A MULTICRITERIA PREVENTIVE MAINTENANCE APPROACH AND ITS APPLICATION IN THE AFTER-SALES SERVICE OF A TRUCK AND BUS COMPANY

ÇOK KRİTERLİ BİR ÖNLEYİCİ BAKIM YAKLAŞIMI VE BİR KAMYON VE OTOBÜS ŞİRKETİNİN SATIŞ SONRASI SERVİSİNDE UYGULANMASI

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Submitted to
Graduate School of Science and Engineering of Hacettepe University
as a Partial Fulfillment to the Requirements
for the Award of the Degree of Master of Science
in Industrial Engineering

2019

This work titled "**A Multicriteria Preventive Maintenance Approach and Its Application in the After-Sales Service of a Truck and Bus Company**" by **GÜRKAN GÜVEN GÜNER** has been approved as a thesis for the Degree of Master of Science in Industrial Engineering by the Examining Committee Members mentioned below.

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ÖZET

ÇOK KRİTERLİ BİR ÖNLEYİCİ BAKIM YAKLAŞIMI VE BİR KAMYON VE OTOBÜS ŞİRKETİNİN SATIŞ SONRASI SERVİSİNDE UYGULANMASI

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Otomotiv endüstrisinde hizmet veren şirketler için müşteri memnuniyetinin sağlanması, şirket prestijinin yükseltilmesi ve dolayısı ile de müşteri havuzunun genişletilerek şirket gelirinin artırılması açısından kritik öneme sahiptir. Beklenmedik bir arıza sonucunda araçların yolda kalması problemi, araçların zamanında hizmet verememesi ve dolayısıyla da müşteri memnuniyetsizliğinin oluşması ile sonuçlanmaktadır. Günümüzde zaman faktörünün ne derece kritik olduğu göz önünde bulundurulduğunda, özellikle gıda ürünleri, yolcu veya askeri mühimmat taşıyan araçlar için taşınan ürünlerin zamanında teslim edilebilmesi amacıyla araçların arıza sonucu yolda kalmaması çok değerlidir.

Bu çalışmada, belirtilen sorunun en aza indirilebilmesi adına çok kriterli bir önleyici bakım yaklaşımı geliştirilmiştir. Önleyici bakım uygulaması kapsamında, araçlara yolda kalmadan önce bakım hizmetinin verilmesi ve müşteri memnuniyetinin artırılması planlanmıştır. Bunun için öncelikle müşterileri yolda bırakabilecek kritik öneme sahip araç parçalarının belirlenmesi, daha sonra bu araç parçalarının arızalanma olasılıklarının kapsamlı olarak analiz edilmesi, araç parçaları için önleyici bakım planı oluşturulması ve analizlerden elde edilen sonuçlar ışığında müşterilerin bilgilendirilmesi hedeflenmiştir. Kritik parçalar Çok Kriterli Karar Verme yaklaşımlarıyla belirlenmiştir. Daha sonra kritik parçaların her biri için arızalanma olasılık dağılımları ve parametreleri tespit edilmiş ve araçların yolda kalma olasılıkları belirlenen faktörler açısından hesaplanmıştır. Önleyici bakım planları oluşturulurken müşteri maliyeti, şirket maliyeti, araç yetkili servisinin kapasite kullanımı ve olası diğer tüm faktörler göz önünde bulundurulmuş ve bu faktörlerden en uygun olanları belirlenerek çalışmada kullanılmıştır.

Önerilen bu çok kriterli önleyici bakım yaklaşımı, Ankara’da müşteri memnuniyetini artırmak amacıyla yeni önleyici bakım stratejileri geliştirmeyi hedefleyen bir otobüs ve kamyon firması üzerinde uygulanmıştır. Geçmiş yıllardan alınan ayrıntılı veriler incelenerek öncelikle önleyici bakım için kritik parçalar belirlenmiştir. Daha sonra bu parçalar için araç bazında servis ve yol yardımı verileri incelenmiş ve parçaların güvenilirlikleri üzerine istatistiksel analizler gerçekleştirilmiştir. Bu analizlerin sonuçlarıyla da maliyet ve servis kapasitesi gibi faktörler göz önüne alınarak alternatif bakım planları oluşturulmuştur. Çalışmanın, uygulama yapılan firma ve otomotiv endüstrisinde hizmet veren diğer işletmeler için yüksek müşteri memnuniyetine sahip önleyici bakım planları geliştirilmesi açısından yol gösterici olması hedeflenmektedir.

Anahtar Kelimeler: Önleyici Bakım, Güvenilirlik Analizi, Çok Kriterli Karar Verme, Arıza Analizi, Satış Sonrası Hizmet.

ABSTRACT

A MULTICRITERIA PREVENTIVE MAINTENANCE APPROACH AND ITS APPLICATION IN THE AFTER-SALES SERVICE OF A TRUCK AND BUS COMPANY

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June 2019, 64 pages

Providing customer satisfaction has critical significance for companies that give service in automotive industry in terms of enhancing company’s prestige and consequently, increasing company’s profit by expanding customer volume. The problem of being stranded on the road as a result of an unexpected failure leads to not being able to give timely service, and consequently, customer dissatisfaction. Considering the criticality of time nowadays, especially for vehicles that transport food products, passengers or ammunition, not being stranded on the road as a result of failure is very valuable in terms of delivering the transported products timely.

In this study, a multiple criteria preventive maintenance approach was developed to minimize the stated problem. Within the scope of preventive maintenance implementation, giving maintenance service to vehicles before they become stranded on the road and increasing customer satisfaction were planned. For this purpose, firstly determining vehicle parts that have critical importance that can make customers stranded on the road, and then comprehensively analyzing failure probabilities of these vehicle parts, forming the preventive maintenance plan and informing customers based on the results were aimed. Critical parts were determined by Multiple Criteria Decision Making (MCDM) approaches. Then, for each critical part, failure probability distributions and parameters were determined, and probabilities of being stranded on the road for vehicles were evaluated with respect to determined factors. When forming preventive maintenance plans, customer cost, company cost, capacity usage of authorized vehicle service and other probable factors were considered and most appropriate ones were used in the study.

This proposed multiple criteria preventive maintenance approach was implemented on a truck and bus company in Ankara that aims to develop new preventive maintenance strategies with the intent of increasing customer satisfaction. By investigating detailed data gathered from past years, firstly critical parts were determined for preventive maintenance. Then, service and roadside assistance data on the basis of vehicles for these parts were investigated and statistical analyses on reliabilities of parts were performed. By results of these analyses, alternative maintenance plans were formed considering factors like cost and service capacity. This study aims to become a guide for the implemented company and other companies in automotive industry in developing preventive maintenance plans that have higher customer satisfaction.

Keywords: Preventive Maintenance, Reliability Analysis, Multiple Criteria Decision Making, Failure Analysis, After Sale Service

TEŞEKKÜR

Lisansüstü eğitimim süresince engin bilgi ve tecrübelerinden fazlaca faydalanma fırsatı bulduğum, sadece bilimsel anlamda değil her anlamda sahip oldukları bilgi birikimleriyle öğrencilerine yol gösteren, desteklerini hiçbir zaman benden esirgemeyen ve her zaman yanımda olduklarını fazlasıyla hissettiren çok değerli hocalarım Sayın Dr. Öğr. Üyesi Ceren TUNCER ŞAKAR'a ve Sayın Dr. Öğr. Üyesi Barbaros YET'e,

Hayatım boyunca hiçbir desteğini benden esirgemeyen ve her zaman yanımda olan aileme,

Sonsuz Teşekkür Ederim.

Gürkan Güven GÜNER

Mayıs 2019, Ankara

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ABBREVIATIONS

AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
DM	Decision Maker
ELECTRE	Elimination et Choice Translating Reality
MAUT	Multi-Attribute Utility Theory
MCDM	Multiple Criteria Decision Making
MTBR	Mean Time between Replacements
MTTF	Mean Time to Failure
PROMETHEE	The Preference Ranking Organization Method for Enrichment Evaluation
SAW	Simple Additive Weighting
SMART	The Simple Multi Attribute Rating Technique
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution

1. INTRODUCTION

Preventive maintenance is a type of maintenance operation that is implemented at a pre-established period before a failure occurs or causes serious problems to the system, so it is a time dependent maintenance operation. The aim of the preventive maintenance operation is to increase the system's reliability and decrease the system's failure rates, make the system continue its operations without interruptions and minimize costs that are due to these interruptions of the system. For example, one of the most prevalent preventive maintenance implementations is automotive oil alteration process. The purpose of this operation is discharging the oil from the engine before the pollution of the oil causes extreme corrosions to parts of the engine and so, minimizing the cost of failures.

Any well-planned preventive maintenance operation can really be productive for the system but this question has to be answered before the maintenance is implemented, "Is this preventive maintenance operation really essential for the system?". Redundant preventive maintenance implementations can cause unnecessary interruptions in the system and costs caused by loss of time. On the other hand, there can be a real need for preventive maintenance practices for the system but unfavorable planned maintenance practices can again cause excessive costs. Because of all of these reasons, before deciding to implement preventive maintenance operations to the system, the system must be completely analyzed for realizing the necessity of preventive maintenance practices; and if they are necessary, these practices must be well-planned to avoid extra costs.

Although preventive and predictive maintenance are sometimes used interchangeably, they are actually different concepts. Although both maintenance concepts try to find solutions for extending the product's life cycle, prevent improbable failures and save profit of company, they differ in some ways. Preventive maintenance is implemented while the machine is under normal operation for preventing probable failures and decreasing time loss. At the determined time, machine is broken down and preventive operations on this machine are implemented. Preventive maintenance is planned by a schedule that depends on certain periods which are usually determined by the producer with respect to usage level of the machine. For instance, forklift producers recommend implementing preventive maintenance in each 150 to 200 hours of forklift usage. Implementing preventive maintenance can extend the life cycle of machine, raise the efficiency, and decrease the cost of maintenance operations. Predictive maintenance, on the other hand, directly monitors system (or machine) performance throughout normal work or process for predicting the defect. Therefore, instead of scheduling maintenance by usage level (hours) without considering performance, like in previous preventive maintenance example about forklifts, firms monitor and check conditions like greasing and noise corrosion of machine continuously for determining actual mean time of failure. The major difficulty of the predictive maintenance is that this maintenance type is extremely based on information and making accurate interpretation depends on this information. Predictive maintenance is generally accepted as a type of preventive maintenance method. As opposed to preventive and predictive maintenance, some maintenance applications are performed after the failure occurs. Corrective Maintenance is a type of maintenance, which is applied on the system (machine, item, etc.) after the failure happens without any schedule. Corrective maintenance can be implemented as urgent or deferred according to type of problem to the system. Figure 1.1 illustrates the types of maintenance strategies.

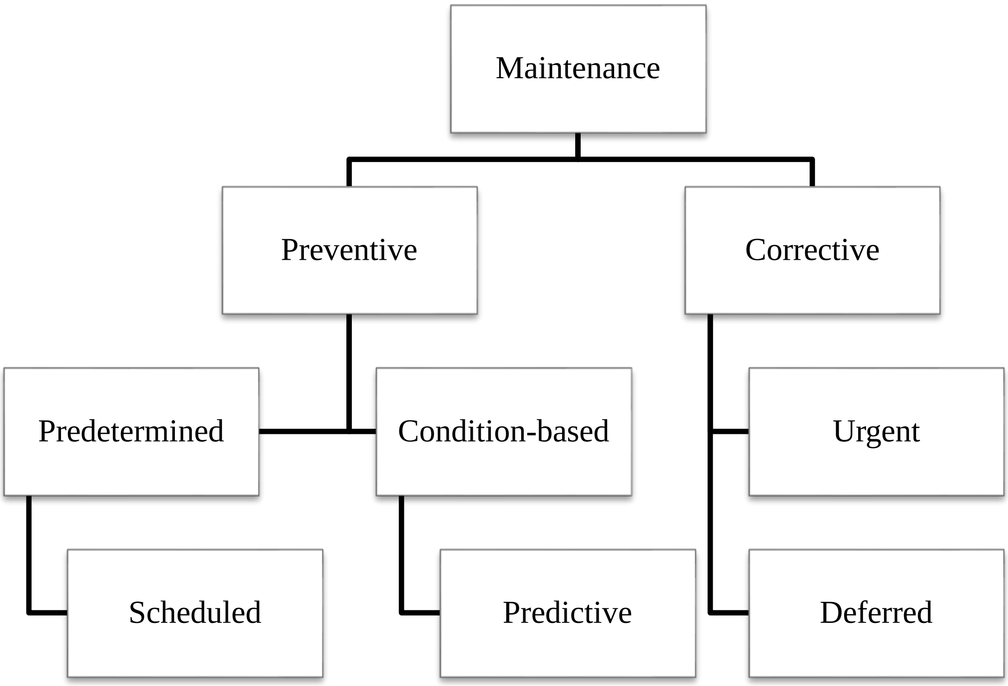

Figure 1.1. Types of maintenance strategies

Intrinsically, there is a direct proportion between amount of preventive maintenance actions and cost of these actions. However, if preventive maintenance actions are reduced, corrective maintenance actions increase to fix the failure where these two kinds of maintenance methods are used in a system. Therefore, it can be said that there is an inverse proportion between cost of corrective maintenance actions and amount of preventive maintenance actions in these kinds of systems. The aim of the Decision Maker (DM) is to find the optimal amount of preventive maintenance actions that minimizes the total cost which is the sum of preventive and corrective maintenance costs. The relationship between the preventive and corrective maintenance is as the following figure (Risktec official website).

