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# Fuel Efficiency Assessment with DEA

Evren Kiyamaz

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FUEL EFFICIENCY ASSESSMENT WITH DEA

THESIS

Evren KIYMAZ, First Lieutenant, TUAF

AFIT-LSCM-ENS-10-07

DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY

**AIR FORCE INSTITUTE OF TECHNOLOGY**

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AFIT-LSCM-ENS-10-07

# FUEL EFFICIENCY ASSESSMENT WITH DEA

THESIS

Presented to the Faculty  
Department of Operational Sciences  
Graduate School of Engineering and Management  
Air Force Institute of Technology  
Air University  
Air Education and Training Command  
In Partial Fulfillment of the Requirements for the  
Degree of Master of Science in Logistics and Supply Chain Management

Evren KIYMAZ, B.S.E.E.

First Lieutenant, TAAF

March 2010

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## FUEL EFFICIENCY ASSESSMENT WITH DEA

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First Lieutenant, TUAF

Approved:

/signed/

25 Mar 2010

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William Cunningham, PhD (Member)

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## *Abstract*

In this study, Data Envelopment Analysis (DEA) is used to calculate Air Mobility Command (AMC) airlift fuel efficiency for C-17 aircraft. Fuel is a strategic asset for the United States Air Force and suitable alternatives are not yet feasible or available in the quantity required.

The Air Force is pursuing several initiatives to conserve energy and operate more efficiently while sustaining the same level of effectiveness and safety. In order to manage these initiatives, it must measure how well it is doing. To measure airlift efficiency, the AMC Fuel Efficiency Office established a 7 factor weighted Fuel Efficiency Index (FEI). To produce a monthly score, AMC assigned weights for each factor. DEA does not require such a priori assumptions and finds the best set of weights that will help each mission to represent itself in the best manner.

The results showed that DEA and FEI agree in trends but a DEA Slack-Based Measure better differentiates inefficiencies than other methods used in the study. Also, the results showed that for current Air Mobility flights, at least 10% input excess or output shortfall occurs each month.

## *Acknowledgements*

This thesis would not have been possible without the help and assistance of many people.

First, I owe Dr. Alan W. Johnson a debt of gratitude for adopting me as a master student and providing me the freedom to research my own ideas. His assistance and willingness helped me make this study possible and made the best school experience.

Second, I would like to show my gratitude and thank to my committee member Dr. William Cunningham for his support and listening and treating to me as a colleague.

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Finally, I wish to express my love and gratitude to my beloved wife; for her understanding and endless love, through the duration of my study.

Evren KIYMAZ

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## *List of Abbreviations*

Abbreviation		Page
USAF	United States Air Force . . . . .	1
US	United States . . . . .	1
DoD	Department of Defense . . . . .	2
AMC	Air Mobility Command . . . . .	6
CONUS	Continental of United States . . . . .	8
DEA	Data Envelopment Analysis . . . . .	12
DMU	Decision Making Unit . . . . .	12
FEI	Fuel Efficiency Index . . . . .	16
IATA	International Air Transportation Association . . . . .	18
FAR	Federal Aviation Regulation . . . . .	19
TSI	Transportation Service Index . . . . .	20
LP	Linear Programming . . . . .	26
ERS	Efficiency Reference Set . . . . .	26
SBM	Slack-Based Measure . . . . .	43

# FUEL EFFICIENCY ASSESSMENT WITH DEA

## I. Introduction

Jet fuel is a necessary strategic asset for effective operations for now and the foreseeable future. The United States Air Force (USAF) has a regular and significant demand for fuel, and alternative fuels are not yet feasible or available in sufficient quantity to be used as a significant substitute.

This chapter introduces the background information about the national and strategic importance of fossil oils, fuel consumption of the United States (US) and USAF, and Air Force Energy Strategy.

The research problem is first stated. Then the research methodology is explained and key assumptions and limitations are noted.

### *1.1 US and USAF Fuel Consumption*

Although the US is the third largest crude oil producer with 5 million barrels per day, most of its petroleum products are imported. As shown in Figure 1.1, crude oil and natural gas plant productions peaked at 11.3 million barrels per day in 1970 (AER, 2008) and has followed a downward trend since then. On the other hand, crude oil imports only showed a downward trend between 1979-1985 but followed an upward trend in most other years. Figure 1.1 also indicates that these imports grew rapidly in the near past (EIA, 2009).

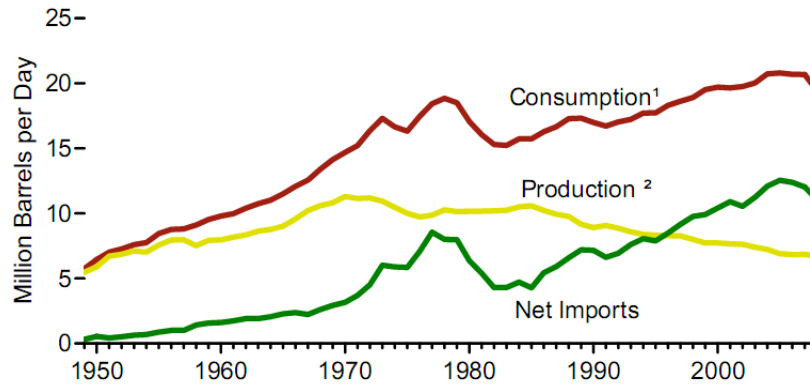


Figure 1.1: US Oil Consumption, Production and Imports.  
 Source: Energy Information Administration, 2008 Annual Energy Review.

The US is the largest petroleum consumer in the world at 19.5 million barrels per day but nearly 58% of that consumption is imported from other countries; including Canada, Saudi Arabia, Mexico, Venezuela, and Nigeria (see Figure 1.2).

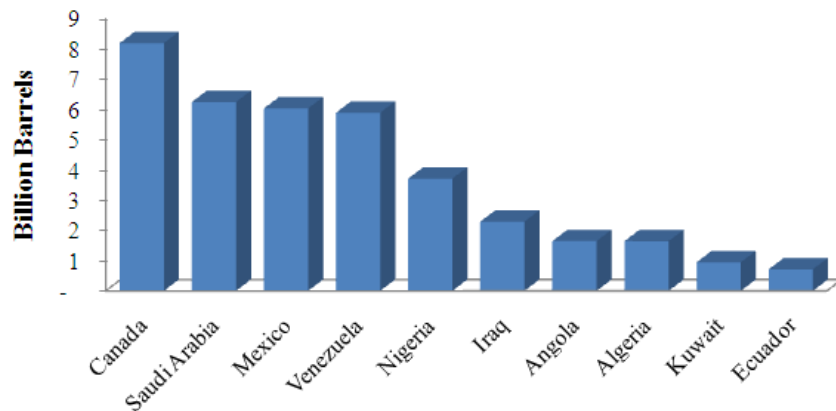


Figure 1.2: Largest Imports by Country of Origin (1998-2008).  
 Source: Energy Information Administration, Imports, Exports and Movements.

The US government consumes only a small amount of fuel/energy of the US demand, but about 90% of the overall government consumption is from the Department of Defense (DoD). Further, the Air Force is the largest single user of petroleum-based fuel. It utilizes more than the total of the other sister services (Karagozian, 2006).

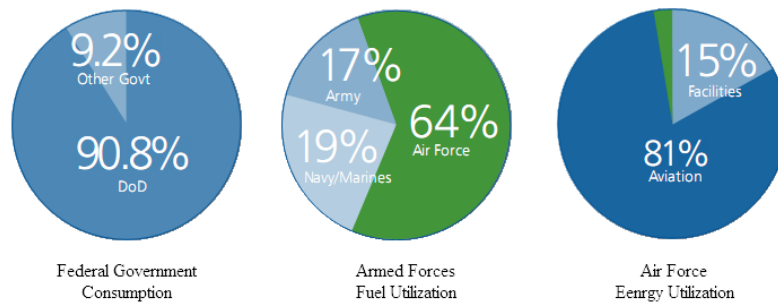


Figure 1.3: Federal Government, DoD and Air Force Fuel Utilization.  
Source: Air Force Energy Strategy.

As depicted in Figure 1.3, in 2007 the Air Force used 64% of DoD fuel and of that amount 81% is for aviation (Energy Strategy). The total amount in Fiscal Year 2008 was 8.5 billion dollars (DESC Fact Book, 2008).

### 1.2 Importance of Fuel

Energy is very important for any country which wants to achieve its economic and industrial goals. Today, it is a strategic resource for countries and firms. Also, since almost every item from logistics, transportation and production to everyday consumer products are dependent on energy in different forms, countries are more dependent on energy than ever before.

Transportation - critical for any nation's operations - is very dependent on petroleum products since other energy forms are not yet feasible to produce in sufficient quantity. Therefore, consumers of fuel need to be more conservative and fuel efficient in everything airmen do. Fuel efficiency is a hot topic nowadays for governments. President Obama recently remarked that even though the US represents only

5% of the whole world's population, it has nearly one fourth of the world's demand of oil. He continues that it comes at a price of vulnerability. The US spends 20% of its import on foreign oil and that oil comes from the countries that include Canada, Saudi Arabia, Mexico, Venezuela, Nigeria, Iraq etc. (Garden, 2009).

Also, the U.S. president illustrates the importance of energy by saying:

“So we have a choice to make. We can remain one of the world's leading importers of foreign oil, or we can make the investments that would allow us to become the world's leading exporter of renewable energy. We can let climate change continue to go unchecked, or we can help stop it. We can let the jobs of tomorrow be created abroad, or we can create those jobs right here in America and lay the foundation for lasting prosperity.”

Figure 1.1 shows that more than the half of the petroleum products the US consumes is imported from other countries, thus creating a US dependency and vulnerability on other countries. The US leaders at every level mentions this vulnerability. In a hearing about America's Energy Future, Senator Baucus (2007) stated that the US needs to think about energy because it is very dependent on unstable foreign energy resources and thus any disruption would effect the economy.

In order to reduce oil dependency on other countries, The Energy Policy Act of 2005 states that research, development, demonstrations and commercial applications should be carried out with the following objectives in consideration:

- Increasing the energy conversion efficiency of all forms of fossil energy through improved technologies.
- Decreasing the cost of all fossil energy production, generation, and delivery.



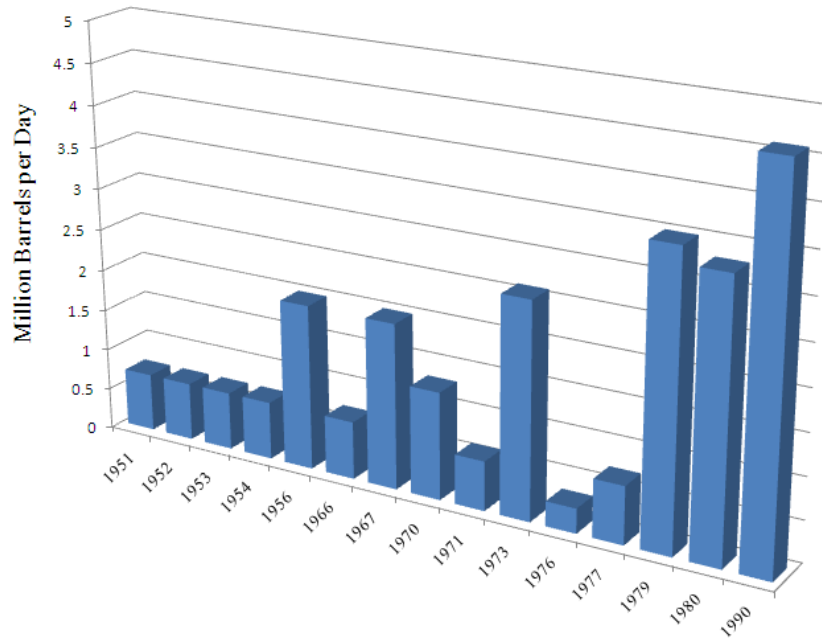


Figure 1.4: Major Disruptions of World Oil Supply.  
Source: Energy Information Administration. 25th Anniversary of Oil Embargo.

- Promoting diversity of energy supply.
- **Decreasing the dependence of the United States on foreign energy supplies.**
- Improving United States energy security.
- Decreasing the environmental impact of energy-related activities.
- Increasing the export of fossil energy-related equipment, technology, and services from the United States.

