps, globes, reports, and charts. As GIS tools and capabilities have advanced, integrating forest transportation planning techniques into GIS has become increasingly feasible. GIS facilitates the swift and accurate evaluation of alternative routes through its specialized techniques. In particular, GIS-based modules such as Network Analyst offer efficient solutions for transportation problems (Akay et al., 2012).ArcGIS Network Analyst is a powerful extension that supports network-based spatial analysis tasks. These tasks include routing, providing travel directions, identifying the nearest facility, and analyzing service areas. This extension enhances the ability to plan and optimize forest transportation routes, ensuring that decisions are informed by accurate and comprehensive spatial analysis.

Network analysis, a well-known technique in operational research, has been extensively employed to solve a wide range of problems, such as determining the shortest path, least cost distance, maximum flow, and more (Başkent, 2004). This methodology, which is considered a variant of linear programming, provides a structured approach to addressing complex issues. Network analysis is particularly notable for its high flexibility and ease of updating, making it one of the most commonly utilized methods. Its adaptability to changing conditions and evolving scenarios makes it an invaluable tool for decision-makers who need to respond swiftly to new information and circumstances.

There are three fundamental components to network analysis: nodes, lines, and flow. Nodes, typically depicted as circles, are represented by numbers inscribed within these circles. The starting and terminating nodes denote the endpoints of the links that connect the nodes. The flow along each link indicates the costs or quantities of various products and services being transferred or regulated. Network analysis is widely applied in solving challenges related to harvest scheduling and transportation planning within the forestry sector. This structured approach helps optimize the movement and allocation of resources, ensuring efficient and cost-effective operations.

1.4 Objectives

This thesis employed a GIS-based network analysis method to develop optimal transportation strategies, addressing both scenarios of minimizing transportation costs and minimizing driving risks. In the first scenario, the focus was on creating transportation plans that aim to reduce costs. This involvesanalyzing various routes and their associated expenses to find the most economical options. In the second scenario, the study concentrated on determining transportation plans that prioritize the safest driving conditions for trucks.

To achieve this, the analysis took into account factors such as road type (e.g., asphalt, gravel, forest road) and road conditions (e.g., good, medium, poor) to assign safety rankings to different road sections. These safety scores are crucial in evaluating the level of risk associated with driving on various segments of the road network. By integrating these considerations, the study aimed to develop comprehensive transportation strategies that balance cost efficiency with driver safety.

The road network data of three Forest Enterprise Chiefs (Paşalar, Sarnıç, and Turfal) within the Bursa Forest Regional Directorate was utilized for implementing the system. The study evaluated the optimal routes for transporting forest products from 30 harvesting units to five distinct forest depots. Two scenarios were considered:

*Scenario I:*The optimal routes for transporting forest products were determined with the goal of minimizing transportation costs. This scenario focused on identifying the most cost-effective paths by analyzing the expenses associated with different routes.

*Scenario II:*The optimal routes for transporting forest products were determined with the goal of maximizing road safety. This scenario emphasized identifying the safest routes by evaluating the safety conditions of various road segments.

2. LITERATURE REVIEW

In several studies, GIS techniques have been employed to investigate the integration of decision support systems with spatial databases to solve vehicle routing problems. Manussaridis et al. (2007) and Keenan (2008) have demonstrated the potential of this integration to optimize vehicle routing. Furthermore, research conducted by Ghiani et al. (2003) has explored real-time solutions that allow for the dynamic updating of vehicle routes. These real-time solutions are crucial as they enable the continuous evaluation and selection of the most efficient routes, taking into account the movement of vehicles, changing conditions on alternative routes or the main road, and possible changes in the destination point.

Keramitsoglou et al. (2004) developed an innovative decision support system in Greece designed to determine the optimal routes for deploying firefighting teams in the event of forest fires. Their comprehensive study investigated the impact of various variables, including road type, road condition, and population density, on the route optimization process. By analyzing these factors, they aimed to improve the efficiency and effectiveness of firefighting operations, ensuring that teams could reach affected areas quickly and safely.

In a similar vein, Bonazountas et al. (2007) also focused on enhancing firefighting logistics through advanced decision support systems. They employed Geographic Information System (GIS) methods combined with network analysis to estimate the time required for firefighting vehicles to reach fire incidents. Their system utilized a raster-based road network to accurately calculate travel times to the fire zones. Additionally, they incorporated factors such as the need for water refilling, which is critical in ensuring continuous firefighting efforts. This method allowed for a more precise and reliable estimation of response times, ultimately contributing to more effective firefighting strategies.

Imani et al. (2012) demonstrated the efficacy of planning forest road alignment using a shortest path algorithm and Geographic Information System (GIS), highlighting how GIS-based network analysis, exemplified by the shortest path algorithm in their study, enhances forest transportation planning for safety by optimizing routes, reducing costs, and improving road layout efficiency. They presented an enhanced routing method based on Dijkstra's algorithm and Analytical Hierarchical Process (AHP) to determine optimal routes for timber transportation, showing that roads planned with the shortest path algorithm had 55% lower length and 65% lower cost compared to expert-based planning. This method saved $45,800 USD in comparison to expert-based road planning, emphasizing the significance of optimal timber transportation routes using Dijkstra's algorithm and GIS.Their study also integrated weighted linear combination and the Analytical Hierarchy Process with GIS to further enhance the routing method for forest road alignment.

Akay and Kakol (2014) developed an innovative decision support system utilizing Geographic Information System (GIS) technology to identify the most efficient and cost-effective routes for transporting forest products. They implemented the network analysis method within the "network analyst" module of the ArcGIS application, which allowed them to perform a detailed examination of various transportation routes. This analysis took into account multiple critical factors such as distance, road conditions, traffic patterns, and terrain challenges, providing a comprehensive solution for forest product logistics.Their extensive study revealed that integrating a GIS-based decision support system significantly optimized the routing process. By employing this advanced technological approach, they achieved a 28.29% reduction in transportation costs. This substantial cost saving underscores the system's capability to enhance logistical efficiency and reduce operational expenses. The decision support system not only identified the shortest and fastest routes but also considered economic and environmental factors, ensuring that the chosen routes were sustainable and minimized fuel consumption and emissions.The integration of GIS technology into the decision-making process provided a powerful tool for forest product transportation planning. It enabled forest managers and logistics planners to make informed decisions based on real-time data and comprehensive analysis, leading to improved efficiency, reduced costs, and enhanced overall performance of transportation operations.