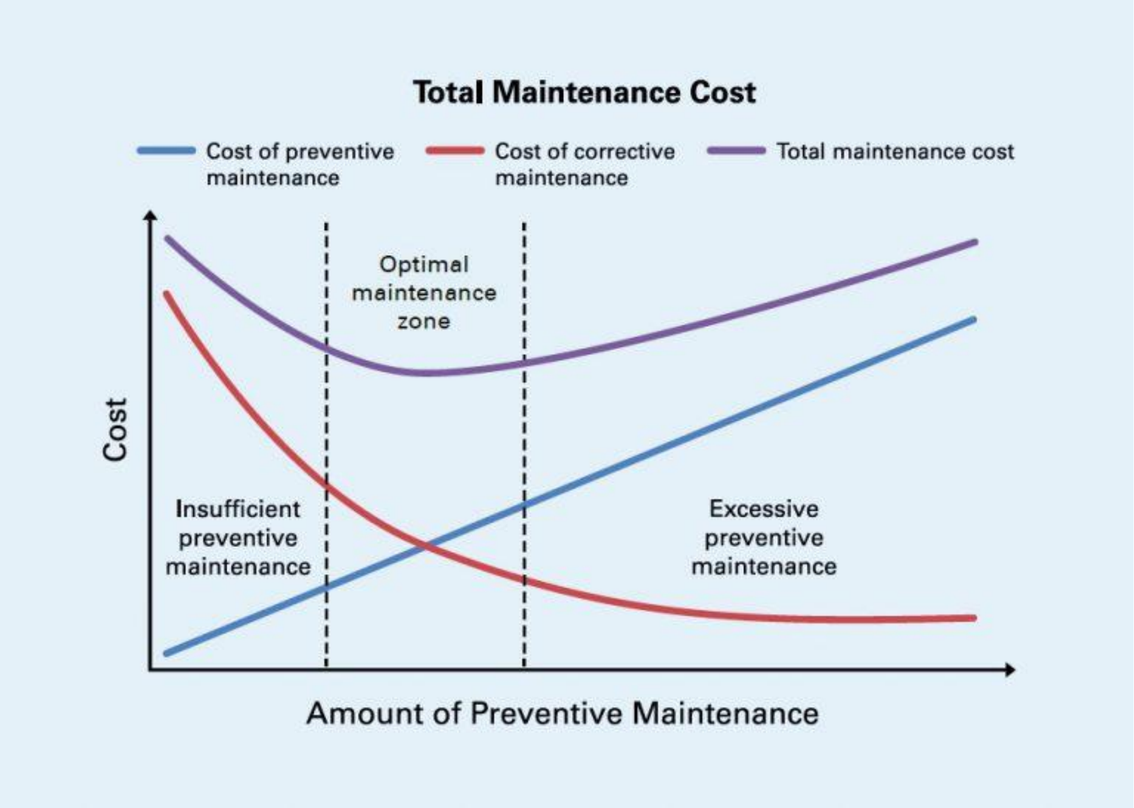

Figure 1.2. The relation between cost and amount of preventive maintenance

It is seen in Figure 1.2 that when amount of preventive maintenance increases, cost of preventive maintenance rises and cost of corrective maintenance decreases. It is seen that insufficient and excessive preventive maintenance actions do not give minimum cost. The optimal amount of preventive maintenance is at the point where corrective and preventive maintenance cost lines intersect. The purpose is finding this point to minimize total maintenance cost.

Preventive maintenance is very important in after sales operations of companies because of the need of keeping customer satisfaction at a high level. Possible defects on a product at undesirable times can create huge time and money losses. Most importantly, this creates customer dissatisfaction about the producing company. This situation can occur in many products but for some of them, undesirable failures must be at the minimum level. For instance, when we inspect the automotive industry, commercial vehicles that transport time-sensitive materials (perishable foodstuff, military supplies, etc.) or passengers must deliver them in correct time as much as possible. Late delivery means loss of money for firms that operate these commercial vehicles. When undesirable failures that make vehicles inoperative occur when the vehicle is on the road, drivers have to pull the vehicle off the road and wait for their authorized service workers to take the vehicle to an authorized service area and fix the problem.

However, depending on the geographical location of the failure, arrival of authorized service workers and the transfer of the vehicle can take a long time. Depending on the type and seriousness of the failure, time spent for fixing the failure can also take a long time. Especially, if the defective part must be changed by a new one but the new part is not available in the country and it must be brought from abroad, waiting time of the vehicle can be significantly long. If all of these time losses exceed the admissible limit of customer, customer dissatisfaction starts to increase for each lost second. To prevent this customer dissatisfaction problem, manufacturing companies must find possible solutions for preventing failures that happen at undesirable times. To obtain long-run and accurate solutions, companies must benefit from scientific methods. By applying a scientific approach to the mentioned problem, all relevant aspects can be considered and comprehensive solutions can be generated.

In this thesis, a preventive maintenance plan is proposed for the vehicles of a truck and bus company in Ankara. Currently, standard and general maintenance practices are applied in the company. However, besides those, the company wants to apply optional and extra preventive maintenance practices. The reason for this is that the company finds customer satisfaction provided by current preventive maintenance applications insufficient. There are several vehicle parts which need to be considered to apply preventive maintenance and there is more than one criterion to evaluate the importance of vehicle parts. Also, reliabilities of vehicle parts differ from each other. By considering all of these conditions, a new preventive maintenance plan is developed to increase current customer satisfaction level. Firstly, critical vehicle parts are selected with multiple criteria decision making (MCDM) methods by considering different factors that determine criticality. Then, statistical analyses are implemented for probability distributions of failure frequencies of vehicle parts. Using reliability tools, maintenance plans that have different reliability levels, maintenance intervals and maintenance costs are developed. Then, total maintenance costs that include and do not include the preventive maintenance cost are compared. The saving ratios that are gained by different preventive maintenance plans are indicated. Also, the authorized service capacity utilization for different preventive maintenance plans are compared to current capacity.

In Section 2 of the thesis, the MCDM methods used are explained and the literature on MCDM and preventive maintenance is reviewed. In Section 3, necessary information and literature review related to reliability and preventive maintenance are provided. In Section 4, the methodology of the preventive maintenance plan for the company and the application results are given. Section 5 finalizes the thesis with conclusions and discussions.

2. MULTIPLE CRITERIA DECISION MAKING

MCDM is a collection of methods used for problems that involve multiple, and generally conflicting criteria. MCDM helps to find the best solution for the Decision Makers (DMs) of the problem. However, there is not a unique optimal solution in these problems since a solution with the best values in all criteria is generally not feasible. Different solutions perform well in different criteria or a combination of them. Therefore, it is required to elicit the preferences of the DM of the problem and obtain the best solutions accordingly.

The problems of choice, ranking and sorting can be solved by MCDM methods (Meyer et al., 2005). The purpose of the problem of choice is to determine a single solution or a small subset of solutions that are best for the DM. The problem of ranking orders the solutions from the most to the least preferred; and the problem of sorting groups solutions in preference ordered classes.

There are several problem solving techniques in the literature for MCDM methods. Among the most widely-used ones, Analytical Hierarchy Process (AHP) is a technique which makes a hierarchy among the purpose, criteria and alternatives to determine the priority level of alternatives based on pairwise comparisons (Saaty, 2006). Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) is used to determine an alternative which has shortest and longest geometric distance to the ideal and nadir solution, respectively. Ideal and nadir solutions are the solutions that include all the best and worst values of criteria, respectively (Olson, 2004). Simple Additive Weighting (SAW) method, which is also known as weighted linear combination method, is used to determine the weighted sum of performance levels for all alternatives (Afshari et al., 2010). Elimination et Choice Translating Reality or Elimination and Choice Expressing Reality (ELECTRE) method uses indexes of concordance and discordance to investigate the relations of outranking for all alternatives (de Almeida, 2007). Simple Multi Attribute Rating Technique (SMART) is a simple method of decision support system that is implemented by weights of each criterion which shows the importance level in comparison with other criteria (Risawandi and Rahim, 2016). Analytical Network Process (ANP) method, which is a more general form of AHP, makes a network among purpose, criteria and alternatives (Saaty, 2004). Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) is an outranking technique that is used for decision situations like choice, prioritization, resource allocation, ranking and conflict resolution (Brans and Mareschal, 2016).

2.1. AHP Method

AHP is an MCDM choice method developed to make a selection among relatively small number of alternatives considering criteria that can be of various nature. AHP makes a hierarchy among the purpose, decision criteria and decision alternatives, and it prioritizes these alternatives. This method was developed by Thomas L. Saaty for the purpose of creating solutions to MCDM problems (Saaty, 1990). In this method, first of all, decision criteria are compared to each other in pairs by the DM to form the comparison matrix. To make these comparisons, the DM uses a significance scale. There are values from 1 to 9 that represent the importance level of a criterion as opposed to another. The significance scale of AHP is in Table 2.1.

Table 2.1. The significance scale of AHP

Value	Value Definition
1	Two criteria have the same significance level
3	First criterion is more significant than the second criterion
5	First criterion is much more significant than the second criterion
7	First criteria is excessively more significant than the second criterion
9	First criterion is absolutely more significant than the second criterion
2,4,6,8	Intermediate values

Assume that there are *m* alternatives and *n* criteria in the problem. The comparison matrix of criteria is made by the DM using significance scale as the following.

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{2.1}$$

The comparison matrix is represented by *A* and each value in the comparison matrix is represented as a_{ij} ($i = 1,\ldots,n$; $j=1,\ldots,n$). After that, percentage significance distributions of criteria are determined. Column vectors of comparison matrix are used to determine significance distributions. These column vectors are as the following.

$$B1 = \begin{bmatrix} b_{11} \\ \vdots \\ b_{n1} \end{bmatrix}, \quad \dots \quad , Bn = \begin{bmatrix} b_{1n} \\ \vdots \\ b_{nn} \end{bmatrix} \tag{2.2}$$

Column vectors are represented by *Bj* and values of vectors are represented by b_{ij}. The values in these column vectors are calculated by the help of following equation.

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{2.3}$$

Then, column vectors are combined as a matrix and the new normalized matrix *C* is created as the following.

$$\begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nn} \end{bmatrix} \tag{2.4}$$

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1n} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nn} \end{bmatrix} \tag{2.5}$$

The values in normalized decision matrix are represented as c_{ij}. By the help of matrix *C*, priority vector *W* is evaluated as the following. The values in priority vector are represented by w_i.

$$w_i = \frac{\sum_{j=1}^{n} c_{ij}}{n} \tag{2.6}$$

$$W = \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} \tag{2.7}$$

After these steps, the consistency ratio *CR* is evaluated to check the consistency between priority vector and *CR*. The calculation of *CR* is made with the help of number of criteria and the main value which is represented by λ. First of all, priority vector *W* and comparison matrix *A* are multiplied and then, the resulting column vector *D* is evaluated to calculate λ.

$$D = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} . \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} = \begin{bmatrix} d_1 \\ \vdots \\ d_n \end{bmatrix} \tag{2.8}$$

The value E_i for each criterion is found by dividing mutual values of column vector *D* and column vector *W.*

$$E_i = \frac{d_i}{w_i} \tag{2.9}$$

The arithmetic mean of all E_i is equal to λ.

$$\lambda = \frac{\sum_{i=1}^{n} E_i}{n} \tag{2.10}$$

After the calculation of λ*,* the consistency indicator *CI* is evaluated by the following equation.

$$CI = \frac{\lambda - n}{n - 1} \tag{2.11}$$

After that, *CI* is divided by the random indicator value *RI* that corresponds to the total number of criteria and *CR* is calculated.

$$CR = \frac{CI}{RI} \tag{2.12}$$

If *CR* is smaller than 0.1, it means that the comparison of criteria is consistent.

The AHP method can also be implemented to compare alternative pairings for each criterion. The implemented steps (use of significance scale, construction of comparison matrix and priority vector, calculation of consistency ratio, etc.) for alternative comparison are the same as the steps of criteria comparison. In this thesis, AHP method was used for only finding the weights of criteria.

2.2. TOPSIS Method

TOPSIS is a ranking method used in MCDM that was developed in 1981 (Hwang and Yoon, 1981). There are many studies in literature that use TOPSIS. These studies are in different areas like supply chain management (Wu, 2007), logistics (Chen et al., 2014)**,** design and production systems (Virmani et al., 2017), business and marketing management (Wu et al., 2010), health and environment management (Yarahmadi et al., 2015)**,** human resources management (Kelemenis and Askounis, 2010)**,** energy management (Sianaki and Masoum, 2013) and water resources management (Tang et al., 2018)

There are seven major implementing steps in TOPSIS method. In the first step, decision matrix is formed. In a decision making problem, assume that there are *m* alternatives and *n* criteria. The decision matrix of this problem is shown as the following.

$$D = \begin{bmatrix} x_{11} \cdots x_{1j} \cdots x_{1n} \\ x_{i1} \cdots x_{ij} \cdots x_{in} \\ x_{m1} \cdots x_{mj} \cdots x_{mn} \end{bmatrix} \tag{2.13}$$

In the matrix *D*, x_{ij} represents the value of i^{th} alternative for j^{th} criterion.

In the second step of analysis, decision matrix is normalized. For the purpose of evaluating all criteria as dimensionless and making comparison between criteria, each x_{ij} value in decision matrix *D* is converted to r_{ij} value with the following normalization equations.

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} \left(X_{ij}\right)^2}} \tag{2.14}$$

$$r_{ij} = 1 - \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} \left(X_{ij}\right)^2}} \tag{2.15}$$

Equation (2.14) and (2.15) are for maximization and minimization criteria, respectively. In the third step of the analysis, weighted normalized matrix is determined. The weighted values v_{ij} in weighted normalized matrix are evaluated by multiplying weight w_j of each criterion and values of criteria r_{ij} in normalized decision matrix.

$$v_{ij} = r_{ij}.w_j \tag{2.16}$$

In the fourth step, ideal and nadir points are calculated. Ideal point that is shown as A^+ is obtained by best performance scores in weighted normalized matrix and nadir point that is shown as A^- is obtained by worst performance scores in weighted normalized matrix. In TOPSIS, determining the alternative that is closest to the ideal and furthest to the nadir point is sought. These are calculated as the following.

$$A^+ = (v_1^+, v_2^+, \dots, v_n^+) \tag{2.17}$$

$$v_j^+ = \max_i v_{ij} \tag{2.18}$$

$$A^- = (v_1^-, v_2^-, \dots, v_n^-) \tag{2.19}$$

$$v_j^- = \min_i v_{ij} \tag{2.20}$$

In the fifth step of analysis, distances to ideal and nadir points are evaluated. Distance of alternative i to ideal point that is shown as d_i^+ and distance of alternative i to nadir point that is shown as d_i^- are evaluated as the following.

$$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2} \tag{2.21}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \tag{2.22}$$

In the sixth step, closeness coefficients CC_i of all alternatives to overall measure are calculated to prioritize alternatives. If a given alternative has the highest CC_i, it means that this alternative shows the best performance.

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{2.23}$$

In the last step of analysis, alternatives are prioritized according to their CC_i values.

2.3. MCDM and Preventive Maintenance Literature Review

In the literature, there are several studies that integrate preventive maintenance and MCDM approaches. For example, Eslami et al. (2014) investigated the selection of preventive maintenance planning method by implementing MCDM techniques and simulation. It is underlined that one of the most important competitive advantage factors is determining and implementing optimal preventive maintenance planning for minimizing total cost and equipment failure and also, increasing system productivity directly. In the study, three different preventive maintenance planning methods were implemented in numerical experiments and simulated in Arena simulation program. Results were compared by two different MCDM methods that are TOPSIS and AHP and then, the most productive preventive maintenance method was determined.