From the 1950's up to today, there have been several oil supply disruptions as plotted in Figure 1.4. The first major disruption that cause price increases and a worldwide crisis was the 1973 Arab Oil Embargo - before which US citizens were consuming energy without any concern about the supply or price increases. After

this oil embargo, major disruptions in oil supplies have increased and the world oil supplies decreased as shown in Figure 1.4. The scale and severity of these disruptions increased as the US needed more and more oil (Hakes et al., 1998).

The Department of Defense and the Air Force rely heavily on fossil-based fuel for mobility. In order to move any weapon systems and their parts and to sustain required level of support, air mobility is vital and this will require huge amounts of fuel (GAO, 2008).

Energy and petroleum-based products will likely to remain a key element for the US and the Air Force for the near future. On the other hand, air mobility is the key to unlocking the strength of the US air power since it enables rapid global access (Hazdra, 2001). Rapid movement of forces in today's operational environment is very important. Operations may range from peace-sustainment and special duties to medical evacuations. When the National Command Authorities task the DoD to achieve any objective, it relies on Air Mobility Command (AMC) to accommodate rapid global mobility requirements (Hazdra, 2001).

AMC is aware that fuel efficiency is very important for becoming independent of foreign oil. Therefore, it takes every measure to conserve energy and this is stated in their mission statement. Gen. Arthur J. Lichte stated AMC's new five focus areas as:

- Win Today's Fight as Part of the Joint/Coalition Force
- Develop and Care for our Airmen and Families

- Enhance Nuclear Mission Support
- Optimize Mobility Partnerships
- Prepare Mobility Forces for the Future

and continued saying:

“The journey to improve effectiveness and efficiencies must become part of daily business across all functional areas. Effectiveness comes in many forms, from customer service to combat employment, to intangible joint effects. Efficiency enables us to do the mission with the fewest resources possible and therefore enable more participation in other vital endeavours. (Lichte, 2008)”

### ***1.3 Air Force Energy Strategy***

The Air Force is focusing on energy efficiency with many initiatives to become more conservative and to decrease reliance on foreign oil. As plotted in Figure 1.5 AF has adopted a three-point strategy:

- Reduce Demand
- Increase Supply
- Change Culture.

On the demand side, Air Force utilizes direct routing whenever possible to reduce flight time and fuel consumption by flying most fuel-efficient profiles, which reduces unnecessary weight from the aircraft. Every excess pound of fuel equals excess fuel burn during the flight. Also, the Air Force initiated several air refueling optimizations and in order to reduce excess fuel burn, adopted efficient ground operations (GAO, 2008).

In addition to reducing demand, the Air Force is trying to increase the fuel supply by researching the possibility of alternative fuels like 50-50 blends or fuels from coal, natural gas and biomass, and renewable and sustainable resources. Today, the Air Force has certified the B-52 to fly on synthetic fuel and is planning to test and certify other platforms in the near future. The goal is to produce jet fuel more effectively inside the Continental of United States (CONUS) via a synthetic fuel blend.

The vision driving Air Force energy strategy is to “Make energy a consideration in everything we do”. This third element of the energy strategy is the most important of all. Cross-functional Energy Management Groups meet quarterly to discuss and exchange ideas and research, development and integration efforts and integrate aviation, facility and ground equipment energy supply and demand priorities (Energy Strategy). The Secretary of Air Force issued a letter to all Airmen communicating these goals and energy conservation. The Secretary stated the importance of energy conservation and the importance of being fuel independent and charged every airman to develop ways to conserve energy (Aimone, 2007).

As listed in the briefing by Advanced Power Technology Office (Mead, 2009), the Air Force Energy Strategic Plan’s demand reduction goals are stated below:

- Cut aviation fuel usage per hour by 10% by 2016,
- Implement fuel efficiency measures for pilots,
- Incorporate pilot fuel efficiency in the syllabus,
- Reduce motor vehicle fleet petroleum consumption by 2% every year,

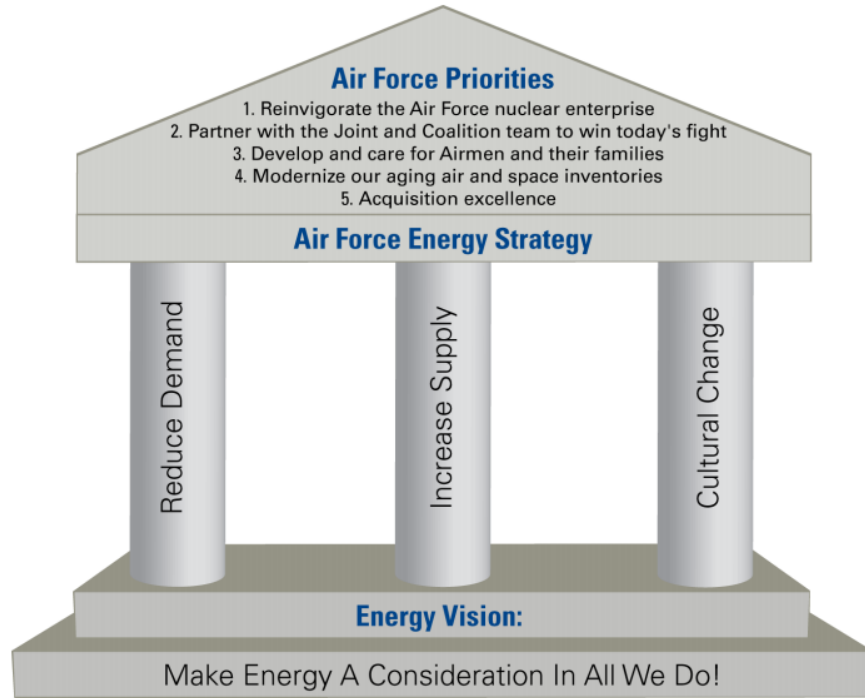


Figure 1.5: Air Force Energy Strategy.  
Source: Secretary of the Air Force AFPM 10-1.1.

- Reduce energy intensity by 3% every year for installations.

The objectives of reducing demand are to (1) increase conservation, (2) improve efficiency and (3) enhance energy security. The implementing objectives are listed as below:

- Fly efficiently as possible,
- Develop highly efficient aircraft,
- Increase jet engine performance,
- Develop fuel efficient equipment,
- Improve infrastructure,
- Procure energy efficient vehicles and items,

The goals of increasing supply are to:

- Increase non-petroleum-based fuel use annually by 10% for motor vehicles,
- Increase facility renewable energy,
- Acquire alternative fuels from domestic resources in which the blend is even produced domestically.

The objectives of this point are to (1) increase alternative fuels and renewables usage, (2) utilize public private partnerships and (3) enhance energy security.

Implementing objectives are to:

- Develop renewable resources in base,
- Procure commercial alternative energy,
- Test and certify 50/50 blend alternative fuel for all aircraft platforms,
- Increase number of flexible fuel systems,
- Manage costs.

The goals for the cultural change on the other hand are as follows:

- Provide energy leadership,
- Increase energy awareness of all personnel by training by 2010,
- Implement energy curricula at the Academy and Air University by 2010,
- Communicate energy awareness everywhere during 'Energy Awareness Month' each October, where the objectives are (1) leadership, (2) training, (3) education and (4) communication.

The implementing objectives for cultural change focus are:

- Provide energy leadership throughout the AF,
- Provide energy awareness training to all uniform and civilian AF members,
- Develop energy curricula in schools,
- Communicate energy successes and lessons learned,
- Identify and develop privately financed energy sources on underutilized lands.

(Mead, 2009)

#### ***1.4 Problem Statement***

Merriam-Webster's on-line dictionary defines conservation as careful preservation and protection of something: especially planned management of a natural resource to prevent exploitation, destruction or neglect. Therefore, fuel conservation is managing the operation and condition of an airplane to minimize the fuel used on every flight (Anderson, 2006).

The Air Force and AMC are trying to conserve fuel with many initiatives such as reducing mach for the strategic air carriers, reducing weight by removing unnecessary equipment or developing lighter items, reducing contingency fuel, changing weather requirements for alternate air field selection and applying more fuel efficient ground operations. The Air Force defined their goal as reducing fuel consumption by 10% by 2016 while sustaining the same operational efficiency. But in order to manage this

strategy successfully, the Air Force has to measure how well it is doing on achieving reduction of fuel consumption.

This study focuses on measuring the fuel efficiency of missions of the C-17 aircraft operated under Air Mobility Command.

The research question is to determine a method of efficiency measurement for Air Mobility Command. Some investigative questions that support our research question are: (1) How can we measure fuel efficiency? (2) What are the factors that effect fuel efficiency? (3) What is the monthly fuel efficiency score of AMC for C-17 aircraft missions?

### ***1.5 Methodology***

Data Envelopment Analysis (DEA) will be used to determine monthly fuel efficiency. DEA is a non-parametric method to measure relative efficiency of several Decision Making Units (DMU) which have identical inputs and outputs. It can deal with multiple inputs and outputs successfully and it does not require any production function, which makes it easier to apply but also vulnerable to some areas which are discussed in Section 1.6. DEA was first introduced by Charnes et al. (1978) and utilizes Farrell's (1957) efficiency definition. Since this paper examines only C-17 fuel efficiency, it is assumed that a DMU to be a particular C-17 mission.



## ***1.6 Limitations and Assumptions***

Data Envelopment Analysis assumes that each Decision Making Unit is homogeneous. In this study, C-17 missions are used as DMUs and these missions can differ in type. Since all missions are on the same C-17 platform and they all have the capability to create a similar sortie and produce the same amount of output given the same conditions, it is assumed that all missions are homogeneous.

## ***1.7 Summary***

In this chapter, analysis of current U.S DoD oil consumption was provided. Next, the importance of fuel (energy in general) and US dependence to foreign oil and its national strategic importance were highlighted. Then, the Air Force Energy Strategy was described and finally an overview of our research question and methodology was provided.

The thesis is organized as follows: in Chapter 2, a review of the literature of Efficiency definitions and Data Envelopment Analysis are provided. Chapter 3 consists of the journal article that is submitted to the Journal of Operational Research Society and in Chapter 4, a summary and conclusions are derived from the study along with possible research areas for future study.

## II. Literature Review

### 2.1 Chapter Overview

This section introduces efficiency measurement in air transportation and AMC's current method for calculating fuel efficiency. Then, the Transportation Service Index and the Fisher Ideal Index methodology are explained. A brief introduction of Farrell's efficiency is then presented. Farrell (1957) defines a simple measure of efficiency that takes into account multiple inputs. Charnes et al. (1978) takes this efficiency measurement one step further and introduces a mathematical program to measure relative efficiency of homogeneous decision making units, which is widely used today and known as Data Envelopment Analysis (DEA). An application of DEA termed Window Analysis is also discussed. Window Analysis allows one to study the efficiency score of decision making units over a specific time period.

### 2.2 Efficiency in Transportation

Transportation, specifically air transportation, heavily relies on energy which is produced from petroleum-based products. As the AF becomes a global power and needs to move more military items and personnel over longer distances, its dependence to fuel increases. On the other hand, the USA is becoming more dependent on foreign oil, most of which comes from insecure countries. Since air transportation consumes about 15 times as much fuel as trucks and more than 50 times more than railroads and water carriers, a shortage on fuel supplies will have a significant effect on air transportation (O'Connor, 2001).

In order to reduce this dependence on other countries' petroleum, the fuel is needed to be conserved. The AF is taking several steps and developing plans to improve fuel efficiency, decrease demand to conventional fuel and explore alternative fuels.

Gross fuel efficiency can be measured in several ways but the most common measures are the aggregate output per gallon of fuel consumed (Oum and Yu, 1998) as in equation 2.1. This measure is mostly referred as gallons per ton-mile. Here, the output is measured as the distance the freight is moved (distance times freight). The higher the gross efficiency score, the better.

$$Efficiency = \frac{Output(tonmiles)}{Energy Input(gallons)} \quad (2.1)$$

In his study, McLean (2006) reports that efficiency is used in numerous ways. He lists most-used efficiency terms in aviation as:

- aerodynamic efficiency,
- cruising efficiency,
- fuel efficiency,
- propulsive efficiency,
- structural efficiency.

