ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE, ENGINEERING AND TECHNOLOGY

PROPOSING A RELIABILITY AVAILABILITY MAINTAINABILITY (RAM) ANALYSIS IN SHIPBOARD MACHINERY SYSTEMS

M.Sc. THESIS

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Department of Maritime Transportation Engineering

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Thesis Advisor: Prof. Dr. Metin ÇELİK

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

GEMİ MAKİNE SİSTEMLERİNDE GÜVENİLİRLİK KULLANILABİLİRLİK VE BAKIM KOLAYLIĞI ANALİZİ ÖNERİSİ

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Samet BİÇEN, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 512171031, successfully defended the thesis entitled "PROPOSING A RELIABILITY AVAILABILITY MAINTAINABILITY (RAM) ANALYSIS IN SHIPBOARD MACHINERY SYSTEMS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Metin ÇELİK** İstanbul Technical University	....
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Date of Submission : 15 November 2019
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To my spouse,

FOREWORD

In this study, I would like to express my gratitude to my thesis supervisor, Prof. Dr. Metin ÇELİK for his continuous encouragement, guidance, helpful critics and discussions in my studies. I would like to thank and Hızır Gökçe GÜLELÇE, who is technical superintendent for helpful about providing data.

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December 2019

Samet BİÇEN
(Marine Engineer)

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ABBREVIATIONS

CMMS : Computerised Maintenance Management System
DWT : Deadweight Tonnage
F.I.V. : Fuel Injection Valve
FMEA : Failure Modes and Effects Analysis
IRCMA : Intelligent Reliability Centered Maintenance Analysis
ISM : International Safety Management
KW : Kilowatt
MTBF : Mean Time Between Failure
MTTF : Mean Time to Failure
MTTR : Mean Time to Repair
PMS : Planned Maintenance System
RAM : Reliability, Availability, Maintainability
RAMS : Reliability, Availability, Maintainability, Safety
RCM : Reliability Centered Maintenance
TEU : Twenty-Foot Equivalent Unit

SYMBOLS

A	**:** Availability
F	**:** Failure
f	**:** Probability Density Function
M	**:** Maintainability
R	**:** Reliability
t	**:** Time
α	**:** Scale Parameter
β	**:** Shape Parameter
π	**:** Pi
μ	**:** Statistical Average
∞	**:** Infinity
ϕ	**:** cumulative Distribution Function
λ	**:** Parameters of Distribution
σ	**:** Standart Deviation
e	**:** Euler
Γ	**:** Gamma Function

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PROPOSING A RELIABILITY AVAILABILITY MAINTAINABILITY (RAM) ANALYSIS IN SHIPBOARD MACHINERY SYSTEMS

SUMMARY

The purpose of the Reliability Availability and Maintainability (RAM) analysis is to predict the future availability of a system, identify any changes that would be beneficial to the system if needed. It also supports decisions on whether to implement these changes. RAM analysis has been used by companies for many years. Companies conduct RAM analysis in their design and production processes.

Studies on safety and security have increased, especially after World War II. After the mid-20th century, applications in many sectors ranging from war technologies to personal use technologies have increased.These applications were usually done at electronic devices and rocket technologies. In this regard, the first study in which the reliability level is determined exactly and the determined values are proved in the system components with the experiments can be counted as the RAM analysis applied in the production of missiles in Germany.

The defense industry in particular has played a leading role in the implementation and dissemination of RAM analysis.Since the products produced with missile and space technologies are weak in terms of repairability, it is aimed to prevent all possible malfunctions that may occur after using the product with RAM analysis made during the production and design stage.

Ships often use ports and anchorage zones as part of their trade. In addition to the needs of ships such as fuel, oil, spare parts, there are various expenses in ports and iron regions where they come to make evacuation or loading. Malfunctions that may occur during maneuvers, if they affect the ship's ability to move, will increase the fixed costs as well as the payment of the penalty of the ship, the machine or system failing to repair the deformations and the ship will cause additional burdens due to disruption of trade.

The RAM analysis, which we investigate, calculates the probability of failure of the machinery systems during the important operations of the ship. The RAM analysis predicts the period in which future failures will occur using data from previous years. If the recommendations provided by the analysis are applied before a risky operation, the probability of failure will be minimized and the operations will be made healthier.

Before a high-risk ship operation, various measures must be taken to ensure that the ship's machinery systems continue to operate without fail. However, each measure increases the operating costs of the ship. Therefore, before a risky operation, it is necessary to review the standard practices and take additional measures to know the reliability of ship machinery systems and related components and to determine the most appropriate times to be spent for maintenance.

The fuel injectors of a ship's main engine are discussed in the data analyzed. The data of previous years were collected and the relationships between the data were

examined. As a result of the data obtained, the reliability, availability, and maintainability rates of the injectors number 1,2,3,4,5,6 and 7 were calculated.

As a result, the reliability of fuel injection valves decreased with increasing working hours. While the reliability of a newly repaired fuel injector is 100%, it is seen that the reliability rate is reduced to 31-34% when 4000 operating hours are applied in the planned maintenance system.

In the analysis, the availability rates for all fuel injectors were found to be above 99%. This is due to the length of the failure-free operation of the fuel injectors and a short time is needed to fix the failure.

The maintenance operation will be healthy as long as the period of care is 3.5 hours or more. The determination of this time is important in situations that may create time constraints for the ship.

Reliability analysis showed that reliability decreases over time. While it is emphasized that this problem can be solved by reducing the time between the two maintenance plans, it has been evaluated that only the preventive and interim maintenance of the important devices can be satisfied because of the high availability of ships.

GEMİ MAKİNE SİSTEMLERİNDE GÜVENİLİRLİK KULLANILABİLİRLİK VE BAKIM KOLAYLIĞI ANALİZİ ÖNERİSİ

ÖZET

Güvenilirlik, Kullanılabilirlik ve Bakım Kolaylığı (RAM) analizinin amacı, sistemin gelecekteki kullanılabilirliğini önceden tahmin etmek, gerekirse sistemde yararlı olabilecek değişiklikleri tanımlamak ve bu değişikliklerin uygulanıp uygulanmayacağına ilişkin kararları desteklemektir. RAM analizi şirketler tarafından uzun yıllardır kullanılmaktadır. Şirketler tasarım ve üretim süreçlerinde RAM analizi yapmaktadır. Bu sayede şirketler, bir ürünü tarasladıktan sonraki kullanım süreçlerinde olası arızaları ve etkilerini gözleyebilmekte ve ürünle alakalı geliştirmeleri yapabilmektedirler.

Güvenlik ve emniyet konularındaki çalışmalar, özellikle II. Dünya Savaşı'ndan sonra artmıştır. 20. yüzyılın ortalarından sonra, savaş teknolojilerinden kişisel kullanım teknolojilerine kadar birçok sektörde uygulamalar artış göstermiştir. Bu uygulamalar genellikle elektronik cihazlarda ve roket teknolojilerinde yapılmıştır. Güvenilirlik seviyesinin tam olarak belirlendiği ve sistem bileşenlerinde tespit edilen değerlerin deneylerle kanıtlandığı ilk çalışma, Almanya'daki füzelerin üretiminde uygulanan RAM analizi olarak sayılabilir.

Özellikle savunma sanayisi, RAM analizinin uygulanmasında ve yaygınlaştırılmasında öncü bir rol oynamıştır. Füze ve uzay teknolojileri ile üretilen ürünler tamir edilebilirlik açısından zayıf olduğu için, üretim ve tasarım aşamasında yapılan RAM analizi ile ürünü kullandıktan sonra oluşabilecek tüm arızaların önlenmesi amaçlanmaktadır.

Artan teknoloji sayesinde ürünler kullanıma sunulmadan önce birçok testten geçirilebilmekte ve ürünün tasarım hataları ve aktif yaşam süresi boyunca meyadana gelmesi muhtemel arızalar tespit edilip müdahale edilebilmektedir. Böylelikle, ürün piyasaya sunulduğunda olası arızalar, sadece kullanımdan dolayı meydana gelebilecek kullanıcı hataları ve malzeme yorgunluğuna bağlı arızalara indirgenmiş olmaktadır.

Gemiler, icra ettikleri ticaretin bir parçası olarak liman ve demir bölgelerini sıklıkla kullanır. Gemilerin yakıt, yağ, yedek parça gibi ihtiyaçlarının yanı sıra tahliye veya yükleme yapmak için geldikleri limanlarda ve demir bölgelerinde çeşitli masrafları mevcuttur. Manevralar sırasında çıkabilecek arızalar, eğer geminin hareket kaabiliyetini etkileyecek arızalarsa, sabit masrafları arttığı gibi geminin ceza ödemesi, arıza yapan makinede veya sistemde onarılması güç deformasyonlar ve geminin ticareti aksadığı için karşılacağı ayrıca külfetlere neden olacaktır.

Günümüz teknolojisinin geldiği noktada, ticari faaliyetlerde de bir hız yarışı içerisine girilmiştir. Teslim alına yükün/ürünün zamanında ve hatasız bir şekilde teslim edilmesi hem üreticinin çalıştığı alandaki itibarı hem de faaliyetlerine artış sağlayarak devam edebilmesi açısından önemini kat ve kat artırmıştır. Ticari faaliyetlerin bir parçası olarak gemiler, varış noktası olan limanlara zamanınva varamadığı her saat için ceza ödemektedir. Yaşanan zaman kayıpları sadece tek seferlik bir ceza olarak

kalmayıp geminin veya işletmeci firmanın ilerleyen süreçlerinde de ticari faaliyetlerinde azalma ve hatta tamamen durma noktasına gelmesine neden olabilmektedir.

Araştırmasını yaptığımız RAM analizi, geminin önemli operasyonları sırasında makine sistemlerinde arıza meydana gelme olasılığını hesaplamaktadır. RAM analizi, geçmiş yıllara ait verileri kullanarak gelecekteki arızaların hangi periyotlarda meydana geleceğini öngörmektedir. Riskli bir operasyondan önce analizin sunduğu tavsiyeler uygulanırsa arıza olasılığı en aza indirilmiş ve operasyonlar daha sağlıklı yapılmış olacaktır.

Riski yüksek bir gemi operasyonu öncesinde gemi makine sistemlerinin arıza vermeden çalışmaya devam etmesi için bir takım önlemler alınmalıdır. Ancak alınacak her önlem gemi işletim masraflarını artırmaktadır. Dolayısıyla riskli bir operasyon öncesinde gemi makine sistemlerinin ve ilgili bileşenlerinin güvenilirliklerini bilmek ve yapılacak bakımlar için harcanması gereken en uygun süreleri tespit edebilmek için standart uygulamaların yeniden gözden geçirilmesi ve ilave tedbirlerin alınması şarttır.

Muhtemel arızalar, geçmiş veriler değerlendirilerek ve geleceğe dair yorumlamalar yapılarak tespit edilebilir. Bu arızaların şiddeti, muhtemel zamanı, onarım için gerekli insan ve kaynak gücü, arıza meydana geldiğinde sisteme verebileceği zaafiyet ve arızalar meydana gelmeden önce bakımının ne zaman yapılacağı gibi gemi operasyonları için kritik öneme sahip veriler, RAM analizi ile tespit edilebilir.

Güvenilirlik ölçütü, bir geminin çalışan sistemlerinin mevcudiyetini ne kadar süre koruyacağını tespit etmeye yarayan, hangi zaman aralığında ve hangi gemi şartlarında bu mevcudiyetin bozulacağının tespitinde önemli bir ölçüttür. İşletmeci tarafından yine işletmeci insiyatifinde kararlaştırılan güvenilirlik alt sınırına ulaşan bir sistem veya sistem bileşeni için riskli operasyon öncesinde önleyici bakım planlaması yapılması, geminin sistemlerinin sağlıklı çalışması için faydalı olacaktır.

Kullanılabilirlik ölçütü, geminin bir veya birkaç sistem ve sistem bileşeninin istenilen zamanda istenilen görevi eksiksiz yerine getirebilme olasılığının ölçütüdür. Arıza periyodu kısa, arızasız çalışma periyodu uzun olan bir sistem bileşeni için güvenilirlik hesaplamları her zaman yüksek değerlerde çıkmaktadır. Yaptığımız çalışmada da sonuçlar, sistem bileşenlerinin kullanılabilirlik seviyelerini yüksek değerlerde çıkmıştır. Kullanılabilirlik için en anlamlı sonuçlar kısa arızasız çalışma periyodu olup onarımın uzun zaman aldığı sistemler ve sistem bileşenleridir.

Bakım kolaylığı ölçütü, bir sistem veya sistem bileşeninin arıza meydana gelmeden önce koruyucu bakımların yapılabilmesi veya arıza meydana geldikten sonra onarımın yapılabilmesi için kabul edilebilir tamir süresinin ölçütüdür. Bir arızaya yapılacak müdahalenin gerektireceği en az sürenin tayin edilmesi, bakım operasyonunun yapılması gereken zamanın tayininde direkt etkilidir.

Gemilerinin sık liman uğraklı çalışması ve çalışma temposunun yüksek olması sebebiyle RAM analiz uygulaması için bir konteyner firmasının filosundan bir gemi seçilmiştir. Geminin planlı bakım sisteminde yer alan bütün veriler şirket gözetiminde incelenmiştir. Veri aralığının geniş olması, RAM analizinden elde edilecek çıktıların anlamlı veriler olmasını sağlayacağından filonun en eski gemisi seçilmiştir. Planlı bakım yazılımından çekilen veriler titizlikle incelenmiş ve seçilecek sistem bileşeni gemi için kritik öneme sahip olacak şekilde belirlenmiştir. Makineler için en kritik sistem olması ve bu sistem üzerinde meydana gelebilecek bir arızanın doğuracağı sonuçların, özellikle manevralarda, ciddiyetinin yüksek olacağı düşünülerek yakıt sistemi seçilmiştir. Yakıt sistemi içerisinde de en anlamlı veri dağılımı olduğu saptanan ve ana makine için kritik öneme sahip olan yakıt enjektörleri belirlenmiştir.

İncelenen verilerde geminin ana makinesinin yakıt enjektörleri ele alınmıştır. Geçmiş yıllara ait verileri toplanmış ve veriler arasındaki ilişkiler incelenmiştir. Elde edilen veriler neticesinde 1,2,3,4,5,6 ve 7 numaralı enjektörlerin güvenilirliği, kullanılabilirliği ve bakım kolaylığı oranları hesaplanmıştır.

Sonuç olarak, yakıt enjektörlerinin güvenilirliğinin çalışma saatlerinin artmasıyla azaldığı görülmüştür. Yeni tamir edilmiş bir yakıt enjektörünün güvenilirliği %100 iken, planlanan bakım sisteminde 4000 çalışma saati uygulandığında güvenilirlik oranının %31-34 aralığına kadar düştüğü görülmektedir.

Analizde, tüm yakıt enjektörleri için bulunabilirlik oranlarının %99'un üzerinde olduğu tespit edilmiştir. Bu, yakıt enjektörlerinin arızasız çalışma süresinin arızayı gidermek için gereken süreden daha uzun olmasından kaynaklanmaktadır.

Bakım işlemi, bakım süresi 3.5 saat veya daha fazla olduğu sürece sağlıklı olacaktır. Bu sürenin belirlenmesi, gemi için zaman kısıtlamaları yaratabilecek durumlarda önemlidir.

Güvenilirlik analizi, seçilen sistem bileşenleri için güvenilirliğin zamanla azaldığını göstermiştir. İki bakım planı arasındaki süreyi kısaltarak bu sorunun çözülebileceği vurgulanmakla birlikte, gemilerin yüksek kullanılabilirliği nedeniyle sadece önemli cihazların önleyici ve geçici bakımlarının yapılabileceği değerlendirilmiştir. Uygulanacak bakımlar için gerekecek süreler bakım kolaylığı oranına göre değişkenlik göstermekle birlikte bakım için harcanacak zamanın tespitinde önemli referans değerler sağlamıştır.

1. INTRODUCTION

Reliability is defined as the completion of its systems or system components within the specified time and under the specified conditions with failure-free.

A system or system component must operate actively within the life span of the manufacturer. Warranty periods and warranty conditions are determined by machine manufacturers based on the experience gained as a result of post-production tests and feedback from previous productions. The conditions in which a system or machine works and the knowledge/skill level of the operating personnel are the factors that directly affect the healthy life span.

1.1 Terminology

1.1.1 Reliability

The life cycle of a system or system component is described by bathtub in reliability engineering. The Bathtub curve handles the life cycle in three stages. The first stage is the early stage, where production errors and failures are high; the second stage is useful life wherein the failure rates have a low constant value; the third stage is aging, where failure and error rates start to rise.

The failure rate of equipment in the early stage or the aging stage is always high. A newly manufactured equipment will have many failures due to manufacturing problems. The failure rate will be reduced with proper maintenance and system development.

The deterioration rate function of a system or component is generally expressed by a bathtub curve in the economic life (Figure 1.1).

The life of all parts, system and equipment consists of working (childhood and youth), maturity (useful life) and wear and tear (aging) phases. In the early stages of the life cycle from the initial setup of the system to the normal condition time, the probability of failure starts at a proportionally high level and gradually decreases with the life cycle. It is at a certain level in the useful life period and has almost constant degradation rate. In this period, the hardware has the highest operational efficiency. In the last stage of aging, the rate of deterioration shows a rapidly changing rate of wear (Er, 2004).

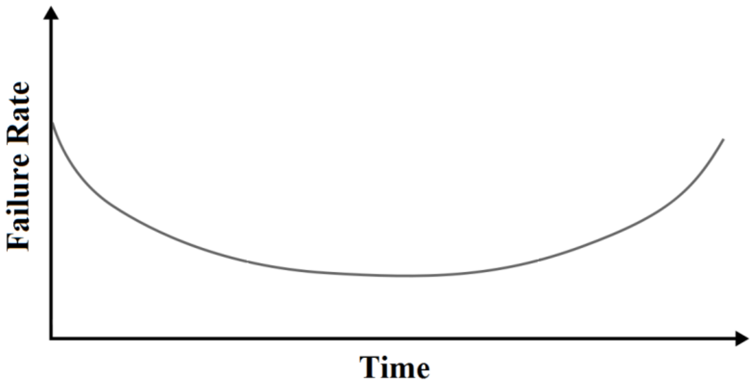

Figure 1.1 : Bathtub curve.

The first deterioration results from design and manufacturing failures. In order to prevent such malfunctions, tests should be carried out initially and necessary precautions should be taken. This time is usually very short for mechanical systems.

Malfunctions in the useful life period, where random faults occur, are often caused by operating failures. In this regard, training of engine officers gains importance.

The failures seen during the wear period are caused by the completion of the life of the equipment and parts and in this case, the lifespan should be extended with preventive and productive maintenance (Erçelebi and Ergin, 1997).

Let T be the random variable time to failure. The reliability at t, R(t), is the probability that the system fails at t (Cha et al, 2004),

$$R(t) = P(T > t) = 1 - p(T \leq t) = 1 - F(t) = 1 - \int_0^t f(t)dt \qquad (1.1)$$

1.1.2 Availability

Availability is defined as the degree to which the system or system components are operable to perform their tasks optimally at an unknown time. This means that an equipment must be available during the waiting period for operation. The extent to which it can perform its task in case of need is explained with availability.

$$A(t) = P\{X(t) = 1\}; t > 0 \tag{1.2}$$

Availability and reliability are two different criteria. Reliability means that a system in use completes its task before failure occurs within a specified period of time, and availability is readily available before commencing work.

The period required to fix the failures and perform maintenance prevents the system from the condition that is available. Assuming maintenance is carried out at a constant rate, it can be expressed as follows in a steady state after a temporary conduct has fixed accessibility (Barberá et al., 2012);

For repairable parts;

$$Availability = \frac{Uptime}{Uptime + Downtime} = \frac{MTBF}{MTBF + MTTR} \tag{1.3}$$

For non-repairable parts;

$$Availability = \frac{Uptime}{Uptime + Downtime} = \frac{MTTF}{MTTF + MTTR} \tag{1.4}$$

1.1.3 Maintainability

Maintainability analysis is used to evaluate the design and operation of the system or system components in terms of maintenance procedures and required resources. The main time intervals that should be considered when performing the maintainability analysis are as follows: Diagnostics, spare parts supply times, administrative delays, disassembly/replacement, repair time, assembly, and testing of proper system operation after repair.

Maintenance is the operation performed at the intervals specified to keep the relevant system or system component in an optimal condition for operation by the manufacturer. A repair is a work performed in accordance with procedures recommended by the manufacturer to return a system or system component that has failed to return to normal operating conditions.

Maintenance and repair operations require different levels of experience and skills for each system or system component. The periods required for maintenance and repair operations vary depending on the competence of the personnel performing the work.

For this reason, one of the works that should be done before determining the time required for maintenance and repair is to determine the competence level of the personnel to perform the work.

In the maintainability analysis, the time required for maintenance is determined as the “mean time to repair” (MTTR).

The maintainability of a system is calculated as follows (Barberá et al., 2012);

$$M(t) = P(T \leq t) = \int_0^t f(t).dt \tag{1.5}$$

$$M(t) = 1 - e^{\left(-\frac{t}{MTTR}\right)} = 1 - e^{-\mu t} \tag{1.6}$$

(MTTR, mean time to repair; μ, constant repair rate; t, operation time.)

The most commonly used maintenance approaches are as follows.

Preventive maintenance work is the maintenance performed by the manufacturer at regular intervals to ensure that the system and system components continue to operate under normal operating conditions. In preventive maintenance performed within the specified periods, the disassembled system parts are replaced with new ones if they are outside the conditions specified by the manufacturer. The purpose of preventive maintenance works is to inspect the systems before they fail and minimize the possibility of malfunctions that may occur while performing their duties.

Preventive maintenance works have an important place in ship machinery systems. These maintenance should be carried out meticulously so that the ships can continue their trade without interruption. Timely and optimal preventive maintenance works directly affect the reliability and availability of the systems. Preventive maintenance should be performed with appropriate materials and competence in order to ensure the most accurate operation of a system at the desired time or to prevent disruption while working.

The most effective system features that preventive maintenance can be applied are as follows:

i. the system component to be maintained must be critical

ii. system component must have recurrent failures

iii. have reduced rates for reliability and maintainability

It is one of the most effective maintenance methods to reduce failure rates. The purpose of preventive maintenance is to reduce the increased failure rate to low levels. Preventive maintenance varies according to the competence of the maintenance personnel and the time of maintenance.

Corrective maintenance work is performed in the fastest and most convenient way to eliminate the malfunctions that occur under normal operating conditions of the system and system components. It is performed outside the maintenance intervals specified by the manufacturer. In corrective maintenance, disassembled system components are restored to normal operating conditions by following the procedures recommended by the manufacturer.

Vessels have a backup of almost every system. Spare systems are equipped while the ship is being manufactured to prevent disruption of the operation of the vessels. When a system or system component fails, the backup of the system is activated and the normal operation of the ship is resumed. In order to carry out corrective maintenance in the event of a malfunction, suitable spare parts, competent personnel and the current operational condition of the ship must be available.

After corrective maintenance work, the maintenance periods of the relevant system or system component should be updated as preventive maintenance work and the next maintenance time should be determined as corrective maintenance work also includes preventive maintenance work. The correct and timely corrective maintenance works directly affect the reliability and availability of the systems.

Predictive maintenance; monitoring of whether the machinery and equipment are operating under normal conditions by periodic measurements and controls, evaluating the results obtained by measuring and checking whether there is a possibility of failure, and if such a possibility exists, planning and performing the necessary maintenance and repair activities at an appropriate time.

Predictive maintenance has been proven to significantly increase the safety of the system (Zhou et al., 2007; Billinton and Allan, 1988). Another definition for predictive maintenance can be made to detect, analyse and correct faults in machinery and equipment before they become problematic, and to measure selected parameters and compare them with predetermined limit values using graphical gradients. The approach used is to predict the future status of machinery and equipment by monitoring current and past status (Tavukçuoğlu, 2003).

As can be understood from the definition of the approach, the main principle of this maintenance system is to examine the performance of the machines and decide when they will need maintenance. The breakdown of production is interrupted for a short time and the predetermined fault is repaired.

Predictive maintenance is to carry out periodic measurements and to address process or machine parameters to predict them before failures occur. Predictive maintenance is the basis of a good reliability program. Instead of preventive maintenance such as lubrication preventing a malfunction, predictive maintenance activities focus on predicting and predicting potential machinery operations.

When a potential failure is predicted, corrective action is given priority for the engine with a malfunction (Tavukçuoğlu, 2003; Kocaciğer, 2003). In this maintenance approach, some parameters related to the engines must be checked and measured. Through these measurements and controls, thoughts can be formed about the working conditions of the machine and thus the causes of the failure and/or damage can be determined. As the cause of the failure is certain, necessary spare parts and equipment are provided and short-term production is stopped and the failure is eliminated.

