

Sourcing of availability services

case aircraft component
support



Jani Kilpi

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Abstract

In the competitive environment of the aviation industry, it is paramount to secure aircraft availability by providing the aircraft fleet with efficient component support. The availability services in general and the aircraft component support in particular are examined in this study under the topics of demand fragmentation, cost structure of the availability services, benefits of inventory pooling and potential ways to implement inventory pooling. Each topic is discussed in a separate paper.

One of the most important factors in the airline operation is the availability of aircraft for their scheduled missions, i.e. the technical dispatch reliability. It is kept at an adequate level by the maintenance, repair and overhaul (MRO) function in the airline. This is accomplished by replacing failed units, i.e. aircraft components, quickly by functional units and repairing the failed ones afterwards. This allows the aircraft to continue operation immediately without waiting for the repair work to be finished.

The demand for aircraft component availability services is inherently fragmented. Airlines operate with varied fleets from a multitude of hubs and have a strong interest in keeping the spare units that support their fleets as close as possible. In contrast, the availability services would significantly benefit from demand consolidation, as the demand is caused by a random phenomenon of component failures. While the cost pressures in the airline industry require efficiency improvements in the availability services, they have to be performed without compromising dispatch reliability.

The airline fleet structure has a significant impact on the airline costs and particularly on the demand fragmentation of the component availability services. Numerical methods are presented here for measuring the uniformity of an aircraft fleet and its potential for achieving scale economies. Considering one airline providing the spare components for its operations in-house, the scale of its fleet determines the cost level of the availability service. When several airlines operate in the same region, the scale of their total fleet determines the potential for achieving scale economies by cooperative arrangements between those airlines. This study includes an empirical analysis of the full history of all commercial jet aircraft. The analysis shows that the average uniformity of the airline fleets has been steadily decreasing, while the average fleet scale has been steadily increasing. Decreasing uniformity causes extensive complexity in the airline management but increasing scale allows new levels of efficiency to be achieved.

The predominant cost item in the availability services is the ownership cost of the spare units, which directly originates from the valuation and depreciation principles applied. The challenge of valuing repairable components is that, unlike other production assets and disposable spare parts, they repeatedly change between production asset role and spare part role. They require different valuation and depreciation rules in these three cases: in the revenue generating role as common production assets, in the insurance-like role as spare components and while they are changing from one role to the other.

III

According to a basic model of availability, a simple but feasible pooling arrangement can save over 30% of the availability service costs if the pool members are willing to endure some delivery delays from a remote pool stock. A pool member experiences higher service level with lower cost but needs to wait for the spare units longer compared to an airline providing its spare components in-house. The cost savings achieved by the whole pool are determined by the total fleet scale of the cooperation.

The pooling benefits in optimal conditions are generally higher when more demand for one component type is served by one pool. Conflicting interests between the potential cooperating parties may easily result in less efficient pooling arrangements. The primary cause of the conflict is the issue of allocating the costs of the availability service between the pool participants, which is complicated by the fragmentation of the spare component demand. A deeper examination of the different ways to implement pooling is required to measure the potential of each alternative to capture pooling benefits in the availability service of aircraft components against a variety of external conditions.

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Tuusula, Finland

November 2008

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Original Papers

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- Paper II:** Kilpi, Jani, 2007. Valuation of Rotable Spare Parts. *HSE working paper* W-438, 25 p
- Paper III:** Kilpi, Jani; Vepsäläinen, Ari P.J., 2004. Pooling of Spare Components Between Airlines. *Journal of Air Transport Management*, Vol. 10. Iss. 2. pp. 137-146
- Paper IV:** Kilpi, Jani; Töyli, Juuso; Vepsäläinen, Ari P.J., Cooperative Strategies for the Availability Service of Repairable Aircraft Components, *submitted for publication*

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List of abbreviations

A/C	Aircraft
AOC	Air Operator's Certificate
AOG	Aircraft On Ground
ASK	Available Seat Kilometre
ATA	Air Transport Association in the United States
ATC	Air Traffic Control
ATD	Average Technical Delay
BITE	Built-In Test Equipment
CAA	Civil Aviation Authority in the United Kingdom
CAGE	Commercial And Government Entity
CFDS	Centralized Fault Detection System
CMC	Central Maintenance Computer
FAA	Federal Aviation Administration in the United States
EASA	European Aviation Safety Agency
FIFO	First-In-First-Out
IATA	International Air Transport Association
JAA	Joint Aviation Authority in Europe
LRU	Line Replaceable Unit
MDT	Mean Down Time
MRO	Maintenance Repair and Overhaul
MTBF	Mean Time Between Failure
MTBUR	Mean Time Between Unscheduled Removals
NFF	No-Fault Found
NHA	Next Higher Assembly
OEM	Original Equipment Manufacturer
RFID	Radio Frequency Identification
SITA	Société Internationale de Télécommunications Aéronautiques
SMP	Self Monitoring Programme
TAT	Turn Around Time
TDR	Technical Dispatch Reliability

PART I: OVERVIEW OF THE DISSERTATION

1. INTRODUCTION

The role of aircraft *Maintenance, Repair, and Overhaul* (MRO) services in the airline industry is to ensure that aircraft are in operative condition before the flights and that they complete the scheduled missions without technical disruptions. The product of aircraft MRO services is the technical reliability of the aircraft and for the airline operator it means aircraft availability and route completion. Lacking technical reliability causes flight delays, diversions and cancellations but is not the only reason for them. The most common reasons like the weather conditions, air traffic control and airport congestion are mostly out of the airline management's control. In contrast, the management possesses all the means to control the technical reliability of their aircraft.

From the viewpoint of MRO services, aircraft availability means that the aircraft is in operative technical condition on time for its flight. This is commonly measured by *Technical Dispatch Reliability* (TDR). The other side of technical reliability, route completion, depends on the quality of the MRO operations and is somewhat outside of the focus of this dissertation.

To tackle the issue of aircraft availability the aviation industry uses *Line Replaceable Units* (LRUs) that are commonly referred to as aircraft components. These units are responsible for the critical functions of the aircraft. In a case of a malfunction, the failed unit can be identified and replaced by an operative spare unit within a reasonable time frame. It may take weeks to repair the failed unit but the aircraft is available to operate its schedule.

The *Component Availability Service* provides the spare units to support the airline fleet, while the *Component MRO Service* performs the MRO activities needed to return the failed units into operative condition. *Aircraft Component Support* includes both of these services, thus covering most of the factors affecting the technical reliability of the aircraft fleet.

In the commercial airline business the most important trend during the last decade has been focusing on costs. There are four major factors contributing to this development. Chronologically the first factor is deregulation, which exposed the industry to the

reality of free competition after decades of peaceful living protected by the commonly agreed fares that were conveniently adjusted upwards according to occasional cost increases. After the deregulation, and partly as a result of it, came the invasion of the low cost business model, which attracted price sensitive leisure travellers away from the services of the traditional airlines as well as altered the buying behaviour of business travellers towards the back of the cabin.

The September 11th terrorist attacks in 2001 caused the demand for air travel to plummet, right when the airlines were deeply indebted after investing in the new aircraft that were ordered during the booming late 1990s. Finally, the price of oil has been continuously rising since 2005 and shows no signs of levelling out. As many airlines see their revenues slowly recovering when the passenger demand increases and the higher travel classes are once again flying full, the cost is exploding.

How efficiently the aircraft component support is performed has a significant impact on the operating costs of an airline. In addition to its own cost, it indirectly sets off those costs that are realized when the technical reliability fails. The challenge in managing the aircraft component support is to balance its cost with the cost of the technical delays so that their sum is minimized.

Earlier airlines performed their MRO services mostly in-house but, as a result of the cost pressures, there has been a trend to increase the use of other sourcing options. In 2006, the market of MRO services was USD 38.9 billion (Jackman, 2008, p. 42). In the same year the worldwide fleet of about 17,000 commercial jets was supported by a total supply of spare parts worth USD 44 billion, of which USD 26.8 billion was held by the airlines (Harrington, 2007, p. 78). Assuming a moderate annual inventory holding cost (15%), the total market of the aircraft spare part availability was USD 6.6 billion. Even if the market for the availability services is smaller than the market of the MRO services, its impact on the flight delays is much more significant.

The component MRO service and the component availability service are essential parts of the aircraft component support but in nature they differ significantly from each other. To efficiently study them, they need to be handled separately but continuously keeping in mind the tight connection between them. These services may be sourced separately or they may be combined into a single aircraft component

support contract. However, when evaluating the sourcing alternatives, the two services must be considered separately.

There is a considerable amount of research done in certain separate areas that relate to aircraft component support. There is, however, no evidence of studies on the subject as a whole. This is the research gap that this dissertation seeks to address.

1.1 Research Objectives

The motivation for putting this dissertation together derives from the observation that sourcing decisions and service contracts on aircraft component support are based on the mindset and principles from the era of in-house dominance. This way of thinking typically regards spare unit purchasing and maintenance workshops as simple cost centres, whose total cost is divided annually by the *Available Seat Kilometres* (ASK) the airline produces. When a method like this is applied to the relevant sourcing decisions, the results are inevitably compromised.

To properly analyse the component availability service it needs to be detached from the component support service, so that the availability service and MRO service are examined as two separate but interlinked services. The demand and cost structure of the availability services also needs to be addressed taking the specific requirements of the aviation industry into consideration. As the benefits of sourcing the availability services derive from the utilisation of the scale efficiencies, i.e. inventory pooling, the final goal is to assess the savings potential of inventory pooling as well as to identify and test various ways of implementing a pool setting.

As a result, the objective of the dissertation is: *to provide guidelines and managerial insight into the sourcing decisions of component availability services by understanding the demand and cost structure of the availability services within the environment of the aviation industry as well as evaluating the savings potential and limitations of the settings that can be implemented to utilise the scale economies of availability services*. This high level objective can be divided into a more practical process of three consecutive phases that are listed as follows:

- 1) To illustrate the role of aircraft component support in the airline operations as well as the dynamics of interaction between the component availability service and the component MRO service.

- 2) To understand the cost structure of the availability services and the factors that cause fragmentation in the demand for aircraft spare components.
- 3) To simulate and model a basic setting of inventory pooling and expand to cover a number of potential ways to implement a pool setting.

The first phase consists of building up understanding of the subject and the aviation industry in general. The outcome is a general introduction to the availability services in the aviation industry including a process description of the aircraft component support.

The second phase focuses on the key factors affecting the component availability service: the cost structure and the demand fragmentation. The cost structure is studied to provide means to availability modelling. Of the three major causes of demand fragmentation (randomness of component failures, multitude of failure locations and airline fleet composition), the random nature of the component failures is studied to facilitate availability modelling as well. The fleet composition is analysed to identify trends in the demand structure and provide the airline management with tools to improve their fleet uniformity.

The last phase starts with building simulation models of availability and inventory pooling. The models are run with an extensive set of data inspired by the real life business environment. Finally, the model results are analysed and reflected against the reality of the industry.

The viewpoint of this dissertation is mainly managerial, keeping at all times in mind the sourcing decisions in the area of component availability services. In addition to creating academic value, it is directed to audiences in the real world airlines. Even if not an actual objective of this dissertation, the principle throughout the study is to utilise existing frameworks to provide valuable results instead of developing new frameworks.

1.2 Topics of the Research

The core of this dissertation lies in the sourcing of availability services. The subject is covered by analysing one important application, aircraft component support. The research ranges from empirical to theoretical analysis presenting, at one end, general characterisation of the aviation industry and, at the other end, specific modelling of the sourcing alternatives. The dissertation consists of a general section, which

describes the aircraft component support as well as four papers, each of which addresses a distinct research gap related to component availability services. The topics of the research can be seen in Figure 1.1.

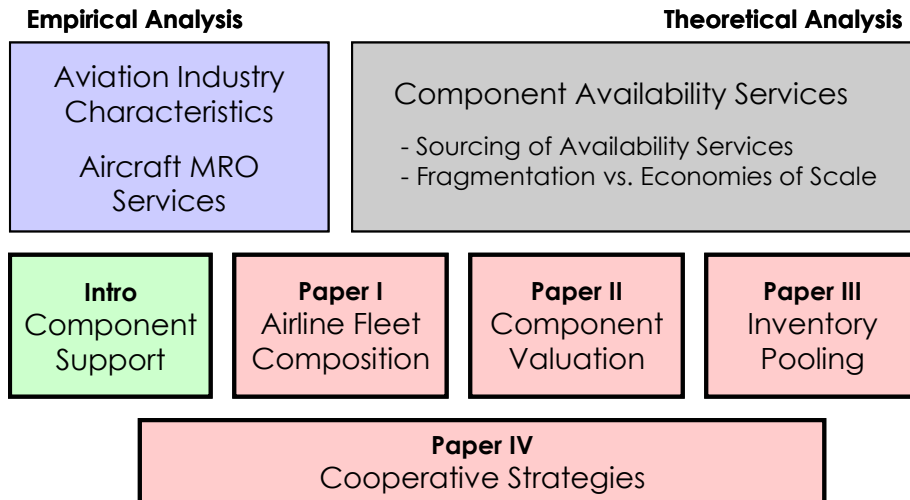


Figure 1.1 Topics of the Research

The research work behind the dissertation includes a general empirical analysis of the aviation industry focusing on the aircraft MRO services. It also includes a theoretical analysis of the component availability services focusing on the sourcing issues and the contradiction between the strong scale economies in the availability services and the inherent fragmentation of their demand.

The general section of the dissertation acts as an introduction to the area of component availability services. An introduction to component MRO services is included in the general section because these services are directly linked to each other as they are the two elements of the component support service.

Paper I (Fleet Composition of Commercial Jet Aircraft 1952-2005: Developments in Uniformity and Scale) is a published article that represents the empirical analysis in the dissertation by analysing the fleet structure of the commercial jets throughout the jet-era. The scope includes all commercial cargo and passenger jets world-wide that have been operated during the period of 1952 to 2005. Together with geographical incoherence of the airports, the airline fleet structure is the most important factor in the demand fragmentation of the component availability services. The size and commonality of the airline's fleet is a major factor in determining the cost level of the

availability service without cooperation. Similarly, the size and commonality of the world-wide or region-wide fleet of aircraft is a major factor in determining the potential for achieving scale economies by cooperative arrangements. This paper introduces a numerical method for measuring the commonality of the aircraft fleet as well as its potential for achieving scale economies. In addition to providing methods for the management in assessing potential fleet structures, these measures are applied to the empirical data to produce trend information.

Paper II (Valuation of Rotable Spare Parts) is a working paper that addresses the most important cost item of the component availability service, the ownership cost of the spare units. This cost item originates directly from the valuation and depreciation principles applied in the internal accounting. In contrast to other production assets and disposable spare parts, repairable components repeatedly change between the production asset role and the spare part role, which creates challenges for their valuation. This paper includes rules of treating repairable components in their revenue generating role as common production assets, in their insurance-like role as spare components and at the moment when they are changing from one role to the other. The value of the aircraft includes the values of all the components that are installed in it and are acting in the production asset role. The installed components are depreciated together with the aircraft, but the share of a certain component remains unclear. The components in the spare part role act like an insurance and only generate income by shortening the downtime of the supported aircraft. According to income method of valuation, the value of the asset is the net present value of its future income generation. As the income generation of the component is dependent on the operation volume of the fleets that it can be used to support, its value in the spare part role depends on the expected remaining service life of those fleets.

Paper III (Pooling of Spare Components Between Airlines) is a published article that shows by an example that a basic and feasible pooling arrangement can save over 30% of the availability service costs if the pool members are willing to make a minor sacrifice in the immediate service levels. As a pool member's spare component needs are satisfied not only from its own local stock, the immediate service level the member experiences is lowered. In contrast, the pool member acquires an access to a larger total stock of spare units, which leads to higher service levels with transfer delay.

Paper IV (Cooperative Strategies for the Availability Service of Repairable Aircraft Components) is a working paper that compares and analyses different cooperative strategies to achieve economies of scale in the environment of fragmented demand. While pooling benefits in optimal conditions are generally higher when more demand for one component type is served by one pool, conflicting interests between the potential cooperating parties may easily result in less efficient pooling arrangements. This paper presents a framework of cooperative strategies (solo, ad hoc cooperation, cooperative pooling, and commercial pooling), in which the potential of each strategy to capture pooling benefits in the availability service of aircraft components can be analysed against a variety of external conditions. According to the analyses, commercial pooling is generally the most efficient strategy as long as the service provider delivers enough pooling benefits to the members and the members are willing to subcontract this critical service. In most cases, cooperative pooling is less efficient than commercial pooling, as the administrative costs of maintaining a cooperative pool increase considerably with every new member. The opportunity of the customer airlines to start a cooperative pool may act as a potential challenge to a service provider considering to exercise monopoly pricing.

1.3 Research Timeline

In this section, the research process behind this dissertation is discussed from the viewpoint of chronology. To understand the characteristics of the aircraft component support as a whole, related subject areas were identified and existing literature reviewed. Distinct research gaps appeared within three subject areas, which were selected for closer scrutiny. These areas are Cost Accounting, Demand Handling and Economies of Scale. The research within these areas was restricted to aircraft components. Extensive research, in the form of simulation, modelling, data mining, literature studies and interviews, was conducted within the three subject areas. An illustration of the research timeline is shown in Figure 1.2, with interactions between the subject areas included.

Cost Accounting was the first subject area to be studied and the research work started at the beginning of 2001. One year later Economies of Scale followed and soon thereafter studies on Demand Handling were initiated as well. This last subject area

immediately appeared to have the best potential for publishing and the research work concentrated on it.

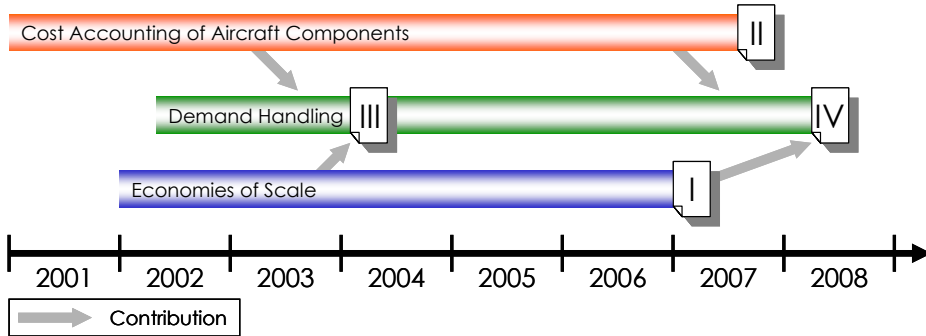


Figure 1.2 Research Timeline

To complete Paper III on inventory pooling, the subject area of Demand Handling required contribution from both the Cost Accounting and Economies of Scale subject areas. The guidelines of calculating the inventory holding costs of aircraft components were inherited from the Cost Accounting area, while the principles of how the economies of scale work in availability services were inherited from the Economies of Scale area. The first results of the fleet composition studies from the Economies of Scale subject area were also included in Paper III, which was published in early 2004.

From the beginning of 2004 to the end of 2006 the research on the three subject areas was conducted separately resulting in the publication of Paper I on airline fleets in early 2007 and the completion of Paper II on component valuation in late 2007. To complete Paper IV on pool implementation, the Demand Handling subject area again required contribution from both Cost Accounting and Economies of Scale subject areas. This time an elaborate analysis of the cost elements within availability service was inherited from the Cost Accounting area to complete the Cost Model and Pooling Simulation. The final results of the fleet composition studies from the Economies of Scale subject area were also utilised in the writing process of Paper IV. This final paper was completed in mid 2008.

1.4 Research Methodology

Paper I on airline fleets is the first extensive data mining effort published in an academic journal concerning the historical data on the worldwide fleets of commercial jet aircraft. All data used in this paper is based on an extract of one database table in

the ACAS database (AvSoft, 2005a). This commercial database table contains the transaction histories of every aircraft from its first delivery until the present day or its retirement. A detailed description of the data extract appears in Appendix B. As a part of the data mining effort, two indices were applied to the data to provide valuable trend information on fleet standardization and fleet scale. The fleet standardization index was based on the work of Pan and Santo (2004) and only slightly modified before application. The fleet scale index was constructed within the research process. The relevant data resulting from the data mining was analysed using standard quantitative methods. For validation and explanation, the resulting trends and datasets were compared to the external factors affecting the aviation industry as well as the financial results of selected individual airlines.

Paper II on component valuation is a purely managerial working paper that fills a distinctive research gap within the cost accounting of repairable spare parts. The most important cost item of holding expensive spare parts like aircraft components is the ownership cost, which is directly derivative of the spare part valuation. While the valuation of both production assets as well as disposable spare parts has been widely discussed in the literature, assets such as rotatable parts that repeatedly change between the production asset role and the spare part role, had not been given the required attention before this paper was written. A deductive research method based on a literature study and industry experience was used to put together a set of valuation principles that take into consideration the changing role of the parts. The annuity method was chosen to capture the depreciation of the parts in the spare part role, and a basic spreadsheet model was constructed to calculate the annuities. An instructive writing style was selected to bring this paper within the grasp of the real world airline management.

Paper III on inventory pooling applies a well established mathematical theorem, Palm's theorem, to an area that it has not been applied to before, i.e. pooling of repairable spare parts. The Demand Model that was constructed for the paper is based on Palm's theorem, according to which the stationary distribution for the number of units in the pipeline is a Poisson process with an assumption that the interval between the arrival of units in the pipeline is negative exponentially distributed (Palm, 1938). Apart from the mathematics within the Demand Model and a limited effort of data mining to characterise the economies of scale within the aircraft fleets, the appearance

of the paper is managerial. The idea was to apply a model to a relevant business case and provide results that are understandable and valuable to the managers of the real world airlines.

Paper IV on pool implementation specifies cooperative strategies for the availability service of aircraft components. While the issue of spares inventory pooling had been discussed in literature earlier, there were no prior studies with descriptive management focus considering a closed loop flow of repairable spare parts. The focus of this paper was also extended beyond plain pooling to address the cooperative strategies for the availability services more generally. The Cost Model and Pooling Simulation that were used to find out which factors contribute to the emergence of a particular cooperative strategy, were built on the Demand Model from Paper III. Apart from the mathematics within the Cost Model and Pooling Simulation definition, the appearance of the paper is managerial. Even if the research process behind this paper involved designing the Cost Model and Pooling Simulation, the focus of the paper is in their application and especially in presenting descriptive managerial results relevant to any industry using a closed loop maintenance process with repairable spare parts.