On the other hand, AMC is interested in an efficiency measure that it can drill down into each component and see how each component effects the overall fuel

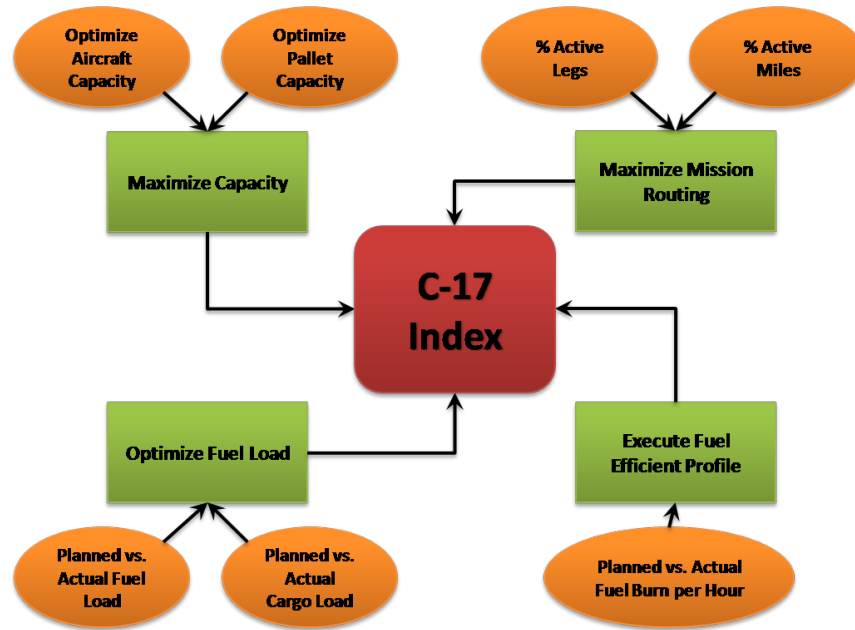


Figure 2.1: Fuel Efficiency Index Illustration.  
Source: AMC Fuel Efficiency Office.

efficiency. Therefore, AMC Fuel Efficiency Office created an efficiency index for each airlift and tanker aircraft.

The AMC Fuel Efficiency Index (FEI) for C-17 aircraft is a weighted average index of 7 factors that includes (1) Percent Active Miles, (2) Percent Active Legs, (3) Pallet Capacity, (4) Aircraft Capacity, (5) Planned vs. Actual Fuel Load, (6) Planned vs. Actual Cargo Load and (7) Planned vs. Actual Fuel Burn per Hour as depicted in Figure 2.1.

The inputs include (1) Number of Total Legs, (2) Total Leg Distance (in miles), (3) Cargo Capacity for that mission(in 1000 lb), (4) Pallet Position Available for that mission, (5) Planned Fuel Load (in lb), (6) Planned Cargo Load (in 1000 lb) and (7) Planned Fuel Burn( in 1,000 gal/hr). The outputs include (1) Number of Active

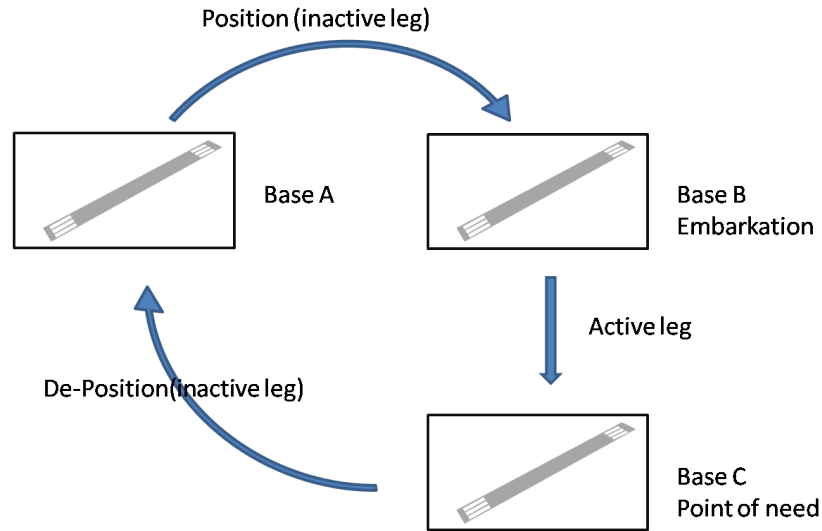


Figure 2.2: Active and Inactive Legs

Legs, (2) Active Leg Distance (in miles), (3) Amount of Cargo Carried (in 1000 lb), (4) Pallet Position Equivalent Utilized, (5) Fuel Load Accuracy, (6) Cargo Load Accuracy and (7) Fuel Burn Accuracy. A more detailed explanation of each input is presented in the next chapter.

A leg is a flight segment on which a stop occurs. An active leg is the mission segment on which the aircraft actually moves the cargo load from point of embarkation to the point of need, while an inactive leg is the segment of the same mission where no cargo is moved, such that this segment was either to position the aircraft for an active leg or to return to home base. This input is important because any unnecessary movement of the aircraft other than for an active leg will add to inefficiency. For example, instead of utilizing an aircraft on the embarkation airfield, if another aircraft is positioned for that mission, the fuel usage will increase. Active legs and inactive legs are depicted in Figure 2.2.

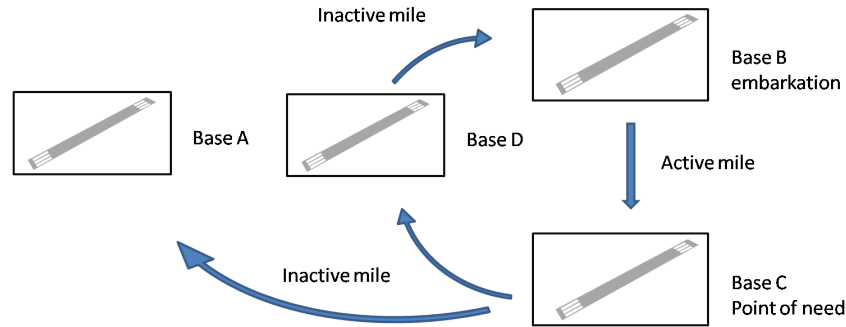


Figure 2.3: Active and Inactive Miles

Analogously, leg distance is the distance between the airfield where the aircraft takes off and the airfield where it lands. An active mile is any mile that an aircraft moves cargo. An inactive mile is a mile where no cargo movement occurs. Leg distance is an important measure because as seen in Figure 2.3 if an aircraft is positioned farther than another aircraft that is available closer, then fuel usage will increase.

Volume utilization is used as an input to account for the situation where volume is fully utilized before the maximum ramp weight is fully utilized. For example, a low density cargo limits the volume of the aircraft while it can still carry extra weight. Pallet position equivalent measure are used to calculate volume utilization.

Weight utilization on the other hand is to increase efficiency by fully loading the aircraft up to the available cabin load. Fully loading the aircraft helps reduce the number of sorties required to carry cargo and accomplish the mission. Thus, it is an important input in the efficiency measurement.

Extra care should be given in the planning phase of a mission. The International Air Transportation Association (IATA) stresses that “accurate and efficient fuel management on the part of the airplane and flight crews improves safety, because it

requires additional attention, accuracy and increased situational awareness.” Thus, it is important first to carefully plan the fuel load then to carefully execute those plans. Any deviation from the fuel load will increase fuel usage either by carrying unnecessary fuel during the entire flight segment, or require landing or air refuelling to get the needed fuel. In her study, Trujillo (1996) notes that pilots and dispatchers allocate more fuel than legal requirements of the Federal Aviation Regulations (FARs) and this amount increases when the flights are over water. On average, today’s jet aircraft burn an extra 3-4% more fuel to carry additional unneeded fuel (IATA, 2004).

Careful cargo planning is also very important since it will add to fuel burn as well. The actual cargo should match the planned cargo. Any deviation will cause additional fuel burn. The deviation will cause planners to plan extra fuel for the mission which will add extra unneeded weight to the aircraft. The IATA states that a lighter aircraft will be safer because it provides “(1) greater terrain clearance on take-off, (2) ability to climb quicker, (3) higher cruise altitude, (4) better stall recovery and lower stall speed, (4) lower approach speed and (5) reduced landing distance and reduced tire and brake wear”.

Fuel burn per hour should be calculated for every flight accurately and once planned carefully, any deviation results from a series of factors like pilot technique, wind, aircraft variations, operational factors etc. Actual fuel burn should come as close to the planned fuel burn as possible.

The overall efficiency index is the weighted average of these 7 factors where the weights are assigned with collaborative expert opinions. A list of equations for each factors as well as FEI are given here:

$$Fuel\ Efficiency\ Index = \sum_{i=1}^7 w_i I_i$$

where the  $I_s$  are:

$$Percent\ Active\ Leg = Total\ Active\ Legs / Total\ Legs$$

$$Percent\ Active\ Miles = Total\ Active\ Miles / Total\ Miles$$

$$Pallet\ Capacity = PPE\ Used / PPE\ Available$$

$$Aircraft\ Capacity = Actual\ Cargo\ Load / Available\ Cabin\ Load$$

$$Fuel\ Load = 1 - (| Actual - Planned | / Planned)$$

$$Cargo\ Load = 1 - (| Actual - Planned | / Planned)$$

$$Burn\ per\ Hour = 1 - (| Actual - Planned | / Planned)$$

where  $w$  is the assigned weight for each index and Actual and Planned indicate actual fuel filled to aircraft or cargo loaded on board or fuel burn per hour during mission and planned fuel to fill to aircraft or cargo to load or fuel burn, respectively.

### 2.3 Transportation Service Index

The Transportation Service Index (TSI) is a monthly index to measure the volume of services performed by for-hire transportation sectors that include (1 trucking,



(2) rail road, (3) inland waterway, (4) pipeline and (5) air freight. Even though it is still under development and is an experimental measure it can be examined to have a better understanding of the current economic conditions.

The index created by Lahiri et al. (2003) utilizes a chained Fisher ideal index method. The Fisher index is an economic index that is the geometric mean of two other indices: Laspeyres and Paasche. The difference between the mentioned indices is that the Laspeyres and Paasche indices are fixed weighted using a single period weights while Fisher is a current-weighted index. The Laspeyres and Paasche indices may over or understate growth while the results of the Fisher Ideal Index will fall between since it is the geometric mean of these two indices.

The equation for the transportation index is given by:

$$I = \sqrt{\frac{\sum_j I_{jm} P_{jy(m-6)}}{\sum_j I_{jm-1} P_{jy(m-6)}} * \frac{\sum_j I_{jm} P_{jy(m+6)}}{\sum_j I_{jm-1} P_{jy(m+6)}}$$

where

$I_{jm}$  is the output index in subsector  $j$  in month  $m$ ;

$P_{jy(m)}$  is the value-added weight for subsector  $j$  in year  $y$ ;

$y(m)$  is the year containing the month  $m$ .

The weights for each subsector are based on “Gross Product by Industries” as given in Figure 2.4. The recent TSI for year 2000-2008 is shown in Figure 2.5.

The main problems of trying to apply this technique to come up with a FEI are

(1) it does not assign weights for each factor: weights for factors should be assigned

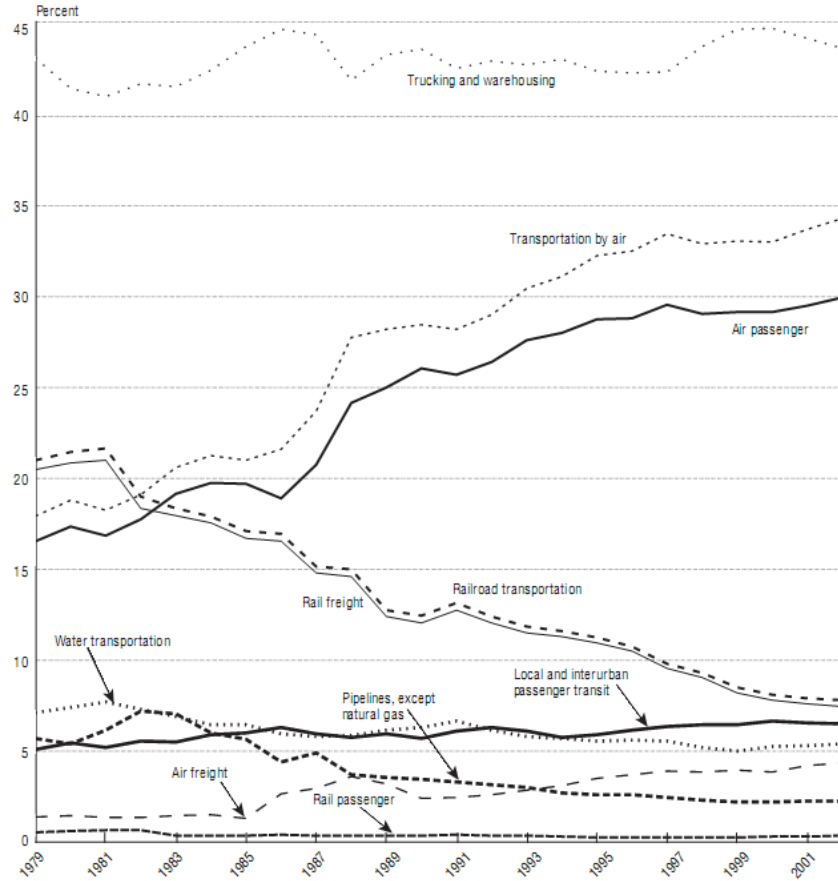


Figure 2.4: Annual Weights for the Aggregation of Transportation.