Akay et al. (2017) developed a comprehensive GIS-based Decision Support System (DSS) designed specifically for the planning and optimization of forest product transportation. This system employs a GIS-based network analysis method that enhances forest transportation plans by systematically determining the most cost-effective routes while ensuring safety by avoiding landslide-prone areas. The DSS utilizes Geographic Information System (GIS) technology to identify the optimal routes for transporting a variety of forest products, including logs, industrial wood, paper, and mine poles, to designated depots.The system's integration of GIS allows for precise analysis and route optimization, which significantly reduces transportation costs. Their study revealed a notable decrease in total transportation expenses, from 88,424 TL to 88,161 TL, highlighting the efficiency of the DSS. Among the various forest products, logs were found to have the highest transportation costs, underscoring the importance of optimizing these routes to achieve significant cost savings.The research conducted by Akay et al. (2017) emphasizes the complexity and high costs associated with forest product transportation. They highlight the critical need for optimized transportation strategies to minimize expenses and improve efficiency. By utilizing the Network Analyst extension in the ArcGIS 10.2 program, their GIS-based decision support system provides a powerful tool for forest managers and logistics planners. This system enables real-time data analysis and route adjustments, ensuring that the transportation of forest products is both economical and reliable. The advanced DSS not only reduces costs but also enhances overall transportation efficiency and safety. This innovative approach to transportation planning demonstrates the significant potential of GIS-based solutions in addressing the logistical challenges of the forestry industry, making it an invaluable resource for optimizing forest product transportation.

Podolskaia et al. (2019) conducted an in-depth study utilizing the ArcGIS network analyzer tool to calculate the travel time and distance required to reach a forest fire. Their research aimed to enhance the efficiency of emergency response by providing a detailed analysis of ground transportation accessibility to fire-prone areas. To achieve this, they constructed a comprehensive map of the fire ground protection area, which served as a critical tool for evaluating accessibility.The study meticulously analyzed ground transportation routes and their accessibility over three distinct time periods, allowing for a dynamic assessment of how quickly and efficiently firefighting teams could reach the affected areas. By using the ArcGIS network analyzer tool, the researchers were able to simulate various scenarios and identify potential bottlenecks or delays in reaching the fire site. This approach provided valuable insights into the optimal routes that could be used under different conditions, ensuring that firefighting efforts could be deployed swiftly and effectively.The study's findings underscore the critical role of advanced GIS tools like the ArcGIS network analyzer in enhancing the preparedness and responsiveness of firefighting operations. By providing a detailed analysis of travel times and distances, the research contributed to more efficient allocation of resources and better management of emergency response efforts. This innovative use of GIS technology exemplifies its potential to significantly improve logistical planning and operational efficiency in managing forest fires.

Akay (2021) conducted a study utilizing GIS-based analysis to optimize logging truck routes by considering road types and conditions, aiming to balance safety and transportation costs. The study found that prioritizing safety led to a 15.76% increase in costs. The research employed a GIS-based network analysis method to develop the optimal transportation plans for two distinct scenarios. In the first scenario, the objective was to design a transportation plan that minimized total transportation costs. Conversely, the second scenario focused on optimizing the transportation plan to ensure the safest possible driving conditions for logging trucks.In this study, GIS technology played a crucial role in analyzing and determining the most effective routes for logging trucks. By evaluating various factors such as road types, conditions, and safety considerations, the analysis provided a comprehensive view of the trade-offs between cost and safety. The first scenario's cost-minimization approach aimed to reduce operational expenses, making it the most economical option for transporting logs. This scenario emphasized efficiency and cost-effectiveness, providing a viable solution for logging companies looking to optimize their transportation budgets.The second scenario, however, prioritized the safety of logging truck drivers. By optimizing routes to avoid hazardous road conditions and ensure safer driving environments, this plan recognized the importance of driver safety and risk mitigation. Although this approach resulted in higher transportation costs, the study highlighted the value of investing in safer routes to prevent accidents and enhance overall safety.

Guenther (2022) conducted a study in which a least-cost roads model was constructed using the province's Digital Elevation Model (PDEM) to identify the most cost-effective paths for operating roads. By generating a cost-surface from the PDEM using a script written in Python's ArcPy module, the study aimed to optimize road construction and maintenance costs. Guenther suggested connecting sites in harvested stands to landings on access roads, thereby enhancing the efficiency of the road network.The findings of the study demonstrated a significant difference in the road network at the 0.05-alpha level, with 41 of 42 individual road pairs showing notable variations. This indicated that the least-cost model provided a substantially different and potentially more efficient road network compared to existing routes. The use of the PDEM and the ArcPy module allowed for a detailed analysis of terrain and cost factors, leading to optimized road paths that minimized expenses while maintaining accessibility.By employing the least-cost roads model, the study highlighted the potential for substantial cost savings and improved operational efficiency in road construction and maintenance. The approach of connecting harvested stands to landings on access roads further emphasized the practical applications of this model in forest management and logistics. The significant differences observed in the road network underscore the effectiveness of using advanced GIS tools and techniques to enhance transportation planning and infrastructure development.

Acasto et al. (2022) developed a methodology to improve transportation planning safety within Peru's tropical forests. They integrated georeferenced and field data with GIS to formulate a road network plan tailored for timber harvesting. Through the utilization of Digital Elevation Models (DEMs), hydrography, and slope maps, they developed least cost paths, ensuring the creation of economically and environmentally optimized road networks. This GIS-based approach surpassed traditional mapping methods, offering superior precision and efficiency in road planning. By leveraging DEMs for the generation of hydrography and terrain slope maps, and creating weighted rasters based on slope and hydrography, Acasto et al. (2022) achieved enhanced economic and environmental outcomes in road network planning.

In the study conducted by Mesquita et al. (2022), an innovative optimization approach was proposed that combines mathematical programming and heuristic techniques to design forest road networks and plan timber transportation, with the aim of enhancing efficiency in forest transportation planning. Their method integrates the design and maintenance of forest road networks, providing comprehensive solutions to timber loading location site selection and transportation challenges. By utilizing a mixed integer programming model alongside heuristic algorithms, the approach efficiently addresses road design, maintenance, timber loading, and transportation concerns.The study emphasizes the synergy between mathematical programming formulations and heuristic solution techniques to optimize forest transportation systems. This combined method not only streamlines the planning process but also minimizes costs associated with timber transportation. By leveraging these advanced techniques, Mesquita et al. (2022) were able to achieve effective forest road network design and optimize timber transportation routes, resulting in significant cost savings.Their findings demonstrated that the integrated approach effectively reduced overall transportation costs while improving the efficiency and reliability of forest road networks. The use of mixed integer programming models with heuristic algorithms provided a robust framework for solving complex transportation and logistics problems in the forestry sector. This approach underscores the importance of integrating advanced mathematical and heuristic methods to achieve optimal solutions in forest transportation planning.

