ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

SAFETY RELATED PRODUCTIVITY IN AIRCRAFT MAINTENANCE

Ph.D. THESIS

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Department of Aeronautics and Astronautics Engineering
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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

UÇAK BAKIMINDA EMNİYET İLİŞKİLİ VERİMLİLİK

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ŞUBAT 2013

Yüksel BOZKURT, a **Ph.D.** student of ITU **Graduate School of Science Engineering,** student ID **511932003**, successfully defended the **thesis** entitled **"SAFETY RELATED PRODUCTIVITY IN AIRCRAFT MAINTENANCE",** which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 31 December 2012
Date of Defense : 15 February 2013

To my grandmother Leyla Tosun who brought up me to be a life warrior, To my husband Salih Bozkurt and to my daughter Türkan Defne Bozkurt for supporting me always in my life,

FOREWORD

Learning is an endless voyage in our lives. Without people we met along this way, it is not possible to be brought up and continue to our journey.
I would like to express my deepest gratitude to Professor Dr. Mehmet Şerif Kavsaoğlu for his valuable guidance, kindness, patience, generous sprit and his positive outlook.
I would like to give my appreciation to my advisory committee members; Prof. Dr. İbrahim Özkol and Associate Prof. Dr. Erkan Bayraktar for their critical commentary and active contribution.
I would like to thank to Dr. İsmail Demir and Dr. Fuat Oktay who encouraged me to think out of my borders and to Bernard Schmidt for reviewing my thesis and adding valuable comments for my thesis.

February 2013

Yüksel BOZKURT
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ABBREVIATIONS

3P	:	Production, preparation, process
5S	:	Improvement tool for increasing efficiency in workplace
A/C	:	Aircraft
AD	:	Airworthiness Directive
AIAA	:	American Instıtude of Aeronautics and Astronautics
AIW	:	Accelerated improvement workshop
AMM	:	Aviation Maintenance Manuel
C-CHECK	:	Aircraft Maintenance C-check
CCR	:	Charnes, Cooper, Rhodes model
CF	:	Correlation coefficient
CRS	:	Constant Return to Scale
DEA		Data Envelope Analysis
DRS	:	Decreasing Return to Scale
DMU	:	Decision Making Unit
EASA	:	European Aviation Safety Agency
FAA	:	Federal Aviation Administration
FP	:	Fractional programming
ICAO	:	International Civil Aviation Organization
JIT	:	Just in Time
LT	:	Lead time
LETTER CHECKS	:	The different time period given by the manufacturer for the aircraft maintenance in order to maintain aircraft airworthy.
IRS	:	Increasing return to scale
IT	:	Information Technology
LP	:	Linear programming
MECI	:	Maintenance Error Catch Index
MEDA	:	Maintenance Error Decision Aid
MEL	:	Minumum Equipment List
MHRS	:	Manhours spent for the letter check
MRO	:	Aircraft Maintenance Repair and Overhaul Center (X,Y,Z are different MRO's)
NB	:	Narrow Body Aircraft
OEE	:	Overall equipment efficiency
ROI	:	Return on Investment
SAFETY ITEMS	:	Items that influence aircraft maintenance quality, these items can be investigated during letter check or during aircraft operations
SI	:	Service Information (It is a letter which give information about modification and changes of a part or on the aircraft)
SMS	:	Safety Management System
TAT	:	Turn around time means Lead Time for an aircraft letter check.

TFP	:	Organizational total factor productivity
VRS	:	Variable Return to Scale
VSM	:	Value Stream Mapping
VTT	:	Takt Time, customer demand, production or service time for a work or product.
X-MRO	:	Aircraft Maintenance repair overhaul company
Y-MRO	:	Aircraft Maintenance repair overhaul company
WB	:	Wide body aircraft
Z-MRO	:	Aircraft Maintenance repair overhaul company

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SAFETY RELATED PRODUCTIVITY IN AIRCRAFT MAINTENANCE

SUMMARY

As a result of Global economical crisis, MRO centers are persuaded to be more productive in their processes. Productivity has a direct relation with affective use of resources such as human beings and material. The goal is to gain more profit by using less resources in aircraft maintenance while maintaining the appropriate level of safety. If productivity is high it does not mean that there is adequate level of safety in a MRO.

Safety is the danger, risk, injury, or loss to personnel and/or property, whether caused intentionally or by accident. All of the aviation rules concentrate the potential implications of human error and human factors failings upon aviation safety and not on how human factors affects the individual's efficiency. However, if good human factors principles are applied within maintenance in order to improve safety, there should also be associated benefits that can be realised for the aviation personnel.

Productivity is; the amount of output per unit of input (labor, equipment, and capital). There are many different ways of measuring productivity. For example, in a factory, productivity might be measured based on the number of hours it takes to produce a good. In the service sector productivity might be measured based on the revenue generated by an employee divided by his/her salary. In a MRO, it might be measured based on the total manhours, materials or time spend divided by number of letter checks.

Efficiency is the evaluation of performance of a unit. The evaluation can be accomplished by calculating level of production in comparison with resources and cost. A level of performance that describes a process which uses the lowest amount of inputs to create the highest amount of outputs. Efficiency relates to the use of all inputs in producing any given output, including personal time and energy. Inputs such as; time, money and raw materials are limited, while maintaining an acceptable level of output or a general production level, they should be conserved. Being efficient means reducing the amount of waste in the inputs. A commonly used measure of efficiency is the ratio; output variables divided by input variables.

Effectiveness is measured by the ratio of 'actual targets / defined targets'. If effectivity and effectiveness have higher values, it shows that the unit is productive and has higher performace than before.

The usual measure of "productivity" also assumes a ratio form when used to evaluate employee performance. 'Output per worker employed" is the example with sales, profit or other measures of output appearing in the numerator. Such measures are sometimes referred to as "partial productivity measures". This terminology is used to

separate them from “total factor productivity measures”. To obtain an output to input ratio value takes account of all outputs and all inputs.
Other problems and limitations are tolerated to evaluate productivity or efficiency when multiple outputs and multiple inputs need to be taken into account. Some of the problems that need to be addressed will be described in more detail with DEA.

Safety related productivity is the total productivity calculated by taking into account of human factor affect.

High productivity is important for competitive MRO’s. If MRO’s can not catch human related errors which affect safety and they can not stop them happening again, these human errors affect productivity too. Some human errors can cause big events such as, in flight turn backs, in flight shut downs, delays that cause big amount of cost to operators. Human errors start to show its affects in operation sometime after a year that the error happened. It is important to find mistake proof solutions for the human errors not to lost customers or money for a MRO.

Safety level is defined by using ICAO risk assessment in civil aviation. Although there is a relation between productivity and safety in reality, it is hard to find a reference in the litterature to show the relation. In this thesis, the relation between safety and productivity is given.

This thesis concerns with a productive MRO. It has increasing effectivity and efficiency by increasing number of maintained aircrafts. But also, it has potential safety problems which can affect its competency in the market. In this thesis, it is also shown that how human errors as part of safety, affect a MRO total productivity and MRO maintenance C-checks and how managers prioritize improvement activities to increase level of relative efficiency by using DEA. X-MRO is choosen for case study. Because data is provided by X-MRO.

Human errors are analysed for X-MRO between years 2006 and 2011. These errors compared with the other two MRO’s to calculate and compare their safety index.

In order to reduce the affect of human errors and to increase the productivity, improvement events which were accomplished in X-MRO beetween 2006 and 2011 are shared. X-MRO total factor productivity, efficiency, effectivity are calculated between years 2007 and 2009 to see the relation between safety and productivity.

A MECI is defined to show the affect of safety on relative efficiency for the letter checks .

DEA is a technique that is used for measurement relative efficiency of similar units in an organization. If there are more than one input and one output it is difficult to calculate performance measurements of units. DEA method was used to compare relative efficiency of twelve A320 aircraft maintenance C-checks which were accomplished in X-MRO by including safety as output. It is used to compare relative efficiencies of C-checks.

As a result of DEA analysis, relative effficiencies of aircraft maintenance for the year 2010 and 2011 for A320&A321 C2-Checks are calculated. Improvement opportunities to reach targeted variables calculated. When 2010 DMU's are evaluated, it is clear that the relative efficiencies of DMU's can be improved without changing MECI in X-MRO. On the contrary in 2011, targeted MECI values increases when input variables decreases. As soon as improvement is needed to reduce resources which are called input variables, the opportunity to catch maintenance errors increases. This indicates that if efficiency increases, there are potentially less maintenance errors can be catched and there will be more opportunity to catch errors in X-MRO.

Bay management is the organization of resources in a dedicated area to improve aircraft maintenance efficiency in a letter check. To use 'Bay Management' is the one of the best ways to increase productivity and relative efficiency of maintenance in a MRO. In our case X-MRO does not use bay management system and all resources were shared while accomplishing C-Checks. If a human error happens and not catches during maintenance it can be reocurred again on the other aircrafts. It affects the total productivity and worse than that it also affects safety. The MECI includes reoccurences to show real affects of safety. DEA is also used to check maintenance error which has an affect on relative efficiency for C-Checks and it can be used efficicently in bay management system.

This application gives the opportunity to use industry data in Civil Aviation. In order to decide area of improvement, to increase productivity, a competitive MRO can use DEA. After DEA analysis, managers can see privileges and they do not spend more time for the areas that have less improvement opportunities. DEA helps to manage 'bay management' system too by showing efficient DMU's. Safety has the same affect on maintenance whether a productive MRO uses general aircraft maintenance with improvements or bay management.

UÇAK BAKIMINDA EMNİYET İLİŞKİLİ VERİMLİLİK

ÖZET

Günümüzde global ekonomik krizin etkilerine rağmen büyüyen MRO pazarında MRO' lar daha üretken olmaya zorlanmaktadırlar. Üretkenliğin, insan, makine gibi kaynakları etkin kullanma ile direk ilişkisi bulunmaktadır. MRO pazarında başarı; verimli çalışarak, daha az kaynak kullanımı ile daha fazla kazanç sağlayarak elde edilir. Dünya üzerinde pek çok şirkette üretkenliği artırıcı çeşitli araçlar kullanılmaktadır; Yalın, Altı Sigma, kısıtlar teorisi, kritik zincir, yaratıcı düşünme teknikleri bunlardan bazılarıdır. Rekabetin kaçınılmaz olduğu günümüzde, rekabet edebilmek için tek şart sürekli gelişimdir. Büyük ölçekli organizasyonlarda sürekli gelişim için; üretkenliği artırıcı araçların yanısıra iyileştirmelerin hangi alanlarda öncelikli olarak çalışılması gerektiğide önem taşımaktadır.

Çağımızın rekabet ortamında şirketlerin sürekli gelişim için, hedeflerini üretkenliği artırıcı metriklerden seçmeleri gereklidir. Uçak bakım planlama önceliklerini belirlemek isteyen bir MRO' nun söz konusu metrikleri belirlemesi ve ölçmesi önemlidir. Rekabetçi bir MRO, gelişime açık alanları belirler, gerektikçede bu alanlarda sürekli iyileştirme faaliyetleri gerçekleştirir. Üretkenlik ve verimlilikte olan dalgalanmalar, kaynakların ve hizmetlerin yönetimi sonucu olarak ortaya çıkmaktadır. Bu dalgalanmalar mali getirinin değişiminede neden olabilir. Rekabetçi şirketlerde mali başarının düşmesi veya mali hedeflere ulaşılamaması istenmeyen bir durumdur. Bu nedenle bir şirkette üretkenlik ve verimliliğin geçmiş yıllara göre sürekli iyileşmesi, şirketin varlığını sürdürebilmesi açısından önem taşımaktadır.

MRO larda rekabeti etkileyen en önemli etkenlerden birisi de uçak bakım emniyetidir. Emniyet, personelin veya şirkete ait bir varlığın, farkında olmadan veya bilerek gerçekleştirilen hatalı işlemler neticesinde hasarlanması, maddi veya ölümcül kayıplara neden olma veya risk seviyesinin durumunu gösteren bir ifadedir. Emniyetin en önemli parçalarından biri insan faktörüdür. Havacılıkta yaşanan kazaların en önemli nedeni insan faktörüdür. Havacılığın ilk yıllarında yaşanan kazaların %80 i uçak,ekipman ve uçak komponentlerinden %20 si ise insan hatalarından kaynaklanmakta idi. Günümüzde ise teknolojinin gelişimi ve uçak ile ilgili sistemlerin yedekli ve hatayı minimize edecek şekilde üretilmesi ile bu oran tersine dönmüştür. İnsan kaynaklı bakım hataları sivil havacılık operatörleri için gerçekleştirilen işlemlerin tekrarına ve gelir kayıplarına neden olmaktadır. En önemliside uçuş ve bakım emniyeti ile direk ilişkisi bulunmaktadır. EASA PART 145 ve FAA PART 145 kurallarında uçak bakımında emniyetin sağlanması ile ile ilgili kurallar bulunmaktadır. Uçak bakımında insan kaynaklı hataları yakalamak için Boeing tarafından geliştirilen MEDA gibi sistemler kurulması gerekmektedir. Uçak bakım emniyetini iyi bir duruma getirmek için uygulanan iyileştirmeler verimliliğe de katkı sağlayacaktır.

Üretkenlik bir sistem girdisinin süreçleri izledikten sonra verdiği çıktıdır. Üretkenliği ölçmek için bir çok ölçüm yöntemi bulunmaktadır. Örnek olarak üretimde ürün başına harcanan saatlerde yapılan iyileştirmeler ölçülebilir ve ölçümler sonucunda gözlemlenen düşüler üretkenliğin artışının ifadesidir. Servis sektöründe ise bir çalışanın şirkete kazandırdığı net karın personelin maaşına oranı ile ölçülebilir. Bu oranın artması söz konusu şirkette üretkenliğin artması anlamına gelecektir.

Verimlilik, bir birim performansının değerlendirilmesidir. Değerlendirme üretim seviyesinin kaynak ve maliyetler karşısında aldığı değer hesaplanarak gerçekleştirilebilir. Verimlilik çıktı üreten tüm girdilerin verimli kullanımı ile ilişkilidir. Girdiler zaman, para, hammadde, insan kaynağı olabilir. Verimlilik için en çok kullanılan eşitlik, 'çıktı/girdi' dir.Verimli olmak, girdi seviyesini azaltmak anlamına gelmektedir.

Etkililik hedeflere ulaşma yüzdesi ile ölçülür. Bir organizasyonda her yıl belirlenen şirket hedeflerinin aylık olarak takibi ve yıl sonunda değerlendirilmesi ise söz konusu hedeflerin yüzde kaçına erişildiği hesaplanır. Bulunan değer etkililiğin ifadesidir.

Etkenlik kaynakların etkin kullanımıdır. Kaynaklar genel olarak makina, insan, malzeme, para, hammadde olabilir. Planlanan girdinin, gerçekleşen girdiye oranı ile ölçülür.

Etkenlik ve etkililiği yüksek olan bir ünitenin performansının yüksek olduğu söylenebilir fakat bu ünitenin toplam faktör verimliliği ve üretkenliği yüksek olmayabilir. Toplam verimliliğe bakıldığında ise bu parametrelerin her birinin önceki yıllara göre artıyor olması, söz konusu ünite verimliliğininde arttığını göstermektedir.

Üretkenliğin ölçümünde de çalışan performansını değerlendiren bir oran kullanılmaktadır. Çalışanın saat başına ürettiği çıktı bir ölçü sayılabilir. Bu tür ölçümler zaman zaman 'kısmi üretkenlik ölçümleri' ismi ile adlandırılırlar. Tüm girdi ve çıktılar bir arada göz önüne alındığında bu değer toplam faktör üretkenliği veya verimlilik olarak adlandırılır.

Uçak bakımında yapılan hataların verimliliği de etkilediğini söylemek uygun olacaktır. Uçak bakımında yapılan hatalar üzerinde kök neden analizinin yapılarak asıl nedenin tespiti ve bir daha gerçekleşmemek üzere önleyici ve düzeltici faaliyetlerin geliştirilmesi önem arz etmektedir. Hatalar tekrar ettiği sürece yeniden işlemler yapılması gerekecek bu da hatalardan kaynaklı maliyetleri artıracaktır.

Bakım hatalarının rekabet üzerinde de olumsuz etkileri bulunmaktadır. Hatalarını tekrarlayan MRO larda bakım maliyetleri de yüksek olacağından müşterilerin MRO seçiminde bu konuda bir kriter belirlemesi kaçınılmazdır. Bu nedenle bakım hataları önceden tespit edilebilir ise MRO larda verimlilik artışı gözlemlenebilir. Bakım hataları sürekli gelişim için iyileştirme fırsatı olarak değerlendirilebilir. Günümüzde bir çok MRO da bakım hatalarını tespit ederek bir daha oluşmasını önlemek amacı ile iyileştirme çalışmaları yapılmaktadır. Öncelikle olay tam olarak tespit edilmektedir. Ardından MEDA araştırma raporu hazırlanmaktadır. MEDA raporları bir uçak tipi için, uçuştan dönmeler, uçuşta motor duruşları, bir saati aşan teknik tehirler uçuş emniyetini etkileyen olayların incelenerek, hazırlanan değerlendirmeler ile düzeltici önleyici faaliyetlerin bildiriminden oluşur. MEDA araştırmalarında kullanılan MEDA kontrol listesi ile hatalar sınıflandırılmakta, hatalara neden olan yardımcı faktörler tespit edilmektedir. Yorgunluk, koordinasyon eksikliği, eğitim eksikliği, ekipman eksikliği, havalandırma, ortamda az ışık bulunması, dökümantasyon yetersizliği, prosedürün yetersiz olması, yönetici baskısı, toplum baskısı ve normlar yardımcı faktörlere örnek olarak verilebilir. Bu faktörlerin tekrarlanma sıklığı arttıkça MRO ların operasyonel risk faktörleride artmaktadır.

Planlı uçak bakımları, üretici tarafından belirlenmiş ve operatör tarafından özel hale getirilmiş, ilk giriş kontrolünden başlamak üzerinde uçak üzerinde gerçekleştirilen tanımlı bir çok aktivitenin tamamlanmasının ardından uçağın müşteriye teslimini içeren çok sayıda aktiviteden oluşur. Üretici tarafından belirlenmiş bakım periyotları uçağın yaşına, kullanımına bağlı olarak farklılık arzedebilir ve uçağı emniyetli olarak uçurabilmek için gerekli aktiviteleri içerir. Günümüzde MRO' lar planlı bakımlarda TAT(Turn Around Time)' ları düşürüp bakım maliyetlerini azaltarak müşteriye zamanında teslimi hedeflemektedirler.

Verimliliği artırıcı iyileştirme çalışmalarının, öncelikle zaman kazanmaya, müşteri taleplerine zamanında yanıt vermeye ve kaynakların uzun süre kullanımına yönelik olması önem arz etmektedir. Çok küçük olsa da yapılacak olan iyileştirmeler ile büyük organizasyonlarda kaynaklardan kazanım sağlanabilir. Örnek olarak; yılda 250 'A' bakımı ve her 'A' bakımı için 18 adamxsaat harcanıyor ise bakım başına 5 adamxdakikalık bir kazanç toplamda 20 adamxsaat lik bir kazanç sağlayarak bir bakım için harcanan insan kaynağı maliyetinde azalmaya neden olacaktır. Günümüzde kullanılmakta olan iyileştirme araçları ile süreçlerdeki darboğazlar tespit edilerek giderilebilir. Fakat bir süreçde yaşanan darboğazın giderilmesi, sözkonusu süreç ile ilişkili diğer süreçlerde darboğazların yaşanmasına neden olabilir.Bu nedenle iyileştirmenin seçildiği nokta önemlidir. Yöneticinin iyileştirmeye açık alanları iyi tespit etmesi ve hangi süreçte çalışma yapılması gerektiğine doğru bir şekilde karar vermesi gerekmektedir. Uygun olmayan kararlar kaynakların israf edilmesine ve verimliliğin düşmesine neden olmaktadır.

İyileştirme araçları benzer iş ünitelerinde göreceli olarak verimlilik değerini karşılaştırma konusunda yetersizdirler. Diğer sektörlerde benzer işlemleri gerçekleştiren ünitelerde göreceli verimlilik karşılaştırılması amacı ile; Oran analizi, parametrik metodlar ve parametrik olmayan metodlar kullanılmaktadır. Oran analizinde bir girdi ve bir çıktı belirli bir zaman diliminde gözlemlenerek verimlilik oranı tespit edilir. Parametrik metodlarda üretim parametreleri tespit edilmek zorundadır, regresyon analizi kullanılır. Bir çıktı ve çok sayıda girdi ile, bir girdi ve çok sayıda çıktı biraradadır. Regresyon analizinde ragresyon eğrisi altında bulunan karar verme üniteleri verimsiz, üzerinde bulunanlar ise verimli kabul edilirler.

Parametrik olmayan metodlarda; belirli kısıtlar dahilinde etkin sınıra olan optimum uzaklık ölçülür. DEA, Cooper , W. W., Seiford L. M., Tone K. tarafından 2000 yılında yayımlanan en çok kullanılan metodlardandır.

DEA bir çok disiplinde kullanılan yöneticiler için bir karar verme aracıdır, örnek olarak; operasyonel araştırma, yönetim kontrol sistemleri, stratejik yönetim, ekonomi, mali işler ve finans insan kaynakları yönetimi, kamu yönetimi, ekip yönetimi, alan yönetimi verilebilir. Bu çalışmada, DEA belirli bir tipteki uçak bakım göreceli verimliliklerini hesaplayarak, iyileştirme fırsatlarını yakalamak için kullanılacaktır.

Charnes, W.Cooper ve E.Rhodes 1978 yılında ilk kez okul bölümlerinin göreceli verimlilik karşılaştırma çalışmalarını gerçekleştirmişlerdir. Daha sonraları hastane, restorant, banka şubeleri nin göreceli verimliliklerini ölçen çalışmalar gerçekleştirilmiştir. 1970 lerin sonlarında ortaya çıkan bu metod çoklu girdi ve çıktıya sahip olan karar verme ünitelerinin göreceli verimliliğini ölçme konusunda yaygın olarak kullanılmaktadır. DEA, bir data setinde bulunan diğer karar verme ünitelerine göre göreceli çıktıları üretmek için mevcut girdiler olan kaynakların nasıl kullandığını değerlendirmek için olanak sağlar. Özellikle kısıtlı kaynaklar ile verimli çalışmak isteyen organizasyonların rekabet gücü tespit edilen iyileştirme fırsatlarının gelişimi ile yakalanabilir.

Günümüzde çok sayıda MRO verimli bakım yönetimi sağlamak amacı ile 'Hücre bölmesi yönetimi (Bay Management)' felsefesini uygulamaktadır. Hücre bölmesi yönetimi (Bay management) planlı bir bakım için belirlenen bir uçak tipinde insan, makina, malzeme kaynaklarının etkin bir biçimde kullanımını ve diğer bay' lar ile göreceli karşılaştırma yolu ile daha iyi yönetilmelerini sağlayan bir metoddur. Bu metodda

- Sabit dok sistemi kullanılır
- Malzemeler kit ler halinde kullanılır
- Zamanında malzeme ve tool teslimi (JIT: Just In Time Delivery) metodu kullanılır
- İnsan, makina ve malzeme akışı sağlanır
- Finansal hedefler bulunmaktadır.

Her bir bay' ın bir yöneticisi bulunur ve bay' ın verimliliğinden sorumludur. Bay' da bulunan personelin ücret ve primleri verimliliklerine göre belirlenir. Bay' ın verimliliği toplam verimlilik, etkenlik ve etkililik hesapları ile ölçülür. Her bay bir önceki yıla göre daha verimli olmak durumundadır. DEA yöntemi kullanıldığında her bir bay' ın insan, makina, malzeme kaynaklarının verimlilik karşılaştırılması yapılabilir ve prim sistemi bu karşılaştırmalar kullanılarak kararlaştırılabilir. Böylelikle yöneticiler çalışanlara adil bir prim dağılımı gerçekleştirilebilir. Bu sayede çalışanların motivasyonları artırılarak iyileştirmeler daha hızlı ve kısa bir sürede gerçekleştirilebilir.

Bu tezde öncelikle bakım emniyetinin en önemli elemanlarından birisi olan insan faktörü X-MRO için yıllara göre incelenip analiz edilmektedir. Söz konusu zaman diliminde farklı MRO' lardaki insan kaynaklı bakım hatalarıda karşılaştırmalı olarak verilmektedir. X-MRO da insan hatasını ve üretkenlik ve verimliliği artırmak için gerçekleştirilen sürekli iyileştirme çalışmaları anlatılmaktadır.

Uçak bakımında insan hatalarını yakalama indeksi adı ile kullanılan bir index tanımlanmıştır. Index değeri ne kadar yüksek olur ise yakalanan hata sayısı artacak, alınacak düzeltici önleyici faaliyetler ile bakım emniyet riski azalacaktır. Bakım emniyet riskinin üretkenliğe direk etkisi bulunmaktadır. Yıllar içinde bu değer azaltılmadığı takdirde MRO nın pazardaki konumunu etkileyecektir. DEA analizinde insan hatalarını yakalama indeksi çıktı olarak kullanılmaktadır.

Bu çalışmada, A320-200 uçaklarında C2 bakımlarının uygulandığı bir MRO' da DEA kullanılarak bakımların verimlilikleri karşılaştırılmaktadır. Her bir karar ünitesi için girdi olarak; uçak bakımında en büyük maliyetlerden birisi olan para birimi bazlı malzeme, TAT (bakım süresi) ve adamxsaat seçilmiştir. Her bir karar ünitesi için çıktı olarak bakımın satışından elde edilen para birimi bazlı satışlar ve bakım hatası yakalama indeksi seçilmiştir. Bakım hataları yakalama indeksi bakım kaynaklı meydana gelen olaylar ile ilgili hazırlanan MEDA raporlarının bir oranını vermektedir. Bu oran ne kadar yüksek olur ise araştırma sayısı artacak, düzeltici önleyici faaliyetlerin gerçekleşme hızına göre hata oranları azalacaktır. Hata oranları kalitesizlik maliyetinin bir göstergesidir ve dikkate alınmalıdır. Verimliliği etkilemesi nedeni ile bu oran bir çıktı olarak kabul edilecektir.

'Hücre bölmesi yönetimi (Bay Management)' sistemine geçecek olan MRO'larda gerçekleştirilecek olan DEA analizleri verimliliğin göreceli ölçümünü sağlayacaktır. Çalışanlara bay' ların verimliliğine göre verilecek olan primler ile motivasyon artacağından toplam verimlilik değerinde de artış beklenmektedir. DEA bir organizasyonda bulunan benzer ünitelerin göreceli verimliliğini ölçmede kullanılan bir tekniktir. Birden fazla girdi ve birden fazla çıktı durumunda performans değerlerinin ağırlıklarının ölçümü zor olacaktır. Bu şartlar altında DEA kullanımı fayda sağlayacaktır.

Sonuç olarak X-MRO' da performans, üretkenlik artışı için gerçekleştirilen iyileştirme çalışmalarının neticesinde, etkenlik ve etkililiğin arttığı gözlemlenmiştir. Fakat toplam faktör verimliliği' nde azalma olduğu tespit edilmiştir. Bu durumda iyileştirme çalışmalarının hangi alanlarda öncelikli olarak uygulanma kararını doğru bir şekilde vermek gerekmektedir. İnsan faktörü etkisi göreceli verimliliği etkilemektedir. DEA ile gerçekleştirilen göreceli verimlilik karşılaştırmaları ile öncelikli geliştirilebilecek alanlar tespit edilebilecektir. Uygulanacak olan iyileştirme teknikleri ile organizasyonel verimliliğin artışı sağlanacaktır. Hücre bölmesi yönetimi (Bay Management)' sistemi kullanılan MRO' larda DEA kullanımı sayesinde göreceli verimlilikler saptanabilecektir.