Predictive maintenance is the realization of this activity at the most appropriate time by determining the maintenance-repair requirements of machinery, parts, and equipment with periodic observation and condition monitoring systems made by using special devices when necessary. Thus, less downtime, labor, and material expenditure are caused and the life of the parts is used longer (Swanson. 2001).

Since the cause of the malfunction is already detected in this system, no time is lost to find the malfunction after the maintenance starts and spare parts may be provided in advance and the maintenance period is shortened. Again, this system can also prevent secondary damage, as the equipment is fully serviced before failure and distribution. For example, in case of failure of any bearing, the bearing can be changed for a short time before the bearing is displaced, the bearing may be damaged as a result of the distribution of parts, such as shaft damage can be prevented, so that the parts are used more efficiently.

Predictive maintenance applications have many benefits in terms of system and system components. Predictive maintenance helps prevent malfunctions that may occur at unexpected times. It increases the normal operating period between the two failures and thus reduces the maintenance costs. Predictive maintenance reduces maintenance time and extends the useful life of the system and system components. It contributes to increasing the reliability, availability, and maintainability of the systems (Kocaciğer, 2003; Carnero, 2006).

1.1.4 Reliability Centered Maintenance (RCM)

Over the last two decades, care has changed considerably compared to other management disciplines. This change is due to the huge increase in the number and variety of physical assets such as factories, equipment and buildings that are required to be maintained around the world. New maintenance techniques, changes in maintenance organizations and responsibilities were required for the maintenance of these assets, which had more complex designs than before.

In addition, care should respond to changing expectations. Increased awareness of which equipment failures affect safety and the environment more, the link between maintenance and product quality, and the reduction of costs by increasing the use of the factory.

These changes test the limits of skills and behaviour in all areas of the industry. Maintenance officers, like engineers and managers, have adopted new adaptations of thought and behaviour. At the same time, the constraints in maintenance systems have become increasingly apparent, despite the widespread use of computers.

In such an environment, managers have sought new maintenance approaches. They always want to prevent the wrong start and dead ends that cause great confusion. One of the strategic frameworks developed for this purpose is “reliability-centered care”. If applied correctly, reliability-centered care can change the business relationship between physical assets and those who use and care for them. It also puts new assets into service more quickly and reliably (Kennedy, 2005; Rausand, 1998).

The definition of RCM should be considered together with the definition of maintenance concept. Maintenance means ensuring and maintaining the work that physical assets need to do. In the light of this definition, RCM is the process that enables the determination of the maintenance requirements of any physical entity within its own operating system (Maubray, 2001).

RCM is the methodology in which the equipment's functionality, failure modes and effects analysis, and the assessment of the failure results determine the required maintenance operations and the time intervals for these operations (Hipkin and De Cock, 2000).

The RCM process requires the Failure Modes and Effects Analysis (FMEA) with an engineering approach. FMEA is a method to prevent existing defects and problems in products and processes. This method is a systematic approach to determine the effect of failures and the steps to prevent them in terms of the functionality and reliability of the process. It is a method aimed at analysing and evaluating and reducing the failures that may occur in the system, design, process or service. The RCM can be an excellent part of the overall maintenance and production strategy (Hipkin and De Cock, 2000).

1.2 Literature Review on RAM and RCM

Developments in reliability-oriented system analysis and maintenance studies, which started in the 1960s and continued to develop until today, are applied in many sectors. There are many studies on the importance and applications of RAM and RCM. Reliability is one of the most important qualities of good engineering practice.

RAM and RCM are very similar approaches. The main difference between RAM and RCM is that the RAM approach is more prominent than RCM in the design and production stages of the products. RCM is a type of approach that aims to improve the cost-effectiveness of maintenance and provide reliable maintenance applications. On the other hand, RAM addresses not only maintenance practices but also the life cycle. In other words, it provides a reliable and usable system structure in the process from the first production phase of a product to the end of its life (De Sanctis et al.,2016).

Rao and Balasubramanya (1986) have analysed to estimate reliability, availability, and maintainability using the Markov technique for repairable Dual-VHF Omni Range (Dual-VOR), a ground-based azimuth navigation system for aircraft. It's another viewpoint, Carlier et al. (1996) proposed recommendations for determining the requirements of the RAMS analysis during the feasibility study of the Artillery

Command and Reconnaissance Vehicle (ACRV) for manned spacecraft with a long orbit stay.

Rausand (1998), in his study examining the structure of the RCM approach, examined that RCM provides a framework for operating benefit in many systematic maintenance approaches. In the study, requirements and information for reliability analysis are emphasized. The study between RCM practitioners and scientists emphasizes that there will be some future changes for RCM with maintenance optimization. In addition, Swanson (2001) conducted a comprehensive survey with plant managers and maintenance managers in his study, which examined the results of the relationships between maintenance strategies and company performance, and examined the relationship between proactive and aggressive maintenance strategies and performance using factor analysis.

Mokashi et al. (2002), RCM applications encountered in the study of problems encountered in the study, the maritime industry and different industries have benefited from the process differences and problems. It is emphasized that the cost and the problems that cannot be solved by other maintenance approaches, especially in the maritime industry, have become a more economical and reliable system with RCM. However, as in any system, it is stated that RCM also has problems in practice.

Induction motors are the most widely used type of electrical machine in the industry. Early diagnosis of abnormal conditions in electric motors is extremely important in terms of the economic and safe operation of industrial processes. In recent years, monitoring and diagnostic studies in industrial systems have been increasing in order to develop new and reliable maintenance technologies. Seker and Ayaz (2002), working on this subject, have examined the situation monitoring and predictive maintenance technologies in RCM and industrial processes and presented information about these issues in their publications. Besides, Gabbar et al. (2003) have conducted studies on the RCM process mechanism and system design integrated with the Computerised Maintenance Management System (CMMS). At the end of this study, they have suggested that the effective way to optimize equipment or plant maintenance can be achieved by combining various maintenance approaches and functional systems and proposed the RCM process for this. They have stated that the maintenance system optimized with CMMS based RCM process has an efficiency over the conventional maintenance approaches. However, Zhou et al. (2007) proposed an RCM model for a system that started to wear out due to a defective maintenance program. It is assumed that the system is continuously monitored and its status is not variable. When the reliability of the system approaches the limit value R, maintenance is performed. In accordance with their simulations, it was observed that the maintenance intervals of the system decreased when RCM was applied.

Eti et al. (2007) aimed to reduce failure frequency and maintenance costs by integrating RAMS and risk analysis into planned maintenance operations in Afam thermal power plant. They discussed failure mode impact analysis, failure mode impact and criticality analysis, feedback information, support systems, and risk analysis. According to Çebi et al. (2008), the RCM method is based on the principle that not all the tools in the process are of the same importance and the superiorities of the method are: Unnecessary control and maintenance activities are eliminated. This reduces maintenance costs and reduces control frequency. Unexpected tool/hardware malfunctions are minimal, requiring critical equipment to concentrate. Hardware reliability increases and root cause analysis can be performed. The high cost of the initial investment, the existence of the cost of educated personnel and equipment, the inability to easily realize the financial profit that the method will provide, are the weaknesses of the method.

Cheng et al. (2008) in their research, to increase the effectiveness of RCM, artificial intelligence technology combined with RCM analysis and the intelligent RCM analysis (IRCMA) examined. The basis of the IRCMA is the use of old records of the RCM analysis as a reference and used during the new analysis. In this way, complex and repetitive tasks in RCM analysis can be simplified. IRCMA improves the efficiency and quality of RCM analysis.

Lundteigen et al. (2009) discussed and identified the main RAMS requirements for safety instrumented systems (SIS). In the study, they have created a new life cycle model for product development with RAMS analysis. They applied the analysis for a high integrity pressure protection system (HIPPS) for offshore oil and gas applications. On the other hand, Sharma and Kumar (2010) applied RAM analysis to the printing press and washing units of a paper mill. The results are intended to help facility personnel analyse system behavior and improve their performance by adopting appropriate maintenance strategies. It's another viewpoint, Díaz et al. (2010) studied how RAMS analysis can assist in deciding warranty management to obtain a stock of spare parts or to anticipate possible complaints from the customer.

Barberá et al. (2012) presented a case study describing the reliability, availability and maintainability analysis of a Copper Melting Process in Chile. The data collected over 16 months were analysed using parameters of some probability distributions such as Weibull, Exponential, Normal and Lognormal distributions. The analysis results showed which subsystems and equipment are critical to reliability and availability.

Barabadi et al. (2015) have conducted a study on the identification and aggregation of all impact factors on the failure and repair processes of a production facility in the Arctic Region. Taking into account the challenges of existing data collection methods and the impact of environmental conditions, they have proposed a methodology for data collection, making RAMS data more applicable and useful for the design and operation of the system in different operating environments.

Corvaro et al. (2017) applied RAM analysis to evaluate the operational performance of the piston type compressor system. In their study, they have identified the most effective maintenance strategy to be applied to the compressor and suggested a new approach to managers.

In this research, it is seen how RAM and RCM applications are applied in different sectors and what these applications are aimed for. The importance of RAM analysis in terms of continuity of systems and production and maintenance costs, especially in the aerospace industry where the maintenance process has its limits, is understood. Preventing unexpected failures and establishing reliability is an indispensable element for commercial activities. The researches highlight the necessity of reliability analysis for the systems and the engineering requirements in this regard.

1.3 Industrial Survey

When the maritime field is examined, it is seen that the planned maintenance system (PMS) software is widely used. PMS is a recording, monitoring and updating system which is established within the scope of international safety management code (ISM), which was established for the safe and long-lasting operation of ships, offshore platforms and another vessel (Bayer et al., 2018).

Many different planned maintenance software is used in marine fleets. The softwares use generally works with the logic that the system and system components are scheduled for maintenance according to working hours or specific date ranges and informing the user when the scheduled time is approached. Maintenance periods for an equipment are determined based on tests performed by the manufacturer and user feedback. The specified maintenance periods are defined in the planned maintenance system software. The equipment is expected to operate smoothly within the specified date or operating time range. If the equipment has completed the defined time period before the malfunction occurs, the PMS software sends a warning to the user to inform them of the need to maintain the equipment.

Information about the equipment being serviced is processed into the PMS software. The maintenance time is updated. The PMS software assigns a new maintenance schedule for the equipment.

If a malfunction occurs before the time of maintenance, the repair is performed on the software, such as periodic maintenance. The new maintenance period is calculated from the repair date and the system is updated.

Systems that have repairable elements and are in continuous operation continue to operate in working-fault-repair-working cycle for an operating period. Each element constituting the system has its own working cycle and is independent of each other (Figure 1.2). A repair is to return a defective element to normal operation.

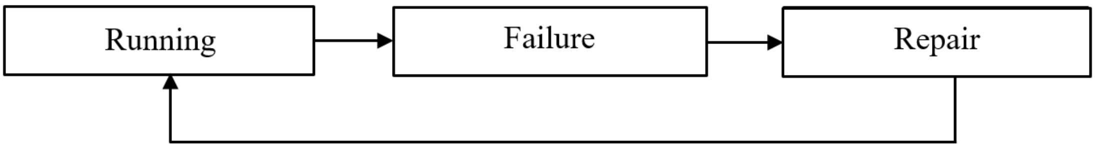

Figure 1.2 : Working cycle of machinery systems.

In the examinations, none of the PMS software showed reliability analysis and reliability based maintenance planning. Maintenance intervals are applied as standard times specified by the manufacturer. Some shipowners have shortened or extended these maintenance periods by specific rates and updated PMS software, especially for older ships. However, these updates are hypothetical, not an analysis result.

Ship owners and operators should prepare and review risk assessment procedures to optimize ship maintenance and to minimize the risk of damage leading to out-of-service life and therefore reduce revenue loss. Priority should be given to measures and corrective actions aimed at improving the reliability of machinery, equipment and systems, including control, inspection and record keeping.

Akyuz and Celik (2017), demonstrated the shortcomings of the standard PMS system and introduced a new PMS concept to address the shortcomings. Through their approach called A'WOT, they explained the limitations of the current PMS, they aimed to ensure that the ships work better with the regulation in maintenance planning by improving the PMS system.

When the maritime sector and other sectors are evaluated in terms of RAM analysis applications, it is seen that the RAM analysis application is not widely used for these systems, although they contain similar critical systems. In order to keep up with the requirements of developing and changing technology, effective maintenance planning for existing systems is required. However, when the maritime sector is examined, it is seen that conventional methods are still used. When it comes to effective maintenance planning, it only comes to mind that quality spare parts and maintenance are recommended by the manufacturer. However, the quality of the spare parts alone should not be a criterion. Maintenance planning should be a reliability-based practice as it is applied in other sectors. With a RAM analysis model to be integrated into PMS software, it is necessary to control maintenance plans and change them if necessary.

1.4 Reliability Analysis Extension to Ship Machinery Systems

Continuity of sailing is expected due to commercial activities. A random fault in the system is beyond the control of engineer officers. The ship machinery system consists of a very complex combined structure. Even the slightest failure of an element of the system will result in poor results such as a power failure. The effect of these failures cannot be accept by the ship operators.

The system must remain within the limits of a number of operating conditions in its performance. These limits are directly related to operation efficiency, such as power and fuel consumption changes. Limits such as material performance, system stability limits and failure limits that are not directly felt by the operators are also important.

In order to reduce the likelihood, frequency and duration of such interruptions and to improve their effects, it is necessary to increase investment in planning and operation processes.

It is clear that economic and reliability limits can be opposite, making it difficult to make operational decisions in both planning and operating processes. The level of investments will also affect the operating limits of the system and therefore directly affect adequate and safe working conditions.

This problem is an issue that power system planners, designers and operators have been dealing with for years. Design, planning, operating criteria and techniques have been developed over the years to address the complexity between reliability, economic and operational boundaries. The techniques and criteria developed were first used in practical applications, all of which are deterministic based and many of them are still in use. The weakness of deterministic criteria is that it does not reflect the probabilistic and random natural behaviour of the system such as consumer demands and element failures.

All factors and uncertainties, which are competing against each other, can be handled in a purposeful and consistent manner, together with their effects, using reliability techniques. The results may be related to the economic aspects of ship machinery system planning and operation. This effect plays an increasing role in current and future ship machinery system developments.

1.5 Purpose of Thesis

RAM analysis; It is an analysis method that aims to ensure that the existing or new systems will be operated in the most efficient way under appropriate conditions and that maintenance activities can be performed with minimum cost and highest accuracy. The RAM analysis method is frequently used to predict the possible failures of an equipment or a system and to perform preventive maintenance activities without failure.

Engine or system manufacturers determine maintenance intervals for the systems and system components they produce. These periods can be date based or running hour based. The maintenance period specified for each system may be different from the maintenance periods specified for the subsystems. In these cases, instead of maintaining all of the system, only maintaining the related subsystems can provide sufficient reliability for system availability and failure-free operation.

The availability of a system is related to the ability to perform the expected task at the requested time. If the maintenance and repair activities of a system are planned and carried out in a minimum time; availability will be high.

Maintenance management on ships is kept under control with planned maintenance systems. Engine manufacturers, as a result of their tests; they provide users with a list of maintenance scheduling times for systems, machines and sub-parts according to the maintenance periods they set. The applications used by the planned maintenance systems inform the users about the systems, machines or subsystems oncoming the maintenance time with the warning mechanism established within this list. The maintenance period of the system components being maintained is processed in these applications and the next period is determined.

However, preventive maintenance does not increase reliability rate to one hundred percent. Unexpected malfunctions may occur in the system due to operating errors, human errors, the quality of the spare parts used and the ship conditions. Any failure will reduce the reliability of the system.

Today, ships are operating non-stop and accordingly the time allocated for maintenance is shortening day by day. However, shortening the maintenance time does not mean that maintenance will not be performed. In order to continue the healthy operation of the systems and their sub-components, preventive maintenance works must be performed in a timely and rapidly. Considering the conditions of the ship, preventive maintenance periods can be postponed or made early maintenance. In these cases, the next maintenance period doesn’t change, but the cost of maintenance rises due to early or late maintenance.

Regulatory maintenance works are non-delayable. In order for the ship to continue its commercial activities, it must work nonstop. Ship machinery systems are usually equipped with spare systems. In case of any failure, the system which is kept in spare is activated and the ship continues to operate. Due to the commercial agreements between ship owners and charterer companies, serious financial obligations arise in cases such as failure of the ship to fulfill its duty, completion of the mission after the specified time and failure to complete the duty. For regulatory maintenance work, the system component that has failed must be repaired at tolerable times and the ship must continue to operate.

The reliability of the ship's system and system components is determined by failure rates. If the reliability and availability of a system or system component is low, maintenance periods will need to be updated to improve performance and prevent potential failures. System components with high failure rate can be identified by the evaluations with RAM analysis and preventive maintenance activities can be applied before the failure occurs.

The main purpose of this thesis is to provide a new function with the integration of RAM analysis into ship planned maintenance systems which are limited to conventional applications. In this way, PMS will gain a productive structure in determining the periods of maintenance operations, calculating the reliability and availability of the systems and determining the periods required for maintenance.

The main objectives in this study are;

i. to systematically utilize PMS records.

ii. to provide a consistent and systematic analysis method.

iii. to create a visualization for the evaluation of analysis outputs.

iv. to produce a knowledge management interface through ship maintenance planning.

v. to provide decision aid to operational and management level at the ship maintenance planning.

Although RAM analysis provides many benefits for the maintenance planning of ship machinery systems, there are some points that are limited. The limitations of the RAM-based PMS are shown as follow;

i. Long-term chartering.

ii. Unnecessary maintenance of some system components

iii. Spare parts requests with an extended delivery time

iv. Low level of data entry

2. METHODOLOGY BACKGROUND

Machinery parts for maritime applications are well established to have very high quality. This means that they are also very reliable. Compared to land-using parts, the parts can be intended to reduce the danger and damages of idle periods by the tough setting. The developer and the owner should be satisfied that the quality of the element should be compensated for increasing costs. Therefore, in addition to efficiency reasons in working circumstances, the choice of machinery, materials and configuration for a vessel shall be guided by its reliability, maintainability and availability indicators.

The reliability, maintainability and availability indicators prediction with related reliable scores is quantitative data to be provided by reliability and maintainability engineering. This data can contribute to stronger performance choices, leading to higher revenues over time. The designers and operators can therefore assess and enhance the forecast on:

i. Frequency of inspection periods

ii. Frequency of repair periods

iii. Frequency of spare parts request

iv. Commercial voyage success

v. Voyage scheduling

2.1 Failure Distribution Model

The failure rate is the frequency at which a system or component fails, where failures are measured per unit of time.

The failure rate is usually time-based, and the rate differs over the system life cycle.

The failure rate is the level of failure, expressed for example in failures per hour, of a designed system or component. In practice, a more commonly articulated and used mean time between failures (MTBF) for quality components or systems is closely related. The failure rate is often time-dependent, and an obvious corollary is that the frequency changes over time compared with the predicted device life cycle.

2.1.1 Mean Time Between Failures

The mean time between failures is the average running time of the repairable system or system components between the two failures.

It is calculated as the ratio of the total running time until the first failures to the number of equipment produced by the equipment produced in industrial systems. In order to calculate these values, a sufficient amount of devices must be produced and started to be used.

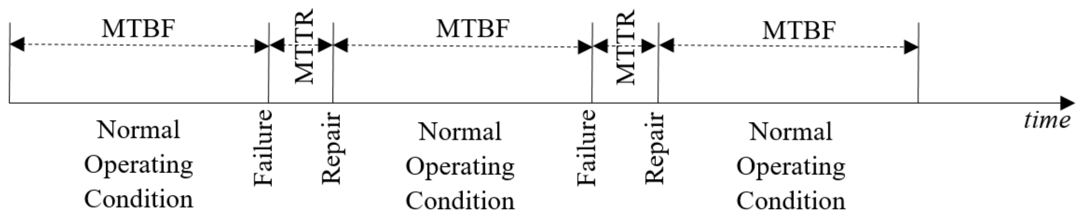

Figure 2.1 : Mean time between failure and mean time to repair cycle.

When ship machinery systems are considered, the mean time between failures should be calculated not by the number of equipment but by the number of failures. This is because the ships have two or three backups of a system or system component. MTBF in ship machinery systems; is calculated as the ratio of the total fault-free operating times of the respective system or system component to the total number of failures within a specified period and a specified fault type (Uzgören et al., 2010).

$$MTBF = \int_0^\infty t.f(t).dt = \int_0^\infty [1 - F(t)].dt = \int_0^\infty R(t).dt \tag{2.1}$$

$$MTBF = \frac{Total\ Working\ Time}{Total\ Number\ of\ Failures} \tag{2.2}$$

Where f(t) is the probability density function and F(t) is cumulative distribution function,

The Mean Time between Failures (MTBF) is a key system reliability parameter for system or component that can be repaired. It is described as the mean time a system operates without failure. MTBF can either be determined by the average running time before a failure occurred or by taking the mean distribution of the failure. Then, a mean or expected value is specified (Uzgören et al., 2010),

$$MTBF = \int_0^\infty tf(t)dt = \int_0^\infty [1 - F(t)]dt = \int_0^\infty R(t)dt \tag{2.3}$$

2.1.2 Mean Time to Failure

Mean time to failure is the average time during which the system component, which cannot be repaired, is replaced with a new one after a failure and regains normal operating conditions until the next failure.

On board, some system components are produced as disposable. These components are replaced when malfunctions occur or during normal maintenance intervals.

For an information on n items with failures $t_1, t_2, \ldots, t_n$, MTTF is defined as;

$$MTTF = \frac{1}{n}\sum_{i=1}^{n} t_i \tag{2.4}$$

2.1.3 Mean Time to Repair

Mean time to repair is the average time required to restore a system or component that has failed to normal operating conditions.

The time required for repair depends on the conditions of the ship, the supply of spare parts and the degree of competence of the personnel to repair.

$$MTTR = \int_0^\infty t.f(t).dt = \int_0^\infty [1 - M(t)].dt \tag{2.5}$$

For an information on n items with repair times $t_1, t_2, \ldots, t_n$, MTTR is defined as;

$$MTTR = \frac{1}{n}\sum_{i=1}^{n} t_i \tag{2.6}$$

2.2 RAM Analysis

Exponential, normal, lognormal and weibull formulas are the most widely used distributions in reliability and maintainability analysis calculations.

For RAM analysis, we will use distribution methods formulas which are probability density function, distribution parameters, mean time between failure, standard deviation, reliability and maintainability formulas (Uzgören et al., 2010).

2.2.1 Normal Distribution

Probability Density Function:	$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}$	(2.7)
Parameters of Distribution:	Mean = μ Standard Deviation = σ	(2.8)
Mean Time Between Failure:	μ	(2.9)
Standard Deviation:	$\sigma = \sqrt{\frac{(t-\mu)^2}{N}}$	(2.10)
Reliability:	$R(t) = 1 - \phi(\frac{t-\mu)}{\sigma})$	(2.11)
Maintainability:	$M(t) = \phi(\frac{t-\mu)}{\sigma})$	(2.12)

$\phi(z)$ is the cumulative distribution function for the standard normal variable (z).

2.2.2 Lognormal Distribution

Probability Density Function:	$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\ln t-\mu)^2}{2\sigma^2}}$	(2.13)
Parameters of Distribution:	Mean = μ Standard Deviation = σ	(2.14)
Mean Time Between Failure:	$e^{(\mu+\frac{\sigma^2}{2})}$	(2.15)
Standard Deviation:	$\sigma = \sqrt{e^{2\mu+\sigma^2}(e^{\sigma^2}-1)}$	(2.16)
Reliability:	$R(t) = 1 - \phi(\frac{lnt-\mu)}{\sigma})$	(2.17)
Maintainability:	$M(t) = \phi(\frac{lnt-\mu)}{\sigma})$	(2.18)

2.2.3 Exponential Distribution

Probability Density Function:	$f(t) = \lambda e^{-\lambda t}$	(2.19)
Parameters of Distribution:	Failure Rate = λ	(2.20)
Mean Time Between Failure:	$1/\lambda$	(2.21)
Standard Deviation:	$\sigma = 1/\lambda$	(2.22)
Reliability:	$R(t) = e^{-\lambda t}$	(2.23)
Maintainability:	$M(t) = 1 - e^{-\lambda t}$	(2.24)

2.2.4 Weibull Distribution

Probability Density Function:	$f(t) = \beta\alpha^{-\beta} t^{\beta-1} e^{-(\frac{t}{\alpha})^{\beta}}$	(2.25)
Parameters of Distribution:	Scale Parameter = α Shape Parameter = β	(2.26)
Mean Time Between Failure:	$\alpha\Gamma(1 + \frac{1}{\beta})$	(2.27)
Standard Deviation:	$\sigma = \alpha\sqrt{\Gamma\left(1 + \frac{2}{\beta}\right) + \Gamma^{2}(1 + \frac{1}{\beta})}$	(2.28)
Reliability:	$R(t) = e^{-(\frac{t}{\alpha})^{\beta}}$	(2.29)
Maintainability:	$M(t) = 1 - e^{-(\frac{t}{\alpha})^{\beta}}$	(2.30)

2.3 RAM Analysis of Ship Machinery Systems

The standard PMS software used on ships operates with the logic of adding the data entered into the system to a predetermined period for determining the maintenance plan. The planned maintenance software processes the entered data and calculates the upcoming periods for maintenance of the systems and components. According to the maintenance periods determined by the manufacturer and processed by the user (technical superintendent and master/chief engineer) informs the maintenance planning. The responsible engineer exchanges information with the technical department and carries out maintenance the system component approaching the maintenance time according to the appropriate navigation and port conditions. During the last maintenance, the operating hours of the system are noted. The operating hours are recorded in the PMS software. The software calculates the maintenance pariod based on the newly entered data and plans the next maintenance.