Source: “Gross Product by Industry” table, Survey of Current Business, November 2001.

first and (2) since the weights assigned for each factor will likely be same each period (unlike the TSI weights as seen in Figure 2.4) then the Fisher Index method will be no more than a simple weighted average. Thus, this approach is not utilized to create a FEI.

## 2.4 Farrell Efficiency

Simply put, efficiency is achieving the most output for a given input. If the amount of input used and the amount of output produced can be measured accurately,

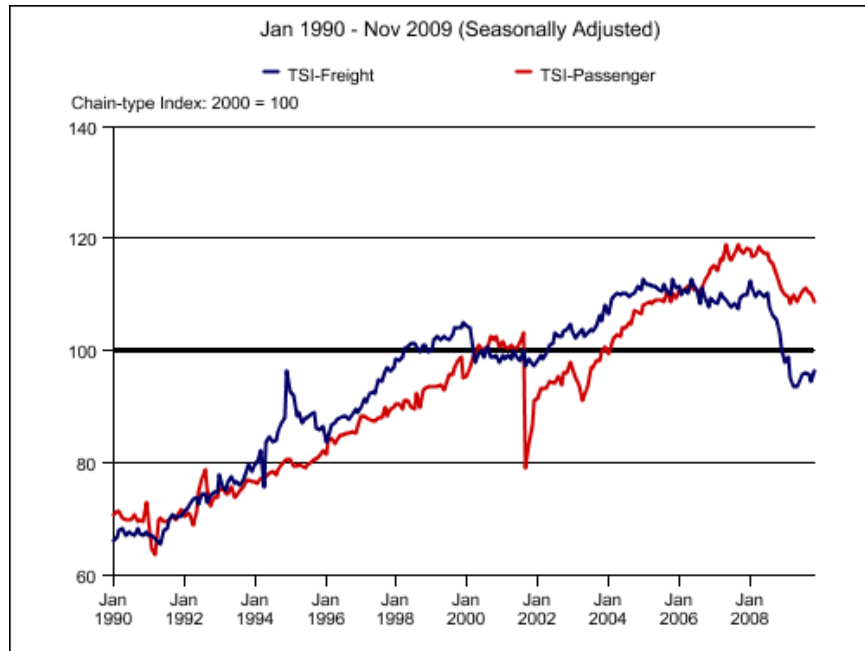


Figure 2.5: Transportation Service Index.  
 Source: Bureau of Transportation Statistics, February 2010.

then the efficiency can easily be calculated. Farrell (1957) mentions this would be generally accepted and in his work, he explains technical efficiency with a simple example.

Consider a production process with two inputs  $x$  and  $y$  and one output with constant returns to scale (which he relaxes in his work later). If the efficient production function is known, then any input-output combination for that production process can be calculated. The result are plotted in Figure 2.6.

Here in the plot, the SS' isoquant represent any input combinations that yield the best possible output which means a perfect efficient process. Any point on the isoquant will be an efficient process. For example, Point Q represent an efficient process which lays on the SS' isoquant. On the other hand, point P represent an

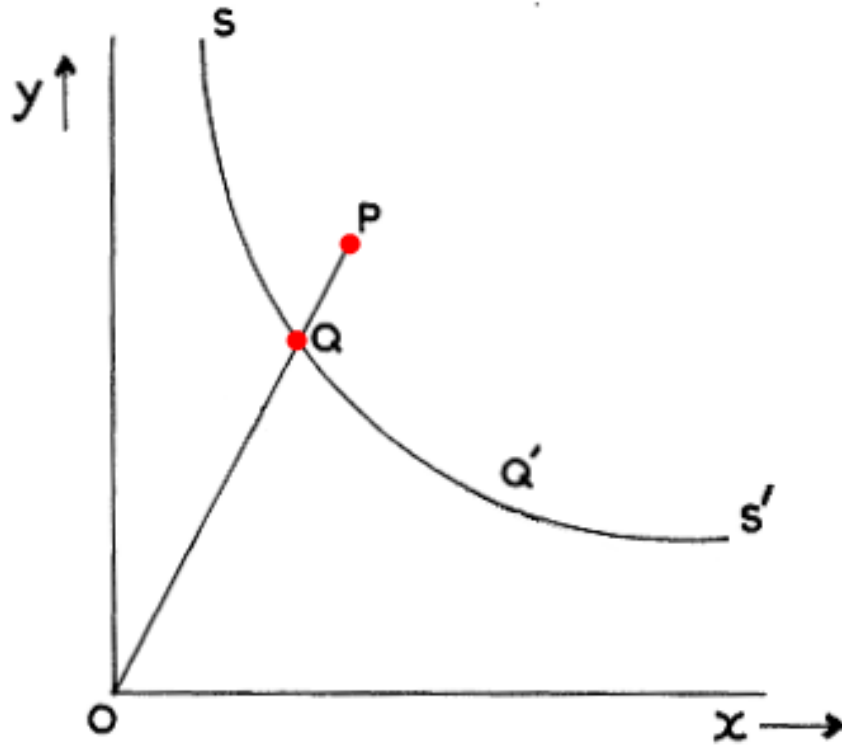


Figure 2.6: Farrell Production Function.  
Source: Farrell (1957).

inefficient process and lays over the  $SS'$  isoquant. Even though  $P$  produces the same unity output like  $Q$ , it uses more inputs ( $x$  and  $y$ ). Therefore,  $P$  is only  $OQ/OP$  times as efficient as  $Q$ . Farrell denotes this ratio of  $OQ/OP$  as technical efficiency. With the same approach, the efficiency of any processes can be calculated easily.

### 2.5 Data Envelopment Analysis

The DEA methodology was first introduced by Charnes et al. (1978) and is based on Farrell's efficiency measure. DEA evaluates homogeneous decision making units to measure relative efficiency. It is a fractional programming method and can handle multiple inputs and outputs. The efficiency of a DMU is defined as the ratio

of the weighted sum of outputs to the weighted sum of inputs. Efficiency of any DMU is then obtained by maximizing that ratio subject to the condition that the similar ratios for every DMU be less than or equal to unity (Charnes et al., 1978).

The fractional programming can be written in the following form:

$$\begin{aligned}
 \max h_0 &= \frac{\sum_{r=1}^s u_r y_{r0}}{\sum_{i=1}^m v_i x_{i0}} \\
 \text{subject to: } &\frac{\sum_{r=1}^s u_r y_{rj}}{\sum_{i=1}^m v_i x_{ij}} \leq 1; \quad j = 1, 2, \dots, n \\
 &v_r, v_i \geq 0; \quad r = 1, 2, \dots, s; i = 1, 2, \dots, m
 \end{aligned} \tag{2.2}$$

where the  $y_{rj}$ ,  $x_{ij}$  are the outputs and inputs of the  $j$ th DMU and the  $u_r, v_i \geq 0$  are the variable weights to be determined by the solution of this problems.  $n$  is the total number of DMUs. The particular mission being evaluated is assigned the subscript 0 to distinguish. All missions including the one under consideration are used in the constraints. Therefore any mission will not be assigned an efficiency of more than 100% (Charnes et al., 1978).

In order to obtain the relative efficiency of each DMU under consideration, the above model is solved  $n$  times. The DMU under evaluation is known as the target DMU. The model allows it to select optimal input and output weights for itself in order to maximize its efficiency score, constrained by no other DMU with the same weights as obtaining more than 100% efficiency rating.

This fractional model in (2.2) can be converted to an equivalent linear model.

The Linear Programming(LP) formulation is shown here:

$$\text{maximize : } \sum_{r=1}^s u_r y_{r0} \quad (2.3)$$

*Subject to :*

$$\sum_{r=1}^s u_r y_{rj} - \sum_{i=1}^m v_i x_{ij} \leq 0 \quad \forall j$$

$$\sum_{i=1}^m v_i x_{i0} = 1$$

$$u_r, v_i \geq 0 \quad \forall r \text{ and } i$$

Each relative inefficient DMU is compared against a set of efficient DMUs and these efficient DMUs compose the Efficiency Reference Set (ERS). A hypothetical composite DMU is created by combining the weighted inputs and outputs of the efficiency reference set units that produces greater or equal outputs with fewer or equal inputs (Rutledge et al., 1995).

In order to illustrate this formulation, the following example is used. Lt. Kiymaz is a project officer at Logistics Headquarters. He is given a project to determine relative efficiency scores of different supply units assigned to the 1st Air Force. The inputs of a given supply unit are the labor hours and the amount of capital (in \$1,000s) and the output is the number of items delivered (all inputs/outputs are weekly values). Values of each DMU are given in Table 2.1.

Table 2.1: Input and Output Values of DMU for Illustration Example

Unit No.	Labor	Capital	Delivery
1	34	70	132
2	25	60	100
3	19	45	55
4	45	74	160

A separate linear program is solved for each DMU in the problem. The following LP problem is solved in order to find relative efficiency score of unit 1:

$$\begin{aligned}
 \text{MAX :} & \quad 132u_1 \\
 \text{Subject to :} & \quad 132u_1 - 34v_1 - 70v_2 \leq 0 \quad \text{efficiency constraint of unit 1} \\
 & \quad 100u_1 - 25v_1 - 60v_2 \leq 0 \quad \text{efficiency constraint of unit 2} \\
 & \quad 55u_1 - 19v_1 - 45v_2 \leq 0 \quad \text{efficiency constraint of unit 3} \\
 & \quad 160u_1 - 45v_1 - 74v_2 \leq 0 \quad \text{efficiency constraint of unit 4} \\
 & \quad 34v_1 + 70v_2 = 1 \quad \text{input constraint for unit 1} \\
 & \quad w_1, v_1, v_2 \geq 0 \quad \text{non - negativity condition}
 \end{aligned}$$

Table 2.2: Efficiency Results for the Example.

Unit No:	Efficiency Rating	ERS and Weightings
1	100%	NA
2	100%	NA
3	73%	(0.038 Unit-1 + 0.5 Unit-2)
4	100%	NA

When the LP is replicated and solved for each supply unit, the efficiency scores are found and given in Table 2.2. The information suggests that unit 3 is inefficient relative to a hypothetical unit that is a linear combination of the inputs and output of units 1 and 2. Unit 3 should produce the same output with only 73% of the inputs.

Table 2.3: Inputs for Visual Example

DMU:	A	B	C	D	E	F	G	H
Input 1	5	3	2	3	4	1	4	2
Input 2	8	6	2	5	1	7	4	9
Output	1	1	1	1	1	1	1	1

To make a visual explanation, let's assume that a production process with two inputs and only one unity output where there are 8 DMUs. The inputs for each DMU are given in Table 2.3. The production of DMUs are plotted in Figure 2.7. Cooper et al. (2000) state that DMUs producing more with less input shall be judged more efficient. Therefore, the DMUs (C), (E) and (F) are the efficient DMUs and the lines connecting them are collectively called the 'frontier line'. One can envelop all data points within the frontier line and this region is called 'the production possibility set'.

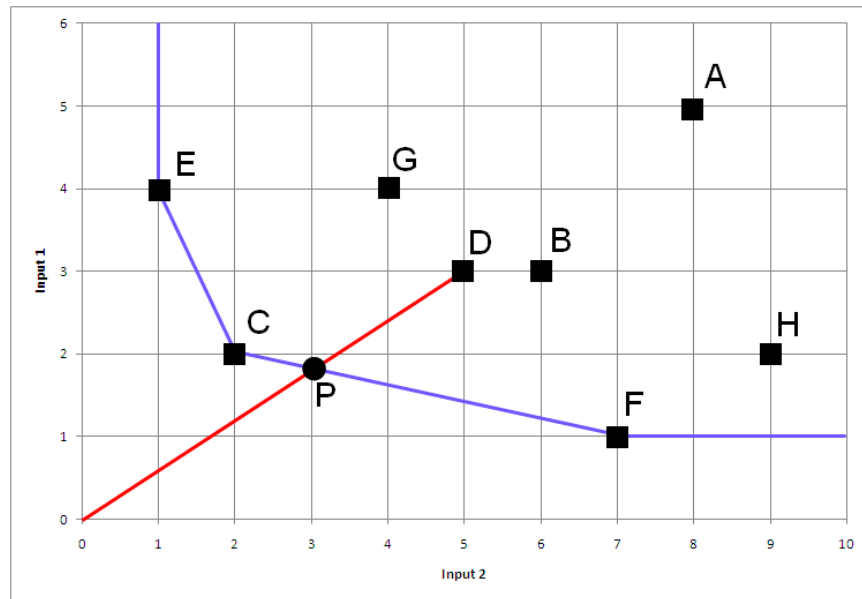


Figure 2.7: A Sample Production Function.