Bu çalışma Sivil Havacılık Sektöründe, uçak, motor veya komponent bakımı gerçekleştiren şirketler arası kıyaslama çalışmalarını belirli bir standartta uygulamak için olanak vermektedir.

1. INTRODUCTION

It is generally agreed today that in business environment, in order to be competitive, continuous improvements in business and operational processes are mandatory. For continuous improvement it is necessary to set targets which can be measured by improvement metrics. The establishment and measurement of these metrics are important for a company to identify maintenance planning priorities. A competitive company defines improvement areas and continuously improves these areas whenever it is necessary, in order to be successful. The reason of the variation in productivity is the management of resources. It may cause the variation in financial performance too.

There is a factor which can not be disregarded in MRO’s and this factor also effects competitiveness in the sector; Human factor. Humans are the cause of accidents. In the early days of flight, approximately 80% of the accidents were caused by the machine. 20% of the accidents were caused by human error. Today on the contrary; approximately 80% of aircraft accidents are due to human error (pilots, air traffic controllers, mechanics, etc.) and 20% are due to machine (equipment) failures. Maintenance errors cause rework and lost revenue for operators. They are potential of safety concerns too. There are written rules; by EASA part145 and by FAA part145 corcerning safety in aircraft maintenance. Operators must have a MEDA system in order to define safety concerns in their daily maintenance activities. Needless to say that maintenance errors affect maintenance productivity. Therefore maintenance errors have an impact on competitiveness. If maintenance errors can be hindered before they happen, this will help to increase productivity in MRO. Maintenance errors are opportunities for continuous improvement.

For the maintenance errors MECI number is defined. MECI is the ratio for catching errors in maintenance. Higher MECI ratios show that there are more errors to catch. MECI has a relation with Total number of MEDA reports for MRO fleet, Number of Aircraft for A320 fleet, Total number of aircraft in MRO fleet, Number of MEDA reports for subject aircraft and Aircraft Maintenance on Time Delivery rate to customer, it is directly related with TAT.

MECI is a number that shows the ability to catch human errors in the aircraft maintenance.

Aircraft maintenance letter checks are the entire set of activities, running from incoming inspection to delivery of aircraft for a specific time period. Depending on the type, age and usage of aircrafts, maintenance letter checks are accomplished in terms of the time period. This period is given by the manufacturer for the aircraft maintenance in order to maintain aircraft airworthiness. Today MRO's are willing to reduce TAT's for letter checks in order to do just in time delivery of aircrafts to customers by decreasing maintenance costs. It is necessary to do productivity improvements to achieve time saving, fast reply to customer demand and use of resources in a long period of time. Great resource savings can be achieved with small improvement of productivity in large organizations. Lean, Six Sigma, Theory of constraints, Critical chain, VSM (Value Stream Mapping) are tools to determine bottlenecks of processes of an organization to locate improvement areas but these tools are not enough to define relative efficiency of similar units. There are some other techniques used for determination of relative efficiency in the other sectors such as; ratio analysis, parametrical methods and non parametrical methods.
DEA has been used in many disciplines; operations research, management control systems, organization theory, strategic management, economics, accounting and finance, human resource management and public administration.

Bay management model is one of the profitable models in aircraft maintenance. Bay management is the organization of resources, such as human, machine, material in a dedicated areas to improve aircraft maintenance efficiency in a letter check. Usage of 'Bay Management' model is one of the way to increase efficiency of maintenance in a MRO. The key elements of Bay Management model are;

- Fixed dock
- Material kitting
- JIT Delivery
- Human, material , information flow
- Financial targets

Each bay has a manager who is responsible for efficiency of the bay. Bay area personnel's performance and their amount of compensation have a relation with bay efficiency. Bay efficiency can be calculated by using total productivity, efficiency and effectiveness. But different bays should be compared in order to define, analyse and improve their processes in order to be more efficient than last year. DEA provides relative efficiency comparison of each bay using main resources such as; man hours, TAT, Material cost. Using DEA will give opportunity to define improvement needed areas; meanwhile it will help managers to decide equitable compensation distribution which is directly related with human motivation.

1.1 Purpose of Thesis

The purpose of the research is to show that the human errors have an impact on aircraft maintenance productivity and how value added decisions can be taken to be more efficient, productive and competitive MRO.

This research is concerned with designation of improvement areas of a MRO by using DEA method, productivity analysis, MEDA report's analysis and lean improvement activities. DEA is used to find relative efficiency of C-Check maintenance against maintenance errors and to choose the most effective maintenance. To compare the relative efficiency of C-Checks, maintenance errors have been added as outputs that they have affect on the performance of aircraft maintenance.

1.2 Literature Review

Increasing clobal competition affects the MROs. Azaranga, et. al. (1998), indicates that top management involvement to improvement activities affects company productivity and customer satisfaction. According to Manthou and Vlachopoulou (2001) agility is an enterprise-wide response to an increasingly competitive and changing business environment. Agile manufacturing help to organisations to be more competitive. İlhan (2007) showed how environmental factors can affects agility of an organisation.

Aircraft maintenance letter checks are the entire set of activities starting from incoming inspection to delivery of aircraft for a specific time period. Depending on the type, age and usage of aircraft, maintenance letter checks are accomplished within the specific time period. This period is given by the manufacturer for the aircraft maintenance in order to maintain aircraft airworthy. Baron (2008) tried to measure safety climate in an aircraft maintenance facility. Boeing published Meda User Guide (2003) to raise maintenance human errors in aviation industry. According to Cardy et. al. (1998), performance ratings in an organisation should reflect the number of persons which caused to error. Marx (2003) stated that professional airmen must work with maximum reliability, with some expected errors When errors do occur, they should report errors and everybody in the organisation can learn of their contributors to prevent future accidents.

Milo, et al. 1998 demonstrated maintenance strategies and their relationship with aircraft reliability that indicates the percentage of scheduled flight delays caused by mechanical problems.

Today MRO's are trying to reduce TAT's for letter checks in order to do just in time delivery to customers while decreasing maintenance costs. It is necessary to do productivity improvements which result in time saving, fast reply to customer demand, use of resources in a long period of time. Great resource savings can be achieved with small improvement of productivity in large organizations. Lean (Womack and Jones, 1996), Six Sigma (George, et al. 2005), Theory of Constraints (Cox and Schleier, 2010), Critical Chain (Goldratt, 1997), VSM (Rother and Shook, 1998), systemathic innovation techniques (Mann, 2009) are tools to determine bottlenecks of processes of an Organization to locate improvement areas but these tools are not enough to define relative efficiency of similar units. Lean product definition process reduces cost (Murman, 2003). Eiff and Suckow (2004) have demonstrated that the process mapping technique is an effective tool to provide insight into critical points in the process where safety problems arise. Eiff and Suckow (2008) also showed that the process mapping strategy is a highly effective tool for searching safety risks caused by poor operational performance and caused by worker. Goto (2001) said that appropriate safety measures help prevention of occupational accidents and improvement of productivity and quality. Yacov (2004) declared that risk assessment and management must be a part of the decision making process for managers .

Refer to Sung (2008) establishing an optimal maintenance policy for a modern aerospace system is important for its operational cost and overall safety of the system.

There are some other technics used to determine relative efficiency in the other sectors such as; ratio analysis, parametrical methods and non parametrical methods.

In ratio analysis; the ratio for one input and one output is observed in a time period.

Managers have to find an analytical method inorder to rank efficient units (Lotfi et.al., 2010). Two different methods for ranking efficient units with stochastic data are proposed.

In parametrical methods; production parameters have to be defined, regression methods is used, one output and several inputs or one input and several outputs are associated. For the regression analysis DMU' s which are under the regression line have been accepted inefficient and DMU' s which are over the regression line have been accepted efficient according to Cooper, et al. (2000).

In nonparametric methods; optimization is used under constraints to measure distance to efficient frontier. The most common methods are DEA slack based envelopment analysis according to Cooper , et al.(2000).

Preliminary work on DEA was undertaken by Charnes, et al.(1978) regarding comparison of school departments performances. Furthermore; DEA method has been used by Banker (1986) to measure hospital efficiency, by Banker, et al. (1986) to measure restaurant efficiency, by Sherman and Gold (1985) to measure operating efficiency of bank branches. Sahin (1999) showed relative efficiency of hospitals in Turkey based on regions. Martin and Roman (2006) accomplished a benchmarking analysis of Spanish commercial airports. Sezen and Doğan (2005) calculated relative efficiencies of military shops by using DEA.

In this research it is important to be clear about the definition of 'productivity', it is defined as output variables divided by input variables. DEA is a technique that is used for measurement of relative productivity of similar units in an organization. If there are more than one input and one output it is difficult to calculate their weights on performance measurements. DEA is an effective tool on that condition.

Bernolak, 1997 gives ratio of combined profitability and productivity. In the study it is indicated that; productivity is output volume per input volume. Mehra and Hoffman (1999) showed that successfull productivity program depends on top management leadership.

In this research; DEA has been used for NB (Narrow Body) A320&A321 Aircraft maintenance efficiency in a MRO. The MRO efficiency is calculated regarding efficiency of targets , effective use of resources, partial factor productivity and total factor Relative efficiency and twelve A320&A321 C2-checks has been evaluated.

Considerable amount of literature has been published on DEA however the usage of DEA in aircraft maintenance is not common. On the contrary there are lots of studies about the comparison of airport performances using DEA method.

Banker and Morey (1986a) evaluated the relative technical and scale efficiencies of

decision making units (DMUs) when some of the inputs or outputs are fixed. Banker and Morey (1986b) introduced the use of categorical variables, both for noncontrollable andcontrollable inputs or outputs, into the DEA approaches.

Rouse, 2002, carried out a study that DEA is used to quantify changes over time in productivity and continuous improvement. The usage of the DEA model which indicates the airline's strategy, provides a view of organizational performance. They reported performance measurement design by giving examples from an aircraft maintenance.

Ozbek, et al. (2009), published a paper in which they indicated the use of an approach in performing relative performance measurement that indicates a transportation-related problem by using the DEA approach.

Beginning from late 1970s, DEA has been a popular method for measuring the relative efficiency of DMU's with multiple inputs and outputs. According to Ozbek, et al. (2009), DEA enables to assess how efficiently an organization, agency, or other unit uses the resources and how to use available inputs to produce a set of outputs, relative to other units in the data set. DEA has been used in many disciplines such as operations research, management control systems, strategic management, economics, accounting and finance, human resource management, and public administration even to define football team's relative efficiency.

Charnes-Cooper-Rhodes Model, Input-Oriented CCR Model; The formulation developed by Charnes, et al. (1978), They used linear programming to extend Farrell's single output divided by single input formulae.

Efficiency measure for the multi output divided by multi input case is used by Ozbek, et al. (2009). The focus was to optimize the ratio of outputs to inputs.

1.3 Hypothesis

The research hypothesis is that increasing maintenance errors cause decreasing total factor productivity in aircraft maintenance.

Even a MRO shows high productivity, it can suffer from poor safety which will affect its competency in the market. Improvement techniques and tools may help to increase organisational efficiency if they are used in the accurately defined areas. In order to decide these areas DEA model shall be used.

In order to come to the hypothesis X-MRO total factor productivity, maintenance errors, contributing factors, partial factor efficiency, efficiency and effectivity of X-MRO data are evaluated.

DEA is applied to twelve aircraft maintenances for years 2010 and 2011 to define improvement opportunies.

As a result of this study;

- The relation between Total factor productivity, improvements and maintenance errors can be defined in a MRO.
- MRO's can decide which maintenance is the most productive.
- MRO's can manage aircraft maintenance letter checks and bay's letter checks based on the results of DEA analysis.
- MRO's can define improvement areas accurately.

2. MAINTENANCE ERROR DECISION AID (MEDA)

2.1 Introduction

Most recently used tool used for determining safety risks in MRO's is MEDA (Maintenance Error Decision Aid). The purpose of this chapter is:

- To give examples of MEDA
- Improve safety risks by using Lean tools
- Improve human risks by using Lean tools and preventive actions.
- Improve productivity while minimizing safety risks

2.2 Historical review

Rankin, Bill in 2003 highlights that humans are the largest cause of accidents;

In the early days of flight, the machine caused approximately 80% of accidents and 20% of accidents were caused by human error.

On the contrary, today, approximately 80% of aircraft accidents are due to human error (pilots, air traffic controllers, mechanics, etc.) and 20% are due to machine (equipment) failures as shown in Figure 2.1.

MEDA development started in 1992 in order to understand the problems of airline customers about manufacturer products. A tool which is related with MEDA was developed in conjunction with airlines. The tool was performed in between 1994-1995 on some airlines. Based on the results of the field study, the tool was improved. In 1995, Boeing decided to present MEDA to all if its airline customers to improve safety. MEDA become the standard for error investigation in the aviation industry (Rankin and Allen, 1996).

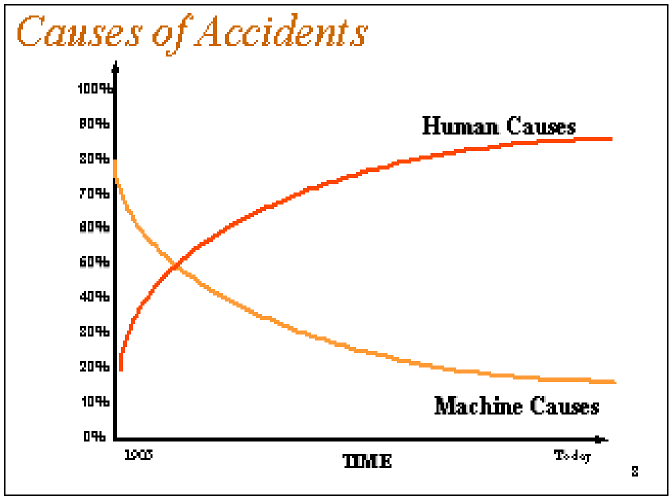


Figure 2.1 : Causes of accidents, adapted from (Graeber,2000).

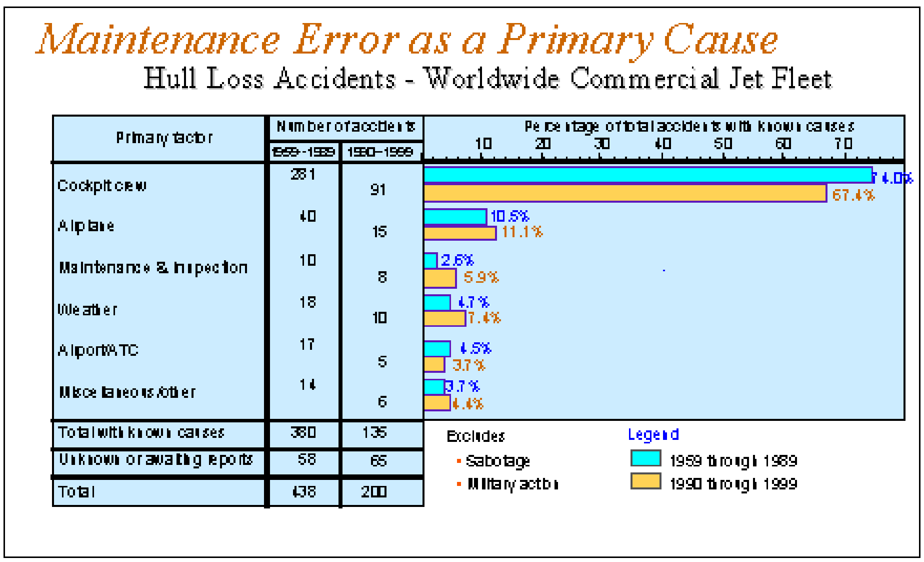


Figure 2.2 : Maintenance Error as a primary cause, adapted from (Rankin,2003)

Figure 2.2. shows that MEDA draws our attention to maintenance error which is a primary cause for hull loss of accidents on worldwide in commercial aviation. MEDA is a process used to investigate errors made by maintenance technicians, support maintenance staff and inspectors. No one wants to make an error. Errors are the results of contributing factors in the work place. Most of these contributing factors are under management control. Managers are responsible to make changes to reduce or eliminate the contributing factors and reduce the probability of future errors.

Marx (1998) stated that; maintenance errors such as wrong installation of a hydraulic valve, the failure to tighten an oil filler cap, or missing a crack which is outside of the limits during inspection of an engine disk, are the types of events within a maintenance organization that ultimately lead to an aircraft failure. To define maintenance error, it is first helpful to define “human error”. When a person should have done other than what they did, then the person has committed an error.

The human errors classified as either violation or error. Soog (2009) declared their definitions as below:

VIOLATION: is a human behavior that intentionally starts from the expected behavior. Violations are often made by well-intentioned maintenance staff who is trying to finish a job. They are not trying to increase comfort or reduce their workload. There are several types of violations.

Routine—Often occur with such regularity that they are automatic. Violating the rule has become a group norm. Often occur when the existing procedure does not lead to the intended outcome.

Situational—Occur because of factors dictated by the employee’s immediate work area or environment. Due to such things as

- Time pressure
- Lack of supervision
- Equipment, tools, or parts unavailability
- Insufficient number of maintenance staff
- Exceptional—Mechanic/inspector breaks standing rules while disregarding the consequences.

ERROR: is a human action (behavior) that unintentionally starts from the expected behavior. Error models;

- Reason’s “Swiss Cheese” model
- The Dirty Dozen
- MEDA contributing factors model

There are three types of errors:

SLIP: An error in executing the steps of a task

Example: The mechanic knows how to install a pump, but turns the wrench too hard and breaks a fitting. Also called an error of commission

LAPSE: An error in retrieving information about a task

Example: A mechanic called to help on a different task after torquing 13 of 15 bolts. When he comes back to his original job, he forgets that he had two bolts left to torque and moves on to the next task.

MISTAKE: An error in planning a task

Example: “I do not need to do the fault isolation, because I have seen the problem before installation the box”

Xavier, 2005 labeled three top items for maintenance error types. They are, Improper installation, improver testing, improper servicing.

CONTRIBUTING FACTORS TO MAINTENANCE HUMAN ERRORS

The contributing factors to maintenance human errors are declared by Sogg and William (2006);

- Pressure
- Fatigue
- Coordination
- Training
- Supervision
- Lack of equipment
- Environment
- Poor Documentation
- Poor procedure

There are two levels of causation

- Cause-in-Fact: If “A” exists (occurred), then “B” will occur.
- Probabilistic: If “A” exists (occurred), then the likelihood of “B” increases.

The most common level of causation in error investigation is probabilistic.

2.3 Error and violation models

Model 1: The contributing factors have probability to cause violation. The violation has probability to cause a system failure. The system failure could cause event. Because of these probabilities, contributing factor could cause an event. An example of Model 1 is given below.

- Mechanic does not use dedicated tool given on task card (violation), that it contributes to an incorrect installation (system failure) because of an under torque bolt.
- This leads to an engine in-flight turn back (event).
- There are reasons why (contributing factors) the violation occurred (e.g., tool is not available in time to do the task or work group norm is not using a tool for torque this bolt).

Figure 2.3 shows process map of Model 1

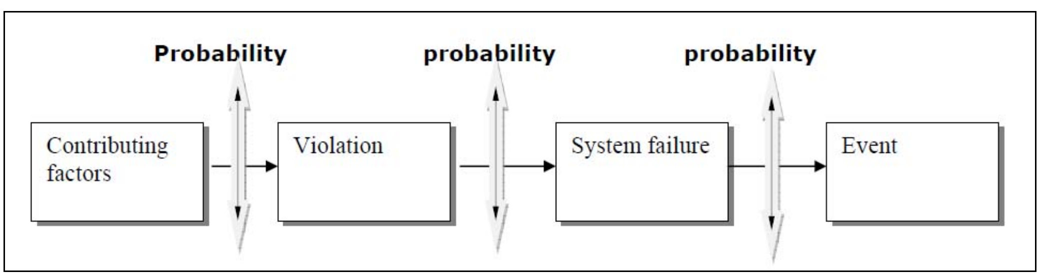


Figure 2.3 : Model 1, adapted from (Sogg and William, 2006).

Model 2: The contributing factors have probability to cause either violation or system failure. The violation and system failure have probability to cause an event. An example of Model 2 is given below.

- The mechanic mistakenly misses a step in the maintenance manual (contributing factor), which leads to an incomplete installation (system failure).
- The mechanic decides not to carry out the operational check (violation); therefore, the task was not done correctly.
- Because an error was made and this was not caught by the operational check, an engine in-flight shutdown (event) occurs.

Figure 2.4 shows process map of Model 2.

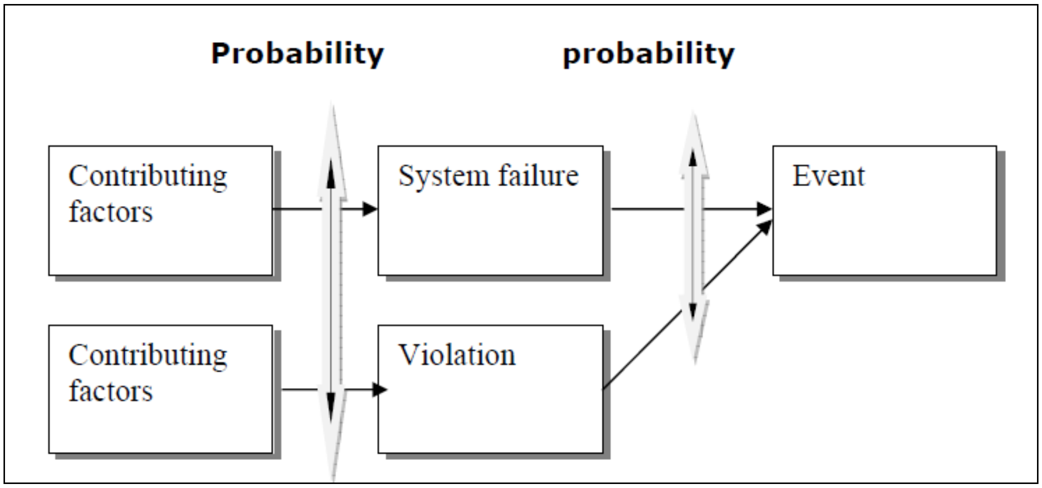


Figure 2.4 : Model 2, adapted from (Sogg and William, 2006).

Model 3: The contributing factors have probability to cause either violation or other contributing factor. The violation and other contributing factor have probability to cause a system failure or violation. The system failure or violation could cause an event. An example of Model 3 is given below.

- The mechanic does not use a torque wrench (violation) which causes to an incomplete installation (system failure).
- The mechanic decides to skip the operational check (violation); therefore, the task was not done correctly.
- Because an error was made and this was not caught by the operational check, an engine in-flight shutdown event occurs

Figure 2.5 shows process map of Model 3.

2.4 Error management

There are methods to manage error (Sogg, 2009).

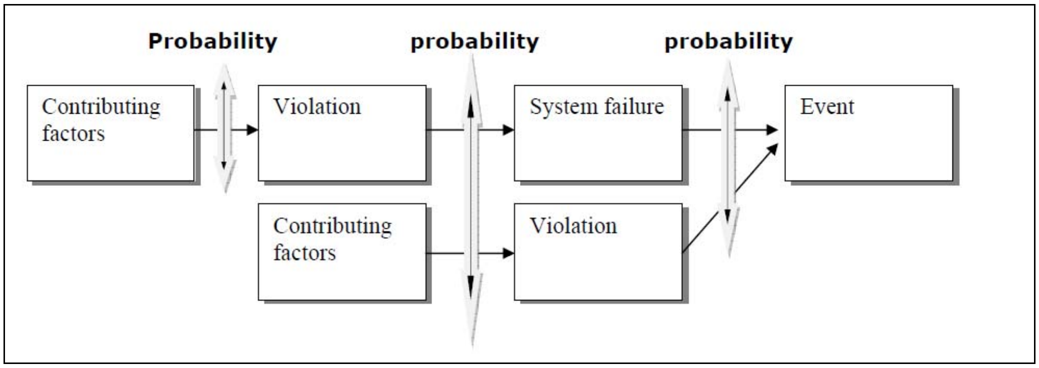


Figure 2.5 : Model 3, adapted from (Sogg and William, 2006).

Error Reduction / Elimination:

- "Fill level" indicator makes easier the life of a mechanic to do the task correct. "Fill level" indicator can be seen by adding a band on IDG oil level display. It helps to stop overfilling.
- Simplified English procedures are understood easily.
- Increased lighting for visual inspection helps to do investigation better.

Error Capturing:

- Tasks are added to find a mistake
- Inspection or functional check are done

Error Tolerance:

Doing maintenance tasks on parallel systems with different Mechanics so that the aircraft is functional after a maintenance error.

Not doing the same maintenance tasks on both engines on an aircraft

Error Audit:

They are quality surveys and audit programs. They are dedicated to find errors.

2.5 Safety Management system

Sogg (2009) described that Safety Management System is a set of policies and processes. Managers used it to fulfill their responsibility to manage the safety risks. Traditional methods for managing safety risks become less effective and efficient. The methods for understanding and managing safety risks are necessary. After determining the contributing factors, the next step is to review potential severity and probability of recurrence in order to assign a risk assessment. SMS helps to increase organization safety. SMS consists of:

- Safety policy and objectives
- Safety risk management
- SMS (program) surveillance and control
- Safety promotion

2.6 Risk management

The description of risk related terms are (Sogg, 2009)**;**

Hazard – Condition, object or activity with the potential of causing injuries to personnel, damage to equipment or structures, loss of material, or reduction of ability to perform a prescribed function.

Risk – It is tthe probability and severity of a hazard (Expected Loss/Unit time or activity).

Severity –It is the possible consequences of a hazard, taking as reference the worst foreseeable situation (loss/loss event).

Probability – It is the likelihood that the consequences of the hazard might occur (loss event/unit time or activity).

$$\text{Risk} = \text{Severity X Probability} \qquad \textbf{(2.1)}$$

A fuel tank leak during flight is hazard. The possibility that a fuel leak may not be repaired properly, resulting in an accident, is one risk.

Safety metrics Maintenance examples

- Flight delays due to maintenance
- In flight turn backs due to mechanical failures
- In flight shut downs due to mechanical failures
- Rejected take-offs due to mechanical failures
- Average number of days for late letter checks
- Maintenance write-ups for several days after any letter check
- Average number of MEL items per aircraft per fleet

The elements of risk management are;

Risk Analysis: It encompasses risk identification and risk estimation. Once a hazard is identified, the risks associated with the hazard must be identified and the amount of risk estimated.

Risk Assessment: It is the probability and severity of the hazard that are assessed to determine the level of risk.

Risk Control: A corrective action plan is developed to reduce the risks to an acceptable level

Monitoring: It is essential to ensure that the corrective action plan is in place, it is effective in addressing the stated issues or hazards.

ICAO Risk assessment matrix for contributing factors is given in Table 2.1 (Sogg, 2009). Risk assessment level defined by using the matrix. The matrix consists of risk severity and risk probability. There are five levels of risk severity and five levels of risk probability. The number of contributing factors of aircraft maintenance errors is traced each year. By calculating number of occurrence of risk, probability is defined. Risk severity is determined according to definition of contributing factors. All defined values for risk probability and decision for risk severity are used in the matrix given in Table 2.1 to define risk level of subject contributing factor.

Table 2.1 : ICAO risk assessment matrix, adapted from (Sogg, 2009).