3. MATERIAL AND METHODS

3.1 Study Area

The study area encompasses three Forest Enterprise Chiefs (Paşalar, Sarnıç, and Turfal), situated on the border of MustafaKemalpaşa Forest Enterprise Directorate (FED) at Bursa Forest Regional Directorate (Figure 3.1). In the execution of the system, five forest depots (Sarnıç, Sünlük, Karapınar, Karaorman, Paşalar Depots) and 30 sample landing areas within the Forest Enterprise Chiefs were considered in the study area. The MustafaKemalpaşaFED provided the locations of depots and landings, as well as the quantity of forest products delivered from each landing areas. (Table 3.1, 3.2, 3.3). In the study area various forest products are produced including logs, mine poles, industry wood, and paper wood. The main tree species in the region include beech (*Fagusorientalis*), oaks (*Quercus* sp.), and fir (*Abiesnordmanniana subsp. bornmulleriana*).

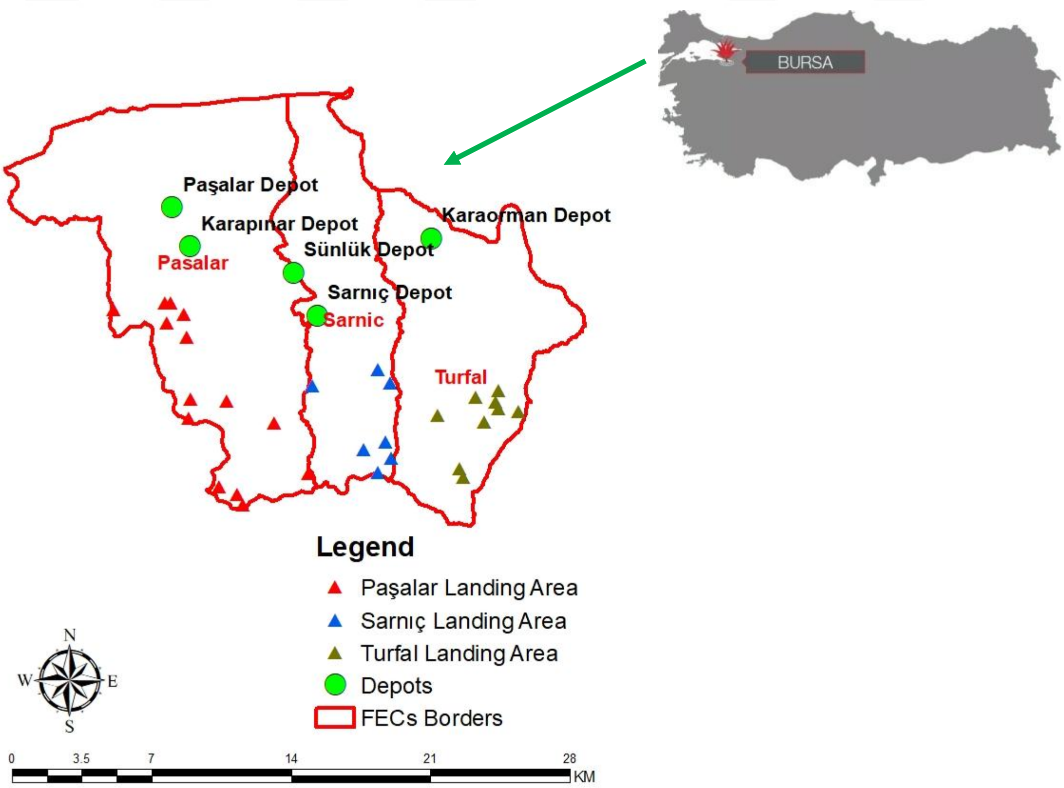

Figure 3.1 : Study area.

Table 3.1 : The amount of extracted timber at the landing areas in Paşalar.

Landings	Volume (m^3)
P1	217.49
P2	878.05
P3	382.62
P4	239.90
P5	2394.53
P6	1206.51
P7	231.49
P8	412.23
P9	499.18
P10	414.97
P11	265.80
P12	601.14
P13	752.53
P14	356.05

Table 3.2 : The amount of extracted timber at the landing areas in Sarnıç.

Landings	Volume (m^3)
S1	938.99
S2	1,300.18
S3	2,111.65
S4	1,366.46
S5	3,721.15
S6	343.99
S7	544.687

Table 3.3: The amount of extracted timber at the landing areas in Turfal.

Landings	Volume (m^3)
T1	165.574
T2	554.387
T3	652.713
T4	702.788
T5	769.16
T6	764.701
T7	2,100.70
T8	206.362
T9	436.346

3.2 Road Network

The road network layer was generated utilizing data derived from the topographic map acquired from the FED (Forest Enterprise Directorate) (Figure 3.2). The road network layer's attribute table will assign five key parameters to each road section: road length, road type, road condition, average vehicle speed, travel time, and road safety score.

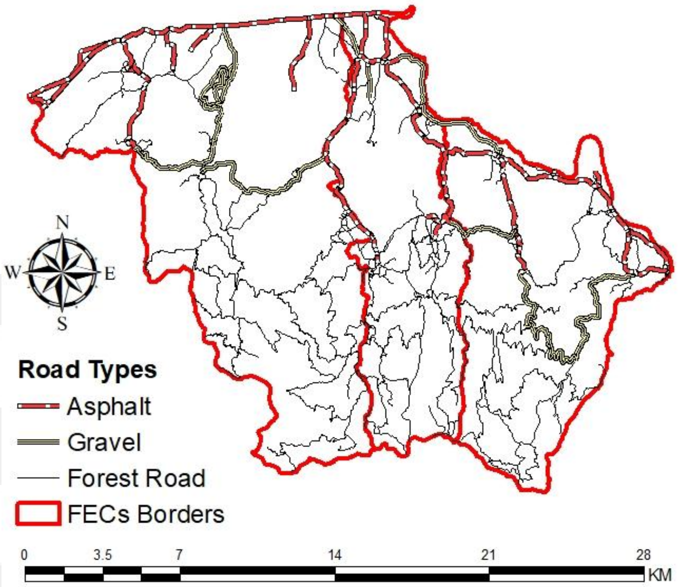

Figure 3.2 : Road network.