Efficiency scores of inefficient units can be calculated with the distance to the efficiency frontier. For example, DMU D is inefficient and the efficiency score for that



DMU can be calculated by dividing the line from origin to efficiency frontier (OP) by the line from origin to DMU (OD). It can be seen that the efficiency score for DMU D is evaluated by a combination of DMUs C and F. Therefore, those DMUs are called the ‘reference set’ for that DMU.

There are several other DEA techniques other than CCR (the model just examined) which take increasing/decreasing or constant and variable returns-to-scale, or slacks that are the input excesses and output shortfalls and etc. Under its weak efficiency model, CCR evaluates the radial (ratio) efficiency and does not account for the zero slacks. To deal with the variable returns-to-scale Banker et al. (1984) propose another model called BCC (Banker-Charnes-Cooper).

The the input-oriented BCC model can be formulated as the linear program:

$$\begin{aligned}
 & \text{Minimize} \quad \theta_B \\
 & \text{Subject to :} \quad \theta_B \mathbf{x}_o - X\boldsymbol{\lambda} \geq 0 \\
 & \quad \quad \quad Y\boldsymbol{\lambda} \geq \mathbf{y}_o \\
 & \quad \quad \quad \mathbf{e}\boldsymbol{\lambda} = 1 \\
 & \quad \quad \quad \boldsymbol{\lambda} \geq 0
 \end{aligned} \tag{2.4}$$

where  $\theta_B$  is the scalar efficiency score,  $\mathbf{x}_o$  is the input matrix for unit under evaluation ,  $\mathbf{y}_o$  is the output matrix for the unit under evaluation,  $X$  and  $Y$  are the input and output matrices, respectively,  $\boldsymbol{\lambda} \in R^n$  where  $n$  is the total number of DMUs and  $\mathbf{e}$  is a row vector with all element being 1.

Since the BCC model introduces an additional constraint to the CCR model, the feasible region will be a subset of the CCR model. Thus, the CCR efficiency scores will be less than or equal to BCC scores.

To take the slacks into account, Charnes et al. (1985) developed the additive model which measures the efficiency of the DMUs dealing with the slacks (inputs excesses and output shortfalls). Even though this model can discriminate between efficient and inefficient units, it lacks a measurement of inefficiency like  $\theta$  in other models. To deal with this lack, Tone (2001) proposes a new model called the Slack-Based Measure (SBM). To visually explain, a new DMU (I) is added to the example in Table 2.3 which uses 1 unit of input 1 and 8 unit of input 2. Figure 2.8 illustrates the new production set. Both DMU F and I gets 100% efficiency score under the CCR model since they are both on the efficiency frontier but F uses one less input to produce the same output with I which means DMU I has 1 slack in input 2.

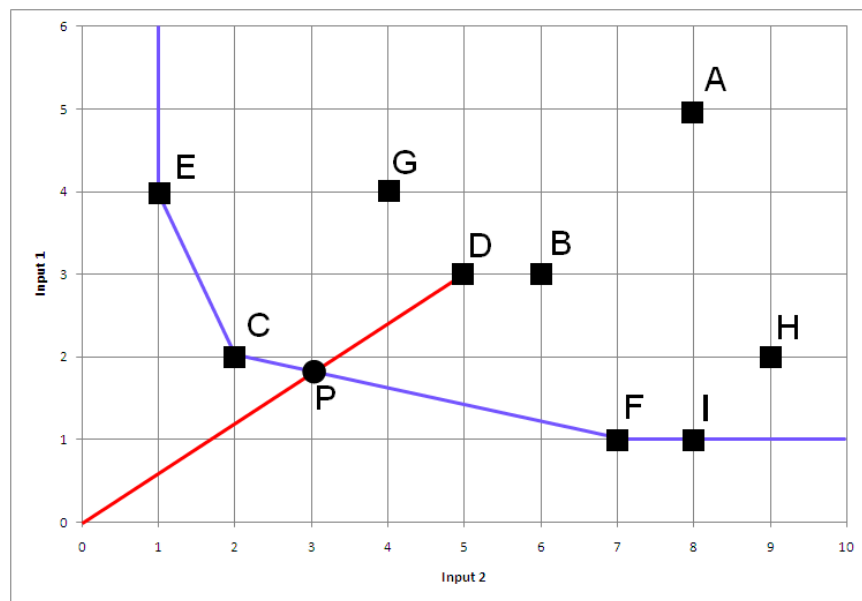


Figure 2.8: New Production Function for SBM CCR comparison.

The linear program for the SBM is given in equation 3.6 in next chapter .

Since the SBM model deals with slacks but the CCR model does not, the SBM efficiency score will be less than or equal to the CCR score.

## ***2.6 Window Analysis***

One use of DEA is as a tool to assess efficiency changes of a DMU or several DMUs over time. Past data of a DMU is generally available. Thus, managers would like to see the performance changes of DMUs over a certain time horizon. Also, assessing variation in efficiency helps managers to decide which periods processes should be adopted as operation policies. There are several ways to do this with DEA.

First, one can add up  $k$  periods data for any DMU and assess its performance as a single unit but this technique omits the information of how does the efficiency of that DMU changes over time. Boussofiane et al. (1991) suggest that variability could be the consequence of changes in the environment like variation in staff or changes in operation policies or even maybe seasonal differences.

Another approach to capture unit efficiency changes over time would be to treat each time period as a different DMU. This method can be applied to a single DMU to capture its own efficiency changes over a certain period of time (Rutledge et al., 1995) or it can be applied to assess several DMUs efficiency changes over time. Then  $nk$  units will be available to be assessed. With this approach, an idea of variability of efficiency of each unit can be observed over time (Boussofiane et al., 1991).

Table 2.4: Classical Window Analysis Example

		Period								
		1	2	3	4	5	6	.	.	$t$
DMU	window 1	$e_{11}$	$e_{12}$	$e_{13}$	$e_{14}$	$e_{15}$				
	window 2		$e_{12}$	$e_{13}$	$e_{14}$	$e_{15}$	$e_{16}$			
	...									
	...									
	window k					..	..	..	..	..

Window analysis, the final approach, is a technique to assess efficiency of a DMU over time as proposed by Charnes et al. (1983). It captures the efficiency changes by assuming DMU input and output values as a different DMU in each period of time like week, month or etc.

In classical window analysis, a window is constructed by using some  $p$  time periods and the input and output values of the DMU in each of the time periods are used. After assessment of the first window, a new window is formed and the first period is dropped. The efficiency of this window is assessed and then a new windows is constructed by dropping the earliest period from the earliest window. This is repeated until the very last period is evaluated in a window.

To illustrate this method an example of the window analysis is constructed and given in Table 2.4 . To assess the DMU a window is formed consisting of 5 time periods. After efficiency scores of the first window are calculated, a second window is formed by dropping first period's data and including the 6<sup>th</sup> period's data. This process is repeated until the last period over the horizon is reached.

Window analysis allows managers to monitor efficiency changes over time, thereby providing them valuable information about the behaviour of the process, operation policy or unit under evaluation. On the other hand, this classical window analysis method has a drawback from a process improvement standpoint (Talluri et al., 1997). In classical window analysis whenever a new window is formed, the earliest period is dropped from the window. However, if the efficiency score of this earliest period is higher than other periods, the new period is not challenged with the best period but misleadingly with the periods with poor performance. Managers would like to track periods with best performances and would like to have periods with good operating practices, rather than less efficient periods.

In order to cope with this drawback of classical window analysis, Talluri et al. (1997) suggest a new 'modified window analysis'. In this new technique, instead of dropping the earliest period whenever a new window is formed, the period with the lowest efficiency score is dropped. According to the authors, this new modified analysis compares new period with the best periods of good overall practices and they continue stating that this analysis is superior to the classical window analysis from a process improvement process since the relative efficiency of a new period is challenged against the best past performer periods.

To illustrate this modified window analysis method, an example is constructed and given in Table 2.5. The first window is the same as the classic analysis, being formed with the first 5 periods. After the evaluation of this first window, a second window is formed by adding the next period and dropping the 3<sup>rd</sup> period since it is

Table 2.5: Modified Window Analysis Example

		Period								
		1	2	3	4	5	6	.	.	$t$
DMU	window 1	$e_{11}$	$e_{12}$	$e_{13}$	$e_{14}$	$e_{15}$				
	window 2	$e_{11}$	$e_{12}$		$e_{14}$	$e_{15}$	$e_{16}$			
	...									
	...									
	window k					..	..	..	..	..

has the lowest efficiency score between other periods in window 1. Again, this process continues until the last period is assessed.

How many periods the window will cover is a concern for the analysis. One can decide the length of the window but Boussofiane et al. (1991) suggest a window to cover periods of time over which operating conditions are similar or where seasonal effects on performance are similar or where some other factor pertaining to the units are being assessed. Also, they emphasize that with the window analysis, the analyst has the ability to control for seasonal factors and investigate only efficiency changes over time.

As a rule of thumb, the total number of DMUs should be several times greater than the total number of inputs plus outputs (Cooper et al., 2000). If the number of DMUs is less than total input and output number then the linear program will not be able to discriminate between efficient and inefficient units; therefore most of them will be assigned as efficient. Since there are only a couple months of AMC data available and have only  $7+7=14$  inputs and outputs, it is not possible to run a window analysis. Therefore, in this study every mission is treated as a different DMU

rather than aggregating them as a month. Also, this will give us the opportunity to distinguish different mission types that achieve either high or low efficiency.

## ***2.7 Strengths and Limitations***

*2.7.1 Strengths.* Data Envelopment Analysis can be a powerful tool when used wisely (Anderson, 1995). It has several superior characteristics compared to other efficiency measurement techniques:

- DEA can handle multiple-input and multiple-output models.
- It does not require an assumption of a functional form relating inputs to outputs.
- DMUs are directly compared against a peer or combination of peers.
- It does not require a common measurement unit for inputs and outputs. For example, one input can be in dollars while the other in percentage and a third one in number of person, without requiring a weighting between them.
- Sensitivity analysis can be applied to determine where most resources are used that inefficiencies occur.

*2.7.2 Limitations.* Although it has some superior characteristics than other methods, the analyst should know the limitations of DEA:

- Since DEA is an extreme point technique, noise, such as measurement error with zero mean, can cause problems.

- DEA measures relative efficiency rather than technical efficiency of a DMU. Thus, if the data set does not have the best possible input-output set then DEA may overstate the efficiency score of DMUs.
- DEA is good at estimating “relative” efficiency of a DMU but it converges very slowly to the mean “absolute” efficiency.
- DEA measures the efficiency of DMU’s rather than their “effectiveness”. Basically, this means that it is well suited for evaluating how much they produce but not for determining if they are producing the right things.
- Since DEA is a non-parametric technique, statistical hypothesis tests are difficult to construct.
- For each DMU in a particular DEA analysis, a new LP should be formulated, therefore it may take intensive computational time.



### III. Article Submission

#### Fuel Efficiency Assessment with DEA

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##### **3.1 Abstract**

Military air forces have a significant demand for fuel, but increasing costs force them to use their fuel as efficiently as possible. We investigated the suitability of Data Envelopment Analysis (DEA) to measure C-17 airlift fuel efficiency for the United States Air Mobility Command (AMC). Airlift missions constitute units in our study. Seven respective inputs and outputs were used and three different DEA models were contrasted. The results show that DEA provides an effective ability to identify fuel usage inefficiencies. A slack-based DEA measure proved superior at differentiating inefficiencies to an established index in use by AMC planners.