1.5 Dissertation Format

Bundled format was selected for this dissertation to ensure its quality and relevance throughout the research process. As the dissertation was written part time and without the possibility of spending extended periods of time to work on it, the process was indeed lengthy and scattered. It would have been very hard and even risky to write a monograph in this manner as the checks for its quality and relevance would have been less explicit and probably too much towards the end of the process.

Each paper in this dissertation has a focused topic and the review processes of the individual papers provided an organized and well advised way of handling the topics. This way each review process constituted a semi-separate research project with enough checkpoints and a distinctive result. This allowed completing four research projects of manageable sizes and durations instead of one that could have been too extensive and lengthy to handle with the available resources.

The most important aspect in submitting the papers for review was the possibility to gain valuable comments and real time feedback from the international research community. The iteration rounds during the review processes brought up new aspects on the topics and opened up new viewpoints to them as well as improved the readability of the papers. This ensured the quality and relevance of the papers when they were completed.

2. AIRCRAFT COMPONENTS IN THE AVIATION INDUSTRY

The aviation industry, like any other industry, has its own specific features that need to be recognised before drawing too many conclusions. In this section a number of issues specific to the aviation industry and aircraft MRO in particular are discussed. Even if there are no direct references to these concepts in the papers, their impact has been taken into account throughout the dissertation project.

During the dissertation project, a number of interviews were conducted to gather different views of the real world aviation industry and aircraft MRO. The list of the interviews appears in Appendix A. These interviews have not been used as references in the dissertation as they revealed confidential information. The permission to publish relevant information from the interviews together with the airline name was not given. Nevertheless, the information gathered in the interviews has implicitly contributed to the research process.

2.1 Operating Environment in the Aviation Industry

The most important general factor in the whole aviation industry is the concept of flight safety. As the industry is able to entail major catastrophes, it is tightly regulated by the aviation authorities and the regulations have an effect on every area of the business. The aircraft MRO industry is particularly tightly regulated as it has a focal position in securing the technical safety of the aircraft.

This regulation and the presence of the authorities make the aviation industry a well defined area to research. It also creates a unique set of industry specific rules which define the operating environment for the companies involved. Naturally, most of the common business rules apply to the air transport industry as well. This has become even more true after a series of deregulative actions were performed by governments around the world during the last three decades of the 20th century. The deregulation did not apply to safety issues but only to commercial issues, exposing the industry to free competition.

2.1.1 Players in the Aviation Industry

There are various players in the aviation industry. The two players that meet the public eye first are the airlines and airports. Special media visibility is also reserved to

the aircraft manufacturers and air traffic control. Behind the scenes there are still other industry members that deserve some attention.

From the point of view of the industry there is always an *operator* behind the *airline*. The operator is responsible for handling the flight operations and must have a valid *Air Operator's Certificate* (AOC) to do that. This signifies that the holder is considered to be competent to secure the safe operation of the specific aircraft detailed in the AOC (Friend, 1992, p.11). The majority of commercial airlines are at the same time operators. An airline may, however, be only a marketing company that has subcontracted the flight operations to an aircraft operator.

Airports are visible parts of the aviation industry, but their role in this study is only minor. The companies in aviation industry tend to locate themselves in the close vicinity of airports, which seems reasonable enough. This means that from the aviation industry's point of view the world is more or less a collection of dots on the map, each of which represents an airport.

The manufacturing of commercial jets centralised during the last two decades of the 20th century. By the year 2000 there were only two companies, Airbus and Boeing, producing modern commercial jets with more than 100 seats. These two rivals dominate the game and compete against each other with different product lines as well as different visions of the future. Boeing invests in smaller long-range aircraft that operate point-to-point routes bypassing the crowded mega hubs, while Airbus builds larger aircraft to transport passengers between the mega hubs as economically and ecologically as possible. There are also two major competitors in the regional jet market, which has traditionally consisted of aircraft with fewer than 100 seats. Canadian Bombardier and Brazilian Embraer dominate this market and are actually stepping up to the area of Airbus and Boeing by introducing jets with more than 100 seats.

Along with the operators, *Air Traffic Control* (ATC) carries the burden of day to day flight safety. In most countries ATC is performed by the government or by a government owned company. There is a tight connection between ATC and the aviation authorities. The role of the ATC is insignificant from the perspective of this study.

The other players in the aviation industry normally evade the public eye, even if their roles are far from insignificant. The most important invisible players in the industry are the aviation authorities. In addition to authorities there are various companies and associations working in the industry. The focal companies of this study, the MRO providers, as well as e.g. catering, cleaning, ground handling and forwarding service providers all belong to this group of background actors. There are national and international associations represented e.g. by the renowned *International Air Transport Association* (IATA) and *Air Transport Association* (ATA) in the USA.

2.1.2 Regulation and Authorities in the Aviation Industry

Flight safety is an international issue. On any flight there can be passengers from several countries and an aircraft may crash virtually anywhere on the planet. This international aspect has encouraged the authorities in different countries to work together and construct regulational systems that are close to each other regarding their effect on the operators.

This cooperation has been seamless in the western hemisphere and it has reached most parts of the globe quite well. Unfortunately there are still regions like the former Soviet Union and the People's Republic of China, where the regulation lacks international influence.

Most of the aviation authorities are national governmental institutions created to supervise aviation activities in a certain country. The most powerful aviation authority is *Federal Aviation Administration* (FAA), the national aviation authority of the United States. *Civil Aviation Authority* (CAA) of the United Kingdom is another remarkable aviation authority.

The European *Joint Aviation Authority* (JAA) was founded in 1970 to harmonise aviation regulations within Europe. All the functions of JAA were absorbed by the *European Aviation Safety Agency* (EASA), which was founded as an agency of the European Union in 2003. As of 2008 EASA has 31 member countries.

Flight safety is the aviation authorities' main responsibility. The authorities try to prevent accidents by regulating everything that has a direct relation to flight safety. The result is that every player in the aviation industry has to acquire a certificate separately for each safety related function it performs. For example, EASA has

rulings that regulate maintenance staff certification (EASA Part-66), continuing airworthiness (EASA Part-M) and maintenance organisation (EASA Part-145).

To acquire a certificate a company has to meet the criteria that are disclosed in the authority rulings. Authorities perform regular but randomly scheduled audits to ensure certificate holder's performance in meeting the set criteria. A company failing to meet the criteria loses the certificate for a certain period of time. Without a certificate the company is practically out of aviation business.

2.1.3 Standards in the Aviation Supply Chain

In addition to forcing regulations on the industry, aviation authorities also create standards. These standards make it easier for the industry participants to follow the regulations. They also enhance the communication on commercial issues between different companies in the industry.

Commercial And Government Entity (CAGE) code is a universal identifier of an organisation or facility in the aviation industry. The coding is adopted from the US government but used in the aviation industry throughout the world. This way the industry has for each participant a common reference that other companies can use when addressing it.

Companies with a complex organisation structure or various production locations may have several CAGE codes. Every subsidiary or function may have its own identifier. Mergers also create companies with more than one CAGE code. The authorities prefer keeping the old CAGE codes instead of merging them as well.

ATA has created an EDI standard, which is designed to fit into the requirements of the air transport industry. This standard is called *SPEC2000*. It contains specifications for common transaction messages needed in the data exchange between companies. It also includes detailed descriptions and instructions concerning the use of the messages.

SPEC2000 messages use a dedicated network to travel from sender to recipient. *Société Internationale de Télécommunications Aéronautiques* (SITA) was founded by the airlines to provide the communication between the airports in Europe as early as 1949. The dedicated SITA network was built to relay various feeds of information between the companies in the aviation industry. Today it works on IP platform and it

is used to transfer e.g. flight schedules, arrival times and catering orders from one company to another as well as aircraft condition information from a distant line station to the home base.

2.1.4 Supply and Demand of the Air Travel Services

The economic well-being in the aviation industry is troubled by a contradiction between the quickly fluctuating demand patterns and slowly adapting supply. This makes the industry generally less profitable than its popularity might suggest. The disproportionate popularity, which is especially typical to airline business, also creates an environment with particularly tough competition.

Aviation industry depends on the passengers and their ticket payments. With a little help from the cargo side, the passengers bring in the majority of the revenue and in effect control the economic situation in the industry. Airline passenger traffic is very sensitive to overall economic environment. When the general economical trend turns downwards, companies immediately cut travel expenses and by so doing decrease the load factor of profitable business seats. When the recession is over, companies quickly increase travelling to gain their share of the expanding markets. As a result, the load factors will increase even before the upturn in the general economy has taken place.

Random events like rising jet fuel prices or public threat of terrorism may also cause peaking costs or plummeting demand. The first Gulf War in the early 1990s caused both of these at the same time taking the whole air transport industry into recession. The terrorist attacks in September 2001 decreased the demand heavily, especially in the US domestic market.

Unlike the fluctuating nature of the demand, the supply of aircraft seats is fairly rigid. The most important reason for this is the fact that in the air transport industry the supply consists of aircraft sized portions. An airline can fly the aircraft or ground it, but it cannot halve it to acquire two small aircraft. While the economic life of an aircraft is over 30 years and it has about 5 years' delivery time, it is highly challenging to react to changes in demand by adjusting supply.

2.2 Maintenance, Repair and Overhaul of Commercial Jet Aircraft

This study focuses on the maintenance, repair and overhaul (MRO) industry in the commercial jet transport. Unless stated otherwise, the discussion hereafter is presented within this scope. Outside of the scope are other aviation MRO areas such as military MRO as a whole, other areas of civil air transport MRO as well as commercial turboprop and helicopter MRO. Of an airline's operating expenditure, MRO typically represents 10-15% (Seristö, 1995, p. 35).

In the early 2008 the annual value of the worldwide MRO market was estimated to be USD 45.1 billion (Jackman, 2008, p. 41). Figure 2.1 shows the trend of this value since 2001. In the figure the market is divided into four functional segments: engine work, component work, aircraft heavy maintenance including modifications and aircraft line maintenance. The values are directly based on an annual MRO forecast produced for the Overhaul & Maintenance magazine by the consulting firms TeamSAI (formerly Strand Associates) and Ascend, Ltd. (Jackman, 2008, p. 41).

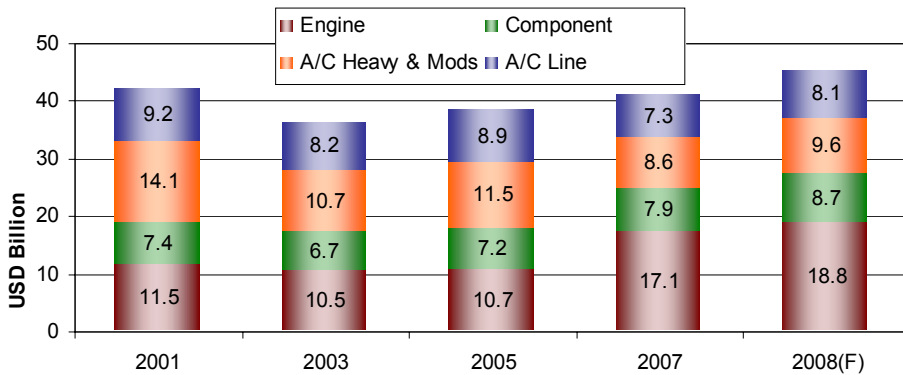


Figure 2.1 Trend of the Worldwide MRO Market Value

Figure 2.2 shows the structure and value distribution of the MRO market in 2006. The distribution of labour and other costs is based on an analysis by AeroStrategy consultancy (Flint, 2005, p. 42). As can be seen in the figure, the engine work is fairly material intensive while aircraft work is more labour intensive. The parts repair can be further broken up to materials, labour and parts repair of the sub assemblies, with a distribution similar to that of the component work.

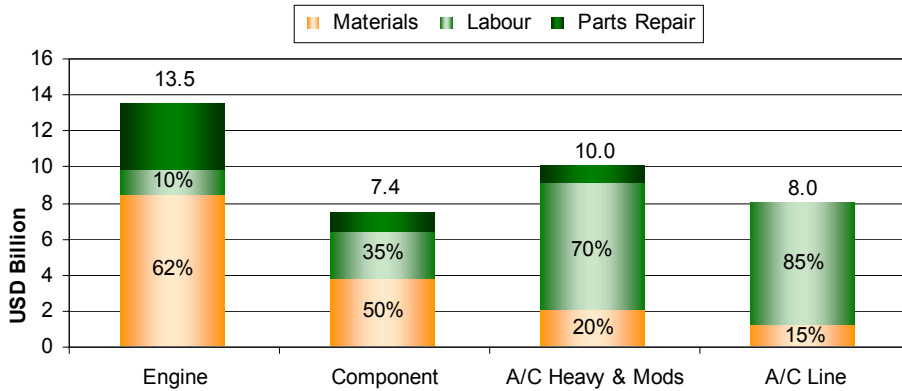


Figure 2.2 MRO Value Distribution 2006

In 2006 the commercial airlines outsourced USD 19.5 billion worth of MRO services, which was about 50% of the MRO market value. The rest of the work was performed by the captive MRO providers. As can be seen in Figure 2.3, on the average 70% of engine and component work, 40% of airframe and 10% of line maintenance work was outsourced (Flint, 2007, p.51). According to Aero Strategy consultancy (Flint, 2007, p.48) the share of outsourced MRO will climb to 65% by 2016. This implies that the trend of increasing outsourcing of MRO services will continue.

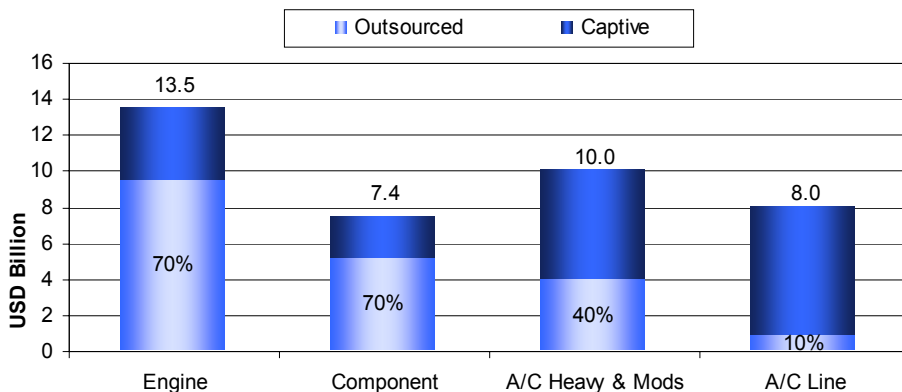


Figure 2.3 MRO Outsourcing 2006

Aircraft line maintenance has to be performed where the plane lands, because it primarily takes place between revenue flights during the plane's natural down time. This work can only be outsourced on those stations where there is a suitable service provider available. In contrast, aircraft heavy maintenance and modifications may be performed almost anywhere. As the cost of the ferry flights is diminutive compared to

the total cost of the maintenance visit, it may very well pay off to look around for heavy maintenance options. For example two heavy checks for Thai Airways MD-11 trijets have been performed by Varig Engineering Services that is located in Brazil, practically around the world from Thailand. Taking into account that 75% of the heavy check cost is labour, it is most probable that airlines will soon gain momentum in seeking heavy maintenance services in the lower price-level countries. It may also happen the other way round. Several heavy checks for China Xinjiang Airlines ATR-72 turboprop aircraft have been performed by Finnair Technical Services in Finland regardless of the two-stop 18-hour ferry flights and the significant labour cost advantage of Chinese mechanics.

The importance of maintenance location further decreases with engines and components. MRO services for these removable items, however, require expensive tooling and technical sophistication. Thus, the competition is not so much about the hourly cost of the mechanic, but about volume, turnaround time, quality and reliability. These attributes are strong with the *Original Equipment Manufacturers* (OEM), who have the potential to attain very high market shares. Another issue favouring the OEMs is the fact that on their own products they control the aftermarket (Flint, 2004, p.38). Air France Industries, the captive maintenance provider of Air France, regards aircraft heavy maintenance as low-margin business while engine and component work are more lucrative (Pilling, 2003).

2.3 Role of Aircraft Components in Aircraft Design

Aircraft design aims to be fail-safe, which means that a single failure should be accommodated by alternative functional units or load paths (Friend, 1992, p.7). The design relies on the system testing and inspection process to detect the initial failure before further malfunction or damage occurs.

An aircraft structure is divided into the body, components and parts. The *aircraft body* consists of the structures that are not normally removed during any maintenance action. Wings are parts of the body, for example. *Aircraft components* are pieces of aircraft that can be removed from it during maintenance. *Line Replaceable Units* (LRU), such as wheels, are quick to replace between flights. Aircraft heavy components, such as engines, require more time to replace. Every component has a special function in the aircraft. Components are always repairable and their

maintenance is performed while not installed in the aircraft. Parts, such as light bulbs, are consumable items which are installed in components or directly in the aircraft body.

The role of the components in aircraft design is to ensure aircraft availability by enabling quick replacement of failed units. If there is a failure in a mission critical function, the component is removed for repair instead of keeping the whole aircraft waiting. Airlines keep functional spare units at hand to replace the failed ones quickly. This allows the aircraft to continue its mission as scheduled and the repair work to be performed later on. Due to their complex functionality and strict authority requirements, aircraft components are relatively expensive. It is generally cheaper to repair than discard them and purchase a new unit as a replacement.

From the viewpoint of criticality, components can be divided into three categories, NO-GO, GO-IF and GO components. NO-GO components are required for the aircraft to function and, if one is failed, the aircraft will stay on ground. GO-IF components are not necessary in every situation for an aircraft to be operative. A failed GO-IF component may, however, limit the aircraft's operational performance by for example increasing the required runway length or decreasing the maximum cruising altitude. Aviation authorities also limit the maximum number of flights that can be performed with a failed GO-IF unit. Since GO components are not required for an aircraft to be operative, the flight schedule is not compromised in case of a failure but the costs related to the failure motivate the operator to replace the failed unit.

This research focuses on the Line Replaceable Units (LRUs) of NO-GO category, which are the key element in securing the aircraft availability. An optimally balanced stock of spare NO-GO units ensures the technical dispatch reliability of the aircraft fleet. NO-GO LRUs are simply referred to as aircraft components throughout the dissertation.

2.3.1 Component Airworthiness

A component is proclaimed airworthy by a certificate document, signed by an authorised aircraft mechanic or technician. The certificate has traditionally been a paper sheet attached to the component in a transparent plastic envelope. As a result of the emerging *Radio Frequency Identification* (RFID) technology, there have been

industry initiatives towards an electronic certificate embedded in an RFID tag directly on the component body.

The common terms to describe the status of the component are *Serviceable* (airworthy) and *Unserviceable* (not airworthy). While installed in an aircraft, a component may become unserviceable as a result of a failure or when it needs scheduled maintenance. After the maintenance or repair operations have been performed, it is certified airworthy and becomes serviceable. Serviceable components carry certificates, while unserviceable ones carry unserviceable tags. Only when installed in an aircraft may the component be separated from the paperwork.

Regardless of its location or status, a component is always under control. This control is put into effect by counting the age and use of the component as well as keeping record of every maintenance action performed on it. The counters that measure the age and use of a component are called *Meters*. The meters are used in defining intervals for different maintenance actions. When the meter value has reached a certain limit after the previous time the action was performed, it has to be performed again. In practice, a component that approaches its usage limit is replaced during the planned maintenance break just before the limit is reached.

One maintenance action interval is defined by one or more meters. If multiple meters are used, none of them can exceed its limit before the maintenance action is performed. Multiple meters are not commonly used with aircraft components. However, they are common when defining maintenance intervals for the engines and the whole aircraft.

In theory, there could be any number of different meters for controlling aircraft components. In practice, only three different meters are used, calendar time, cycles and flight hours. Calendar time is used as a meter when the aircraft usage does not wear the component. This is the case with e.g. the oxygen masks for the passengers. They will hopefully never be used but they have to work when needed. The age of the component is always measured in calendar time.

Cycle means one take off and one landing. Cycle is used as a meter with those components that wear during the take off or landing. The aircraft brakes are maybe the most characteristic components controlled by cycles.

Flight Hour is an hour of aircraft flight time. It is used as a meter when the aircraft usage wears the component and the wear is proportional to the flight time. For example the key components of the cabin pressurisation system are controlled by flight hours.

2.3.2 Effectivity and Interchangeability of Aircraft Components

In addition to controlling the use of the components, the operator is required to control their exact *position* within the aircraft structure. A position is a slot in an aircraft body or another component, where a certain component can be installed. The aircraft body and the components holding these positions are referred to as *Next Higher Assemblies* (NHA). The general rule for component structures is that the NHA can only be serviceable if every one of its positions has a serviceable component installed in it.

The *effectivity* of the component describes the NHAs that it may be installed in. This information is paramount when considering the availability service. The longer the list of NHAs is in terms of aircraft models, the higher is the value of the component for the availability service.

Another way of considering the effectivity is through *interchangeability*, which defines relationships between components. There are three main types of interchangeability, two-way interchangeability, one-way interchangeability and conditional interchangeability.

If two components are two-way interchangeable there is no difference which one is installed regardless of the situation. Thus, the effectivity of these two components is identical. Two-way interchangeable components are also called fully interchangeable. If the interchangeability is one-way only, the first component can replace the second but the second cannot replace the first. Software versions of avionics computers are one example of one-way interchangeability. A newer version can normally replace the older one but not vice versa. If there is conditional interchangeability, one component can replace another on certain condition only. For example, two pneumatic components of different dimensions but the same function may replace each other when installed in a certain aircraft model but not in another model.

2.4 Maintenance, Repair and Overhaul of Aircraft Components

The firsthand responsibility of the component MRO as well as the whole aircraft MRO lies with the airline operator. In Europe and Asia it is regulated by the local aviation authorities that an airline operator has full responsibility for its fleets of aircraft, and it owns the maintenance programs of its aircraft as well as acquires approvals for the programs from its national aviation authority (Burchell, 2003). The MRO service provider assumes responsibility for the performed work as well as related airworthiness issues. The U.S. FAA rules that an airline operator is responsible for the engineering and airworthiness issues even if the work is performed by an external MRO provider. As a result, U.S. airlines generally send around ten representatives to oversee a heavy check performed by an external MRO provider (Flint, 2004, p.40). Regardless of the continent, the trend of increasing subcontracting has increased operators' worries of the quality standards used by the service providers (Chandler, 2003).