The road length will be calculated using the "calculate geometry" tool found in the attribute table. Road types (such as asphalt, gravel, or forest roads) and conditions (ranging from good to poor) will be assessed using FED data. The average vehicle speed will then be determined based on the indicated road types and conditions, as shown in Table 3.4. These parameters collectively inform the assessment of transportation routes and contribute to the development of optimal transportation plans within the GIS-based network analysis framework.

Table 3.4: Average logging truck speeds (km/h) for road types and conditions.

Road Type	Road Conditions		
	Good	Medium	Poor
Asphalt road	60	50	40
Gravel road	40	30	20
Forest road	25	20	15

The logging truck's time of travel for each road section will be calculated as follows:

$$t_i \frac{l_i}{v_i} 60 \tag{3.1}$$

t_i: travel time on road segment i (minutes)

l_i: length of road segment i (kilometers)

v_i: vehicle speed on section i (kilometers per hour).

60: Calculation for converting hours to minutes.

Once the travel duration for every road segment is computed, the transportation expenses (€/m3) will be determined based on the machine rate (€/h), truck load capacity (m3), and trip duration (h):

$$c_i \frac{MR}{\left(\frac{load}{t_i}\right) * 60} \tag{3.2}$$

c_i: transportation cost (€/m^3)

load: capacity (m^3)

MR: machine rate (€/h)

The study will include a logging truck that is widely used in the area. The truck's load capacity and machine rate are 25 tons and 18.57 euros per hour(€/h), respectively(Figure 3.3).

BMC Pro 827

Engine power:	285 PS (210 kW)
Torque:	700 Nm
Weight (bare chassis):	9050 kg
Carrying capacity limit:	22950 kg
Max loaded 1st axle:	7000 kg
Max loaded 2nd axle:	7000 kg
Max loaded axle weight:	18000 kg
Max loaded weight:	32000 kg

Figure 3.3 : Technical specifications of thelogging truck.

In the ultimate phase, the road safety rating will be determined through an expert decision methodology, considering road types and conditions. Road sections' safety rankings will be evaluated on a numeric scale from 1 to 9, with higher scores assigned to sections posing greater risks (Table 3.5).

Table 3. 5: The road safety scores for road types and conditions.

Road Type	Road Conditions		
	Good	Medium	Poor
Asphalt road	1	2	3
Gravel road	4	5	6
Forest road	7	8	9

3.3 Network Analysis

Indeed, the "Network Analyst" extension in ArcGIS provides an extensive suite of tools for network-based spatial analysis. This extension facilitates a range of functions essential for various applications, including routing, which determines the most efficient paths for transportation, and service area analysis, which identifies areas that can be served from a particular location within a specified travel time or distance. Additionally, the extension helps in determining the closest facilities, a critical function for emergency response planning and logistics optimization.

Moreover, "Network Analyst" enables the generation of detailed travel directions, useful for navigation and route planning. Its location-allocation analysis function optimizes the placement of facilities to effectively meet the demands of a dispersed population or service area. By leveraging a sophisticated network model, users can construct and manage networks using data stored within a GIS database seamlessly.

This robust toolset allows users to conduct comprehensive analyses, generating valuable insights to inform decision-making processes across various domains. For instance, it can support urban planning by integrating demographic data, land use information, and environmental factors into spatial analyses. This integration enhances the ability to visualize and interpret complex spatial data, aiding in the modeling of real-world scenarios and prediction of outcomes.

Overall, the "Network Analyst" extension in ArcGIS empowers users to build detailed networks, conduct in-depth spatial analyses, and derive critical insights for optimizing operations, improving efficiency, and addressing complex spatial challenges in various fields.

3.3.1 New closest facility

The new closest facility approach allows for determining the optimal routes between each first response team and potential fire sites within the study region. This method ensures that the response team with the shortest travel time is allocated to each potential fire location. In addition to identifying the primary response team, the system can also determine alternative initial response teams with the second or third shortest travel times, along with their respective routes. This is particularly useful in cases where the primary team may lack sufficient equipment or firefighting personnel.

Furthermore, given the potential for road blockages due to fire, maintenance, or forest operations, certain road segments on the most direct routes can be excluded from the network system by implementing barriers. This flexibility ensures that the routing system remains functional and effective even when some roads are impassable, thereby enhancing the overall efficiency and reliability of the response strategy.

3.3.2 New route

The new route technique within ArcGIS Network Analyst can be crucial for determining the fastest access route from a mobile initial response team to a potential fire area in real-time. This function is essential when response teams encounter unforeseen obstacles or changes in route accessibility due to factors such as the spread of fire or other unexpected circumstances. Additionally, it assists response teams that have deviated from their initial route by recalculating the optimal path to the destination based on their updated position.

By incorporating the current location of the response team, the new route method recalculates the optimal route to the fire area in real-time. This dynamic capability enables response teams to quickly adapt to changing conditions, ensuring timely arrival at the fire site.Moreover, the new route approach can be expanded to consider not only the fastest route but also the safest or most reliable access route in real-time. This can be achieved by strategically placing barriers on specific links within the network to account for road closures or hazardous conditions.This enhancement ensures that response operations are not only efficient but also prioritize the safety of the teams involved.

3.3.3 New service area

The new service area technique within ArcGIS Network Analyst is a valuable resource for evaluating which forested regions are accessible or inaccessible to initial response teams within crucial response time constraints. These response times are determined based on the fire susceptibility levels in each area, as detailed in Table 3.6, utilizing long-term statistical data collected by General Directorate of Forestry during forest fire incidents.

Operating similarly to a GIS buffer analysis, the new service area method begins by establishing a service area point within the network framework. This designated point acts as the focal center from which other network segments can be accessed within a predefined total link value threshold. The resultant area that can be reached constitutes the service area, allowing for the evaluation of regions that initial response teams can access within critical response times. This method ensures that the evaluation takes into account the varying levels of fire risk and accessibility, thereby optimizing the response strategy and enhancing the effectiveness of firefighting efforts.

Table 3.6: Critical response time to forest fires by fire sensitivity levels.