Altuger and Chassapis (2009) investigated multiple criteria preventive maintenance planning by Arena-dependent simulation modeling. Line productivity and equipment exploitation are principal concerns for lots of firms because of their unmediated effect on efficiency. Reaching the peak probable utilization while maximizing throughput develops the line productivity and it presents important rise on the line efficiency. There are several factors which influence the productivity of line. The factor of preventive maintenance plan is the one of most significant factors. In this work, a multiple criteria policy making approach was applied for determining the preventive maintenance plan which brings the optimal benefit and efficiency rates. For proving the determination operation, a bread enwrapping line was applied for a case study. Peripheral situations and line conduct were improved and simulated by implementing Arena-dependent simulation model. The model was implemented as a backing material for the multiple criteria policy making operation.

Nagarur et al. (1997) studied on a multiple criteria approach for choosing preventive maintenance time periods. This study focuses on the issue of identifying best preventive maintenance time periods for machineries in a manufacture center. A paper plant's maintenance scheduling was selected for case study. The classic approach of a single objective function for this kind of an issue was defined, and drawbacks of determining this single purpose were analyzed. The study suggests a new mathematical model which includes a multiple criteria approach. Reliability and expected costs which are selected as two criteria were considered for case study. The PROMETHEE method was applied for solving the problem. Also, sensitivity analysis was implemented for the alteration in the weights of two criteria.

Calvante and de Almeida (2007) studied on making a multiple criteria policy-aiding model by applying PROMETHEE III for preventive maintenance scheduling under unclear situations. The objective of this study is to develop a model which allows more coherent scheduling for preventive maintenance, with controlling defects in the specific context of component failure. In this way, not only the reliability and cost factors were handled, but also the features of various contexts that maintenance operations happen were dealt with. In addition to that, this study targets to contain Bayesian methodology in the work to cope with principal challenges in data of failure.

Almeida (2012) analyzed a multiple criteria model for determination of preventive maintenance time periods in another work. Determining preventive maintenance time periods is a problem which is studied in the literature with various models according to context. This work shows an MCDM model for helping policy makers in selecting the optimal maintenance time period which depends on the integration of contradictory criteria, such as cost and reliability. A method is suggested for applying the model that uses Multi-Attribute Utility Theory (MAUT). In addition to that, with a real life case study, a numerical implementation was used to show the results of the method. The inspection of the obtained outcomes addresses technical issues relevant to the suggested model. This work proves that MCDM is very significant for improving the reliability of the system and also, determining the optimal maintenance.

Hejazi and Nosoohi (2011) developed a multi-purpose approach for contemporaneous identification of spare part amounts and preventive replacement durations. Various mathematical models were offered in the scope of preventive maintenance scheduling to determine best age renewal technique. This study offers a distinctive multi-purpose mathematical model for preventive replacement of a part during scheduling horizon while former works focused primary on conventional cost aims. The suggested model pays regard to various purposes and applicable subjects, such as corrective replacement and results of it, residual life span purpose, and sort of efficiency index. Besides, the mathematical model identifies amount of auxiliary equipment, needed for renewal by the faulty part, to be ensured at the starting of scheduling horizon. The multi-purpose mathematical model is implementable for machineries or materials that are fixed by changing their faulty part by new spare part. The implemented method presents how the technique of epsilon-constraint may be applied to determine favored solution in conditions where access to policy maker is not available. The solution method were presented with computational instances in this study

Al-Najjar and Alsyouf (2003) focused on the problem of determining the most productive maintenance approach by using fuzzy multiple criteria policy making. The most popular maintenance approaches (preventive and condition based maintenance) by applying a fuzzy multi-criteria policy making estimation procedure were investigated. It was presented in the work that the proposed estimation procedure determines the most elucidator approach. Applying the fuzzy MCDM, it is probable to choose the most useful maintenance approach. Therefore, this provides that defects can be decreased to almost zero and higher utilization of life cycle of part may be reached. In this way, the maintenance units in firms can promote more to the management purposes by improving the manufacture operations

Thor et al. (2013) investigated the comparison of multiple criteria policy making techniques from the maintenance determination aspect. The importance of policy making from the maintenance aspect is admitted by the production sector. Proper maintenance policy making improves machine stability and improves both efficiency and output standard. In spite of that, insufficient policy making hinders correct manufacture process and raises manufacture costs. Hence, various MCDM techniques are explored and applied in the maintenance policy making process. This study investigates the implementation of four widely used MCDM methods in maintenance. The techniques are SAW, ELECTRE, TOPSIS and AHP.

Siew-Hong and Kamaruddin (2012) investigated the determination of the best maintenance decision with applying fuzzy multiple criteria policy making technique. It was indicated that it becomes significant to have a manufacture line by more efficiency and less cost because the production companies are encountering greater contestability impression from each other in these days that globalization influence all companies. Maintenance is very important to improve this efficiency level. For having efficient maintenance, identification of best maintenance decision is needed. On the other hand, a poor maintenance policy not only causes to rise of failure frequency but also influence the efficiency negatively. Therefore, an effective MCDM technique that depends on integration of fuzzy TOPSIS was suggested to identify the best maintenance decision in this study.

Triantaphyllou et al. (1997) investigated the problem of identifying the most significant criteria in maintenance decision making. Many decisions of maintenance need the calculation of alternative solutions with regard to some maintenance criteria like reliability, availability, cost, or reparability needs. These conditions can be formulated as MCDM problems. The proportional significance of maintenance criteria is hard to analyze, and because of this, requirement of a sensitivity analysis occurs. In this study, the sensitivity analysis approach that was applied brought a number of counter intuitive outcomes and significantly improved the decision analysis implementation in maintenance operations which are very complex.

Ilangkumaran and Kumanan (2009) studied on the determination of maintenance decision for textile sector by applying hybrid MCDM approach. The objective of this study is to analyze the implementation of AHP by fuzzy environment and TOPSIS for determining a best maintenance policy for a textile sector. An effective pair-wise comparison operation and sorting of alternatives can be made for maintenance policy determination by integration of TOPSIS and AHP with this study. This study develops a new understanding of MCDM methods for determining best maintenance decision for applied sector by the implementation of a numerical case study.

3. RELIABILITY

A commonly approved description of reliability is the system's ability for working under specified working restrictions in a specified time (Modarres, Kaminskiy and Krivtsov, 1999).

The probabilistic definition of reliability is $R(t) = Pr(T \geq t \mid c1, c2, \ldots)$, where t represents the specified time period or cycles of the system's work, T represents the time or cycle that the system failure occurs, $R(t)$ represents the system's reliability and $c1, c2, \ldots$ represent specified conditions like peripheral factors. Generally, in practical terms, $c1, c2, \ldots$ are accepted as implicit in the probabilistic reliability analysis, so the above equation is simplified to $R(t) = Pr(T \geq t)$.

3.1. Reliability Life Data Analysis

Reliability Life Data Analysis means analyzing and modeling the investigated component or system lives. The term "life data" refers to the operation time before failure of component. Lifetimes of components can be measured in different metrics like hours, miles or age. Main requirements or steps to perform a life data analysis by the DM are as the following Table 3.2.

Table 3.1. Steps of life data analysis

Step	Description
1	Obtaining the life data of component
2	Determining the distribution of lifetime that fit the data
3	Determining the parameters of fitted distributions
4	Specify the life characteristics like reliability or mean life of the component

3.1.1. Commonly Used Probability Distributions in Reliability

Some distributions are generally better than other distributions in showing life data. These distributions are generally named as "lifetime (or life) distributions". The Weibull distribution can be an example of popular lifetime distributions. Sometimes, the term life data analysis is named as "Weibull Analysis". Some of the other distributions that are performed commonly in life data analysis are Normal, Exponential and

Lognormal distributions. Also, there are other distributions like Gamma, Logistic and Loglogistic that are used in many references in literature.

The Weibull distribution which is founded by Waloddi Weibull, is a commonly used distribution in life data analysis for modeling times to failure of various items or systems and strength of components. Parameters of the Weibull distribution are the shape parameter (or slope) α, the scale parameter (or characteristic life) β and the location parameter (or failure free life) γ. Probability density function (pdf) of 3-Parameter Weibull distribution is as the following.

$$f(t) = \frac{\alpha}{\beta}\left(\frac{t-\gamma}{\beta}\right)^{\alpha-1} e^{-\left(\frac{t-\gamma}{\beta}\right)^{\alpha}} \tag{3.1}$$

where $f(t) \geq 0$, $t \geq 0$ or γ, $\alpha \geq 0$, $\beta \geq 0$ and $-\infty < \gamma < +\infty$. The cumulative density function (cdf) of the 3-ParameterWeibull distribution is as the following.

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\beta}\right)^{\alpha}} \tag{3.2}$$

The reliability function of the distribution is $R(t) = 1 - F(t)$. Therefore,

$$R(t) = e^{-\left(\frac{t-\gamma}{\beta}\right)^{\alpha}} \tag{3.3}$$

The failure rate function $\lambda(t)$ of 3-Parameter Weibull distribution is as the following.

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\alpha}{\beta}\left(\frac{t-\gamma}{\beta}\right)^{\alpha-1} \tag{3.4}$$

If the location parameter γ is equal to 0, then it is named as 2-Parameter Weibull distribution. The pdf of 2-Parameter Weibull distribution is as the following.

$$f(t) = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1} e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \tag{3.5}$$

The cdf of 2-Parameter Weibull distribution is as the following.

$$F(t) = 1 - e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \tag{3.6}$$

The reliability function of the 2-Parameter Weibull distribution is as the following.

$$R(t) = e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \tag{3.7}$$

The failure rate function of the 2-Parameter Weibull distribution is as the following.

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\alpha}{\beta}\left(\frac{t}{\beta}\right)^{\alpha-1} \tag{3.8}$$

The mean or the mean time to failure (MTTF) of 2-Parameter Weibull distribution is as the following.

$$MTTF = \Gamma(\frac{1}{\alpha} + 1)\beta \tag{3.9}$$

Also, there is 1-Parameter Weibull distribution whose location parameter is again equal to 0 but it assumes that the shape parameter is a constant value. Therefore, the scale parameter is the only unknown in 1-Parameter Weibull distribution.

The Exponential distribution is another commonly used distribution in life data analysis. This distribution is a special case of Weibull distribution where the shape parameter α is equal to 1. The pdf of 2-Parameter Exponential distribution is as the following.

$$f(t) = \lambda e^{-\lambda(t-\gamma)} \tag{3.10}$$

where $f(t) \geq 0$, $\lambda > 0$ and $t \geq \gamma$. The parameter λ means constant failure rate and γ is the location parameter of Exponential distribution. The cdf of the 2-Parameter Exponential distribution is as the following.

$$F(t) = 1 - e^{-\lambda(t-\gamma)} \tag{3.11}$$

The reliability function of the 2-Parameter Exponential distribution is as the following.

$$R(t) = e^{-\lambda(t-\gamma)} \tag{3.12}$$

The failure rate function of 2-Parameter Exponential distribution is as the following.

$$\lambda(t) = \frac{f(t)}{R(t)} = \lambda \tag{3.13}$$

The Exponential distribution has constant failure rate λ. If the location parameter γ is equal to 0, then it is named as 1-Parameter Exponential distribution. The pdf of 1-Parameter Exponential distribution is as the following.

$$f(t) = \lambda e^{-\lambda t} \tag{3.14}$$

where $f(t) \geq 0$, $\lambda > 0$ and $t \geq 0$. The cdf of the 1-Parameter Exponential distribution is as the following.

$$F(t) = 1 - e^{-\lambda t} \tag{3.15}$$

The reliability function of the 1-Parameter Exponential distribution is as the following.

$$R(t) = e^{-\lambda t} \tag{3.16}$$

Another commonly used probability distribution in life data analysis and reliability is Normal distribution (also known as Gaussian distribution). Normal distribution is helpful to model lifetimes of consumable materials. It is a 2-parameter probability distribution with mean μ and standard deviation σ parameters. The pdf of the Normal distribution is as the following.

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{t-\mu}{\sigma}\right)^2} \tag{3.17}$$

The reliability function of the Normal distribution is as the following.

$$R(t) = \int_{t}^{\infty} f(x)dx = \int_{t}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{x-\mu}{\sigma}\right)^{2}} dx \tag{3.18}$$

The failure rate function of the Normal distribution is as the following.

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{t-\mu}{\sigma}\right)^{2}}}{\int_{t}^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-1}{2}\left(\frac{x-\mu}{\sigma}\right)^{2}} dx} \tag{3.19}$$

The Gamma distribution, which is also known as Erlang distribution, is sometimes used in life time analysis and reliability. It is a flexible life distribution model. The pdf of the 3- Parameter Gamma distribution is as the following.

$$f(x) = \frac{\left(\frac{x-\gamma}{\beta}\right) e^{\left(-\frac{x-\gamma}{\beta}\right)}}{\Gamma(\alpha)\beta} \tag{3.20}$$

where β (scale parameter) > 0, α (shape parameter) > 0 and γ (location parameter) > 0. The formula of $\Gamma(\alpha)$, which means the Gamma function of α is as the following.

$$\Gamma(\alpha) = \int_{0}^{\infty} x^{\alpha-1} e^{-x} dx \tag{3.21}$$

The cdf of the 3-Parameter Gamma distribution is as the following.

$$F(x) = \frac{\Gamma x(\alpha)}{\Gamma(\alpha)} \tag{3.22}$$

The formula of $\Gamma_x(\alpha)$, which is the incomplete Gamma function of x and y is as the following.

$$\Gamma x(\alpha) = \int_{0}^{x} t^{\alpha-1} e^{-t} dt \tag{3.23}$$

If the location parameter γ is equal to 0, the distribution is named as 2-Parameter Gamma distribution. The cdf of 2-Parameter Gamma distribution is as the following equation.

$$f(x) = \frac{\left(\frac{x}{\beta}\right) e^{\left(-\frac{x}{\beta}\right)}}{\Gamma(\alpha)\beta} \tag{3.24}$$

The mean or MTTF of 2-Parameter Gamma distribution is as the following.

$$MTTF = \alpha\beta \tag{3.25}$$

3.2. Optimal Replacement Policies

In general terms, replacement means the process of replacing something in a system by its equivalent. In this thesis, preventive maintenance plans are developed for replaced vehicle parts.

The replacement process can be performed as preventive replacement or failure replacement. Preventive replacement is performed before the failure of component occurs. On the other hand, failure replacement is performed after the component failure occurs. These two types of replacements have costs of replacement for the DM. The aim is minimizing the total cost of replacements. Therefore, it is very important to plan optimal replacement policy that balances replacement costs and gives the best result. Also, determining which components must be considered for preventive or failure replacement is very crucial. In this section of the thesis, some probabilistic replacement models in the literature were described by formulations. Purposes, assumptions, cost functions and parameters of each model were indicated. Then, the most proper model for the problem of this thesis was determined by its reasons and parameters of the implemented model were specified.