Most airlines still have their own MRO divisions or at least they hold a major stake in the privatised MRO provider that used to be part of the airline. This applies primarily to the flag carrier airlines but not necessarily to the smaller privately owned airlines. Especially the low-cost airlines tend to focus on the core business of operating aircraft and subcontract the maintenance services among other auxiliary functions. All airlines subcontract some MRO services as it is not cost-effective or even possible to perform all necessary operations on every fleet and every component in-house. In addition to maintaining their own fleet, most airline MROs offer maintenance services to other airlines. Traditionally, airlines have offered maintenance services to other airlines to fill the gaps in the production schedule of the airline's own fleet resulting in increased utilisation of the maintenance equipment. Lately it has become more and more popular to build new capacity to cater for external demand as an effort of achieving higher economies of scale.

In addition to airline MROs there are also so called independent MRO service providers, which offer MRO services without operating aircraft themselves. Some independent MROs offer aircraft maintenance services and are thus located within airports. Most component MRO providers are located in the industrial areas away from airports, where the property prices are not as high as in the direct vicinity of an airport. Many aircraft component OEMs act like an independent MRO by offering

MRO services for its own products. Selling the products cheaper and hoping for lucrative profits in the after sales services is not uncommon in the aviation industry either. In the component MRO industry, the OEMs are in an especially good competitive position as they control the manuals, tools and spare parts needed in the MRO provision as well as the capability certification with the mandate given by the aviation authorities. The OEMs also have the appeal to gather high volumes and thus enjoy economies of scale.

There are also pure availability service providers in the component MRO market. These players do not perform any MRO services, so they do not need an authority certificate for their operation. They only keep inventories of spare units and offer logistics services for urgent delivery. The repairs are handled by other MRO providers, which they use as subcontractors. There are two common ways in which the availability providers offer their services. Airlines can purchase pool access, so that they can lower their own spare unit stock and use the service provider's pool instead. Another option for the airline is to keep its own spares stock and borrow spare units from the availability service provider in an event of stock-out.

Airline MROs commonly maintain those components that support their own fleets, which is not necessarily a very focused way of conducting component MRO business. Independent MRO providers can simplify the issue by focusing on a group of components or at least ignore some component categories. In this way scale economies can be enhanced. For example Spairliners specialises only in the new Airbus A380 components (Buyck, 2007), while many Original Equipment Manufacturers specialise in supporting the components they produce regardless of the aircraft types they are applicable to. In addition, there are wide ranging service providers like A J Walter that stocks over 4 million parts and supports all modern commercial jets with over 100 seats (Paylor, 2007).

2.4.1 Component MRO Operations

The maintenance operations that an MRO service provider is allowed to perform on a component are collected on its *Capability List*. The capability list includes the part numbers of all the component that the service provider can work on. The manufacturer (OEM) of the component defines the skills, manuals, tools and spare parts that are required to perform a certain maintenance operation on a certain

component. When the service provider fulfils the requirements, it may include the component part number and the maintenance operation on its capability list. The aviation authorities perform regular audits on MRO providers to ensure that the OEM requirements are constantly followed.

Regarding aircraft components, there are six different types of maintenance operations: Removal/Installation, Check, Restoration, Repair, Overhaul and Modification. The very basic maintenance operation for a component is *Removal* from the Next Higher Assembly (NHA). This is usually performed before any other maintenance operation, even if some operations may be performed while the component is installed. In a removal there is normally no need for spare parts. When removing a component from an NHA there is always a need to replace it to keep the NHA serviceable. Thus for every removal an *Installation* has to be made. An installation does not normally require any spare parts either.

In a *Check* the airworthiness of a component is checked. This includes inspection and a series of tests to find out if the component is in a condition to continue its service. If the component passes the tests it becomes serviceable. The purpose of a check is to make sure that the component will stay serviceable until the next check. If the check reveals something that threatens the airworthiness during that period, an overhaul or certain maintenance action has to be performed. In a check there may be some spare parts needed because the component may have to be disassembled. The checks are performed between certain intervals according to the component's meter values.

A *Restoration* is very close to a check but in addition to checking the airworthiness of the component, some basic operations like lubrication or cleansing are performed on it. A restoration generally requires some materials in addition to the spare parts needed in a check. The restorations are performed between certain intervals according to the component's meter values.

When a failure is detected in a component that is installed in an aircraft, it is removed and replaced by a serviceable unit. A failure can also be detected during another maintenance action. The failed unit needs *Repair*. When the repair work is completed successfully, the component becomes serviceable and may continue its service. If it cannot be repaired, it has to be scrapped. In a repair, there is a need for a large variety of spare parts to be available, even if only a few of them will actually be used.

Virtually any part in the component may have to be replaced. The repair work cannot be planned but its total volume for the whole fleet can be estimated with moderate level of accuracy.

An *Overhaul* is a planned set of maintenance actions performed on a component. Some components have certain overhaul intervals and an exact list of actions which have to be performed according to these intervals. The purpose of an overhaul is to keep the component serviceable until the next overhaul. Overhauls require even a larger variety of spare parts than repairs, but it is quite accurately known in advance which ones will be used. The overhauls can usually be planned like checks, because they are performed between certain intervals.

A *Modification* is a maintenance action in which the component part number changes. In a modification the component is changed so that it gets new features. With those features it becomes a more advanced component and receives a new part number. Modifying an aircraft component is like upgrading its version. Advancing technology drives the airlines to modify long-lived components, as it allows them to utilise new technology without investing in new components. Modifications require a large number of spare parts, which are known well in advance.

Turn Around Time (TAT) is a concept used in describing the time that it takes for one component to pass through a process of maintenance operations. In the research on availability services, the focus is on the repair TAT, which means the average time between the event when a failed component is removed from an NHA until the moment when it is stored and ready to be used as a spare unit.

2.4.2 Component MRO Resources

Several kinds of resources are required in providing component MRO services. The resources listed here include only the primary ones; various resources needed to provide background operations are omitted. The following list by Friend (1992, p.84) is quite general and thus applies to almost any kind of maintenance work:

- Buildings and maintenance facilities
- Trained labour with appropriate skills
- Supply of spare parts
- Technical manuals including work instructions
- Tools and maintenance equipment
- Store space for units waiting for maintenance or ready for service

Buildings and maintenance facilities are the very basic resource needed to provide component MRO service. Normally these resources do not differ much from the other industries, but for those MRO providers located at airports, there may be access restrictions and limitations to increase capacity by expanding the facilities.

Trained labour is without question the hardest resource to manage in the component MRO business. The authorities specify very thoroughly the skills and training needed to perform maintenance work. No educational institution can produce a certified aircraft mechanic. A process of no less than five years from a trainee to a mechanic is required to achieve that.

Component MRO and especially repair work requires a large supply of spare parts as it cannot be predetermined which parts are necessary to repair the unit. The scale economies apply, so the relative value of the spare parts inventory decreases when the repair volume increases.

The OEM provides the necessary manuals for completing the maintenance operations as well as for understanding the component functionality. The MRO provider normally produces work instructions for the most common repair procedures in-house.

In general, component MRO requires expensive tooling and equipment. This is one of the most important drivers of the scale economies in the MRO workshop. It is not uncommon that one set of tooling or a piece of test equipment only applies to one component, so high volumes are crucial to justify the investment.

2.4.3 Detecting Component Failures

From the perspective of this dissertation, the focal point in the component flow is the moment when it appears to fail and needs to be replaced. That event creates an unexpected spare unit demand, which the availability service is prepared to handle. It may sound controversial but advancing technology tends to increase the unexpected spare unit demand relative to the expected spare unit demand.

The aviation industry first shifted from predefined usability cycles into predefined overhaul intervals and more recently into predefined checking intervals. In the past a component used to be scrapped after a certain number of landings. In the second phase, the same component was overhauled after a certain number of landings. In the

third phase, it is checked after a certain number of landings and, depending on how well it performs, it will be scrapped, overhauled, repaired or just reinstalled. These are commonly referred to as *hard time* methods and they result in a rather high expected demand for spare units.

As technology has advanced, aircraft systems are increasingly designed to *fly until fail*. At first glance, this does not seem to be in line with the zero tolerance of safety hazards in the aviation industry. This principle has not, however, caused any compromises to flight safety. To ensure safety en route, all mission critical systems that use this principle are backed up with redundancy. They are duplicated, triplicated or even quadruplicated. For example the crucial hydraulic system in an MD-11 aircraft is triplicated.

With an increasing number of fly until fail components in the aircraft, failure detection has become an issue of great importance. A component failure that has already occurred can be detected by a pilot or line mechanic either by trial or buy using a *Centralised Fault Detection System* (CFDS) or a *Central Maintenance Computer* (CMC). Modern aircraft are equipped with CFDSs and CMCs that collect information from *Self Monitoring Programmes* (SMP) and *Built-In Test Equipment* (BITE) which are included in the components themselves (Aircraft Economics, 1997, p.VI; Aircraft Commerce, 2006). The purpose of these systems is to troubleshoot aircraft's systems and identify faulty components. CFDS only displays the faults it finds, but CMC is also able to classify them by criticality and assist the mechanics in repairing them. These systems are working all the time, but thorough checks are run before and after every flight.

The advanced analysis tools that monitor trends of aircraft systems performance can also predict failures, so corrective actions can be taken in advance (e.g. Flint, 2002a, p.46; Moorman, 2005, p.57). Predicted or not, a component failure is always a random phenomenon and considered unexpected from the perspective of this dissertation.

The term *No Fault Found* (NFF) is used to describe situations when a component is removed in the belief that it has failed, but later on no fault can be identified. There are generally two cases of NFF. In the first one the removed component is incorrectly identified as failed, i.e. it was removed instead of or in addition to the component actually causing the failure. The main reasons to this are inadequate troubleshooting

methods, limited time to do the troubleshooting, misleading fault reports and the increasing complexity of modern aircraft. The second case of NFF relates to difficulties to repeat the failure in the workshop. In spite of the advanced testing equipment available, there are still faults that only occur when the component is installed in an aircraft and flying at the cruising altitude. If the fault in question is anything like this, the workshop will believe that this NFF belongs to the first group and the component is fully functional. This leads into a cycle of removals, recertifications and installations, while the unit never actually functions properly. A component in this vicious circle is often referred to as a *rogue unit*.

2.4.4 Measuring Aircraft Availability

Measuring aircraft availability differs significantly from measuring the availability of a system that runs 24 hours every day. This section provides concepts and methods for measuring aircraft availability compared to measuring a full time system availability.

Mean Time Between Failure (MTBF) is a concept used in describing system reliability. MTBF means the average time from one system failure to the next one. *Mean Down Time* (MDT) is the average time the system is in failure before it becomes available. A traditional way of measuring system availability is to compare its total availability time to the calendar time. System availability is therefore always between zero and one, zero meaning totally unavailable and one meaning always running. A common way to calculate the average system availability is as follows:

$$A = \frac{MTBF}{MTBF + MDT} \quad (1)$$

where A equals aircraft availability. This method of measuring availability works fine with systems running 24 hours a day every day of the year. Aircraft are not flying like that, even if most airlines would like them to be. An average commercial aircraft operates only 7-9 hours per day (AvSoft, 2005b). The remaining 15 - 17 hours it is waiting for departure either in its base or at one of the airline's destinations. If an airline calculates that its aircraft's availability is 23 hours and 15 minutes on the average per day, it is not good enough. What is important for an airline and its passengers is whether those 45 minutes of down time occur when the aircraft should depart or when it is waiting idle. Theoretically even an average availability of 12

hours per day would be perfect for an airline if the down time fitted conveniently amidst the flight schedule.

It is easy to see that aircraft availability is not about a high percentage, it is all about timing. From the viewpoint of aircraft components, the failure is fixed elsewhere but the removal and installation of the component affect aircraft availability. A *scheduled removal* occurs when a component is removed from an aircraft according to a maintenance plan. Normally this means that there is a maintenance operation that needs to be performed before a certain meter limit is exceeded. Scheduled removals do not decrease aircraft availability, as they can be performed during natural down time in the flight schedule. An *unscheduled removal* occurs when a component is removed from an aircraft because of a suspected failure in it. An unscheduled removal has a risk of affecting aircraft availability, regardless of whether there actually is a failure or not.

Mean Time Between Unscheduled Removals (MTBUR) is a concept used in describing component reliability. If the removed component is always correctly identified and there really is a failure in it, MTBUR equals MTBF. Because of the No Fault Found (NFF) factor, the MTBUR of a component is generally shorter than its MTBF. As all unscheduled removals carry the same potential of decreasing aircraft availability, MTBUR is a better measure for the reliability of aircraft components than MTBF.

From the viewpoint of MRO services, the most suitable measure of aircraft availability is *Technical Dispatch Reliability* (TDR). It compares on-time departures of an aircraft to all its departures. From the maintenance perspective it is of course necessary to count out all non-technical delay factors, like catering arriving too late or boarding progressing too slowly. TDR is presented as a number between zero and one just as the general availability discussed above. It can be calculated for any time period and for any selection of departures as follows:

$$\text{TDR} = \frac{\text{DEPS}_{\text{notd}}}{\text{DEPS}_{\text{all}}} \quad (2)$$

where $\text{DEPS}_{\text{notd}}$ equals the number of departures with no technical disruptions and DEPS_{all} equals the total number of departures. Most airlines are interested not only in

the number of delayed flights but also in how much they are delayed. For this purpose TDR should be accompanied by *Average Technical Delay* (ATD). It can be expressed as the length of an average delay caused by technical factors. The calculation can be performed as follows:

$$ATD = \frac{\sum_{i=1}^n DLY_i}{DEPS_{all} - DEPS_{notd}} \quad (3)$$

where n equals the number of technical delays during the time period and DLY_i equals the duration of the i:th technical delay. By using TDR and ATD together an airline can measure its aircraft availability in a way that reflects its actual needs. With these measures it is easy to compare e.g. different aircraft types or aircraft of the same type maintained by different MRO providers.

2.5 Optimising the Inventory Levels of Aircraft Spare Components

The issue of optimising spare component stock is of extensive complexity. In this dissertation, the mathematic modelling only considers the most important factors to keep the models simple and results comprehensive, as the focus here is in the sourcing of availability services. However, even the studies that focus on spare part optimisation simplify the problem considerably and leave relevant factors unmentioned. There is no evidence of an academic publication including an exhaustive list of factors that affect the spare component optimisation, let alone a model that could handle them all.

As there is a multitude of complex factors affecting the optimal level of the spare stock, all the efforts of optimisation are simplified to some extent. Theoretically, it would be possible to build a simulation that takes all the factors into account, but there would still be an issue with less than sufficient quality and quantity of the input data. In spite of this, a number of IT solutions have been developed to assist in the optimisation. Three current examples of commercial spare parts optimisation solutions are OPUS10 by Sysstecon, Servigistics service parts management solution and Click Commerce Service Parts Optimization (former Xelus). Boeing have evaluated some commercial software packages and after finding them relatively ineffective, consequently started their own software development (Croft, 2005, p.31).

Alternatively, as Davidson (1980, p.147) concludes, it would be possible to use some basic model as guidance and begin with a relatively low level of spare stock, then take advantage of the first few years' real life experience to accumulate the spares supply in order to provide satisfactory service levels.

This section identifies a considerable number of factors that should be taken into account when calculating optimal stock levels for aircraft spare components.

2.5.1 Basic Factors of Spare Component Optimisation

The four basic factors that need to be considered when optimising the spare component stock are: component reliability, repair turnaround time, number of units in the supported fleet and cost of owning one spare unit. In addition to these component specific factors it is necessary to know the cost of a shortage situation. According to Alfredsson (1997, pp.5, 16) the number of aircraft components in repair at any given time follows a Poisson distribution. Together with this knowledge the first three factors allow the calculation of the average frequency of shortage situations as a function of the number of spare components. Subsequently it is easy to calculate the number of spare units that minimizes the total cost, as presented in Paper III. A similar calculation needs to be performed for each component separately.

However, the result of this calculation is valid in 'laboratory conditions' only. In the real world, this basic method can only provide guideline value that needs to be adjusted taking other affecting factors into account.

2.5.2 Industry Independent Factors

This section provides an introduction to general factors that apply to any industry where repairable spare parts are used. Taking these factors into account in the optimisation would definitely lead to more reliable results. All these factors have been analysed in the academic literature but separately from one another.

The basic optimisation assumes that component reliability is constant. This is a reasonably valid approximation as most of the reliability is embedded in the design and manufacturing quality of the component. There are two issues, however, that should be considered regarding reliability: the challenge of estimating the reliability (e.g. Henderson, 2000, Charruau et al, 2006 and Hsieh et al, 2008) and the effect of preventive maintenance (e.g. Nguyen and Murthy, 1981). The reliability data used in

the basic optimisation may be based on limited experience or different usage conditions. It should be understood that the reliability data becomes more and more accurate when the usage experience in similar conditions increases. Proper caution assumed, sharing of reliability data between companies in the industry would profit everyone. It is also evident that preventive maintenance increases reliability. With optimal preventive maintenance policies and enough reliability data at hand, the component reliability can be optimised so that the total cost of preventive maintenance and failures is minimized.

The basic optimisation also assumes that the repair turnaround time is constant. This is a very strong assumption, which is hardly ever valid in the real world. On one hand, the workshop can temporarily reduce its repair turnaround time, i.e. expedite the repair process, if a particular type of component has lower stock than the others. The flexibility to perform a priority repair like this allows a lower number of spare components. The effect of this factor has been simulated by Pyke (1990) but it only concerns shortage situations. On the other hand, demand peaks inevitably extend the repair turnaround time temporarily as it would otherwise require unlimited workshop capacity. Compared to the basic optimisation, all restrictions in repair capacity increase the number of spare units needed. Díaz and Fu (1997) have included capacity restrictions in their spare part optimisation models.

Another factor to consider, which is not industry specific, is the so called multi-echelon system. In such a system the failures may occur in several geographic locations while the spare component stock is also distributed between a number of locations. A multi-echelon system presents an extra challenge for the spare part optimisation, as it is necessary to decide how many units to stock in each echelon. A reliable and rapid logistics network is also needed to balance supply and demand between the echelons. This can be performed reactively with emergency transshipments or proactively with balancing transshipments. Assuming the same total demand of spare components, a multi-echelon system always requires more spare units than a single location. A multi-echelon system with emergency transshipments generally needs fewer spare units than a system of similar size where the echelons are isolated from one another. If the stock levels are proactively balanced between the echelons with transshipments, the system will generally need even fewer spare units. The METRIC system to handle multi-echelon settings for rotatable spares was first

introduced by Sherbrooke (1968), later on improved to MOD-METRIC by Muckstadt (1973) and finally further improved to VARI-METRIC again by Sherbrooke (1986) with assistance from Graves (1985).

2.5.3 Aviation Specific Factors

This section provides an introduction to the factors which are very important in the aviation industry and may apply to other industries as well. At least within aviation industry, these factors increase the accuracy of the optimisation beyond the level attained in the previous section. It appears that these factors have not been discussed in the academic literature on spare component optimisation.

In commercial aviation it is almost always possible to combine the multi-echelon systems of different operators to one multi-echelon system of a higher scale. This is commonly called inventory pooling. Pooling arrangements allow operators to utilise economies of scale and treat several inefficient spare inventories as one efficient spares supply. Assuming an efficient logistics network, these arrangements generally lower the total level of spare component stocks. Carter and Monczka (1978) construct a model to study pool implementation as well as spare part pooling as a commercial service, but limit their work to consumable spare parts and other consumable items with random demand. There are also studies with advanced mathematical models but limited managerial analyses, in which the pooling of repairable spare parts is achieved by emergency or priority shipments between the pool stocks and the point of need. Lee (1987) considers lateral emergency transshipments between two identical bases, while Axsäter's (1990) alternative model applies to two non-identical bases as well. Similar results are presented by Dada (1992), but with bounded approximation error. Tagaras (1989) shows that pooling always improves service levels at both locations of an inventory system with two locations. Tagaras and Cohen (1992) consider a model which allows nonzero replenishment lead times to be applied. More recently Grahovac and Chakravarty (2001) discuss inventory sharing and lateral transshipments of expensive low-demand items, which is a characterisation also applicable to aircraft spare components. Axsäter (2003) introduces a new decision rule for lateral transshipments to minimize the expected cost, assuming that the transshipments are immediate but incur costs. Wong et al (2005) present a model that uses two types of transshipments, normal and delayed, and permits more than two

bases. Their work is motivated by the inventory problem of repairable aircraft spare components. Herer et al (2006) propose a model that focuses on the advantages of proactive transshipments. Inventory pooling is investigated further in Papers III and IV.

Most suppliers in the aircraft MRO industry offer an expedited *Aircraft On Ground* (AOG) delivery schedule on spare components. Even if there are no units left in their own spares stock or in any spares pool at hand, it is possible to borrow a spare unit or purchase a new unit from a supplier and get it delivered very quickly. If there are agreements concerning these methods with reliable, short enough lead-times, they may have a substantial decreasing effect on the number of spare units needed.

Many aircraft MRO providers perform both line and heavy maintenance in the same base. This allows the service provider to cannibalise aircraft that are undergoing a heavy maintenance check to fill a spare component shortage in the line maintenance. When optimising the spare component stock, the expected number of units found in the aircraft in heavy checks can be counted as spares for the line maintenance business.

In commercial aviation practically every shortage is quickly filled using one of the methods mentioned above. As a result the standard queuing policies, i.e. service disciplines of the shortages, are not necessarily optimal. The spare component optimisation models introduced in the literature generally use *First-In-First-Out* (FIFO) service discipline because it minimizes the average waiting time. However, as the shortages are filled anyway, there is little gain in minimising the waiting time. A conditional service discipline that leaves the shortages waiting for the whole repair turnaround time would generally result in a lower number of spare units needed.