The only decision-making mechanism in standard system operation is PMS software. The system is not carry out maintenance unless the PMS software warns of the maintenance period. Unexpected failures in systems are exceptions.

The RAM analysis helps determine the reliability of systems and the optimum time needed for maintenance. The data from the PMS software is processed in the RAM analysis to determine the possibility of the system failing at any time interval. In addition, the availability and maintainability of the system are other outputs of the RAM analysis.

Planned maintenance systems contain long-term data on ship machinery systems. Data from previous years constitute the source for the RAM analysis. The data collected for the years under normal operating conditions of the systems are processed in the RAM analysis. These data examine the intervals at which past failures occurred and the correlation relationship between them. As a result of the data obtained as an output, the optimum maintenance period for the relevant machinery systems is calculated. Data from the RAM analysis gives the tips to the engineers on the reliability and maintainability of the systems. If the engineers who perform the maintenance deem it appropriate to perform the maintenance operation and they carry out the maintenance, the new maintenance time entered into the PMS software creates new resources for the RAM analysis. If maintenance operation is not to be performed, the next maintenance schedule is expected.

The output of the RAM analysis can be monitored for each desired operating hour. It is the initiative of engineers and managers to interpret the outputs and take the necessary measures.

2.4 Proposed Framework

The standard PMS system used onboard is the only decision-making unit for planning maintenance. It does not generate an instruction for maintenance before the maintenance time specified by the manufacturer is reached.

In the standard PMS software, the maintenance decision is based only on the engine's running hours. Nevertheless; maintenance planning is an issue that needs to be taken more seriously. Conditions such as spare parts, voyages, and maneuvering are as important as when maintenance will be performed. If maintenance planning is made considering all the conditions, it becomes effective planning. Otherwise, adequate prerequisites for maintenance may not have been met at the time the software alerts for maintenance.

As shown in Figure 2.2, if RAM analysis is added to the standard PMS system, this lack of system can be remedied slightly. In this new system, which we will call knowledge management unit, machinery data collected for PMS, voyage plans, weather reports, maneuver records, etc. reports are processed in the RAM analysis. The RAM analysis evaluates into three categories. At the desired running hour; machinery data get for ship and company managers in the categories of reliability, availability, and maintainability. The company and ship managers in the decision-making position decide whether there is a need for an early maintenance plan according to the conditions of the ship. If it is decided to make an early maintenance planning for the related engine, maintenance operation is performed and the planning period of the maintenance for the related engine is updated in the PMS system. Since each new system update will improve the data repository, the model outputs will vary continuously.

If no early maintenance planning is performed, the routine PMS period is expected. Expecting a routine PMS period will also contribute to the data repository to improve the RAM analysis.

The knowledge management unit provides the possibility of failure of the required machinery systems before a risky operation of the ship and the determination of the optimal times required to maintain.

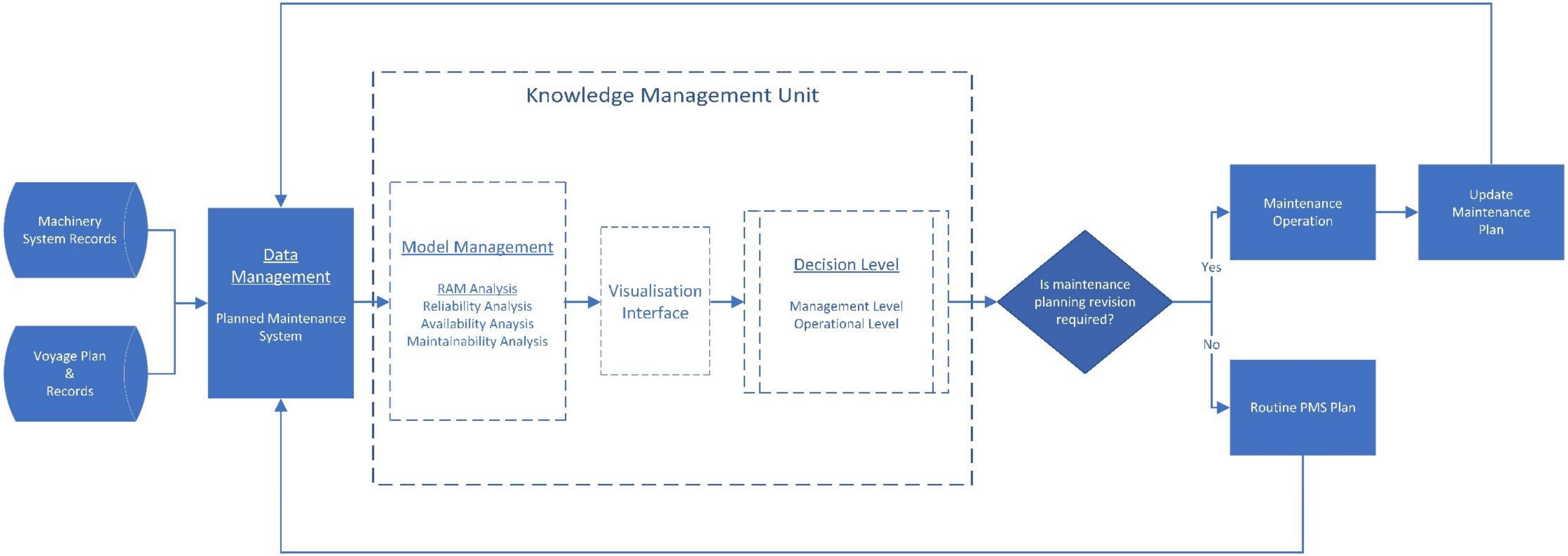

Figure 2.2 : Proposed Framework.

3. FIELD STUDY

3.1 Scope

Shipping Company-A owns 36 different tonnage container ships and 6 oil tankers. The company operates in the Mediterranean, Black Sea and Marmara Sea regions of Europe and Africa.

The oldest ship of the company was built in 1993. The newest vessel was built in 2017. The company has 5 vessels with 2800 TEU capacity, 3 vessels with 2600 TEU capacity, 4 vessels with 2500 TEU capacity, 8 vessels with 1600 TEU capacity, 2 vessels with 1400 TEU capacity and 12 vessels with 1200 TEU capacity. The company has approximately 61800 TEU containers and 14751 dwt oil carrying capacity.

The data was obtained from the planned maintenance system of the company vessel, Ship-A, under the supervision of the company official. It was built in May 2001 and has a capacity of 1208 TEU. The vessel has MAN B&W 7S50MC-C model main engine that is 11060 kw power.

The main engine is 7-cylinder, 2-stroke direct drive diesel engine. The cylinder diameter is 50 cm.

3.2 Review of PMS Records

When the planned maintenance system is examined, the data entered since 2005, the date when the ship joined the company, was seen. Maintenance periods of all systems and system components, maintenance level, maintenance procedures, dates and times of maintenance are available in the software. The importance of the maintenance is grouped as low, medium and high depending on the functions of the component on the ship and the availability of spare parts.

The fact that there was no data entry or there were irregular intervals in the shipyard processes after the purchase of the ship in 2005, the data after 2006 were evaluated.

Considering the length of service and maintenance of the ship, it is seen that much data cannot be processed in the software.

Data for the main engines and generators were collected and examined. The data has been determined for the generators, It was seen as they have not regular and there are deficiencies between them. When the data collected for the main engine is examined, it is found that many components are serviced once or twice for the total running times. This is due to the fact that the maintenance periods of these components correspond to long working hours. To achieve meaningful results, the fuel injectors were evaluated because the maintenance period was short.

The planned maintenance system includes the running hours during which maintenance is performed, but there is not include operating hours for maintenance. The operating hours for maintenance were accepted by the technical inspector of the company, the chief engineer, based on experience.

3.3 System Oriented Approach

In standard PMS software, the system works as follows. In the planned maintenance system, the ship is divided into two departments, deck, and machinery. There are separate sections for each department. When the software is run and any department is selected, the spare parts inventory list of the department, the planned maintenance list of the machinery and equipment, and the deficiency reports sections related to malfunctions appear.

For example; when the machinery department is selected and opened the planned maintenance list, the names of all systems in the engine room will be listed. In the sub-headings of the listed systems, sub-lists of the subsystems and system components of the systems shall be opened. When we select the main engine, all components of the main engine will appear in the sub-list. The sub-headings of these components appear as customized headings such as the lubrication system, fuel system, air system. The historical work list of equipment can be followed by following these steps. Maintenance procedures for each system component are determined in separate periods. These periods consist of the values specified in the manual provided by the manufacturer.

After the maintenance of the system or system components, the running hours during which the maintenance is performed is updated. After this update, the new maintenance date is scheduled based on the software's defined period.

3.4 Data Collection

Data in these processes were ignored since the data in the first years of the ship's commercial activities were recorded at irregular intervals. The ship has a seven-cylinder main engine. There are two fuel injection valves for each cylinder in the ship's fore and aft positions. As the two injection valves of the cylinder have interfered during the maintenance and repair operations, the same working hours were found in the records. For this reason, the injection valves were listed with the cylinder number and the two injection valves were treated as one injection valve.

In the process of obtaining the data, the main engine of Ship-A was around 90000 operating hours. The records in the period of 2006-2019, which constitute a meaningful range from the data recorded since 2005, were examined. Due to the shortage of data in the maritime sector and the lack of recording events, not all of the selected data were included in the study, although those due to planned maintenance were included. For this reason, it was accepted that every maintenance performed was caused by the malfunction.

The main engine manufacturer has set the scheduled maintenance period of the fuel injection valves to 4000 operating hours. In planned maintenance, the desired maintenance process is to disassemble the injection valve from the main engine, to test the fuel injection valve opening pressure, to check whether the injection valve is voiding through the nozzle holes, if there is not void, the position of the pressure between the reference values, if there is no leakage, the opening pressure is adjusted to the desired level and reassembled to the main engine. If leakage occurs in the injection valves under high pressure, it is desirable to remove the injection valve and distribute all its parts. Cleaning of parts, replacement of o-rings, measuring of injection valve spring height, changing if not within reference values, removal of deformation of the non-return valve and thrust spindle surfaces, removal of deformation of thrust spindle and spindle guide surfaces, and control of tension in non-return valve if necessary. After all, operations are performed, nozzle hole diameters are checked. Within the permissible range of values, all parts of the injection valve are assembled as described by the manufacturer. The opening pressure is adjusted after the injection valve is collected. The ready injection valve is mounted on the main engine.

When these operations are taken into consideration, even if the fuel injection valves are not dismantled to that's internal parts, that can be considered as a fault record due to irregular opening pressure. In this case, it is foreseen that the received data will be evaluated as the fault record.

Table 3.1 : Total downtimes for cylinder number 1-7.

Cylinder No	Number of Failure	Total Downtime
1	19	58.9
2	20	61.75
3	19	58.75
4	19	57.75
5	18	54.9
6	21	64.55
7	19	57.85

Table 3.2 : Total running hours for cylinder number 1-7.

Cylinder No	Number of Failure	Total Running Hours
1	19	63763
2	20	61203
3	19	63342
4	19	63406
5	18	62428
6	21	64663
7	19	64956

3.5 Data Analysis

The logical data of the collected data between 2006-2019 were evaluated. Each operating hour in the system indicates the time when the injection valve was removed from the main machine and brought back into operation. Using the obtained running hours, the time between failures was calculated. Calculated intervals between failures were evaluated in terms of correlation coefficients using "Minitab v16.2.4" software. The exponential, lognormal, normal and weibull distribution methods were determined according to the correlation coefficient. In the correlation graphs (also Table 3.5 to Table 3.11), Appendix A, weibull distribution is preferred as the method of distribution of time between failures. In the correlation graphs (also Table 3.12 to Table 3.18),

Appendix C, normal distribution is preferred as the method of distribution of time to repair. For each injection valve pair, weibull and normal distributions were used to determine the failure rate, reliability and unreliability rates. The formulas between (2.7) and (2.12) are used in the normal distribution calculations. The formulas between (2.25) and (2.30) are used in the weibull distribution calculations.

For the shape and scale parameters in the formulas of the weibull distribution method, values generated from Apppendix B graphs were used. Probability Density Function was calculated using the scale and shape parameters in the formula (2.25).

For the mean and standard deviation parameters in the normal distribution method formulas, values generated from Apppendix D graphics were used. Probability Density Function was calculated using the mean and standard deviation parameters in the formula (2.7).

Table 3.3 : Mean time to repair.

Cylinder No	Mean Time To Repair (operation hours)
1	3.100
2	3.088
3	3.092
4	3.039
5	3.050
6	3.074
7	3.045

Table 3.4 : Probability density function for mean time to failure.

Cylinder No	Mean Time to Failure	Probability Density Function
1	3356	0.0013
2	3051	0.0322
3	3334	0.0112
4	3337	0.0043
5	3468	0.00125
6	3079	0.0438
7	3419	0.003804

Table 3.5 : No:1 F.I.V. MTBF and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.939	3345.74	178.751
Lognormal	0.879	3357.64	185.812
Exponential	*	2211.92	411.974
Normal	0.905	3355.95	160.557

Table 3.6 : No:2 F.I.V. MTBF and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.968	3054.85	238.835
Lognormal	0.917	3078.18	270.198
Exponential	*	2148.93	403.262
Normal	0.946	3051.15	217.399

Table 3.7 : No:3 F.I.V. MTTF and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.928	3328.70	250.645
Lognormal	0.854	3340.40	270.745
Exponential	*	2275.99	431.430
Normal	0.885	3333.79	210.342

Table 3.8 : No:4 F.I.V. MTBF and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.931	3325.02	204.492
Lognormal	0.872	3339.07	216.948
Exponential	*	2236.36	419.999
Normal	0.895	3337.16	182.651

Table 3.9 : No:5 F.I.V. MTBF and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.863	3454.14	230.444
Lognormal	0.764	3454.13	234.249
Exponential	*	2281.21	436.072
Normal	0.838	3468.22	173.882

Table 3.10 : No:6 F.I.V. MTBF and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.947	3084.53	268.248
Lognormal	0.886	3107.56	305.999
Exponential	*	2175.40	399.006
Normal	0.919	3079.19	228.903

Table 3.11 : No:7 F.I.V. MTBF and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.885	3405.50	242.260
Lognormal	0.791	3406.57	251.780
Exponential	*	2267.21	423.573
Normal	0.834	3418.74	186.611

Table 3.12 : No:1 F.I.V. MTTR and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.980	3.09547	0.048150
Lognormal	0.986	3.10096	0.048354
Exponential	*	1.89030	0.338640
Normal	0.988	3.10000	0.047974

Table 3.13 : No:2 F.I.V. MTTR and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.976	3.08356	0.040958
Lognormal	0.983	3.08817	0.040882
Exponential	*	1.86171	0.323258
Normal	0.985	3.08750	0.040617

Table 3.14 : No:3 F.I.V. MTTR and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.977	3.08799	0.042488
Lognormal	0.981	3.09279	0.042276
Exponential	*	1.87337	0.334528
Normal	0.983	3.09211	0.041949

Table 3.15 : No:4 F.I.V. MTTR and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.928	3.03615	0.030537
Lognormal	0.958	3.03970	0.030382
Exponential	*	1.82369	0.324079
Normal	0.958	3.03947	0.030406

Table 3.16 : No:5 F.I.V. MTTR and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.961	3.04683	0.029910
Lognormal	0.967	3.05027	0.029454
Exponential	*	1.83458	0.335365
Normal	0.968	3.05000	0.029355

Table 3.17 : No:6 F.I.V. MTTR and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.958	3.06965	0.042162
Lognormal	0.975	3.07443	0.042288
Exponential	*	1.85154	0.313582
Normal	0.976	3.07381	0.042098

Table 3.18 : No:7 F.I.V. MTTR and distribution correlation coefficient.

Distribution	Correlation Coefficient	Mean	Standard Error
Weibull	0.946	3.03944	0.051621
Lognormal	0.977	3.04570	0.052689
Exponential	*	1.87192	0.336727
Normal	0.977	3.04474	0.052702

3.6 Visualisation of Results

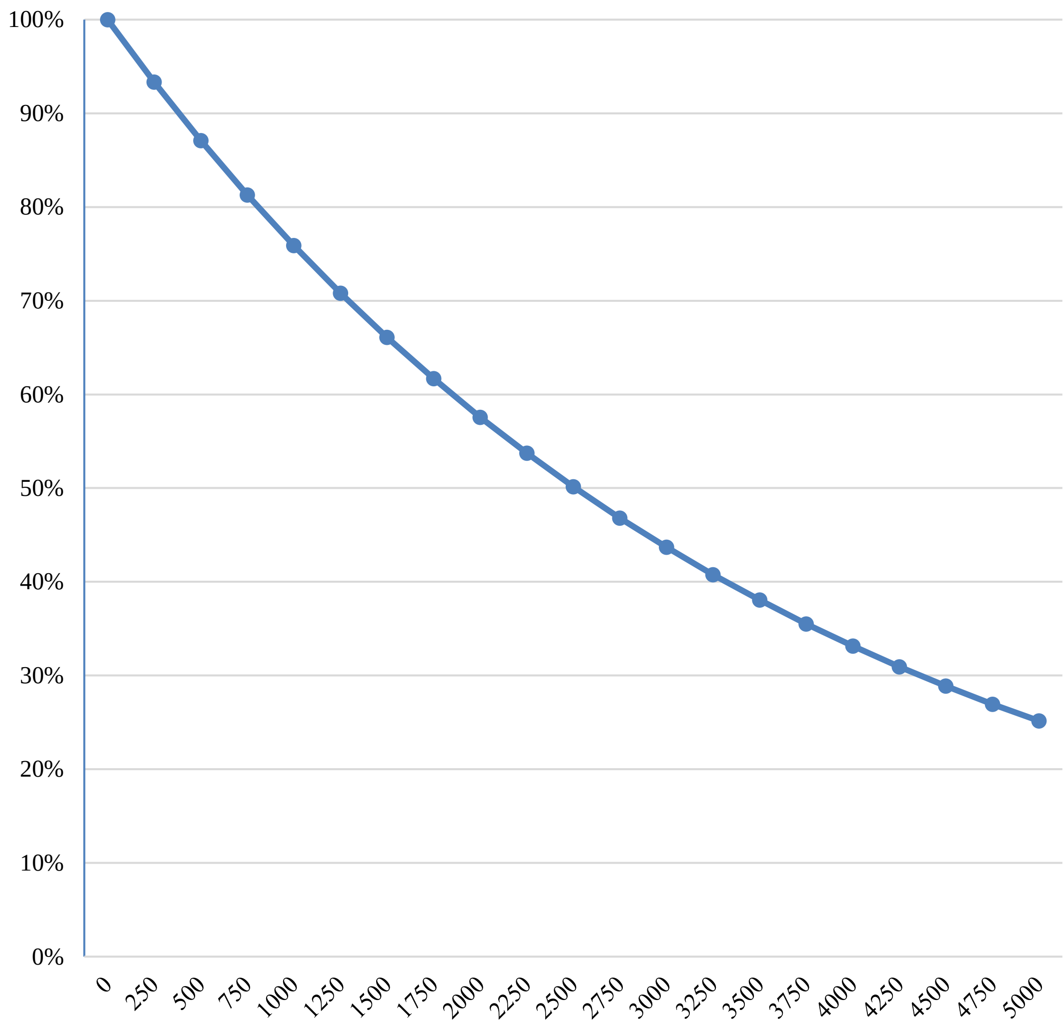

Figure 3.1 : No:1 M/E F.I.V. reliability rate.

The lowest maintenance/repair period was 1816 running hours and the highest maintenance/repair period was 4015 running hours. The average maintenance/repair period was calculated as 3356 running hours.

As can be seen in the graphs (Figure 3.1), the reliability of the No:1 Fuel Injection Valve decreases as the operating hours increase. While the reliability of a repaired fuel injection valve is 100%, after 1000 running hours of fuel injection valve reliability has reduced to 76%. After 2750 running hours, the reliability rate has reduced to less than 47%. When it comes to 4000 working hours applied in the planned maintenance system, the reliability rate has decreased to 33%.

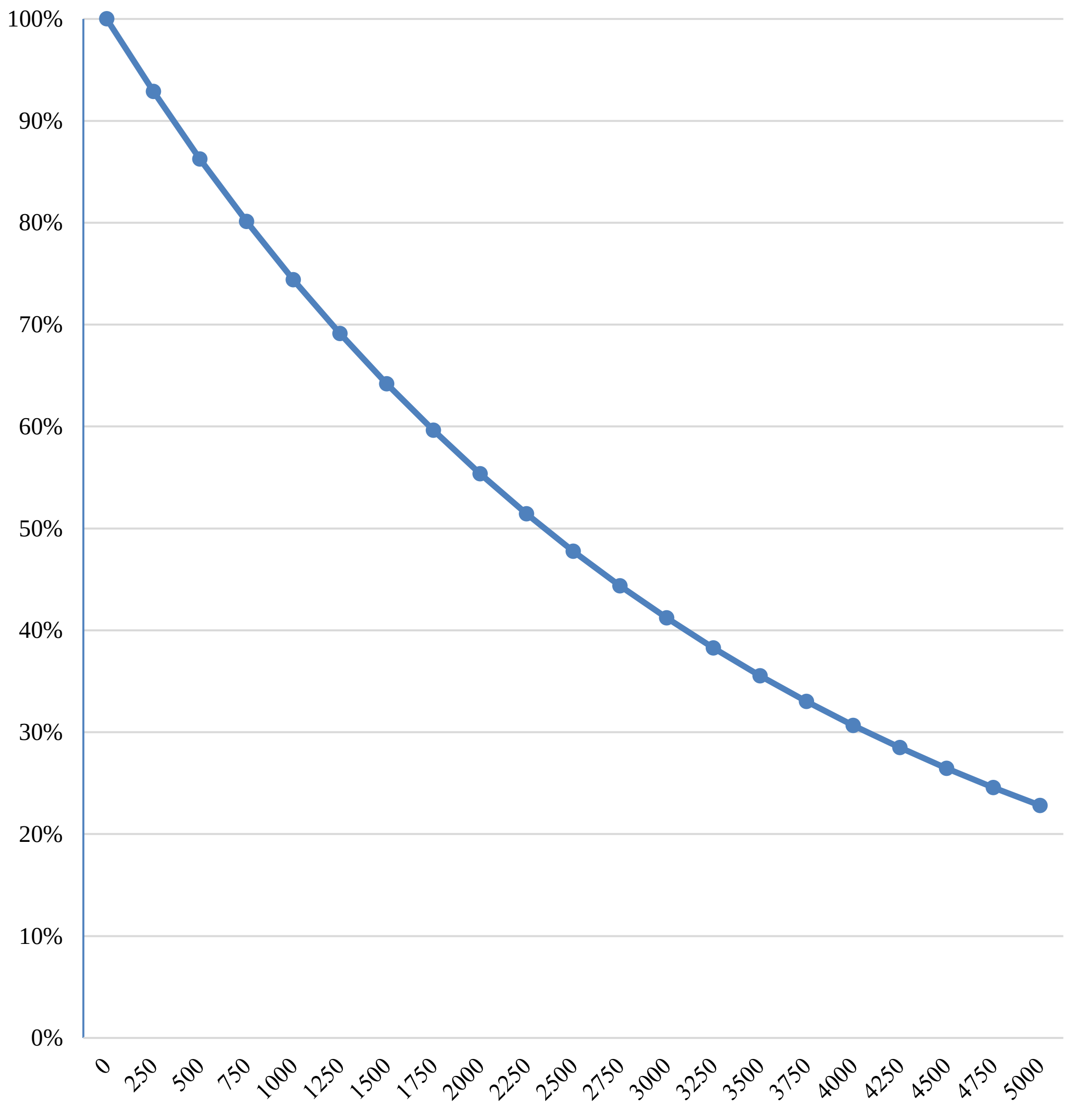

Figure 3.2 : No:2 M/E F.I.V. reliability rate.