3.2.1. Constant Interval Policy (or Block Policy)

Sometimes unexpected failures that make components inoperative occur at replaceable components in the system, and because of this reason, components should be replaced. Because failures are sudden and unexpected, it is assumed that failure replacement can be costlier than preventive replacement. Therefore, implementing preventive replacement plan for decreasing number of defects is very crucial for DMs. However, unnecessary preventive replacements increase the cost of replacement. Therefore, there should be a balance to minimize total replacement cost. In other words, optimal replacement plan must be performed. It is assumed that there is a long period of operation time for component. Model construction for this problem is as the following (Rausand and Hoyland, 2004).

t: Preventive replacement time
k: Total cost of failure replacement
c: Total cost of preventive replacement
$H(t)$: Mean number of failures in time interval (0, t)
$CA(t)$: Total expected replacement cost at time t

At this point, total expected cost means sum of the preventive replacement cost and failure replacement cost.

$$CA(t) = \frac{c + kH(t)}{t} \tag{3.26}$$

3.2.2. Age Based Policy

This type of preventive replacement policy is similar to Block Policy but in this instance, time of preventive replacement depends on component age. The problem is the same as the problem in Block Policy, balancing preventive and failure replacement. However, now, the methodology is determining the optimal preventive replacement age of the component to minimize the total replacement cost. Model construction is as the following (Rausand and Hoyland, 2004a).

t: Preventive replacement time (age)
$F(t)$: Cumulative density function of probability distribution at time t
$MTBR(t)$: Mean time between replacements for time t
$MTTF$: Mean time to failure
$CE(t)$: Cost efficiency at time t

$$MTBR(t) = \int_0^t \left(1 - F(t)\right)dt \tag{3.27}$$

$$CA(t) = \frac{c + kF(t)}{\int_0^t \left(1 - F(t)\right)dt} \tag{3.28}$$

The cost of not implementing preventive maintenance is found by $t = \infty$.

$$CA(\infty) = \frac{c + k}{MTTF} \tag{3.29}$$

$$CE(t) = \frac{CA(t)}{CA(\infty)} = \frac{c + kF(t)}{\int_0^t \left(1 - F(t)\right)dt} \cdot \frac{MTTF}{c + k} \tag{3.30}$$

3.2.3. Age Based Policy with Duration of Replacement

The definition of the problem is the same as the previous age based policy. However, replacements are not performed immediately, there is a time that is needed to perform replacement at this time. The model construction is as the following (Jardine and Tsang, 2013).

T_f: Time that is needed to perform failure replacement
T_p: Time that is needed to perform preventive replacement

Total expected cost of replacement per cycle is same as previous age based policy section.

$$CA(t) = \frac{c + kF(t)}{\left(t + T_p\right)(1 - F(t)) + \left(MTBR(t) + T_f\right)F(t)} \tag{3.31}$$

3.2.4. Group Replacement Policy

Sometimes, rather than replacing components one by one, they can be replaced as a group. The main reason for this is that, sometimes replacing them as a group can have less cost than replacing them separately. The assumption in this problem is that replacing policy is based on replacing components as a group at certain time intervals and if it is necessary, performing failure replacement. Model construction of this problem is as the following (Jardine and Tsang, 2013a).

c: Cost of replacing one component by group replacement
N: Total amount of components in group

$$CA(t) = \frac{Nc + NH(t)k}{t} \tag{3.32}$$

3.3. Reliability and Preventive Maintenance Literature Review

There are many studies in the literature where reliability analysis is used for preventive maintenance problems.

Maximov et al. (2015) presented an analytical optimization method for preventive maintenance policy which includes periodic maintenance and replacement in a maintainable system that has current failure rate datum. They calculated number of optimal preventive maintenance and their time intervals analytically based on Weibull distribution. The presented method's validity was confirmed by numerical examples.

Kiyak (2012) illustrated the significance of preventive maintenance for aviation sector based on a simple numerical example. They calculated reliability values when the preventive maintenance is implemented and when not implemented and compared the mean failure time and system reliability. This showed the significance of implementing preventive maintenance in the aviation sector.

Kao et al. (2009) presented optimal preventive maintenance policy for leased equipment by decreasing failure rate. It was assumed that the lifetime of the equipment has Weibull probability distribution. With different numerical examples, optimal preventive maintenance policies were determined for equipment that have different leasing periods.

Rausand (1998) presented a structural approach for reliability centered maintenance and described its steps. This approach has twelve main steps including functional failure analysis, data gathering and analysis, choice of maintenance operations, and analysis of preventive maintenance.

Zhao (2003) presented a mathematical model that defines a preventive maintenance policy based on critical reliability level for a system that can be damaged. The model calculates different preventive maintenance time intervals for different failures and maximizes the system reliability. The model also aimed to increase system's availability by minimizing total cost.

Attia et al. (2011) presented the best warranty and preventive maintenance decision for a four-level system where each level defines the failure state of the system. Transition probabilities between levels were calculated by a Markov process. It was assumed that failure and repair times have Exponential distributions. Different preventive maintenance implementations for different scenarios such as implementing or not implementing preventive maintenance were presented by using their mathematical model.

Su and Wang (2014) presented preventive maintenance policies and optimization model for second hand products that are sold by warranty. The mathematical model aims to maximize the vendor's profit. The assumptions of the model include second hand products have property of wear and they are repairable, product failures are independent, product failures can be determined instantly, the vendor can correct all failures in the warranty period and all preventive maintenances in the warranty period are made by the vendor and there isn't any cost for the customer. Numerical analyses showed that warranty period interval, the previous life cycle of a second hand product and preventive maintenance policies impacts vendor's expected profit.

Husniah et al. (2013) presented preventive maintenance and a service strategy that considered both product's age and usage amount assuming imperfect repair. They presented mathematical models for implementing and not implementing preventive maintenance. Their analysis showed that preventive maintenance can decrease costs

Kim et al. (2004) developed a mathematical model that calculates the optimal implementation time of preventive maintenance in warranty period based on Weibull distribution. The parameters of the model included the product's life cycle, warranty period, cost of maintenance, product's age and level of preventive maintenance implementation. The optimal preventive maintenance implementation time intervals were determined by using numerical examples for different scenarios.

Wang et al. (2002) presented a reliability centered maintenance implementation for the navigation sector. Yun et al. (2011) presented optimal preventive maintenance time intervals for certain parts of a railway system. The total cost of availability and life cycle were aimed to be optimized short term and long term maintenance. The costs were calculated using simulation and some numerical examples were solved for investigating the impact of model parameters on optimal solution.

Fritzsche and Lasch (2012) suggested an integrated logistic model for spare part maintenance planning in the aviation industry. They presented a dynamic prediction model for selecting the maintenance method. They aimed to maximize supply of spare parts by providing optimal interaction of parts in various flight networks and also to minimize the cost. They validate the model using simulation and assessed the airline's profit with different preventive maintenance strategies and the amount of demanded spare.

Moghaddam (2013) suggested a multiple criteria preventive maintenance and replacement time planning model in a production line that consists of more than one work station using goal programming. The maintenance periods in each work station were equal and maintenance operations were divided into three as repair, replacement and taking no action. The model aimed to minimize total cost and maximize system reliability and availability.

Ebrahimipour et al. (2015) also developed a multiple criteria model for preventive maintenance planning in a multiple production line that consists serial and parallel machines. Failure times were assumed to have Weibull distributions and factors like available work force and condition of spare part inventory were considered in the developed model.

Perez-Canto and Rubio-Romero (2013) presented a model for preventive maintenance planning for different kinds of power plants. The objective was to determine the plants that stop production periodically because of security reasons. They validated the proposed model based on areal-life energy system.

Hadidi et al. (2012) investigated the interaction of production and preventive maintenance planning for one machine that consists random failures. The system assumed “as good as new” repairs and failure times with Weibull distributions. The objective is determining production and preventive maintenance planning that minimizes the total weighted completion times. The problem is formulated by mixed integer programming which models production planning and maintenance decisions jointly.

Aghezzaf et al. (2016) aimed to maximize the system reliability by considering the production capacity and assuming imperfect repair. Developed model was formulized and solved as a mixed integer non-linear problem and the validity was confirmed by numerical experiments. It was noted that the calculation time of the model could be improved.

Our review showed that most previous preventive maintenance research is in the aviation sector or for production systems. However, works that use reliability tools in preventive maintenance problems for after sale service practices are on a limited scale. Therefore, it is aimed that this thesis is going to be a beneficial resource to provide contributions to the mentioned need in the literature.

4. PREVENTIVE MAINTENANCE PLAN FOR THE COMPANY

4.1. Problem Definition

In this thesis, a multiple criteria preventive maintenance plan is suggested for a truck and bus company in Ankara. Currently, standard and general maintenance operations are implemented in the after sale service operations by the company. However, the company aims to implement optional and high-grade preventive maintenance operations to increase customer satisfaction. The customers cannot operate their duties when unexpected failures occur. The aim is making customers (vehicles) continue their duties without interruptions by optimal preventive maintenance plans. In this way, the company wants to prevent customers from preferring other competitor companies. The number of spare parts (415) is very high to implement preventive maintenance on all of them and there is more than one criterion to consider when determining significance levels of vehicle parts. In addition to this, reliabilities of spare parts are not the same. These are the other aspects of the preventive maintenance problem of the company. Also, the company wants to minimize the total maintenance cost and total vehicle arrivals to the service, at the same time. Because of all of these reasons, the company needs to have a scientific and methodologic perspective to handle its preventive maintenance problem. The company saves maintenance data of vehicles and spare parts continually. Investigating this data and making statistical analyses, a new preventive maintenance plan is suggested to improve current maintenance plans of the company by considering all of these factors.

4.2. MCDM for the Company

In this study, to handle the stated problem, an MCDM approach was developed and the application of this approach in the after sale service of the company was carried out. In order to find possible solutions to the mentioned problem, all critical vehicle parts that can cause the vehicles to be stranded on the road were determined and failure rates of these parts were comprehensively analyzed. In consideration of these analyses, preventive maintenance implementation projections for vehicle parts were performed. To determine the critical vehicle parts, three criteria were chosen for MCDM. These criteria were selected based on data availability and opinions of company representatives.

The first criterion is the total number of vehicles that are maintained for a certain vehicle part in a year. Total number of vehicles that are maintained for each of the 415 spare parts in a year were determined.

The second criterion is the average waiting time of vehicles in authorized service area for a certain vehicle part. To determine the average waiting time (day) of vehicles in authorized service area for a spare part, the difference between vehicles' entering and leaving time of authorized service was determined.

The last criterion is the average unit cost of a spare part. Unit price information of spare parts is in the type of unit price ranges in the data file. Therefore, to calculate an average of unit prices, central values of each unit price range were used. For example, for a unit price that has a range of 201 and 400 TL, central value of this unit price category is 300TL. Similarly, central values of all unit price ranges were determined and average of these mean values were calculated to find the averages of unit price categories.

The criteria weights were calculated by the AHP method. A survey was prepared to compare criteria according to the significance scale. Three surveys were filled by three authorized people in the company and three different criteria weight vectors were calculated. Then, using these weights, AHP weighted TOPSIS analysis was performed to spare parts and three critical part lists were formed. After combining them, a new critical spare part list was formed. Then, this new spare part list was presented to authorized people in company to receive opinions. After the meetings, final critical part list to implement preventive maintenance was formed. Sections 4.2.1-4.2.3 give details of this process.

4.2.1. Pre-processing of Data

Firstly, to determine the critical vehicle parts, the data file that includes road assistance information for 14 months (November 2015 to December 2016) was procured from the company. This data includes the information of total 1,267 different vehicles and 1,198 different spare parts with total 6,725 work orders. The data file includes information about the vehicle identification number, vehicle type, vehicle age, the date that vehicle enters the authorized service, the date that vehicle leaves the authorized service, spent kilometer level until the failure, fuel consumption until the failure, operation time of motor (hours) until the failure, name of spare parts, and unit prices of spare parts. There are twelve unit price categories that represent certain price ranges (TL) for spare parts in the data file. Spare parts that have unit prices only between 0 and 200 TL were deleted from the file since they are accompanying parts and they were not considered as the cause for failures. After this process, a total of 415 different spare parts and 942 vehicles were determined, which have a total of 2,445 work orders in the data file.

4.2.2. AHP Analysis for Criteria Weights

A survey for criteria weighting was prepared to apply AHP analysis. This survey was filled by three authorized people in the company. In the survey, comparing criteria importance levels between each other was requested from authorized people. To make pairwise comparison, authorized people used 1 to 9 significance scale that was mentioned before. Comparison results for each survey are as the following.

Table 4.1. Pairwise comparison results of criteria

	Survey 1			Survey 2			Survey 3		
	C1	C2	C3	C1	C2	C3	C1	C2	C3
C1	-	4	3	-	1/7	3	-	3	4
C2	1/4	-	1	7	-	9	1/3	-	3
C3	1/3	1	-	1/3	1/9	-	1/4	1/3	-

In Table 4.1, Table 4.2 and Table 4.3, C1, C2 and C3 represent criterion of total number of vehicles, average waiting time in authorized service and average unite price respectively. Then, AHP weights of C1, C2 and C3 were calculated for each survey. Also, consistency ratios were calculated and as a result, it was seen that all comparisons were consistent. This implemented survey can be seen in Appendix-2 part of the thesis. The results are in Table 4.2. Because the surveys did not produce a common general result, and because we did not want to lose individual preference information by aggregating the survey result, it was decided that three surveys were considered separately. All three weight vectors taken into consideration in TOPSIS.

Table 4.2. AHP weights of criteria

Survey 1			Survey 2			Survey 3		
C1	C2	C3	C1	C2	C3	C1	C2	C3
0.634	0.174	0.192	0.149	0.785	0.066	0.614	0.268	0.117

4.2.3. TOPSIS Analysis to Form Critical Part List

The AHP weighted TOPSIS method was implemented for all 415 spare parts according to each survey's criteria weights individually. After these three implementations, three critical part lists were created. In these three individual lists, parts were prioritized. The first 10 parts in each list were selected and combined. After the combination process, the overall list that contains 20 distinct critical parts was obtained. The values of these 20 parts in each criterion are in Table 4.3.

Table 4.3. The criteria values of spare parts obtained by TOPSIS

Part	C1	C2	C3
Part-1	166	4.43	145.60
Part-2	146	8.95	78.21
Part-3	113	4.19	4642.56
Part-4	92	6.69	866.41
Part-5	63	7.74	768.41
Part-6	60	3.71	50.50
Part-7	55	6.54	2321.81
Part-8	53	7.92	1071.88
Part-9	48	7.91	491.66
Part-10	32	2.18	468.75
Part-11	1	96	700
Part-12	1	82	50,500
Part-13	1	82	300
Part-14	1	74	50,500
Part-15	2	47.50	50,500
Part-16	1	47	50,500
Part-17	1	45	50,500
Part-18	4	38.50	500
Part-19	2	38.50	300

Part-20	1	38	700

This critical part list were sent to the authorized people in the company for them to evaluate the criticality levels of the parts and decide on the most critical parts in the list. Also, the whole part list that includes 415 spare parts was sent to company and it was asked that if it was necessary to add new critical part to the critical part list. Authorized people checked the critical part list in accordance with their company experiences and it was decided that 6 parts were more critical than other parts in the list. Therefore, number of parts that were taken into consideration for analysis was reduced to 6 from 20. Also, it was decided by company representatives that there is no need to add new part to the critical part list. The new data file which includes information about only these 6 critical spare parts that were selected by company officials was gathered from the firm. This new data file contains three years of information (from January 2015 to December 2017). The data file includes total 2,255 different vehicles with total 5,652 work orders.