Almost all optimisation models assume that the supported equipment needs to be operational for 24 hours a day and 365 days a year. This is actually not the case with aircraft. According to year 2003 fleet performance data of major airlines in the ACAS database (AvSoft, 2005b), even the most efficient passenger airlines can only achieve 13-15 hours of utilisation per day with their best, typically long-haul, fleet. The average level is somewhere around 7-9 hours per day. In case of a component failure in the middle of a flight, which does not result in a diversion, the remainder of the flight is not yet considered down-time. New technology monitoring systems detect

failures in-flight and relay them to the ground staff, who can immediately start finding replacement units (Moorman, 2005, p.58). The time window for replacing the failed unit lasts until the aircraft is scheduled for its next flight, without causing any trouble to traffic. By rerouting aircraft, it is even possible to stretch that time window with only a moderate cost. All extra time after the failure before punitive effects take place decreases the number of spare units needed. A theoretical model of aircraft rerouting is introduced by Rosenberger et al (2003), while Mathaisel (1996) presents a practical system of handling aircraft rerouting. The spare part optimisation model developed by Bridgman and Mount-Campbell (1993) takes into consideration the scheduled idle periods of supported equipment, but not the fact that an aircraft can usually complete its flight normally even if there is a component failure during the flight.

3. SOURCING OF AIRCRAFT COMPONENT SUPPORT

This section presents the business logic of the aircraft component support including the component availability services as well as the component MRO services. The area is discussed from the viewpoint of sourcing, leaving out elements that are of lower relevance from that perspective.

3.1 Sourcing in the Context of Availability Services

The term *sourcing* first appeared in textbooks on material management in the early 1960s. An early article by O'Connell and Benson (1963) captures the essence of sourcing in a timeless, general definition: "Sourcing is a two-fold process: it is investigative, then acquisitive. It searches, discovers and subsequently rejects or acquires.". This article already contains most of the key issues of today's global sourcing trend. As early as 1973, Drucker (p. 735) stated that every company, even a local one, should be managed as if operated in a global economy.

Globalisation is inevitable, as it is not fuelled by politicians, economists or business managers who could perhaps be controlled by the law, but by advancing technology especially on the areas of communication and mobility that are universally considered as civil rights, thus relatively well beyond the reach of artificial restrictions. In the global business environment mere buying or procurement is not sufficient, since the selection and variety of all available products and services is simply too complicated to be mastered using a typical process of a request for quotation, agreement negotiations and signing the contract.

In this study the term sourcing is used in a particular sense - as a sufficiently advanced method of procurement suitable for the challenges of the ever more complex global business environment. Instead of choosing between comparable products or services, sourcing begins with a research of comparable business scenarios, each of which require potentially very different products and services. The result of sourcing is a *way of conducting business* that supports company strategy, based on a network of external products, services and solutions as well as internal processes. Instead of ending up with one agreement, sourcing leads to a flexible but consistent portfolio of agreements and partnerships with a number of external and internal parties.

There is an acquiring organisation as well as providing organisations in sourcing in the same way as in traditional buying. Each of the involved providing organisations is responsible for supplying a clearly defined part of the total sourced solution. For the solution to work, the relationship and responsibilities between the acquiring organisation and each of the providing organisations must be clearly defined. In this study these connections between organisations are called *interfaces*.

During the sourcing effort it is necessary to compare the total costs of alternative business scenarios. They include the explicit costs of products and services, as well as the administrative costs of all interfaces. In addition to these costs, the implicit costs of the quality of products and services should also be included in the total cost calculations (See e.g. Tagaras and Lee, 1996). The net effect of increasing and decreasing synergies on the other functions of the company or corporate group should also be considered. The amount of the administrative cost, closely related to Williamson's (1981) transaction cost, of an interface depends on its complexity. Sourcing is all about weighing and balancing the explicit costs, interface complexity and synergy effects of the compared business scenarios.

It should also be noted that the providing organisations may very well be other departments in the acquiring company or separate companies in its own corporate group. Today's complicated and frequently changing corporate structures with numerous holding companies and cross-ownership may actually fade the ownership relations between two organisations. As a result, it is not feasible to bluntly divide sourcing into insourcing and outsourcing. Instead, the focus should be on the interface complexity that measures the same matter in a more elaborate, continuous (non-binary) way and provides useful information for decision-making.

There are two major factors in the interface complexity: the degree of conflicting interests between the parties and the nature of information flow needed for the providing organisation to fulfil its commitment. There are always some conflicting interests between the parties, even if they are two departments of the same company. The more conflicting interests there are, the more difficult it is to agree on particulars and settle forthcoming disputes, i.e. the more complex is the interface. In today's information-centric business environment every provision needs several information transfers back and forth between the parties to succeed. The more diversified and

voluminous information needs to be transferred, the more difficult it is for the parties to produce it sufficiently both in the qualitative and quantitative sense, i.e. the more complex is the interface.

3.2 Processes in the Aircraft Component Support

The aircraft component support is a service in which components proceed from being installed in an aircraft to being removed, repaired and again installed in an aircraft. It also includes all the logistics and analytics services that are required in order to secure the technical reliability of aircraft as far as it depends on components. Economies of scale are strong with component support services, so there is a considerable potential to be realized by increasing the service volumes.

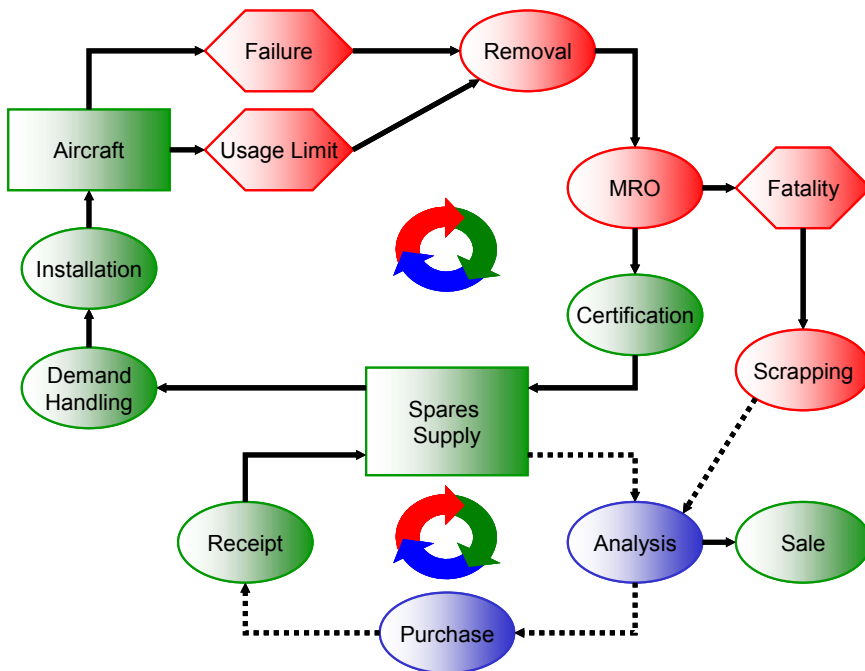


Figure 3.1 Double Loop of the Component Support

Figure 3.1 shows how the key processes of the aircraft component support can be presented in a form of a double loop. The focal point of the processes is the spares supply placed between the two loops. In the figure, stable locations of the components are presented as rectangles, process steps as ellipses and random or triggered events as hexagons. Those phases of the loop where the units are unserviceable are presented in red, while the ones where they are serviceable are in green. The phases presented in

blue are not connected to any particular component unit, so the serviceability status is not applicable. Solid arrows represent real unit flows, while dashed arrows stand for information flows.

The action in the upper loop or *repair loop* of the aircraft component support flow is reasonably frequent. From the viewpoint of a fleet of aircraft there are typically dozens of transactions every day. Regarding one unit it may, however, spend years installed in an aircraft before entering the repair loop. Compared to the upper loop, the process of the lower loop or *replenishment loop* is performed quite infrequently. Even the fastest wearing components, aircraft tyres, go through the repair loop of retreading multiple times before being scrapped and starting the replenishment process. Some components can go through a virtually unlimited number of repairs and overhauls without wearing out, thus making the replenishment loop obsolete after the initial provisioning.

3.2.1 Repair Flow of Aircraft Components

When an airline operator takes a new fleet of aircraft into use, all the components are either installed in the delivered aircraft or stored in the spares supply as a result of the initial provisioning process. The repair loop is initiated by a removal of a component from an aircraft. This is caused by a component failure or its usage hitting a limit.

Every time when there is a removal of an *unserviceable* (functionally deficient) component from an aircraft, there has to be an installation of a similar *serviceable* (fully functional) component in the aircraft before it may continue its operation. The component failure actually causes the need for the installation, thus creating a demand for a spare unit in the spares supply. It is in the interests of the airline operator to maximize aircraft utilisation by keeping spare units ready to be installed whenever needed.

After being removed from an aircraft, the unserviceable component is sent to a workshop. Depending on the reason of its removal, a number of maintenance, repair or overhaul operations are performed on it. When it is fully functional, it is certified and sent to the spares supply. With the certification the component becomes serviceable. However, during the workshop visit it may be realized that the cost of the remaining operations would be higher than the replacement cost of the component, so

it is no longer economical to continue working. This fatality leads to the scrapping of the unit.

3.2.2 Spare Part Inventory

In the focal point of the double loop figure there is the spares supply. This is the location where all the spare units reside in the initial setting of a new fleet beginning its operations. Gradually, when the operating volumes of the new fleet increase, the spares will start getting scattered around the repair loop.

Spare units are identical in function to units installed in the aircraft. The only difference between them is the insurance-like role of a spare unit compared to the revenue generating role of an installed unit. In time, installed units fail and the roles change, so no individual aircraft component stays in the spares supply for long. If the rotation is working well, all the units take turns in being in revenue generating role and being a spare.

3.2.3 Replenishment of Aircraft Components

The most important phase in the double loop is the analysis of the spare unit count, as it has a significant effect both on the technical reliability of the aircraft fleet and the cost of the aircraft component support. The replenishment loop involves constant monitoring of external conditions and the analysis is triggered whenever they change. The result of the analysis is the optimal number of spare units that should be kept in the repair loop.

The most important factors to be considered in the analysis are the expected demand of spare units, the turnaround time of the repair process and the required service level of the spares supply. As a result of the analysis, a corrective action may be taken on the number of spare units in the repair loop, i.e. a sale of an excess unit or a purchase of a new unit. A more detailed list of factors affecting the analysis was already provided in Section 2.5.

3.3 Service Packages in the Aircraft Component Support

For sourcing purposes, the processes in the aircraft component support are organized in five service packages. Figure 3.2 divides the double loop of the rotatable flow into service packages. These packages are constructed so that each of them represents a

separate area of responsibility that integrates with the other areas through easily definable interfaces. When making the sourcing decisions, these packages represent the smallest entities that should be contracted separately.

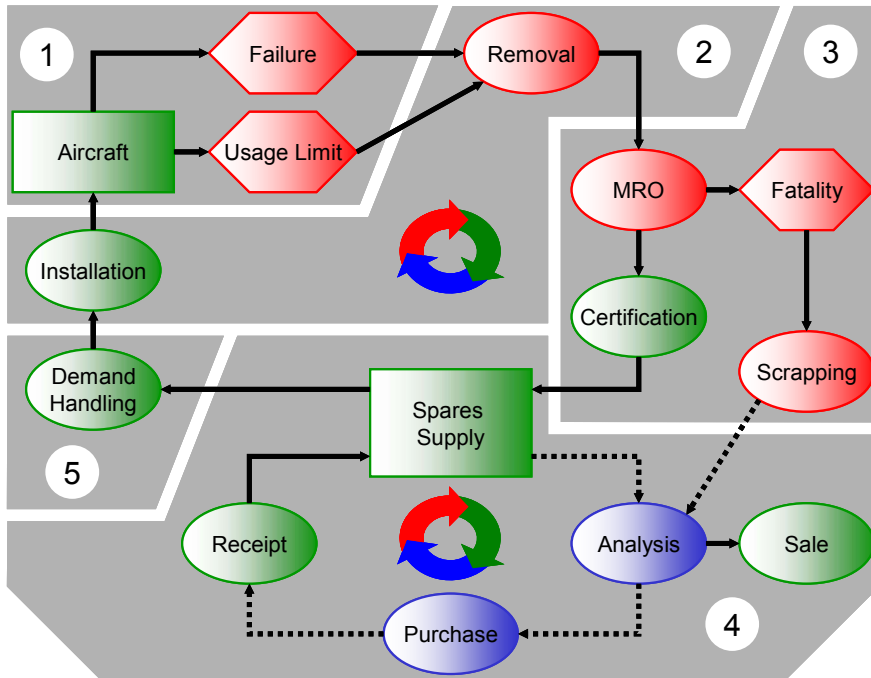


Figure 3.2 Service Packages in the Aircraft Component Support

3.3.1 Components Installed in Aircraft

An airline operator has full and indivisible responsibility for the airworthiness of its aircraft. Thus, service package 1 can only be performed within the airline operator's technical organisation. Actually, this service package does not include any process steps but only the responsibility for monitoring the condition and usage limits of the components installed in the aircraft.

3.3.2 Aircraft Line Maintenance

Component removals and installations are considered aircraft line maintenance instead of component support. Even if components are involved in this service package 2, from the airline's viewpoint it is more aircraft maintenance than component maintenance. It is outside the scope of this study to consider the sourcing alternatives of aircraft line maintenance.

The interface between service packages 1 and 2 is straightforward. A removal is triggered by a notice from the airline operator indicating that a component failure has been detected or a component usage limit is approaching. An installation always follows the removal.

3.3.3 Component MRO Services

Service package 3 includes the component MRO service. It is the first service package that can be regarded as component support. Its function is simply to repair unserviceable components. The most important factors in the component MRO service are quality, cost and turnaround time.

The MRO process is triggered by a component removal in service package 2. The interface between service packages 2 and 3 requires a delivery of the removed unit from the line maintenance facility to the MRO workshop. After certification, the serviceable unit is delivered to the spares supply through the interface between service packages 3 and 4.

3.3.4 Spare Component Availability in the Long Term

Service package 4 includes the spares supply and the whole replenishment loop. It covers the long term element of the component availability service by providing the spare unit coverage for the majority of demand situations.

The physical process of availability service mainly consists of receiving serviceable units in the spares supply from service package 3, warehousing the spares supply within service package 4 and delivering spare units to service package 5 when needed. The physical processes of receiving new spare units in the spares supply and delivering sold excess units out of the supply are also carried out occasionally within service package 4.

3.3.5 Demand Handling in the Short Term

The final service package (5) covers the short term element of the component availability service. Within service package 5 the spare component demand is met using the cascade of alternative sources as shown in Figure 3.3.

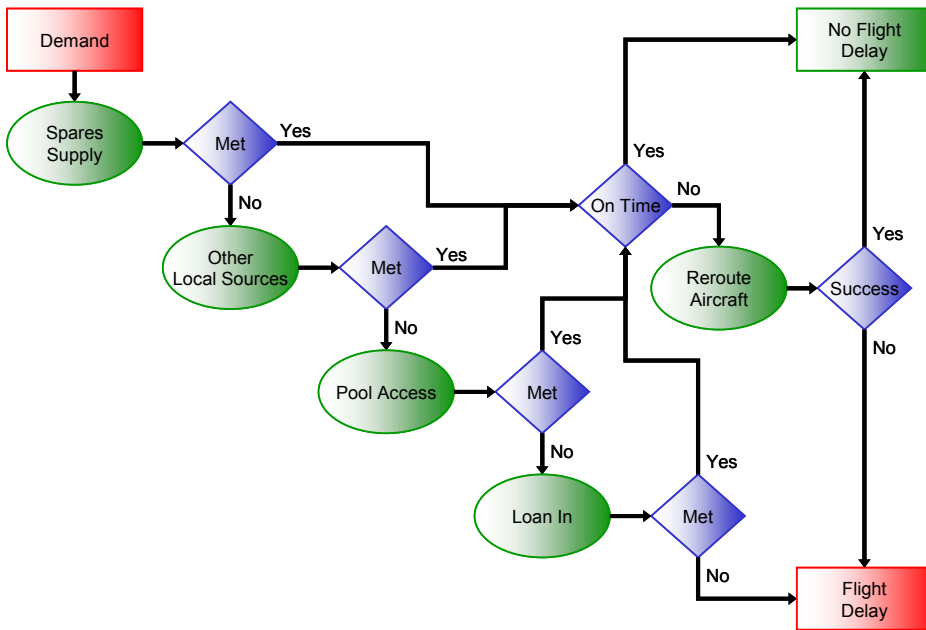


Figure 3.3 Handling Spare Component Demand

The trigger to demand handling is the removal of the failed unit in service package 2, which creates the spare component demand. The first goal here is to locate and deliver the spare unit to service package 2 in time to install it before the aircraft in question is scheduled to depart. As the scheduled downtimes of aircraft are generally short, there is only a limited time to reach the goal successfully.

Even if the first goal is not reached, the flight is not necessarily delayed. Often there are other similar aircraft in the same base with more scheduled downtime, which can be rerouted to the mission. If the rerouting is successful there are no flight delays, the passengers are satisfied and there is some more time to locate the spare unit. As no airline can afford to keep spare aircraft, there is always a limit in the slack that can be created by rerouting. The second goal of demand handling is to get the spare unit to service package 2 so that it can be installed before the rerouting options are exhausted.

The first source of spare units is the spares supply. It should cover most of the demand requests if the analysis within service package 4 is performed adequately. If the spares supply is empty, there are normally alternative local sources, where the spare unit can be found. For example aircraft undergoing heavy maintenance do not need their components before the maintenance visit is over. If there are no local sources available, the next alternative is to look at the accessible pool stocks that are within

reasonable transport time. Finally, as all the other alternatives fail, there is always the loan market that offers spare units to airlines against a considerable loan fee.

3.3.6 Total Care Agreements in the Aircraft Component Support

The service packages described above are the smallest entities of aircraft component support that should be contracted separately. It is, however, possible and often advisable to combine several of them under one contract. Theoretically, all the MRO functions of the airline can be contracted under one complex agreement. A more common level of aggregation is to combine the component support of one aircraft fleet under a total care agreement.

In an ideal total care agreement the airline pays a certain amount of money for each flight hour and landing that the aircraft in the fleet operate and everything in the service packages 3, 4 and 5 is taken care of. The airline's line maintenance removes failed units from the aircraft and immediately receives serviceable ones to replace them.

3.4 Sourcing Alternatives in Use

Traditionally most of the component support services have been performed in-house by the MRO division of the airline. There are also various external service providers in the market offering component support services and their popularity has been increasing among airlines. Additionally, an in-house MRO division can achieve economies of scale by selling component support services to other airlines. Regarding component availability services there is also an alternative of pooling spare part inventories with other airlines to achieve economies of scale.

Each service provider in the component support market requires an authority approval stating that the workshop is certified to perform general aircraft related work. In addition, every service provider has a capability list describing exactly which components it is certified to maintain. The list also includes the maintenance operations the workshop is certified to perform on each component. The aviation authorities frequently audit the service providers by checking their capabilities to perform various maintenance operations on the components that show in their capability lists.

Keeping up the approved capability of providing MRO services to a certain component has a high fixed cost. If the volumes created by the airline's own fleet are low, it is more economical to either contract MRO services to an external service provider or attract more volume by selling MRO services to other airlines. Keeping up the capability to provide availability services generally has a low fixed cost. However, the demand distribution of spare units favours high volumes, so the case in effect is the same as with MRO services.

Even if the airline selects the in-house alternative for the component support, its capacity cannot necessarily cope with the demand peaks. This holds for the MRO workshop in regard to limited throughput capacity as well as the availability service in regard to a limited number of units in the spares supply. Overflowing MRO work can be sent to an external service provider while the unmet spares demand can be dealt with by loan arrangements.

4. REVIEW OF THE RESULTS

This chapter reviews the main findings of the individual papers included in this dissertation.

4.1 Fleet Composition of Commercial Jet Aircraft

The economies of scale in the aircraft component support directly result from the size and commonality of the supported aircraft fleets. While the size and commonality of the supported fleet determines the immediate cost level of the support service, the size and commonality of the world-wide or region-wide fleet of aircraft determines the potential for achieving pooling benefits.

The main outcome of Paper I is a method of assessing the commonality and size of an aircraft fleet in a format of one numerical value. The commonality of the fleet was referred to in Paper I as fleet uniformity. It was measured by the fleet standardisation index that takes into account the variety of the fleet and ignores its size, thus allowing comparisons between airlines of different sizes. Fleet uniformity is a major factor affecting the unit cost and financial performance of an airline.

For the purposes of aircraft component support, another measure was required. It combines the fleet size and commonality allowing the assessment of the potential for achieving scale economies. This measure was referred in Paper I as fleet scale. As the fleet size is included in the measure, it loses the ability to directly compare the uniformity of different sized fleets. Instead, it gains the ability to directly compare the scale of fleets with different levels of uniformity. The fleet scale is best suitable for assessing alternative fleet change scenarios within an airline.

In addition to introducing measures for the fleet uniformity and scale, Paper I uses these measures in an analysis of the full history of all commercial jet aircraft world-wide. In general, the average uniformity of the airline fleets has been steadily decreasing from the beginning, while the average fleet scale has been steadily increasing. Paper I identifies market trends affecting the airline industry that reinforce these developments. Airline consolidation decreases uniformity and increases scale in the short term. During an economic boom the airline fleets expand uncontrollably in size and variety, also decreasing uniformity and increasing scale. This happens as new aircraft are taken into the fleets and old ones are retrieved from their parking slots,

where they were deposited during the previous downturn. The fleet uniformity is also in danger as the manufacturers of the regional jets are stepping up one category and beginning to compete directly against the traditional narrow-body aircraft with the new higher capacity variants of their aircraft.

Paper I also identifies market trends affecting the airline industry that counteract with these developments but so far have turned out to be weaker. During an economic downturn the airlines retire or park older aircraft, adjusting capacity to better meet the lower demand. This increases uniformity if aircraft types or even models leave the fleet, and decreases scale if only the number of aircraft decreases with all the models still staying within the fleet. As regards older fuel thirsty aircraft, rising jet-fuel prices have a similar effect as a downturn. The consolidation of aircraft manufacturers in the large aircraft segment also increases the fleet uniformity in the long term by narrowing the alternatives for the airlines.

4.2 Valuation of Spare Components

In the component availability service, the most important cost item is the ownership cost of the spare units. As the ownership cost is the sum of the value depreciation of the unit and the interest on its residual value, the valuation of spare components is the key to determining the cost of availability service.