##### **3.2 Background**

Aviation fuel will remain a necessary strategic asset for effective military operations until feasible alternatives are available in sufficient quantity. The United States Air Force (USAF) uses more fuel than its sister services combined, as shown in Figure 3.1. History suggests that oil supply disruptions increase in scale and strength as oil demand grows (Hakes et al., 1998). Therefore, reducing oil dependency is an

important goal for military planners, and one way to achieve that goal is to use fuel as efficiently as possible. To measure efficiency, USAF Air Mobility Command planners established a fuel efficiency index (FEI) for each cargo aircraft type in inventory as the weighted sum of seven factors. The weights were subjectively determined based on expert opinion. The AMC planners were concerned that their FEI was not sufficiently sensitive to be useful, and asked us to investigate improvements. In this paper, we first briefly review index numbers and describe the AMC FEI. We then provide a brief overview of Data Envelopment Analysis and three particular variants, and show how it can be effectively used to measure fuel efficiency over time. We conclude with recommendations for further research.

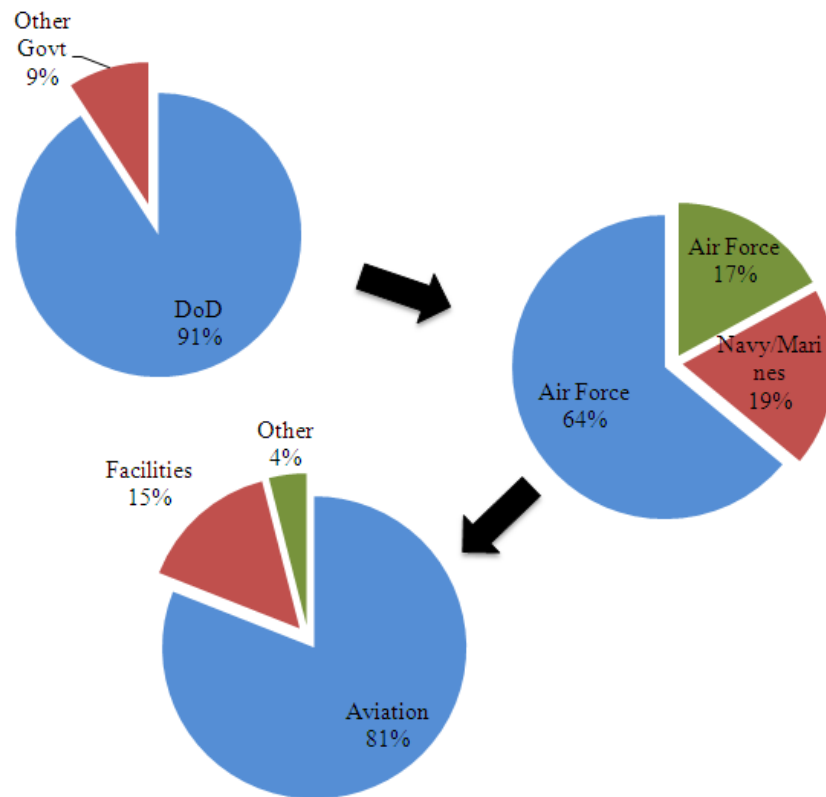


Figure 3.1: Federal Government, DoD and Air Force Fuel Utilization.  
Source: Air Force Energy Strategy.

### 3.3 Index Numbers and the AMC FEI

An index number is an average economic indicator of changes of different commodities in price or quantity over a specific time frame. The consumer price index, for example, is the most common known index number that measures the changes in retail prices that consumers pay. Index numbers are used in a wide range of area like comparing business activities, cost of living etc.

Since index numbers capture and measure the changes, it is appropriate to study them for our purpose of measuring AMC fuel efficiency. The US Department of Transportation (DOT) uses a chained Fisher ideal index termed the Transportation Service Index (TSI) to measure changes in the volume of services performed by for-hire transportation sectors Lahiri et al. (2003). The index proposed by Fisher (1922) is a geometric mean of the Laspeyres (PL) and Paasche (PP) indices. The mathematical formulations of these indices are given below,

$$P_P = \frac{\sum p_{i,t_n} \cdot q_{i,t_n}}{\sum p_{i,t_0} \cdot q_{i,t_n}} \quad (3.1)$$

$$P_L = \frac{\sum p_{i,t_n} \cdot q_{i,t_0}}{\sum p_{i,t_0} \cdot q_{i,t_0}} \quad (3.2)$$

$$P_F = \sqrt{P_P \cdot P_L} \quad (3.3)$$

where  $P$  is the change in price level,  $p_{i,t}$  represents the price of  $i$ th item in time period  $t$ ,  $q_{i,t}$  represents the quantity of  $i$ th item in time period  $t$ ,  $t_0$  is the base period

and  $t_n$  is the period of interest. The Lapeyres and Paasche indices are fixed-weighted, using the weights of a single period, and may respectively over or underestimate growth. On the other hand, the Fisher index - as the geometric mean of Laspeyres and Paasche-will fall between them.

The TSI is calculated using the gross product by industries as weights for each subsector. Gross product by industries shows the relative contribution of each sector or subsector to the overall industry. These relative contributions change over time when one sector produces more output than the other in terms of economic value. The weights will thus vary as each sector's role grows or declines in relative contribution to the overall industry.

The fuel efficiency index (FEI) was created by AMC's Fuel Efficiency Office to measure the respective efficiency changes for C-5, C-17, C-130, KC-10 and KC-135 aircraft over time. It is a weighted average index of 7 factors that include 1) percent active miles, 2) percent active legs, 3) pallet capacity, 4) aircraft capacity, 5) planned vs. actual fuel load, 6) planned vs. actual cargo load and 7) planned vs. actual fuel burn per hour. Expert opinions by AMC staff were used to determine the factor weights for each aircraft. The main problem in applying index number theory to the AMC FEI is that the factor weights were defined by AMC planners as constant over time, with the result that the Laspeyres, Paasche and Fisher indices become a simple weighted average.

Calculating fuel usage for an aircraft mission is an iterative process because of the dynamic change in aircraft weight as fuel is burned. Therefore, tying all FEI factors into a single functional form is difficult. Further, the FEI weights - being based only on expert opinions - are therefore subjective and make FEI validity vulnerable. Desired fuel efficiency index characteristics should : 1) not require any prior assumptions about input and output weights; 2) require objective weights values; 3) not require establishing prior mathematical functional forms between inputs and outputs; and 4) be unit independent so dissimilar units like the number of flight legs, distance, or cargo weight can be simultaneously evaluated.

### **3.4 DEA**

Data Envelopment Analysis (DEA) is a mathematical technique proposed by Charnes et al. (1978) to measure efficiency of similar decision making units (DMUs) with a fractional program that can handle several inputs and outputs. The efficiency of any given DMU is defined as the ratio of weighted sum of all outputs to the weighted sum of all inputs which is the efficiency definition proposed by Farrell (1957).

DEA enjoys world-wide application. Emrouznejad et al. (2008) report that more than 4,000 DEA research articles and books were published by 2007. DEA has been used to compare efficiencies in many areas like schools (Colbert et al. (2000), Lewin and Morey (1981)), hospitals (Banker et al. (1986), Rutledge et al. (1995), Gunes and Yaman (2009)), airlines (Schefczyk (1993), Scheraga (2004), Adler and Golany (2001), Ray (2008)), production (Chauhan et al. (2006), Day et al. (1995)), energy(Hu and

Kao (2007), Ramanathan (2000), Chen et al. (2009)), maintenance units (Charnes et al. (1983)) and many more.

The program is based on the Pareto-Koopmans efficient production function which assigns any DMU 100% efficiency score only if:

1. None of its outputs can be increased without either increasing one or more of its inputs or decreasing some of its other outputs
2. None of its inputs can be decreased without either decreasing some of its outputs or increasing some of its other inputs.

The fractional program for the model can be written as:

$$\begin{aligned}
 & \text{maximize } \theta_0 = \frac{\sum_{r=1}^s u_r y_{r0}}{\sum_{i=1}^m v_i x_{i0}} \\
 & \text{subject to} \\
 & \frac{\sum_{r=1}^s u_r y_{rj}}{\sum_{i=1}^m v_i x_{ij}} \leq 1 \quad j = 1, 2, \dots, n \\
 & v_r, v_i \geq 0 \quad r = 1, 2, \dots, s; i = 1, 2, \dots, m
 \end{aligned} \tag{3.4}$$

where the  $y_{rj}$ ,  $x_{ij}$  are the outputs and inputs of the  $j$ th DMU and the  $u_r, v_i$  are the variable weights to be determined by the solution of this problems.  $n$  is the total number of mission for our study and  $m$  and  $s$  are the number of inputs and outputs, respectively. The particular mission being evaluated is assigned the subscript

0 to distinguish. All missions including the one under consideration are used in the constraint set. Therefore no mission will not be assigned more than 100% as efficiency rating (Charnes et al., 1978). With this approach, DEA gives chance for every DMU to represent itself in the most favourable manner.

This fractional program can easily be converted to an equivalent linear program (Charnes et al., 1978). The efficiency score of each DMU is found by replicating after the objective function to reflect the DMU under consideration.

$$\begin{aligned}
 & \text{maximize } \theta = \sum_{r=1}^s u_r y_{r0} \\
 & \text{Subject to} \\
 & \sum_{r=1}^s u_r y_{rj} - \sum_{i=1}^m v_i x_{ij} \leq 0 \quad \forall j \\
 & \sum_{i=1}^m v_i x_{i0} = 1 \\
 & u_r, v_i \geq 0 \quad \forall r, i
 \end{aligned} \tag{3.5}$$

The above program is known as the CCR (Charnes-Cooper-Rhodes) model and examines the ratio of inputs and outputs to capture the relative efficiency of units under evaluation. The  $\theta$  is called the ratio efficiency and any DMU with a  $\theta^* = 1$  with zero slacks is called CCR-efficient. Since the introduction of the CCR model, several other models have been proposed that deal with return-to-scale issues, zero or negative inputs or outputs. CCR model does not take into account the input excess and output shortfalls while a Slack-Based Measure (SBM) of efficiency proposed by

Tone (2001) takes slacks in the objective function and measure efficiency in a scalar form with the following fractional program:

$$\begin{aligned}
 \text{minimize } \rho &= \frac{1 - \frac{1}{m} \sum_{i=1}^m \frac{s_i^-}{x_{io}}}{1 + \frac{1}{s} \sum_{r=1}^s \frac{s_r^+}{y_{ro}}} \\
 \text{subject to } \mathbf{x}_o &= X\boldsymbol{\lambda} + \mathbf{s}^- \\
 \mathbf{y}_o &= Y\boldsymbol{\lambda} - \mathbf{s}^+ \\
 \boldsymbol{\lambda}, \mathbf{s}^-, \mathbf{s}^+ &\geq 0
 \end{aligned} \tag{3.6}$$

where the  $X$  and  $Y$  are the input and output matrices of unit under evaluation, respectively where there are  $m$  inputs and  $r$  outputs with a total number of  $n$  DMUs.  $\boldsymbol{\lambda}$  is a nonnegative vector in  $\mathbb{R}^n$  and the slack variable vectors  $\mathbf{s}^-$  and  $\mathbf{s}^+$  indicates the respective input excess and output shortfall.

DEA is also used as a tool to assess efficiency changes of a DMU or several DMUs over time. The approach is to treat each time period as a different DMU. This method can be applied to a single DMU to measure its own efficiency over time or it can be applied to assess several DMUs. This method is called window analysis (Charnes et al., 1983). In window analysis, a window is constructed by using  $p$  time periods and each time period of each DMU is treated as a different DMU. Once the efficiencies are assessed, another window is constructed by dropping the earliest period and adding the the next period.



Window analysis is modified by Talluri et al. (1997) by dropping the lowest scoring DMU instead of earliest period. They defend that this new modified model is superior because it allows new periods to challenge the best past performer periods.

In order to run a DEA, the number of DMUs should be several times greater than the total number of inputs plus outputs (Cooper et al., 2000). Otherwise, the model will not be able to discriminate between efficient and inefficient units. Since, only 4 months of data were available to us, and 14 inputs and outputs in our model, it was not possible to run a window analysis. Also, averaging missions data by month will smooth the differences between mission.

Rutledge et al. (1995) studied the relative efficiency of twenty-two months of a non-profit hospital with 5 inputs and 5 outputs. They assumed that each month's data of hospital was a different DMU. As expected, the results showed that only 4 months out of 22 achieved scores less than 100%. If more data were available, the model might better discriminate efficiency changes.

### ***3.5 A DEA-based Fuel Efficiency Index***

In this section, application of DEA methodology to the missions of C-17 airframe operating under AMC is presented. The data, obtained from AMC's Fuel Efficiency Office, consists of usable missions for September through December 2009. These included 620 of 1436 missions in September, 704 of 1492 missions in October, 693 of 1363 missions in November and 710 of 1347 missions in December. Unusable mission data were the result of missing information for those missions.