	Fire Sensitivity Levels				
	I	II	III	IV	V
Critical Response Time	20 min	30 min	40 min	50 min	60 min

In this study, the "new closest facility" approach will be utilized to identify the optimal routing options for two distinct scenarios. In the first scenario, transportation planning will focus on minimizing transportation expenses. These expenses will be assigned to the connections that represent the road segments within the network database.In the second scenario, the emphasis will be on ensuring the safest driving conditions for logging trucks. The links representing the road segments in the network database will be assigned safety scores. Finally, both scenarios will be evaluated based on total transportation costs and the hauling routes for forest products from each landing site. This comprehensive assessment will provide insights into the most cost-effective and safest transportation strategies for forest product logistics.

4. RESULTS AND DISCUSION

4.1 Road Network Data

The total road network length in the study area is determined as 519 km. The majority of these roads are forest roads (70.71%), followed by asphalt paved roads (17.73%) and stabilized roads (11.56%).Considering the condition of the road networks in the study area, 16.95% of the roads are classified as good, 71.10% as medium and 11.95% as poor. It was determined that half of the asphalt paved roads were in good condition, 44.57% were in medium condition and the remaining roads were in poor condition (5.43%). Considering the gravel roads, it was determined that 41.67% of the roads were in good condition, 38.33% were in medium condition and the remaining roads were in poor condition (20.00%). As for forest roads, it was determined that most of the roads were in medium condition (83.11%), 12.26% were in poor condition and 4.63% were in good condition.

4.2 Transportation Plan for Minimum Cost

The results indicated that the total transportation costs of all tree FECs was 22109.53 € in the first scenario considering only cost. It was found that the total transportation costs for Paşalar, Sarnıç, and Turfal FECs were 7,207.72 €, 8,916.93 €, and 5,984.87 €, respectively. The transportation cost summaries for the landing areas are shown in Table 4.1, 4.2, and 4.3.Total forest products transported to landing areas in Paşalar FEC was 8,852.50 m^3, while it was 10,327.11 m^3 and 6,352.73 m^3 in Sarnıç FEC and Turfal FEC, respectively. It was found that average unit transportation costs were 0.94 €/m^3, 0.82 €/m^3, and 0.88 €/m^3 for Paşalar, Sarnıç, and Turfal FECs, respectively. Aso (2014) reported that the average unit transportation cost of forest products was found to 1.35 €/m^3 in a study conducted in the city of Kahramanmaraş in 2014. It is assumed that the road conditions were relatively not good in this study which reduce the logging truck speed and increased the travel time, which them leads to higher transportation cost.

Table 4.1 : The transportation cost summary for Paşalar FEC.

Landings	Unit Cost (€/m^3)	Volume (m^3)	Total Cost (€)
P1	0.774	217.49	168.34
P2	0.455	878.05	399.51
P3	0.746	382.62	285.43
P4	0.449	239.90	107.72
P5	0.409	2394.53	979.36
P6	0.653	1206.51	787.85
P7	0.958	231.49	221.76
P8	1.153	412.23	475.30
P9	1.011	499.18	504.67
P10	0.81	414.97	336.13
P11	1.064	265.80	282.82
P12	1.614	601.14	970.23
P13	1.502	752.53	1130.30
P14	1.568	356.05	558.29

Table 4.2 : The cost summary for Sarnıç FEC.

Landings	Unit Cos (€/m^3)	Volume (m^3)	Total Cost (€)
S1	0.409	938.99	384.05
S2	0.423	1,300.18	549.98
S3	0.554	2,111.65	1169.85
S4	0.915	1,366.46	1250.31
S5	1.232	3,721.15	4584.46
S6	1.099	343.99	378.05
S7	1.102	544.687	600.25

Table 4.3: The cost summary for Turfal FEC.

Landings	Unit Cos (€/m^3)	Volume (m^3)	Total Cost (€)
T1	0.676	165.574	111.93
T2	0.732	554.387	405.81
T3	0.8	652.713	522.17
T4	0.658	702.788	462.43
T5	0.846	769.16	650.71
T6	0.723	764.701	552.88
T7	1.213	2,100.70	2548.15
T8	1.116	206.362	230.30
T9	1.147	436.346	500.49

It was found that the Sünlük Depot did not receive any forest products. All of the forest products from landings in Sarnıç FEC and Turfal FEC were transported to their own depots, Sarnıç and Karaorman Depot, respectively (Table 4.4).

Table 4.4: The routes from landing to depots for minimum cost scenario

FEC	Routes for Minimum Cost
Paşalar	P1 - Paşalar Depot
Paşalar	P 2 - Paşalar Depot
Paşalar	P 3 - Paşalar Depot
Paşalar	P 4 - Paşalar Depot
Paşalar	P 5 - Karapınar Depot
Paşalar	P6 - Karapınar Depot
Paşalar	P 7 - Karapınar Depot
Paşalar	P8 - Karapınar Depot
Paşalar	P9 - Karapınar Depot
Paşalar	P 10 - Sarnıç Depot
Paşalar	P 11 - Sarnıç Depot
Paşalar	P12 - Sarnıç Depot
Paşalar	P 13 - Sarnıç Depot
Paşalar	P 14 - Sarnıç Depot
Sarnıç	S 1 - Sarnıç Depot
Sarnıç	S2 - Sarnıç Depot
Sarnıç	S 3 - Sarnıç Depot
Sarnıç	S 4 - Sarnıç Depot
Sarnıç	S 5 - Sarnıç Depot
Sarnıç	S6 - Sarnıç Depot
Sarnıç	S 7 - Sarnıç Depot
Turfal	T 1 - Karaorman Depot
Turfal	T 2 - Karaorman Depot
Turfal	T 3 - Karaorman Depot
Turfal	T 4 - Karaorman Depot
Turfal	T 5 - Karaorman Depot
Turfal	T 6 - Karaorman Depot
Turfal	T7 - Karaorman Depot
Turfal	T 8 - Karaorman Depot
Turfal	T 9 - Karaorman Depot

In Paşalar FEC, forest products from four landings (P1-P4) were transported to Paşalar Depot and five landings (P5-P9) were to Karapınar Depot; however, five landings (P10-P14) were transported to other FEC's Depot (Sarnıç Depot). Akay and

Erdaş(2007) also reported that some of the products were transported to different FEC's Depots, which can be allowed based on a special protocol between two FECs. Figures 4.1-4.3 illustrates the most efficient routes for minimizing transportation costs in the first scenario.