The main contribution of Paper II is a set of valuation principles, which takes into account the fact that repairable spare components do not follow the same depreciation rules as other production assets or disposable spare parts. In contrast to these more common asset types, repairable components repeatedly change between the production asset role and the spare part role, which creates challenges for their valuation. Paper II includes rules of treating repairable components in their revenue generating role as common production assets, in their insurance-like role as spare components and at the moment when they are changing from one role to the other.

The value of the aircraft includes the values of all the components installed in it. These components are in the production asset role. When the aircraft is depreciated, the installed components are also depreciated, but the share of the total aircraft value that belongs to a certain component cannot be defined. The components in the spare part role only generate income by shortening the downtime of the supported aircraft.

According to the income method of valuation, the value of the asset is the net present value of its future income generation. As the income generation of the component is dependent on the operation volume of the fleets that it can be used to support, its value in the spare part role depends on the expected remaining service life of those fleets. There are also minor factors affecting the value like e.g. the quality of maintenance operations and repairs performed on the component.

In the production asset role the value of the component follows the depreciation of the particular aircraft it is installed in. In the spare part role its value depends on the future service life of all the aircraft that it can be used to support. These values are inherently different and the value of the component actually changes between these two values every time it is installed or removed.

4.3 Pooling of Spare Components between Airlines

The most important result in Paper III is to provide tangible evidence of cost savings in the component availability service, which can be achieved through inventory pooling. Based on the scale economies in the component availability service, a conclusion was made that even relatively large airlines should utilise some form of inventory pooling. Subcontracting, service providing and inventory pooling were identified as methods of realising the scale economies. All these strategy alternatives were discussed but the results were based on a cooperative pooling arrangement between two or more airlines. At this stage, no further analysis was performed to identify differences or preferences between the alternative methods.

In more detail, Paper III shows that in a perfectly feasible pooling arrangement the spare component inventories can be lowered by over 30% by making a minor sacrifice in short time service levels. A pool member needs to wait for the spare units longer compared to an airline providing its spare components in-house because the units are stored in a remote stock. In contrast, the pool member has access to a larger total stock of spare units, which leads to higher absolute service levels. Pool members in the centrally located bases generally experience shorter logistics delays than those based in the more remote locations.

The cost savings achieved by the pool members are determined by the total fleet size of the cooperation. It is also generally valid that the smaller the airline's fleet is in

comparison to the total fleet size of the cooperation, the higher is the savings potential for that particular airline. On the other hand, the more similar the sizes of the cooperating airlines are, the higher is the savings potential of the total cooperative effort. Even two airlines with fleets of equal size can realize considerable savings by cooperating with each other.

4.4 Cooperative Strategies for Component Availability

Paper IV continues from the point where Paper III concludes. This paper regards the benefits of the scale economies in the availability service as a known fact and focuses on comparing the alternative strategies in realising these benefits. As Paper III already states, the pooling benefits in optimal conditions are generally higher when more demand for one component type is served by one pool. The conditions are, however, seldom optimal and conflicting interests between the potential cooperating parties may easily result in less efficient pooling arrangements.

The most important result of Paper IV is a framework of cooperative strategies, in which the potential of each strategy to capture pooling benefits in the availability service of aircraft components can be analysed against a variety of external conditions. Four cooperative strategies were chosen in the analysis. According to solo strategy, availability services are performed in-house so that the airline provides the service only for its own fleet. The other three strategies that actually involve cooperation are ad hoc cooperation, cooperative pooling and commercial pooling.

Neighbour airlines that have some fleet commonality easily drift into a loose form of cooperation by providing a loan unit against a fee when there is an aircraft on ground needing it. Assuming that the parties are roughly equal in demand volume and that there are efficient logistics connections between their bases, both parties could lower their home base stocks and rely on loans from the other party. In this ad hoc cooperation there is no contractual commitment between the airlines and each one pays standard fees for the loans. Both parties gain from lowering their stocks, and their loan payments tend to nullify each other in the long run.

In cooperative pooling two or more airlines with fleet commonality formally agree upon a set of rules to share their spares inventories of certain aircraft component. Within the rules there are clauses that determine the benefit sharing principles,

response times to spares needs, logistics arrangements between the parties, and inventory distribution between the affected bases, as well as the priorities in the stock-out situations. When a member replaces a failed unit with a spare unit out of the pool, it becomes responsible for delivering the failed unit back to the pool after it has been repaired.

Contrary to the partnership based strategies, commercial pooling is market based. In this strategy an airline subcontracts the availability service to a service provider, who offers the service on the market. Against a fixed annual fee, the airline gets spare units from the service provider when it needs them. There is a formal agreement between the service provider and the airline, which covers service fees, delivery lead times and liability in delay situations, in addition to the general clauses covered by the cooperative pool agreements.

The main finding in the analyses was that commercial pooling tends to prevail when the service provider is willing to deliver pooling benefits to the members and the members have the courage to subcontract this critical service. If the airline is cautious about letting an external service provider handle a support function that has a direct effect on the dispatch reliability of its flights, it may seek other alternatives. Provided that there is an airline with required fleet commonality that is located nearby and willing to collaborate, ad hoc cooperation is a feasible alternative.

Another finding in the analyses was that in most cases cooperative pooling is less efficient than commercial pooling. The administrative costs of maintaining a cooperative pool increase rapidly with every new member, thus limiting the possibilities of capturing extensive pooling benefits by inviting a large number of members. Cooperative pooling would be at its best with two airlines with fleets that have mutual commonality but are not widely used by other airlines in the region. Additionally, the opportunity of the customer airlines starting a cooperative pool has an important role of acting as a potential challenge to a service provider who considers exercising monopoly pricing.

Paper IV also discusses and compares the sharing criteria of the pooling benefits between the members. Three criteria were selected to undergo closer scrutiny: according to the annual demand volume, equal relative savings from joining the pool, and according to relative incremental pool contribution. While the volume based

criterion seems the most intuitive way to share benefits, the high demand members gain slightly more benefits compared to the low demand members in a pooling arrangement using this criterion. An important effect of this finding is that it encourages the pool to seek as small new members as possible. There is actually a demarcation point after which a large new member would take more benefit out of the pool than it would bring into the pool, thus making it outright unprofitable to let it join.

5. DISCUSSION AND CONCLUSIONS

In this chapter the managerial implications of this dissertation are discussed collectively crossing the boundaries of the individual papers. The applicability of the results to industries other than aviation is also discussed. Subsequently, the theoretical implications of this dissertation are discussed together with the notable limitations of the research results. Suggestions for further research are covered in the final section.

5.1 Managerial Implications

Regarding aircraft component support airline management faces decision making challenges on three different timescales. In the long term, they make decisions on the fleet structure of the airline thus fixing the potential of the scale economies within the airline's own fleet. In the medium term, they make the sourcing decisions and contracts related to purchasing and providing the services of aircraft component support. In the short term, they face situations in which the standard support process fails and decisions are needed to cover up the shortage and return the aircraft back to service.

The fleet structure is a long term commitment that has to be considered by the airline management with special care. In the fleet decisions the challenge is to balance aircraft variety needed for routes of different lengths and passenger demands with the fleet uniformity needed to keep down the operating costs. In addition to component support and other areas of the aircraft MRO services, the fleet uniformity affects several major functions in the airline, e.g. crew pairings and aircraft routings. In the literature the uniformity of the airline's fleet has been identified as an important cost driver affecting its operational performance (e.g. Seristö and Vepsäläinen, 1997, p. 21).

The fleet scale is presented here as a measure that outperforms fleet uniformity in quantifying the potential of achieving economies of scale. For example, it would be more cost effective to provide component support for a fleet of 20 Boeing 757s and 20 Airbus A330s than for a fleet of only three Boeing 757s, even if the former fleet has significantly lower fleet uniformity. It is the purpose of this study to bring the fleet scale measure available for the use of airline management when they are comparing alternative fleet scenarios. The power of this relatively simple measure is in providing

a clear and comparable assessment for each scenario, which can then be used as one criterion when selecting the preferred fleet composition. Paper I on airline fleets is positioned to assist airline management in taking the fleet scale into consideration when making long term fleet decisions.

The focus of this dissertation is on the medium term decision making, which includes sourcing decisions and contract negotiations related to purchasing and providing the services of aircraft component support. Financial tools are also provided to help management in making better judgement in the sourcing decisions concerning component availability services. This study takes into consideration the special characteristics of the repairable spare parts and provides a valid method of costing availability services. When the cost of providing the availability service in-house can be reliably estimated, it is easier to compare it to other sourcing alternatives that are available. Successful sourcing decisions lead to cost savings and competitive advantage.

Of the available sourcing options, the dissertation focuses on the spares inventory pooling. It provides a model of calculating the pooling benefits and a framework to compare the different cooperative strategies that are available for realizing pooling benefits. This study helps the airline management to take all sourcing options into account when considering component availability services. The main goal here is to provide tools for airline management to calculate the pooling benefits of different strategy alternatives and make the right choice between them.

The benefit sharing logic of a pooling arrangement has a major effect on the viability of that particular arrangement. The intuitive way of sharing the benefits based on volume favours large members compared to the smaller ones. This results in a conflicting situation in which small entrants are more attractive to the current members than larger ones even if the larger ones would enhance the total pooling benefits more than the smaller ones. Especially with cooperative pooling efforts between airlines it is important that the management pays close attention to the benefit sharing criteria. For a cooperation like this to succeed in the long run, the benefit enjoyed by each member needs to be directly proportional to the incremental contribution that the member brings to the total benefit of the pooling arrangement.

Paper II on component valuation as well as papers III and IV on spares inventory pooling are all positioned to assist airline management in medium term sourcing decisions. These decisions are in fact planning tasks that represent the proactive side of component support. When a failure actually happens, it needs to be tackled using the reactive side of component support. If the proactive work has been performed well, the reactive work is easy. In contrast, neglected proactive work leads to difficulties in the short term decision making. The general flow of the short term decision making is presented in Section 3.3.5 but its deeper logic is outside the scope of this dissertation.

All the research completed within this dissertation was produced in relation to the aviation industry and more specifically the MRO services of the commercial jet aircraft. The results, however, should be applicable to any industry in which the equipment utilisation requires quick replacement of functional system components, which are repairable and of high value. This definition includes surface transports like trains and vessels as well as complex production machinery like paper mills or robotic production lines.

It may not be only these systems that will be using repairable components in the future. When repairable components are used in a closed loop material flow, the environmental load of the maintenance process is generally lower than with disposable spare components, which are discarded after use. In the conditions of rising environmental awareness, industries currently relying on disposable components will experience increasing pressure to start using repairable components. When the public actually begins to emphasise environmental factors in the purchase decisions, the manufacturers of consumer products begin to gain competitive advantage from adopting processes with lower environmental load.

Together with the environmental factors, advancing technology and higher requirements for availability also drive industries towards using repairable components. With every round of new technology, the appliances become more and more difficult to repair and the work requires equipment of higher and higher complexity. So far this development has led to discarding the failed component or more commonly the failed unit as a whole, as the repair work would cost more than producing a new appliance. Undoubtedly the environmental factors will induce the

industries to avoid these wasteful processes and the cleaner alternatives require either recyclable or repairable components. Recycling works better with simple components, while repair is more suitable for the more complex ones.

In today's world the value of time seems to be ever increasing. The availability requirements currently in use in the business sector are slowly entering the consumer sector. Wouldn't it sound good, if the car salesman promised you that your new car is available for your use 99.9% of the time? As long as that limit is kept, you would pay a small amount of money for each kilometre you drive. In case of a component failure, the repair shop would ask you to drive by, so that they could replace the failed unit while-you-wait. If the promised availability were not met, you would receive compensation. This arrangement is actually a component support contract for a car. Many designs and processes in the consumer car industry would need to be fundamentally changed for this vision to become reality. With some current car models, a mechanic is required to spend one hour removing and installing the fender just to change a light bulb.

It is easy to imagine that the rotatable spare part ideology will reach the consumer sector some day soon. The most complex consumer products like cars, personal computers, home entertainment centres as well as central heating and cooling systems could be repaired on-site or while-you-wait by replacing the faulty component with a spare unit. The customer would not need to know about the duration or particularities of the resulting repair process.

5.2 Summary of Research Contribution

The contribution of this research is discussed here by summarising the results and their limitations. The results are tightly connected to availability services in general and aircraft component support in particular. The emphasis is on the sourcing of the service as it offers a natural setting for comparing different ways of providing availability services.

The potential for the scale economies in aircraft component support is studied by analysing empirical data on airline fleets. This dissertation provides a method of describing aircraft fleet uniformity and scale using two simple numerical values. As the economies of scale in the aircraft component support tightly relate to the

uniformity and scale of the supported aircraft fleet, these measures can be used to compare the cost of supporting different aircraft fleets. Applying these measures to the empirical fleet data on commercial jet aircraft leads to the conclusion that the average uniformity of the airline fleets has been steadily decreasing, while the average fleet scale has been steadily increasing.

The most important cost item in the availability services is the ownership cost of the spare units, which is closely scrutinised in this dissertation. When the availability service is provided using repairable spare units like aircraft components, the costing is significantly more complex than with consumable spare units. This study includes rules of treating repairable aircraft components in their revenue generating role as common production assets and in their insurance-like role as spare components. In the production asset role the value of the component follows the depreciation of the particular aircraft it is installed in. In the spare part role its value depends on the number of occasions it can be used to prevent a flight delay, which further depends on the number and future service life of the aircraft that it can be used to support.

The scale economies in the availability services can be utilised through inventory pooling. By relying on an externally or jointly provided availability service with a bit longer lead times it is possible to save over 30 % of the service cost. The total cost saving is determined by the overall fleet size of the cooperation, while the individual member's saving potential is determined by its fleet size in comparison to the whole fleet. The savings distribution can be rearranged by applying various benefit sharing criteria. It is most efficient to share the benefit according to relative incremental pool contribution, even if it would seem more intuitive to share it according to annual demand volume. The pooling benefits in optimal conditions are generally higher when more demand for one component type is served by one pool. The conditions are, however, seldom optimal and conflicting interests between potential cooperating parties typically result in less efficient pooling arrangements.

To properly assess the research contribution the following limitations should be noted.

From the premises of the dissertation as a whole the historical review of the aircraft fleets was limited to jet aircraft. This limitation somewhat compromises the results up to the mid 1970s because of the significant share of propeller aircraft in the airline fleets before that. Thus deeper analyses in the study were limited to the time period

after 1975. When the measures fleet uniformity and scale were structured and presented, there was an intention to test them properly against empirical data. The measures were applied to an exhaustive set of fleet data so their ability to describe actual fleet configurations was tested rigorously. The tests on how the measures correlate with the airline costs were, however, less exhaustive. The fleet uniformity measure was tested against a real life data set containing the financial results of a small number of sample airlines. It remains unclear whether this sample is representative of the airline industry in general. The verification of the fleet scale measure against airline MRO costs was omitted from the study due to missing or unreliable cost data.

When analysing component valuation, it would have been important to test the results against the accounting policies of the real life airlines. Even if financial data concerning airline industry and aircraft MRO business is available, it is on a general level. To test the valuation of aircraft components it would be necessary to access the internal accounting data on a reasonably detailed level. During the dissertation process, several representatives of airline and MRO management were interviewed. Fragments of the relevant data were revealed in the interviews but the permission to publish the results even in a loose connection with the name of the airline was not given. To enable the relevant empirical tests the number of respondents should be large enough, allowing each airline to retain its privacy. The study on component valuation also assumes a low inflation rate and an unrestricted access to relevant input data. As regards the first assumption the results of the study are not necessarily valid with companies operating in the third world. Nevertheless, as most of the airline industry is currently located in the more developed countries, this limitation is of low relevance. There are, however, particular challenges within airlines and MRO providers to access all the data required to calculate the component values.

The models and simulations on inventory pooling are relatively simple and there are several limitations in them compared to the real world setting of pooling spare component inventories. As there is a large number of factors affecting the aircraft availability and inventory pooling, it was necessary to balance the computational complexity and limitations of the models by excluding selected factors. Of the ways to secure aircraft availability, only the most important ones were included in the models. These are the local spares supply, emergency pool access and loan in. For

example proactive transshipments and aircraft rerouting were not included. The following cost elements of inventory pooling were included in the models: inventory holding, handling, loan-in and interface costs. Transfer and wait costs were excluded. Because of the omitted factors, the results of the models are valid in certain restricted but relevant settings.

5.3 Further Research

During the dissertation project a number of interesting subjects were identified as potential directions for further research. These ideas are discussed below.

Within the scope of this dissertation, the fleet uniformity and scale measures were applied to the fleets of commercial jet aircraft. They would evidently be applicable to other types of fleets as well. It would be interesting to apply the measures to fleets of vessels, trains or trucks operated by shipping, railway and cargo transport companies. Sticking to aircraft, business aviation with its small jets, propeller aircraft and helicopters could provide a supplementary application. Furthermore, the armed forces would offer a large number of different fleets to be analysed. The possible applications there could start from the military aircraft and range through military ships, tanks and other terrain vehicles as well as all kinds of weapon systems. All these fleets have the common requirement of spare component support and their operation has similar characteristics to the operation of commercial jet aircraft. Therefore the unit operating cost of these fleets should correlate with their uniformity and scale.

The research conducted here on component valuation focuses on general principles which lay a foundation for more detailed research. There are interesting issues still to be covered in the valuation of repairable spare components in their two roles. Installed in an aircraft in its revenue generating role the component's value is a share of the whole aircraft value. However, it remains to be determined, how large share of the whole should be assigned to each component. What is the value of the aircraft body that cannot be assigned to any component? Can it be negative so that the total value of all components installed in an aircraft would exceed its value? Additionally, some components can be installed in several aircraft types, one of which could be old and another considerably newer. Installed in a new one the component is valuable but installed in an old one it would be almost worthless.

Staying in a spares stock in its insurance-like role the component's value depends on its ability to prevent flight delays. The saved cost of the prevented delays can be considered as income generation. As the failures causing the flight delays constitute a random phenomenon with known distribution, the expected number of prevented flight delays per time unit can be calculated based on the composition and operations data of the supported fleet. Using the income method of valuation it would be worthwhile to calculate the present value of the future delay savings regarding various scenarios of supported fleets. It is easy to see that the resulting value of a spare component in an isolated stock supporting a small fleet would be significantly lower than that of a unit in a pool supporting a number of large fleets. It should also be possible to estimate the market value of the spare component on the basis of key data on all the fleets that it could support. This includes how many spare units are used to support these fleets, what their composition is and how they are operated. It would be interesting to see the effect of the phase-out of an old aircraft type on the value of a component that can also be used to support a newer aircraft type.

This dissertation has emphasised inventory pooling as a sourcing option with high potential of utilising the scale economies in the component availability services. The pooling benefits are generally higher when more demand for one component type is served by one pool, which practically means more pooling participants. Like in any cooperation between companies, there are evident obstacles to implement inventory pooling. The most important obstacles are the fear of losing control and the difficulty to implement fair benefit sharing criteria. Even if component support is a support function to the operations, it is highly mission critical. To rely on external parties in providing such service requires special confidence from the management. Inventory pooling is based on statistics, so the business benefit for the participants can be allocated equally only in the long term. Regardless of the selected criteria, the benefit sharing will inevitably seem unfair for one or more participants if the considered period is short. Only in the long run are the benefits balanced, but it may be difficult to get the members to stay long enough. Interesting results might be found by analysing these obstacles more thoroughly and by developing ways to counter them, thus assisting companies to organize larger and more efficient pool settings.

The models and simulations in this dissertation assume that the availability service is provided by a single stock or pool. Even if the models can manage the overflow

demand to be covered by external loans, they cannot handle multiple spares stocks supporting a single fleet. As the real life airlines are increasing the outsourcing of component support services, there would soon be real use for a model that could manage the local stock as the primary source of support, external pool as the secondary one and external loans as the last resort.

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This list of references includes the references from the four papers in Part II of the dissertation. References to papers in Part II have been excluded.

Appendix A: Industry Interviews

Fernandez, Gavin (Procurement Manager, Components), Cathay Pacific Airways, Hong Kong, May 2005

Fuchs, Steffen (Associate), McKinsey & Company, Toronto, August 2007

Gibbs, Christopher (General Manager, Engineering Commercial), Cathay Pacific Airways, Hong Kong, May 2005

Glime, Steve (Production Support Manager), American Airlines, Tulsa, Oklahoma, July 2007

Grider, Chris (Commodity Manager), American Airlines, Tulsa, Oklahoma, July 2007

Hill, Jeremy (Managing Director, M & E Purchasing), American Airlines, Tulsa, Oklahoma, July 2007

Holliday, John H. Jr. (Inventory Management Interiors, Rawstock & Chemicals), American Airlines, Tulsa, Oklahoma, July 2007

James, Jimmy (Purchasing Manager), American Airlines, Tulsa, Oklahoma, July 2007

Koskentalo, Mikko (Manager, Avionics), Finnair, Helsinki, December 2000

Lee, Carmen (Procurement Manager, Line Maintenance and Base Maintenance), Cathay Pacific Airways, Hong Kong, May 2005

Luimstra, Reinier Y. (Director Operational Purchasing), KLM, Amsterdam, August 2007

Luis, Steve (Tech Crew Chief), American Airlines, Tulsa, Oklahoma, July 2007

Ploeger, Harm G.M. (Project Manager Component Trading), KLM, Amsterdam, August 2007

Raevuori, Seppo (Vice President, Technical Support of Operations), Finnair, Helsinki, December 2000

Teague, Stephen (Procurement Manager, Engines), Cathay Pacific Airways, Hong Kong, May 2005

Turtiainen, Paavo (Vice President, Technical Operations), Finnair, Helsinki, May 2007

Vilenius, Jarmo (Executive Vice President, Technical Division), Finnair, Helsinki, November 2000

Wong, Carman (Purchasing & Project Executive), Cathay Pacific Airways, Hong Kong, May 2005

Yim, Ricky (Assistant Procurement Manager), Cathay Pacific Airways, Hong Kong, May 2005

Appendix B: Data of the Fleet Composition Study in Paper I

The original data extract

The original data extract was selected from the ACAS database by filtering out the irrelevant aircraft categories as can be seen in Table 1, thus limiting the selection to wide-body jets, narrow-body jets and regional jets.