Risk probability	Risk severity				
	Negligible A	Minor B	Major C	Hazardous D	Catastrophic E
5 – Frequent	5A	5B	5C	5D	5E
4 – Occasional	4A	4B	4C	4D	4E
3 – Remote	3A	3B	3C	3D	3E
2 – Improbable	2A	2B	2C	2D	2E
1 – Extremely improbable	1A	1B	1C	1D	1E

Probability levels are given in Table 2.2 and severity levels in Table 2.3.

Table 2.2 : Probability levels, adapted from (Sogg, 2009).

Probability	
1-EXTREMELY IMPROBABLE	Mishap impossible
2-IMPROBABLE	Postulated event (Has been planned for, and may be possible, but not known to have occurred)
3-REMOTE	Has occurred rarely (Known to have happened, but a statistically credible frequency cannot be determined)
4-OCCASIONAL	Has occurred infrequently (Occurs on order of less than once per year and is likely to reoccur within 5 years)
5-FREQUENT	Has occurred frequently (Occurs on order of one or more per year and likely to reoccur within 1 year)

The Risk Management Matrix consists of four severity categories and four likelihood categories or probabilities as shown in Table 2.3. Each contributing factor is associated with a risk level depending on the severity of the factor and the likelihood associated with the occurrence of the contributing factor. The combination of a severity and the probability of occurrence help the management to identify the risk level of a contributing factor. These contributing factors are under management control and they have potential for improvement. The MEDA investigation consists of an interview with the mechanic(s), who made the error, to understand the contributing factors. The management takes a decision in order to understand which contributing factors need improvement to reduce future errors.

Table 2.3 : Severity levels, adapted from (Sogg, 2009).

Severity	
Level 0-A **NEGLIGIBLE**	**No damage or injury or adverse consequences**
Level 1-B **MINOR**	Personnel First Aid, no disability or lost time Public Minor impact, may appear in local media Environment Contained release Equipment Minor damage, potential organizational slowdown/ potential downtime
Level 2-C **MAJOR**	Personnel Lost time injury, no disability Public Local media, loss of confidence / some injury potential Environment Small uncontained release Equipment Minor damage, leads to organizational slowdown/ minor downtime
Level 3-D **HAZARDOUS**	Personnel Disability/ severe injury Public National media coverage, exposed to hazard that could/ will cause injury Environment Moderate uncontained release Equipment Major damage, results in major slowdown/ downtime
Level 4-E **CATASTROPHIC**	Personnel Fatal, life threatening Public Exposed to life threatening hazard Environment Large uncontained release Equipment Loss of critical equipment, shutdown of organization

For the risk assessment, severity and probability levels defined. In the risk assessment matrix, the severity level that intersects with the probability level is a code, which consists of a letter and a number. According to the region, the code has a color that states criteria of the risk shown in Table 2.4.

Table 2.4 : ICAO risk tolerability, risk assessment index adapted from (Sogg, 2009).

Assessment risk index	Suggested criteria
3E, 4D, 4E, 5C, 5D, 5E	Unacceptable under the existing circumstances
2D, 2E, 3C, 3D, 4C, 5A, 5B	Risk control/mitigation requires management decision
1D, 1E, 2C, 3B, 4A, 4B	Acceptable after review of the operation
1A, 1B, 1C, 2A, 2B, 3A	Acceptable

Probability multiplied by the severity equals risk level. Definition of ICAO risk levels is given in Table 2.5. If a MRO has Level 3 risk, it must implement sufficient control measures to reduce risk.

Table 2.5 : ICAO risk levels, adapted from (Sogg, 2009).

VALUES	RISK LEVEL	ACTION
0-10	**LEVEL 1**	**Minimum Risk Proceed after considering all elements of risk**
11-30	**LEVEL 2**	**Moderate Risk Continue after taking action to manage overall level of risk**
>30	**LEVEL 3**	**High Risk STOP: do not proceed until sufficient control measures have been implemented to reduce risk to an acceptable level**

2.7 Case Study

On this case study, the improvement actions for human errors and their contributing factors for X-MRO improvement actions are evaluated. Improvement actions started in the beginning of 2006. Customer fleet size for X-MRO is given in Figure 2.6 and detected number of error distribution is given in Figure 2.7. Additionally Y-MRO and Z-MRO evaluated to show contributing factor distribution and risk factor comparison.

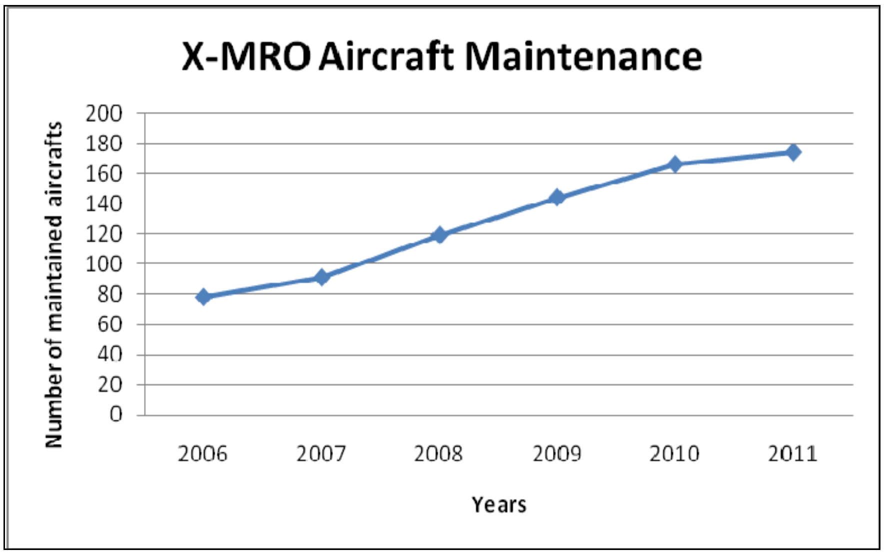


Figure 2.6 : X-MRO Number of aircraft maintenance.

X-MRO, Y-MRO and Z-MRO are three different companies. Their main business is aircraft maintenance. In order to compare risk factors for the X-MRO, Y-MRO AND Z-MRO, error types evaluated and contributing factors are defined.

Improvement tools used in order to take corrective action of the errors. X-MRO used lean tools such as 5S, AIW, VSM for improvement of the root causes between the years 2006-2011.

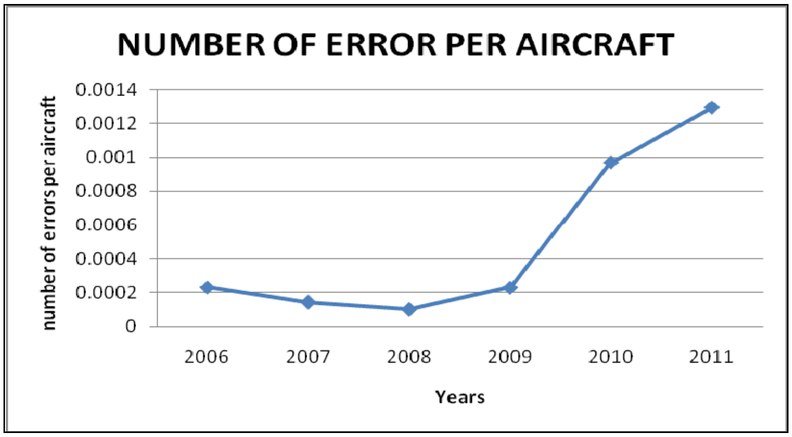


Figure 2.7 : X-MRO number of error distribution for different periods.

Sogg and William (2006) stated that the maintenance human errors can be classified as;

- Improper installation
- Improper servicing
- Incorrect/improper repair
- Improper fault isolation/testing
- Foreign object damage
- Events caused to injury
- Other

In Figure 2.7, it is shown that number of errors is increasing by years for the X-MRO. In 2010, number of all types of errors increases. From Figure 2.8, it is observed that improper installation has the highest rate for the subject years. Secondly, improper fault isolation/testing causes most of the errors.

Y-MRO and Z-MRO are evaluated to show error type distribution.

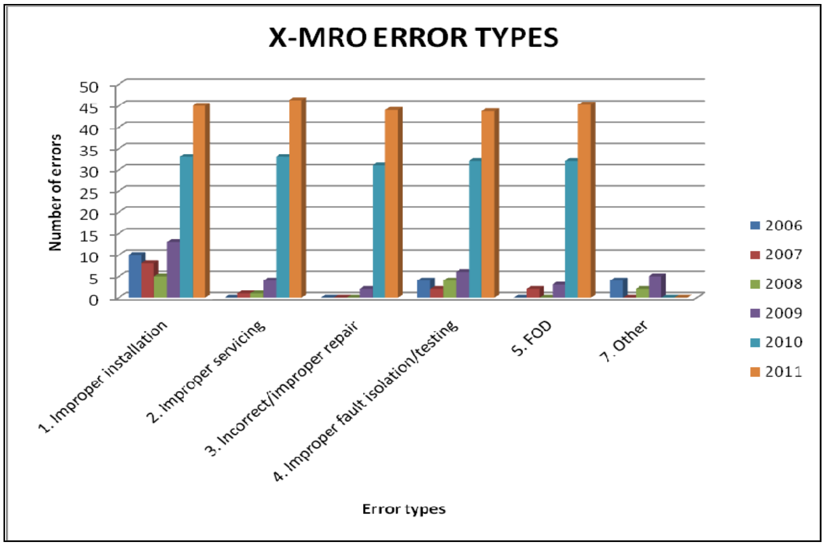


Figure 2.8 : X-MRO error types for different periods.

Hall (2003) showed that Y-MRO has the same errors as given in Figure 2.9. Improper installation has the highest rate. Secondly, improper fault isolation/testing causes most of the errors.

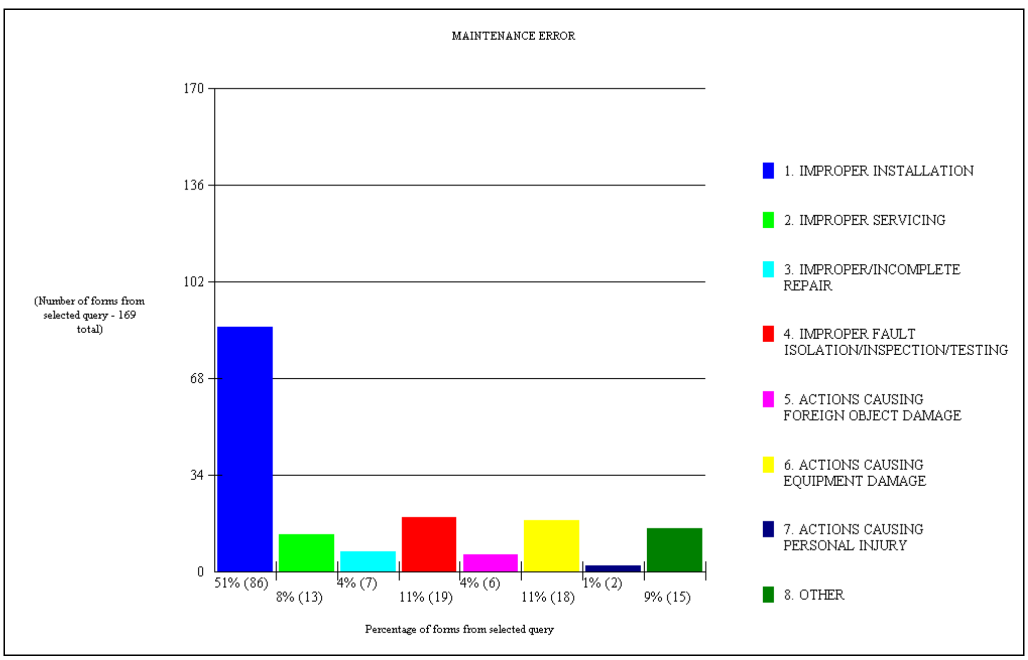


Figure 2.9 : Y-MRO error types for 2003, adapted from (Hall, 2003).

Skinner (2003) showed that Z-MRO has the same errors as given in Figure 2.10.Improper installation has the highest rate between error types. Secondly, improper fault isolation/testing follow improper installation.

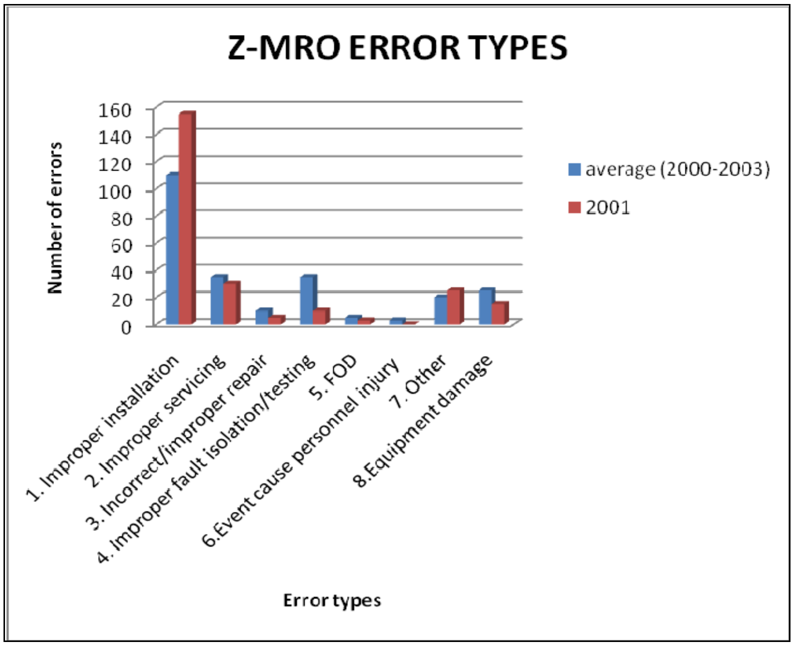


Figure 2.10 : Z-MRO error types for 2003, adapted from (Hall, 2003).

When X-MRO, Y-MRO and Z-MRO are compared, it is seen that they have the same type of errors that have highest rates: Improper installation and improper fault isolation/testing. The reasons of improper installation can be classified as:

- Required equipment not installed
- Wrong equipment/parts installed
- Improper location
- Incomplete installation
- Extra parts installed
- Access panel not installed
- Not activated/deactivated
- Damaged
- Other

Figure 2.11 shows X-MRO improper installation error classification. The reasons for improper installation are shown in Figure 2.11. 'Damaged' and 'required equipment not installed' have higher occurrences than the others do.

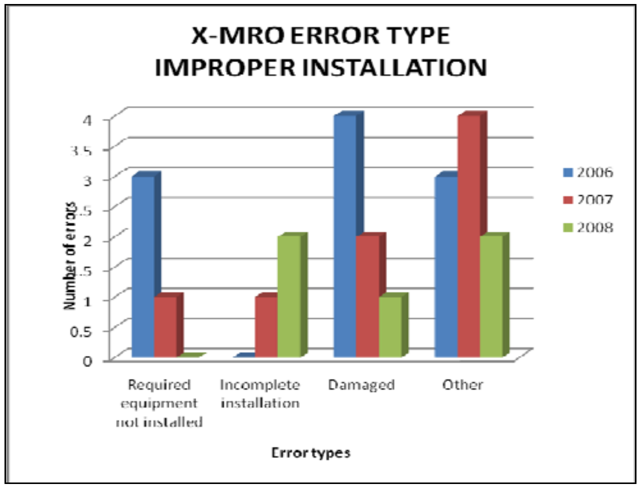


Figure 2.11 : The reasons for improper installation for X-MRO.

The reasons of improper fault isolation, testing can be classified as

- Not performed required test
- Wrong/lack of required test
- Not performed required Trouble Shooting
- Performed wrong Trouble Shooting
- Not performed required check
- Performed wrong check
- Other

Figure 2.12 shows X-MRO improper fault isolation, testing error classification for the years 2006, 2007 and 2008. The reasons for improper fault isolation, testing are shown in Figure 2.11. ‘Performed wrong check’ and ‘not performed required check’ have higher occurrences than the other occurrences.

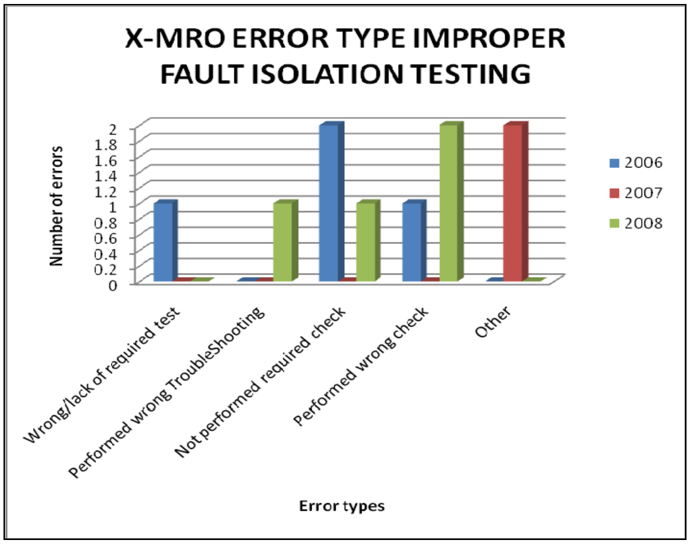


Figure 2.12 : The reasons for improper fault isolation, testing for X-MRO.

X-MRO errors and root causes between 2006 and 2008 are given in Figure 2.13.

X-MRO's contributing factors per aircraft is given in Figure 2.14. As it is seen, number of contributing factors, which causes errors, is increasing by years.

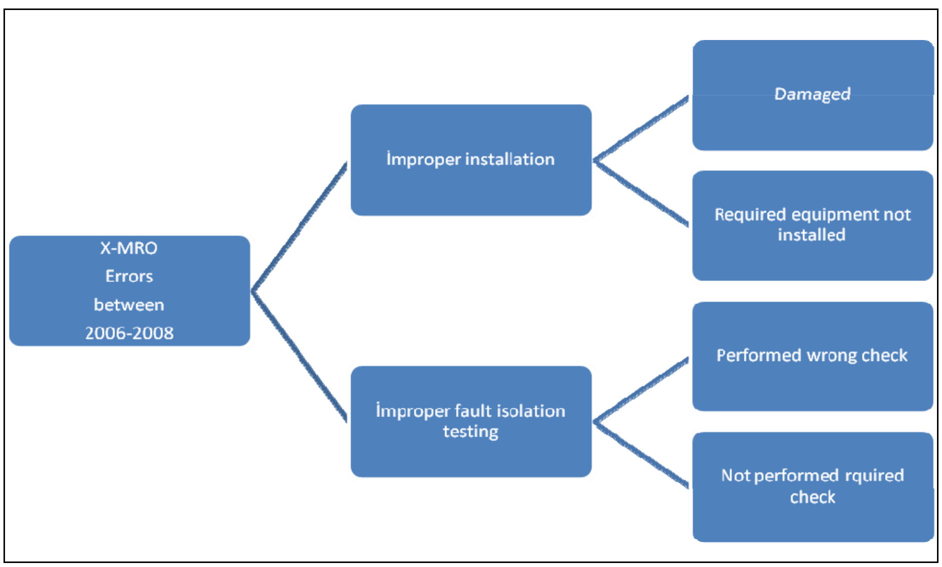


Figure 2.13 : X-MRO error details.

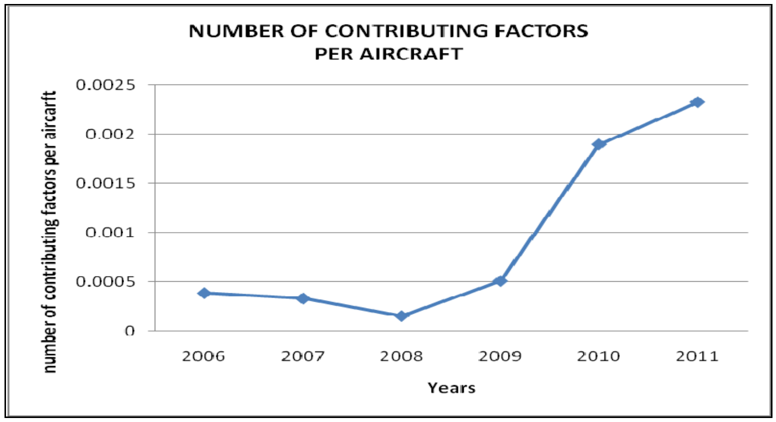


Figure 2.14 : X-MRO number of contributing factors per aircraft.

Sogg and William (2006) stated that contributing factors could be classified as:

- Information (work cards, procedures, manuals, service bulletins, EO, etc.)

  Equipment/Tools/Parts
- Airplane design/configuration
- Job/Task
- Technical Knowledge/Skills
- Factors Affecting Individual Performance
- Job Environment Leadership/Supervision
- Poor Communication
- Other

Figure 2.15 shows that between years 2006 and 2011, as a contributing factor, ‘information’ / ‘equipment, tool, parts’/ ‘Job, task’ have more frequency than the other contributing factors in X-MRO. It shows that information is not used and there are problems to use right equipment, tools, parts and to understand job, task.

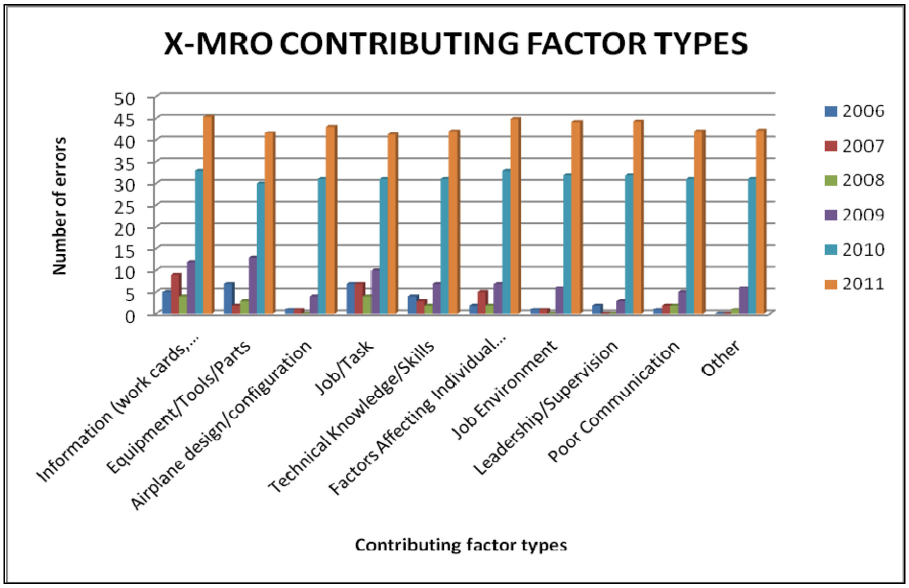


Figure 2.15 : X-MRO contributing factor classification.

According to Hall (2003), the main contributing factor for Y-MRO is the 'information' contributing factor as shown in Figure 2.16, which is similar in X-MRO shown in Figure 2.15.

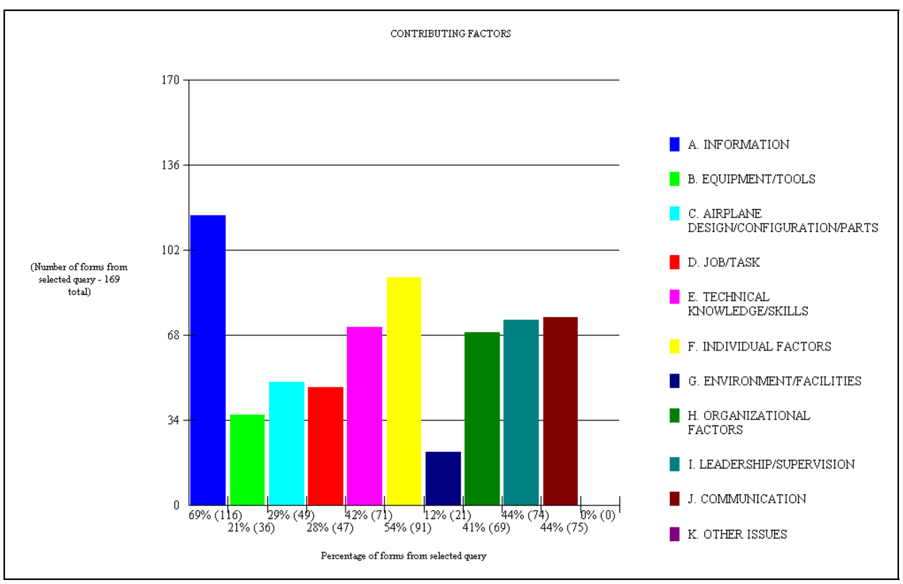


Figure 2.16 : Y-MRO Contributing factor distribution, adapted from (Hall, 2003).

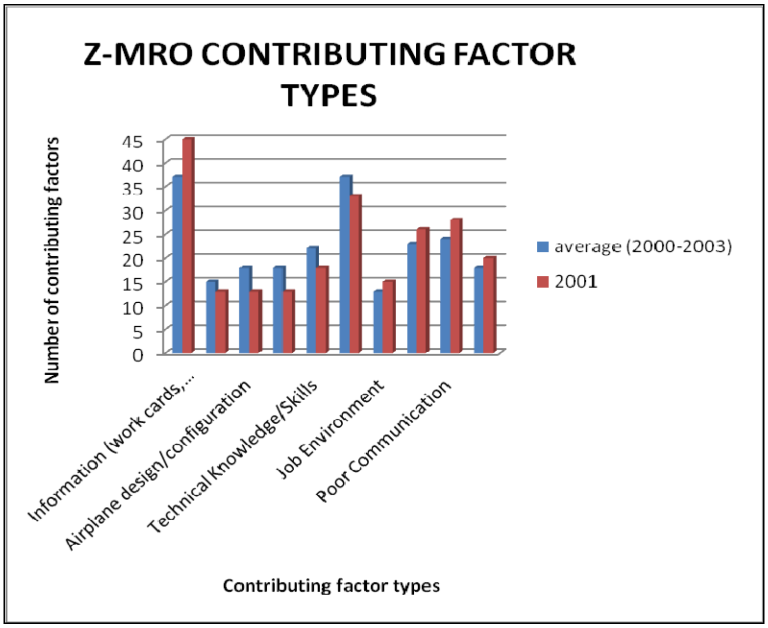


Figure 2.17 : Z-MRO Contributing factor distribution, adapted from (Hall, 2003).

Skinner (2003) showed that the main contributing factor for Z-MRO is the 'information' contributing factor as shown in Figure 2.17. It is similar with X-MRO contributing factors as shown in Figure 2.15.

When X-MRO, Y-MRO and Z-MRO are compared, they have the same type contributing factors; information. Sogg and William (2006) stated that 'information' could be classified as:

- Not understandable
- Unavailable
- Incorrect
- Too much/Conflicting information
- Update process is too long/complicated
- Information not used
- Other

Sogg and William (2006) stated that 'Equipment, tools' can be classified as;

- Unsafe
- Unavailable
- Unreliable
- Non-calibrated

- Inappropriate for the task
- Cannot be used in intended environment
- No instructions
- Too complicated
- Not used
- Other

Figure 2.18 shows that; ‘information not used’ has most frequency between information contributing factors in X-MRO.

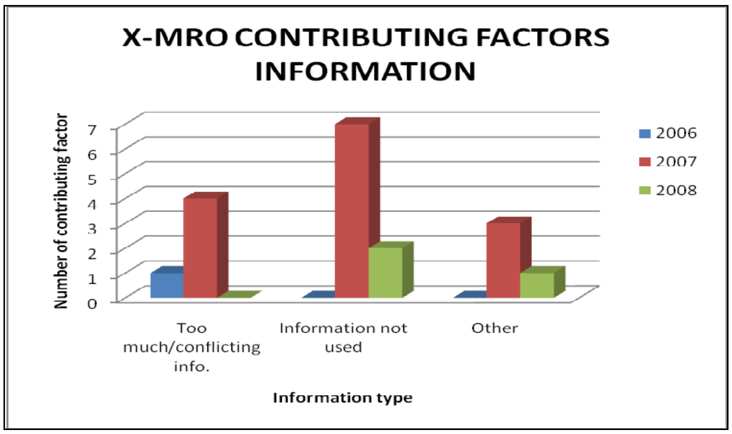


Figure 2.18 : X-MRO contributing factor ‘information’ classification.