The lowest maintenance/repair period was 1138 running hours and the highest maintenance/repair period was 4060 running hours. The average maintenance/repair period was calculated as 3051 running hours.

As can be seen in the graphs (Figure 3.2), the reliability of the No:2 Fuel Injection Valve decreases as the operating hours increase. While the reliability of a repaired fuel injection valve is 100%, after 1000 running hours of fuel injection valve reliability has reduced to 74%. After 2750 running hours, the reliability rate has reduced to less than 44%. When it comes to 4000 working hours applied in the planned maintenance system, the reliability rate has decreased to 31%.

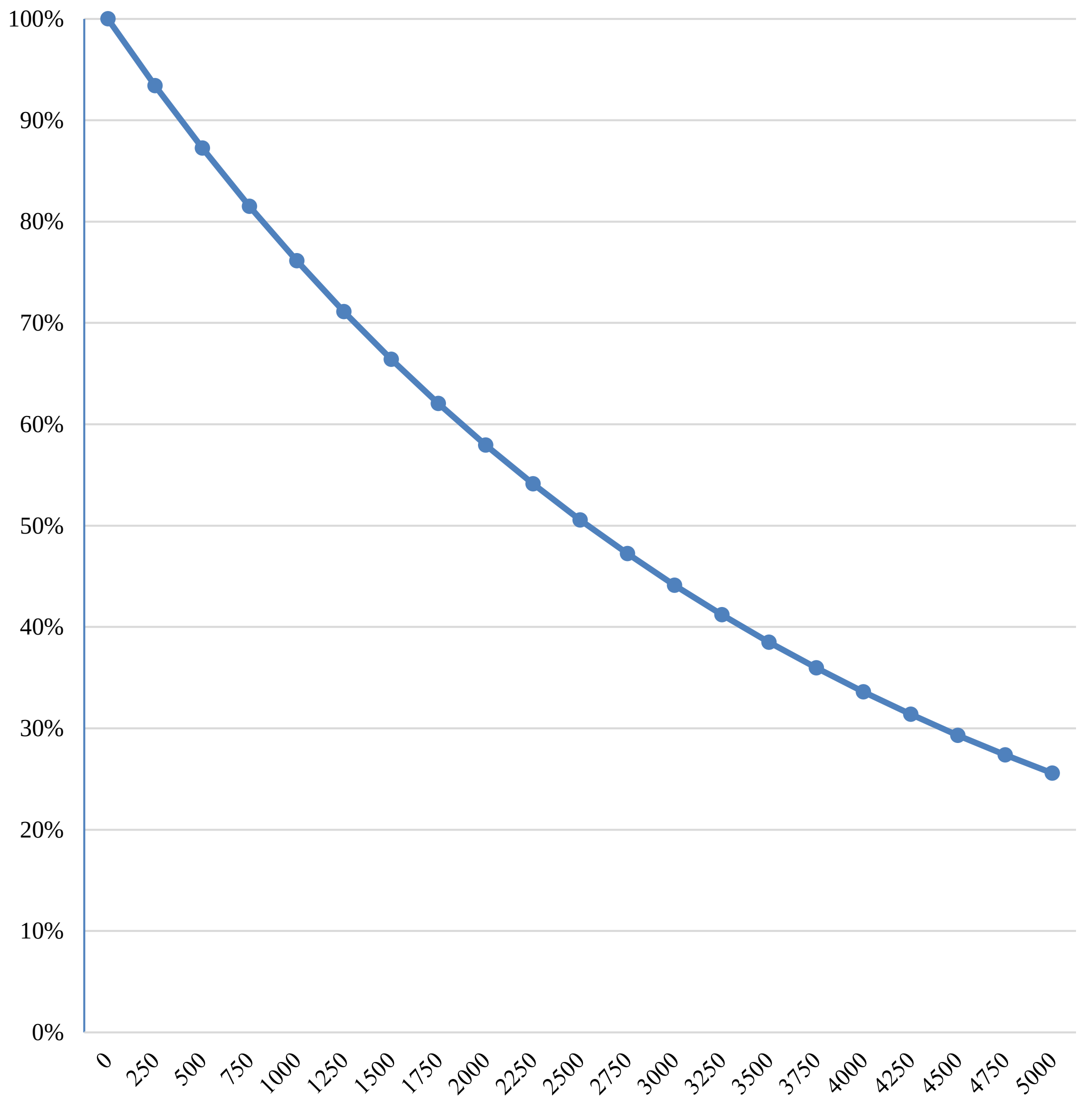

Figure 3.3 : No:3 M/E F.I.V. reliability rate.

The lowest maintenance/repair period was 1094 running hours and the highest maintenance/repair period was 4227 running hours. The average maintenance/repair period was calculated as 3334 running hours.

As can be seen in the graphs (Figure 3.3), the reliability of the No:3 Fuel Injection Valve decreases as the operating hours increase. While the reliability of a repaired fuel injection valve is 100%, after 1000 running hours of fuel injection valve reliability has reduced to 76%. After 2750 running hours, the reliability rate has reduced to less than 47%. When it comes to 4000 working hours applied in the planned maintenance system, the reliability rate has decreased to 34%.

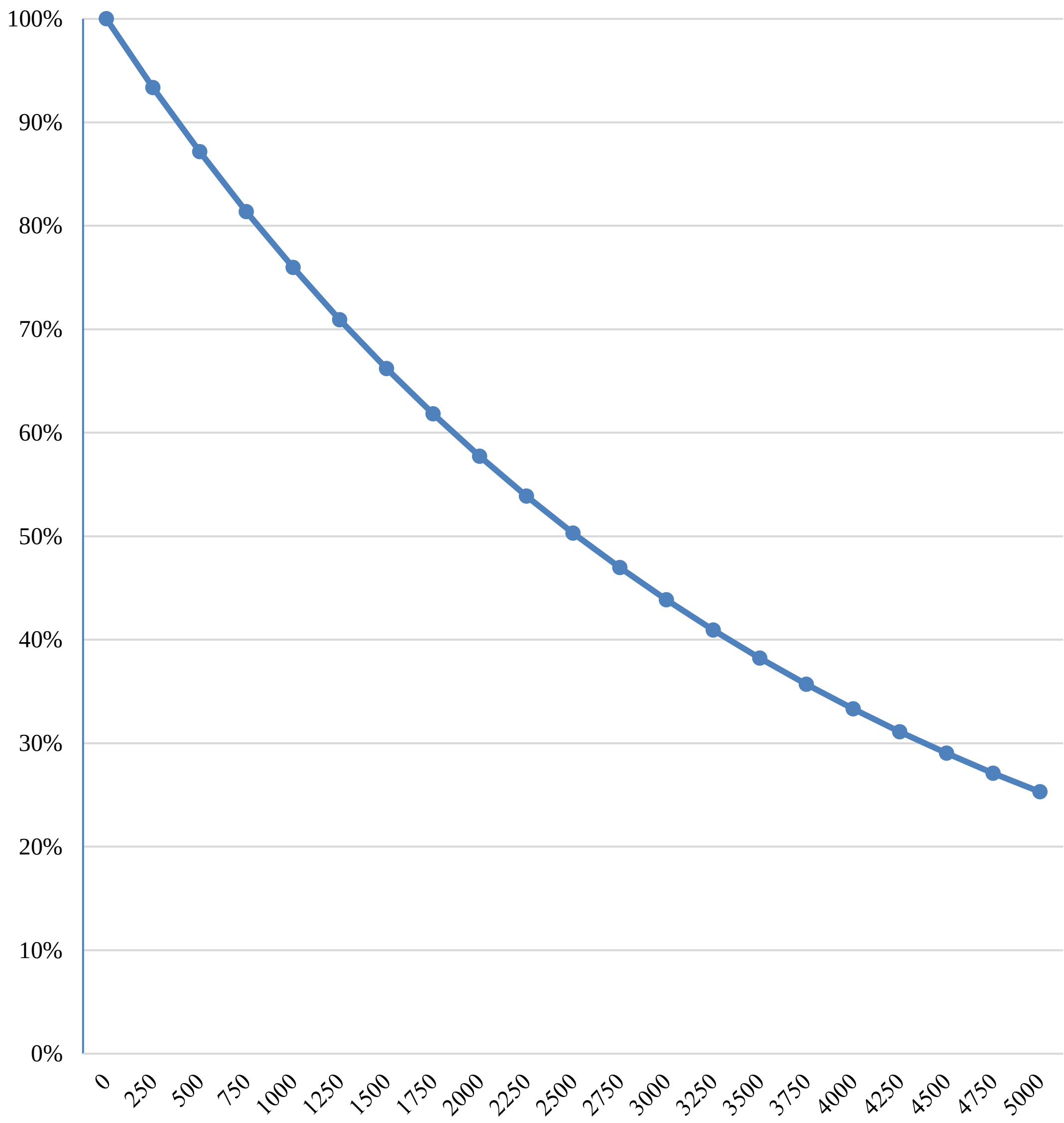

Figure 3.4 : No:4 M/E F.I.V. reliability rate.

The lowest maintenance/repair period was 1701 running hours and the highest maintenance/repair period was 4054 running hours. The average maintenance/repair period was calculated as 3337 running hours.

As can be seen in the graphs (Figure 3.4), the reliability of the No:4 Fuel Injection Valve decreases as the operating hours increase. While the reliability of a repaired fuel injection valve is 100%, after 1000 running hours of fuel injection valve reliability has reduced to 76%. After 2750 running hours, the reliability rate has reduced to less than 47%. When it comes to 4000 working hours applied in the planned maintenance system, the reliability rate has decreased to 33%.

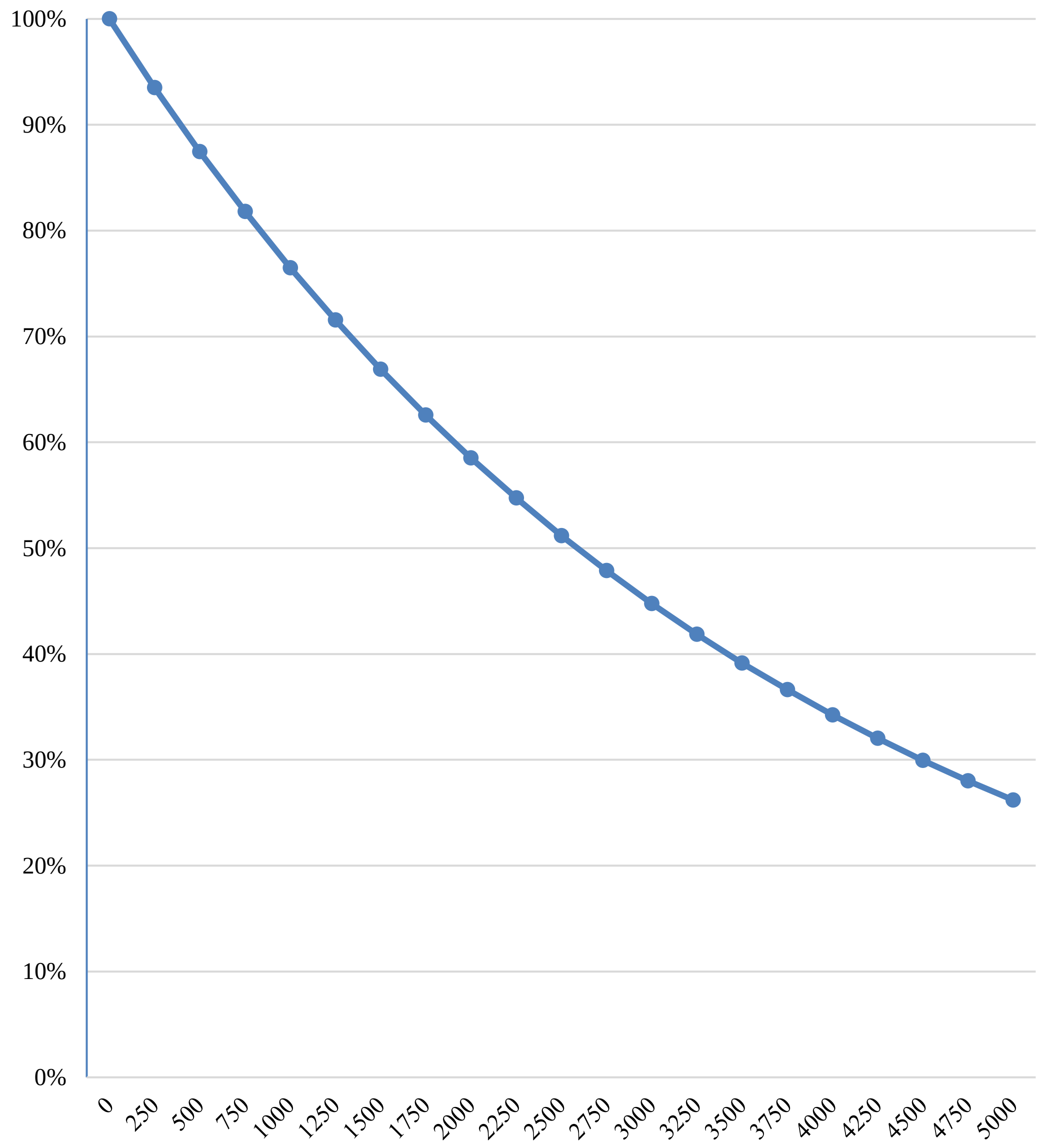

Figure 3.5 : No:5 M/E F.I.V. reliability rate.

The lowest maintenance/repair period was 1012 running hours and the highest maintenance/repair period was 4122 running hours. The average maintenance/repair period was calculated as 3468 running hours.

As can be seen in the graphs (Figure 3.5), the reliability of the No:5 Fuel Injection Valve decreases as the operating hours increase. While the reliability of a repaired fuel injection valve is 100%, after 1000 running hours of fuel injection valve reliability has reduced to 76%. After 2750 running hours, the reliability rate has reduced to less than 48%. When it comes to 4000 working hours applied in the planned maintenance system, the reliability rate has decreased to 34%.

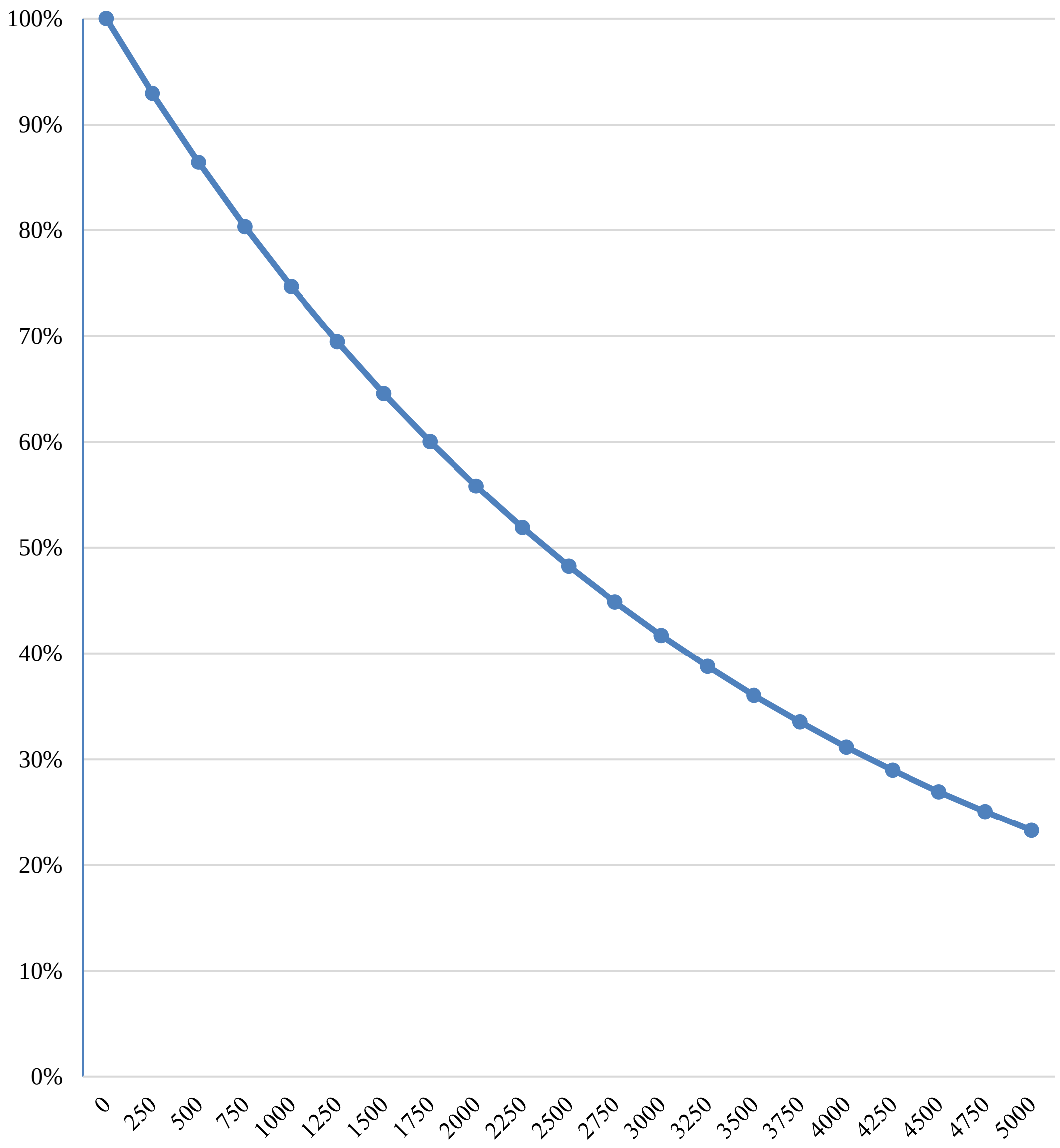

Figure 3.6 : No:6 M/E F.I.V. reliability rate.

The lowest maintenance/repair period was 911 running hours and the highest maintenance/repair period was 4169 running hours. The average maintenance/repair period was calculated as 3079 running hours.

As can be seen in the graphs (Figure 3.6), the reliability of the No:6 Fuel Injection Valve decreases as the operating hours increase. While the reliability of a repaired fuel injection valve is 100%, after 1000 running hours of fuel injection valve reliability has reduced to 75%. After 2750 running hours, the reliability rate has reduced to less than 45%. When it comes to 4000 working hours applied in the planned maintenance system, the reliability rate has decreased to 31%.

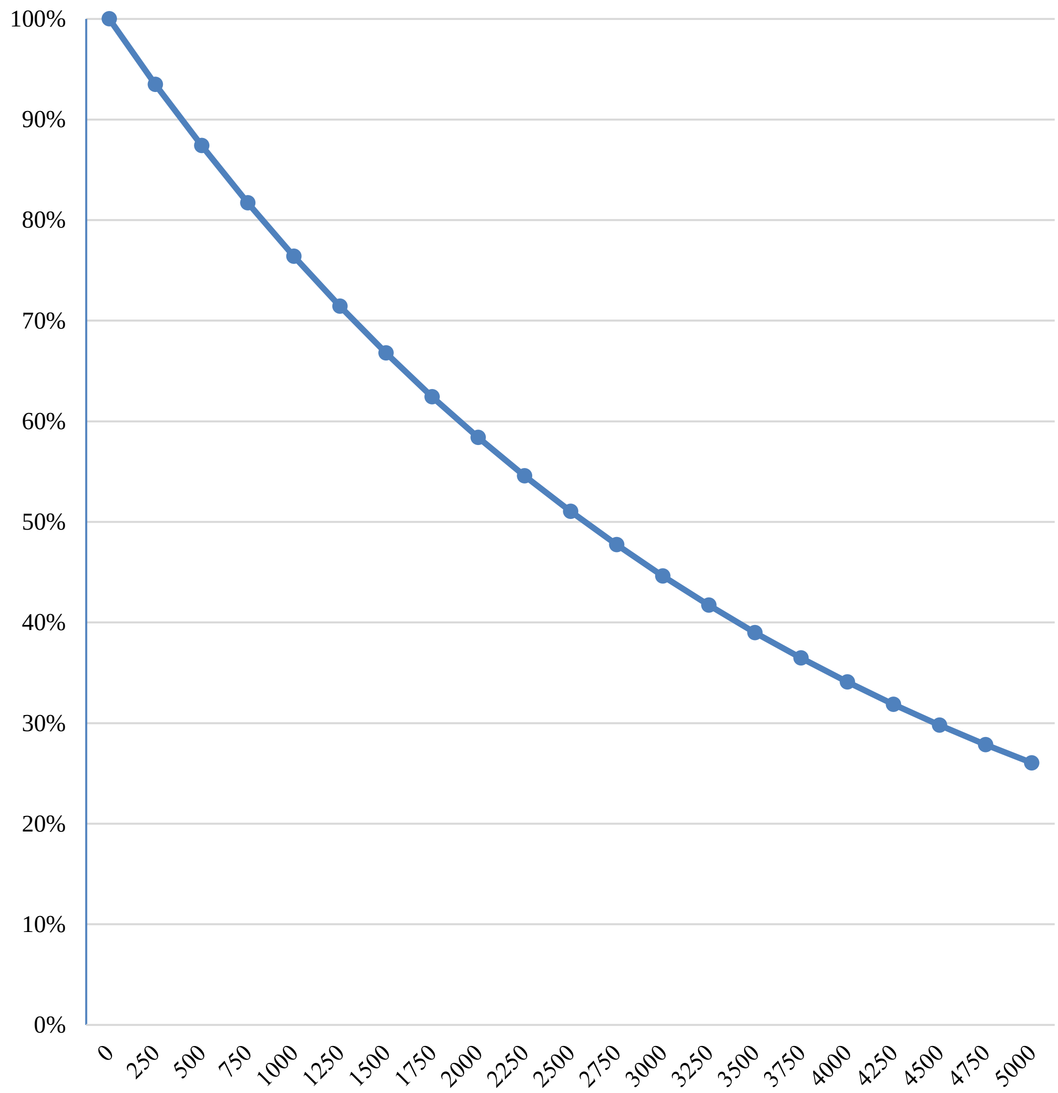

Figure 3.7 : No:7 M/E F.I.V. reliability rate.

The lowest maintenance/repair period was 1074 running hours and the highest maintenance/repair period was 4080 running hours. The average maintenance/repair period was calculated as 3419 running hours.

As can be seen in the graphs (Figure 3.7), the reliability of the No:7 Fuel Injection Valve decreases as the operating hours increase. While the reliability of a repaired fuel injection valve is 100%, after 1000 running hours of fuel injection valve reliability has reduced to 76%. After 2750 running hours, the reliability rate has reduced to less than 48%. When it comes to 4000 working hours applied in the planned maintenance system, the reliability rate has decreased to 34%.

As can be seen in the graphs (Figure 3.8), the reliability of the injection valves decreases as the operating hours increase. While the reliability of a repaired fuel injection valve is 100%, after 1000 running hours of fuel injection valve reliability has reduced to 74-76%. After 2750 running hours, reliability rate has reduced to less than 50%. When it comes to 4000 working hours applied in the planned maintenance system, the reliability rate has decreased to 31-34%.

The acceptable limit for the reliability ratio is directly related to the operator's expectations and the navigation/port conditions where the ship is located. The fact that the reliability ratio is too low is indicative of a failure. The occurrence of an unexpected fault during the navigation time may not pose serious problems in terms of cost. However, a malfunction that may occur during the port manoeuvre will result in high costs for the operating company. Keeping the reliability ratio high at all times is convenient for the safety of the ship.

The graph below shows a comparison of the reliability rates of the fuel injection valves (Figure 3.8).

As can be seen in (Figure 3.9), the availability rates for all fuel injectors were found to be above 99%. This is due to the length of the failure-free operation of the fuel injectors and a short time is needed to fix the failure.