Category	Selected or Not Selected
Business Jet	Not Selected
Russian-built Jet	Not Selected
Small Commercial Turboprop	Not Selected
Wide-body Jet	Selected
Narrow-body Jet (100+ seats)	Selected
Military Transport	Not Selected
Piston Engine Aircraft	Not Selected
Regional Jet (<100 seats)	Selected
Russian-built Turboprop	Not Selected
Turboprop	Not Selected

Table 1 Selection of relevant aircraft categories

The original data extract consists of transaction histories of 23 317 western built commercial jet aircraft from 15 aircraft manufacturers, representing 51 aircraft types and 516 aircraft models. The time period of the transactions begins on 27th July, 1949 when the first De Havilland Comet was registered and ends on 21st February, 2005, right before the version 03/2005 of the database was published. In the original data extract there are 5 966 different operators including financial organisations, aircraft lessors, government and military entities, private persons, business jet operators as well as passenger and cargo airlines. The total number of transactions in the original data extract is 110 599.

Data filtering

Before the analysis it was necessary to filter out unnecessary data items. The result is a clean set of data for the analysis that will be called here the *base data*.

Firstly, all aircraft types and models with no actual commercial use were removed from the original data extract. For example Boeing Business Jet, Boeing 707-E3A AWACS (Airborne Warning And Control System) and Boeing 747-200VC25 Air Force One are not built for commercial airlines but for business, military or government use. There are also a number of aircraft types such as Embraer 195 and

Airbus 380 that are yet to begin their commercial use and so far only operated by their manufacturers for testing and marketing.

Secondly, all operators that cannot be regarded as commercial were removed from the original data extract. A considerable number of organisations under the operators category in the original data extract are not real operators as they do not accumulate aircraft usage, but only own aircraft for example to lease them out to actual operators. There are also operators in the original data extract that accumulate aircraft usage but are not even remotely commercial. For example operators that mainly use aircraft for military, government or research and development purposes were filtered out of the data set. In this study, plain business operators are not considered as commercial airlines. Even the ones like PrivatAir that operate business versions and occasionally even standard passenger versions of commercial jets were filtered out of the data set. These all-premium airlines are in a line of business, which Sweetman (2005, p. 28) calls elite and unconventional air travel and which is not established enough to be considered commercial in this study.

Thirdly, the original data extract includes transactions that are unnecessary considering the analysis performed for this study. The final data analysis is performed on an annual basis by taking a snapshot of the world-wide fleets at the very beginning of every year. Thus, only transactions that cover at least one of the annual snapshots are significant. As each transaction has a from date and to date, all transactions that do not have any snapshot moments between them were filtered out. If there is a transaction dated on 1st January, it is assumed here that the annual snapshot is timed before it. Non-commercial transactions by commercial operators were also filtered out as well as transactions like owner name change that have no effect on commercial operators' fleets.

Finally, all redundant transactions were removed from the data set. From the viewpoint of the analysis performed for this study, only some of the fields in the original data extract are significant. If there were multiple transactions having equal values in every significant field, they were replaced by a single transaction.

The base data

The base data consists of transaction histories of 22 527 commercial jet aircraft from 14 aircraft manufacturers representing 45 aircraft types and 407 aircraft models. The time period of transactions begins on 4th February, 1952 when the first De Havilland Comet (cn 6005) was delivered to BOAC and ends on 21st February, 2005. In the base data there are 2166 different passenger and cargo operators. The base data includes 48 879 transactions.

The fields in the base data can be seen in Table 2. 18 of the 22 fields originate directly from the ACAS database. The analyses in this study required four additional fields to be generated in the base data. The fields are Aircraft Family, Number of Engines, Engine Type and Operator Class. The process of generating values to each of these fields will be discussed later on in this section.

Field	Field Description
1	Aircraft Manufacturer
2	Aircraft Family
3	Aircraft Type
4	Aircraft Model
5	Aircraft Serial Number (Constructor No = cn)
6	Aircraft Registration
7	From Date of the transaction
8	To Date of the transaction
9	Aircraft Status as of March 2005 (Active, Written-off, Retired)
10	Aircraft Operational Role (Passenger, Freighter)
11	Transaction Type - see Table 5 for decodes
12	Operator Name
13	Three Letter ICAO Operator Code
14	Operator's Country of Origin
15	Operator's World Region
16	Operator's Major World Region code
17	Aircraft Category (Wide-body, Narrow-body, Regional)
18	Engine Manufacturer
19	Engine Type
20	Engine Model
21	Engine Count
22	Operator Class - see Table 7 for decodes

Table 2 Base data fields

The aircraft manufacturer in ACAS database is not necessarily the original manufacturer of the aircraft but sometimes the company that after mergers and acquisitions has taken responsibility of supporting the aircraft. In Table 3 there are all the ACAS manufacturers that are represented in the base data.

Aircraft Manufacturer in ACAS database	Transactions
Aerospatiale	637
Airbus	5 980
British Aerospace / Aerospatiale (B/A)	14
British Aerospace (BAe)	2 320
Boeing	24 917
Bombardier	1 505
Convair	209
Dassault	11
Dornier	148
Douglas & McDonnell Douglas (Douglas)	9 700
Embraer	1 165
Fokker	1 557
Lockheed	702
Vereinigte Flugzeugwerke (VFW)	14

Table 3 Aircraft manufacturers in the base data

Aerospatiale has acquired Sud Aviation, so it is marked as the manufacturer of Sud Aviation SE-210 Caravelle in the base data. British Aerospace BAe is a merger of British Aircraft Corporation (BAC 1-11), Avro (Avro 146), De Havilland (Comet), Hawker Siddeley (Trident) and Vickers (VC10), so it is marked in the base data as the manufacturer of all the aircraft types in brackets. Because of these two business arrangements British Aircraft Corporation / Sud Aviation Concorde has British Aerospace / Aerospatiale as its manufacturer in the base data. Commonality between the aircraft types mentioned above is actually as low as between any types from different manufacturers, which falsely increases the fleet uniformity and scale in the analyses in which they are represented.

Table 4 shows all aircraft families and types that have transactions in the base data as well as the aircraft category and number of engines for each aircraft type. The categorisation of the aircraft types into aircraft families is performed on the basis of common knowledge of the aircraft types. As there is no concrete definition for the term aircraft family, the division is somewhat arbitrary. Generated values in the additional Number of Engines field of the base data are based on common knowledge of the aircraft types.

Manufacturer	Family	Type	Category	Engines	Transactions
Aerospatiale	SE-210	SE-210	Narrow-body	2	637
Airbus	A300/310	A300	Wide-body	2	729
		A300-600	Wide-body	2	426
		A310	Wide-body	2	629
	A32S	A318	Narrow-body	2	21
		A319	Narrow-body	2	725
		A320	Narrow-body	2	2 145
		A321	Narrow-body	2	475
	A330/340	A330	Wide-body	2	445
		A340	Wide-body	4	385
B/A	Concorde	Concorde	Narrow-body	4	14
BAe	1-11	1-11	Narrow-body	2	845
	146	146	Regional	2	1 023
	Comet	Comet	Narrow-body	4	164
	Trident	Trident	Narrow-body	3	212
	VC10	VC10	Narrow-body	4	76
Boeing	707	707	Narrow-body	4	1 949
	717	717	Narrow-body	2	202
	720	720	Narrow-body	4	387
	727	727	Narrow-body	3	5 536
	737Initial	737	Narrow-body	2	3 996
	737Classic	737	Narrow-body	2	4 329
	737NG	737	Narrow-body	2	1 836
	747Classic	747	Wide-body	4	1 992
	747-400	747	Wide-body	4	727
	757/767	757	Narrow-body	2	1 867
		767	Wide-body	2	1 562
	777	777	Wide-body	2	534
Bombardier	CRJ	CRJ	Regional	2	1 505
Convair	CV880	CV880	Narrow-body	4	115
	CV990	CV990	Narrow-body	4	94
Dassault	Mercure	Mercure	Narrow-body	2	11
Dornier	328JET	328JET	Regional	2	148
Douglas	DC10/MD11	DC10	Wide-body	3	1 169
		MD10	Wide-body	3	41
		MD11	Wide-body	3	388
	DC8	DC8	Narrow-body	4	2 311
	DC9	DC9	Narrow-body	2	3 083
	MD80	MD80	Narrow-body	2	2 541
	MD90	MD90	Narrow-body	2	167
Embraer	135/140/145	135	Regional	2	150
		140	Regional	2	74
		145	Regional	2	888
	170	170	Regional	2	53
Fokker	F100	F100	Regional	2	762
	F28	F28	Regional	2	795
Lockheed	L1011	L1011	Wide-body	3	702
VFW	VFW614	VFW614	Regional	2	14

Table 4 Aircraft families and types in the base data

It should be noted that Boeing 717 was McDonnell Douglas MD95 before the acquisition of McDonnell Douglas commercial aircraft division by Boeing. Boeing is marked as its manufacturer in contrast with other Douglas and McDonnell Douglas aircraft that have Douglas as their manufacturer. As the commonality between Boeing 717 and McDonnell Douglas MD90 is certainly higher than with any Boeing types, changing Boeing 717 to McDonnell Douglas MD95 in the base data would improve the reliability of the analyses in which it is represented.

Table 5 contains all transaction types used in the base data. Interestingly, almost 50 per cent of the transactions are deliveries, which means that aircraft do not move over from one operator to another very often. There are no explicit transactions for retirement or write-off in the base data, because those events are indicated by the Aircraft Status field in all the transactions of the aircraft.

Transaction Type Description	Transactions
Delivered new or taken into commercial use for the first time	22 527
Operator name change	2 650
Operator change due to a merger	1 973
Operator change due to a transfer between joint companies	195
Operator change, other	16 473
Converted so that aircraft model changes (freighter conversions not included)	983
Freighter conversion (permanently from passenger to cargo configuration)	948
Engine change	2 511
Change between a passenger and freighter role (applies to convertible aircraft)	619

Table 5 Transaction types in the base data

All engine manufacturers and types that have transactions in the base data can be seen in Table 6. Values in the additional Engine Type field of the base data are generated simply by cutting the dash-number out of the engine model.

Even if the manufacturers are marked in the base data as separate, some of them are actually quite closely related to each other. Pratt & Whitney and Pratt & Whitney Canada are most certainly related, while CFM International is a joint company of Snecma Moteurs, France and General Electric Company, USA. These issues among the engine manufacturers probably cause bias towards lower fleet uniformity and scale in the analyses.

Engine Manufacturer	Engine Type	Transactions
CFM International	CFM56	8 850
General Electric Aero Engines	CF34	1 558
	CF6	4 219
	CJ805	209
	GE90	168
International Aero Engines	V2500	1 507
Pratt & Whitney	JT3	3 891
	JT4	305
	JT8D	15 296
	JT9D	1 965
	PW2000	587
	PW4000	1 592
Pratt & Whitney Canada	PW306	148
Rolls-Royce	AE3007	1 112
	AVON	593
	BR715	202
	GHOST	14
	RB211	2 321
	RCO	198
	SPEY	1 852
	TAY	827
	TRENT 500	55
	TRENT 700	163
	TRENT 800	196
Rolls-Royce Snecma	593-610	14
	M45H	14
Textron Lycoming	ALF502	720
	LF507	303

Table 6 Engine manufacturers and types in the base data

Table 7 contains decodes for the Operator Class field. Generated values in this additional field of the base data are based on the operational role, transaction type and earlier transactions of each aircraft.

Operator Class	Operator Class Description
Primary passenger	Passenger aircraft first delivered to current operator
Secondary passenger	Passenger aircraft in use by its second operator
Tertiary passenger	Passenger aircraft in use by its third operator or any operator after that
Primary freighter	Cargo aircraft first delivered to current operator
Converted freighter	Aircraft converted from passenger to cargo use for the current operator
Secondary freighter	Cargo aircraft in use by its second operator or any operator after that

Table 7 Operator classes in the base data

PART II: ORIGINAL PAPERS

PAPER I

Fleet Composition of Commercial Jet Aircraft 1952-2005: Developments in Uniformity and Scale

Jani Kilpi

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Fleet composition of commercial jet aircraft 1952–2005: Developments in uniformity and scale

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Abstract

The fleet composition of an airline is important in determining its costs and operational performance. This composition can be measured using numerical values. An index for measuring fleet uniformity is available, and a structured way of measuring fleet scale is introduced here. The history of all jet aircraft operated by commercial passenger or cargo airlines world-wide is analyzed both in general terms and using these measures. The analysis shows that uniformity in airline fleets has been steadily decreasing, while their scale has been steadily increasing.

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Keywords: Airline; Aircraft fleet; Fleet commonality

1. Introduction

The fleet composition of an airline is important in affecting its operational performance (Seristö and Vepsäläinen, 1997). The challenge of airline management in fleet planning is to balance the benefits of a uniform fleet and the choice of suitable aircraft for different missions. We examine developments in airline fleet composition and standardization using a Fleet Standardization Index (de Borges Pan and Espirito Santo, 2004) with the aim of analyzing the role of fleet composition of jet aircraft operated by passenger or cargo airlines globally looking in particular at the uniformity of fleets¹.

The analysis is based on one database table in the ACAS database (AvSoft, 2005). This table contains the transaction histories of every aircraft from its first delivery until the present day or its retirement. The last transaction dated is for 21st February 2005. Before analysis the data were filtered, so that only western built commercial jet aircraft that were used for commercial purposes by commercial passenger or cargo operators remain in the set. All irrelevant transactions are also filtered out. Table 1 contains a summary of the 48 879 transactions that represent the histories of 22 527 commercial jet aircraft from 14 aircraft manufacturers representing 45 aircraft types and 407 aircraft models.

2. Aircraft fleet composition

The term ‘fleet’ is generally used to describe any collection of aircraft. Here the concentration is on airline

(footnote continued)

and Mathaisel, 1985). Lohatepanont and Barnhart (2004) discuss integrated models and solution algorithms that simultaneously optimize the selection of flight legs and the assignment of aircraft types to legs. Models of aircraft routings and fleet assignments are applied to a practical environment as an information system by Armacost et al. (2004) and Subramanian et al. (1994). Beaujon and Turnquist (1991) offer a single framework that covers both fleet planning and fleet assignment.

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¹There is little published aircraft fleet analysis especially covering a large number of airlines and a long period of time. An example is Adrangi et al. (1999) who analyze the change in the fleet composition of 9 major operators in the US during a 13-yr period. Seristö (1995) analyzes a 1-yr data snapshot concerning 42 major airlines world-wide and includes consideration of the effects of fleet composition on airline performance. New (1975) discusses airline fleet planning in a dynamic environment, where old aircraft become obsolete and new aircraft types with improved performance become available. Jenkins (1987) uses advanced planning methodology to select aircraft types and to plan aircraft fleets. Most material dealing with airline fleets concentrate on scheduling and fleet assignment, typically taking the fleet composition as given (Etschmaier

Table 1
Transaction summary of the data set

Transaction type description	Transactions
Delivered new or taken into commercial use for the first time	22 527
Operator name change	2650
Operator change due to a merger	1973
Operator change due to a transfer between joint companies	195
Operator change, other	16 473
Converted so that aircraft model changes (freighter conversions not included)	983
Freighter conversion (permanently from passenger to cargo configuration)	948
Engine change	2511
Change between a passenger and freighter role (applies to convertible aircraft)	619

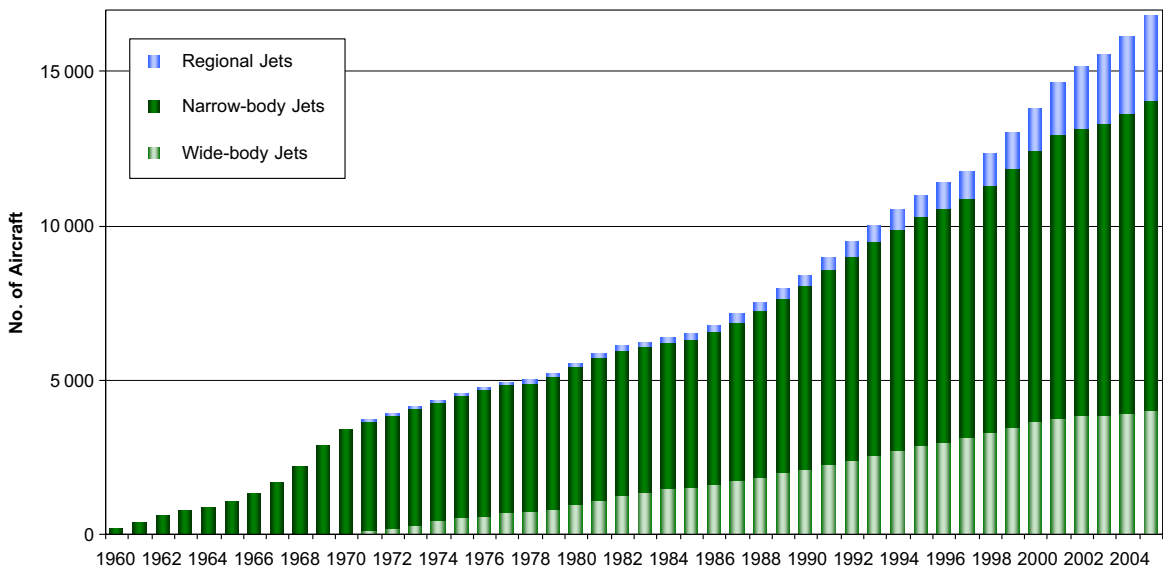


Fig. 1. Global fleet by aircraft category.

fleets but trends involving particular fleets such as the total fleet of top 20 airlines are also examined. Fleet composition is taken to refer to the similarities and differences in the technical and operational characteristics between the individual aircraft in that particular fleet. Theoretically this definition takes into account a considerable number of factors from the minimum cockpit crew to the tooling needed to service the aircraft. In assessing fleet composition the two major structural elements of the aircraft, fuselage and engines, are used. Put simply, a commercial jet aircraft is a fuselage with two to four engines attached to it. To further simplify the issue, it is assumed that the differences in these structural elements appear at three levels only. The first and most important level of detail is the manufacturer of the element.

The second level of detail for the fuselage is the aircraft family. The differences between aircraft belonging to the same family are typically limited, relating to the length of the fuselage, payload capacity and engines. From the

operator's perspective, they can have common flight and cabin crews as well as common spare components. One aircraft family may include different aircraft types like Boeing 757 and 767. On the contrary, there can be even three different aircraft families within one aircraft type, as Boeing 737-200, 737-500 and 737-600 all belong to different aircraft families. This family concept has not been established with engines, so the second level of detail for the engines is simply the engine type. The third level of detail for the fuselage and engines is aircraft model and engine model.

3. General development of fleet composition

As can be seen in Fig. 1, the production capacity of the airline industry has grown constantly regardless of occasional global crises. The world-wide jet aircraft fleet has averaged an annual growth rate of 4.7% between 1971 and 2005. According to Costa et al. (2002) the average annual

growth rate of the world-wide passenger traffic during that period was 6.2%, which is in line with the figure above, taking into account that the average seat capacity of an aircraft has increased during that period as has the average load factor.

Airlines experience more volatile economic fluctuations than many other industries (Costa et al., 2002). While this cyclical environment causes the profits of carriers to vary from strong positive to alarming negative, it has less effect on the fleet growth. One reason for this is the long lead time of aircraft orders, which causes new aircraft ordered during the peak period to be delivered during the following recession.

Of the 17 000 or so commercial jetliners flying in 2005 the top 50 airlines operate ca. 9000, which means about 180 aircraft/airline. The corresponding figure was only ca. 60 aircraft/airline in 1970. The average airline however, had a fleet of 21 aircraft in 2005, which would almost apply to 1970 as well. During this period the number of airlines has increased from 180 to 800.

While the airline industry has been growing, there has also been an enlargement in the aircraft types available (Fig. 2). In the 1960s all aircraft were narrow-bodies and there was competition between a large number of relatively small manufacturers. The early 1970s brought the wide-body jets to market as well as jets with less than 100 passenger seats. The latter were colloquially known as regional jets from the beginning even if the term only became established much later. In the 1980s aircraft families started to appear in the market as the new generation workhorse types (Boeing 757, 767, 737 Classic, Airbus A320 Series) were introduced. The early 1990s

brought a new generation of wide-bodies to market paving the way for the dominance of twin-engine aircraft in the long-haul traffic. From the mid-1990s new types have largely been launched only among regional jets.

Fig. 3 compares the average fleets for narrow-bodied aircraft by geographic region from 1960 to 2005. As can be seen, North America has enjoyed the largest average fleets from the beginning. The differences would be even greater if the comparison were between the total fleets, as North America airlines have generally used their aircraft much longer than their European or Asian counterparts.

The first steep increase in fleets in the late 1960s was caused by the replacement of propeller aircraft by the first generation jets. Twenty years later the second generation of jets were already established in the market and North American airlines phased them in rapidly to satisfy the booming demand following deregulation. Even during the downturn of the early 1990s, average fleets continued to increase even as older types of aircraft were retired. Similar developments can be seen in the other regions but on a smaller scale.

4. Fleet standardization index

de Borges Pan and Espirito Santo (2004) developed an index suitable for comparing the composition of different aircraft fleets. Their Fleet Standardization Index or *Índice de Padronização de Frotas (IPF)* is still at a developing stage but can be utilized. The index only takes into account the variety of the fleet and ignores its size, thus allowing comparisons between airlines of very different sizes. The index is used with a slight modification to comply with the

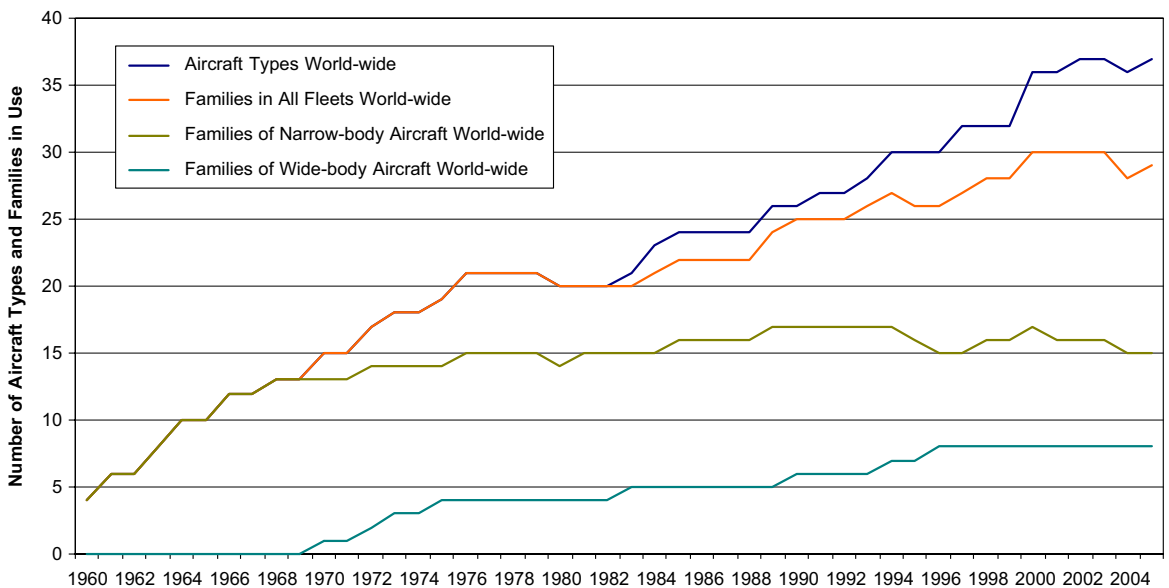


Fig. 2. Number of aircraft types and families in use.