Figure 2.19 shows that; ‘not used’ and ‘not used in intended environment’ contributing factors have more frequency than the other contributing factors in X-MRO.

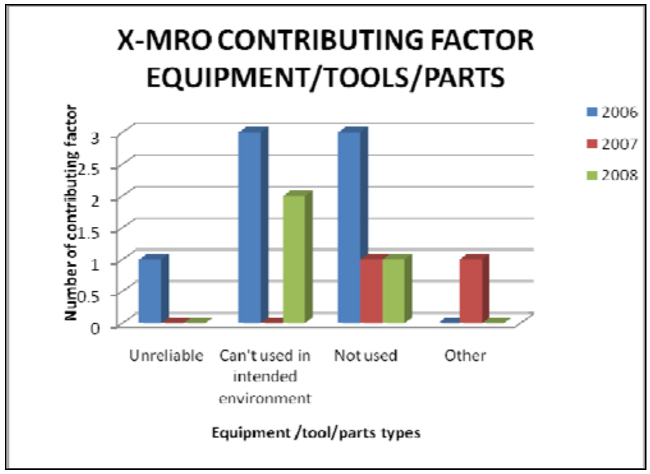


Figure 2.19 : X-MRO contributing factor 'Equipment/tools/parts' classification.

Sogg and William (2006) stated that 'Job/task' could be classified as:

- Repetitive/Monotonous
- Complex/confusing
- New task
- Boring
- Inadequate planning
- Not used in required conditions
- No instructions
- Other

Figure 2.20 shows that; 'repetitive/monotonous' has most frequency as Equipment/tools/parts contributing factors in X-MRO.

X-MRO contributing factor's root causes between 2006 and 2008 are given in Figure 2.21. X-MRO published annual analysis reports that declare errors, contributing factors and corrective action taken. Contributing factors are the main sources of risk assessment calculations.

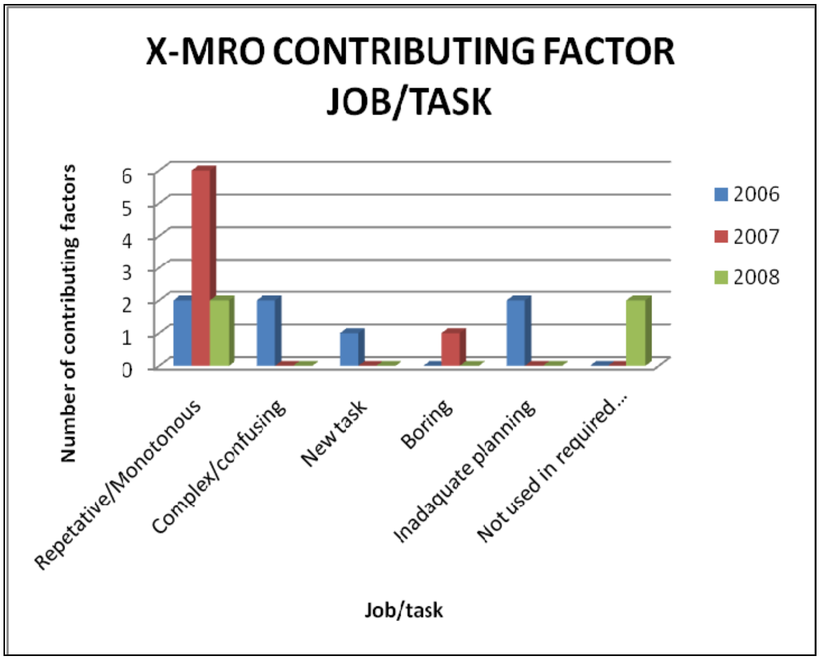


Figure 2.20 : X-MRO contributing factor 'Equipment/tools/parts' classification.

The definition of contributing factors and their cycle of occurrence is used for risk index calculations. Information, equipment/tool/parts, job/task are not used or not used in intended environment. Too much/conflicting information and repetitive/monotonous task are the contributing factors of errors between year 2006 and 2008 in X-MRO.

Sogg and William (2006) stated that corrective actions could be classified as:

- Maintenance procedures
- Checks
- Maintenance manual
- Job card
- Engineering publications
- Engineering order
- All operator letter
- Training tools
- Internal publications
- Company or maintenance policy
- Other

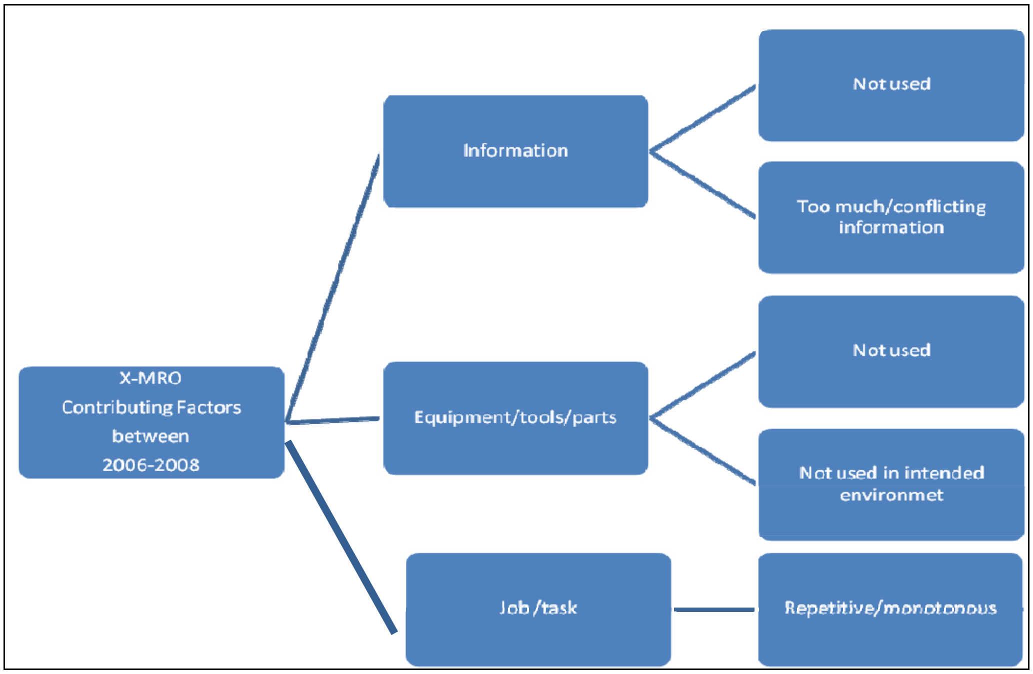


Figure 2.21 : X-MRO contributing factor details.

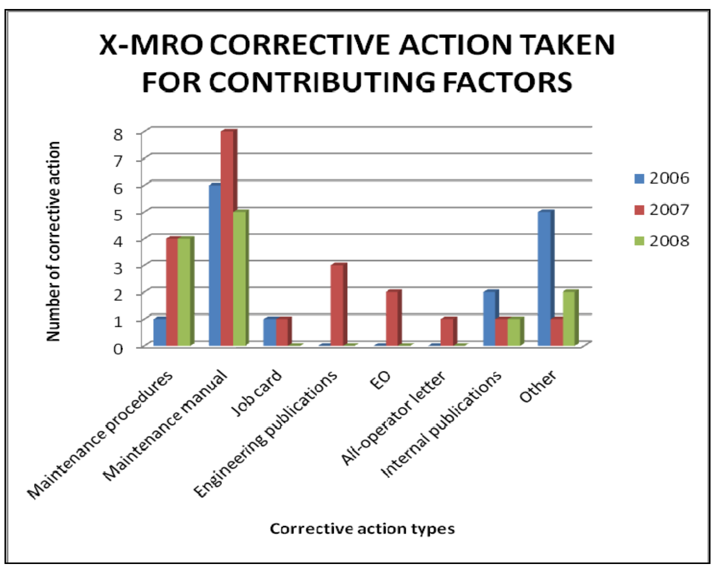


Figure 2.22 : X-MRO corrective actions.

In order to prevent errors and their contributing factors, X-MRO takes several corrective actions. The distributions of those actions are given in Figure 2.22 which states that ‘Maintenance Manuel’ and ‘Maintenance procedure’ revision are the mostly accomplished corrective actions.

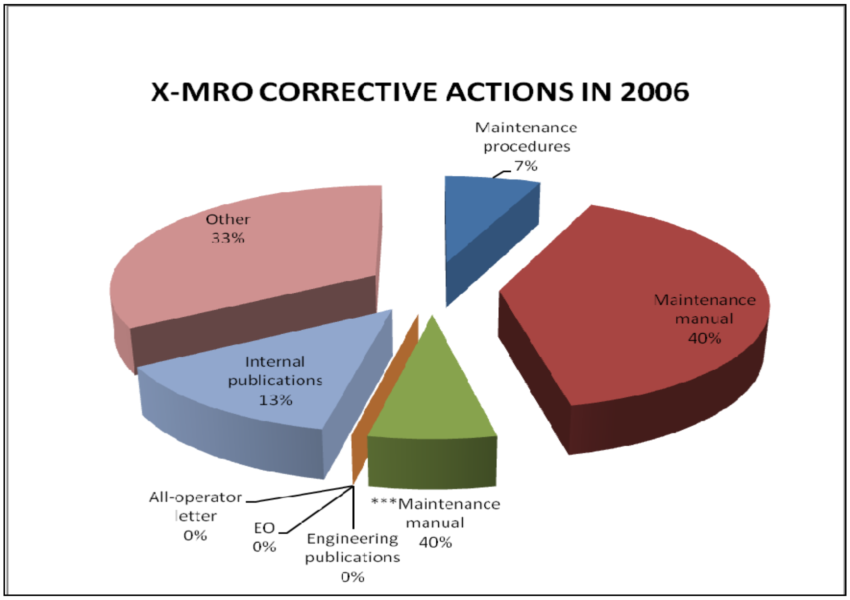


Figure 2.23 : X-MRO corrective actions in 2006.

X-MRO Corrective actions by years are shown in Figure 2.23 for 2006, in Figure 2.24 for 2007, in Figure 2.25 for 2008. Equipment, tools, parts and job/task are reviewed to take corrective action. Figure 2.23 shows that maintenance manuals have been revised to take corrective action taken.

At the beginning of 2006, X-MRO started to learn Lean philosophy. The teams came together to define and find solutions of bottlenecks. The improvement activities were hold on:

- Coffee maker overhaul
- Video cassette player overhaul
- Brake unit packaging and overhaul
- High pressure turbine nozzle assy overhaul
- Combuster case assy overhaul
- High Pressure Compressor forward case assembly overhaul
- High pressure turbine shroud/ Low pressure turbine nozzle assembly overhaul
- High pressure compressor rotor assembly overhaul
- Forward lavatory leak check
- Secondary stablizer trim brake test
- Aircraft cleaning
- Flap removal, cleaning, non-destructive testing, repair and installation

- Installation of High pressure turbine blades and blade retainer
- Galley, lavatory, seat removal
- Auxiliary power unit vortex door hinge lubrication

By the improvements of overhaul processes which has bottlenecks in 2006, in 2007 most frequently seen contributing factor was Information (work cards, procedures, manuals, service bulletins, EO, etc.).

The root cause for the information factor was information not used. In order to take preventive action, maintenance manuals are controlled and revised as shown in Figure 2.24.

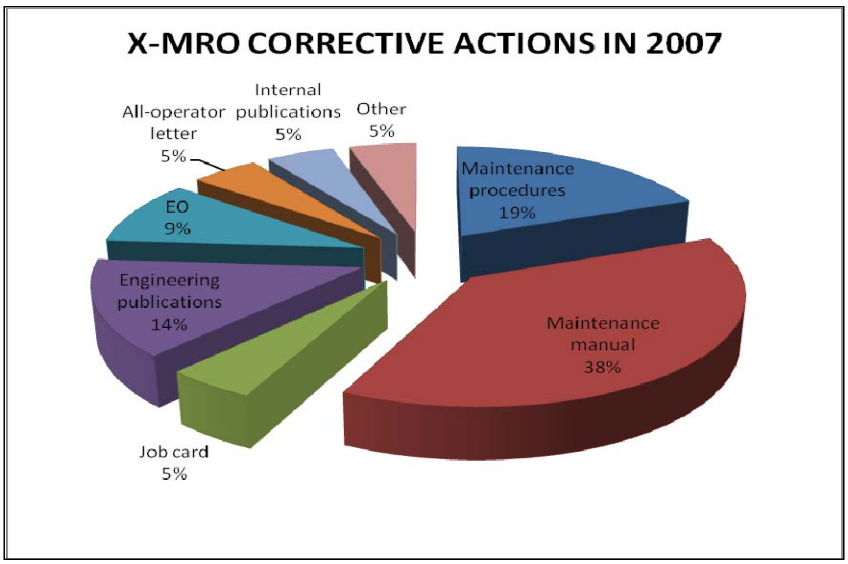


Figure 2.24 : X-MRO corrective actions in 2007.

In 2007, The improvement activities were hold on in X-MRO ;

- Oxygen bottles overhaul
- Rudder power control unit overhaul
- Main fuel pump overhaul
- Aircraft Painting
- High pressure compressor rear case machining
- B737-800 A check
- Fan blade removal
- Inner panel removal
- B737-800 Integrated drive generator disassembly

By the improvements of check, removal, disassembly processes which had bottlenecks in 2007, most frequently seen contributing factor were information (work cards, procedures, manuals, service bulletins, EO, etc.) and job/task in 2008. The root cause for the information factor was information not used. The root causes for job, task were Repetitive/Monotonous. Maintenance manuals are controlled for preventive action as shown in Figure 2.25 in X-MRO.

In 2008, The improvement activities were hold on in X-MRO ;

- Engine and landing gear harness overhaul
- Side wall panel coating
- Nickel-aluminum coating convex side of blade
- Ultrosonic part cleaning tool design
- X-RAY tube holder tool design
- B737-800 C-check kitting
- Health check, relief valve test kitting
- B737-400 avionic C –Check kitting
- Airworthiness directives tracing system

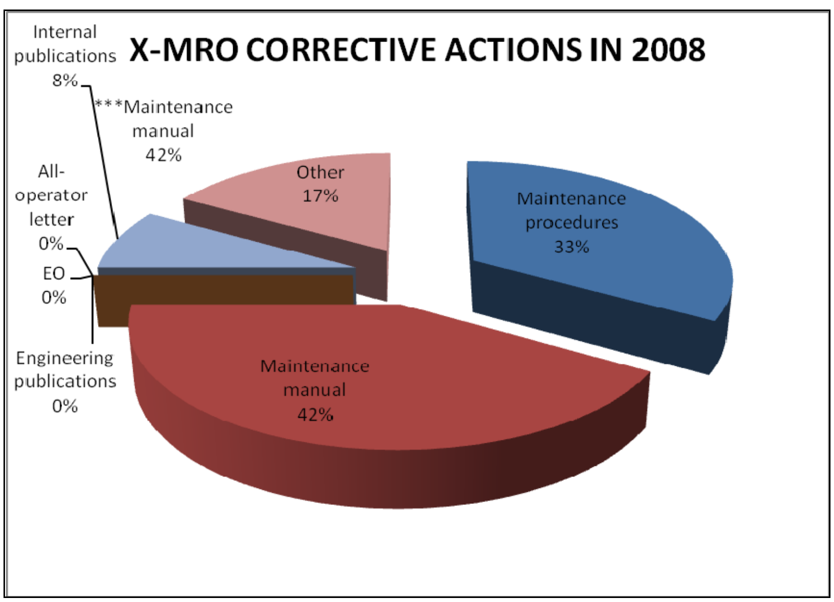


Figure 2.25 : X-MRO corrective actions in 2008.

2.8 Risk assessment of X-MRO, Y-MRO, Z-MRO

In order to do risk assessment of the contributing factors for X-MRO, it has been accepted that these factors caused minor severities. The risk index calculated based on the information given in sub chapter 2.6 Risk management.

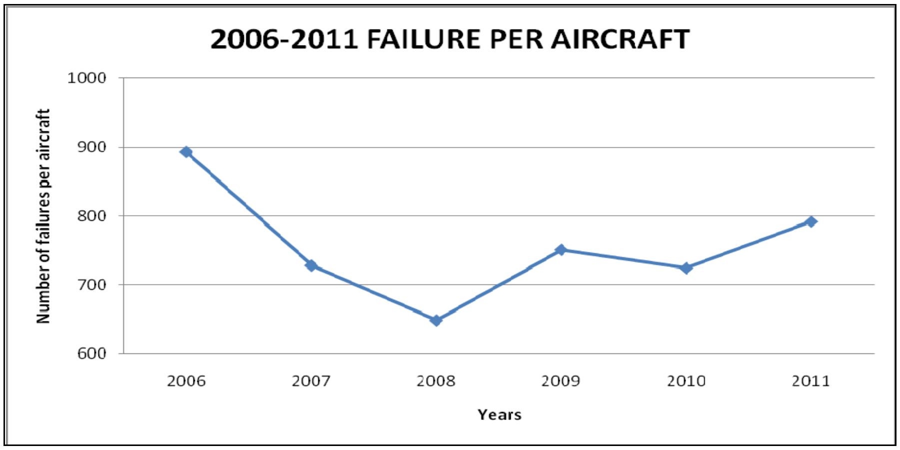


Figure 2.26 : X-MRO number of maintenance failures per aircrafts during operation.

X-MRO used lean continuous improvement techniques between years 2006 and 2011. X-MRO has error, contributing factor data between 2006-2011. Number of maintaned aircrafts is increasing by years in X-MRO as shown in Figure 2.6. Because of new aircrafts are included to the fleet, failures per aircraft decreases by years as shown in Figure 2.26.

The reason for decreasing of failures is the fleet age. New manufactured aircrafts are joined to X-MRO fleet between the year 2006 and year 2011. MROs should do risk assessments to prevent errors. ICAO risk assessment study helps to determine risk levels of MROs. On the Table 2.6 risk assessment is accomplished for each contributing factors in X-MRO by using Table 2.1, Table 2.2, Table 2.3, Table 2.4, Table 2.5. Depending on the contributing factors severity and probability levels, the risk codes are calculated and used on the Table 2.6. All the severity and probability levels are taken from the Table 2.6 and added together. The risk index is calculated as 35. It shows that there is a high maintenance risk in X-MRO refers to Table 2.5.

Refer to Table 2.6, High Risk available in information and job task contributing factors. X-MRO should stop the activities related with these factors and should not proceed until sufficient control measures applied to reduce risk to an acceptable level. For the other yellow colored contributing factors in Table 2.6, X-MRO should review the operation.

Table 2.6 : Risk Index calculation table for X-MRO.

CONTRIBUTING FACTORS	SEVERITY AND PROBABILITY LEVELS
Information (work cards, procedures, manuals, service bulletins, EO, etc.)	**FREQUENT 5B- Risk control/mitigation requires management decision- Unacceptable—but operation cancontinue while the risk is mitigated to an acceptable level.**
Equipment/Tools/Parts	**OCCASIONAL-4B- Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Airplane design/configuration	**REMOTE 3B- Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Job/Task	**FREQUENT-5B Risk control/mitigation requires management decision- Unacceptable—but operation cancontinue while the risk is mitigated to an acceptable level.**
Technical Knowledge/Skills	**OCCASIONAL-4B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Factors Affecting Individual Performance	**OCCACIONAL-4B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Job Environment	**REMOTE-3B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Leadership/Supervision	**REMOTE-3B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Poor Communication	**OCCASIONAL-4B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**

On the Table 2.7 risk assessment is accomplished for each contributing factors in Y-MRO by using Table 2.1, Table 2.2, Table 2.3, Table 2.4, and Table 2.5. Depending on the contributing factors severity and probability levels, the risk codes are calculated and used on the Table 2.7.

Table 2.7 : Risk Index calculation table for Y-MRO.

CONTRIBUTING FACTORS	**SEVERITY AND PROBABILITY LEVELS**
Information (work cards, procedures, manuals, service bulletins, EO, etc.)	**FREQUENT -5B- Risk control/mitigation requires management decision-Unacceptable—but operation cancontinue while the risk is mitigated to an acceptable level.**
Equipment/Tools/Parts	**REMOTE 3B-- Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Airplane design/configuration	**REMOTE-3B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Job/Task	**REMOTE-3B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Technical Knowledge/Skills	
Factors Affecting Individual Performance	**FREQUENT-5B Risk control/mitigation requires management decision-Unacceptable—but operation cancontinue while the risk is mitigated to an acceptable level.**
Job Environment	
Leadership/Supervision	**OCCASIONAL-4B- Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Poor Communication	

When all the severity and probability levels are taken from the Table 2.7 and added, risk index is calculated as 23. It shows that there is a moderate maintenance risk in Y-MRO. Refer to Table 2.7; continue after taking action to manage overall level of risk. Refer to Table 2.7, High Risk available in information and factor effecting individual performance, contributing factors. Y-MRO should stop the activities related with these factors and should not proceed until sufficient control measures applied to reduce risk to an acceptable level. For the other yellow colored contributing factors in Table 2.7, Y-MRO should review the operation before continue to operation.

On the Table 2.8 risk assessment is accomplished for each contributing factors in Z-MRO by using Table 2.1, Table 2.2, Table 2.3, Table 2.4, and Table 2.5. Depending on the contributing factors severity and probability levels, the risk codes are calculated and used on the Table 2.8.

Table 2.8 : Risk Index calculation table for Z-MRO.

CONTRIBUTING FACTORS	SEVERITY AND PROBABILITY LEVELS
Information (work cards, procedures, manuals, service bulletins, EO, etc.)	**FREQUENT-5B- Risk control/mitigation requires management decision- Unacceptable—but operation cancontinue while the risk is mitigated to an acceptable level.**
Equipment/Tools/Parts	**REMOTE-3B- Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Airplane design/configuration	**REMOTE-3B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Job/Task	**OCCASIONAL-4B- Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Technical Knowledge/Skills	**OCCASIONAL-4B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Factors Affecting Individual Performance	**FREQUENT-5B Risk control/mitigation requires management decision- Unacceptable—but operation cancontinue while the risk is mitigated to an acceptable level.**
Job Environment	**REMOTE-3B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Leadership/Supervision	**OCCASIONAL-4B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**
Poor Communication	**OCCASIONAL-4B Acceptable after review of the operation. Acceptable—but requires active monitoring to insure risk remains at acceptable levels.**

When all the severity and probability levels are taken from the Table 2.8 and added, risk index is calculated as 35. It shows that there is a moderate maintenance risk in Z-MRO. Refer to Table 2.8; continue after taking action to manage overall level of risk.

Refer to Table 2.8, High Risk available in information and factor effecting individual performance, contributing factors. Z-MRO should stop the activities related with these factors and should not proceed until sufficient control measures applied to reduce risk to an acceptable level. For the other yellow colored contributing factors in Table 2.8, Z-MRO should review the operation before continuing the operation.

2.9 MEDA Examples

In order to stop risk level, MRO' s should use MEDA to take preventive, corrective action. On this section MEDA examples are given.

Example 1: Dexter (2003) prepared MEDA investigation flowcharts, some of them are given below;

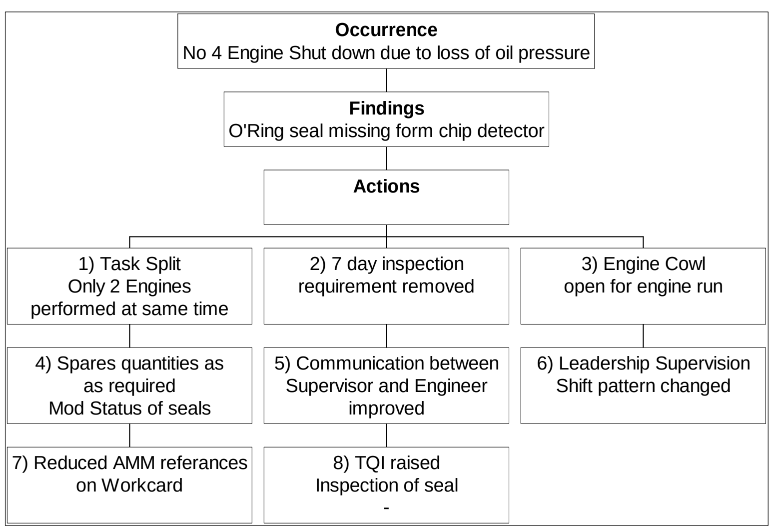


Figure 2.27 : MEDA investigation flow chart, adapted from (Dexter, 2003).

In the flow chart, event is explained. BAe 146 No 4 Engine Chip Detector seal was found missing after an in-flight shut down and diversion to London Gatwick resulted in ferry flight to Liege for Engine replacement. The cost of the seal was 10 pence.

Total cost including Engine Change, Engine Repair, Diversion was: €390,000.00.000. As a result of root cause analysis;

- Communication between Supervisor and Engineer is improved.
- Leadership, supervision shift pattern is cahanged.
- AMM references on workcard are reduced.
- Quality inspector raised inspection of the seal.
- No disciplinary action was taken

Example 2: Procedures to avoid brake intermix; the modified brakes must not be intermixed with non-modified brakes due to performance characteristics. To prevent intermix; the following precautions accomplished. An identification tag attached to the brake wear pin. Blue dots painted on the piston housings (near the quick disconnect boss) of the modified brakes. Aircraft manuals updated to identify modified aircraft.

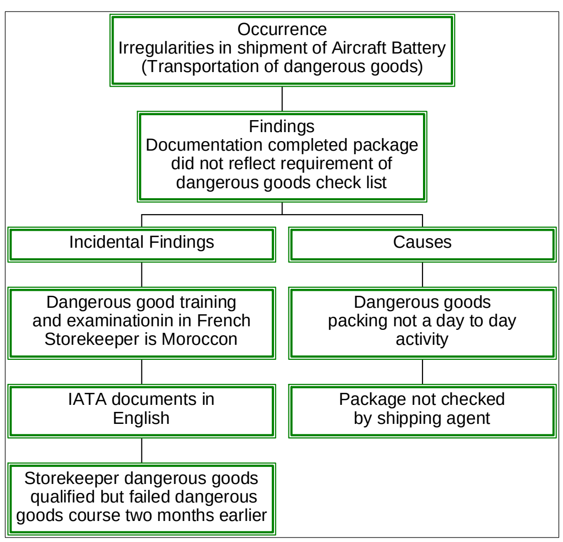


Figure 2.28 : ABC Main Landing Gear Brake intermix adapted from (Dexter, 2003)

CAUTION: If a non-modified brake unit found installed on a modified aircraft, contact to maintenance control department. The brake unit must be replaced before further flight and a one-time accomplishment of AD and SI must be scheduled. If a modified brake unit found on a non-modified aircraft, contact the maintenance control department. The brake unit must be replaced before further flight (accomplishment of SI and AD is not required). Related MRO has incorporated cautions and notes in the removal and installation procedures in the ABC Aircraft Maintenance Manuel to aid the Aircraft Maintenance Technician's performing this task. Incorrect spacer/nut installation is suspect on the aircraft that had failed bearings.