When the maintainability rates were examined (Figure 3.10), it was calculated as 0% as long as the time required for maintenance was less than 2.5 hours. When a 3-hour maintenance schedule is made, the maintainability rates of the fuel injectors are as follows: No#1 fuel injector 30.85%, No#2 fuel injector 30.81%, No#3 fuel injector 30.02%, No#4 fuel injector 38.14%, No#5 fuel injector 34.01%, No#6 fuel injector 34.69%, No#7 fuel injector 42.03%. With a maintenance schedule of 3.1 hours, the maintainability rates of the fuel injectors are as follows: No#1 fuel injector 50.00%, No#2 fuel injector 52.85%, No#3 fuel injector 51.79%, No#4 fuel injector 67,82%, No#5 fuel injector 65.99%, No#6 fuel injector 55.55%, No#7 fuel injector 59.82%. When a 3.5-hour maintenance schedule is made, the maintainability rates of the fuel injectors are as follows: No#1 fuel injector 97.72%, No#2 fuel injector 99,09%, No#3 fuel injector 98.98%, No#4 fuel injector 99.98%, No#5 fuel injector 99.99%, No#6 fuel injector 98.85%, No#7 fuel injector 97.97%.

As can be seen from the results, the maintenance operation will be healthy as long as the period of care is 3.5 hours or more. The determination of this time is important in situations that may create time constraints for the ship.

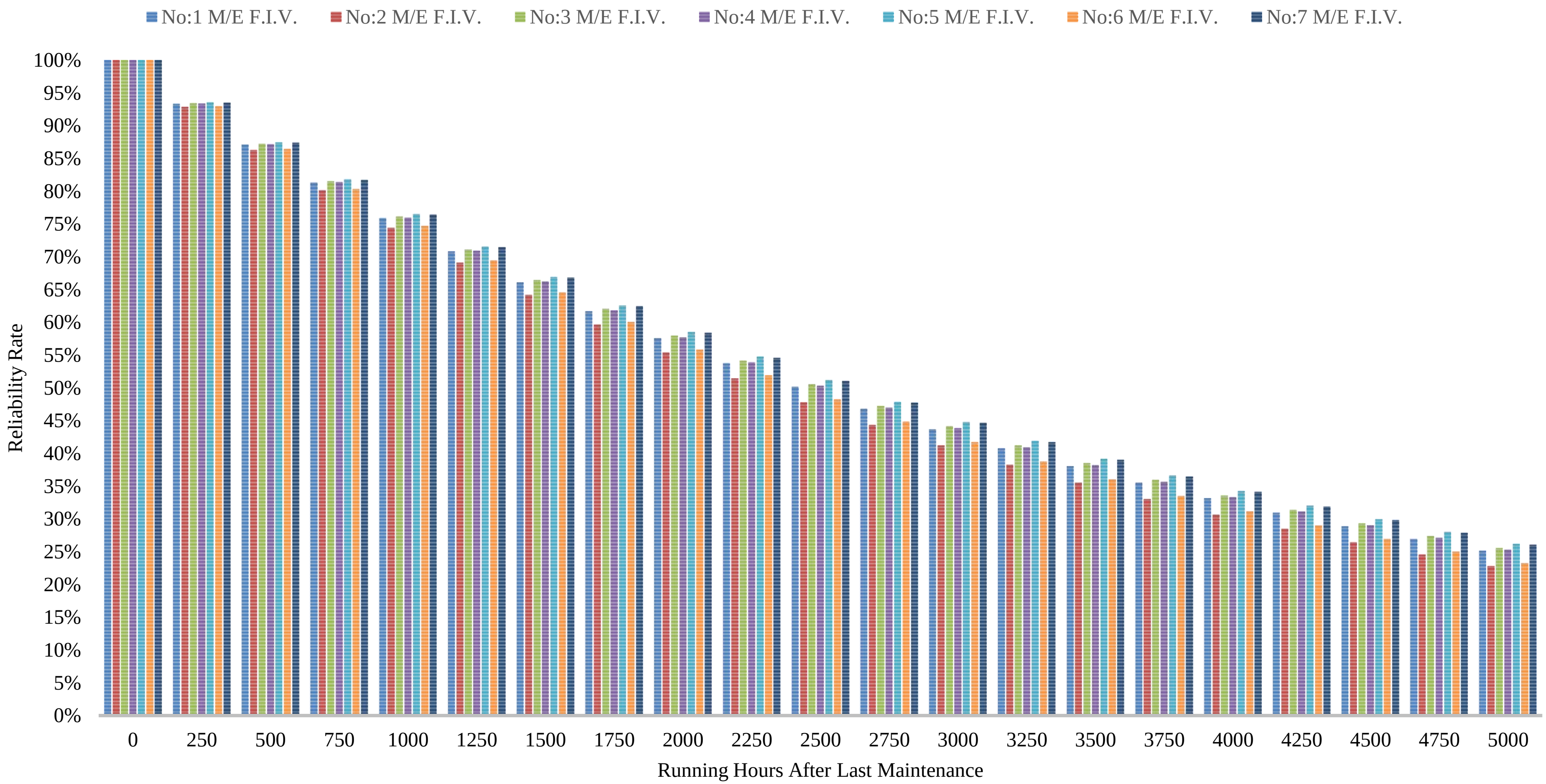

Figure 3.8 : Reliability rates of main engine fuel injection valve.

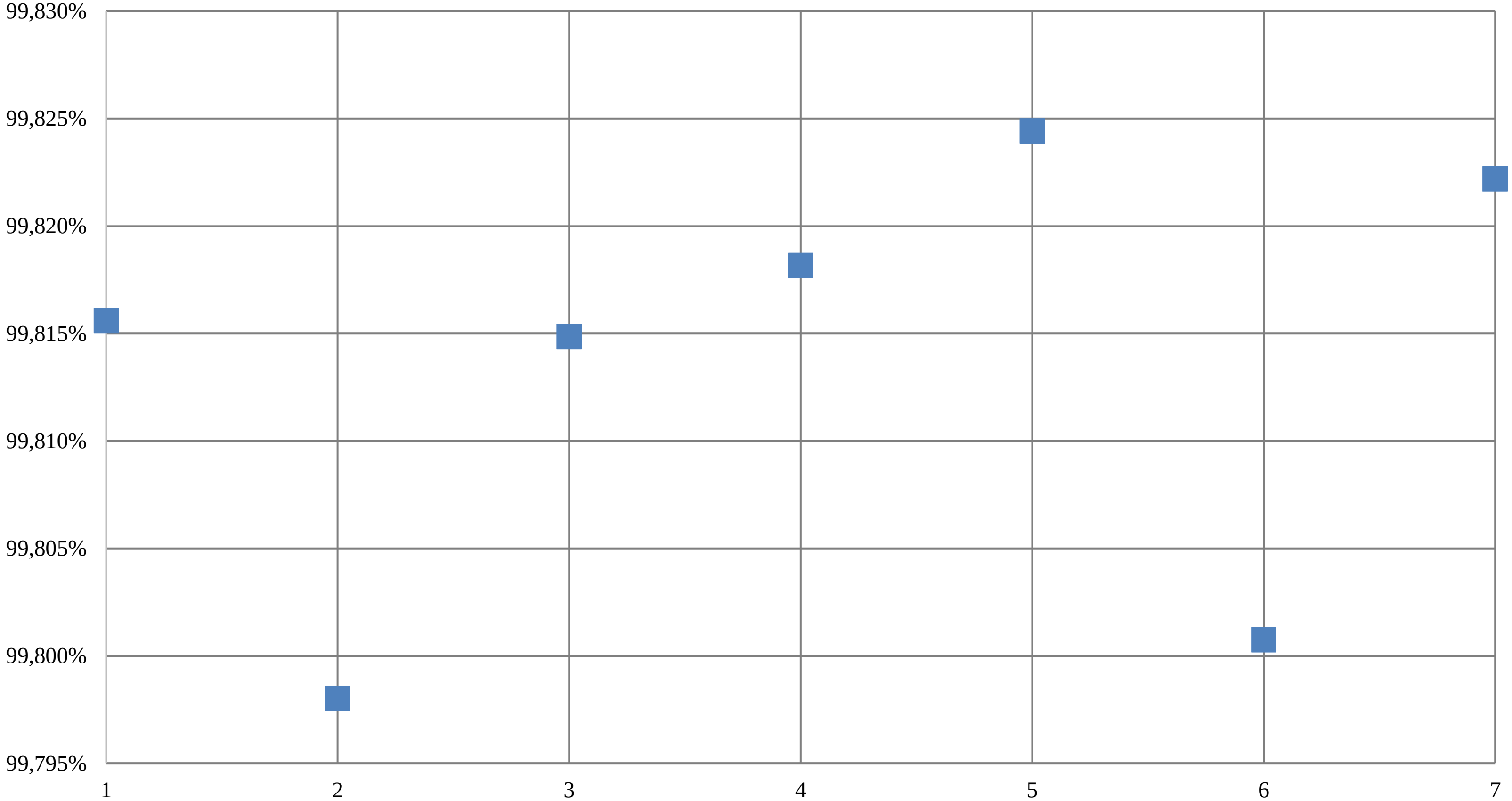

Figure 3.9 : Availability rates of main engine fuel injection valve.

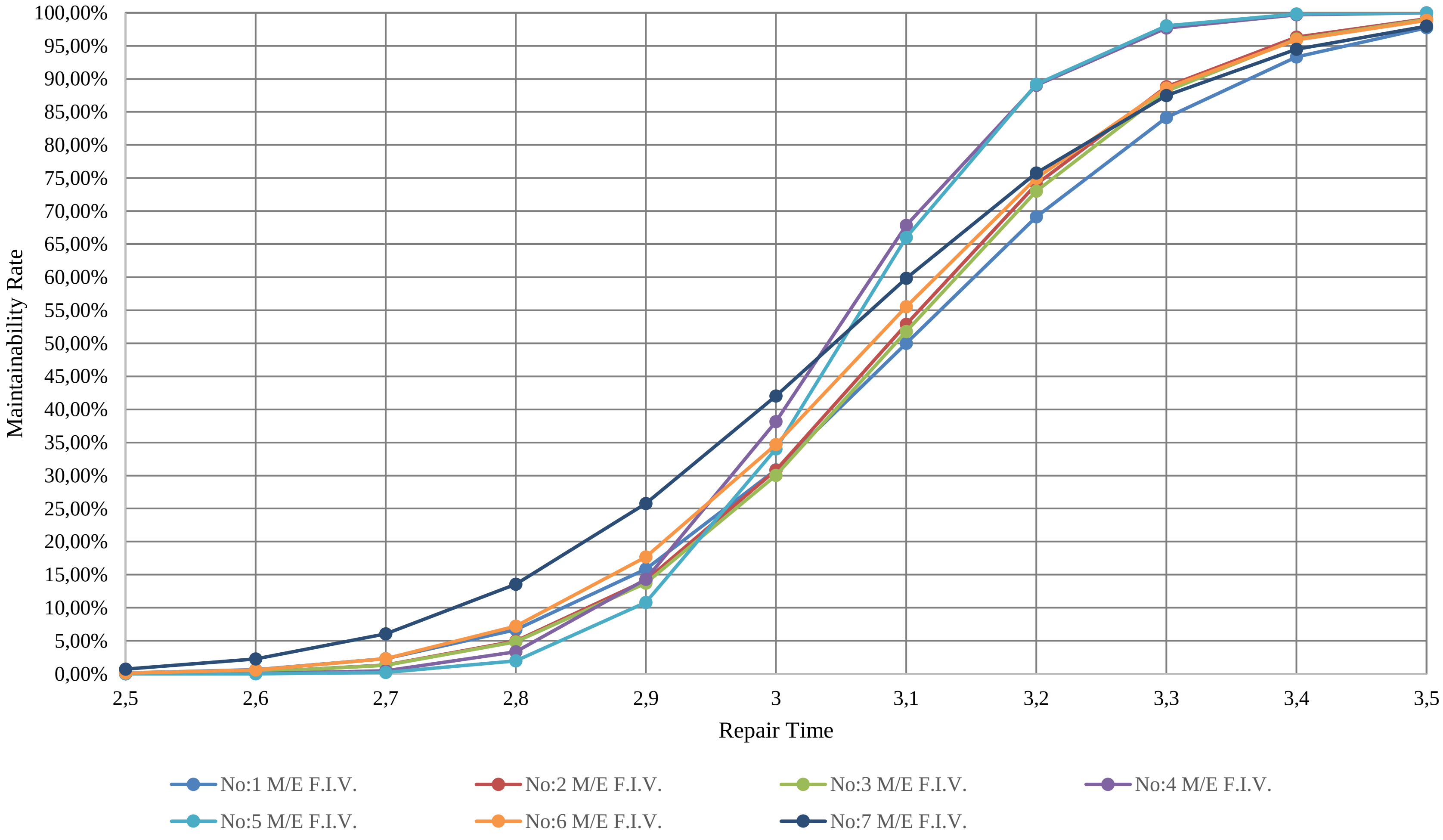

Figure 3.10 : Maintainability rates of main engine fuel injection valve.

4. CONCLUSION

Trade has become the most indispensable subject in the world in every age. Ships have contributed both to the facilitation and acceleration of this trade. Ships are the most widely used means of transportation both in international freight transportation and tourism.

Through today's technologies, we strive to do all our work fast and with the least error. For this purpose, we use new technologies directly or we take care to use our existing systems with the most effective and least error. However, how much are we doing that on the ships?

The most important problem that occurs during the routine operation of the ships is the machinery malfunctions that prevent the operation of the ship. Although the machinery systems are regularly maintained, the quality of the fuels and lubricating oils used, the mistakes made by the operating engineers and the quality of the spare parts used can cause the malfunction at unexpected times.

Failures that may occur especially in port entry-exit, strait crossings, cruising in bad weather conditions and similar situations where ship operations are risky can create significant negative results for the ship. Failures that may occur at undesired times will cause both material and blue damage. Therefore, correct maintenance and prevention of unexpected malfunctions become important.

Before a high-risk ship operation, various measures must be taken to ensure that the ship machinery systems continue to operate without failure. However, each measure increases the operating costs of the ship. Therefore, before a risky operation, it is necessary to review the standard practices and take additional measures to know the reliability of ship machinery systems, subcomponents and to determine the most appropriate times to be spent for maintenance.

The RAM analysis, which we investigate, calculates the probability of failure of the machinery systems during the important operations of the ship. The RAM analysis predicts the period in which future failures will occur using data from recent years. If the recommendations provided by the model are applied before a risky operation, the probability of failure will be minimized and the operations will be made safer.

The fuel injectors of a ship's main engine are discussed in the data analysed. The data of previous years were collected and the relationships between the data were examined. As a result of the data obtained, the reliability, availability, and maintainability rates of the injectors number 1,2,3,4,5,6 and 7 were calculated.

The decreasing tendency of the reliability rates of injectors 2 and 6 were found to be higher than other injectors. Due to the fact that the average duration of failure-free operation of the respective injectors is less than the other injectors and they fail more during the total engine running time.

After calculations of availability rates, it was found that, all injectors have an availability rate of over 99%. The high availability of the injectors is due to the fact that these injectors have a long interval between two failures and a short interval maintenance and adjustment time.

The maintainability of injectors 4 and 5 are higher than other injectors when the working hours for maintenance exceed 3 hours. This may be caused from the maintenance time obtained on the basis of the data which is lower in these injectors.

However, it is difficult to access the data due to thesis limitations at some points. With the revisions to be made in PMS records, it may be possible to collect data and analyze the results without creating extra workload for the employees and preparing the maintenance planning. It is not specified whether the maintenance is planned or periodical at the planned maintenance systems. Adding this distinction to PMS software will contribute to right data collection. Besides, general statements are included in the explanation part filled by the responsible engineer about the operation performed. This situation does not adequately express the content of the transactions. Another feature that should be added to the PMS system is the time spent on the operation. This data, which is especially necessary for maintainability analysis, will play an important role to determine the spent time according to the work performed in the maintenance operation and during determining the time required for the maintenance that should be planned before the critical operations.

Another feature needs to be added to the PMS system is the monitoring of spare parts inventory. During maintenance planning, the status of spare parts inventory can be checked automatically and deficiencies for maintenance operation can be determined by the system. Inventory monitoring is important for both right and rapid maintenance.

Due to these deficiencies, some limitations were encountered during the thesis study. Elimination of these deficiencies before the studies is one of the important conditions for obtaining a right RAM analysis.

When the data is analysed, it is decided that integrating the RAM analysis into the PMS system will enable the decision-making roles of ship to operate effectively, especially in critical equipment. To use the knowledge management unit effectively, the maintenance on ships should be processed more regularly and then, the data processed should be elaborated. If the data to be processed are correct, the results will make it easier to perform the most effective maintenance at the right time and to avoid unexpected failures.

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APPENDICES

APPENDIX A : Correlation coefficient between failure-free times.
APPENDIX B : Weibull distribution plotting.
APPENDIX C : Correlation coefficient between repair times.
APPENDIX D : Normal distribution plotting.

APPENDIX A : Correlation coefficient between failure-free times.

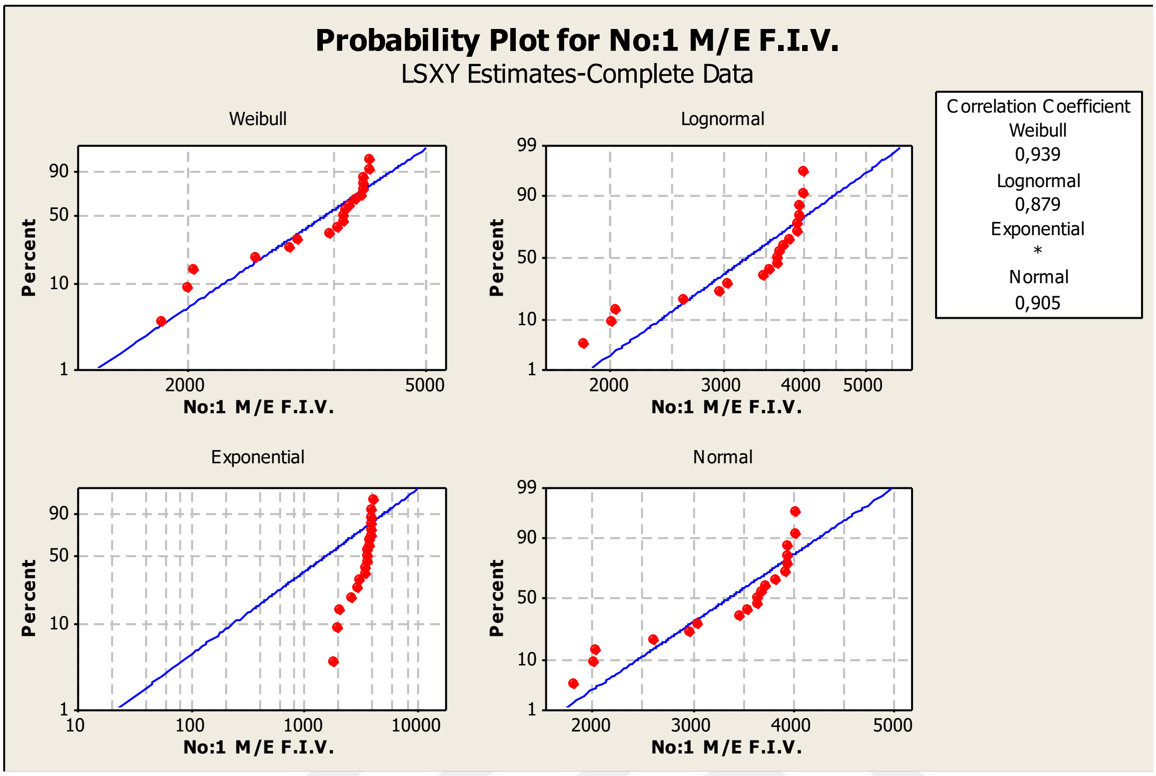

Figure A.1 : No:1 F.I.V. correlation coefficient between failure-free times.

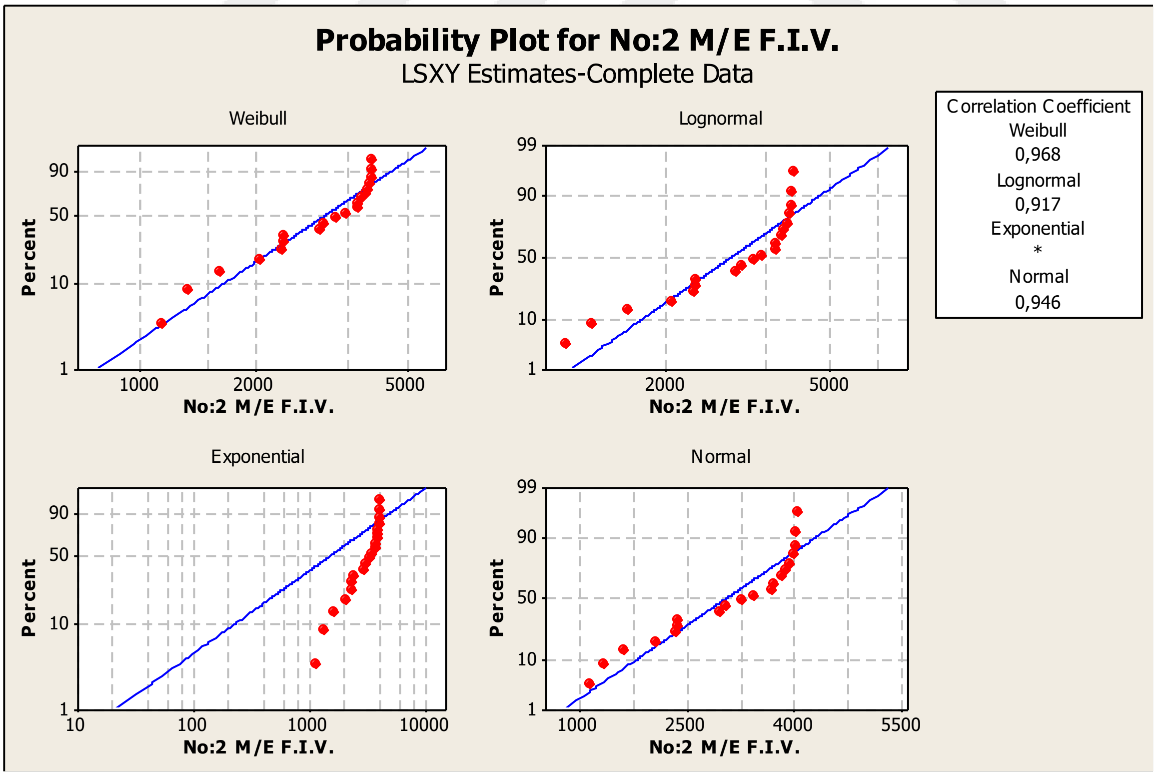

Figure A.2 : No:2 F.I.V. correlation coefficient between failure-free times.

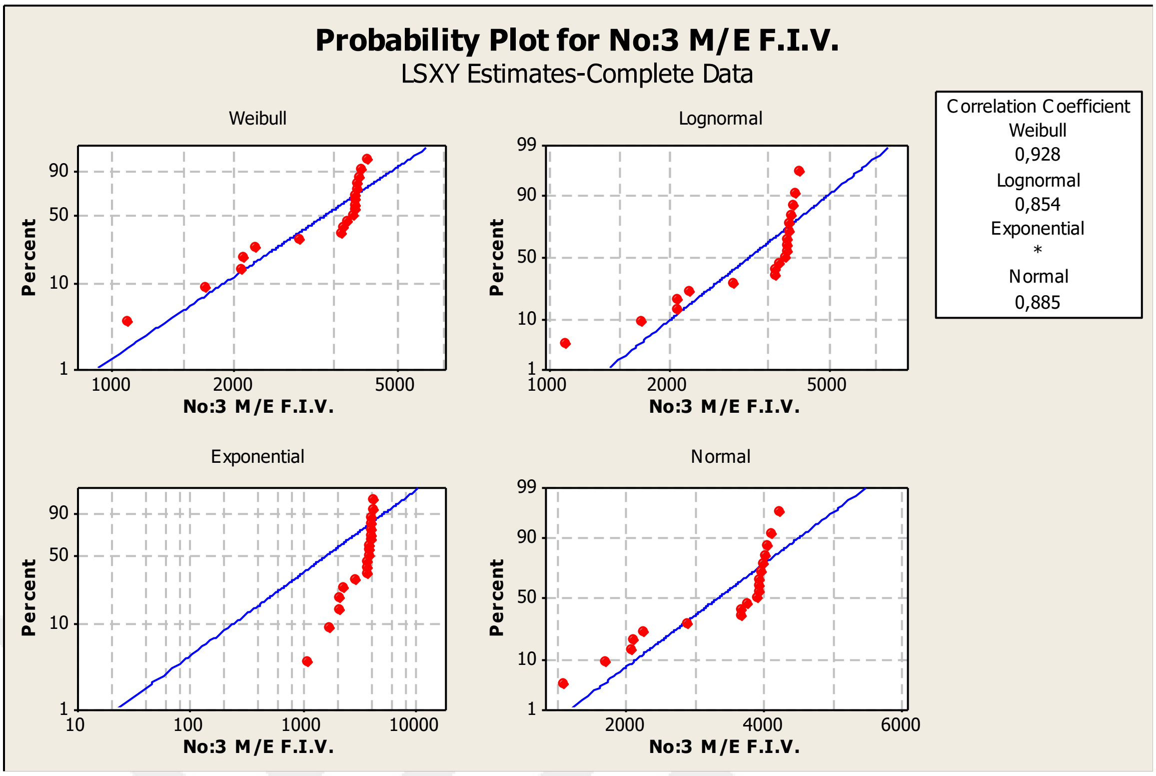

Figure A.3 : No:3 F.I.V. correlation coefficient between failure-free times.