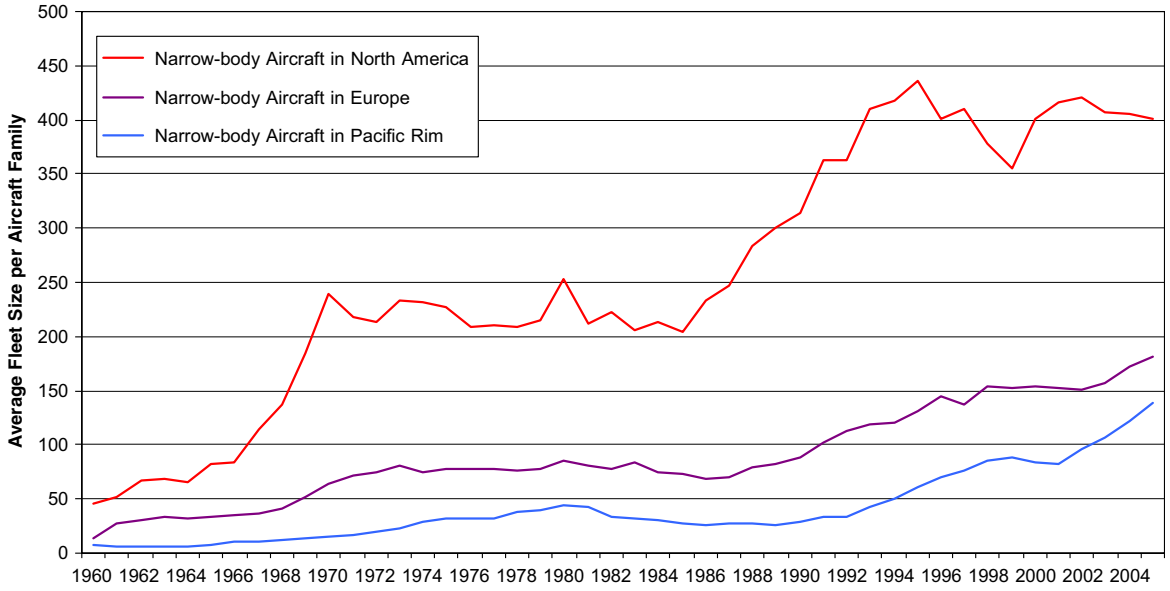


Fig. 3. Average fleet size per narrow-body aircraft family by main region.

way the fleet composition is defined. Three levels of detail are used here for fuselage and engines in contrast with the original index, where there are only two levels of detail for the fuselage.

The *IPF* of a fleet is calculated on the basis of auxiliary indices; *IPC* for the fuselage and *IPM* for the engines:

$$IPF = \alpha_1 IPC + \alpha_2 IPM, \quad (1)$$

where $\alpha_1 + \alpha_2 = 1$ with $\alpha_1 = 0.6$ and $\alpha_2 = 0.4$ used throughout. The *IPC* of the total fleet is calculated on the basis of the partial indices *IPPC* for each of the aircraft manufacturers represented in the fleet:

$$IPC = \frac{\sum IPPC}{\text{number of manufacturers}}. \quad (2)$$

The *IPPC* of one aircraft manufacturer in the fleet is calculated on the basis of the partial indices *IPPCM* for each aircraft family of that manufacturer in the fleet:

$$IPPC = \frac{\sum IPPCM}{\text{number of families from the manufacturer}}. \quad (3)$$

Finally, the *IPPCM* of one aircraft family in the fleet is calculated:

$$IPPCM = \frac{\text{number of aircraft in the family}}{AMF \times TFC}, \quad (4)$$

where *AMF* is the number of aircraft models in the family and *TFC* the total number of aircraft in the fleet. Similar calculations apply to the auxiliary index *IPM* for the engines. The *IPM* of the total fleet is calculated on the basis of the partial indices *IPPM* for each engine manufacturers

found in the fleet:

$$IPM = \frac{\sum IPPM}{\text{number of manufacturers}}. \quad (5)$$

The *IPPM* of one engine manufacturer in the fleet is calculated on the basis of the partial indices *IPPCM* for each engine type of that manufacturer in the fleet:

$$IPPM = \frac{\sum IPPCM}{\text{number of types from the manufacturer}}. \quad (6)$$

Finally, the *IPPCM* of one engine type in the fleet is calculated:

$$IPPCM = \frac{\text{number of engines of the type}}{EMT \times TFM}, \quad (7)$$

where *EMT* is the number of engine models of that type and *TFM* the number of engines in the fleet. Following these formulas $0 < IPF \leq 1$ (where the value 1 means only identical aircraft with identical engines in the fleet). As the variety of aircraft and engines in the fleet increases, the index value decreases. The index value is also logarithmic in nature, easily dropping from unity but only with difficulty getting close to zero.

An example of a calculation of the fleet standardization index for an imaginary airline fleet is given in Table 2. This fleet of 20 aircraft is made up of 5 Airbus A319 aircraft with CFM56-5B4 engines, 5 Airbus A320 aircraft with CFM56-5B6 engines, 5 Airbus A340-300 aircraft with CFM56-5C2 engines, 2 Airbus A330-200 aircraft with CF6-80 engines, and 3 Boeing 777-200ER aircraft with GE90-94B engines. This fictional fleet has index value of 0.182. One sees that

Table 2
Example of calculating the fleet standardization index

Level	A/C mfr	Family	# of aircraft	# of models	# of families	# of mfrs	Index
<i>IPPCC</i>	Airbus	A32S	10	2			0.25000
<i>IPPCC</i>	Airbus	A330/340	7	2			0.17500
<i>IPPC</i>	Airbus				2		0.21250
<i>IPPCC</i>	Boeing	777	3	1			0.15000
<i>IPPC</i>	Boeing				1		0.15000
<i>IPC</i>	All		20			2	0.18125
Level	Eng. mfr	Eng. type	# of engines	# of models	# of types	# of mfrs	Index
<i>IPPM</i>	CFM	CFM56	40	3			0.26667
<i>IPPM</i>	CFM				1		0.26667
<i>IPPM</i>	GE	CF6	4	1			0.08000
<i>IPPM</i>	GE	GE90	6	1			0.12000
<i>IPPM</i>	GE				2		0.10000
<i>IPM</i>	All		50			2	0.18333
<i>IPF</i>	Coeff. 1	0.6		Coeff. 2	0.4		0.18208

the smaller sub fleets of Boeing 777 and Airbus A330 bring down the index even if they have engines from the same manufacturer. The reasonably high index value is typical of small or medium airlines. Of the airlines studied here for the index value the closest to this in 2005 was 0.182 for Alaska Airlines.

5. Trends and observations of fleet uniformity

The fleet standardization index is calculated annually for 90 airlines for 1976–2005. Earlier years were overlooked because of the significant share of propeller aircraft in the fleets until the early 1970s. The calculations indicate that since 2000 most of the top 20 airlines have an index value considerably lower than 0.1 with the lowest value of 0.04 associated with Air France in 2003. Of the smaller airlines, most of the traditional full-service carriers have values close to 0.1 with Air New Zealand, Hawaiian Airlines, Singapore Airlines, Virgin Atlantic and perhaps unexpectedly Alitalia, having values well over 0.1. The low-cost carriers Southwest and JetBlue exhibit the highest values—JetBlue had uniform fleet of Airbus A320 aircraft in 2005, although it later diversified and acquired Embraer 190 aircraft.

Fig. 4 shows the trend of the average index value of the top 20 operators from 1976 to 2005. As can be seen, the general trend has been downward. An analysis of the data reveals that the supply of jet aircraft types has constantly diversified, and that the majority of the largest operators have utilized this opportunity and ordered a larger variety of aircraft to comply with their diversified needs. The average time that major airlines use new aircraft types has also shortened, which increases the frequency of the periods with less uniform fleets as older types of aircraft are being phased out and newer types phased in.

Even one airline like Piedmont Aviation or Southwest Airlines that operates a very uniform fleet can change the average index value significantly. This would only require two or three major airlines to radically standardize their fleet to return the average index value back to the early 1980s level.

General trends of the airline industry have also affected the index value. In the mid-1980s more new aircraft types were launched than during any other time between 1976 and 2005. As this coincided with an economic boom it did not take long for the top 20 airlines to assimilate these new types into their fleet. The older aircraft were only retired or sold during the next downturn that came with the first Gulf war, showing an increase in the average index value. The downturn caused by the terrorist attacks in 2001 also had negative effects on the airline industry, but the average index value rose. During the late 1990s the decrease in the index value was less steep than during the preceding boom. On the other hand, the decline lasted for more than 5 years.

Seristö and Vepsäläinen (1997) suggest that a uniform fleet generally leads to better financial results although no formal estimates are made. The fleet standardization index combined with airline financial results², however, allow this to be tested. Ten major airlines of different size and fleet composition was selected to represent the industry. Calculations for 1997–2005 are performed. The correlations between the fleet standardization indices and operating profit percentages of the airlines were estimated for each year. Correlations are generally high, varying between 0.32 in 1997 and 0.81 in 2000. The average correlation in these years is 0.64. Based on these results it seems that

²The airline financial results data used are collected from the World Airline Reports published annually in *Air Transport World*. The report is published annually in the July issue, and reports published in the years 1998–2006 are used.

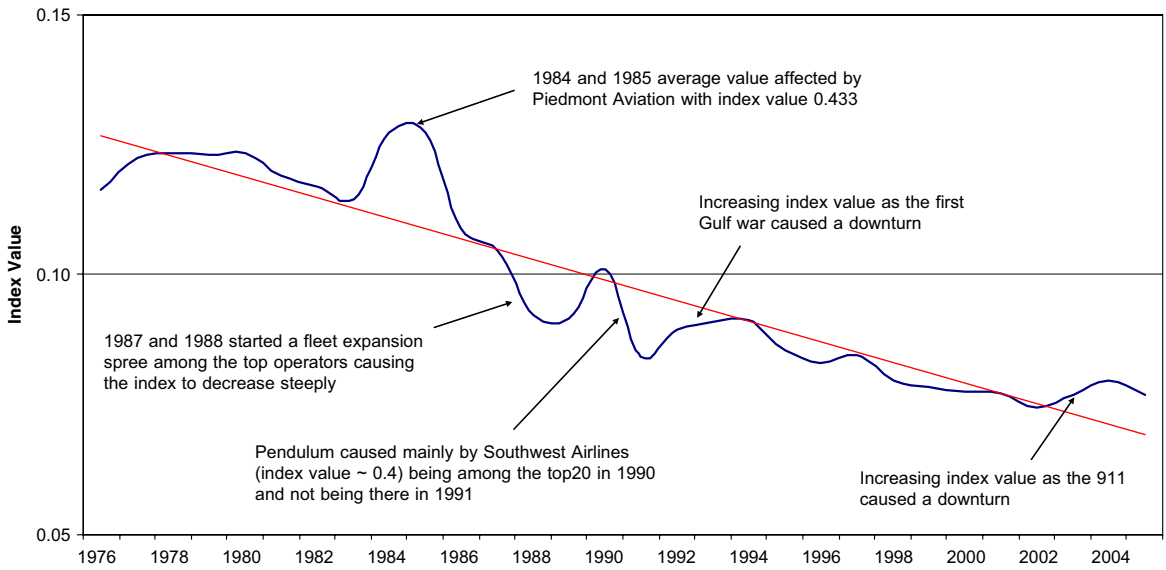


Fig. 4. Fleet standardization index—average of world top 20 operators.

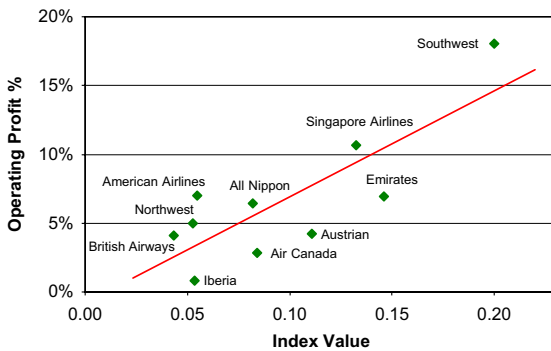


Fig. 5. Fleet standardization index versus airline financial results for 2000.

airlines with uniform fleets generally show better financial results than those with more diversified fleets. Fig. 5 shows the plot of the highest correlation year 2000: airlines below the line show worse results than their fleet composition would suggest, while the opposite is true for those above the line.

6. Fleet scale analysis

The fleet standardization index ignores the fleet size, which is a significant shortcoming. For example aircraft maintenance costs are largely driven by fleet size, mainly because of the high infrastructure cost of a maintenance production line and the long maintenance intervals of modern aircraft. There are significant differences in maintaining a fleet of one Airbus A319, one Airbus A320 and one Airbus A321 aircraft or a fleet of 30 aircraft

including a number of A319s, A320s and A321s, even if these fleets are equally uniform.

de Borges Pan and Espirito Santo (2004) provide a basis for a measure that combines information on fleet size and structure: fleet scale. This is not intended to replace the fleet standardization index but to complement it. As the fleet size is included in the measure, it loses the ability to directly compare the hardware mix of different sized fleets. Instead, it gains the ability to compare the scale of fleets with different levels of uniformity. Fleet scale is calculated using the same three levels of detail for fuselage and engines as those used in calculating the fleet standardization index.

The fleet scale S of a particular airline is calculated on the basis of the auxiliary scales SF for the fuselage and SE for the engines:

$$S = \beta_f SF + \beta_e SE, \quad (8)$$

where, $\beta_f + \beta_e = 1$. These coefficients determine the relative impact of one fuselage and one engine in the total fleet scale. Constant values $\beta_f = 0.8$ and $\beta_e = 0.2$ for estimation. The SF of the total fleet is calculated on the basis of the summary figures at all three levels of detail regarding the fuselage:

$$SF = \beta_{f1} A_{mfr} + \beta_{f2} A_{fam} + \beta_{f3} A_{mod}, \quad (9)$$

where A_{mfr} is the average number of aircraft/manufacture in the total fleet, A_{fam} the average number of aircraft/aircraft family in the total fleet, A_{mod} the average number of aircraft/aircraft model in the total fleet and $\beta_{f1} + \beta_{f2} + \beta_{f3} = 1$. These coefficients determine the relative impact that the variety in each of the three levels of detail causes in the auxiliary scale SF . The values $\beta_{f1} = 0.5$, $\beta_{f2} = 0.3$ and $\beta_{f3} = 0.2$ are adopted. The SE of the total

fleet is calculated on the basis of the summary figures at all the three levels of detail regarding the engines:

$$SE = \beta_{e1} E_{mfr} + \beta_{e2} E_{typ} + \beta_{e3} E_{mod}, \quad (10)$$

where E_{mfr} is the average number of engines/manufacturer in the total fleet, E_{typ} the average number of engines/engine type in the total fleet, E_{mod} the average number of engines/engine model in the total fleet and $\beta_{e1} + \beta_{e2} + \beta_{e3} = 1$. These coefficients determine the relative impact that the variety in each of the three levels of detail causes in the auxiliary scale SE. Values of $\beta_{e1} = 0.5$, $\beta_{e2} = 0.3$ and $\beta_{e3} = 0.2$ are assumed.

In these formulas, fleet scale has no upper limit and it reaches its lower limit of 1.2 when there is only one aircraft with two engines in the fleet. One aircraft with three or four engines produces a fleet scale of 1.4 or 1.6, respectively. As the fleet size of any aircraft model increases, the fleet scale also increases. Conversely, as the variety of aircraft and engines in the fleet increase, the fleet scale decreases.

An alternative way of formulating a measure that takes into account both fleet size and structure would be to multiply the fleet size by the fleet standardization index. A separate measure of fleet scale is preferred because of its less logarithmic nature. Of all calculated nonzero values of the fleet standardization index, over 50% were under 0.15, whereas the fleet scale gives a considerably wider spread of results. Comparable hypothetical calculation of the fleet scale for the same imaginary airline fleet as in Table 2 can be seen in Table 3. The calculations produce a fleet scale of 10.1 that roughly equals 8–9 identical twin jets. A possible way to increase fleet uniformity and scale would be to replace the Boeing 777-200ER aircraft with slightly smaller Airbus A330-300 aircraft or slightly larger

Airbus A340-600 aircraft. Both alternatives would lead to an all-Airbus fleet, but the latter would inevitably bring up a new engine manufacturer Rolls-Royce. The fleet scales in these improved cases would be 15.4 with A330-300 and 14.5 with A340-600.

The fleet scale was calculated for the same 90 airlines as the fleet standardization index using the same 30-yr period. The results indicate that the fleet scales of the largest carriers are not always the highest. Low-cost carriers like Southwest and JetBlue are the easiest to distinguish among the carriers. In 1997 Southwest passed the world's largest operator American Airlines in fleet scale and continued on its growth path thereafter. JetBlue only started its operations in 1999 but had already passed the 12th largest operator Lufthansa in fleet scale 6 years later.

Air Canada and Canadian Airlines demonstrated the effect of an acquisition on fleet size. The fleet scale of Canadian Airlines was 32 when it was acquired by Air Canada in 2001. At that time Air Canada had a fleet scale of 38. If their fleet compositions had been similar, the fleet scale of Air Canada would have been the sum of those figures (70) after the acquisition—it only increased to 52 as the fleet compositions were slightly different. Afterwards, Air Canada started phasing out some older aircraft types to utilize the scale potential of the acquisition. By 2005 this effort had decreased Air Canada's fleet scale to 47; no types disappeared, but the older fleets had been reduced more than the newer fleets had increased.

Fig. 6 shows the trend of average fleet scale of the top 20 operators. As can be seen, the general trend has been upward most of the period. During that time the fleet scale has increased from the high 50s to high 90s, which roughly equals a change from 50 to 80 identical twin jets.

Table 3
Example of fleet scale

Level	A/C mfr	Family	# of aircraft	# of models	# of families	# of mfrs	Scale
	Airbus	A32S	10	2			
	Airbus	A330/340	7	2			
	Airbus				2		
	Boeing	777	3	1			
	Boeing				1		
Total			20	5	3	2	
Average				4.00	6.67	10.00	
SF		Coefficients		0.2	0.3	0.5	7.80
Level	Eng. mfr	Eng. type	# of engines	# of models	# of types	# of mfrs	Scale
	CFM	CFM56	40	3			
	CFM				1		
	GE	CF6	4	1			
	GE	GE90	6	1			
	GE				2		
Total			50	5	3	2	
Average				10.00	16.67	25.00	
SE		Coefficients		0.2	0.3	0.5	19.50
Scale	All	Coeff. 1		Coeff. 2	0.2		10.14

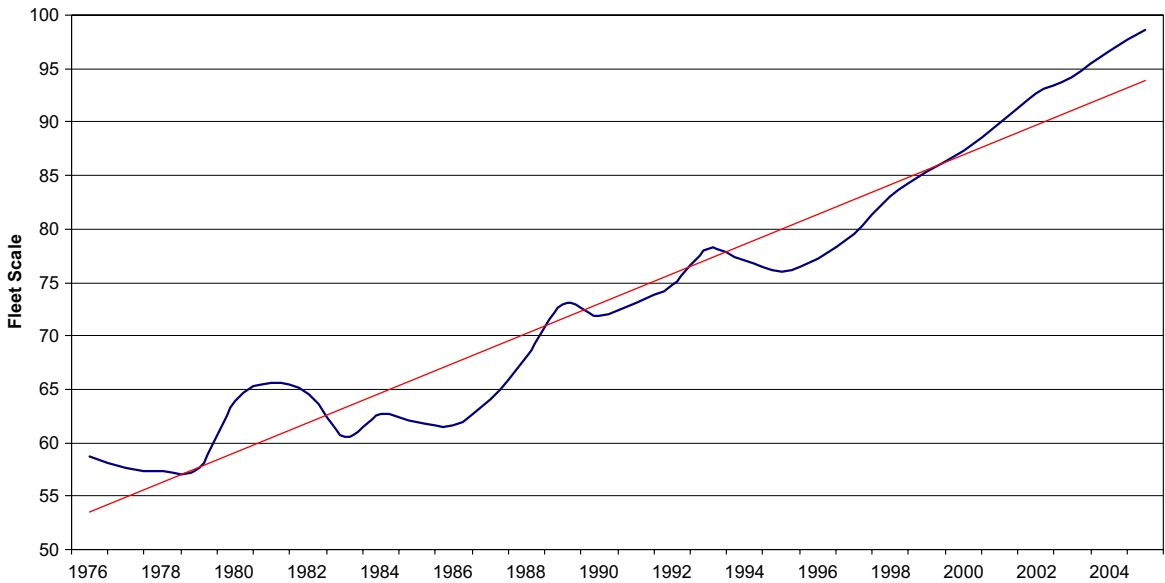


Fig. 6. Fleet scale—average of world top 20 operators for 1976–2005.

An analysis of the detailed data behind this figure reveals that the constantly decreasing fleet uniformity of the largest operators is more than offset by the sheer increase in their fleet sizes. In 1976 the average fleet size of a top 20 operator was 130 aircraft while in 2005 it was 300 aircraft.