A caution in the AMM included a "Shake" inspection in the installation procedure prior to lowering the aircraft off the jack. Wheel assemblies shipped from the shop with a temporary instruction tag attached to the wheel valve stem reminding AMTs of the "caution" in the AMM to shake the wheel assembly after torque wheel nut. Because of root cause analysis, it has been declared that:

- Correct installation will have axle threads protruding beyond the nut. The wheel will not be loose during shake inspection.

- Incorrect installation will not have axle threads protruding. The wheel will wobble during the shake inspection.

2.10 MECI number

In this study, MECI is defined as a MRO safety level. MECI is the ratio for catching errors in maintenance. Higher MECI ratios show that there are more errors to catch. MRO has lower safety level. In order to explain MECI some preliminary definitions are given below;

- TMR=Total number of MEDA reports for MRO fleet
- NAFA320=Number of Aircraft for A320 fleet
- TNAFA=Total number of aircraft in MRO fleet
- NMRFSA=Number of MEDA reports for subject aircraft
- AMOTD= Aircraft Maintenance on Time Delivery rate to customer, it is directly related with TAT

MECI has a relation with TMR, NAFA320, TNAFA, NMRFSA and AMOTD. MECI can be calculated as;

$$\text{MECI u} = \text{TMR x} \frac{\text{NAFA320}}{\text{TNAFA}} - \text{NMRFSA} \quad \textbf{(2.2)}$$

$$\text{MECI} = \underbrace{\frac{\text{MECI u}}{\text{TMR}}}_{\text{Undetectable maintenance error ratio}} \text{ x AMOTD} \quad \textbf{(2.3)}$$

MECI is a number, which shows the ability to catch human errors in the aircraft maintenance.

2.11 Conclusion

X-MRO is evaluated for the period of 2006-2011. Number of errors increased by the years as a result of continous improvement activities slowed down. As a result of lack of improvements operational risk reached more than maximum level.

It can be concluded that if continuous improvements increases, severity and probability of errors decreases and as a result, operational risk factor decreases.

3. PRODUCTIVITY

3.1 Purpose

Productivity is the amount of output per unit of input (labor, equipment, and capital) (Ramsay, 1995). There are many different ways of measuring productivity. For example, in a factory productivity is measured based on the number of hours it takes to produce a good. In the service sector, productivity is based on the revenue generated by an employee divided by his/her salary. In a MRO, it is based on the total man-hours, materials or time spend divided by the number of c-checks.

For today's competitive age, productivity metrics are the most important targets for the MRO's. In order to be productive, it is necessary to set measurement metrics not only for labor hours but also other metrics that can affect productivity such as; energy, error management. In this chapter, productivity is defined. X-MRO partial and total factor productivities are calculated.

3.2 Measurement of Productive efficiency

Poorly prepared operational processes affect safety performance. The loss of control of processes, inability to effectively identify analyse and resolve operational performance problems by Managers and work goals of organization cause undesirable situations that will effect safety and productivity (Eiff and Suckow, 2008).

Fried, et al. (2008) stated that airline performance has varied, because of revenues and costs as indicated in Figure 3.1, 3.2, 3.3.

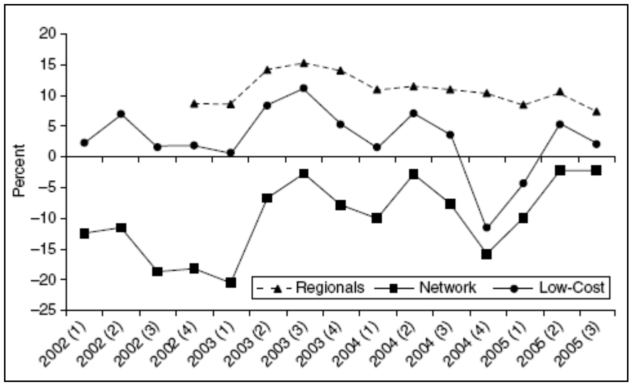


Figure 3.1 : Domestic operation profit margin, adapted from (Fried, et al, 2008)

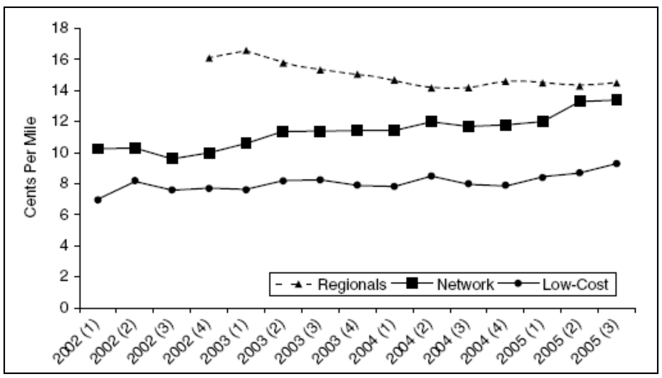


Figure 3.2 : Airline domestic unit revenue, adapted from (Fried, et al, 2008)

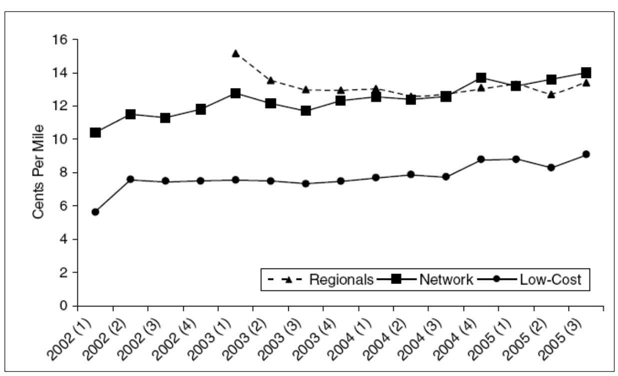


Figure 3.3: Airline domestic unit cost, adapted from (Fried, et al, 2008)

The variation in productive efficiency, in both the management of resources and the management of services, will be a significant source of variation in financial performance.

Cost inefficiency can be “technical,” arising from excessive resource usage. The low-cost airlines may have relatively low unit costs because they utilized part time labor and because they use leased, rather than purchased aircraft.

Low-cost airlines have relatively low unit costs. Because well management of their resources such as human, machine, equipment and physical areas. This results in minimum average in cost.

Coelli, et al. (2005) defined productivity; input used to produce output ;

To illustrate the difference between productivity and efficiency, consider a simple production process. In the process a single input {x) is used to produce a single output (y). The line OF' in Figure 3.4 represents a production frontier. It is used to define the relationship between the input and the output. The production output (y), the line OF' in Figure 3.4 represents a production frontier. It defines the relationship between the input and the output. The production frontier represents the maximum output reachable from each input level.

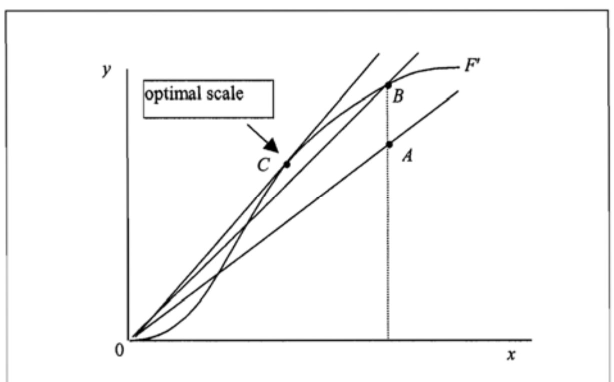


Figure 3.4 : Production frontiers and technical efficiency, adapted from (Coelli, et al 2005)

If we consider productivity, comparisons through time, an additional source of productivity change, called technical change. This involves advances in technology that may be represented by an upward shift in the production frontier. This is described in Figure 3.5 by the movement of the production frontier.

When period one and zero are compared; in period one, all firms can technically produce more output for each level of input, relative to what was possible in period zero.

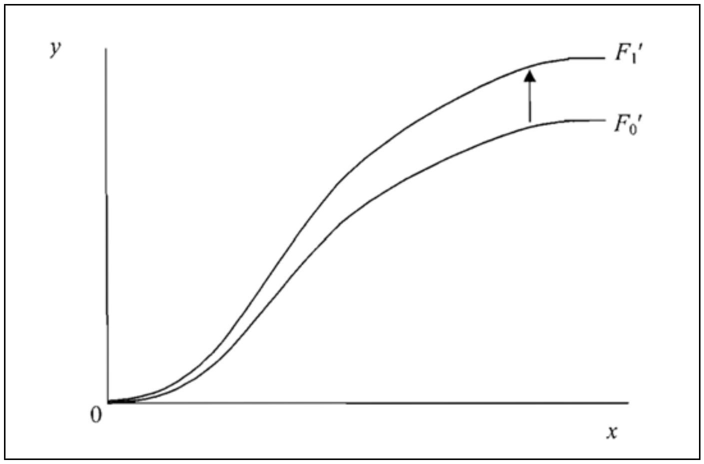


Figure 3.5 : Technical Change between two periods, adapted from (Coellii et al. 2005)

If information on prices is available, and a behavioral assumption, such as cost minimization or profit maximization, is appropriate, then performance measures can be planned which combine this information. In such cases, it is possible to consider reserve efficiency, in addition to technical efficiency. Reserve efficiency in

Input selection involves selecting the mix of inputs (e.g., labor and capital) that

produces a given quantity of output at minimum cost (given the input prices which

beat). Reserve and technical efficiencies combine to provide an overall economic efficiency measure. This is an example of embodied technical change, where the technical change embodied in the capital input.

Consider a firm that uses amounts of N inputs (e.g., labor, machine, raw materials) to produce a single output. The technological possibilities of such a firm can be summarized using the production function q=f(x) where q represents output and x =N*1 vectors of inputs to produce output.

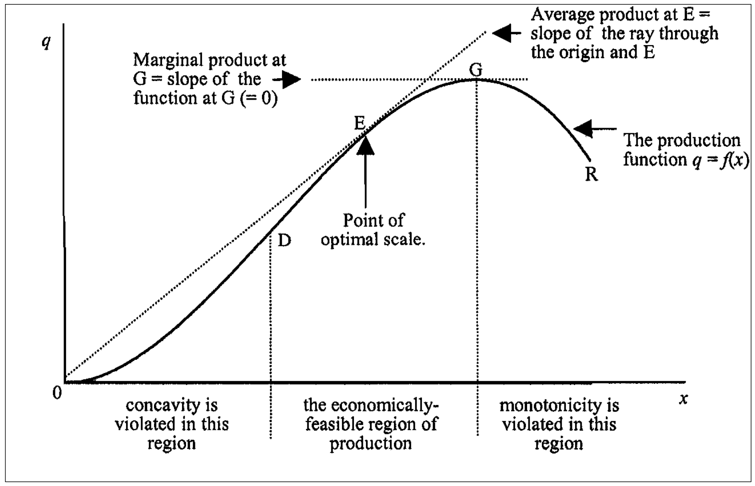


Figure 3.6 : Point of optimal scale, adapted from (Coelli,et al.2005).

It is consistent with all properties along the curved segment between points D and G. It referred as the economically feasible region of production. Within this region, the point E is the point at which the average product maximized. This point referred as the point of optimal scale (of operations). There is an optimum point for productive efficiency. A company can have lower efficiency than the other firms can in an industry; it could be due to one or more of:

• Technical (managerial) inefficiency,

• Quality differences in inputs and outputs,

• Measurement error,

• Unused capacity

•Environment: physical and/or regulatory.

3.3 Return on investment (ROI) of Safety Management

Blanco (2000) highlighted that without sustained benefit, the organization has no future in a competitive market. Benefit cannot sustain without efficiency; efficiency cannot sustain without safety. Therefore, safety is a core issue.

There is link between inefficiency and safety. Aircraft maintenance human factor risk increases with decreasing efficiency in the organization. As an example the injuries history of a MRO is shown in Table 3.1.

Table 3.1 : The injuries history of a MRO, adapted from (Blanco, 2000).

FOURTEEN YEAR INJURY HISTORY OF 808 WORKERS

injuries per worker in 14 year history	total injuries over the 14 years	# of workers in sub-group	predicted for case of equal chance
6	6	1	0
5	60	12	1
4	68	17	6
3	129	43	32
2	188	94	118
1	205	205	291
0	0	436	359
average per worker	total injuries	total workers	
0.812	656	808	

When the injury history is evaluated, it is seen that;

- Molten metal and process burns because of spills, mismatched capacities and inadequate repairs.
- Back injury rolling cable spools over uneven terrain
- Back injury while heaving to tighten large nut in very close and hazardous confined areas using a three-person team equipped with jerry-rigged 6 foot wrench
- Assorted injuries while rushing to repair key equipment that routinely failed prematurely
- Slips and falls at exits and entrances to process buildings, especially during freezing season

These are the unplanned events caused by mismanagement. Incident prevention programs provide affective countermeasures to failure because:

- Some human, organizational and managerial failure factors can be identified and corrected before a failure happens,

- The process of preventing failures strengthens the organization's resilience and improves its ability to anticipate and correct failure factors and prevent failures.

- Failures are inefficiencies, and inefficiencies are waste; fewer failures lead to greater efficiencies.

One "operating theorem" of the organization;

$$\text{Total productive capability} = \text{useful capability} + \text{waste} \qquad \textbf{(3.1)}$$

Where waste is all productive capability or activity that damages the business environment, customer does not pay for it.

Gray (2009) demonstrated that the commercial airlines are demanding efficiency from commercial MRO's. Commercial airlines claim they improve their efficiency by retiring the older, inefficient aircrafts, engines, and components. This increases pressure on commercial MRO facilities to decrease the out-of-service (aircraft on ground) time of aircraft, components, and engines, while maintaining quality, reliability, and reduced labor costs. Improvements in efficiency increase profitability; gains in efficiency are the result of automated maintenance solutions.

Regarding to Gray (2009) study, the AIAA claims that future demands will require transformation of commercial aircraft. According to the AIAA, the aircraft transformation will include safety, security, and affordability. It will be environmentally friendly.

Floor management (also known as asset management) will be a primary area for improvement. Asset management represents a MRO plant's single largest capital investment; any improvements made in floor management strategies influences the rate of return. Many IT solution systems are available to increase productivity and reduce operating cost.

3.4 Organizational Productivity

Kaya (2008) stated that productivity means organizational performance. Organizational processes should consist of value added processes. The productivity can be described in two ways:

Narrow description; Productivity is the effectiveness of outputs over efficiency of inputs.
Wide description ; Productivity is the organizational performance.

Effectiveness is the rate of reaching organizational targets.

$$\text{Effectiveness} = \text{Actual output} / \text{Planned output} \qquad \textbf{(3.2)}$$

Example;
Actual production = 100 aircraft maintenance/year
Planned production=180 aircraft maintenance /year
Effectiveness=%55

Efficiency is the rate of using resources

$$\text{Efficiency} = \text{Expected input} / \text{Actual input} \qquad \textbf{(3.3)}$$

Example;
Standart Manhours=5 hours
Actual Manhours=8 hours
Efficiency=%62

Önder (2008) indicates that: in a productive organization, effectiveness and efficiency must be good as shown by Scherman in Table 3.2.

Table 3.2 : The Schermerhorn filter, adapted from (Önder, 2008).

Effectiveness (reaching to targets)

	bad	**good**
High	Effective but not efficient	**Effective and efficient**
low	Not effective & not efficient	Efficient but not effective

Efficiency (usage of resources)

Ramsay (1995) mentioned that organizational efficiency is evaluated as given as below;

$$\text{TFP} = \text{system output} / \text{total system input} \qquad \textbf{(3.4)}$$

Inputs are material, manhours, energy, equipment.

According to Önder (2008) to be, more profitable, total factor productivity shall pass a critical point. See Figure 3.7.

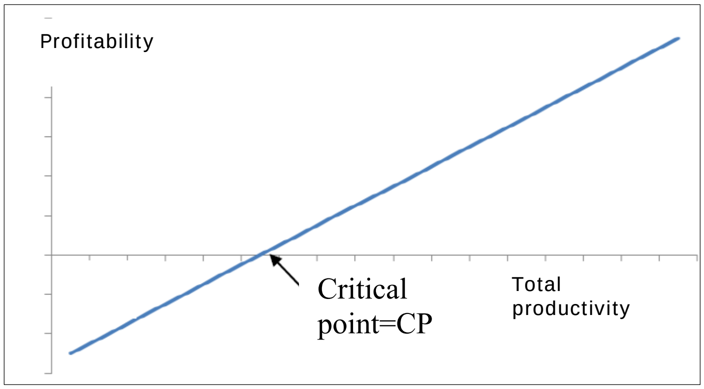


Figure 3.7 : Total productivity, profitability relation, adapted from (Önder, 2008).

Profitability=Net income/ Available resources **(3.5)**

Kaya (2008) stated that in order to increase total productivity, continuous improvements of organizational processes needed. If there is a problem, or bottleneck on the processes, efficiency decreases.

X-MRO's TFP is evaluated to calculate profitability. X-MRO used lean continuous improvement techniques between 2006 and 2011 to decrease human errors, increase productivity and profitability. In order to evaluate profitability the values given on the figures are evaluated. Ramsay (1995) show that different types of efficiencies are evaluated as given below;

Energy partial factor efficiency per aircraft=
(Endorsement /Money spend for energy) /per aircraft **(3.6)**

Manhours partial factor efficiency per aircraft =
(Endorsement /Money spend for manhours) /per aircraft **(3.7)**

OEE partial factor efficiency per aircraft =
(Endorsement /Money spend for OEE) / per aircraft **(3.8)**

Total factor productivity per aircraft=
(Endorsement /Money spend for energy,manhours,OEE) / per aircraft **(3.9)**

X-MRO focused on the efficiency and effectiveness in Aircraft Maintenance and A/C Component overhaul shops. Önder (2008) indicates that in a highly productive organization, effectiveness and efficiency must be good as shown by Schermerhorn (Önder, 2008) in Table 3.2. In X-MRO, productivity is reviewed by three parameters:

- Efficiency
- Effectivity
- Total factor productivity

Between 2006 and 2011, the improvement events result in decreasing cycle time of the processes in X-MRO. Lean management is used to improve all basic processes such as; proposal, planning, aircraft maintenance, component overhaul, landing gear overhaul, engine overhaul, engineering support, delivery to customer, customer relation. Figure 3.8 shows X-MRO cycle time improvements by years.

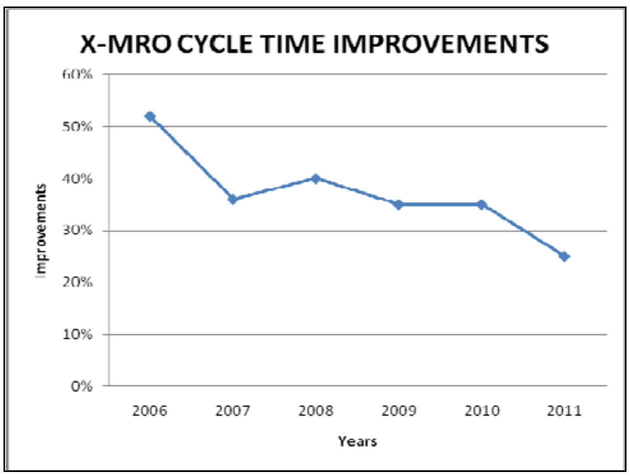


Figure 3.8 : X-MRO Cycle time improvements by years.

In order to define organizational productivity, the efficiency parameters mentioned before are tracked. Partial factor efficiency is calculated. For energy, partial factor efficiency per aircraft is calculated by adding all consumed natural gas, electricity, water costs in X-MRO based on Formulae 3.7. Figure 3.9 shows that energy partial factor efficiency decreases between 2007 and 2009.

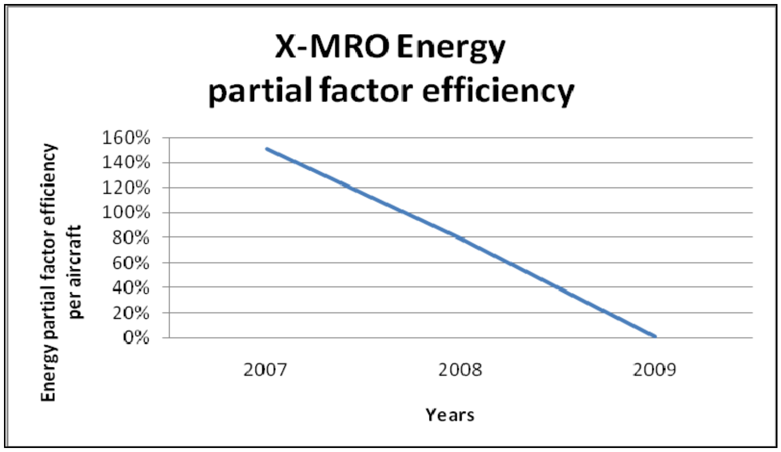


Figure 3.9 : X-MRO energy partial factor efficiency.

Man-hour partial factor efficiency per aircraft is calculated by adding all man-hour spend in X-MRO aircraft maintenance, overhaul shops, engineering support, planning and other maintenance support activities based on Formulae 3.8. Figure 3.10 shows that man-hour partial factor efficiency decrease between 2007 and 2009.

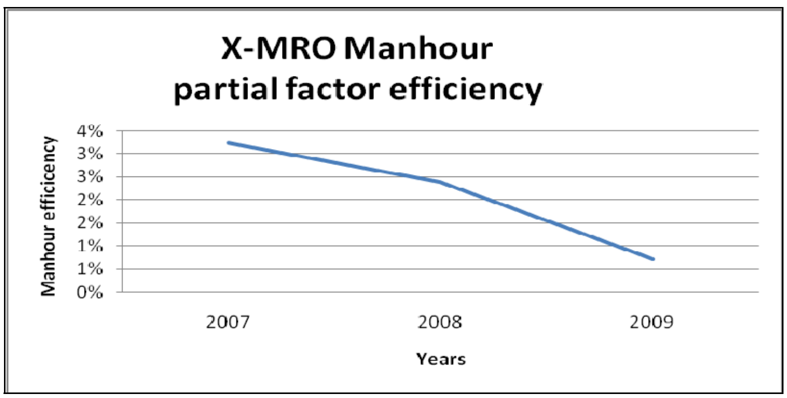


Figure 3.10 : X-MRO manhour partial factor efficiency.

Overhaul equipment partial factor efficiency per aircraft is calculated by adding all costs of equipments included their depreciation value in X-MRO based on Formulae 3.9. Figure 3.11 shows that overhaul equipment partial factor efficiency decreases between 2007 and 2009.

TFP is calculated based on Formulae 3.10. Man-hour, equipment and energy costs are used to calculate it. Figure 3.12 shows X-MRO TFP decreases between 2007 and 2009. Even there are improvement activities, total factor productivity decreases in X-MRO as shown in Figure 3.8, Figure 3.9, Figure 3.10 and Figure 3.11.

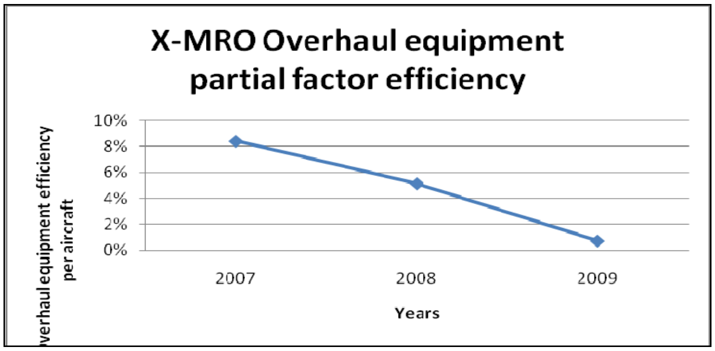


Figure 3.11 : X-MRO overhaul equipment partial factor efficiency.

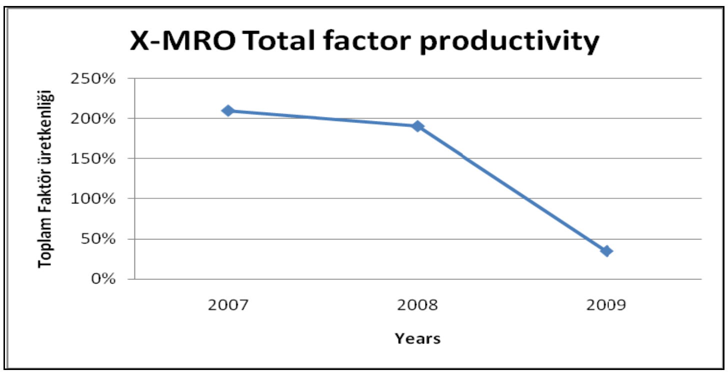


Figure 3.12 : X-MRO total factor productivity.

X-MRO calculated effectiveness and efficiency reference to Table 3.2. Effectivity which shows reaching to targets, set at the beginning of each year as shown in Figure 3.13.

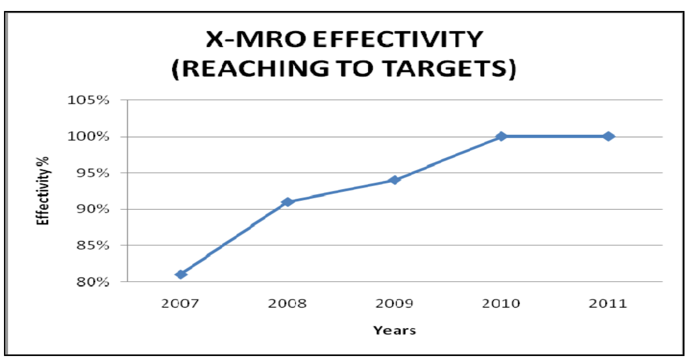


Figure 3.13 : X-MRO effectivity.

Effectivity that shows reaching to targets, is calculated by setting targets at the beginning of each year and measuring differences between actual and planned targets at the end of the year. X-MRO effectivity is shown in Figure 3.13.

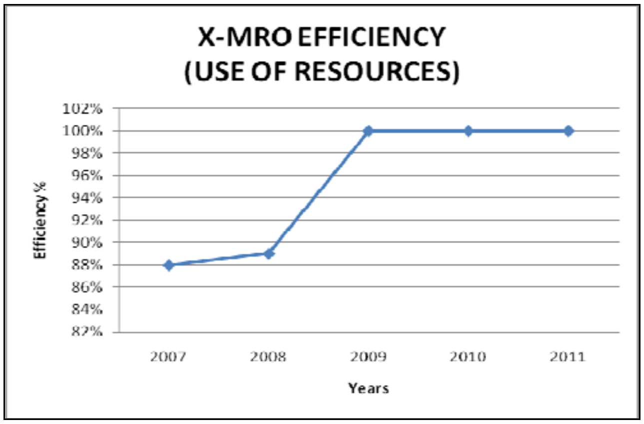


Figure 3.14: X-MRO efficiency.

Efficiency that shows efficient use of resources is calculated by the ratio of planned input, which is calculated at the beginning of the year, and actual input, which is calculated at the end of the year. Figure 3.14 shows X-MRO efficiency.

3.5 Conclusion

As it is seen on Figures beginning from 3.9 to 3.14, total factor productivity and partial factor efficiencies decrease but efficiency and effectivity increase in X-MRO. This represents that improvement activities creates capacity by reducing cycle time of X-MRO processes. Efficiency and effectivity increases by increasing capacity. The improvement activities help to organization but there is no strategic decision taken by managers to choose improvement areas and no deployment of unsupported improvements. As a result, total factor productivity decreases.

If Section 2 and 3 results are evaluated together;

- Total factor efficiency decreases with cycle time improvements decreases.
- Effectivity and efficiency increase independent from total factor efficiency.
- If number of errors increases, effectivity and efficiency become stable.
- Total factor efficiency decreases by increasing number of errors.
- There is a direct relation between total factor productivity and number of errors, which has relation with organization risk level.