To deal with the zeros in output or input data, Tone (2001) suggests two methods. The first method is to delete the slack variable that correspond to the input that is zero from the set of variables that will be determined by the model and then to remove the  $s/x$  (or  $s/y$ ) term corresponding to the same slack from the objective function and reducing number of input ( $m$ ) or output ( $s$ ) by the number of deleted slack.

The second method is to replace the output data with a very small positive number. The idea is that if a DMU has a potential to produce the output corresponding to zero value, then a very small positive value can be assigned. Thus, the unit is penalized for not producing this output. The same approach can be used with the negative values as well. In this study, the second approach is selected, by assigning a very small positive value (0.1) to zero values to penalize those missions for not producing corresponding output.

The inputs and outputs are the disaggregated factors identified by AMC's Fuel Efficiency Office and currently used by their FEI. We used their factors to enable a direct comparison with their index. Further, data for other potential factors were not readily available.

The inputs include: (1) Number of Total Legs; (2) Total Leg Distance (in miles); (3) Cargo Capacity for that mission(in thousands of pounds); (4) Pallet Position Available for that mission; (5) Planned Fuel Load (in lb); (6) Planned Cargo Load (in thousands of pounds); and (7) Planned Fuel Burn( in thousand gal/hr). The outputs

include: (1) Number of Active Legs, (2) Active Leg Distance (in miles); (3) Amount of Cargo Carried (in thousands of pounds); (4) Pallet Position Equivalent used; (5) Fuel Load Accuracy; (6) Cargo Load Accuracy; and (7) Fuel Burn Accuracy. Each inputs are now defined.

A leg is a mission portion defined by specified start and stop points. Number of Total Legs is the entire sum of all legs during a particular mission while an active leg is defined as the leg on which cargo is carried. For example, as shown in Figure 3.2 , an empty aircraft that flies from Base A to Base B (Airport of Embarkation) to load its cargo and fly to Base C (point of need), unloads and returns to Base A will have a Number of Active Legs of 1 and Number of Total Legs of 3.

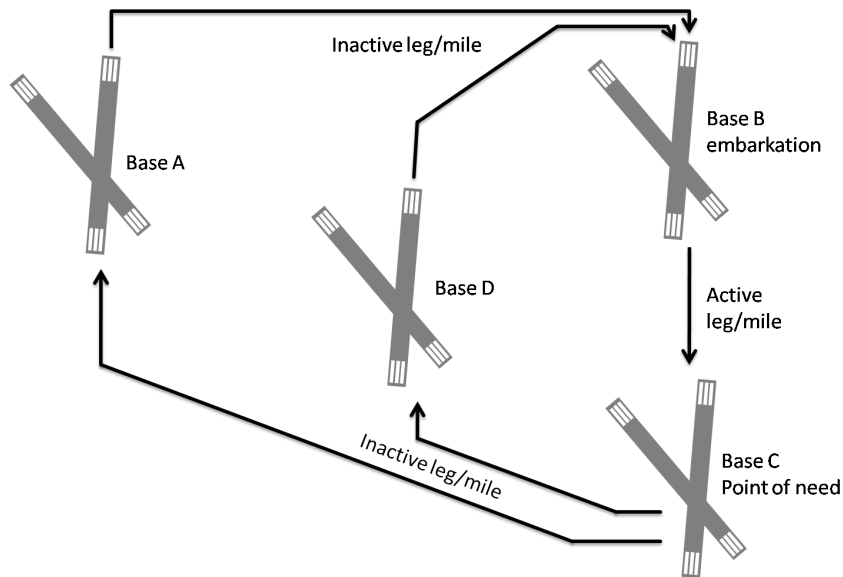


Figure 3.2: Active and Inactive Legs and Miles.

Analogous to leg numbers, total leg distance is the sum of all miles a mission flies. An active mile is defined as the total miles cargo is moved.

Cargo capacity for a mission is calculated by multiplying number of total legs by cargo carrying capacity, which is 160,000 pounds for C-17 aircraft.

C-17 aircraft have 18 pallet positions. Pallet position available is calculated by multiplying number of total legs by C-17 pallet positions. Used pallet position equivalents are the number of pallets used during the mission execution.

Planned cargo load is calculated during the mission planning. The changes in the cargo load during execution will show itself as a deviation in fuel burn per hour from the planned fuel burn. On the other hand, the amount of cargo carried is the actual cargo moved during mission execution.

Planned fuel burn, similar to the planned cargo load, is calculated during the mission planning and the deviations are the result of several factors like pilot ability, weather, unexpected air traffic control delays, etc.

Fuel load, cargo load and fuel burn accuracy outputs are the deviations from planned amounts and calculated as:

$$Accuracy = 1 - \frac{|ActualAmount - PlannedAmount|}{PlannedAmount} \quad (3.7)$$

The DEA results are not effected by scaling therefore any scaling in cargo amounts, fuel loads are admissible and Charnes et al. (1983) states that “this is, too, is an advantage not only for purposes of computation but also for avoiding the need for recourse to the elaborate procedures that are sometimes needed to avoid the effects of using different scales in different parts of the same study”.

The formulated formulas based on related DEA models were solved using Microsoft Excel ® with the Premium Solver™ add-in.

### **3.6 Results**

DEA allows managers to have insights about the decision making units with important outputs (Lewin and Morey, 1981), which are the relative efficiency score of each DMU and the levels of improvement requirements to move inefficient DMUs to the efficient frontier.

In Table 3.1, a comparison of the outputs for the three DEA methods used in this study is given. For December 2009, average CCR-efficiency was 91.3% and 300 missions were given efficiency score of 100%. BCC (VRS) efficiency for the same month was 94.4% with an increase of 3.1% and 411 missions were 100% efficient. SBM-efficiency was 62.3% with a decrease of 29.0% as expected with only 87 missions achieving 100% efficiency. The Fuel Efficiency Index, developed by AMC/FEO (an absolute efficiency score) for this month was 74.4%.

For November 2009, average CCR-efficiency was 90.14% and 317 missions were given efficiency score of 100%. BCC (VRS) efficiency for the same month was 92.79% with an increase of 2.64% and 388 missions were 100% efficient. SBM-efficiency was 64.52% with a decrease of 25.63% as expected with only 97 missions achieving 100% efficiency. The FEI for this month was 57.10%.

For October 2009, average CCR-efficiency was 90.41% and 302 missions were given efficiency score of 100%. BCC (VRS) efficiency for the same month was 92.76%

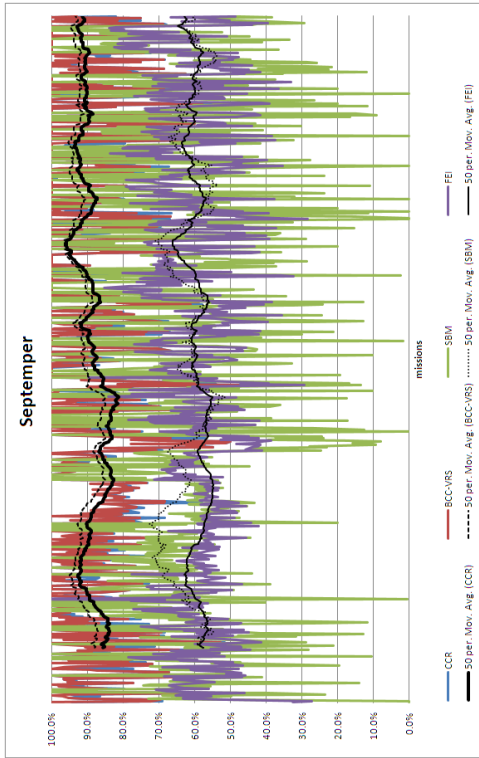
Table 3.1: Comparison of DEA Methods Used in This Study.

	Methods			
	CCR	BCC (VRS)	SBM	FEI
Average Efficiency				
September	88.89%	91.17%	61.75%	59.53%
October	90.41%	92.76%	62.75%	60.35%
November	90.14%	92.79%	64.52%	57.10%
December	91.32%	94.41%	62.28%	74.38%
Number of 100% Efficient Missions				
September	231	293	71	NA
October	302	365	72	NA
November	317	388	97	NA
December	300	411	87	NA

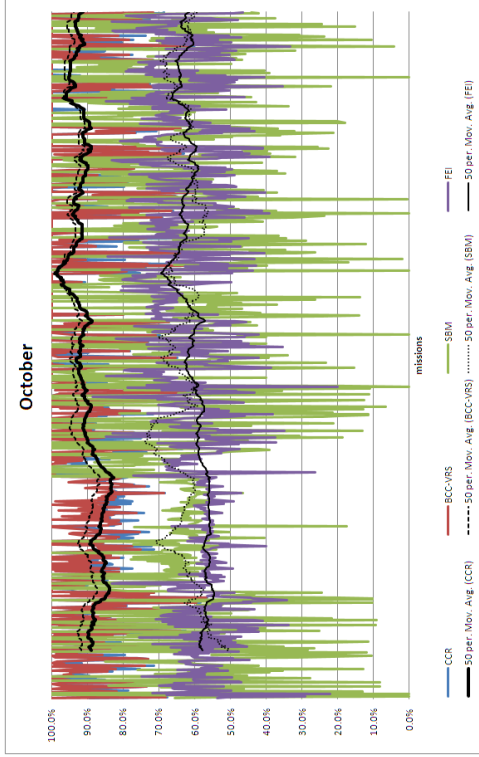
with an increase of 2.36% and 365 missions were 100% efficient. SBM-efficiency was 62.75% with a decrease of 27.65% as expected with only 72 missions achieving 100% efficiency. The FEI for this month was 60.35%.

For September 2009, average CCR-efficiency was 88.89% and 231 missions were given efficiency score of 100%. BCC (VRS) efficiency for the same month was 91.17% with an increase of 2.28% and 293 missions were 100% efficient. SBM-efficiency was 61.75% with a decrease of 27.14% as expected with only 71 missions achieving 100% efficiency. The FEI for this month was 59.53%.

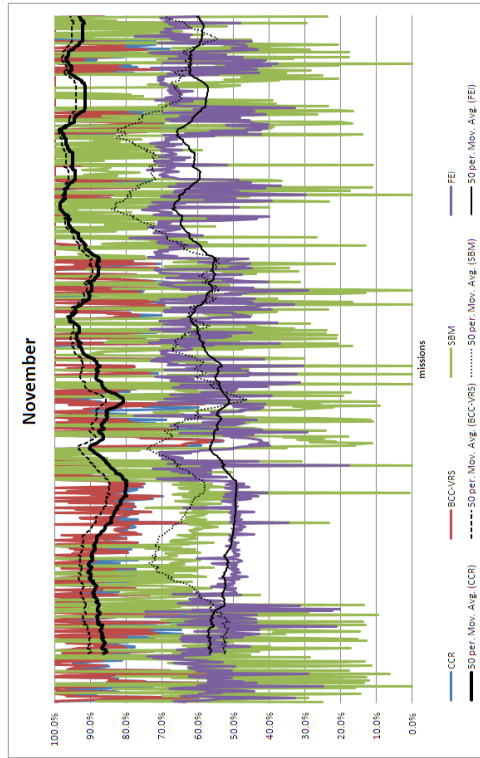
Figure 3.3 summarizes the comparison of missions with a 50 period moving average over-imposed. It is clear that all efficiency measures agree with each other in trend but the SBM differentiates inefficiencies better than other methods. The inefficiencies - which is the input excess and output shortfalls - are plotted in Figure 3.4, where months are superimposed on a target (bullseye) plot to focus the efforts to achieve higher efficiencies and move towards the center of the plot.



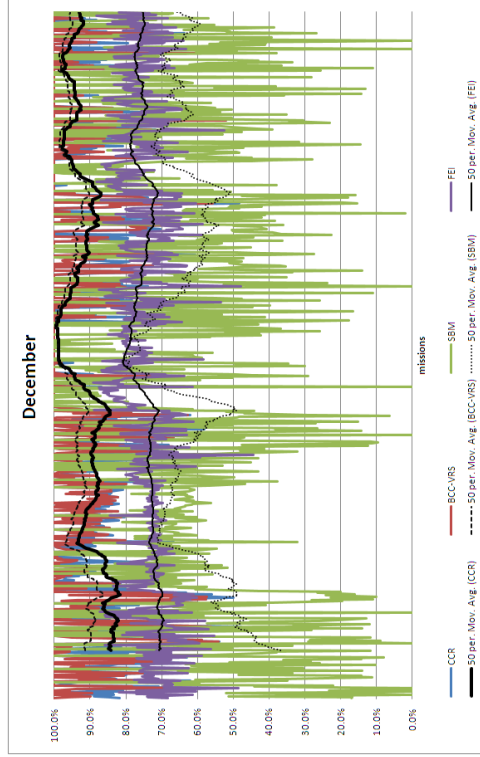
(a) September Moving Average Plot



(b) October Moving Average Plot



(c) November Moving Average Plot



(d) December Moving Average Plot

Figure 3.3: 50 Period Moving Average Plots.