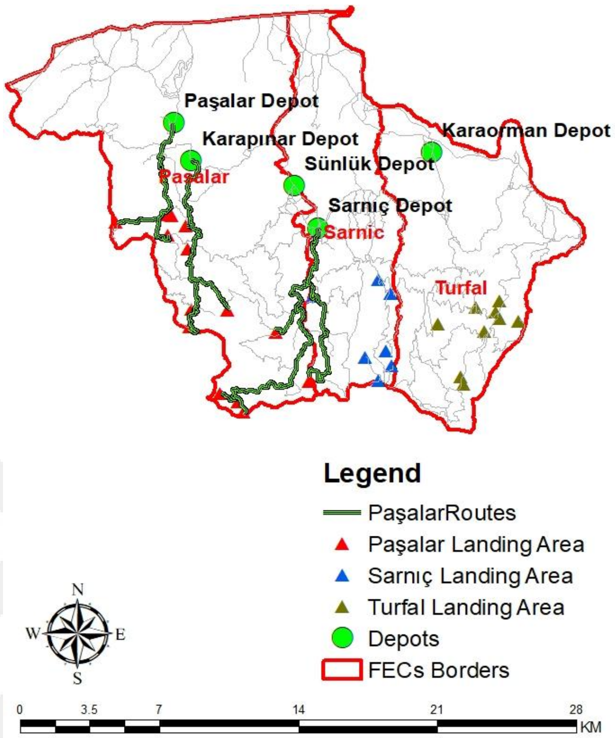

Figure 4.1: The optimum routes for minimum cost in Paşalar FEC.

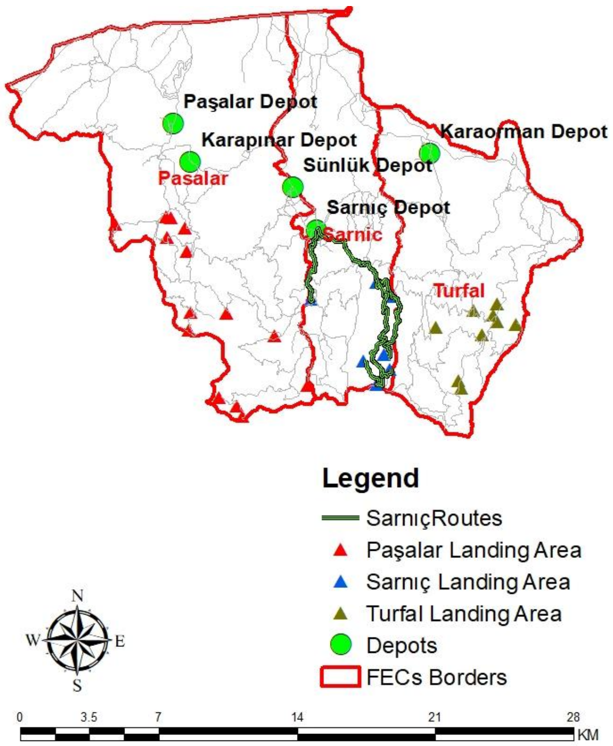

Figure 4.2: The optimum routes for minimum cost in Sarnıç FEC.

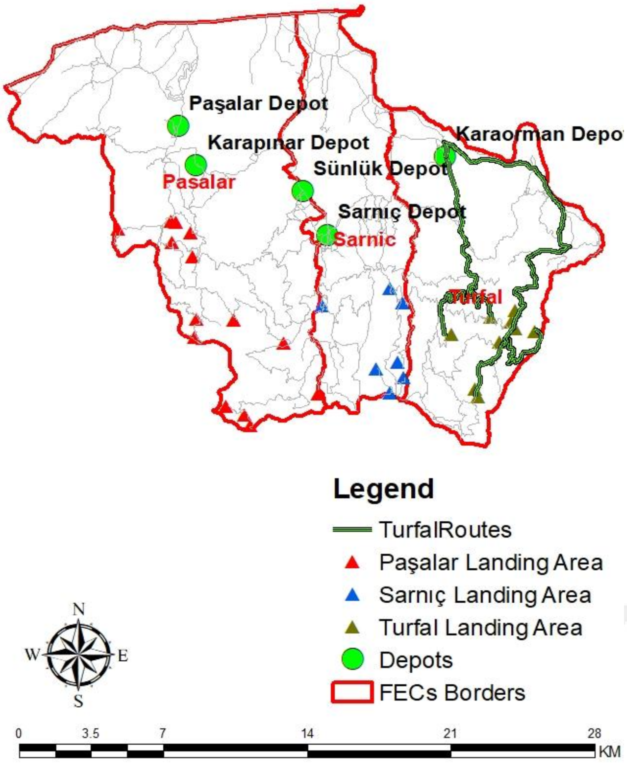

Figure 4.3: The optimum routes for minimum cost in Turfal FEC

4.3 Transportation Plan for Driver Safety

The results indicated that the total transportation safety costs of all tree FECs was 34,984.22 € in the second scenario considering only safety. It was found that the total transportation safety costs for Paşalar, Sarnıç, and Turfal FECs were 9,812.80 €, 17,238.90 €, and 7,932.53 €, respectively. The transportation safety cost summaries for the landing areas are shown in Table 4.5, 4.6, and 4.7.It was found that average unit transportation safety costs were 1.3 €/m^3, 1.6 €/m^3, and 1.2 €/m^3 for Pasalar, Sarnıç, and Turfal FECs, respectively.

The optimum routes that consider safety in the second scenario are shown in Figure 4.4-4.6. It was found that the Paşalar and Sünlük Depots did not receive any forest products. All of the forest products from landings in Turfal FEC were transported to its own depot (Karaorman Depot) (Table 4.8). In Paşalar FEC, forest products from nine landings (P1-P9) were transported to Karapınar Depot and five landings (P10-P14) were to Sarnıç Depot. On the other hand, in Sarnıç FEC, products from one landing (S1) were transported to its own depot (SarnıçDepota) while from six landings (S2-S7) were to other FEC’s Depot (Karaorman Depot).

Table 4.5: The transportation safety cost summary for Paşalar FEC.

Landings	Unit Cost (€/m^3)	Volume (m^3)	Total Cost (€)
P1	0.985	217.49	214.23
P2	0.66	878.05	579.52
P3	0.89	382.62	340.53
P4	0.66	239.90	158.33
P5	0.576	2394.53	1379.25
P6	0.89	1206.51	1073.79
P7	1.245	231.49	288.20
P8	1.235	412.23	509.10
P9	1.041	499.18	519.65
P10	1.469	414.97	609.60
P11	1.52	265.80	404.02
P12	2.203	601.14	1324.30
P13	2.176	752.53	1637.51
P14	2.176	356.05	774.77

Table 4.6: The safety cost summary for Sarnıç FEC.