4. DATA ENVELOPMENT ANALYSIS (DEA) METHOD

In this thesis, DEA method is used for the analysis of A320 aircraft C-Check maintenance data. Cooper, et al. (2000) stated that DEA provides a number of additional opportunities for use. This includes opportunities for collaboration between analysts and decision-makers, which extend from collaboration in choices of the inputs and outputs to be used and includes choosing the types of “what-if” questions to be addressed. Such collaborations extend to “benchmarking” of “what-if” behaviors of competitors and include identifying potential (new) competitors that may emerge for consideration in some of the scenarios that may be generated.

Kecek (2010) stated that input oriented models define non-efficient DMU s input reduction, in order to reach certain level of output.

Fukuyama (2001) declared that returns to scale is a local notion and projected points, the measurement of input, has significant roles and output expansions as well as directions toward which the scale returns are gauged. The term returns to scale arises in the context of a firm's production function. It refers to changes in output resulting from a proportional change in all inputs where all inputs increase by a constant factor. If output increases by same proportional change then there are constant returns to scale (CRS). If output increases by less than that proportional change, there are decreasing returns to scale (DRS). If output increases by more than that proportional change, there are increasing returns to scale (IRS). Thus the returns to scale faced by a firm are imposed and are not influenced by economic decisions or by market conditions. A firm's production function can show different types of returns to scale in different ranges of output. Generally, there can be increasing returns at relatively low output levels, decreasing returns at relatively high output levels, and constant returns at one output level between those ranges.

4.1 Decision Making Unit (DMU)

A DMU is the entity, which is responsible for converting inputs into outputs and DMUs performances are evaluated. In managerial applications, DMUs are banks, department stores and supermarkets and also carmakers, hospitals, schools, public libraries. In engineering, DMUs may take such forms as airplanes or their components such as jet engines. For securing relative comparisons, a group of DMUs is used to evaluate each other with each DMU having a certain degree of managerial freedom in decision-making (Cooper, 2000). In this thesis, DMUs are A320 aircraft C-Check maintenances. Since its introduction in the late 1970s, DEA has been a popular method for measuring the relative efficiencies of DMU's with multiple inputs and outputs. DEA enables one to assess how efficiently a firm, organization, agency, or such other unit uses the resources available inputs to generate a set of outputs relative to other units in the data set (Ozbek et al. 2009). DEA used in many disciplines such as operations research, management control systems, organization theory, strategic management, economics, accounting and finance, human resource management, and public administration.

4.2 Data Envelopment Analysis (DEA) application

Golany and Roll (1989), stated that DEA composed six major phases as discussed below:

Phase 1—Definition and Selection of Decision-Making Units

DEA is a method to measure the relative efficiency of "comparable" units with an ultimate goal of improving their performance. A homogenous set of units DMU's needs to be included in the analysis. As the size of the decision increases, decision makers will use a greater proportion of prescribed decision criteria stated by Sutcliffe, et al. (2001).

- The units should be performing the same tasks with similar objectives. It may also be an assumption that common technologies should use among the units.
- The input-output variables characterizing the process of the units in the data set should be identical except for the differences in their magnitude or values.
- The units should be performing under the same market conditions.

- The units should be operating in similar environmental conditions as these conditions greatly affect the overall performance of units. Nonetheless, this criterion can be met and to overcome this issue, formulations that can take the affects of exogenous factors into consideration can be used as discussed earlier.

DMUs to be included in the DEA models can be selected at two levels:

- DMUs can actually represent different units/ organizations or
- DMUs can represent different time periods for a single unit/organization.

In the thesis twelve A320 C2 checks represents different units.

In the latter case, the analysis is time-based. Preferably, the time periods should be naturally broken and correspond to seasonal or fiscal cycles of budgeting or measuring periods. If the time period is chosen to be too long, it may obscure significant changes taking place within it. On the other hand, if it is chosen to be too short, it may give an incomplete picture of the DMU's process and activities.

Phase 2—Definition, Selection, and Measurement of Input and Output Variables

DEA does not need any production function equation of a parametric form for the solution of the specified model. Any variable can be included in the model. It is not necessary to specify functional or parametric relationships. Even a variable that is not an economic resource or a product but just an attribute of the environment or of the production process, it can be included in the DEA model.

As DEA allows flexibility in the choice of input-output variables' weights, the greater the number of variables included in the analysis, the lower the level of its discrimination can be get.

Boussofiane, et al. (1991) suggested that the number of DMUs should be larger than The number of DMUs should be larger than m+t where m+t is the sum of the number of inputs and number of outputs. In the thesis three inputs ; manpower, TAT, material cost are choosen to give 2 outputs; sales and MECI. The sum of inputs and outputs=m+t =3 + 2= 5 and number of DMU's must be at least six. Twelve A320 C2 check are choosen as DMU.

Once the initial list is developed, this list should be reinvestigated and clarified to include only the most relevant and important variables. Such clarification performs in three ways as explained below.

Way 1; Judgmental process:

This process formed of examination of the variable list by decision makers of the convenient field. Decision makers identify some variables as repeating virtually the same information. Decision makers assume some variables not to be too important. This judgment process, as performed by the decision makers, generally results in the clarification of the list through the help of the answers given for the following questions

Question1: Is the variable related to one or more of the production objectives set for the process?

Answer1: TAT is related with production objectives.

Question2: Does the variable possess relevant information that is not included in the other variables?

Answer2: Yes, TAT is not included manpower and material cost.

Question3: Is the data for the variable readily available or measurable, and sufficiently reliable?

Answer3: Yes, the data is taken from real aircraft maintenance records.

Way 2; Quantitative methods:

There are certain quantitative methods to refine the list of variables. The first one is related to reducing the number of variables. Some variables can be aggregated into one variable. A good example of this is the cost. Variables as “number of people,” “gallons of fuel,” and “KWH of electricity” measured in terms of cost, resulting in the reduction of number of variables. The regression analysis that identify the correlation between variables and/or statistical analysis may also help eliminating redundancies and reducing the number of variables. Some variables typically the uncontrollable ones used to rescale all other variables in the analysis, again resulting in the reduction of total number of variables.

Way 3; DEA based methods:

The variables that remain in the list so far are used to run the DEA model. Variables that consistently get very small weights may be removed from the list as they have little impact on the efficiency scores. To test the discriminating power of different variables, the DEA model can be run with a series of combinations of these variables. Then some techniques can be used to group the DMUs based on the resulting efficiency scores. DMU groupings can be observed as established after each run of the model with different combinations of variables. One can identify the variables that have little discriminating power and then it can be removed from further consideration.

Phase 3—Selection of the DEA Model and Formulation

A number of fundamental DEA models and formulations were present. During the establishment of a DEA model, if it is known that the DMUs in the data set are experiencing variable returns to scale, a new formulation, which takes care of their scale inefficiencies and thus results in a new efficient frontier and efficiency scores, should be used. Such new formulation and DEA model, which was proposed by Banker, et al. (1989) is called the Banker, Charnes and Cooper; BCC mode.

With the addition of this model, the fundamental DEA models can be grouped as

- The models for DMUs with constant returns to scale CCR formulations or the models for DMUs with variable returns to scale BCC formulations and

- Input-oriented models or output-oriented models.

To select the right model, one needs to answer the following series of questions

Question: Are the DMUs within the data set experiencing constant returns to scale or variable returns to scale? (Answer of the question will help deciding on whether to use the CCR or the BCC formulation.)

If we increase TAT, Manpower and material cost Sales and MECI increases (MECI has negative relation with risk index). The answer is CCR.

Question: Are the decision makers more flexible and interested in changing increasing/maximizing the outputs of the DMUs or changing, reducing/minimizing, the inputs of the DMUs? (Answer of the question will identify whether to use an input-oriented or output-oriented model). The decision makers are more flexible and they are interested in changing reducing/minimizing, the inputs of the DMUs. The answer is input oriented because we need to minimize:

- Manpower because of lack of skilled aircraft Technicians in the market,
- TAT to deliver aircraft just in time to delight our customers,
- Material cost to reduce cost.

Phase 4—Application of DEA Models

This is the phase in which the models identified in phase 3 are run by including the variables identified in phase 2 and DMUs identified in phase 1. Given the heavy computation requirements of the DEA models, usually this phase performed with the help of appropriate software that designed to solve DEA problems.

Phase 5—Post DEA Procedures

There is no guarantee that the initial selection of DMUs and variables are correct and that this serves the best purpose of the analysis. Therefore, the issues discussed in phase 1, phase 2, and phase 3 may require the application of DEA models in phase 4 in an iterative fashion. Additionally, it may be useful to obtain more than one set of results as derived from different selection of DMUs, variables, and/or models/formulations.

DEA results are very sensitive to even small errors within the input-output variables' data. Moreover, since DEA is a nonparametric method, it may not be possible to estimate the confidence as used in statistics with which DEA results are calculated.

Thus, DEA results should be viewed with caution and should be used only after appropriate sensitivity analysis is conducted. Some of the possible sensitivity analyses that can be conducted are:

- Running the DEA model one more time after removing the efficient DMUs from the data set and
- Running the DEA model one more time after removing some variables from the list of variables that was used in the initial run of the DEA model.

Phase 6—Presentation and Analysis of Results

The results of DEA is used to direct decision makers' attention to developing a better understanding of the reasons why some DMUs are located on the efficient frontier and why others are inefficient. DEA may trigger decision makers to try to identify the differences in formal structures, operational practices managerial practices, field practices or other organizational factors of the DMUs that may account for the observed efficiency differences in these DMUs. The overall objective of DEA is to assign organizational meaning to the observed efficiency differences. And also to determine the organizational changes that the inefficient DMUs will need to undertake and how to implement such changes. The common method used to reach such objective is using the peer DMUs identified by the model benchmarking, describing, and documenting the best practice processes of such DMUs that are located on the efficient frontier.

The DEA results are used as guidelines for managerial actions. As calculated targets for inputs and outputs indicate potential performance and efficiency increases for inefficient DMUs. However, use of the DEA results is not known in practice. The major reasons may be the complex mathematical formulations and computations of DEA and poor presentation of DEA results to the decision makers. Because of this issue, DEA results should be presented in a very lean way, possibly with the use of some charts and easy-to-follow tables.

The following criteria are used for the selection of DMU's (Dyson et al. 2001; Golany and Roll 1989):

- The units should be performing the same tasks with similar objectives
- The input-output variables characterizing the process of the units in the data set should be identical except for the differences in their magnitude or values.
- The units should be performing under the same market conditions.
- The units should be operating in similar environmental conditions

The fundamental DEA models can be grouped as;

- The models for DMU's with CRS (CCR formulations) and input-oriented models or output-oriented models.

- The models for DMU's with VRS (BCC formulations) and input-oriented models or output-oriented models.

To select the right model, one needs to answer the following series of questions;

Question1; Are the DMU's within the data set needs CRS or VRS? (Answer of the question will help to decide on using the CCR or the BCC formulation).

Answer1: In this study the answer is CRS.

Question2; Are the decision makers interested in increasing/maximizing the outputs of the DMU's or reducing/minimizing, the inputs of the DMU's?

Answer2: Answer of the question will identify to use an input-oriented or output-oriented model. In this study, the answer is input-oriented model.

4.3 Charnes, Cooper, Rhodes, Input Oriented CCR Model

The formulation developed by Charnes et al. 1978, uses linear programming to extend Farrell's single output/single input efficiency measure for the multi-output/multi-input case (Ozbek et al. 2009). The focus is to optimize the ratio of outputs to inputs by solving for a group of weights that satisfy a system of linear equations. A commonly used measure of efficiency is:

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} \qquad \textbf{(4.1)}$$

Cooper, et al. (2000) stated that this formula is used as the measure of efficiency. The usual measure of "productivity" also assumes a ratio form if it is used to evaluate worker or employee performance. "Output per worker hour" or "output per worker employed" is example with sales, profit or other measures of output. Such measures referred as "partial productivity measures." This terminology distinguishes them from "total factor productivity measures," because to obtain an output-to input ratio value takes account of all outputs and all inputs. Moving from partial to total factor productivity measures by combining all inputs and all outputs to obtain a single ratio helps to avoid imputing gains to one factor (or one output) that are assignable to some other input (or output).

Formulation 1

$$(FP_0): \text{maximize } Q_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}} \qquad \textbf{(4.2)}$$

Subject to;

$$\frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1; \quad j=1,\dots\dots,n \qquad \textbf{(4.3)}$$

$$u,v \geq 0 \qquad \textbf{(4.4)}$$

Where Q_0 is the efficiency score of the DMU, which is under consideration. Its value ranges between 0–100%.

n is the number of DMUs in the data set,

s is the number of outputs,

m is the number of inputs,

y_j , x_j are known outputs and inputs of the jth DMU and they are all positive.

u,v≥ 0 are the variables of 'outputs' and inputs' weights to be determined by the solution of this optimization problem.

Formulation 2;

$$(LP_0): \text{maximize } Q_0 = \sum_{r=1}^{s} u_r y_{r0} \qquad \textbf{(4.5)}$$

Subject to;

$$\sum_{i=1}^{m} v_i x_{i0} = 1 \qquad \textbf{(4.6)}$$

$$\sum_{r=1}^{s} u_r y_{rj} \leq \sum_{i=1}^{m} v_i x_{ij}; \quad j=1,\dots\dots,n \qquad \textbf{(4.7)}$$

$$u,v \geq 0 \qquad \textbf{(4.8)}$$

where ;

Q_0 is the efficiency score of the subject DMU n is the number of DMUs in the data set,

s is the number of outputs,

m is the number of inputs,

y_j , x_j are known outputs and inputs of the jth DMU and they are all positive.

u,v≥ 0 are the variables of 'outputs' and inputs' weights to be determined by the solution of this optimization problem.

The model presented in Formulation 2, seeks the weights v_i for each input and weights u_r for each output of the DMU. Under investigation, that maximizes the efficiency score of that DMU. Subject to the constraint that such weights, when applied to the output-to-input ratios for all other DMUs in the data set, including the DMU under investigation, result in efficiency score which equals to or less than one. The efficiency score and the weights of the input and output variables for each DMU can be calculated by solving the linear program formulation presented above for each DMU in the data set. The weights calculated are DMU-specific; such weights do not need to be identified by the decision-maker and instead they are determined and optimized by the DEA model.

The efficiency mentioned above is called the input reducing efficiency within the context of DEA. It indicates the level by which the inputs used by a DMU can be reduced without changing the level of outputs produced by such DMU.

Formulation 3;

$$(LP_0)\text{: minimize } H_0 = \sum_{i=1}^{m} v_i x_{i0} \quad \textbf{(4.9)}$$

Subject to

$$\sum_{r=1}^{s} u_r y_{r0} = 1 \quad \textbf{(4.10)}$$

$$\sum_{r=1}^{s} u_r y_{rj} \le \sum_{i=1}^{m} v_i x_{ij}\text{; } j=1,\dots\dots,n \quad \textbf{(4.11)}$$

$$u,v \ge 0 \quad \textbf{(4.12)}$$

Where H_0 is the weighted sum of the inputs of the DMU that is under consideration; n is the number of DMUs in the data set,

s is the number of outputs,

m is the number of inputs,

y_j , x_j are known outputs and inputs of the jth DMU and they are all positive.

$u,v \geq 0$ are the variables of 'outputs' and inputs' weights to be determined by the solution of this optimization problem.

4.4 DEA-FRONTIER program

DEA-FRONTIER program is a software which is used for DEA programming (www.deafrontier.net). It can be run for CRS and VRS with input oriented or output oriented models.

4.5 Conclusion

For the subject DMU's of the present study, the target is to reduce / minimize the inputs of the DMU's. Input-Oriented CRS model is used to define relative efficiencies of twelve A320-200 aircraft C2 maintenance checks.

5. APPLICATION OF DEA IN AIRCRAFT MAINTENANCE

In this chapter, application of DEA in aircraft maintenance is explained. A320 aircraft C-check maintenance data is used. Maintenances are accomplished in X-MRO. Human error added as output to DEA calculations. Data with human error affect and without human error affect are used.

During maintenance in X-MRO, for the effective usage of manpower, supervisors give tasks temporarily to Technicians. It causes human errors during maintenance because changing tasks and working aircrafts, disturb concentration of Technicians. The same no concentration happens to Technicians if they walk away from the aircraft in order to get tools and materials for their tasks to finish. Bay management system prevents this kind of errors.

5.1 Practical Application of This Study

In the application, data is taken from production planning reports of a MRO, which has Maintenance capacity more than 150 aircrafts in 2010 and 2011. The MRO has capability to maintain several types of aircraft included A320&A321. The presentations had been prepared to compare planned and actual data for each maintenance check. The actual maintenance data is available for the year 2010 and 2011 for A320&A321 C2-Check aircraft maintenance.

To achieve a reasonable level of discrimination is that the number of DMU's should be at least or greater than 'm' plus 't' where 'm' is the number of inputs and't' is the number of outputs according to Boussofiane, et al. (1991). Man-hours, TAT and Material cost are taken as inputs. Sales and MECI are taken as outputs. DMU's are the aircrafts, which their C2 maintenance accomplished in 2010 and 2011.

5.2 An example for single input single output case: A320&A321 C2-check

Cooper, et al. (2000), stated that for evaluation of performance of the organizations, commonly used formula to measure of efficiency is given:

$$\text{Efficiency} = \text{output}/\text{input} \qquad \textbf{(5.1)}$$

Man-hours spent for each C2-check is taken as single input, ‘sale in unit currency’ for each C2-check is taken as output. Sales values are not taken directly for the X-MRO privacy, sales are divided by a constant number and result of the divisions is taken as ‘sale in unit currency’ for the calculations. Taking 12 Aircraft maintenance C2-checks which is labeled from 1 to 12 on the first column of the below table ‘sale (in unit currency) /man hours rate’ is calculated.

Table 5.1 : DMU s, single input and single output.

DMU	MANHOURS	SALE IN UNIT CURRENCY	SALE IN UNIT CURRENCY /MANHOURS
1	2154	126606	58.78
2	2250	123403	54.85
3	2236	127404	56.98
4	2173	121966	56.13
5	2305	125260	54.34
6	2241	124067	55.36
7	2259	118823	52.60
8	2554	122888	48.12
9	2475	120676	48.76
10	2490	115153	46.25
11	2532	125176	49.44
12	2814	126290	44.88

The man-hours per C2-check and sale (in unit) s per C2-check are as recorded in each column. The right column shows the sale (in unit) per man-hours, a measure of “productivity” often used in management and investment analysis. According to Equation 1, by this measure, DMU 1 is identified as the most efficient C2-check and DMU 12 as least efficient.

These data is represented by plotting “man hours” on the horizontal and “sale (in units currency)” on the vertical axis. The slope of the line connecting each point to the origin corresponds to the sale (in unit) per man hours and the highest such slope is attained by the line from the origin through B. This line is called the “efficient frontier.”

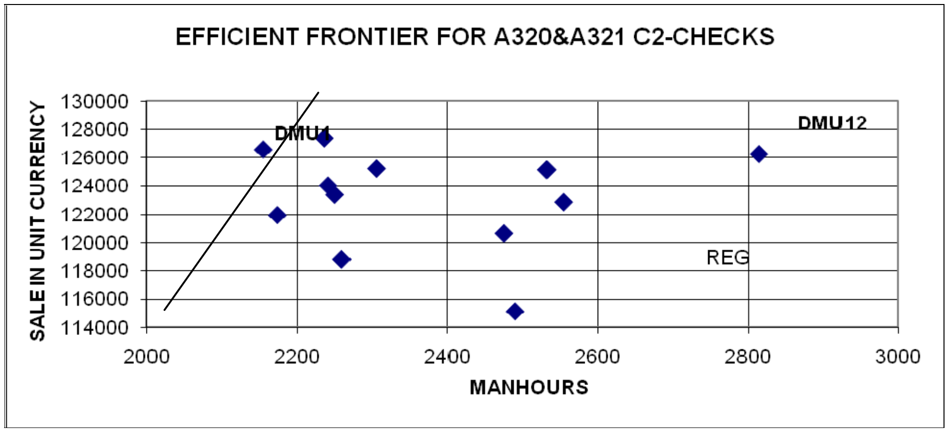


Figure 5.1: Efficient frontier.

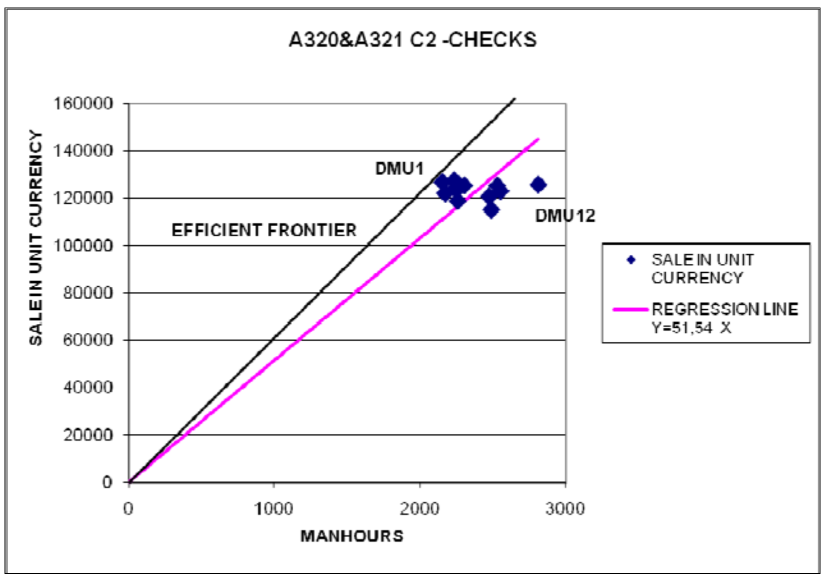


Figure 5.2: Regression line, sale in unit currency versus manhours.

Figure 5.2 shows the regression line passing through the origin which, under the least squares principle, is expressed by Y = 51,54X. This line, as normally determined in statistics, best fit line of these data points and so the points above it can be defined as excellent and the points below it as inferior or unsatisfactory. The frontier line designates the performance of the best C2-check (DMU1) and measures the efficiency of other C2-checks by deviations from it.

According to Cooper, et al. (2000), a difference exists between statistical approaches via regression analysis and DEA. The statistical approach reflects “average” or “central tendency” behavior of the observations while the DEA deals with best performance and evaluates all performances by deviations from the frontier line. These points of view result in different approaches to improvement. DEA identifies a point like DMU1 for future examination or it serves as a "benchmark" to be used in looking for improvements.

The frontier line stretches to infinity with the same slope. It is not reasonable. This line is affective in the range of interest and calls it the constant returns-to-scale. Compared with the best C2-CHECK, DMU1, the others are inefficient. The efficiency of other DMUs relative to DMU1 can be measured.

0<=salesper manhours of DMU's/sales per manhours of DMU1<=1 (5.2)

and arrange them in the following order by reference to the results shown in Table (5.3).

1 = DMU1 > DMU3 > DMU4 >DMU6…......DMU10 > DMU12 = 0.76 (5.3)

The worst DMU12 attains %76 of DMU1 s efficiency.

Table 5.2 : DMU s, single input and single output.

DMU	EQUATION 2
1	1,0001
3	0,9695
4	0,9550
6	0,9420
2	0,9332
5	0,9247
7	0,8950
11	0,8412
9	0,8296
8	0,8187
10	0,7869
12	0,7636

DMU12 can be improved by decreasing manhours or increasing sale in unit currency.

5.3 An example for two inputs and single output case: A320&A321 C2-CHECK

According to Cooper, et al. (2000), for multiple inputs and outputs and their treatment, see Table 5.3, which lists the performance of twelve A320&A321 C2-Checks that each of them has two inputs and one output.

Input 1: Man-hours

Input 2: Material cost in unit currency

Output: Sale in unit currency

Table 5.3 : Two inputs and one output case.

DMU	MANHOURS	MATERIAL COST IN UNIT CURRENCY	SALE IN UNIT CURRENCY
1	2154	9523	130000
2	2250	10768	130000
3	2236	4231	130000
4	2173	3732	130000
5	2305	6982	130000
6	2241	12567	130000
7	2259	3720	130000
8	2554	6623	130000
9	2475	9301	130000
10	2490	4470	130000
11	2532	3044	130000
12	2814	3750	130000

Notice that the sale in unit currency is unitized to 130.000 units under the constant returns-to-scale assumption. Input values are normalized to values for getting 130000 unit of sale. C2-Checks are plotted, taking as axes, which may be thought of as "unitized axes" in Figure 5.3. DMU1, DMU11 are the efficient C2 checks. DMU1 and DMU4 are the reference set for inefficient DMU5.

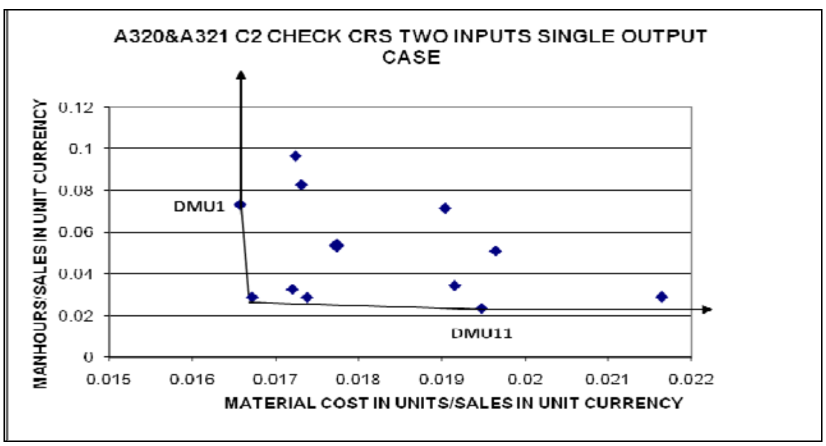


Figure 5.3: Two inputs and one output production possibility set.

5.4 An example for single input and two outputs case: A320&A321 C2-CHECK

According to Cooper, et al. (2000), for multiple inputs and outputs and their treatment, see Table 5.4. On the list the performance of twelve A320&A321 C2-Checks each with single input and two outputs are available.

Input 1: Man hours

Output1: Sale in unit currency

Output2: MECI

Table 5.4 : Single input and two outputs case.

DMU	MANHOURS	SALE IN UNIT CURRENCY	MECI
1	2770	126000	52.24%
2	2345	124000	48.61%
3	2150	124000	35.00%
4	2486	125000	35.00%
5	1431	124000	38.46%
6	1119	121000	40.23%
7	1312	123000	44.87%
8	1335	123000	50.00%
9	1294	122000	35.00%
10	1496	124000	58.33%
11	1213	122000	42.17%

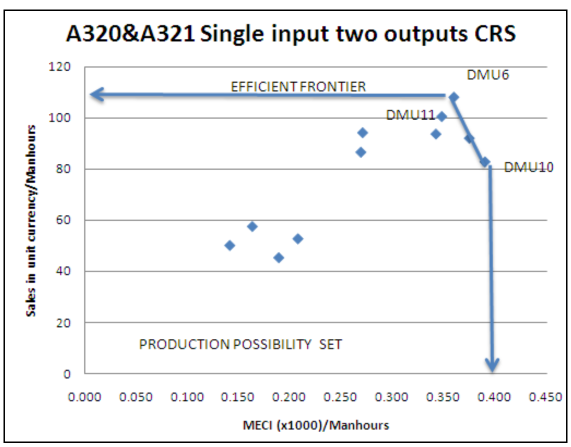


Figure 5.4: Single input and two outputs production possibility set.

C2-Checks are plotted, taking as axes, which it may be thought of as "unitized axes" in Figure 5.4. DM5, DMU10 are the efficient maintenance checks. They are the reference set for inefficient DMU11.