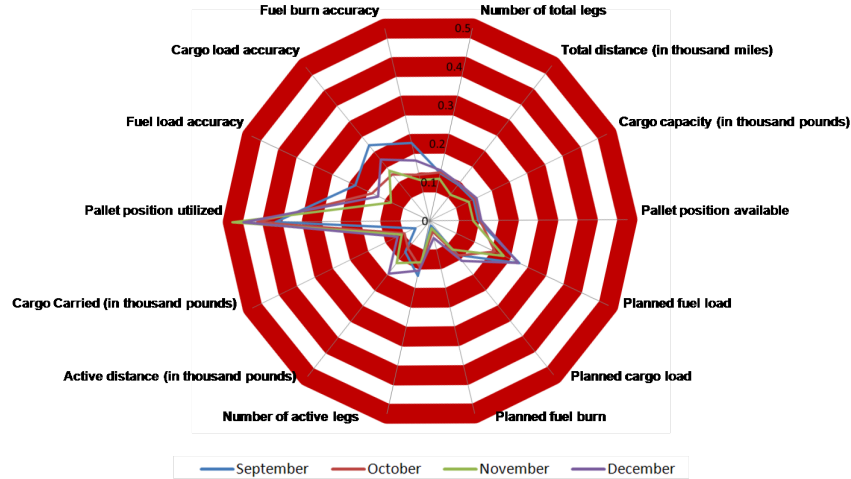


Figure 3.4: Bullseye Plot for Slacks of SBM Model.

The extent of mission slacks within AMC C-17 airframe for December 2009 can be summarized as follows:

- A potential increase of 47.2% in PPE utilization.
- A potential increase of 92,483 pounds of cargo movement (9.1%).
- A potential increase of 2,179,857 more active miles (16.9%).
- A potential increase of 14.6%, 20% and 15.7% in fuel load, cargo load and fuel burn accuracy respectively.
- A potential reduction of 3,185,843 miles in total (12%).
- A potential reduction of 13% in cargo capacity and PPE availability.
- A potential reduction of 24.8%, 12.9% and 4.4% in fuel, cargo and burn planning.

The management should look forward to find the reasons of the inefficiencies and should apply the best performing mission's practices to those with lower efficiency scores. For example, the frequent changes in the flight plan or cargo plan may be the



result of unexpected situations arising and a better communication and collaboration may reduce the last minute changes. There may be several reasons causing inefficiencies, for example Trujillo (1996) reports that pilots and dispatchers allocate twice as much reserve fuel than regulations require. Therefore, it is important to acknowledge the planners and pilots with the true data about dimensions of unnecessary fuels are burned as a result of inappropriate considerations. Further analysis about the new regulations for contingency and alternate fuels may help reduce the unnecessary fuel loads. The more accurate navigation and landing systems available to aircraft today may dictate reconsidering these regulations and conservative planner policies.

### ***3.7 Conclusion***

We examined the potential for DEA to measure fuel efficiency for military cargo aircraft missions. The relative efficiency of approximately 2,700 recent C-17 missions was studied using 7 respective predetermined inputs and outputs. Four methods, including CCR, BCC, SBM and FEI are calculated and respective input excess and output shortfalls for each month are plotted to identify efficiencies and their magnitudes.

The SBM model results suggest that management focus on cargo planning, fuel load planning and fuel burn per hour planning could immediately increase fuel efficiency by decreasing unnecessary fuel burn and reducing excess fuel weight. The results also conclude that the volume of an aircraft (in term of PPE) is only about 50% used.

DEA provides a straightforward technique to measure airlift fuel efficiency without any need for prior assumptions on functional forms or factor weights. Unlike FEI, the SBM provides an efficiency measure, and not a utilization measure. The overall impact determined within the model, relative to the other measure where FEI measure is dependent on assigned weights which makes it vulnerable to subjective changes.

Further research should relax the assumption of homogeneous missions where each type may be evaluated within itself to see the effects on efficiency. The FEI is calculated for airlift and tanker aircraft other than C-17 which include C-5, C-130, KC-10 and KC-135. Therefore, a further comparison of those aircraft using the SBM method would be appropriate.

Finally, the results of this study should be combined with a cost analysis to help Air Force managers to focus on the areas where actions can be taken with the most return for fuel efficiency.

### ***3.8 Disclaimer***

The views expressed are those of the authors, and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

## *Appendix A. Bluedart*

The United States is the third largest crude oil producer with about 5 million-barrel-per-day but still imports 60% of total demand from other countries like Canada, Saudi Arabia, Mexico, Venezuela, Nigeria, Iraq, Angola, Algeria, Kuwait, Ecuador etc. History suggests that oil supply disruptions increase in scale and strength as oil use increases. Therefore, reducing dependency on foreign oil remains a top priority.

Aviation fuel is a necessary strategic asset for effective operations through the foreseeable future. The U.S. Air Force uses more fuel than its sister services combined, and yet alternatives are not feasible or available in sufficient quantity to be used as a significant substitute.

The Air Force is focusing on energy efficiency with many initiatives to become more conservative and to help reduce reliance on foreign oil. The USAF has adopted a three-leg strategy:

- Reduce demand for conventional fuel supplies,
- Increase supply of alternative energy resources,
- Change culture to make energy a consideration in everything airmen do.

The ultimate USAF goal is to reduce conventional fuel usage by 10% in 10 years, while sustaining effectiveness. In order to achieve this goal, the USAF must be able to measure how efficiently it uses fuel.

The Air Mobility Command developed a fuel efficiency index (FEI) to measure airlift and tanker aircraft fuel efficiency. The FEI is a weighted average of several

factors involving cargo capacity, cargo movement, and fuel usage. Each factor is weighted with regard to their relative importance. The weights are subjectively defined by subject experts, which makes the FEI vulnerable to criticism.

A broad definition for the efficiency would be weighted outputs over weighted inputs. The problem lies not with the inputs and outputs but the weights of how each component is assessed. Also, the lack of a proper mathematical function makes it hard to develop an efficiency measure. To come up with a mathematical relation that ties all the inputs and outputs together is very hard because of the dynamic nature of aircraft fuel usage.


Data envelopment Analysis (DEA), is a data oriented technique to evaluate homogeneous decision making units (DMU) like mission to measure relative efficiency. It has been used in many sectors like banks, schools, airlines, manufacturing companies etc. It provides a straightforward alternative for measuring fuel efficiency over time. DEA does not require any prior assumptions about weights and does not require any particular mathematical relation between inputs and outputs. It can handle multiple inputs and outputs simultaneously and does not require a common unit: units can include miles, pounds, percent etc.

Compared to FEI, DEA method is derived computationally with all inputs and outputs taken into account while FEI has no interaction between them. The overall impact is determined within the model, relative to other measures where FEI is dependent on subjectively assigned weights. DEA is a relative efficiency metric and


from a kaizen stand point where there is no ultimate goal but continues improvement, it help managers to focus on areas that have room for improvement.

The results of our study show that the AMC could increase airlift capability while reducing the inputs by at least 10%. They also show that a slack-based measure (SBM)– a DEA model variation – discriminates efficiency changes better than other DEA models like CCR (Charnes-Cooper-Rhodes) and BCC (Banker-Charnes-Cooper). On the other hand, this method is more computationally intensive and requires certain computer software capabilities based on the number of missions to be compared.

Appendix B. Quad Chart



## Fuel Efficiency Assessment with DEA




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**ADVISOR**  
Dr. Alan Johnson

**READER**  
Dr. William Cunningham

#### AMC FUEL EFFICIENCY INDEX



#### DATA DEVELOPMENT ANALYSIS

Data Development Analysis (DEA) is a data oriented technique to evaluate management decision making units (DMU) with financial inputs and outputs to measure relative efficiency. DEA was first introduced by Charnes et al (1978) and extends Farrell (1857)'s efficiency definition with a fractional program.

**DEA:**

- Is used in many sectors like schools, banks, airlines, manufacturing companies etc.
- It is a non-parametric method.
- DMU can be compared against peer or combinations of peers.
- Does not require a common measurement unit.
- Does not require any mathematical relation between inputs and outputs.

#### MODELS

##### CCR (Charnes-Cooper-Rhodes)

$$\text{Minimize } \theta_0 - \sum_{j=1}^n \lambda_j \theta_j$$

$$\text{Subject to } \theta_0 - \sum_{j=1}^n \lambda_j \theta_j \leq \theta_0$$

$$\sum_{j=1}^n \lambda_j \theta_j = 1$$

$$\theta_j \geq 0, \lambda_j \geq 0, j=1, 2, \dots, n$$

##### BCC (Banker-Charnes-Cooper)

$$\text{Minimize } \theta_0 - \sum_{j=1}^n \lambda_j \theta_j$$

$$\text{Subject to } \theta_0 - \sum_{j=1}^n \lambda_j \theta_j \leq \theta_0$$

$$\sum_{j=1}^n \lambda_j = 1$$

$$\theta_j \geq 0, \lambda_j \geq 0, j=1, 2, \dots, n$$

#### AMC VPI

- Validating inputs.
- No interaction with other variables.
- SEA will impact on efficiency measure if dependent on assumed weights.
- An absolute efficiency metric.
- Weights are defined by expert opinion (subjective).

#### DEA

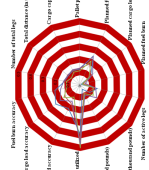
- No efficiency metrics.
- Derived computationally with all other variables taken into account.
- Output oriented.
- Interpreted within the model, relative to the other measures.
- Relative efficiency metric.
- Weights are defined via the model (Objective).

#### RESEARCH QUESTIONS

This study measures the fuel efficiency of Air Mobility Command C-17 aircraft missions:

- How can we measure fuel efficiency?
- How can we improve fuel efficiency?
- How can a AMC C-17 aircraft fuel efficiency index best be formulated?

#### RESULTS



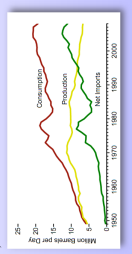
Output Exceeded the Benchmark (Green)

Output Met the Benchmark (Yellow)

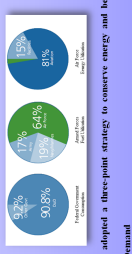
Output Below the Benchmark (Red)

#### BACKGROUND

The United States is the third largest market of aerospace with 5 million barrels per day, but must import most supply from other countries like Canada, Saudi Arabia, Mexico, Venezuela, Nigeria, Iraq, Angola, Algeria, Kuwait etc.



The Air Force is the largest user with consumption greater than the other services combined.



The AF Force has adopted a three point strategy to conserve energy and become more fuel efficient:

- Increase Supply
- Reduce Demand
- Change Culture

Month	CCR	BCC (VRS)	SIM	FEL
September	88.89%	93.19%	47.94%	93.93%
October	90.41%	92.23%	42.27%	60.33%
November	90.41%	92.23%	44.62%	37.16%
December	89.24%	94.41%	42.23%	74.82%
Number of 100% Efficient Missions	231	263	71	NA
September	317	385	57	NA
November	317	388	57	NA
December	300	411	87	NA

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<b>14. ABSTRACT</b> Data Envelopment Analysis (DEA) is used to calculate Air Mobility Command (AMC) airlift fuel efficiency for C-17 aircraft. Fuel is a strategic asset for the United States Air Force and suitable alternatives are not yet feasible or available in the quantity required. The Air Force is pursuing several initiatives to conserve energy and operate more efficiently while sustaining the same level of effectiveness and safety. In order to manage these initiatives, it must measure how well it is doing. To measure airlift efficiency, the AMC Fuel Efficiency Office established a 7 factor weighted Fuel Efficiency Index (FEI). To produce a monthly score, AMC assigned weights for each factor. DEA does not require such a priori assumptions and finds the best set of weights that will help each mission to represent itself in the best manner. The results showed that DEA and FEI agree in trends but a DEA Slack-Based Measure better differentiates inefficiencies than other methods used in the study. Also, the results showed that for current Air Mobility flights, at least 10% input excess or output shortfall occurs each month.					
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