Landings	Unit Cos (€/m^3)	Volume (m^3)	Total Cost (€)
S1	0.444	938.99	416.91
S2	1.819	1,300.18	2365.03
S3	1.363	2,111.65	2878.18
S4	1.71	1,366.46	2336.65
S5	2.02	3,721.15	7516.72
S6	2.02	343.99	694.86
S7	1.892	544.687	1030.55

Table 4.7: The safety cost summary for Turfal FEC.

Landings	Unit Cos (€/m^3)	Volume (m^3)	Total Cost (€)
T1	0.802	165.574	132.79
T2	0.947	554.387	525.00
T3	0.91	652.713	593.97
T4	0.947	702.788	665.54
T5	1.701	769.16	1308.34
T6	0.997	764.701	762.41
T7	1.446	2,100.70	3037.61
T8	1.411	206.362	291.18
T9	1.411	436.346	615.68

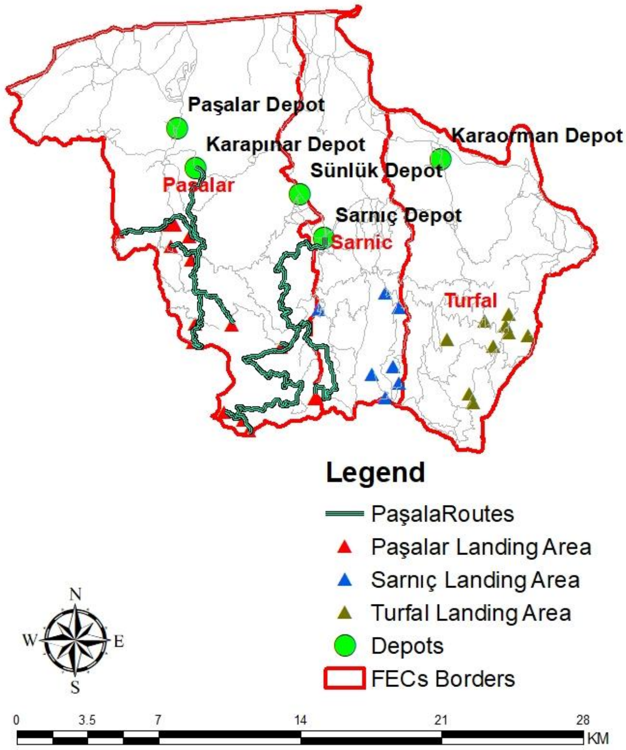

Figure 4.4: The optimum routes for safety in Paşalar FEC.

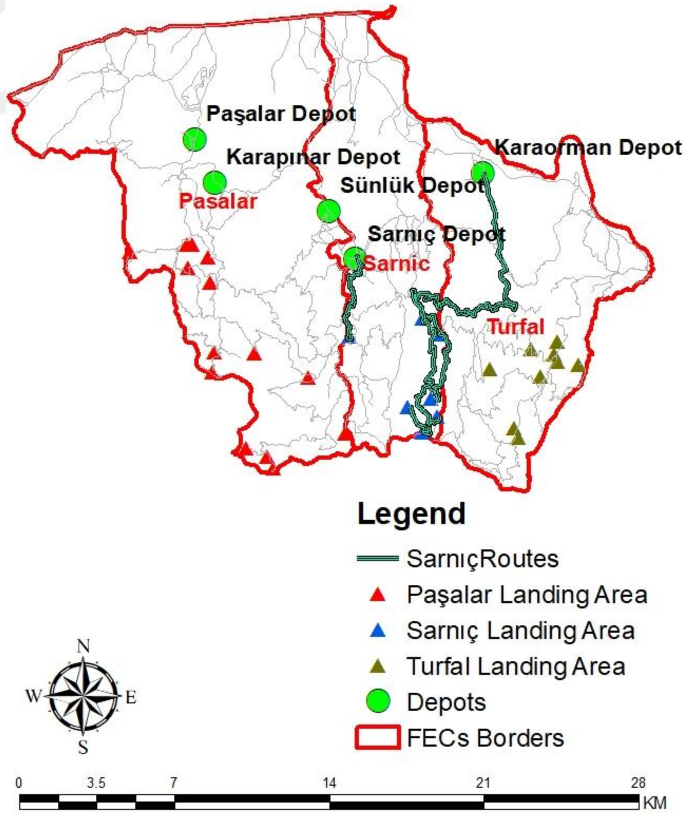

Figure 4.5: The optimum routes for safety in Sarnıç FEC.

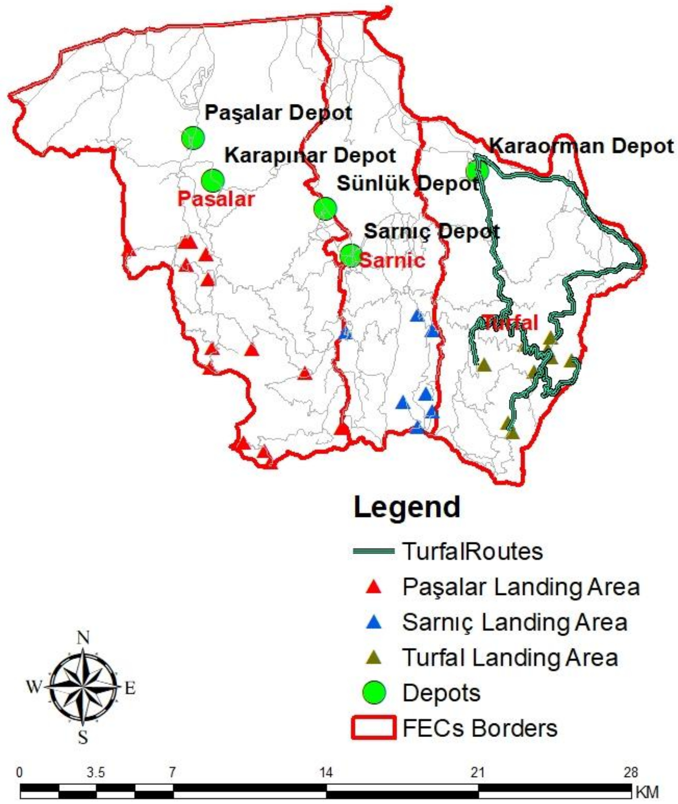

Figure 4.6: The optimum routes for safety in Turfal FEC.