5.5 An example for fixed weights; A320&A321 C2-CHECK

According to Cooper, et al. (2000), the situation in Table 5.5 which records behavior intended to serve as a basis for evaluating the relative efficiency of twelve A320 aircraft C2-checks in terms of two inputs (man hours, TAT) and two outputs (sale in unit currency, MECI).

Input 1: Man hours

Input 2: TAT

Output1: Sale in unit currency

Output2: MECI

One way to simplify matters would be to weight the various inputs and outputs by pre-selected (fixed) weights. The resulting ratio would then yield an index for evaluating efficiencies. For instance, the weight;

v_2 (weight for material cost in unit currencys): v_1 (weight for man hours) =1

u_2 (weight for MECI): u1 (weight for sale in unit currency) =1

would yield the results shown in the row labeled "Fixed". (Notice that these ratios are normalized so that the maximum becomes unity, example; dividing by the ratio of DMU7) This simplifies matters for use, but raises other questions such as justifying ratios.

Table 5.5 : Two inputs and two outputs case.

DMU	MANHOURS	TAT	SALE IN UNIT CURRENCY	MECI
1	2154	6.3	126606	58.14%
2	2250	7	123403	32.56%
3	2236	6	127404	28.00%
4	2173	7	121966	28.00%
5	2305	6	125260	28.00%
6	2241	8	124067	32.56%
7	2259	6.3	118823	33.73%
8	2554	5	122888	28.00%
9	2475	7.3	120676	41.79%
10	2490	9	115153	31.11%
11	2532	6	125176	27.78%
12	2814	5	126290	28.00%

DEA, by contrast, uses variable weights. Calculated CRS efficiency is given on Table 5.6 to compare fixed and variable weights. The weights chosen in a manner that assigns a best set of weights to each C2 Check. The term “best” means that the resulting input-to output ratio for each C2 Check maximized relative to all other C2 Check when these weights assigned to these inputs and outputs for every C2 Check. The row labeled CCR in Table 5.6 shows results obtained from DEA using what called the “CCR model” in DEA. The “best ratio” result is general, under the following conditions:

- All data and all weights are positive (or at least nonnegative),
- The resulting ratio must lie between zero and unity and
- These same weights for the target entity (C2 Check) are applied to all entities.

Consequently, the entity being evaluated cannot choose a better set of weights for its evaluation (relative to the other entities). In each case, the evaluation is affected from a point on the efficient frontier so that a value like 0.80 for C2 Check, means that it is 20% inefficient.

Table 5.6 : Two inputs and two outputs case, weights.

DMU	INPUT2/ INPUT1	FIXED WEIGHTS FOR INPUTS	OUTPUT2/ OUTPUT1	FIXED WEIGHTS FOR OUTPUTS	FIXED RATIO-OUTPUT/INPUT	UNITIZED FIXED WIGHTS	CRS Efficiency
1	4,421	0,999	0,00005	0,800	0,800	0,264	1
2	4,786	1,082	0,00007	0,933	0,862	0,285	0,973
3	1,892	0,428	0,00007	0,904	2,112	0,698	1
4	1,717	0,388	0,00007	0,944	2,430	0,803	1
5	3,029	0,685	0,00007	0,919	1,341	0,443	0,959
6	5,607	1,268	0,00007	0,928	0,732	0,242	0,980
7	1,647	0,372	0,00007	1	2,685	0,888	0,995
8	2,593	0,587	0,00007	0,937	1,598	0,528	0,855
9	3,758	0,850	0,00007	0,954	1,123	0,371	0,878
10	1,795	0,406	0,00007	0,999	2,463	0,814	0,873
11	1,202	0,272	0,00006	0,809	2,976	0,984	1
12	1,332	0,301	0,00007	0,912	3,025	1	0,945

5.6 Description of three inputs, two outputs and DMU s for A320&A321 C2-CHECK

INPUTS;

X1: Input 1: Man hours

X2: Input 2: Material Cost In Unit Currency

X3: Input 3: TAT

OUTPUTS;

Y1: Output1: Sale In Unit Currency

Y2: Output2: MECI

DMU's are chosen as twelve different A320&A321 aircrafts. C2 planned Aircraft Maintenance check efficiencies are evaluated for the same type of aircraft for the years of 2010 and 2011. DMU Tables are given in Table 5.7 (2010) and 5.8 (2011)

Table 5.7 : DMU's, INPUTs and OUTPUTs for A320 C2 check

2010	INPUTS			OUTPUTS	
DMU	MANHOURS	MATERIAL COST IN UNIT CURRENCY	TAT(DAYS)	SALES IN UNIT CURRENCY	MECI (%)
1	2154	9523	6.3	126606	58.14%
2	2250	10768	7	123403	32.56%
3	2236	4231	6	127404	28.00%
4	2173	3732	7	121966	28.00%
5	2305	6982	6	125260	28.00%
6	2241	12567	8	124067	32.56%
7	2259	3720	6.3	118823	33.73%
8	2554	6623	5	122888	28.00%
9	2475	9301	7.3	120676	41.79%
10	2490	4470	9	115153	31.11%
11	2532	3044	6	125176	27.78%
12	2814	3750	5	126290	28.00%

Table 5.7 shows twelve A320&A321 C2 checks that are applied in the MRO in 2010. Each C2 check is shown as a DMU. C2 check inputs and outputs are inserted to Table 5.7. It is seen that each C2 maintenance inputs and outputs are different from each other. TAT is fluctuating between 5 and 9 days. This is not acceptable for customer satisfaction. Customers would like to hear standard numbers for the same type maintenance to do fleet programming. It is a very important metric for customers. Man hours spent for maintenance is important for calculation of the maintenance cost. Although work force compensation varies from country to country, if trained labor is limited, it is important to use it efficiently. For the twelve C2 maintenance considered, man-hour values change as shown on the Table 5.7

Table 5.8 shows twelve A320&A321 C2 checks that are applied in the MRO in 2011. The same type of inputs and outputs are inserted to Table 5.8.

5.7 CORRELATION BEETWEEN INPUTS AND OUTPUTS

Correlation is a relation between two different variables. Correlation factor shows the relation between the inputs and outputs. The correlation coefficient varies from '-1 to +1'. '-1' indicates perfect negative correlation, and '+1' indicates perfect positive correlation. There must be no strong correlation between the input and output variables (Kecek, 2010). If there is a strong correlation between the input and output variables, it indicates that the variables are not selected correctly. One of the variables can e removed without effecting on efficiency ratios (Norman and Stoker, 1991). The correlation tables are given in Table 5.9 and Table 5.10 for the inputs and outputs of A320 C2 check, for the years 2010 and 2011.

Table 5.8 : DMU's, INPUT s and OUTPUTs for A320 C2 checks.

2011	**INPUTS**			**OUTPUTS**	
DMU	**MANHOURS**	**MATERIAL COST IN UNIT CURRENCY**	**TAT(DAYS)**	**SALES IN UNIT CURRENCY**	**MECI (%)**
1	2770	857	11.3	126000	52.24%
2	2345	12638	13	124000	48.61%
3	2150	6893	9	124000	35.00%
4	2486	109	6	125000	35.00%
5	1431	8587	6	124000	38.46%
6	1119	1147	5.7	121000	40.23%
7	1312	3657	5.3	123000	44.87%
8	1335	7477	6.4	123000	50.00%
9	1294	5568	5.8	122000	35.00%
10	1496	17447	4.7	124000	58.33%
11	948	2611	5.4	110000	50.00%
12	1213	11875	8.8	122000	42.17%

The correlation coefficient is used to determine the relationship between two properties. As an example: the relationship between the population of a location and the use of public transportation is given. The equation for the correlation coefficient is:

Array1, is a cell range of values.

Array2, is a second cell range of values.

x and y are the sample means AVERAGE(array1) and AVERAGE(array2).

$$Correl(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \quad (5.4)$$

In Table 5.9, since there are no strong correlations between the variables, it is not needed to change the variables.

Table 5.9 : Correlations between the inputs and outputs for A320 C2 checks accomplished in 2010.

	INPUTS			OUTPUTS	
DMU	**MANHOURS**	**MATERIAL COST IN UNIT CURRENCY**	**TAT(DAYS)**	**SALES IN UNIT CURRENCY**	**MECI**
MANHOURS	1	-0.356	-0.326	-0.056	-0.347
MATERIAL COST IN UNIT CURRENCY	-0.356	1	0.324	0.137	0.478
TAT(DAYS)	-0.326	0.324	1	-0.644	0.143
SALES IN UNIT CURRENCY	-0.056	0.136	-0.644	1	0.079
MECI (%)	-0.347	0.478	0.143	0.0739	1

In Table 5.10, since there are no strong correlations between the variables, it is not needed to change the variables.

Table 5.10 : Correlations between the inputs and outputs for A320 C2 checks accomplished in 2011.

	INPUTS			OUTPUTS	
DMU	**MANHOURS**	**MATERIAL COST IN UNIT CURRENCY**	**TAT(DAYS)**	**SALES IN UNIT CURRENCY**	**MECI**
MANHOURS	1	-0.143	0.674	0.614	-0.019
MATERIAL COST IN UNIT CURRENCY	-0.143	1	0.131	0.194	0.393
TAT(DAYS)	0.674	0.131	1	0.339	0.106
SALES IN UNIT CURRENCY	0.614	0.194	0.339	1	-0.135
MECI (%)	-0.019	0.393	0.106	-0.134	1

5.8 CORRELATION BEETWEEN INPUTS OUTPUTS AND EFFICIENCY

DEA Frontier program is run for input oriented CRS efficiency. Efficiencies of subject DMU's are given in Table 5.11 for the year 2010 and for the year 2011.

Relative efficiencies of twelve A320 aircraft, which had C2 check maintenance in 2010, and relative efficiencies of twelve A320 aircraft, which had C2 check maintenance in 2011, are given in Table 5.11. Since C2 check aircraft maintenance is not applied every year to each aircraft, DMU's which represent these checks are different.

Table 5.11 : Efficiencies of DMU's for A320 C2 checks accomplished in 2010 and 2011.

2010 DMU Name	2010 Efficiency
1	1.000
2	0.933
3	1.000
4	1.000
5	0.971
6	0.942
7	1.000
8	1.000
9	0.836
10	0.852
11	1.000
12	1.000

2011 DMU Name	2011 Efficiency
1	0.943
2	0.464
3	0.602
4	1.000
5	0.898
6	1.000
7	1.0000
8	0.883
9	0.941
10	1.000
11	1.000
12	0.867

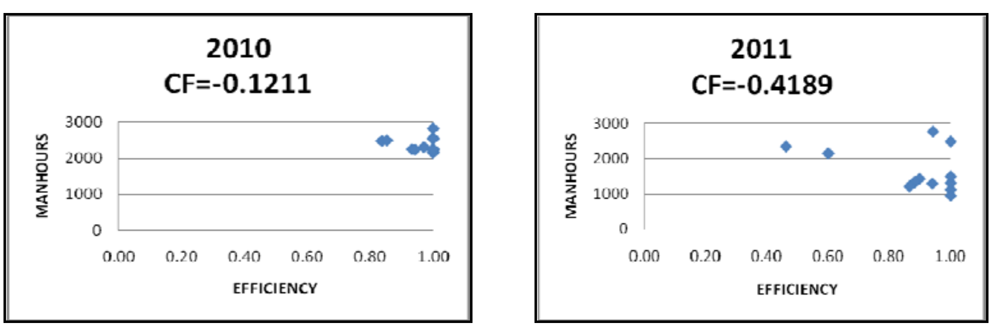


Figure 5.5: Correlation between man hours and efficiency for A320 C2 check accomplished in 2010 and 2011.

Figure 5.5 shows that there is no strong correlation between man-hours and efficiency in 2011 and in 2010.

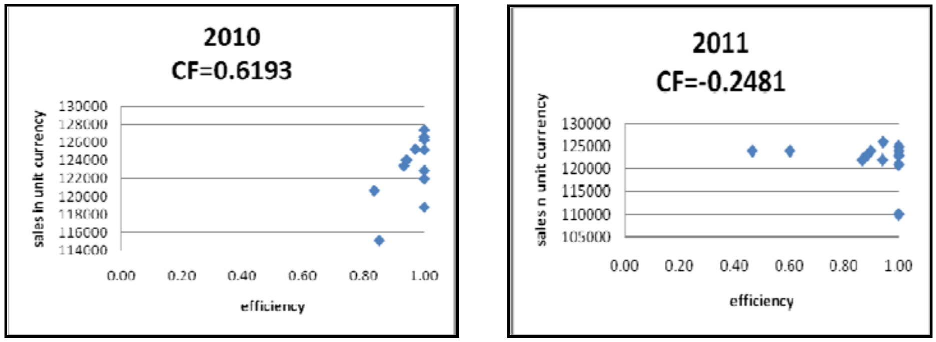


Figure 5.6: Correlation between 'sales in unit currency' and efficiency for A320 C2 checks accomplished in 2010 and 2011.

Figure 5.6 shows that there is no strong correlation between sales in unit currency and efficiency in 2011 and in 2010. Both figures indicate that there is no strong correlation between DMU's, input, output variables. As a result, there is no need to change input and output parameters.

5.9 EFFICIENCY OF DMU' S

For 2010 A320 C2 check, DMU 1, 3,4,7,8 are the most efficient units and they can be used as reference units for improvement efficiencies of other units given as Table 5.12. To increase efficiency of DMU5, necessary input and output value calculation is done by using optimal lambdas with benchmark on Table 5.12.

In order to get efficient target values of variables, reference DMU's variables of Table 5.12 are multiplied with lambdas, which are given by DEA Frontier program. For example for DMU10: DMU1, DMU4 and DMU7 are used as reference DMU's. These reference DMU's variables are multiplied by optimal lambdas to get targeted variables for DMU10. Lambdas are coefficients to reach efficient targets for DMU's. The calculation is done by DEA Frontier program; an example is given below regarding this calculation;

Table 5.12 : 2010 NON-EFFICIENT DMU's and references for improvements.

DMU Name	Efficiency	Sum of lambdas	Return to scale	Optimal Lambdas with Benchmarks	Reference DMU	Optimal Lambdas with Benchmarks	Reference DMU	Optimal Lambdas with Benchmarks	Reference DMU
1	1.00000	1.000	Constant	1.000	**DMU-1**				
2	0.93311	0.975	Increasing	0.975	**DMU-1**				
3	1.00000	1.000	Constant	1.000	**DMU-3**				
4	1.00000	1.000	Constant	1.000	**DMU-4**				
5	0.97068	0.987	Increasing	0.012	**DMU-1**	0.874	**DMU-3**	0.100	**DMU-8**
6	0.94190	0.980	Increasing	0.980	**DMU-1**				
7	1.00000	1.000	Constant	1.000	**DMU-7**				
8	1.00000	1.000	Constant	1.000	**DMU-8**				
9	0.83625	0.952	Increasing	0.709	**DMU-1**	0.243	**DMU-3**		
10	0.85247	0.956	Increasing	0.043	**DMU-1**	0.382	**DMU-4**	0.531	**DMU-7**
11	1.00000	1.000	Constant	1.000	**DMU-11**				
12	1.00000	1.000	Constant	1.000	**DMU-12**				

X for DMU5= (X1; X2;X3)=

(DMU1 inputs) x 0,012+ (DMU3 inputs) x 0,874 x (DMU8 inputs) x 0.1 **(5.5)**

X for DMU5= (X1;X2;X3)=

(2154;9523; 6.3) x 0,012+ (2236;4231; 6) x 0,874 x (2254;6623;5) x 0.1 **(5.6)**

Y for DMU5= (Y1;Y2)=

(DMU1 outputs) x 0,012+ (DMU3 outputs) x 0,874 x (DMU8 outputs) x 0.1 **(5.7)**

Y for DMU5= (Y1;Y2)=

(126606;0.5814) x 0,012+ (127404;0.28) x 0,874 x (122888;0.28) x 0.1 **(5.8)**

CRS is used to determine targeted values. For the optimal lambdas, Return to Scale is 'constant' as shown in Table 5.12.

For 2011 A320 C2 checks, DMU 4,6,7,10,11 is the most efficient units and they can be used as reference units for improvement efficiencies of other units given as Table 5.13.

In order to get efficient targeted values of variables, which are given, in Table 5.13, the reference DMU variables of Table 5.13 are multiplied with lambdas, which are given by DEA Frontier program. For example for DMU9: DMU6, DMU7 and DMU11 are used as reference DMUs. These reference DMU variables are multiplied by optimal lambdas to get targeted variables for DMU9. The calculation is done by DEA Frontier program; an example is given below regarding this calculation;

X for DMU2= (X1;X2;X3)=

$$\text{(DMU10 inputs) x 0,043+ (DMU11 inputs) x 1.078} \tag{5.9}$$

X for DMU5= (X1; X2; X3) =

$$(1496;17447;4.7) \text{ x } 0{,}043+ (948;2611;5.4) \text{ x } 1.078 \tag{5.10}$$

Y for DMU5= (Y1;Y2)=

$$\text{(DMU10 s outputs) x 0,043+ (DMU11 s outputs) x 1.078} \tag{5.11}$$

Y for DMU5= (Y1; Y2) =

$$(124000;0.58) \text{ x } 0{,}043+ (110000;0.50) \text{ x } 1.078 \tag{5.12}$$

Table 5.13 : 2011 NON-EFFICIENT DMU's and references for improvements.

DMU Name	Efficiency	Sum of lambdas	Return to scale	Optimal Lambdas with Benchmarks	Reference DMU	Optimal Lambdas with Benchmarks	Reference DMU	Optimal Lambdas with Benchmarks	Referen ce DMU
1	0.94301	1.398	Decreasing	0.766	**DMU-4**	0.632	**DMU-6**		
2	0.46362	1.122	Decreasing	0.043	**DMU-10**	1.078	**DMU-11**		
3	0.60158	1.012	Decreasing	0.249	**DMU-6**	0.685	**DMU-7**	0.078	**DMU-10**
4	1.00000	1.000	Constant	1.000	**DMU-4**				
5	0.89812	1.017	Decreasing	0.599	**DMU-6**	0.400	**DMU-10**	0.018	**DMU-11**
6	1.00000	1.000	Constant	1.000	**DMU-6**				
7	1.00000	1.000	Constant	1.000	**DMU-7**				
8	0.88319	1.076	Decreasing	0.082	**DMU-6**	0.264	**DMU-10**	0.730	**DMU-11**
9	0.94081	1.002	Decreasing	0.740	**DMU-6**	0.013	**DMU-7**	0.249	**DMU-11**
10	1.00000	1.000	Constant	1.000	**DMU-10**				
11	1.00000	1.000	Constant	1.000	**DMU-11**				
12	0.86679	1.109	Decreasing	1.109	**DMU-11**				

5.10 EFFICIENT INPUT AND OUTPUT TARGETS

Target values of DMU's are calculated by running DEA Frontier program for 2010 A320 C2 check DMU's. The target input and output values for DMU's are shown on Table 5.14. All target input and output variables for each DMU are given in Table 5.14 for 2010 and in Table 5.15 for 2011. To find potential improvements, target and actual input and output values inserted into a Table. Improvement calculated as given below:

$$\text{Improvement} = (\text{Target Value} - \text{Actual Value}) / \text{Actual Value} \qquad \textbf{(5.13)}$$

Since input oriented CRS model is used, efficient target input values expected to be lower than the actual values to have improvement. The efficient output target values expected to be stay the same or lower than the actual values.

Table 5.14 shows that efficient input target values are lower than the actual values given in Table 5.7. On the contrary, output target values are higher than the actual values.

Table 5.14 : Target inputs and outputs for 2010 A320 C2 check DMU's.

Efficient Input Target					**Efficient Output Target**	
DMU Name	**Efficiency**	**MANHOURS**	**MATERIAL COST IN UNIT CURRENCY**	**TAT(DAYS)**	**SALES IN UNIT CURRENCY**	**MECI (%)**
1	1.00000	2154.00	9523.00	6.30	126606.00	58.14%
2	0.93311	2099.51	9282.08	6.14	123403.00	56.67%
3	1.00000	2236.00	4231.00	6.00	127404.00	28.00%
4	1.00000	2173.00	3732.00	7.00	121966.00	28.00%
5	0.97068	2237.43	4480.23	5.82	125260.00	28.00%
6	0.94190	2110.80	9332.02	6.17	124067.00	56.97%
7	1.00000	2259.00	3720.00	6.30	118823.00	33.74%
8	1.00000	2554.00	6623.00	5.00	122888.00	28.00%
9	0.83625	2069.72	7777.96	5.92	120676.00	48.01%
10	0.85247	2122.65	3810.54	6.29	115153.00	31.11%
11	1.00000	2532.00	3044.00	6.00	125176.00	27.78%
12	1.00000	2814.00	3750.00	5.00	126290.00	28.00%

Table 5.15 shows improvement potential for variables, which has lower relative efficiencies. The input variables for DMU2, DMU5, DMU6, DMU9, DMU10 can be decreased by using improvement techniques such as Lean tools, six sigma etc. If input variables are decreased output variables for subject DMUs stay the same or increase in small amount. MECI is same for 2010 for these DMUs.

Table 5.15 : Improvement potential for 2010 A320 C2 check DMU's.

DMU	EFFICIENCY	MANHOURS IMPROVEMENT	MATERIAL COST IN UNIT CURRENCY IMPROVEMENT	TAT IMPROVEMENT	SALES IN UNIT CURRENCY IMPROVEMENT	MECI IMPROVEMENT
2	0,973	2,68%	64,12%	3,78%	0,00%	0,00%
5	0,984	1,64%	36,03%	1,64%	-1,36%	0,00%
6	0,981	1,95%	68,77%	17,33%	0,00%	0,00%
9	0,891	10,93%	57,20%	10,93%	-3,31%	0,00%
10	0,873	12,73%	16,51%	22,22%	-5,92%	0,00%

Table 5.16 shows that efficient input target values are lower than the actual values given in Table 5.8 for 2011. On the contrary, output target values are higher than the actual values.

Table 5.17 shows improvement potential for variables, which have lower relative efficiencies. The input variables for DMU1, DMU2, DMU3, DMU5, DMU8, DMU9, DMU12 can be decreased by using improvement techniques such as Lean tools, six sigma etc. If input variables decreased, output variables for subject DMUs stay the same or increase.

Table 5.16 : Inputs and outputs for 2011 A320 C2 check DMU's.

		Efficient Input Target			Efficient Output Target	
DMU Name	EFFICIENCY	MANHOURS	MATERIAL COST IN UNIT CURRENCY	TAT(DAYS)	SALES IN UNIT CURRENCY	MECI (%)
1	0.943	2612.15	808.16	8.20	172240.01	52.24%
2	0.464	1087.19	3572.52	6.03	124000.00	56.45%
3	0.602	1293.39	4146.66	5.41	124000.00	45.28%
4	1.000	2486.00	109.00	6.00	125000.00	35.00%
5	0.899	1285.21	7712.13	5.39	124000.00	48.31%
6	1.000	1119.00	1147.00	5.70	121000.00	40.23%
7	1.000	1312.00	3657.00	5.30	123000.00	44.87%
8	0.883	1179.06	6603.61	5.65	123000.00	55.21%
9	0.940	1217.41	5238.44	5.46	122000.00	44.87%
10	1.000	1496.00	17447.00	4.70	124000.00	58.33%
11	1.000	948.00	2611.00	5.40	110000.00	50.00%
12	0.867	1051.42	2895.84	5.99	122000.00	55.46%

Table 5.17 shows that for targeted values of MECI, there are improvement opportunities. Targeted MECI values are higher than the actual values.

Table 5.17 : Improvement potential for 2011 A320 C2 check DMU's.

DMU	EFFICIENCY	MANHOURS IMPROVEMENT	MATERIAL IN UNITS CURRENCY IMPROVEMENT	TAT IMPROVEMENT	SALES IN UNIT CURRENCY IMPROVEMENT	MECI IMPROVEMENT
1	0.943	5.70%	5.70%	27.44%	-36.70%	0.00%
2	0.464	53.64%	71.73%	53.64%	0.00%	-16.12%
3	0.602	39.84%	39.84%	39.84%	0.00%	-29.37%
5	0.898	10.19%	10.19%	10.19%	0.00%	-25.61%
8	0.883	11.68%	11.68%	11.68%	0.00%	-10.42%
9	0.941	5.92%	5.92%	5.92%	0.00%	-28.20%
12	0.867	13.32%	75.61%	31.94%	0.00%	-31.51%

On Table 5.16 and 5.17 positive percentages mean that the subject input variable value can be decreased by using process improvement tools mentioned on Section 1; introduction. The negative percentages on the output variables mean that the subject variable's value can be increased via minimizing input variables.

Increasing MECI number shows opportunities to catch human error in aircraft maintenance. Table 5.17 shows that targeted MECI can be increased.

5.11 Results

For the year 2010, the most efficient A320 C2 checks are for DMU 1, 3, 4,7,8,11,12 aircrafts. When X-MRO is performing DMU 2, 5, 6, 9, 10 aircraft maintenance, resources could not be used efficiently. These are non-efficient DMUs for 2010. The improvement potentials for man-hour, material unit cost and TAT are available for DMU 2, 5, 6,9,10 aircrafts as shown in Figure 5.7, Figure 5.8 and Figure 5.9. Man-hour, material unit cost and TAT can be reduced for these DMUs.

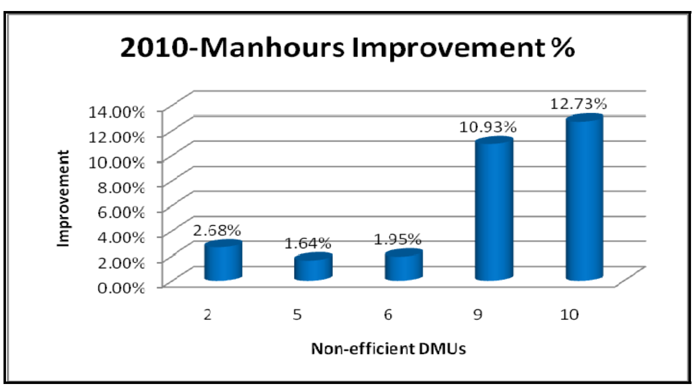


Figure 5.7 : Manhour improvement opportunities for 2010 non-efficicent DMUs.

In 2010, thirty MEDA reports were published for X-MRO fleet and average MECI is 31% for efficient DMUs. If MECI ratio is low, this means that the human errors are detected in maintenance environment.

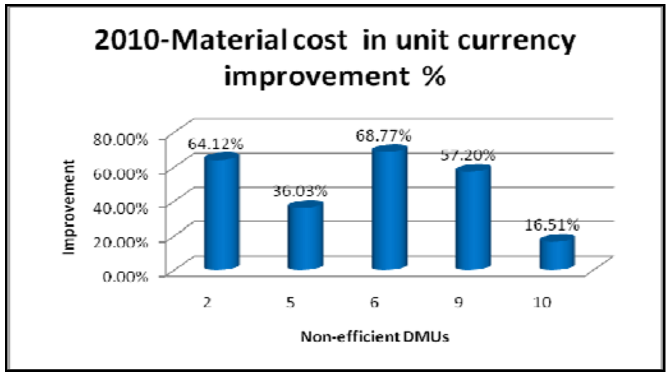


Figure 5.8 : Material cost in unit currency improvement opportunities for 2010 non efficicent DMUs.