Each of the 6 different spare parts has different sub-group part variety in itself. For example, one spare part can have five or more variety according to technical specifications. With subgroup varieties of each spare parts, considered number of spare part is 20 in total.

4.3. Reliability Analysis

In order to calculate failure time frequencies of these vehicle parts, factors of distance (kilometer level), engine run time (hours) and fuel consumption amount (liter) that vehicles spent until failures were considered. The distance that vehicles spent until the failure was chosen to calculate failure frequencies, because for fuel consumption and engine run hour, data was not sufficient and there were erroneously entered lines. Outlier kilometer values indicating possible data entry errors, were identified and removed. Probability distributions that fit best to distance between failures for each spare part were determined by EasyFit software. Spare parts that have sample size of less than five were eliminated from the critical part list. *MTTF*, *MTBR*, costs per kilometer and cost efficiency values were evaluated for each spare part according to age based replacement policy assuming that an age of a vehicle is determined by the total distance (kilometers) covered by the vehicle. In order to determine the optimal kilometer levels for the preventive maintenance policy, the *MTBR*, cost and cost efficiency values were calculated for different preventive maintenance time (age) intervals between 5,000 and 500,000 kilometers with 5,000 kilometer increments for each spare part. These calculations were done by using R software. Different cost ratios were also considered in these calculations. Total costs were calculated for each failure replacement cost scenario and these costs were compared to the cost value that occurs when preventive maintenance is not implemented. Also, average authorized service capacity usages for different preventive maintenance plans were calculated and reported. Section 4.3.1 and Section 4.3.2 provide the details of these analyses.

4.3.1. Life Time Analysis

Seven spare parts were remained in the critical part list after removing the parts with insufficient amount of data (sample size of less than five) for the validity of reliability analysis. The sample size for each spare part after removing outliers is shown in Table 4.4. It was decided that the Part-2 which has the sample six of 6 was needed to be remained in the critical part list because the company representatives indicated that this part is very crucial for implementing preventive maintenance and so, it should be considered in critical part list for their past company experiences. The one of the most important reasons of this is the unit price (cost of preventive maintenance) of this part is very high to company. Because the sample size of this part is very small, the results of reliability analyses of this part should be considered in this context.

Table 4.4. Number of distance data for each spare part

Spare Part	Part-1	Part-2	Part-3	Part-4	Part-5	Part-6	Part-7
Number of Data	115	6	527	103	23	295	331

By using EasyFit statistical software, spare parts' kilometer levels were tested to determine whether the kilometers between failures can be fitted to a specific probability distribution or not. The proper theoretical distributions were used for reliability analysis. The distributions that were tested were Weibull, 3-parameter Weibull, Exponential, 2-parameter Exponential, Gamma, 3-parameter Gamma and Normal probability distributions because these are flexible and proper distributions for failure life time analyses. Table 4.5 shows the best fitting distributions, parameters and p-values for those parts based on the Kolmogorov-Smirnov test for 95% confidence interval applied in EasyFit.

Table 4.5. Goodness of fit results

Spare Part	Best Fitted Distribution	Parameters	p-value
Part 1	Gamma (2-Parameter)	$\alpha = 1.5216$, $\beta = 1.7034E+5$	0.3124
Part 2	Weibull (2-Parameter)	$\alpha = 1.3005$, $\beta = 53{,}297$	0.7456
Part 3	Gamma (2-Parameter)	$\alpha = 1.8969$, $\beta = 63{,}267$	0.4483
Part 4	Weibull (2-Parameter)	$\alpha = 1.5167$, $\beta = 2.2624E+5$	0.3078
Part 5	Weibull (2-Parameter)	$\alpha = 1.7027$, $\beta = 40{,}186$	0.9193
Part 6	Gamma (2-Parameter)	$\alpha = 3.3657$, $\beta = 44{,}863$	0.4340
Part 7	Gamma (2-Parameter)	$\alpha = 2.9624$, $\beta = 37{,}873$	0.9293

4.3.2. Optimal Preventive Maintenance Policy

The problem in this study contains probabilistic (stochastic) failure times. The age based replacement policy that is mentioned in Section 3 is used for preventive replacement policy. The reason of this is the spare parts are subject to wear off by usage as time independent and available data limitations to implement other replacement polices like downtime minimization and age based policy with replacement duration. The group replacement policy was not implemented because the spare parts were not identical and the optimal times for replacement were very different. Therefore, it was not very economical to implement this replacement policy. In addition, the company accepts the idea of implementing age based replacement policy for spare parts as proper solution. The parameter of time t that component (spare part) reaches certain age refers to the certain distance (kilometer level) that spare part reaches before failure happens in this study. Therefore, the parameter t in age based replacement policy is redefined as d (distance) in this study.

To make analyses for different scenarios, different failure replacement cost values were used. The cost ratio r is evaluated as the following.

$$r = \frac{failure\ replacement\ cost}{preventive\ replacement\ cost} = \frac{k}{c} \tag{4.1}$$

To make analyses in different scenarios, four different *r* values are considered. These are 1.5, 3, 5 and 10. The costs of preventive replacements in this study are average unit prices of spare parts that are mentioned before. It is assumed that the corrective maintenance cost includes the average unit prices of parts and also, some additional costs like cost of transporting the vehicle to service after the failure, all operational costs in the service and costs because of customer dissatisfaction. Therefore, all *r* values that are used for different cost scenarios are greater than 1. The higher *r* values like 5 and 10 indicates the assumption of higher additional costs. The preventive and corrective maintenance costs for different scenarios of spare parts are in Table 4.7.

Since preventive maintenance times of trucks are often defined in levels of 5,000 kilometers, the parameter *d* is calculated for the kilometer level between 5,000 and 250,000 kilometers by 5,000 increments. Also, 500,000 kilometer level was used as the maximum possible *d* in the analysis. In addition, the *MTBR* and *MTTF* in age based policy are redefined as *MDBR* (Mean Distance Between Replacements) and *MDTF* (Mean Distance to Failure) in this study.

Table 4.6. Costs of preventive and failure replacement (TL) for different cost ratios

Spare Part	*c*	*k* (*r*=1.5)	*k* (*r*=3)	*k* (*r*=5)	*k* (*r*=10)
Part 1	500	750	1,500	2,500	5,000
Part 2	2,500	3,750	7,500	12,500	25,000
Part 3	500	750	1,500	2,500	5,000
Part 4	500	750	1,500	2,500	5,000
Part 5	600	900	1,800	3,000	6,000
Part 6	700	1,050	2,100	3,500	7,000
Part 7	300	450	900	1,500	3,000

The *MDBR*, cost per kilometer and cost efficiency are calculated by equations (3.27), (3.28) and (3.30), respectively.

Larger number of cost efficiency means lower efficiency. The *MDTF* is calculated for different parts according to equation (3.9) for 2-Parameter Weibull distribution and equation (3.25) for 2-Parameter Gamma distribution. The cumulative density function, *F(d)* of spare parts are calculated with equations (3.6) for 2-Parameter Weibull distribution and equation (3.24) for 2-Parameter Gamma distribution. *MDTF* values for each spare part are as the following table.

Table 4.7. The *MDTF* values

Spare Part	*MDTF*
Part 1	259,189
Part 2	49,220
Part 3	120,011
Part 4	203,969
Part 5	35,851
Part 6	150,995
Part 7	112,195

For example, determined optimal values for Part-7 are shown in Table 4.9. The cost efficiency graph for Part-7 is shown in Figure 4.1. Optimal values and cost efficiency graphs of other spare parts can be seen in Appendix-1. The *d** represents the best preventive maintenance distance (kilometer).

Table 4.8. The optimal values for Part-7

	CA(d)/ CA(∞)*	*d**	*MTBR(d*)*	*CA(d*)*
r =1.5	0.9634	115,000	88,071	0.0064
r=3	0.8306	70,000	63,220	0.0088
r=5	0.6940	50,000	47,634	0.0111
r=10	0.5072	35,000	34,284	0.0149

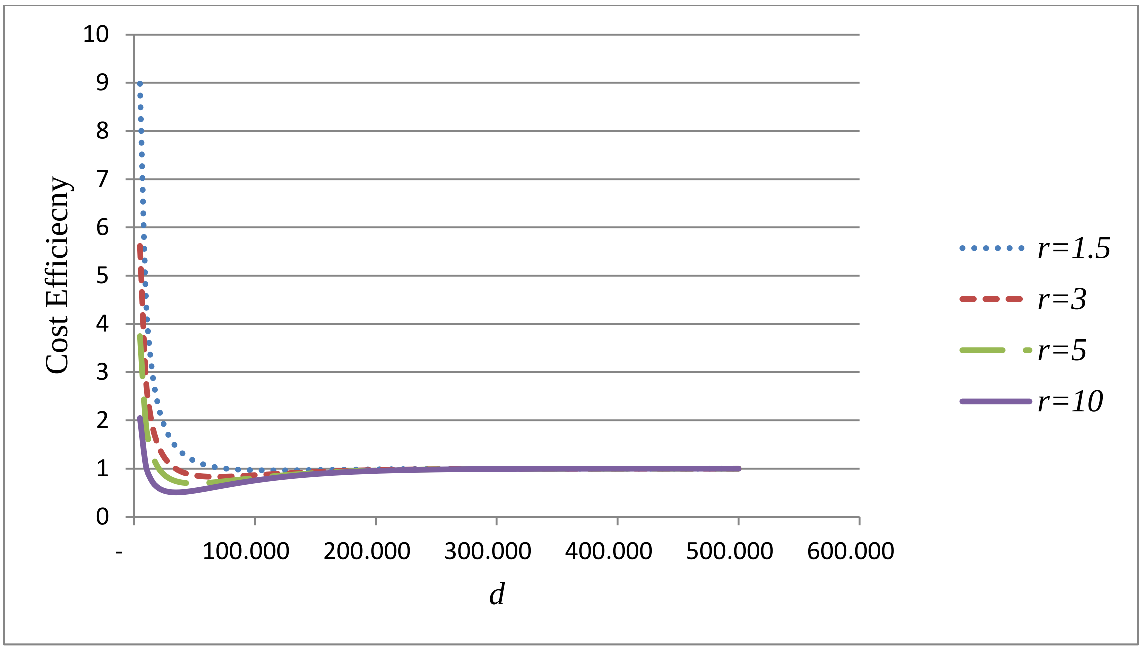

Figure 4.1. The cost efficiency graph for Part-7

It is seen in Figure 4.1 that when *r* increases (failure replacement cost increases), the value of cost efficiency gets better. If cost efficiency values are greater than 1, it means there should not be preventive maintenance implementation. If it is lower than 1, preventive maintenance should be applied. If cost efficiency value is exactly 1, it means cost of implementing and not implementing preventive maintenance are equal.

For some spare parts, there is not an optimal kilometer value for preventive maintenance. In other words, the optimal $d^* = \infty$ for low *r* values. It means that the cost of implementing preventive maintenance is higher than the cost of not implementing preventive maintenance for certain cost ratio scenarios. Therefore, in this kind of situations, the DM should not implement preventive maintenance.

4.4. Alternative Scenarios for Different Cost Ratio Values and Maintenance Periods

Alternative preventive maintenance scenarios were implemented to spare parts for different *r* values and periods. The total costs that include and do not include preventive maintenance are compared. The total cost per km that occurs when preventive maintenance is not implemented, $CA(\infty)$ is calculated by the equation (3.29). Results for different *r* values for all seven parts are as the following table.

Table 4.9. The total cost, $CA(\infty)$ for different r values for all spare parts

Cost Ratio, r	$CA(\infty)$
$r = 1.5$	0.2036
$r = 3$	0.3258
$r = 5$	0.5003
$r = 10$	0.9172

The total cost per km and saving ratios that are gained by certain preventive maintenance periods are shown in the following tables. These periods are 5,000, 20,000, 50,000, 100,000, 150,000 and 500,000 kilometers. Also, cost per kilometers are shown for the situation of not implementing preventive maintenance at all. For example, the 20,000 km preventive maintenance plan means that calling the vehicle to the authorized service for each 20,000 km spent of vehicle. For some spare parts, because the optimal maintenance values are not same or very close to each other, it was seen that these parts should be replaced in different arrivals of vehicle to the service rather than being replaced together for corresponding preventive maintenance period. The total cost per km and saving ratios for all preventive maintenance periods are shown in Appendix-1a and Appendix-1b sections.

Table 4.10. Alternative preventive maintenance scenarios for $r = 1.5$

d	$CA(d)$	Saving Ratio (%)
5,000	0.2010	1.26
20,000	0.2011	1.24
50,000	0.2012	1.19
100,000	0.2027	0.43
150,000	0.2026	0.48
500,000	0.2035	0.01
∞	0.2036	0

Table 4.11. Alternative preventive maintenance scenarios for $r = 3$

d	$CA(d)$	Saving Ratio (%)
5,000	0.3067	5.86
20,000	0.3084	5.33

50,000	0.3118	4.28
100,000	0.3165	2.84
150,000	0.3205	1.60
500,000	0.3196	1.90
∞	0.3258	0

Table 4.12. Alternative preventive maintenance scenarios for $r = 5$

d	*CA(d)*	Saving Ratio (%)
5,000	0.4401	12.02
20,000	0.4408	11.88
50,000	0.4553	8.98
100,000	0.4769	4.66
150,000	0.4880	2.45
500,000	0.4999	0.07
∞	0.5003	0

Table 4.13. Alternative preventive maintenance scenarios for $r = 10$

d	*CA(d)*	Saving Ratio (%)
5,000	0.7090	22.69
20,000	0.7101	22.57
50,000	0.7739	15.61
100,000	0.8549	6.79
150,000	0.8859	3.40
500,000	0.9161	0.11
∞	0.9172	0

Also, service capacity usages for different preventive maintenance scenarios were considered. For this aim, first of all kilometer values and durations (days) between failures were derived for each vehicle. Then, the average kilometer that is spent in a day and year was calculated. The calculations were made assuming 365 working days in a year. The total vehicle number that service is implemented to in a year was calculated as 846. The average arrival number of a vehicle in a year was calculated as 1.8. Then, total expected vehicle arrivals for different preventive maintenance scenarios in a year that is shown in Table 4.15 were compared with the current number of total vehicle arrivals in a year that is 1,551. The average number of arrival of each vehicle in a year and total expected vehicle arrivals for all preventive maintenance periods in a year can be seen in Appendix-1c section of thesis.