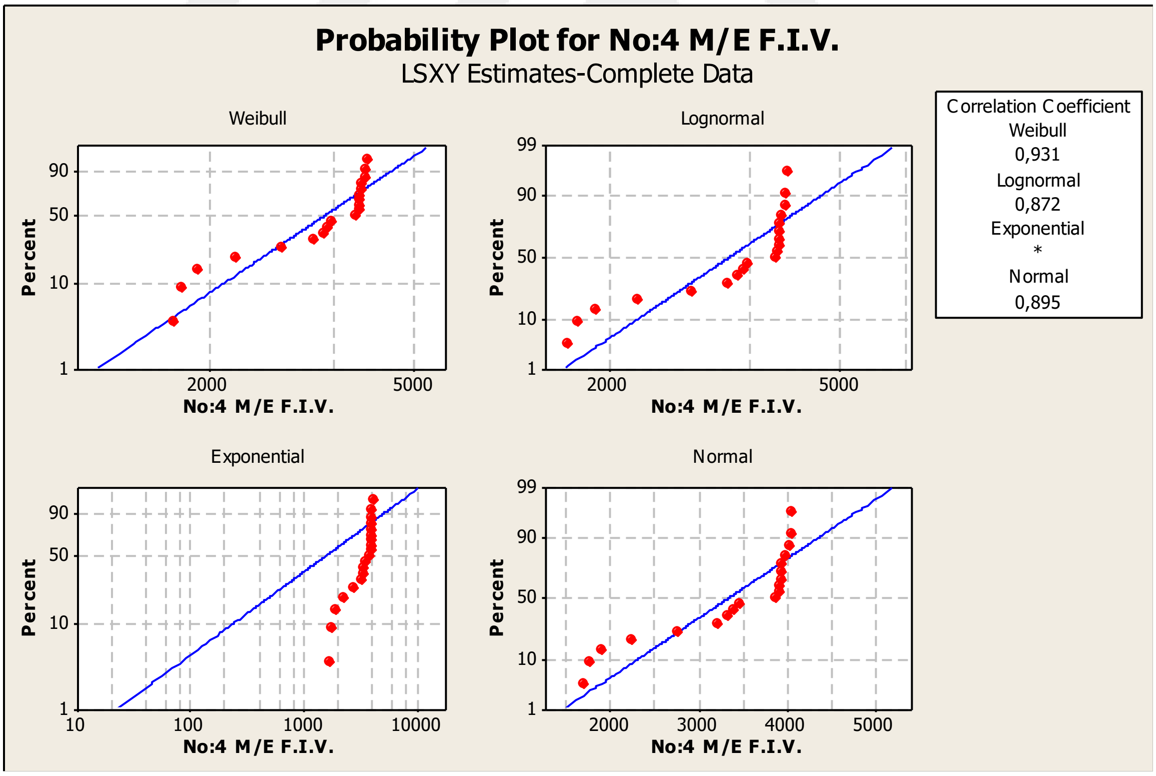

Figure A.4 : No:4 F.I.V. correlation coefficient between failure-free times.

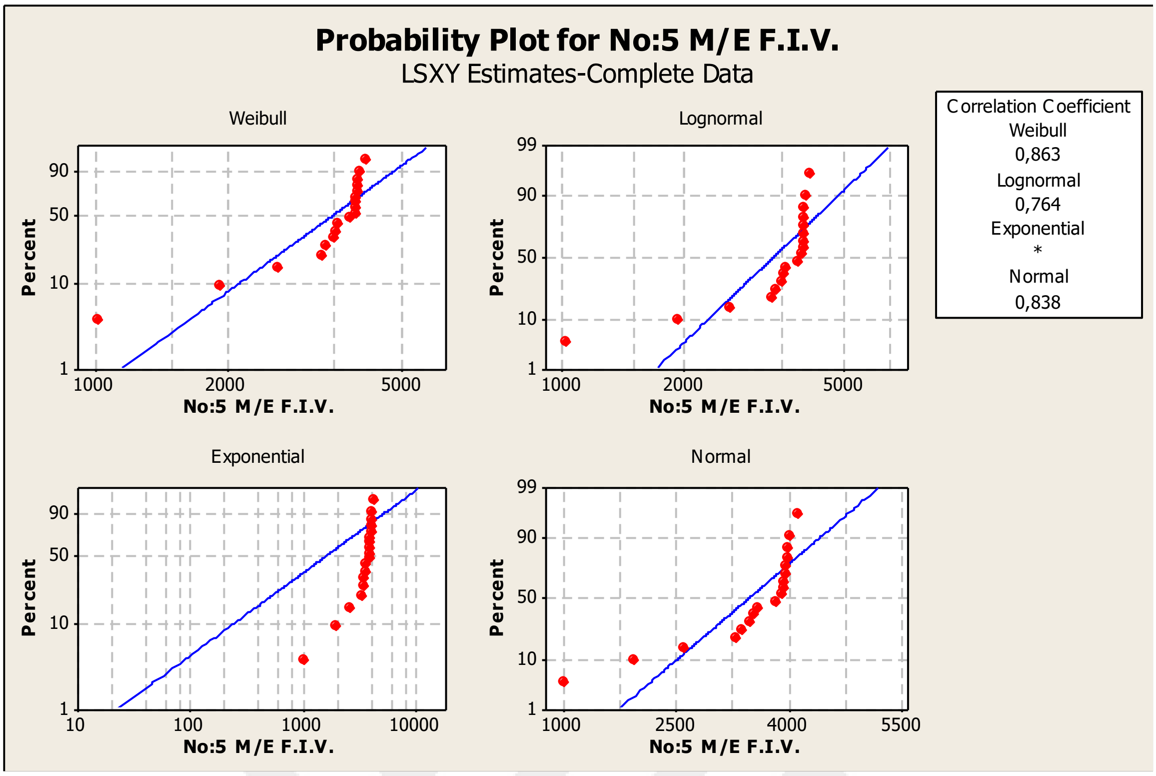

Figure A.5 : No:5 F.I.V. correlation coefficient between failure-free times.

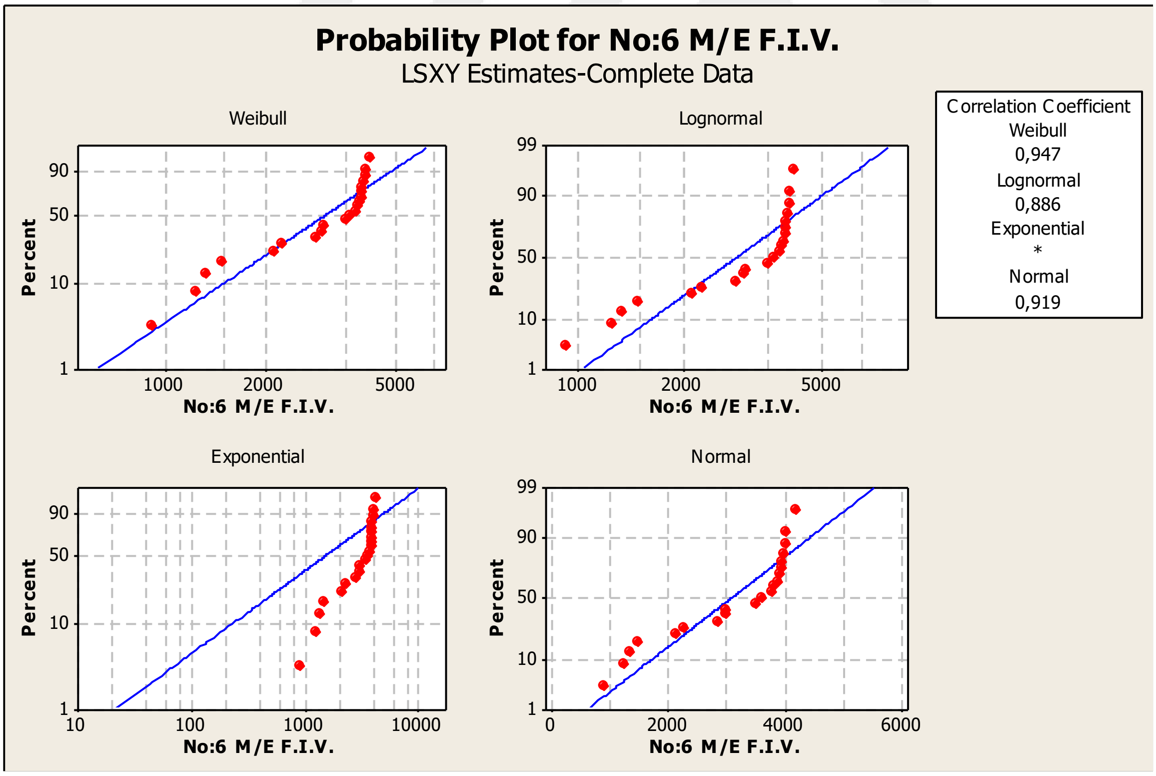

Figure A.6 : No:6 F.I.V. correlation coefficient between failure-free times.

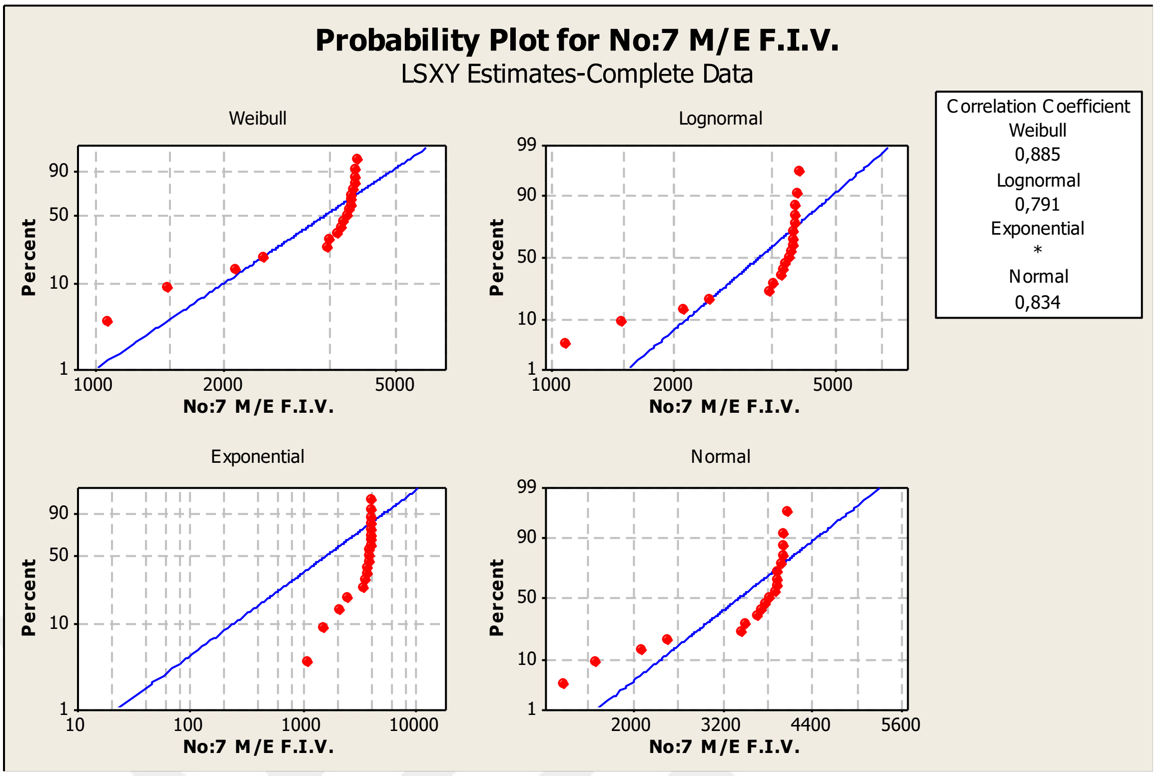

Figure A.7 : No:7 F.I.V. correlation coefficient between failure-free times.

APPENDIX B : Weibull distribution plotting.

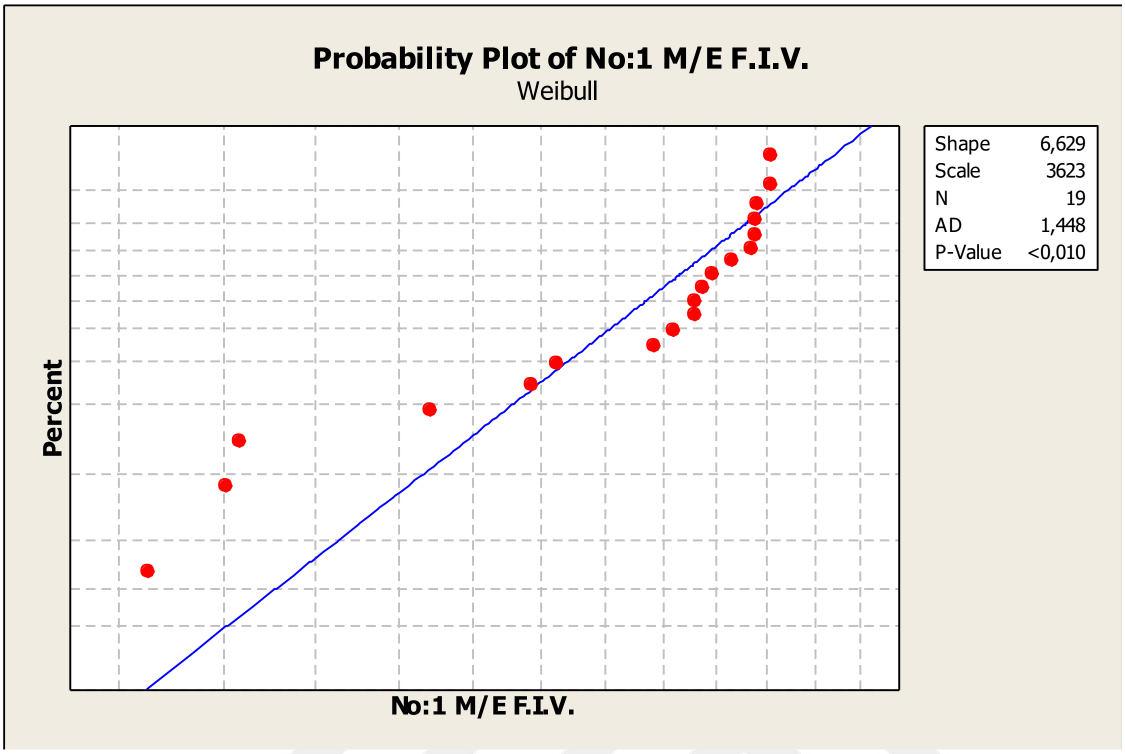

Figure B.1 : No:1 F.I.V. weibull distribution plotting.

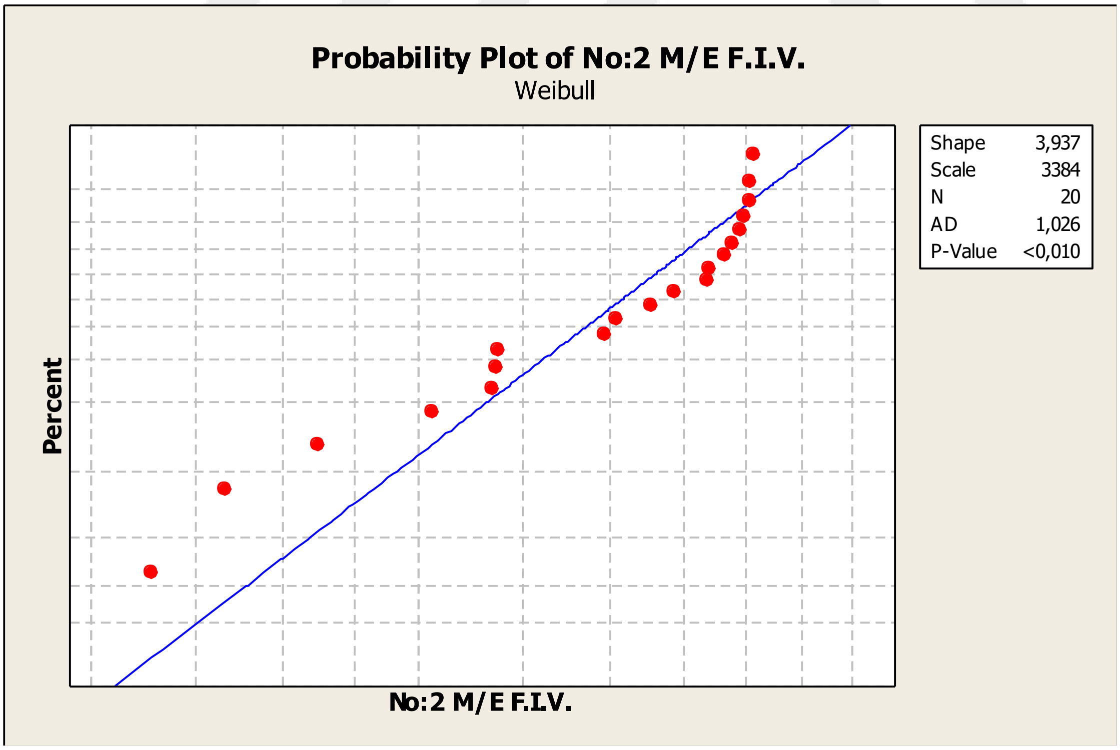

Figure B.2 : No:2 F.I.V. weibull distribution plotting.

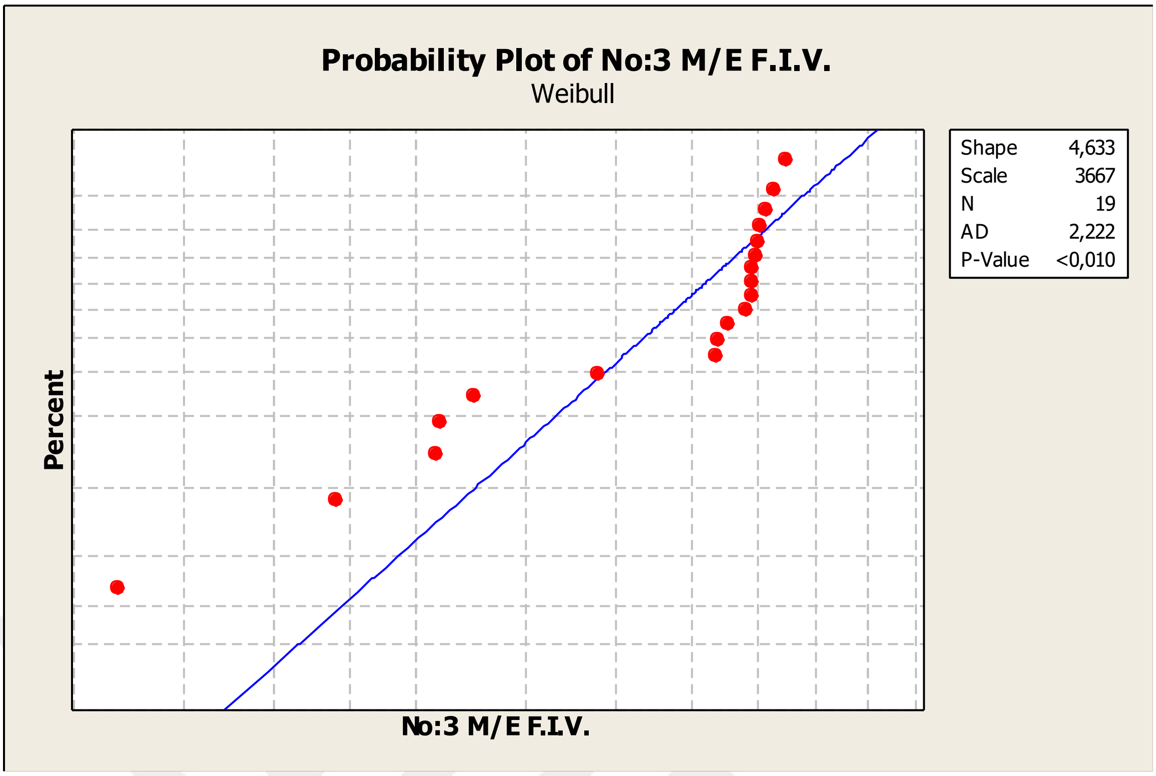

Figure B.3 : No:3 F.I.V. weibull distribution plotting.

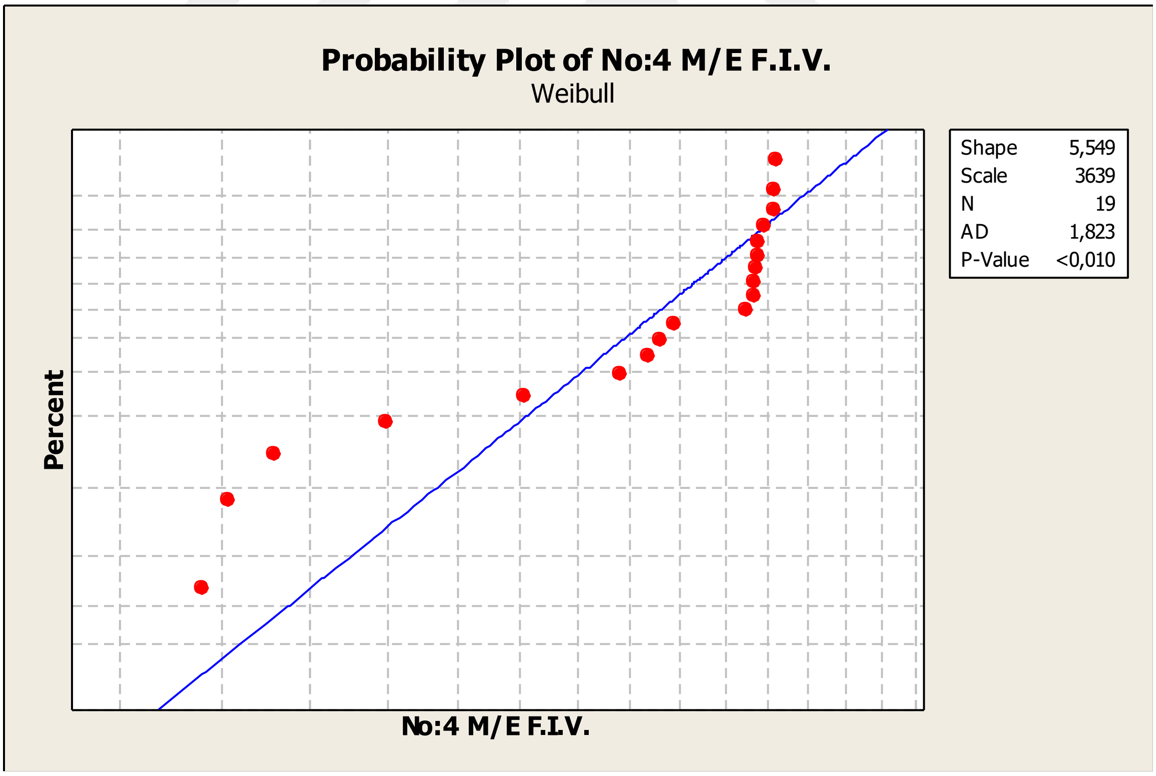

Figure B.4 : No:4 F.I.V. weibull distribution plotting.