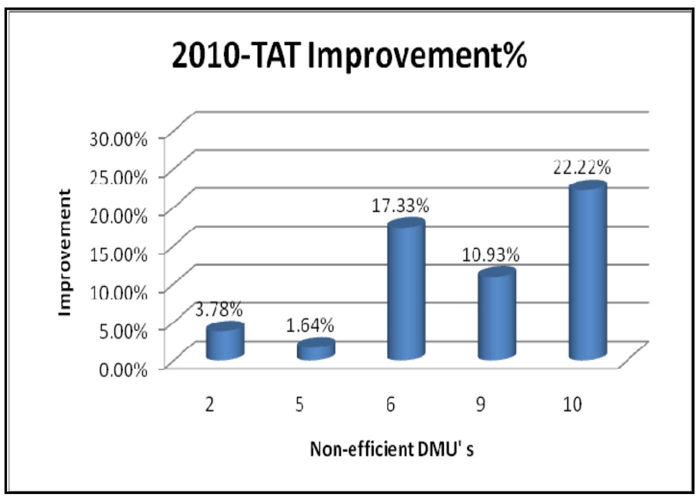


Figure 5.9 : TAT improvement opportunities for 2010 non-efficicent DMU's.

For the year 2011, the most efficient A320 C2 checks are DMU 4,6,7,10,11 aircrafts. During DMU 1, 2, 3, 5, 8, 9, 12 aircraft maintenance, resources are used inefficiently. DMU 1, 2, 3, 5, 8, 9, 12 are non-efficient DMUs for 2011. The improvement potential for man-hours, material cost in unit and TAT, is available for DMU 1, 2, 3, 5, 8, 9, 12 aircrafts as shown in Figure 5.10, Figure 5.11, and Figure 5.12. Man-hour, material cost in unit and TAT can be reduced for these DMUs.

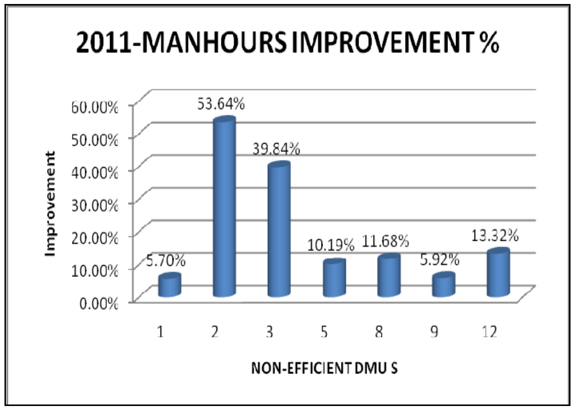


Figure 5.10 : Manhour improvement opportunities for 2011 non-efficicent DMU's.

.In 2011, ten MEDA reports have been published for MRO fleet and average MECI is 47% which is higher than the MECI number of non-efficient DMUs. If MECI ratio is higher than the MECI ratio of other DMUs, this means that there are opportunities to catch the human errors in the maintenance. The errors cannot be detected in maintenance environment even the subject maintenance is efficient.

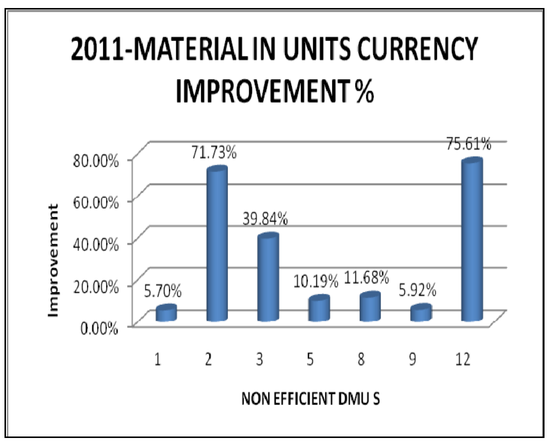


Figure 5.11 : Material in unit currency improvement opportunities for 2011 non-efficient DMU's.

All outputs, inputs of DMUs for the years 2010 and 2011 are compared on the Table 5.14 and Table 5.16. The maintenances, which accomplished in 2010 and 2011 in X-MRO, are reviewed.

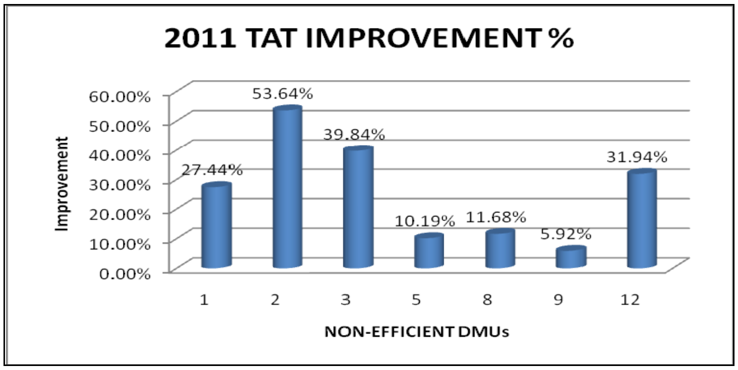
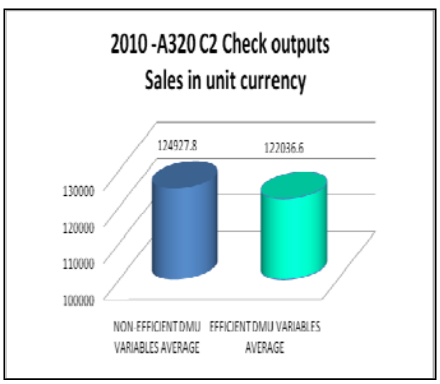


Figure 5.12 : TAT improvement opportunities for 2011 non-efficicent DMU's.

As a result of reviewing of these maintenances, the outputs shown in Figure 5.13 and Figure 5.14 for the year 2010 and 2011;

Refer to Figure 5.13; sales in unit currency values for non-efficient DMUs are higher than efficient DMUs values for both in 2010 and in 2011.



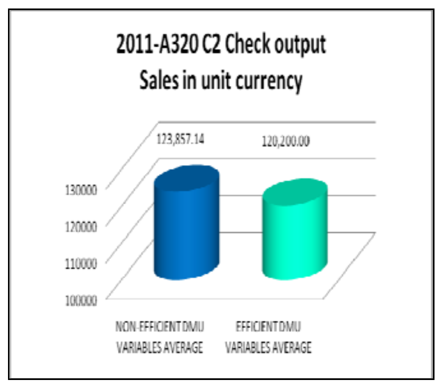


Figure 5.13: Comparison of efficient and non-efficient DMU's sales in unit currency for the year 2010 and 2011.

Refer to Figure 5.14; the MECI values for non-efficient DMUs are higher than the MECI values for efficient DMUs in 2010. The non-efficient DMU's MECI numbers are lower than efficient DMU's MECI numbers in 2011.

The input variables of 2010 and 2011 DMUs, which are man-hours, and TAT, compared in Figure 5.15 and 5.16.

The targets give the improved values, which are desired for efficient maintenance. As an example; in 2011 in order to reach to the targets; the decision for the first improvement area should be DMU2's TAT.

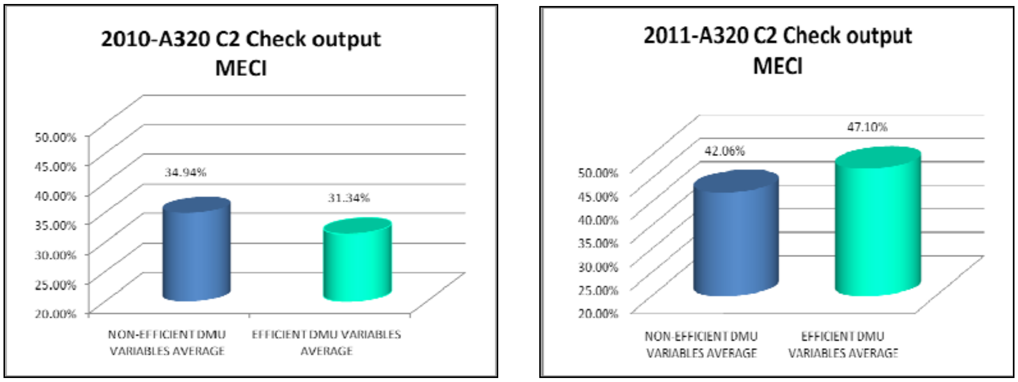


Figure 5.14 : Comparison of efficient and non-efficient DMU's MECI for the year 2010 and 2011.

In 2010, in order to reach the targets, the decision for the first improvement area should be DMU10's TAT. It can be achieved by using improvement techniques.

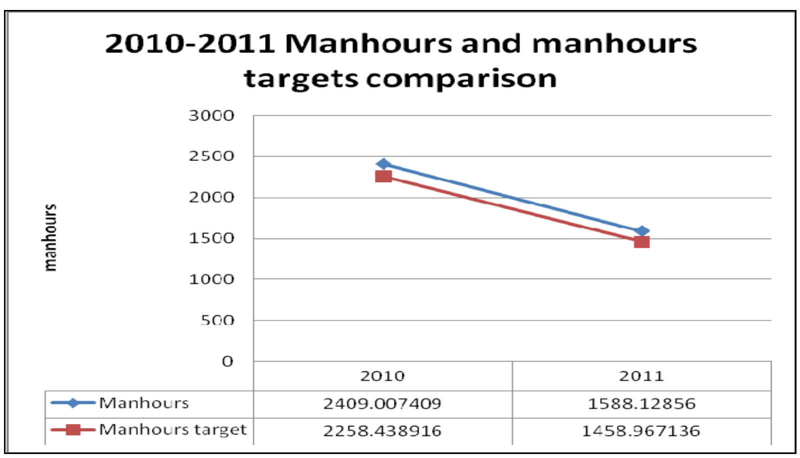


Figure 5.15 : Comparison of DMU's inputs (manhours)for the year 2010 and 2011.

As shown in Figure 5.17, the MECI number which is an output variable, increases by year, it means that there are more opportunities to catch human errors in X-MRO in year 2011 than year 2010.

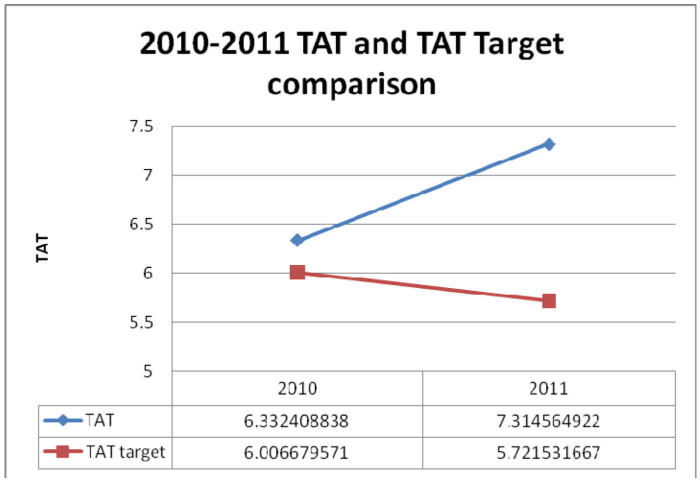


Figure 5.16 : Comparison of DMU's inputs for the year 2010 and 2011.

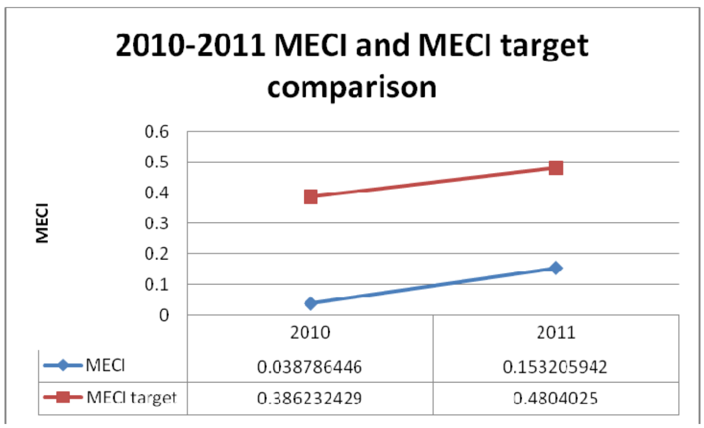


Figure 5.17: Comparison of DMU's outputs for the year 2010 and 2011.

5.12 Use of DEA for ' bay management' in aircraft maintenance

Bay management is the organization of resources, such as human, machine, material in a dedicated area to improve aircraft maintenance efficiency in a letter check.

Using 'Bay Management' is the one of the best ways to increase efficiency of maintenance in a MRO.

- Fixed dock
- Material kitting
- JIT Delivery
- Human, material , information flow
- Financial targets

are the key elements of Bay Management philosophy. Each bay has a manager who is responsible for efficiency of the bay. Point of use of tooling is important in order to increase affectivity for a bay. In Figure 5.18, there is an example of bays in a HAECO (2007). All tools, materials and human resources are available close to each bay.

Figure 5.19 shows tool room, dock office and human walking before relocation and after relocation of each bay. It is obvious that after relocation less man-hour is needed for accomplishment of maintenance. Beside relocation, just in time delivery of materials, point of use of tooling and close dock availability help to reduce man-hour in a bay.

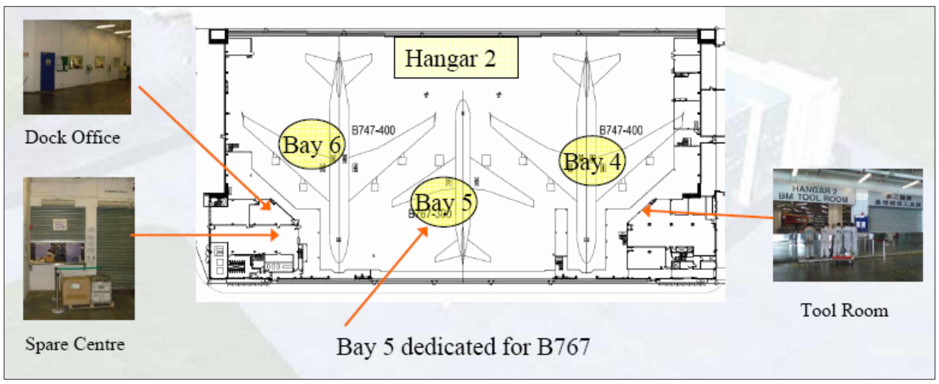


Figure 5.18: Grouping of Document, Spare and Tooling from different locations the hangar to an area around the aircraft, adapted from (HAECO, 2007).

Figure 5.20 shows travel improvements after using bay management system.Walking reduced 67% by using bay management phylosophy.

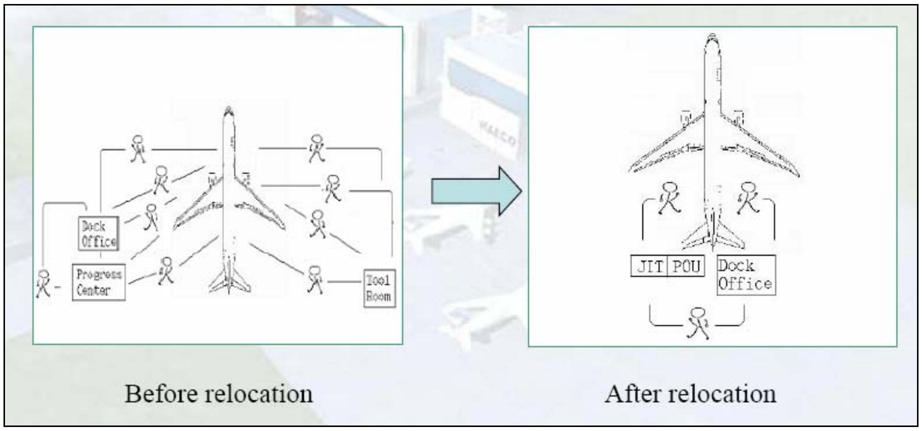


Figure 5.19: Relocation for bays, adapted from (HAECO, 2007).

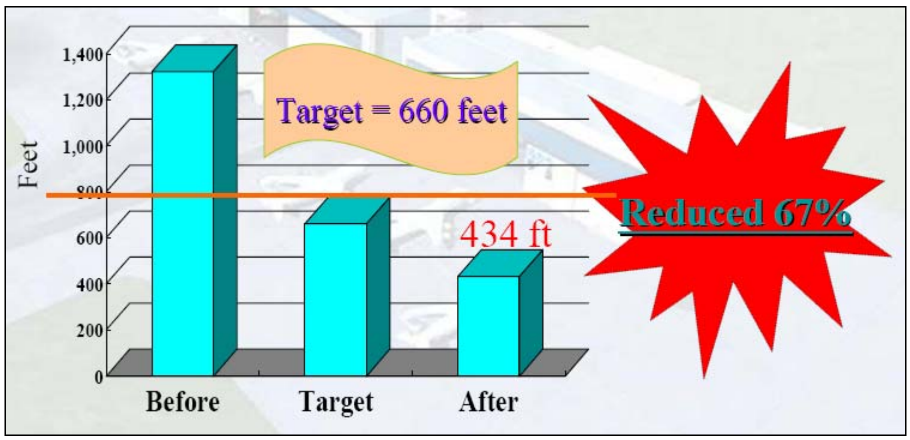


Figure 5.20: Bay management improvements Travel by feet, adapted from (HAECO, 2007).

Figure 5.21 shows cycle time improvements on travelling, spare/ tooling, core work and document flow. Bay layout and kitting pictures are given in Figure 5.22.

Bay efficiency is calculated by using total productivity, efficiency and affectivity. However, different bays should be compared in order to define relative efficiency.

DEA provides relative efficiency comparison of bays using main resources such as; man-hours, TAT, Material cost in units. To use DEA, gives opportunity to define improvement necessary areas.

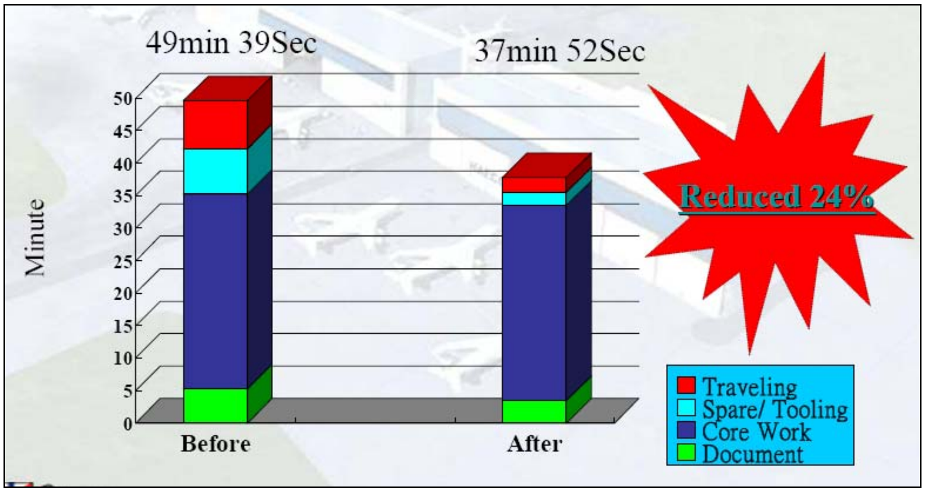


Figure 5.21: Bay management improvements, cycle time, adapted from (HAECO, 2007).

Most of the MRO's are using bay management model in aircraft maintenance.

Figure 5.22: Bay management kitting in a MRO.

Each bay has a manager who is responsible for efficiency of the bay. Bay area personnel's performance and their amount of premium have a relation with bay efficiency.

5.13 CONCLUSION

In section 4, it is stated that X-MRO productivity is decreasing even it has increasing efficiency and effectivity when 2010 and 2011 are compared. Safety, which is presented by MECI in section 5, affects productivity. When the year 2010 DMUs are evaluated, it is clear that, the relative efficiencies of DMU's can be improved without changing MECI in X-MRO. On the contrary, in the year 2011, targeted MECI values increases when input variables decreases. Improvement is needed to reduce resources, which are called input variables, the opportunity to catch maintenance errors increases. This indicates that if efficiency increases, there is potentially more opportunity to catch error in X-MRO.

X-MRO needs to take necessary corrective actions to decrease maintenance risks and to increase productivity.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

In a competitive market, managers have time constraints. They should decide to work on improvement necessary areas to raise the operation standards. DEA is one of the useful tools for aircraft maintenance managers to compare performances of maintenance checks. By comparison, of relative efficiencies of C2 checks, managers can decide area of improvement opportunities. DEA used to compare relative efficiency of aircraft maintenances of X-MRO in the present study. The results of the present study demonstrate that:

- Relative efficiencies of C2 checks can be compared by using DEA input oriented CRS model.
- Input and output variable's values which belong to efficient DMU's, are lower than the input and output variable's values which belong to non-efficient DMU's for both 2010 and 2011.
- It shows that non-efficient DMU's consume more manpower and material cost in unit than the efficient DMU's.
- Efficient DMU's maintenance TAT is less than the non-efficient DMU's TAT. This is good for the MRO because this situation creates more capacity.
- There are more improvement opportunities in 2011 than in 2010 based on Table 5.15 and Table 5.17.

X- MRO could be more productive in 2011 than 2010. However, this does happen as mentioned in section 4. Even X-MRO uses less resource, number of errors and their contributing factors increase by years in X-MRO. Organizational productivity that is tracked by four metrics (effectivity, efficiency, partial factor efficiency, total factor productivity) decreases by the increase of errors. Undetectable maintenance errors have higher ratios in 2011 compared with 2010. In 2011, in order to decide improvement areas for non-efficient DMUs, MECI does not stay the same. It shows that there are opportunities for improvements but with the help of stable MECI.

Lean management, six-sigma, theory of constraints and critical chain can be used to improve DMUs. Using one of these methods for a DMU, will result in deployment of others too if management continuously supports these activities.

Regarding our hypothesis, total factor productivity has direct relation with improvements and indirect relation with human errors. Available total factor productivity, improvement and number of human error data are used to show the relation for the variables.

If errors increases and improvement effort decreases, total factor productivity decreases too. Concerning conclusion of Section 3, effectivity and efficiency have no direct relation with total factor productivity in X-MRO. Even efficiency and effectivity increases, total factor productivity decreases.

Empirical formulae can be written for the relation of variables such as formulae 6.1.

$$\text{Total factor productivity } \alpha \ [(\text{Improvements/errors}) - k] \qquad \mathbf{(6.1)}$$

For X-MRO, control points might be set, improvement activities must continue to prevent occurrence of errors, to decrease human errors and to have increasing total factor productivity in the future. Overhaul organizational productivity efficiency, effectivity, partial factor efficiencies and total factor productivity must be higher than previous values.

6.2 Recommendation

For the future studies, by using total factor productivity, improvement and error data researchers can use the equation 6.1 to define total factor productivity of MRO's.

Researchers can use DEA to compare relative efficiencies of MRO shops, line and base maintenance, 'A' checks, 'D' checks, manager's performances, tool shops, different hangars to decide improvement necessary areas.

Relative efficiency measurement will drive competition if bay management has chosen for MRO management system. The MROs, which are accomplishing bay management, can get benefits from DEA to compare relative efficiencies of aircraft maintenances. For the other MROs, DEA can also be used to compare relative efficiency of aircraft maintenances as it is used in the present study. The difference between two types of MROs is; Bay management uses fewer resources compared with X-MRO maintenance management.

Researchers can use DEA to compare bay management with the other maintenance philosophies.

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Professional Experience and Rewards:

ACE CONTINOUS IMPROVEMENT MANAGER, December 2011-Present

TEC Turkish Engine Center- Istanbul, Turkey

Selected Contributions:

- ✓ Develop and manage ACE events.
- ✓ Export control Non-US BAER
- ✓ ACE Associate
- ✓ Accomplishment of 1st annual innovative thinking contest

PROCESS IMPROVEMENT MANAGER, February 2008-December 2011

Turkish Airlines Technic - Istanbul, Turkey

Selected Contributions:

- ✓ Start up Process Improvement Management
- ✓ %50 Improvement of Custom supply chain, component overhaul, engineering processes
- ✓ Develop and manage 5S , Level 2/5

- ✓ Develop and manage employee recommendation system for 4 years
- ✓ Managed and trace 130 MEDA reports for improvement Human / System Errors in Aircraft Maintenance.
- ✓ Coordination of 185 Lean workshop (AIW, VSM, 3P, Innovation)
- ✓ 30 Lean workshop leadership
- ✓ 55 Lean workshop coaching accomplished between 2006-2011 .

FLEET ASSET ACTING MANAGER, November 2009 –March 2010, Turkish Airlines Technic - Istanbul, Turkey

Selected Contributions:

- ✓ Manage 2 phase-in, 2 phase-out projects

QUALITY IMPROVEMENT & PRODUCTIVITY CHIEF ENGINEER , May 2006 –February 2008, Turkish Airlines Technic(Company changed) - Istanbul, Turkey

QUALITY IMPROVEMENT & PRODUCTIVITY CHIEF ENGINEER , April 2006 –May 2006, Turkish Airlines - Istanbul, Turkey

Selected Contribution:

- ✓ Prepare MEDA (Maintenance Error Decision Aid) Reports,
- ✓ Coordinate MEDA researches, meetings, trace report results
- ✓ Trace all the written unconformities to GM by all authorities
- ✓ Give Lean Trainings
- ✓ Coordinate & accomplished LEAN workshops inside the organization.
- ✓ Company internal auditor; Auditing C-check Maintenance , A check Maintenance, Structural repair , cabin interior processes. Aircraft Maintenance Directorate Departments and their processes.

PRACTICAL TRAINING CHIEF ENGINEER , December 2001-April 2006 , Turkish Airlines - Istanbul, Turkey

Selected Contribution:

- ✓ De/anti-icing practical training
- ✓ A310/A330/A319CJ ETOPS maintenance procedures training
- ✓ Hidden damage inspection
- ✓ M.E.L. description and usage
- ✓ Fuel leaks and trouble -shooting methods
- ✓ Company procedures training for contracted Airline Technicians
- ✓ A/C Toilet servicing
- ✓ Regulatory courses ; MME, JAR145, FAR145, JAR-OPS1 Subpart M
- ✓ Company internal auditor; Auditing C-check Maintenance , A check Maintenance, Structural repair , cabin interior processes. Aircraft Maintenance Directorate Departments and their processes.

LINE MAINTENANCE ENGINEER , June 1999 -December 2001, Turkish Airlines - Istanbul, Turkey

Selected Contribution:

- ✓ De/anti-icing practical training, Technical Procedure Training (TPM,MOE,MME)

- ✓ A310 and A340 hydraulic leaks training, RJ 70/100 main landing gear servicing training,Toilet servicing training, A310 ETOPS maintenance procedures training
- ✓ Company internal auditor; Auditing C-check Maintenance , A check Maintenance
- ✓ Structural repair , cabin interior processes in Aircraft Maintenance Directorate Departments and their processes
- ✓ Develop new tools to use in maintenance
- ✓ Give trainings to mechanics and contracted mechanic in outstations .

HYDRAUMECHANICAL SYSTEM ENGINEER , June 1996 -June 1999, Turkish Airlines - Istanbul, Turkey
Selected Contribution:
✓ A340 Hydraulic pump modifications

RESEARCH AND TEACHING ASSISTANT , December 1990 –June 1996 , Istanbul Technical University Faculty of Aeronautics &Astronautics - Istanbul, Turkey
Selected Contribution:
✓ Turkish Military Air Force project about : Investigation of 3D aerodynamic characteristics of a bomb adapter

PRACTICAL TRAINEE , May 1992 -November 1992, R&D Weight and balance Department – CASA , MADRID, SPAIN
Improvement of existing production included designing, and developing techniques for CN-235M cargo and QC aircraft (Supported by Turkish Military and Defense Industry).

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Bozkurt, Y., Kavsaoğlu M.S., 2012: Productivity calculation in aircraft maintenance. *1st National Aviation Technology and practices (UHAT) Conference.* 20-22 December 2012, İzmir, Turkey.