Table 4.14. The yearly arrivals

Preventive Maintenance Period	Average Number of Arrivals of Each Vehicle in a Year due to Preventive Maintenance	Expected Total Vehicle Arrival in a Year due to Preventive Maintenance
5,000	58.91	49,842.04
20,000	14.72	12,460.51
50,000	5.89	4,984.20
100,000	2.94	2,492.10
150,000	1.96	1,661.40
500,000	0.58	498.42
∞	0	0

For each *r* scenario, the graphs of total maintenance cost per km and expected vehicle arrival due to preventive maintenance in a year for seven certain preventive maintenance plans are illustrated. These plans that are for 5,000, 20,000, 50,000, 100,000, 150,000 and 500,000 kilometer preventive maintenance periods can be seen in the graphs near the related points. Also, condition of not implementing preventive maintenance plan is shown in graphs. These graphs are as follows.

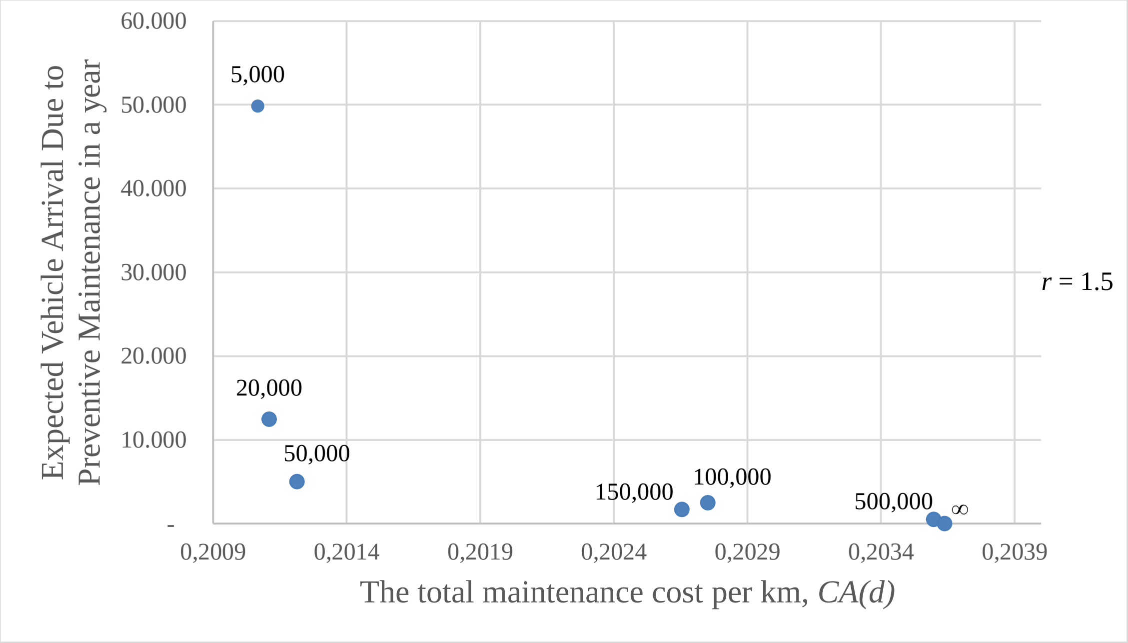

Figure 4.2. Total cost per km and total vehicle arrival in a year for *r* = 1.5

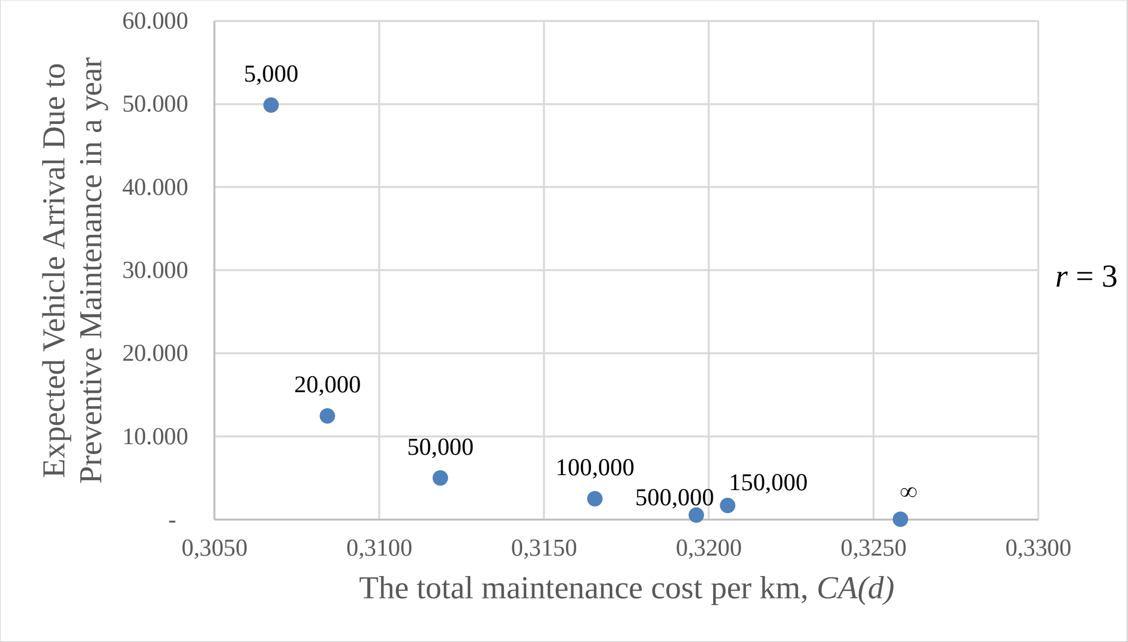

Figure 4.3. Total cost per km and total vehicle arrival in a year for *r* = 3

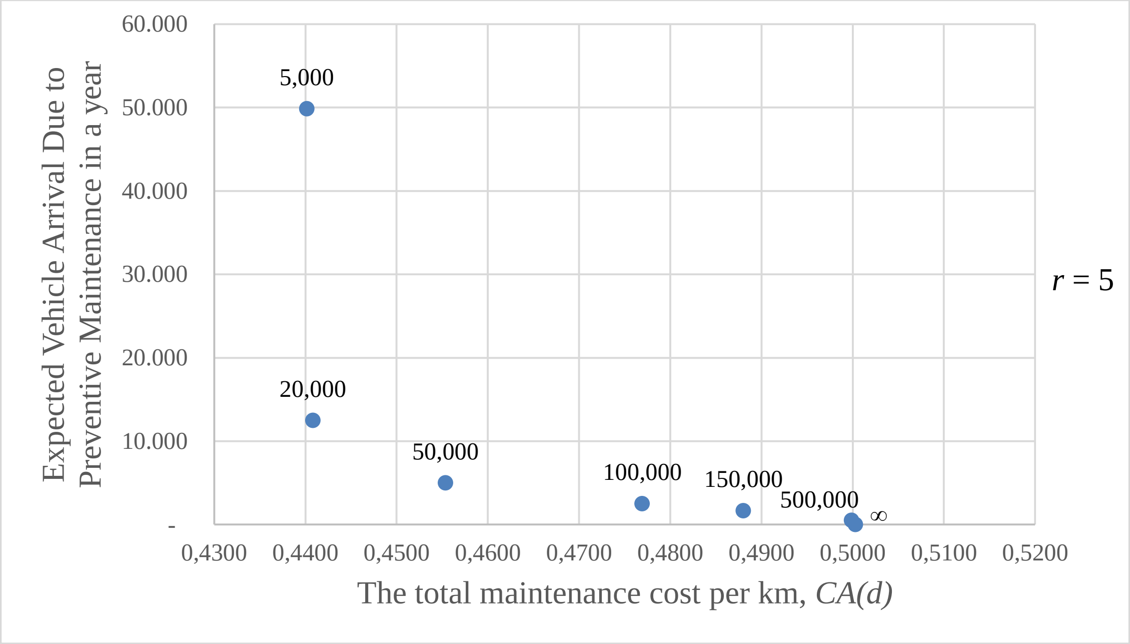

Figure 4.4. Total cost per km and total vehicle arrival in a year for *r* = 5

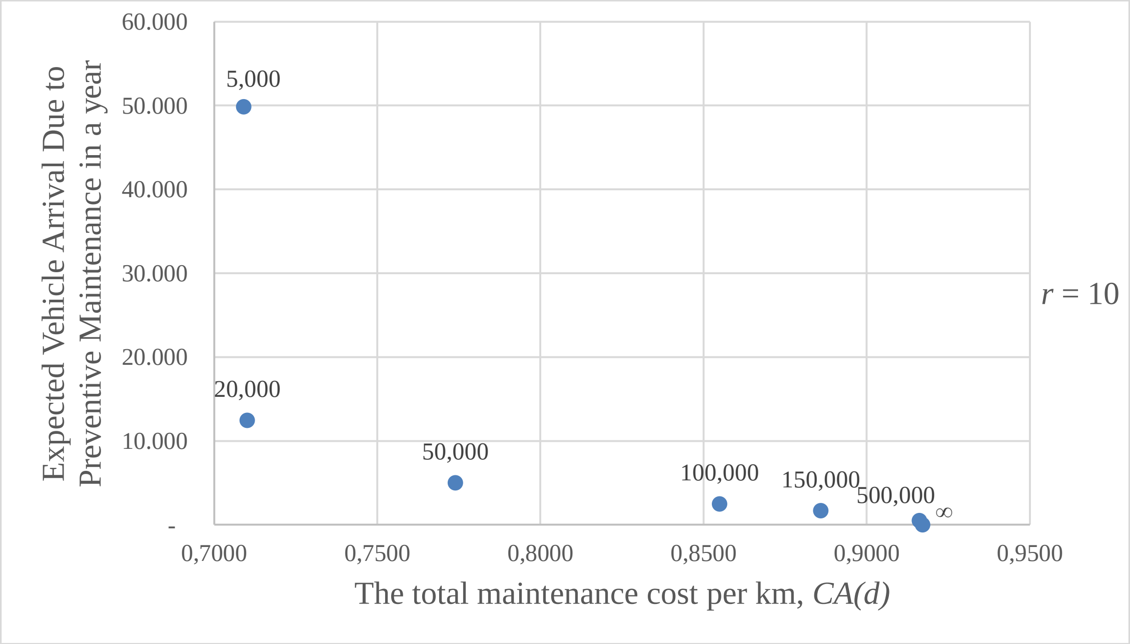

Figure 4.5. Total cost per km and total vehicle arrival in a year for *r* = 10

It is seen in Figure 4.2., Figure 4.3., Figure 4.4. and Figure 4.5. that when the kilometer level for preventive maintenance plan increases, the cost per kilometer generally rises but total vehicle arrivals in a year decreases. The purpose is minimizing both the total replacement cost per kilometer and total expected vehicle arrival in a year. Therefore, the DM should choose best plan according to the priorities for cost saving and service capacity usage.

The relation between preventive maintenance plans and vehicle arrivals to authorized service is important to avoid excessive service workload. It is seen from results that some preventive maintenance plans give almost equal value of total cost per kilometer. For example, for the cost ratio scenario where *r* is equal to 1.5, total costs per kilometer are almost equal for 100,000 and 150,000 km plan of preventive maintenance. In these situations, the DM should implement higher kilometer level maintenance plan to minimize expected total vehicle arrivals to authorized service in a year.

The relation between cost savings and the level of corrective maintenance cost are directly proportional. In other words, when the cost ratio *r* increases, the saving amount rises. Because the preventive maintenance plan was implemented to spare parts which currently preventive maintenance is not implemented by company, comparison of cost savings between current and suggested plans was not available. According to the results, the maximum cost savings ratios (percent) for *r* = 1.5, *r* = 3, *r* = 5 and *r* = 10 are 1.26, 5.86, 12.02 and 22.69, respectively for 5,000 km preventive maintenance plan. However, this plan gives maximum vehicle arrivals to the service, so the DM should choose the best plan that give optimal arrivals to the service according to its capacity conditions and customer expectations. In other respects, the minimum cost savings ratios (percent) for *r* = 1.5, *r* = 5 and *r* = 10 are 0.01, 0.07 and 0.11, respectively for 500,000 km preventive maintenance plan. For *r* = 3, the minimum cost saving ratio is 1.9 by 250,000 km rather than 500,000 km. It shows that, when the implemented preventive maintenance period increases, the cost savings do not always decrease because of the variations in optimal maintenance times of spare parts. This kind of situations can be seen for other preventive maintenance plans for each cost ratio scenario in Appendix-1b. In addition, for all preventive maintenance plans, the costs per kilometer and the total expected vehicle arrivals can be seen in Appendix-1a and Appendix-1c, respectively.

5. CONCLUSIONS

In this thesis, a multiple criteria preventive maintenance approach was developed for the after sale service of a bus and truck company. Firstly, criteria to consider when determining the criticality levels of different spare parts were selected. AHP was implemented to determine criteria weights. Then, AHP weighted TOPSIS analysis was used to determine the critical part list. After the discussions between company members, the final critical spare part list was formed. In reliability analysis, the distances between failures were used to determine best fitted failure probability distributions and parameters. Then age based replacement policy was implemented to calculate best times to implement preventive replacement. The optimal MTBR, cost efficiency and total replacement costs per kilometer values were calculated. Also, cost per kilometer of not implementing preventive replacement was evaluated. The saving ratios that are gained by preventive replacement implementation were indicated for different preventive maintenance periods. Furthermore, to consider the service capacity limit, total expected vehicle arrivals in a year for each preventive maintenance period were calculated and compared to the current average vehicle arrivals. Finally, the relation between total expected vehicle arrival to service and total cost per kilometer for each preventive maintenance plan was presented for each cost ratio scenario.

After the implemented analyses, it was seen that implementing preventive maintenance can cause higher cost than not implementing preventive maintenance for some spare parts in certain cost ratio scenarios. Therefore, results show that the preventive maintenance plan should not be implemented to these parts in this kind of situations. Moreover, it was presented that the cost savings by preventive maintenance differ according to corrective maintenance cost. Results show that cost saving ratios generally increase when the kilometer level of preventive maintenance plan decreases. However, it was shown that, in some situations, the higher kilometer maintenance plan can give better results on cost saving. Also, results showed that the total expected vehicle arrival to the service is inversely proportional to the level of preventive maintenance plan.