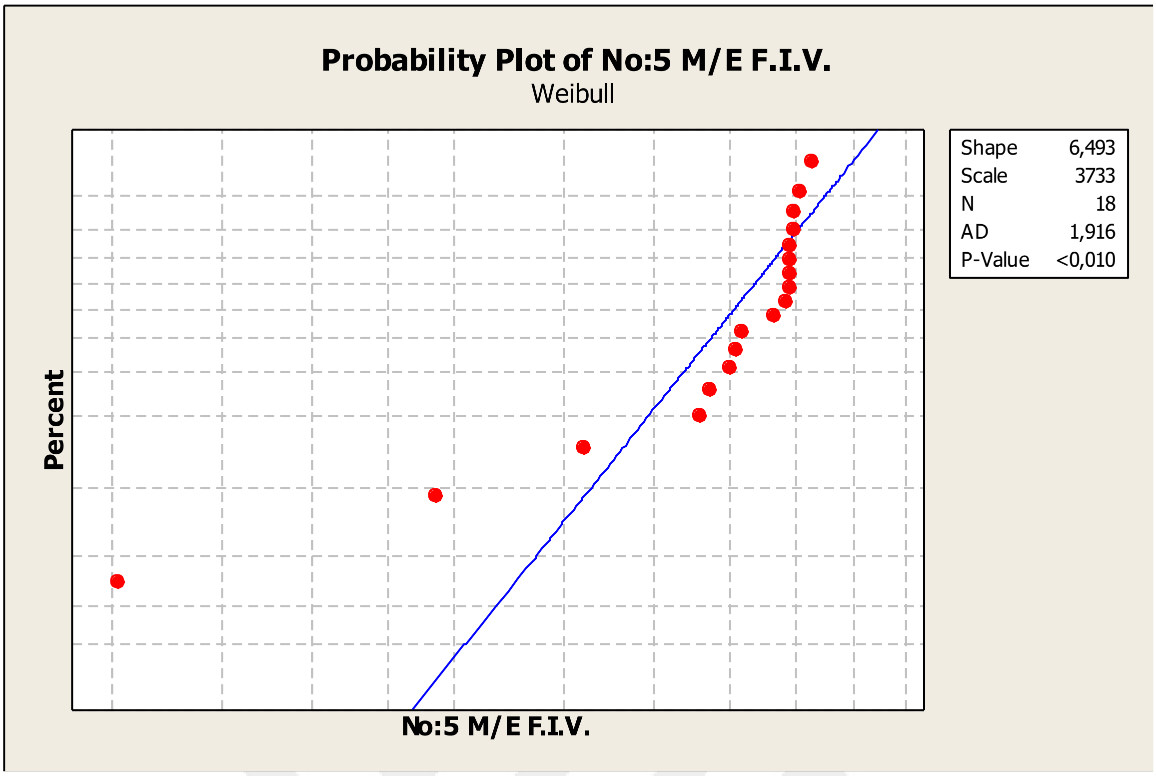

Figure B.5 : No:5 F.I.V. weibull distribution plotting.

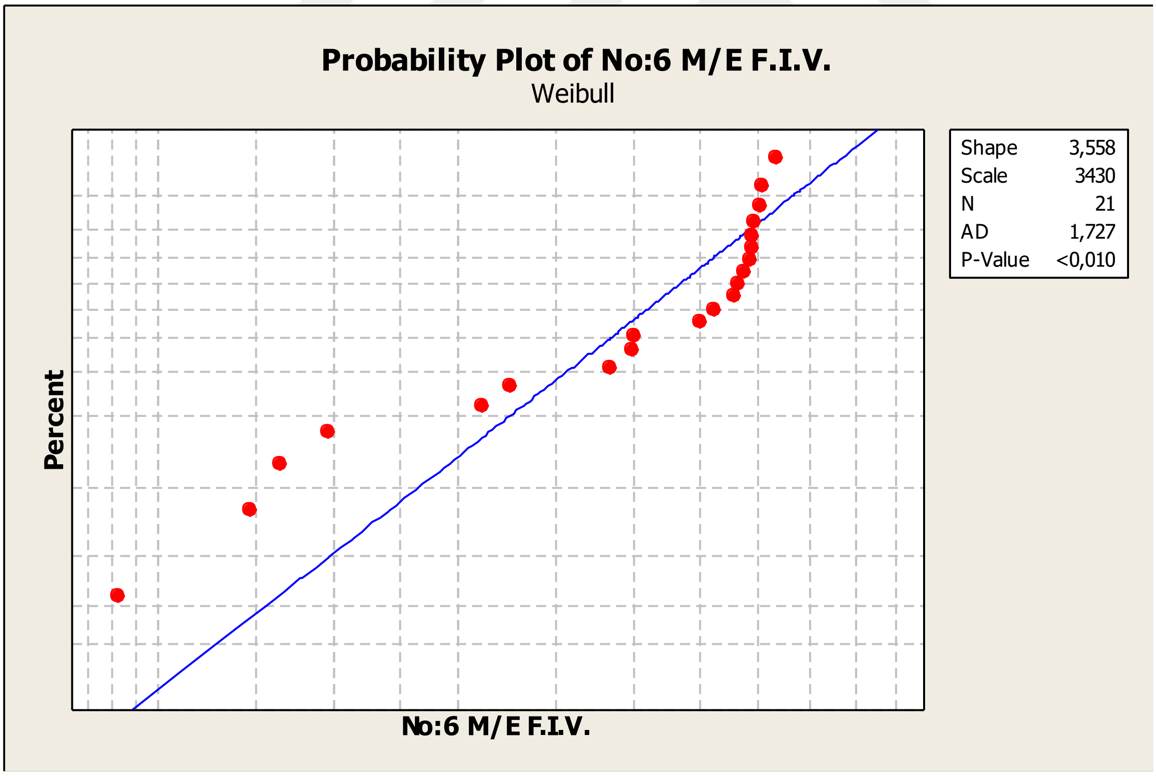

Figure B.6 : No:6 F.I.V. weibull distribution plotting.

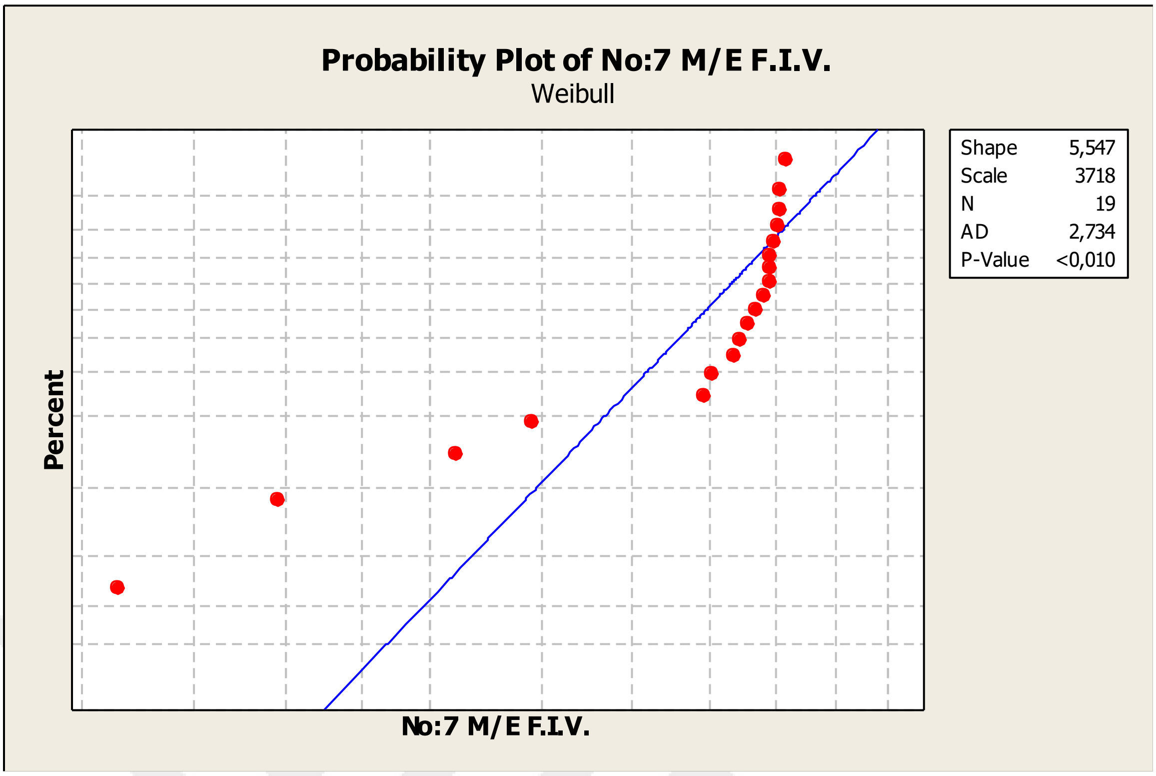

Figure B.7 : No:7 F.I.V. weibull distribution plotting.

APPENDIX C : Correlation coefficient between repair times.

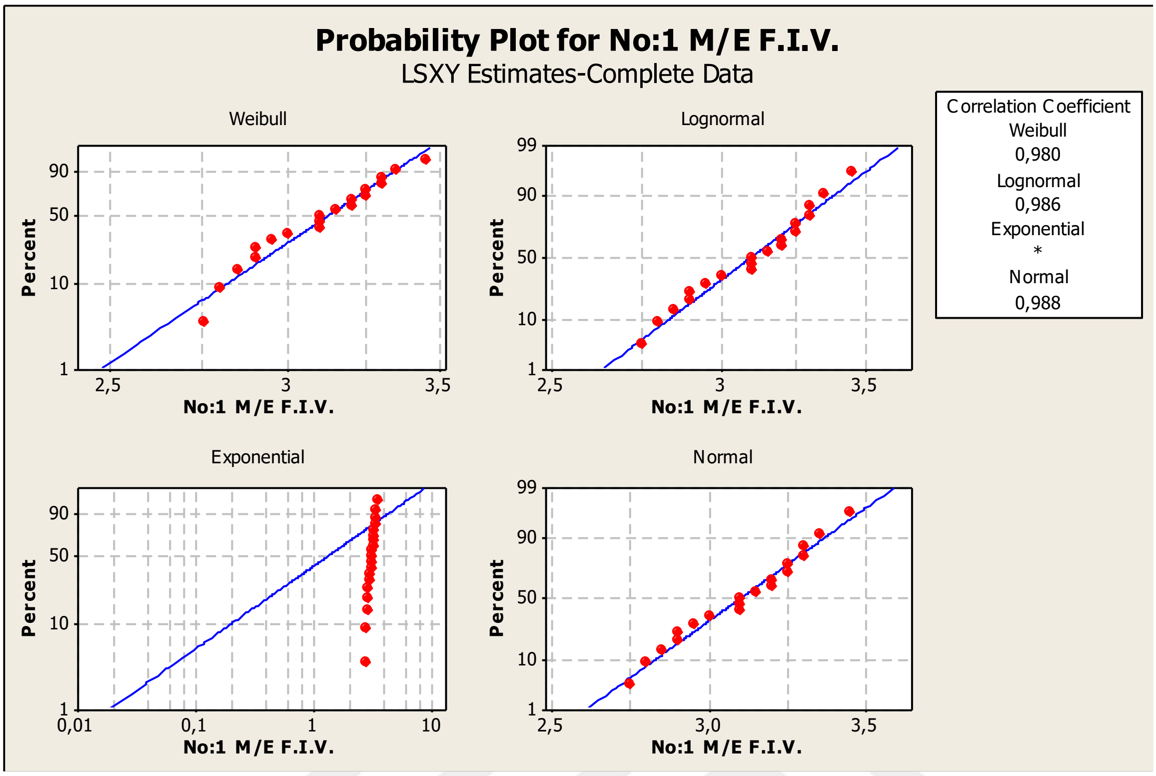

Figure C.1 : No:1 F.I.V. correlation coefficient between repair times.

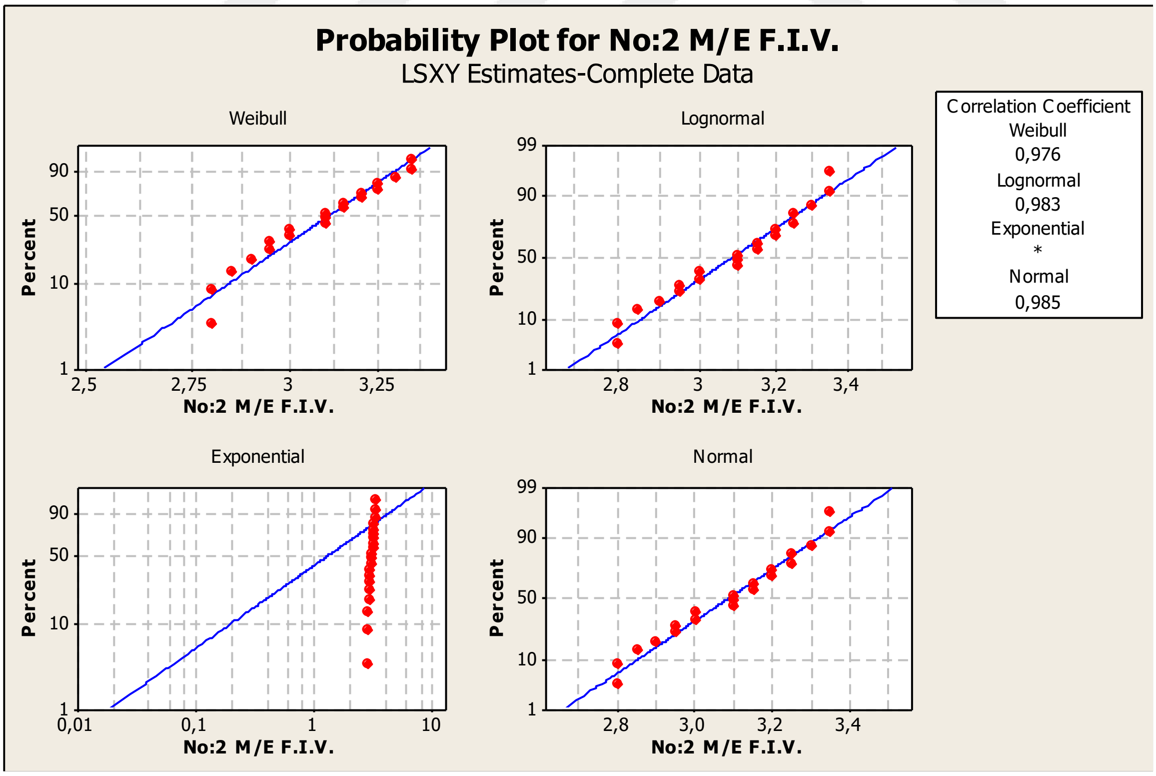

Figure C.2 : No:2 F.I.V. correlation coefficient between repair times.

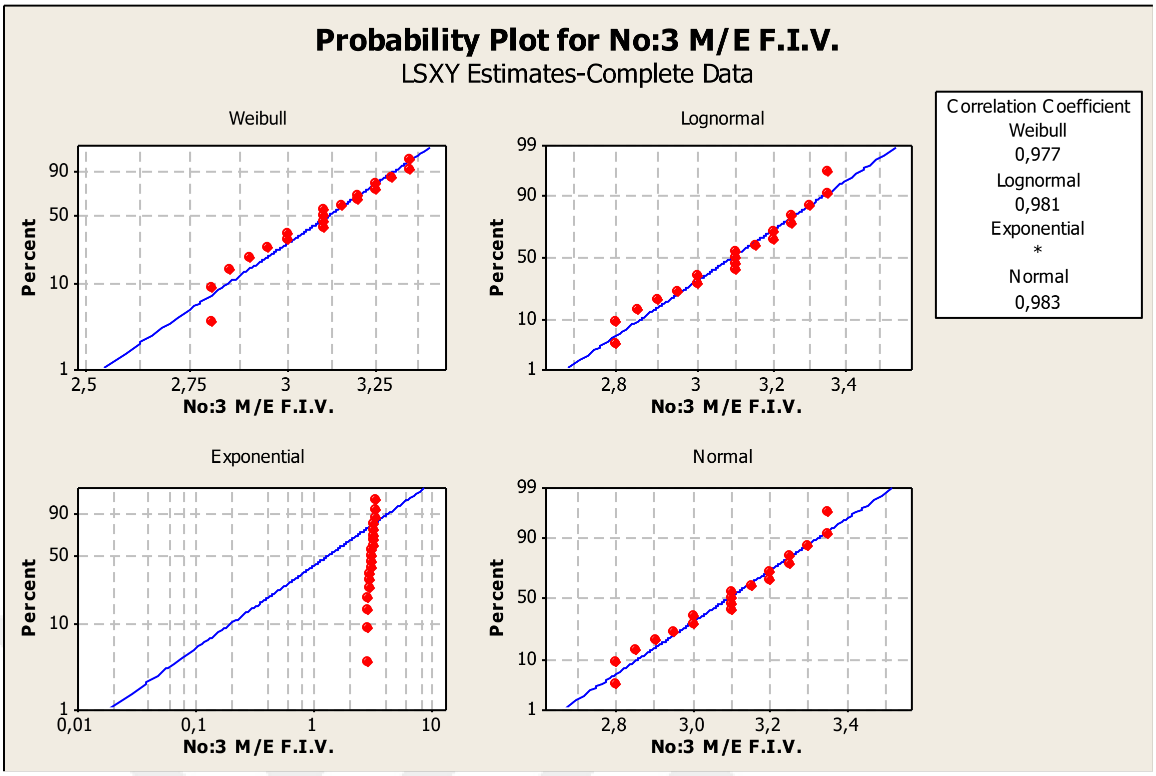

Figure C.3 : No:3 F.I.V. correlation coefficient between repair times.

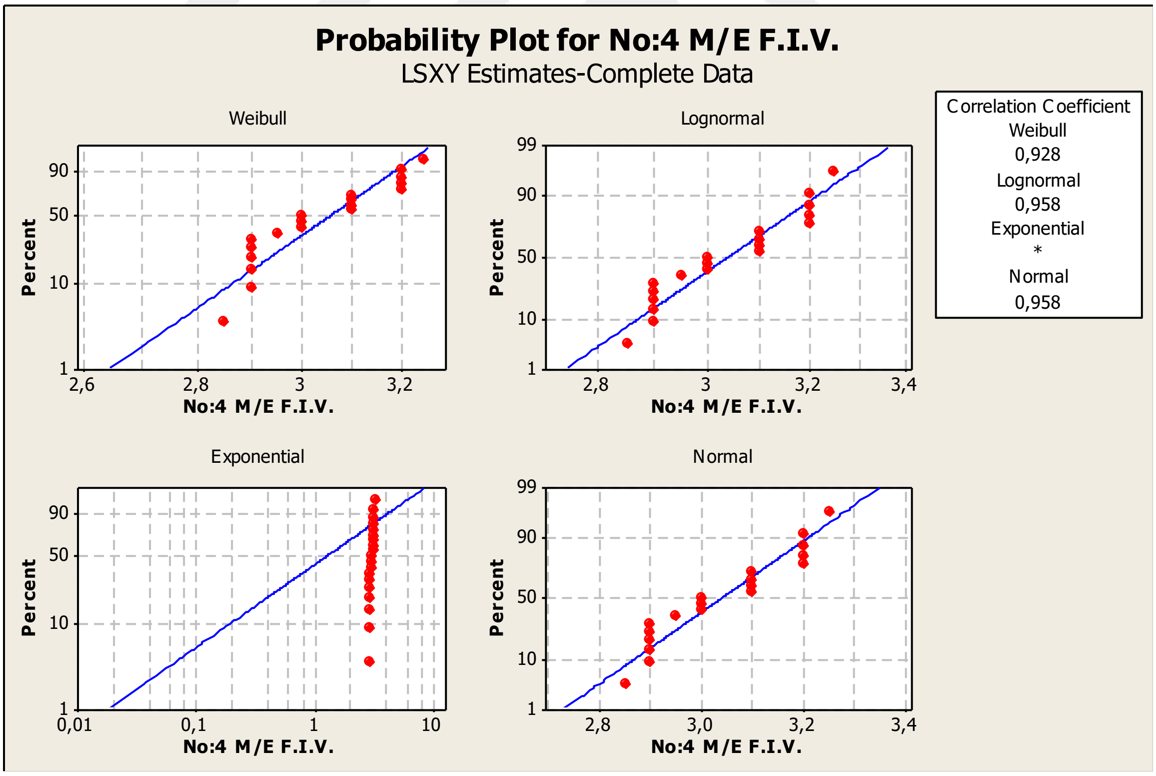

Figure C.4 : No:4 F.I.V. correlation coefficient between repair times.

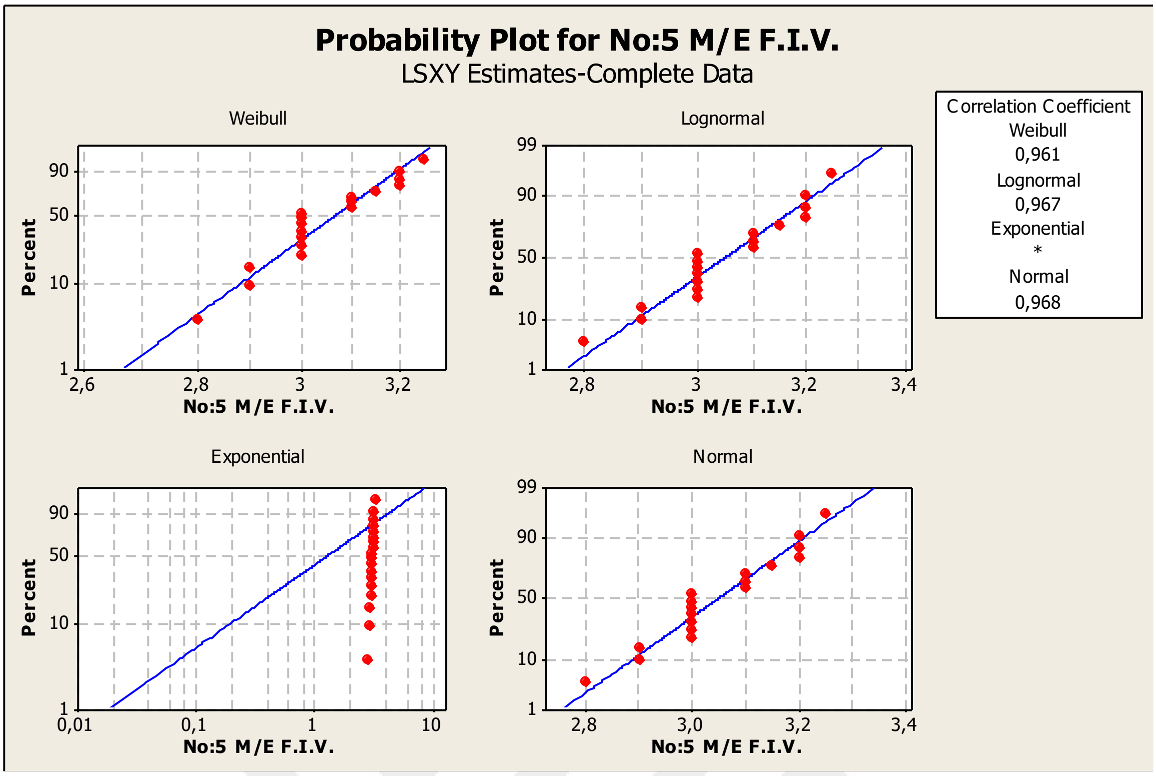

Figure C.5 : No:5 F.I.V. correlation coefficient between repair times.

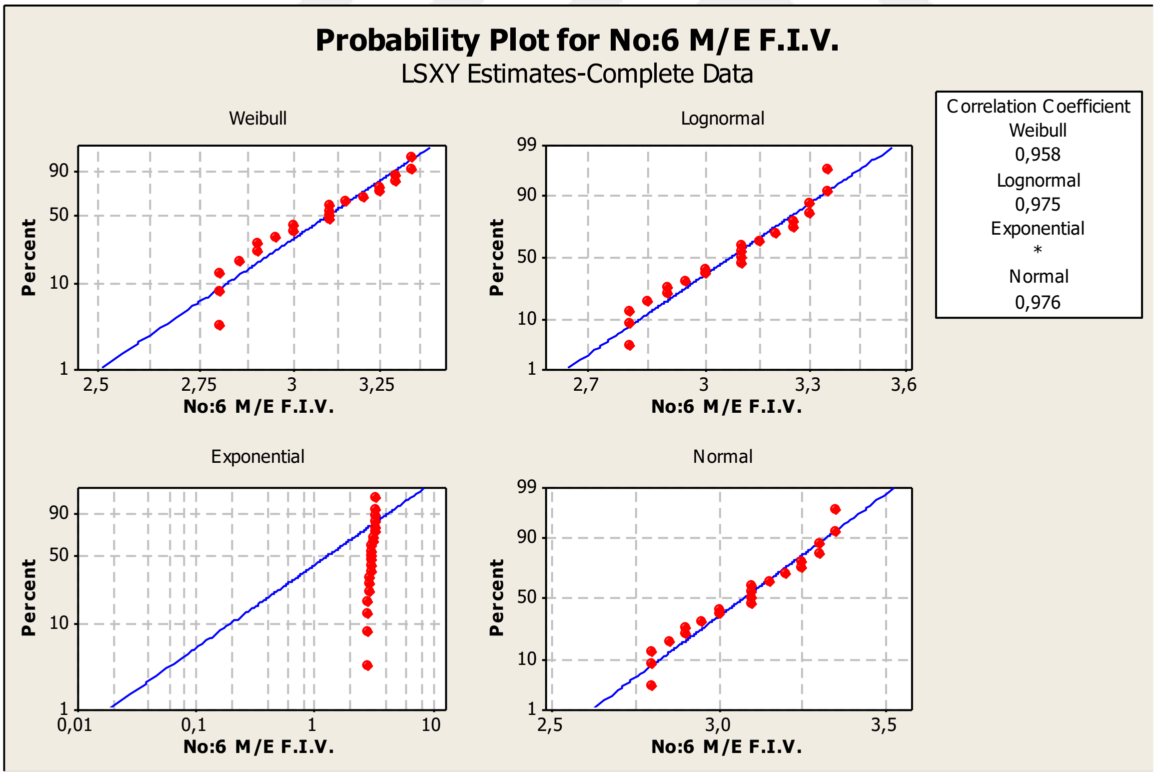

Figure C.6 : No:6 F.I.V. correlation coefficient between repair times.