Table 4. 8: The routes from landing to depots for safety scenario

FEC	Routes for Safety
Paşalar	P1 - Karapınar Depot
Paşalar	P2 - Karapınar Depot
Paşalar	P3 - Karapınar Depot
Paşalar	P4 - Karapınar Depot
Paşalar	P5 - Karapınar Depot
Paşalar	P6 - Karapınar Depot
Paşalar	P7 - Karapınar Depot
Paşalar	P8 - Karapınar Depot
Paşalar	P9 - Karapınar Depot
Paşalar	P10 - Sarnıç Depot
Paşalar	P11 - Sarnıç Depot
Paşalar	P12 - Sarnıç Depot
Paşalar	P13 - Sarnıç Depot
Paşalar	P14 - Sarnıç Depot
Sarnıç	S1 - Sarnıç Depot
Sarnıç	S2 - Karaorman Depot
Sarnıç	S3 - Karaorman Depot
Sarnıç	S4 - Karaorman Depot
Sarnıç	S5 - Karaorman Depot
Sarnıç	S6 - Karaorman Depot
Sarnıç	S7 - Karaorman Depot
Turfal	T1 - Karaorman Depot
Turfal	T2 - Karaorman Depot
Turfal	T3 - Karaorman Depot
Turfal	T4 - Karaorman Depot
Turfal	T5 - Karaorman Depot
Turfal	T6 - Karaorman Depot
Turfal	T7 - Karaorman Depot
Turfal	T8 - Karaorman Depot
Turfal	T9 - Karaorman Depot

4.4 Comparison of Transportation Plans

The results indicated that total transportation cost increased in the second scenario of considering safety by 58.23% (12874.70 €) (Table 4.9). In terms of cost differences in each FEC, transportation cost increased in the second scenario by 36.14%, 93.33%, and 32.54% for Paşalar, Sarnıç, and Turfal FECs, respectively. It was found that the highest amount of increase in the second scenario was in Sarnıç FEC since the total volume transported from Sarnıç FEC was much more than the ones transported from the other FECs. In the previous studies, it was reported that transportation cost is directly influenced by the amount of product transported (Akay and Erdaş, 2007).

Table 4.9: Totaltransportation cost comparison of two scenarios

FECs	Total Volume (m^3)	Minimum Cost Scenario (€)	Safety Scenario (€)	Differences
PaşalarFEC	8852.50	7207.72	9812.80	2605.08
SarnıçFEC	10327.11	8916.93	17238.90	8321.96
Turfal FEC	6,352.73	5984.87	7932.53	1947.65
Total	25,532.34	22109.53	34984.22	12874.70

According to the results in Paşalar FEC, the average unit cost differences was 0.326 €/m^3 while the average transportation cost differences of the forest products transported from 14 Landings was 186.08 €. In Sarnıç FEC, the average unit cost differences was 0.791 €/m^3 while the average transportation cost differences of the forest products transported from 7 Landings was 1188.9 €.

In the case of Turfal FEC, the average unit cost differences was 0.296 €/m^3 while the average transportation cost differences of the forest products transported from 9 Landings was 216.4 €. The transportation cost Comparison for the landing areas are shown in Table 4.10, 4.11, and 4.12.Therefore, the cost of transportation for the case of driver safety increased in for each hauling route for three FECs.

Table 4.10: The transportation cost comparison for Paşalar FEC.

Landings	Unit Cost	Cost
P1	0.211	45.89
P2	0.205	180.00
P3	0.144	55.10
P4	0.211	50.62
P5	0.167	399.89
P6	0.237	285.94
P7	0.287	66.44
P8	0.082	33.80
P9	0.03	14.98
P10	0.659	273.47
P11	0.456	121.21
P12	0.589	354.07
P13	0.674	507.21
P14	0.608	216.48

Table 4.11: The cost comparison for Sarnıç FEC.

Landings	Unit Cost	Cost
S1	0.035	32.86
S2	1.396	1815.05
S3	0.809	1708.32
S4	0.795	1086.34
S5	0.788	2932.27
S6	0.921	316.81
S7	0.035	430.30

Table 4.12: The cost comparison for Turfal FEC.

Landings	Unit Cost	Cost
T1	0.126	20.86
T2	0.215	119.19
T3	0.11	71.80
T4	0.289	203.11
T5	0.855	657.63
T6	0.274	209.53
T7	0.233	489.46
T8	0.295	60.88
T9	0.264	115.20

5. CONCLUSIONS AND RECOMMENDATIONS

In this study, the transportation plans were developed by considering two scenarios in which one aimed to minimize transportation cost and other aimed to provide logging truck drivers with safe transportation. The results indicated that optimum routes were different in two scenarios. As anticipated, the transportation expenses in the second scenario exceeded those of the first scenario.

In the road network analysis, design speed of the logging trucks varies depending on road type (asphalt, gravel, forest road) and road conditions (good, medium, poor); therefore, these variables affected the productivity and the cost of transportation. The road safety scores were assigned to the road sections according to the road type and road conditions, thus, they also affected the transportation safety of logging truck drivers.In this scenario, the optimal routes prioritizing transportation safety often diverged from those aimed at minimizing transportation costs. Consequently, forest products from certain landing areas were transported to different depots compared to the first scenario.

The sample transportation plans indicated that GIS-based network analysis can be effectively used by decision-makers who are willing to pay more to ensure safety of the logging truck drivers. On the other hand, forest transportation activities can be affected when there is any accident or operation delay on the unsafe forest roads, which will increase the total transportation cost and overall cost of producing forest products. Therefore, preferring safe transportation would save money in long run as forest transportation operation will more likely to continue whole season without any delay due to road safety issues.

In the future studies, the effects of improving forest roads (Type-B secondary roads) standards on transportation safety should considered. Forest roads should be properly reconstructed according to safety requirements. Improving forest roads standards may require some major costs; however, the total major repair and road maintenance cost will be dramatically decrease in long run.

Additionally, enhanced forest roads will not only guarantee transportation safety but also offer improved access to forest resources for various forestry activities including reforestation, protection, management, logging operations, and recreational purposes.Another subject related with the effect of preferring safety in forest transportation would be investigating the total net revenue of the transportation cost by considering sale prices of the forest products in forest depots. The selling price of the forest products may vary as their prices would be less in forest deport located in rural areas or far from the production sites.

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