The DMs primarily aim to minimize preventive maintenance costs per kilometer to make higher maintenance cost savings. However, the practical considerations must be kept in mind. The kilometer level of preventive maintenance plan is very important to make customers continue their duties without interruptions. It is also important not to exceed the service capacity level. For example, in this study, the maintenance plan with 5,000 kilometer service period gives minimum cost for each scenario. However, it is not realistic to give maintenance service in every 5,000 kilometers. Because it means that, vehicles should be given maintenance service 5 times in a month and 60 times in a year approximately. In addition, the corrective maintenance cost has an important effect on preventive maintenance cost. It changes the cost saving amounts substantially. However, it is difficult to calculate exact value of corrective maintenance. Therefore, it is very important to consider different levels of corrective maintenance costs.

In this thesis, there were two kinds of data limitations in reliability analysis. First limitation was, when analyzing the life times, the distances between consecutive failures were considered to implement preventive maintenance because the useable data for fuel consumption and engine run time were insufficient. In future studies, different kinds of factors can be considered in reliability analyses and the results can be compared in terms of preventive maintenance implementations. The other limitation is, when determining the optimal replacement policy, the durations of implementing preventive maintenance and downtimes of vehicles were not available. Therefore, age based policy with duration of maintenance and downtime minimization can be implemented in the future if this data becomes available. The data used in thesis includes different types of busses like inner city or intercity busses, and different types of trucks like tow truck or trailer truck. However, identification of these vehicle types were not available from data. Therefore, preventive maintenance plans were implemented according to spare part types. In future studies, vehicle types can be a factor to consider when implementing preventive maintenance. In this study, the corrective maintenance costs were considered as different multipliers of the preventive maintenance costs. In future works, some other approaches can be developed to calculate exact corrective maintenance costs.

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APPENDIX

Appendix-1: The optimal values and cost efficiency graphs for spare parts

Table 1. The optimal values for Part-1

	CA(d)/ CA(∞)*	*d**	*MTBR(d*)*	*CA(d*)*
r = 1.5	1	∞	∞	∞
r = 3	1	∞	∞	∞
r = 5	0.9696	235,000	169,740	0.0112
r = 10	0.8759	110,000	97,290	0.0185

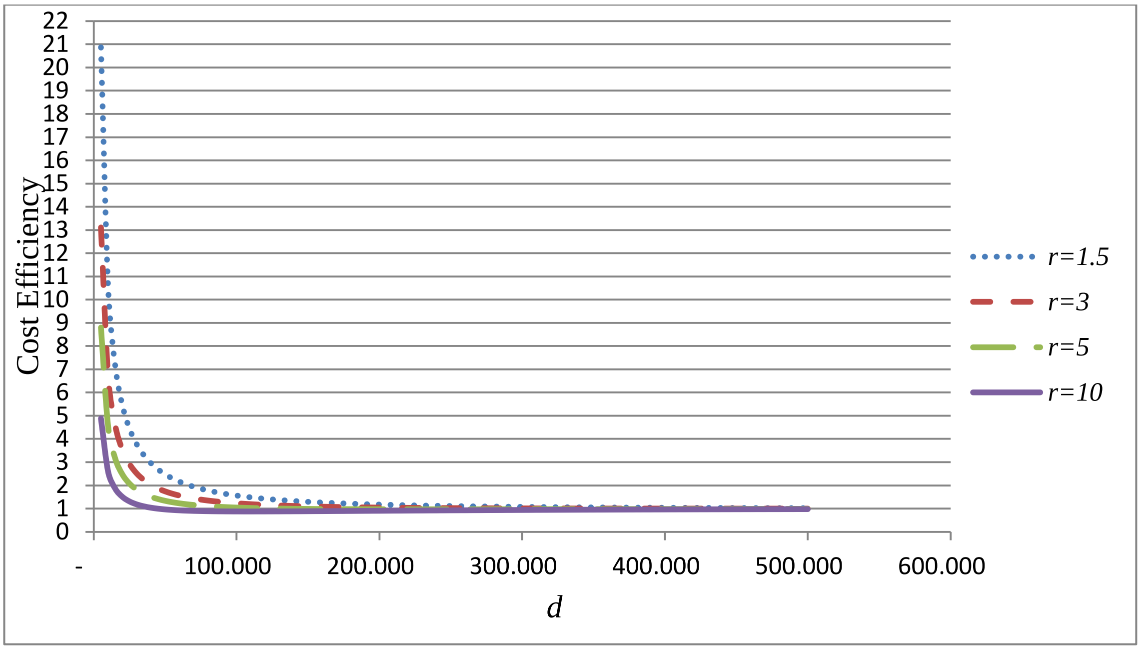


Figure 1. The cost efficiency graph for Part-1

Table 2. The optimal values for Part-2

	CA(d)/ CA(∞)*	*d**	*MTBR(d*)*	*CA(d*)*
r = 1.5	0.9995	160,000	48,788	0.1269
r = 3	0.9830	70,000	41,043	0.1997
r = 5	0.9445	45,000	32,646	0.2878
r = 10	0.8616	25,000	21,383	0.4814

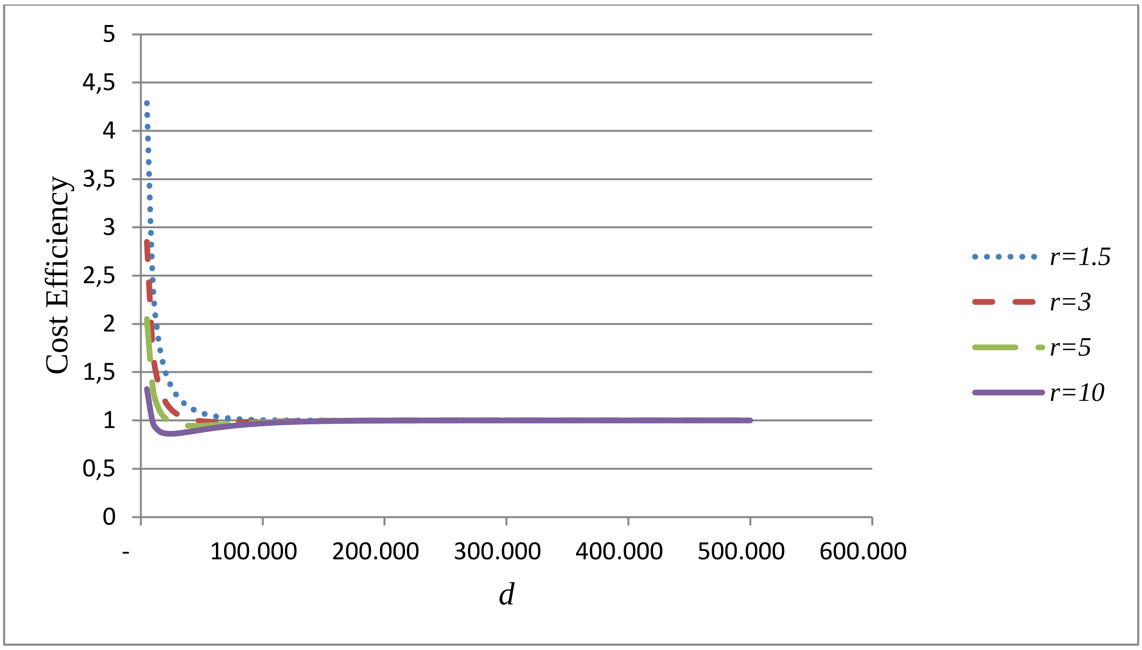


Figure 2. The cost efficiency graph for Part-2

Table 3. The optimal values for Part-3

	CA(d)/ CA(∞)*	*d**	*MTBR(d*)*	*CA(d*)*
r = 1.5	0.9998	405,000	119,275	0.0104
r = 3	0.9648	115,000	84,652	0.0160
r = 5	0.8856	70,000	60,330	0.0221
r = 10	0.7356	40,000	37,642	0.0337

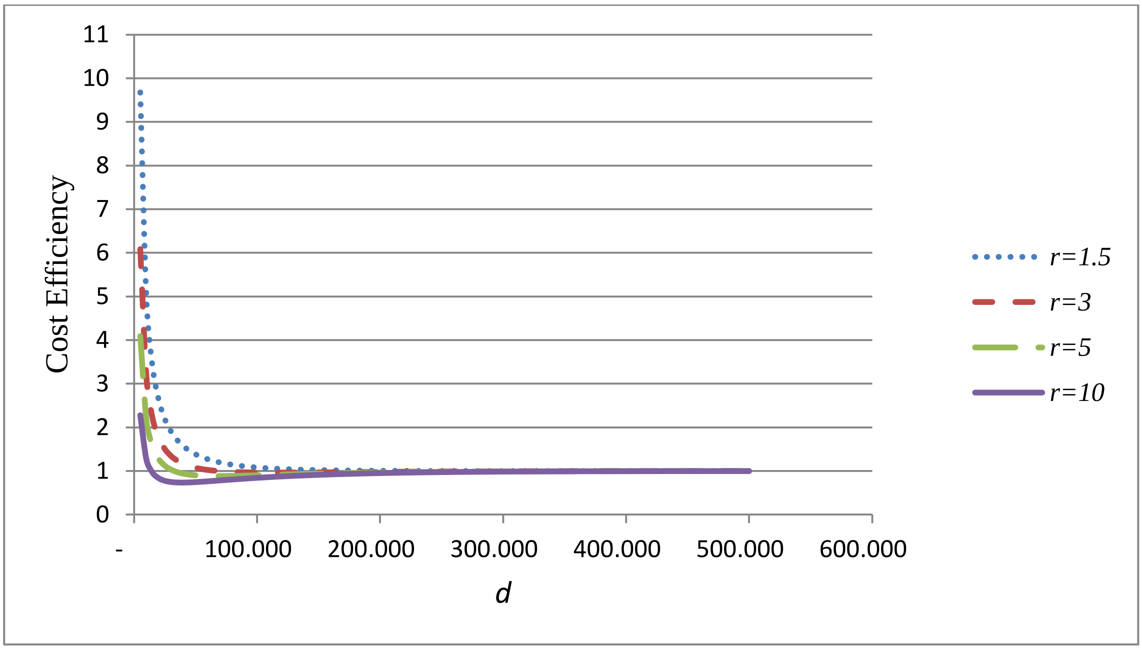


Figure 3. The cost efficiency graph for Part-3

Table 4. The optimal values for Part-4

	CA(d)/ CA(∞)*	*d**	*MTBR(d*)*	*CA(d*)*
r = 1.5	0.9866	325,000	184,791	0.0050
r = 3	0.9251	185,000	141,345	0.0071
r = 5	0.8474	130,000	110,420	0.0097
r = 10	0.7200	80,000	73,834	0.0152

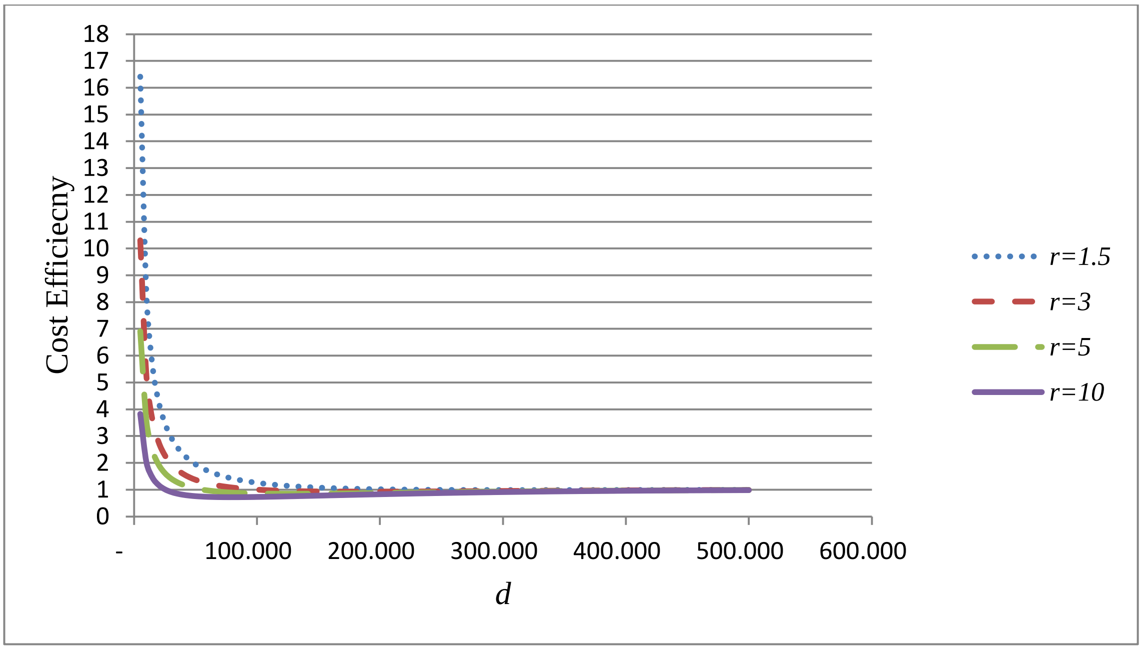


Figure 4. The cost efficiency graph for Part-4

Table 5. The optimal values for Part-5

	CA(d)/ CA(∞)*	*d**	*MTBR(d*)*	*CA(d*)*
r = 1.5	0,9636	45,000	30563	0,0403
r = 3	0,8712	30,000	24346	0,0583
r = 5	0,7705	20,000	17940	0,0773
r = 10	0,6284	15,000	14020	0,1175

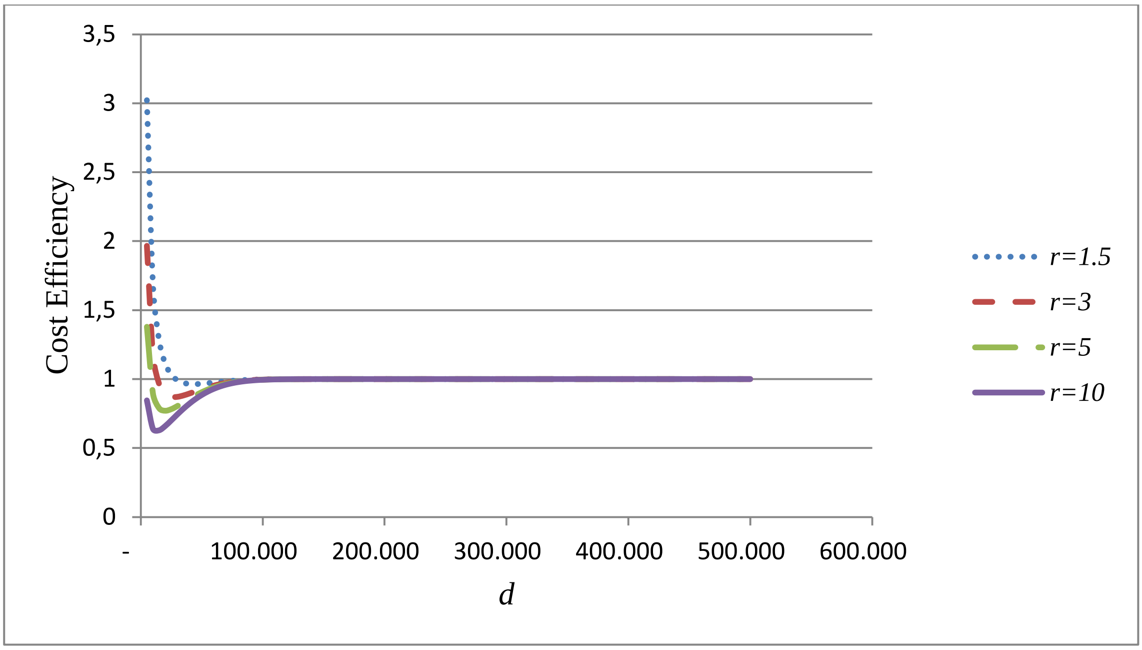


Figure 5. The cost efficiency graph for Part-5

Table 6. The optimal values for Part-6

	CA(d)/ CA(∞)*	*d**	*MTBR(d*)*	*CA(d*)*
r = 1.5	0,9422	140,000	113968	0.0109
r = 3	0,7897	85,000	79359	0.0146
r = 5	0,6463	65,000	62752	0.0179
r = 10	0,4594	50,000	49132	0.0234