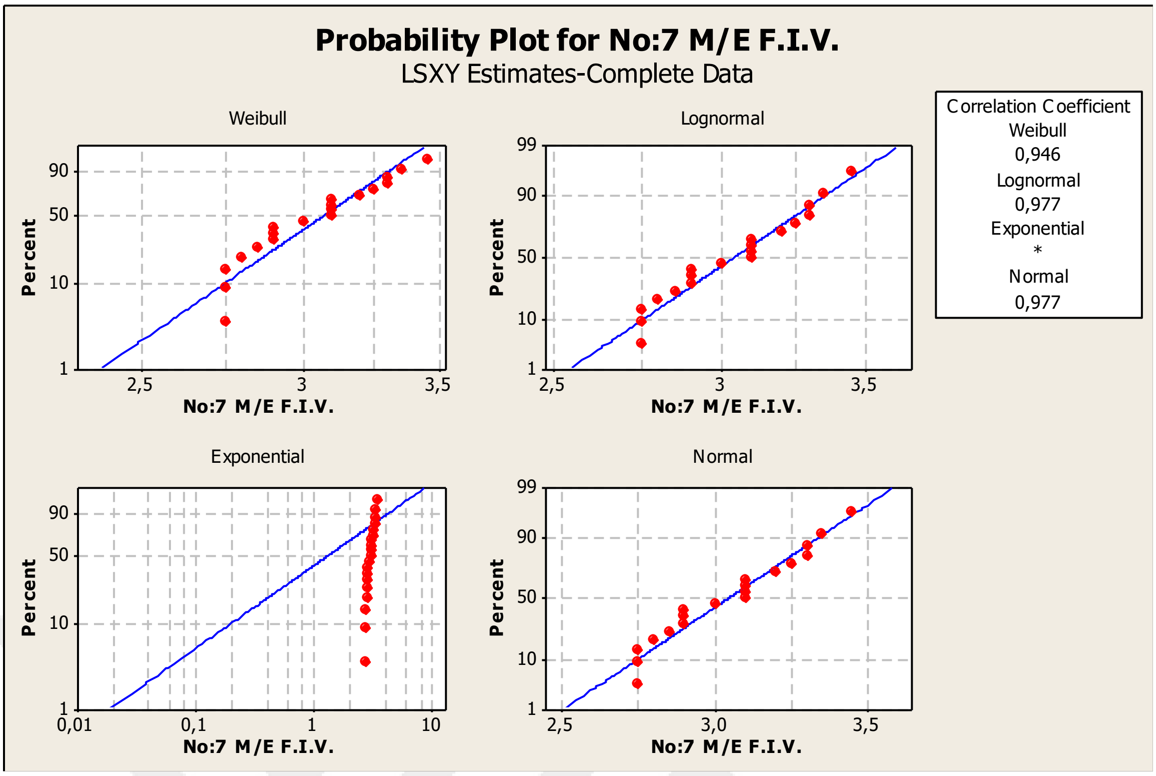

Figure C.7 : No:7 F.I.V. correlation coefficient between repair times.

APPENDIX D : Normal distribution plotting

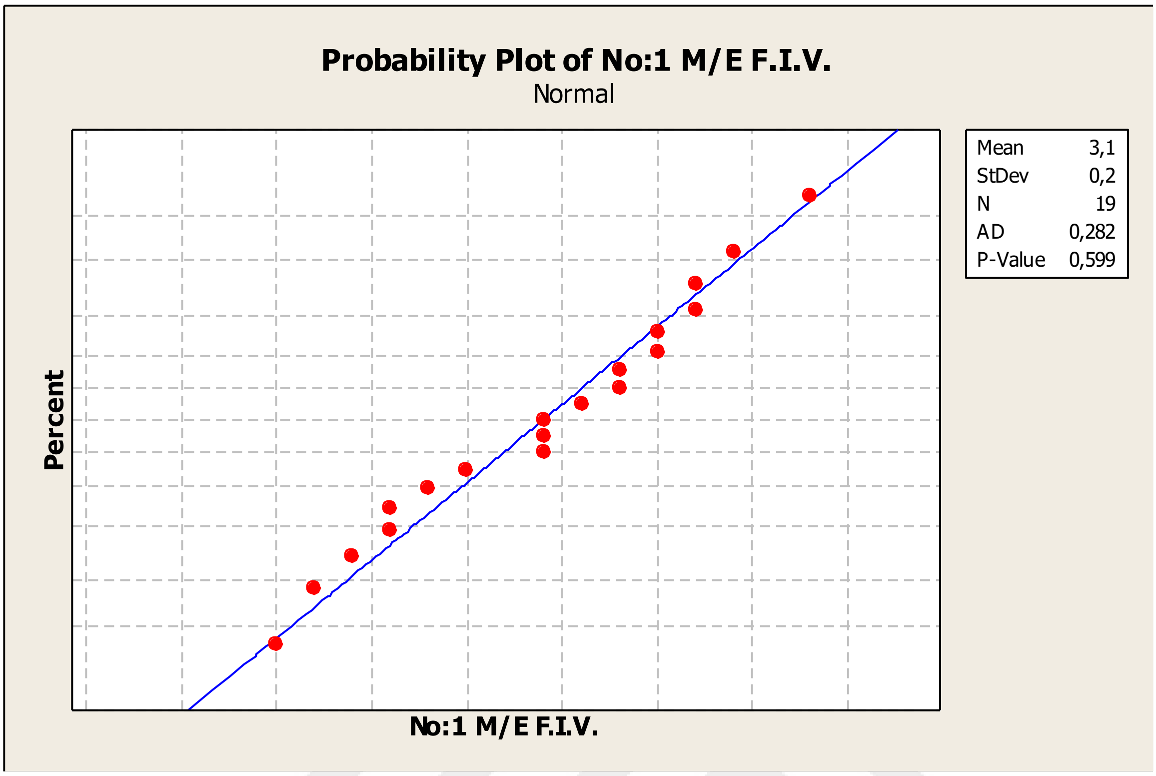

Figure D.1 : No:1 F.I.V. normal distribution plotting.

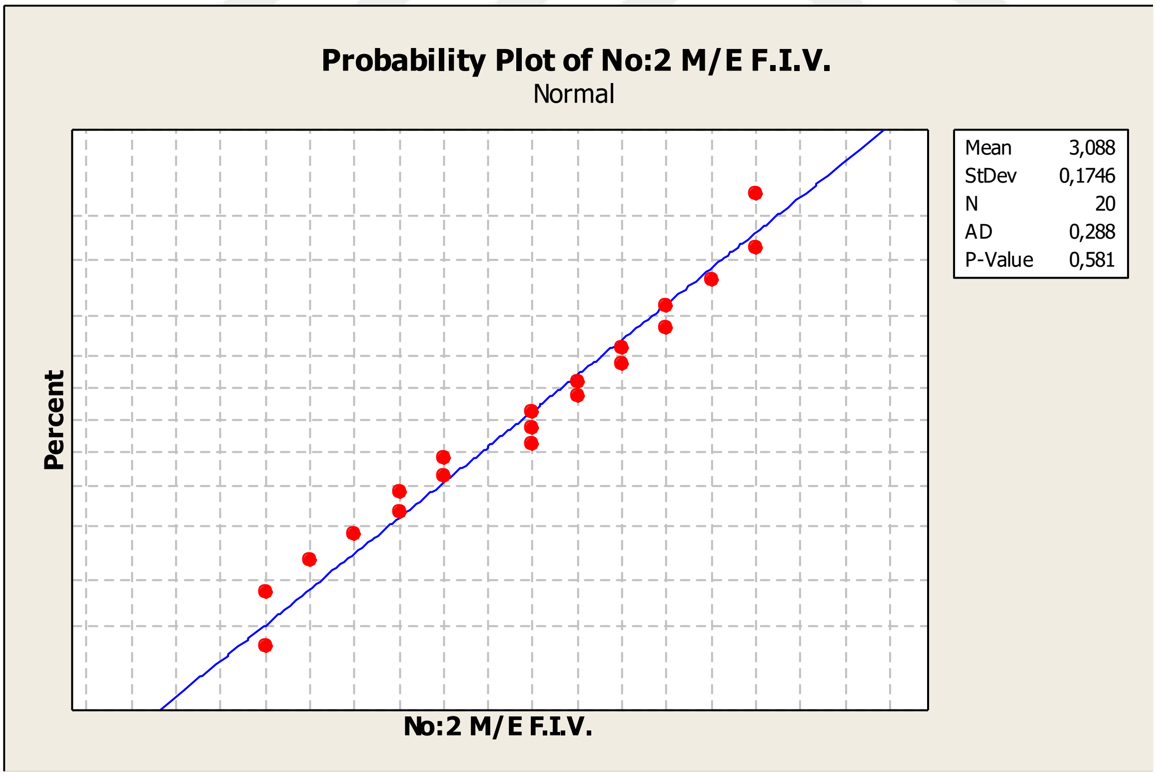

Figure D.2 : No:2 F.I.V. normal distribution plotting.

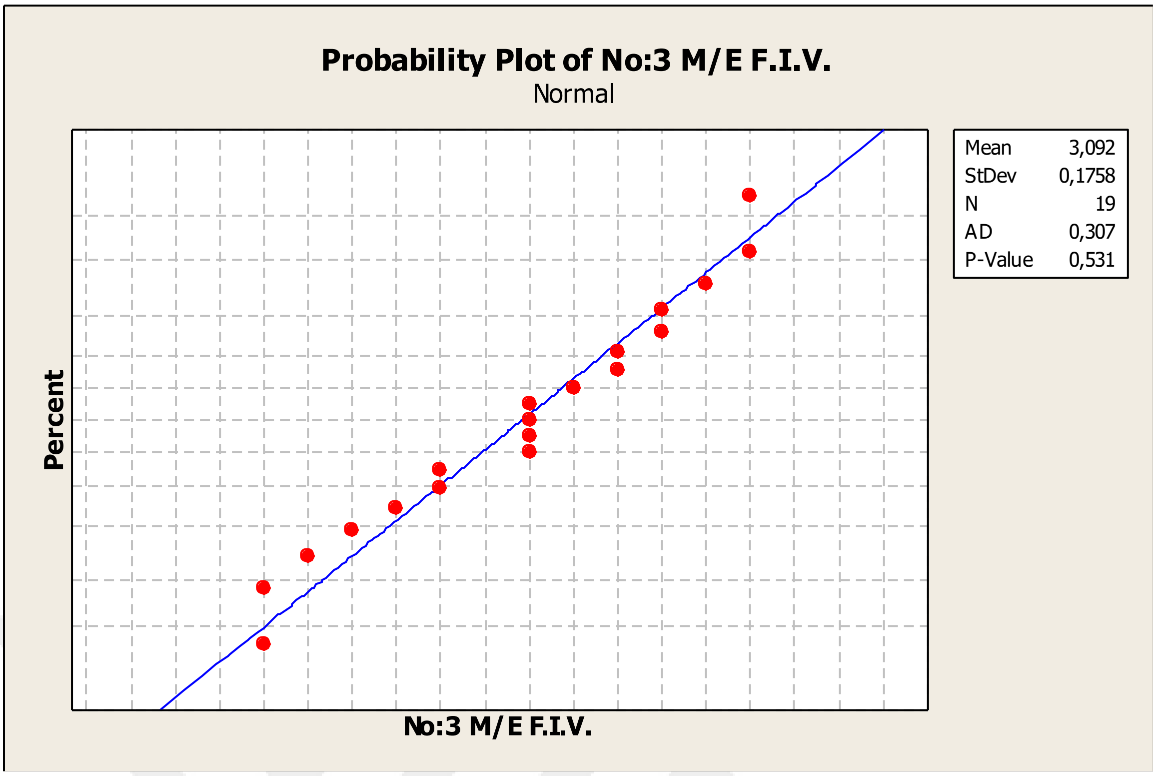

Figure D.3 : No:3 F.I.V. normal distribution plotting.

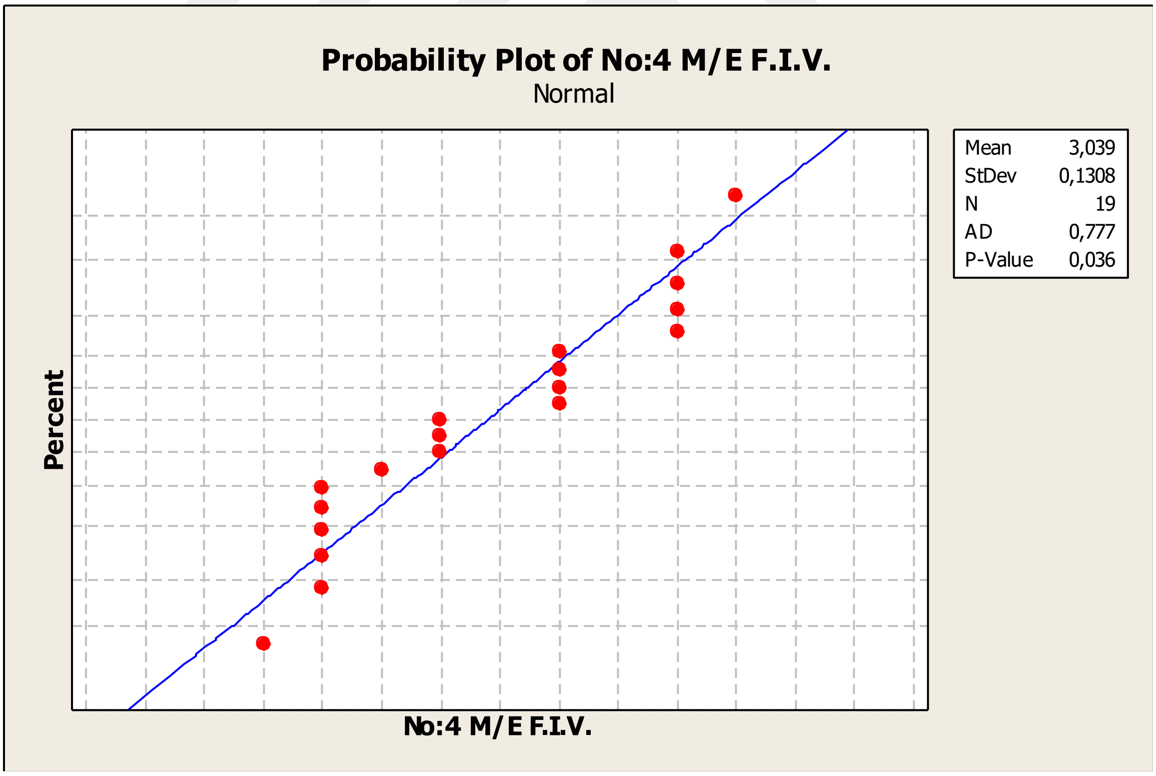

Figure D.4 : No:4 F.I.V. normal distribution plotting.

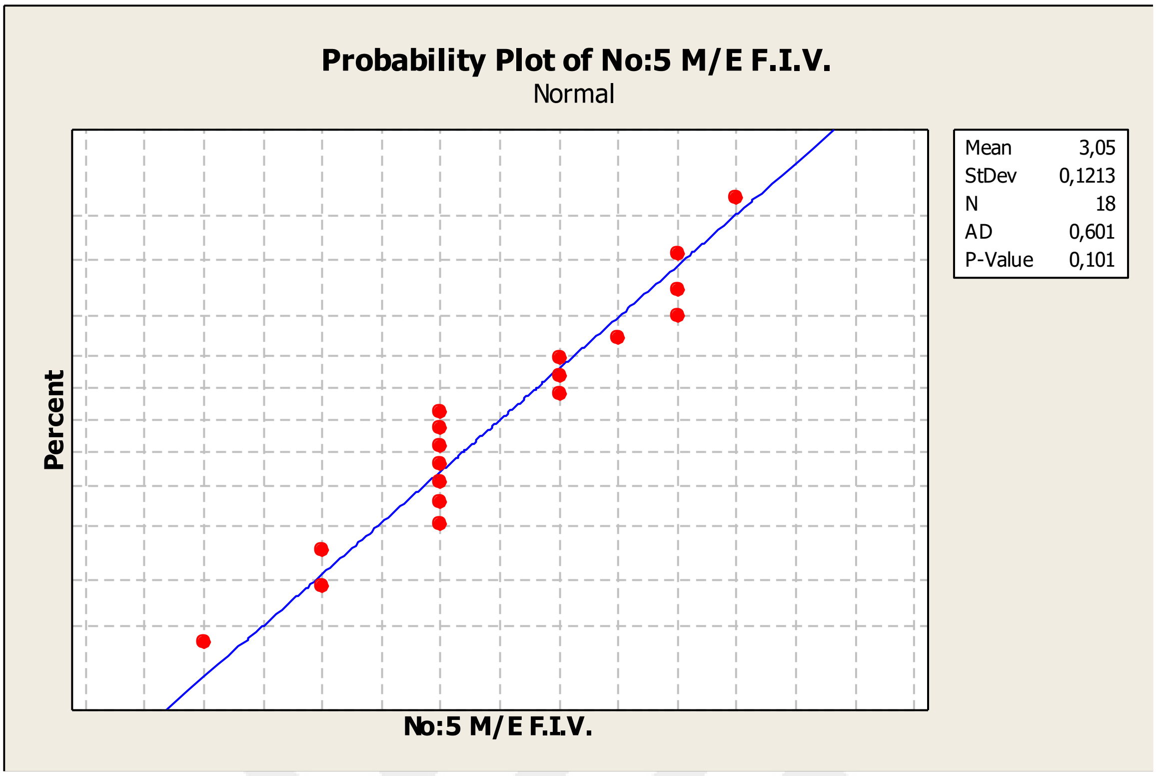

Figure D.5 : No:5 F.I.V. normal distribution plotting.

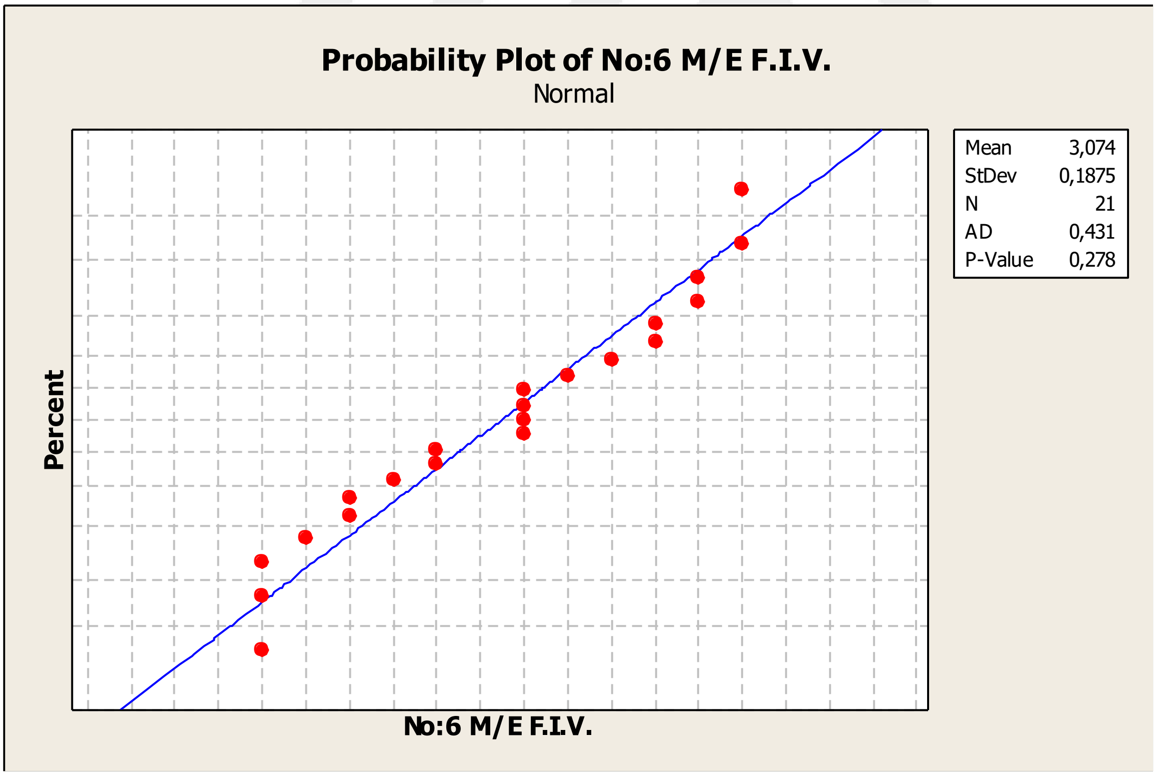

Figure D.6 : No:6 F.I.V. normal distribution plotting.

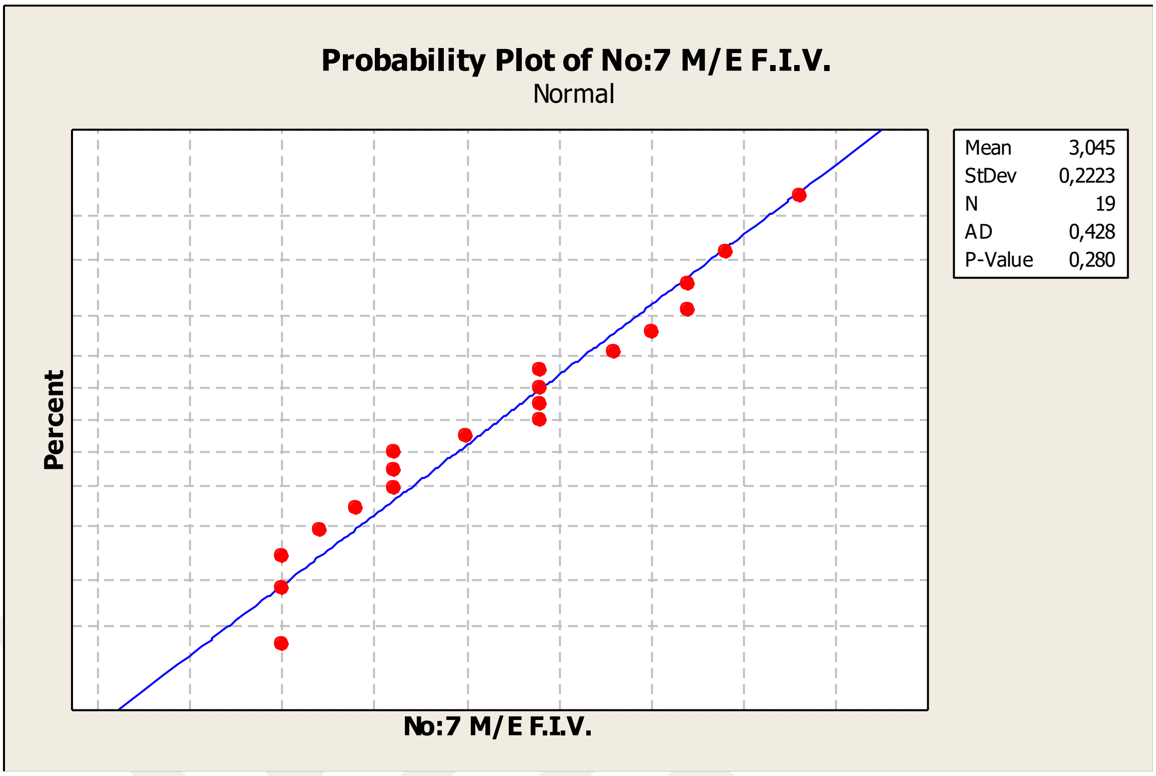

Figure D.7 : No:7 F.I.V. normal distribution plotting.

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