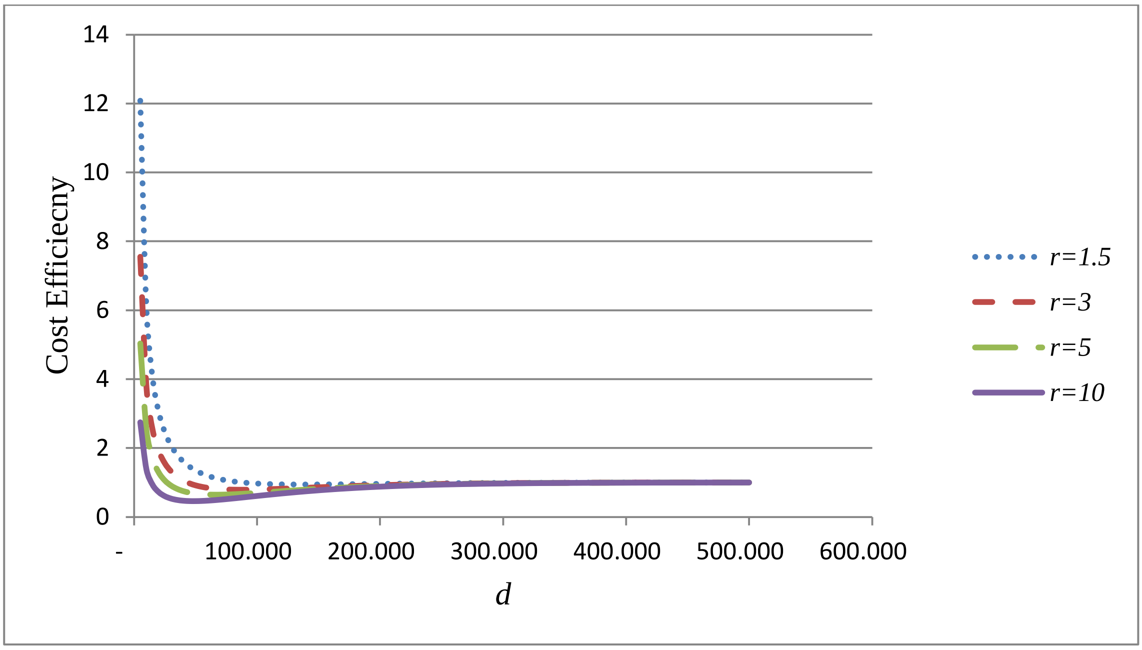


Figure 6. The cost efficiency graph for Part-6

Appendix-2: The total replacement cost per kilometer for all preventive maintenance periods and different *r* values

Table 7. The costs per km for all preventive maintenance periods for different *r* values

Period	*r* = 1.5	*r* = 3	*r* = 5	*r* = 10
5,000	0.2011	0.3067	0.4402	0.7091
10,000	0.2011	0.3067	0.4404	0.7096
15,000	0.2011	0.3068	0.4422	0.7119
20,000	0.2011	0.3084	0.4408	0.7102
25,000	0.2012	0.3069	0.4419	0.7143
30,000	0.2016	0.3072	0.4461	0.7245
35,000	0.2014	0.3076	0.4483	0.7371
40,000	0.2012	0.3086	0.4498	0.7489
45,000	0.2011	0.3102	0.4525	0.7615
50,000	0.2012	0.3119	0.4554	0.7740
55,000	0.2014	0.3128	0.4574	0.7860
60,000	0.2016	0.3132	0.4598	0.7969
65,000	0.2018	0.3136	0.4622	0.8069
70,000	0.2020	0.3139	0.4647	0.8161
75,000	0.2021	0.3143	0.4671	0.8244
80,000	0.2023	0.3147	0.4694	0.8319
85,000	0.2025	0.3152	0.4716	0.8386
90,000	0.2026	0.3156	0.4736	0.8446
95,000	0.2027	0.3161	0.4754	0.8500
100,000	0.2028	0.3165	0.4769	0.8549
105,000	0.2028	0.3170	0.4784	0.8594
110,000	0.2027	0.3175	0.4798	0.8635
115,000	0.2027	0.3179	0.4811	0.8672
120,000	0.2027	0.3184	0.4823	0.8706
125,000	0.2027	0.3188	0.4834	0.8737
130,000	0.2027	0.3193	0.4845	0.8766
135,000	0.2027	0.3197	0.4854	0.8792
140,000	0.2026	0.3200	0.4864	0.8816
145,000	0.2026	0.3203	0.4872	0.8839
150,000	0.2027	0.3206	0.4880	0.8860
155,000	0.2027	0.3209	0.4888	0.8879
160,000	0.2027	0.3211	0.4895	0.8897
165,000	0.2027	0.3214	0.4901	0.8914
170,000	0.2028	0.3216	0.4908	0.8929
175,000	0.2028	0.3219	0.4913	0.8943
180,000	0.2028	0.3221	0.4918	0.8957
185,000	0.2029	0.3223	0.4923	0.8969
190,000	0.2029	0.3225	0.4928	0.8981
195,000	0.2030	0.3227	0.4932	0.8992
200,000	0.2030	0.3228	0.4936	0.9002
205,000	0.2030	0.3230	0.4939	0.9011
210,000	0.2031	0.3231	0.4943	0.9020
215,000	0.2031	0.3233	0.4946	0.9028
220,000	0.2031	0.3234	0.4949	0.9036
225,000	0.2032	0.3235	0.4952	0.9043
230,000	0.2032	0.3237	0.4955	0.9050
235,000	0.2032	0.3220	0.4957	0.9056
240,000	0.2032	0.3221	0.4960	0.9062
245,000	0.2033	0.3221	0.4962	0.9068
250,000	0.2033	0.3221	0.4964	0.9073

500,000	0.2036	0.3196	0.4999	0.9162
∞	0.2036	0.3258	0.5003	0.9172

Appendix-3: Saving ratios for all preventive maintenance periods and different *r* values

Table 8. The cost saving ratios (%) for all preventive maintenance periods for different *r* values

Period	$r = 1.5$	$r = 3$	$r = 5$	$r = 10$
5,000	1.26	5.86	12.02	22.69
10,000	1.24	5.86	11.97	22.64
15,000	1.26	5.85	11.61	22.38
20,000	1.24	5.34	11.89	22.57
25,000	1.20	5.81	11.68	22.13
30,000	1.02	5.72	10.84	21.01
35,000	1.08	5.59	10.39	19.64
40,000	1.22	5.28	10.10	18.35
45,000	1.25	4.81	9.56	16.98
50,000	1.19	4.29	8.98	15.62
55,000	1.09	3.99	8.57	14.31
60,000	1.00	3.88	8.10	13.12
65,000	0.91	3.74	7.61	12.03
70,000	0.82	3.67	7.11	11.03
75,000	0.74	3.54	6.64	10.12
80,000	0.65	3.41	6.18	9.30
85,000	0.57	3.26	5.75	8.57
90,000	0.51	3.13	5.34	7.92
95,000	0.47	2.99	4.98	7.33
100,000	0.44	2.85	4.67	6.79
105,000	0.42	2.70	4.37	6.30
110,000	0.45	2.56	4.10	5.86
115,000	0.46	2.42	3.84	5.46
120,000	0.47	2.28	3.60	5.09
125,000	0.48	2.14	3.38	4.75
130,000	0.48	2.02	3.17	4.43
135,000	0.48	1.89	2.97	4.15
140,000	0.49	1.79	2.79	3.88
145,000	0.49	1.70	2.61	3.64
150,000	0.48	1.61	2.45	3.41
155,000	0.47	1.52	2.30	3.20
160,000	0.46	1.44	2.16	3.00
165,000	0.45	1.36	2.03	2.82
170,000	0.43	1.29	1.91	2.65
175,000	0.41	1.22	1.80	2.50
180,000	0.39	1.15	1.69	2.35
185,000	0.37	1.09	1.60	2.22
190,000	0.35	1.03	1.51	2.09
195,000	0.34	0.97	1.42	1.97
200,000	0.32	0.92	1.35	1.86
205,000	0.30	0.87	1.27	1.76
210,000	0.28	0.82	1.20	1.66
215,000	0.27	0.78	1.14	1.57
220,000	0.25	0.74	1.08	1.49
225,000	0.23	0.70	1.02	1.41
230,000	0.22	0.66	0.97	1.33
235,000	0.20	1.16	0.92	1.26
240,000	0.19	1.15	0.87	1.20
245,000	0.18	1.15	0.82	1.14
250,000	0.17	1.14	0.78	1.08

500,000	0.02	1.90	0.08	0.11
∞	0	0	0	0

Appendix-4: Average number of arrivals and total expected vehicle arrivals for all preventive maintenance periods

Table 9. The average arrival amount of a vehicle and expected total vehicle arrival in a year for all preventive maintenance periods

Period	Average Arrival Amount in a year	Expected Total Vehicle Arrival in a year
5,000	58.91	49,842
10,000	29.46	24,921
15,000	19.64	16,614
20,000	14.73	12,461
25,000	11.78	9,968
30,000	9.82	8,307
35,000	8.42	7,120
40,000	7.36	6,230
45,000	6.55	5,538
50,000	5.89	4,984
55,000	5.36	4,531
60,000	4.91	4,154
65,000	4.53	3,834
70,000	4.21	3,560
75,000	3.93	3,323
80,000	3.68	3,115
85,000	3.47	2,932
90,000	3.27	2,769
95,000	3.10	2,623
100,000	2.95	2,492
105,000	2.81	2,373
110,000	2.68	2,266
115,000	2.56	2,167
120,000	2.45	2,077
125,000	2.36	1,994
130,000	2.27	1,917
135,000	2.18	1,846
140,000	2.10	1,780
145,000	2.03	1,719
150,000	1.96	1,661
155,000	1.90	1,608
160,000	1.84	1,558
165,000	1.79	1,510
170,000	1.73	1,466
175,000	1.68	1,424
180,000	1.64	1,385
185,000	1.59	1,347
190,000	1.55	1,312
195,000	1.51	1,278
200,000	1.47	1,246
205,000	1.44	1,216
210,000	1.40	1,187
215,000	1.37	1,159
220,000	1.34	1,133
225,000	1.31	1,108
230,000	1.28	1,084
235,000	1.25	1,060
240,000	1.23	1,038

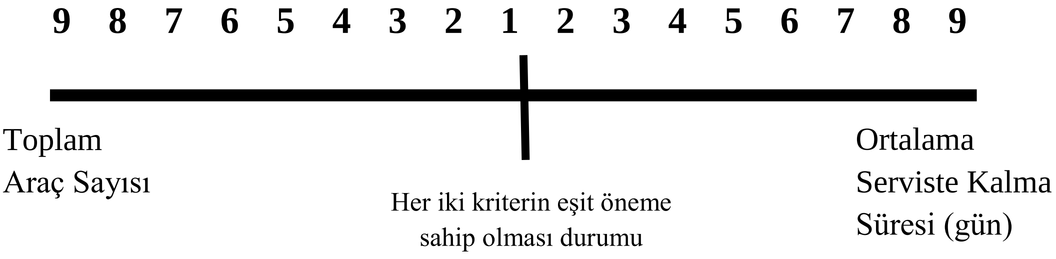
245,000	1.20	1,017
250,000	1.18	997
500,000	0.59	498
∞	0	0

Appendx-5: Survey

Aşağıda yer alan sorularda, ikili olarak verilen kriterlerin hangisinin diğerinden daha kritik olduğu sorulmuştur.

Değer	Değer Tanımı
1	Her iki kriterin eşit öneme sahip olması durumu
3	Kritik kriterin diğer kriterden daha önemli olması durumu
5	Kritik kriterin diğer kriterden çok daha önemli olması durumu
7	Kritik kriterin diğer kriterden çok daha güçlü bir öneme sahip olması durumu
9	Kritik kriterin diğer kriterden mutlak olarak önemli olması durumu
2,4,6,8	Ara değerler

1) Toplam Araç Sayısı – Ortalama Serviste Kalma Süresi (Gün)



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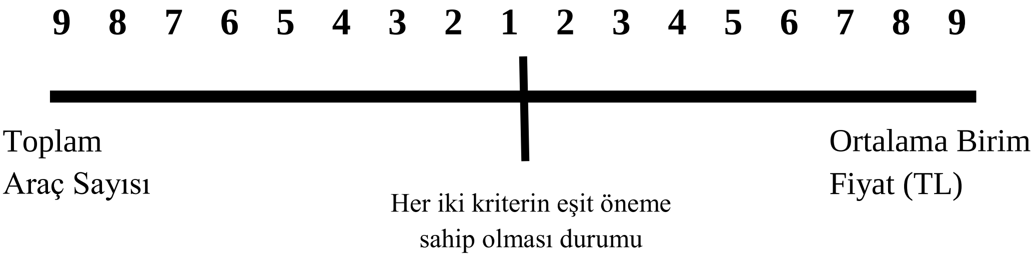

3) Ortalama Serviste Kalma Süresi (Gün) - Ortalama Birim Fiyat (TL)

9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9

Ortalama Serviste Kalma Süresi (gün)

Her iki kriterin eşit öneme sahip olması durumu

Ortalama Birim Fiyat (TL)

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GRADUATE SCHOOL OF SCIENCE AND ENGINEERING
THESIS ORIGINALITY REPORT

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ADVISOR APPROVAL

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Assist. Prof. Dr. Ceren TUNCER ŞAKAR

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