In contrast with the fleet standardization index, economic fluctuations are not very visible in the average fleet scale. It seems that the most significant deviations from the trend line coincide with the launch timeline of the new aircraft types. The fleet scale stabilizes or decreases when new aircraft types are introduced and increases rapidly when already established aircraft types are phased in by the airlines. The mid-1980s witnessed a number of new aircraft types that were phased in rapidly during the economic boom of the late 1980s. The mid-1990s witnessed a number of new wide-body aircraft that are important especially for the top 20 airlines. They were phased in during the late 1990s.

7. Conclusions

The uniformity of airline fleets has been steadily decreasing, while the average fleet scale has been steadily increasing. We find that airline consolidation decreases uniformity and increases scale in the short term although uniformity could be increased by management resolution in the long term. During an economic boom airline fleets expand in size and variety producing more diversity in their composition and increasing their scale. This happens as new aircraft are taken into fleets and cocooned ones are

retrieved from “park”. Fleet diversity is also increasing as high-capacity variants of regional jets are beginning to compete with the traditional narrow-body aircraft.

Market trend effects counteracting with these developments exist but are not strong. During an economic downturn airlines retire or park older aircraft, adjusting capacity to better meet the new situation. This increases uniformity if aircraft type leaves the fleet entirely and decreases scale if only the number of aircraft decreases. Regarding the older, less fuel-efficient aircraft, jet-fuel prices have a similar effect as a downturn. The consolidation of aircraft manufacturing in the large aircraft segment of the market also increases fleet uniformity in the long term by narrowing the alternatives for carriers.

Regarding the techniques used and their potential in airline planning, it is found that the fleet standardization index allows an airline to benchmark its fleet uniformity against different sized competitors. The fleet scale is best suitable for assessing alternative fleet change scenarios within an airline.

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PAPER II

Valuation of Rotable Spare Parts

Jani Kilpi

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Jani Kilpi

VALUATION OF ROTABLE SPARE PARTS

Abstract

Rotable spare parts are insurance-like assets that are kept available to maximise the utilisation of the supported production equipment. Financially, they are easily treated like regular production equipment even if their value preserving characteristics would require different treatment. In this study, the two functional roles of rotable parts are identified and a distinction between the spare part role and the production asset role is made in the financial sense. This study also shows that the most suitable method for the valuation of rotable spare parts is the annuity method, and that the values of rotable spare parts are mainly dependent on the remaining service life of the supported production equipment. The effect of different valuation methods on the outsourcing decisions concerning rotable spare parts is discussed.

Keywords:

Valuation; Cost of ownership; Rotable spare parts; Outsourcing; Aviation; Annuity

1. Introduction

Rotable spare parts are held to support critical production processes by ensuring that production equipment is available for use when needed. This activity is called here the rotable spare part availability service. As it is basically balancing the spares inventory cost with the cost of production equipment downtime, the ownership cost of the rotable spare parts is a key factor in managing this service.

The key area of decision-making that is affected by the cost of spare part ownership is outsourcing, which has become a focal issue in today's business environment in its various forms. In outsourcing decisions regarding rotable spare part availability, it is necessary for the management to compare the ownership cost to the subcontracting cost. These decisions are not only made by the end customers of the availability service. At least in the aviation industry, practically every service provider in the value chain has the alternative of further subcontracting the availability service instead of providing the service using its own parts.

No empirical data of how companies value their rotatable spare parts were found when this study was prepared. Practical experience in the aircraft maintenance business indicates, however, that companies have been using and probably still use value data from the financial accounting in managerial decision-making regarding rotatable spare parts. As the financial accounting value is produced according to legislation for purposes very different from managerial decision-making, using it may well be misleading.

Rotatable spare parts are also easily treated like other assets as regards valuation and cost accounting. It will be shown in this study that rotatable spare parts form an asset category of their own, which behave unlike any other type of asset. Treating them like consumable spare parts or workshop machines may produce arbitrary results when outsourcing decisions on availability service are made.

The aim of this study is to provide tools for determining the total cost of owning rotatable spare parts. This will be accomplished by applying the concept of annuity to calculate the managerial accounting value of a rotatable spare part through its lifetime. It will also be shown that the value of a rotatable spare part is not primarily dependent on its own age or condition, but on the remaining service life of the fleet of equipment that it is supporting.

Valuation, service life and ownership cost of assets like production equipment have been widely discussed in the literature (e.g. Hotelling, 1925; Marston et al., 1953; Ijiri and Kaplan, 1969; Hall, 1971; Blades, 1983; Jorgenson, 1996). However, unproductive insurance-like assets such as rotatable spare parts have not been given the attention that their special characteristics would require. They also seem to be neglected in the practical business environment when it comes to ownership cost.

It is the purpose of this study to be applicable in all the industries where rotatable spare parts are involved. The air transport industry and aircraft spare components are used here as examples.

1.1 Financial and managerial accounting values

An important issue in valuation is that there is rarely a single figure that could be identified as the value of something. Almost every item in inventory has a historic value equal to its purchase price, a current value equal to its market value and a replacement

value equal to the sum needed to buy a new similar item. In addition to these real-world values, every item has accounting values i.e. agreed upon values that have been chosen to represent its value for various purposes. Most likely all these values differ from each other at any given moment, perhaps with an exception of the exact moment when the item was purchased.

The first type of accounting value is referred to here as the *financial accounting value*. It represents historical information suitable for periodical financial statements whose main audience consists of taxation authorities and other external stakeholders. The emphasis in providing this kind of information is to be complete and precise on the summary level. No additional benefit comes from providing this information quickly or in great detail.

Another type of accounting value is referred to here as the *managerial accounting value*. It represents topical information suitable for managerial control and swift decision-making. The managerial accounting value should preferably be as close to the actual market value of the item as economically viable. It is, however, better to produce a less precise value promptly than a very accurate value too slowly.

Johnson and Kaplan (1987, p.161) point out that organisations rarely distinguish between information needed promptly for managerial control and information provided periodically for summary financial statements, even if that would clearly make sense.

The financial accounting value mentioned above can also be referred to as the *traditional accounting value*, compared to the IFRS principles (Reinstein and Weirich, 2002, p.62) that direct the financial accounting value closer to the managerial accounting value. Brazell and Mackie (2000, p.541) report that the U.S. legislation governing fixed asset depreciation is being modified in the same direction.

1.2 Rotable spare parts

The term rotatable part is used here with the meaning of a complex module which has an important function in the production equipment and which can be replaced quickly by a spare unit. The rotatable nature of the part means that, in case of failure, it is generally less expensive to repair it than discard it and purchase a new unit as a replacement. After the repair has been completed, the unit is stored as a spare. The purpose of

keeping spare units at hand is to increase the utilisation of the production equipment by limiting the downtime to the time that it takes to replace the failed unit.

A rotatable spare part is identical in function to a unit installed in production equipment. The only difference between them is the insurance-like role of a spare part compared to the revenue generating role of its counterpart. In time, the installed unit fails and the roles change, so no individual rotatable part is a spare for long. If the rotation is working well, all the units take turns in being in revenue generating role and being a spare.

Depending on the part design, it is possible for units to have very long service lives. For example, many aircraft components can go through a practically unlimited number of repairs and overhauls without wearing out, thus having a service life equal to the economic life of the supported aircraft type. In real life, there are naturally rotatable spare parts that deteriorate with age regardless of the maintenance operations performed on them. Nevertheless, this study assumes that the only phenomenon affecting the service lives of the rotatable spare parts is the obsolescence caused by advancing technology and consequently the retirement of supported equipment. Blades (1983, p.18) identifies mortality and survival functions suitable to be applied to this distinct case which he calls 'simultaneous exit'.

1.3 Fleet of equipment

The term *fleet of equipment* is used here with the meaning of a group of similar pieces of production equipment or machinery which are supported by a number of rotatable spare parts. In the air transport industry, for example, a fleet of equipment is a fleet of aircraft operated by an airline representing the same aircraft type. A fleet of aircraft is supported by a number of spare components or line replaceable units (LRUs).

It is not necessary that the fleet is owned by a single company. If a group of companies have outsourced the spare part availability service to one service provider, all their production equipment belongs to the same fleet from the service provider's viewpoint.

1.4 Research on valuation, depreciation and service lives

Hotelling (1925) was one of the early researchers to discover how the value of production equipment and the cost of its output are interrelated. He was probably the first one to claim in an academic paper that depreciation is the decrease in the present value of the future returns of a production equipment. Marston et al. (1953) discuss

present value depreciation in their exhaustive volume on valuation and depreciation, and even introduce the possibility of calculating depreciation by setting the annual operation returns constant over the years. They, however, conclude that the present value method of depreciation is more suitable to be used in economy studies than in real life cost accounting.

Hall (1971) introduces an econometric model of estimating asset values by applying regression analysis to historical price data. A comprehensive selection of studies accomplished using Hall's model has been analysed by Jorgenson (1996).

Ijiri and Kaplan (1969) introduce the concept of probabilistic depreciation, which assumes that the service life of an asset is not known in advance. Ijiri and Kaplan (1970) further develop the concept to recalculate the probabilities sequentially each year of the service life. Friberg (1973) continues their work and extends the concept to be applicable with varying salvage value. Probabilistic depreciation in these variations could be used in the valuation of rotatable spare parts with age related mortality.

Blades (1983) has studied service lives of fixed assets from the perspective of national economy. From a viewpoint closer to this study, service lives have been studied by Goolsbee (1998), who finds a significant number of factors that influence the retirement of capital goods by studying the phase-out of Boeing 707 aircraft from the operation of the U.S. major carriers.

2. Determining the managerial accounting value

The purpose of this study is to provide a method for calculating the managerial accounting values of rotatable spare parts to determine the total cost of owning them. First it is necessary to understand the special characteristics of rotatable spare parts. After that it will be shown that the most suitable method to determine the managerial accounting value of rotatable spare parts is the use of equivalent annual annuity (EAA).

2.1 Rotable spare part as an asset

An intuitive way of valuing rotatable spare parts would be to bundle them together with the production equipment they are supporting and depreciate these two assets in a similar manner. This method has been used by some airlines in the past but it completely ignores today's trend towards specialisation, outsourcing and network

economy. It is getting more and more rare that an airline operator itself owns the spares; at least the owner is a different business unit in the airline company with its own income statement and balance sheet. According to Jackman (2006, p. 50) 65 per cent of the aircraft component business was outsourced in 2005 and the figure is estimated to increase to 75 per cent by 2010.

The value chains in the availability service can be long. In traditional airline companies the operations department commonly makes a full service contract with the in-house maintenance department. Then the maintenance department may contract out the component support of one fleet of aircraft to an external service provider like Lufthansa Technik or SR Technics. As these providers tend to work more and more as global service integrators (Burchell, 2006) they may further outsource the support of some components to other service providers. Every one of these parties has to decide whether to subcontract the availability service of a certain rotatable spare part or provide the service using its own parts.

It should be realised that in the network economy rotatable spare parts are production assets of the maintenance industry, instead of supporting assets of the actual production industry serving the end customers. They are, however, different from many other production assets. A rotatable spare part is like an insurance to be offered to customers for protection against the risk of extended production equipment downtime. This insurance-like nature of a rotatable spare part means that it is at work when it lies on the shelf collecting dust. Its role is to wait until the unexpected happens and it is needed for the supported equipment to continue working. When that happens, it is no longer a spare part, it is a part of that supported equipment in the functional as well as financial sense. The failed part will be repaired and in time takes the position of the spare part on that dusty shelf.

The value of production equipment includes the values of all the rotatable parts installed in it. When production equipment is depreciated, the installed units are also depreciated, but you cannot tell the share of the total value that belongs to a certain rotatable part. This uncertainty, together with the major difference in roles, leads to the fact that valuation of the rotatable spare parts has to be separated from valuation of the installed rotatable parts. It is like attaching the value tag to the shelf where the spare unit is stored, instead

of attaching it to the unit itself. Thus, the value of a rotatable part actually changes every time it is installed or removed.

In contrast, the value of the production equipment as well as the value of the rotatable spare part inventory remain unchanged after a replacement operation. It is assumed that in the revenue generating role, the installed and removed unit are equal in value. In the spare part role, the value of the removed unit equals the value of the installed unit after it has been repaired to serviceable condition. This logic leads to the fact that all rotatable spare parts that are interchangeable with each other must have the same value. To simplify the valuation, this study assumes that a rotatable spare part is always in serviceable condition and functionally as good as new when it is being valued.

There are basically two ways of treating rotatable spare part values in financial accounting. Seago (1996, p.347) has studied court cases in the U.S. and found out that at least under local legislation they can be treated as *inventory* or as *depreciable assets*. Holloway (1997, p.229) suggests that aircraft spare parts should preferably be treated as depreciable assets, still leaving the final decision to local accounting and tax regulations. As regards the managerial accounting value, the only plausible way of treating rotatable spare parts is as depreciable assets. The total value of an inventory item is generally written off at one time. Depending on the interpretation this may be when it is used for the first time or when it is scrapped. Both of these alternatives are unsuitable for expensive parts with long service lives.

The only way that a spare part generates income is by shortening the downtime of the supported production equipment. Instead of trying to estimate the amount of income, this study focuses on the fact that the savings in downtime are steady in the long run. This is because the downtime is initiated by a random phenomenon, system failure. As the number of random events increases in the long run, the law of large numbers reduces the variation. It is also assumed here that the nominal downtime cost of production equipment remains unchanged through its whole productive life. Consequently, the nominal income generated by a rotatable spare part will be uniformly distributed over its service life.

When the income approach of valuation is applied, it is evident that the value of a rotatable spare part is heavily dependent on the remaining service life of the supported equipment. There are also minor factors affecting the value like, for example, the

quality of maintenance operations and repairs performed on the spare part. Shallcross (1995) argues that high maintenance quality and good reputation of the maintenance service provider has a significant effect on the value of a second-hand aircraft. The same should apply to aircraft components as they are maintained by the same service providers as the aircraft.

The reasonably strong assumption of the nominal downtime cost of production equipment remaining unchanged is necessary for the simplicity of this study, and is somewhat relieved by the fact that the inflation rate is generally lower than the nominal discount rates used. Feldstein (1981, p.39) has studied the relationship of inflation and depreciation and concludes that real discount rates typically lie between 4 and 7 per cent.

2.2 EAA approach of valuation

The concept of net present value (NPV) is widely used in capital budgeting as well as in costing of assets and financial instruments (e.g. Horngren et al., 2000, p.751). NPV can also be applied to calculate depreciation of fixed assets, especially in managerial accounting. When the annual cash flows produced by the asset are constant, the NPV method of depreciation reduces to the annuity method (Kaplan, 1982, p.549), also referred to as equivalent annual annuity (EAA). By using EAA it is easy to calculate the constant annual payment needed to cover an investment if the discount rate and the payback period are known. In this study the EAA method is adapted to serve the needs of rotatable spare part valuation.

The income approach of valuation uses the logic of the EAA method in the opposite direction. It is based on an assumption that the value of the asset equals the present value of the future income generated by it (Marston et al., 1953, p.198). When the EAA method is used backwards, the investment means the value of the asset and it is calculated using the generated annual income, discount rate and the service life of the asset.

Since the income generated by a rotatable spare part is steady over the years, it is reasonable to pay a constant annual fee for the part being available. Considering all the possible valuation methods this fee, the total annual cost of ownership of a rotatable spare part, only remains constant with the EAA approach.

Spahr et al. (1999) extend the concept of annuity beyond the equivalent annual annuity. Based on their work, it seems possible to calculate annuities with any pattern of annual cash flows, as long as the annual cash flow is greater than or equal to the amount of annual interest. Actually, if the depreciation is allowed to be negative, there should be no restrictions to the pattern. From this perspective, the essential remaining characteristic of annuity is that it focuses on total annual cash flow instead of interest and depreciation separately. This would make it possible to calculate annuities with increasing nominal cash flows, and to let go of the assumption of nominal cost of production equipment downtime being uniform throughout the service life.

2.3 Financial accounting value

Financial accounting value represents the spare part value for external accounting purposes. From the viewpoint of this study, the most important alternative method of valuation is the use of the financial accounting value as the managerial accounting value. The importance is not due to the suitability of the method but to the unfortunate assumption that it is very much used. The popularity originates probably from the fact that taxation authorities require it for financial statements in any case. If no better values exist, it is tempting to use the one available regardless of how misleading results it may produce.

There are basically two different methods to determine the annual depreciation in financial accounting. With *accelerated depreciation* the residual value is decreased by a fixed percentage at the end of each year. The value never reaches zero but infinitely approaches it. *Straight-line depreciation* decreases the residual value by an even amount every year from its acquisition until the end of its life span when its value reaches zero. Estimation of the service life, which is not necessary with the accelerated depreciation, is the weakness of this method. Of the two methods, however, the straight-line depreciation is considerably more suitable for determining the managerial accounting value of rotatable spare parts. This is because the method assumes a uniform distribution of service for the depreciated asset through its life (e.g. Ijiri and Kaplan, 1969, p.743). It is naturally possible for a company to use straight-line depreciation in managerial accounting and accelerated depreciation in financial accounting.

In financial accounting it is generally most economical for the owner to depreciate the rotatable spare parts reasonably quickly. If the accelerated depreciation is in use, local

legislation sets the maximum percentage by which the residual value may be depreciated annually. When the part is sold or scrapped, its estimated share of the residual value is written off from the balance sheet.

3. Applying the EAA approach of valuation

This section introduces a simple method of calculating annuities. With the results of the calculations it is then possible to compare the EAA approach with its competitors. The final section deals with the allocation of the cost of ownership between different fleets of equipment.

3.1 Calculating annuities

The mathematics behind annuities are straightforward. A suitable formula for basic calculations can be found in any textbook on finance (e.g. Brealey and Myers, 1991, p.35):

$$PV = C \left[\frac{1}{r} - \frac{1}{r(1+r)^t} \right] \quad (1)$$

where C equals the Annual cash flow, i.e. annual cost of ownership, r equals the annual interest rate, t equals the remaining duration of the annuity in years and PV equals the present value of the annuity.

The expression in brackets is called the *annuity factor* and will be referred to here as A. The only factors affecting it are the annual interest rate r and the remaining duration of annuity in years t. Because the only thing affecting the service life of the rotatable spare part is assumed to be the retirement of the supported production equipment, and the age of the individual spare unit is mostly unknown, the annuity calculations are based on the remaining service life of the supported equipment.

If the annuity factor A and the present value of annuity PV are known, the annual cost of ownership C can be calculated as follows:

$$C = \frac{PV}{A} \quad (2)$$

If the annuity factor A and the annual cost of ownership C are known, the present value of annuity PV can be calculated as follows:

$$PV = C \cdot A \quad (3)$$

Theoretically, the present value of a rotatable spare part at the beginning of its service life is its purchase price. It is, however, already regarded as second-hand when it is received from the supplier. The new owner can only resell it under its original purchase price. Reasons for this devaluation include the risk of the seller trying to get rid of an unreliable or mistreated unit, and the lack of warranty in such second-hand agreements. Akerlof (1970) identified this phenomenon and calls it the market for lemons. In this study the term second-hand factor means a percentage of the original purchase price that is activated as a cost immediately when the spare part is purchased. When calculating annuities the initial present value is obtained by subtracting the second-hand factor from the purchase price.

The annual cost of ownership consists of two different types of cost: interest on invested capital and depreciation of that investment. With annuities, the sum of these two factors remains constant over time but their respective shares of the total do change. In the beginning the sum consists mainly of interest but towards the end the share of depreciation increases.

It is important to notice that the interest rate in the annuity calculations actually means the discount rate or the opportunity cost of capital instead of the cost of borrowing. What may cause confusion here is the fact that annuities are commonly used with loan calculations and in those cases the interest rate means the cost of borrowing.

An example illustrates the calculation of annuity. If the annual interest rate is 17 per cent and the duration of the annuity is 5 years, value 3.199 for the annuity factor A can be calculated using Equation (1). If the price of a new rotatable spare part is US\$3 000 and the second-hand factor is 10 per cent, it is easy to calculate the US\$300 depreciation of year 0 caused by the second-hand factor. The initial value of the spare part is thus US\$2 700. The annual cost of ownership of US\$844 is then calculated using Equation (2). From year 1 to 5 the interest is calculated by taking 17 per cent of the spare part value at the end of the previous year. Depreciation is calculated by subtracting the annual interest from the cost of ownership. Finally, the value at the end of the current year is calculated by subtracting the annual depreciation from the value at the end of the previous year. Alternatively, the value at the end of any year can be calculated using Equation (3) with the annuity factor A calculated for that year. The results of the example can be seen in Table 1.

Year	Cost of ownership	Interest	Depreciation	Value (end of year)
0	\$300		\$300	\$2 700
1	\$844	\$459	\$385	\$2 315
2	\$844	\$394	\$450	\$1 865
3	\$844	\$317	\$527	\$1 338
4	\$844	\$227	\$617	\$721
5	\$844	\$123	\$721	\$0
	\$4 520	\$1 520	\$3 000	

Table 1 Results of the annuity example

In this example the share of depreciation is quite high right from the beginning, which derives from the short duration of the annuity. Service lives of rotatable spare parts are commonly much longer but the duration of 5 years was chosen here to save space.

3.2 Comparison to other approaches

In this section the EAA approach is compared to two alternative approaches, accelerated depreciation and straight-line depreciation, both representing the financial accounting value.

It is rather easy to notice that accelerated depreciation is only suitable for assets with increasing risk of retirement and decreasing capability to generate income. Straight-line depreciation is usable with assets like rotatable spare parts, if the difference between the total future income and the net present value of all future income is not considered significant. This may be the case with short service lives or low rates of interest. Actually, straight-line depreciation is a special case of annuity with no interest.

In the middle third of the service life, where the difference between the straight-line depreciated value and the annuity value is greatest, there are two real life factors to support the preference of the annuity value. New unit prices are hardly lowering to compensate for the diminishing service life, which increases the demand for second-hand units in the middle of the service life. Furthermore, there is an intuitive logic to acquire low risk new units at the beginning of the service life but to be satisfied with higher risk second-hand units in the middle of the service life. This should also increase the demand for second-hand units during the middle third.

Figures 1, 2 and 3 show the annual interest and depreciation of a US\$10 000 investment recovered in 30 years using the annual interest rate of 10 per cent. An annual depreciation rate of 15 per cent of the residual value is used with accelerated depreciation.

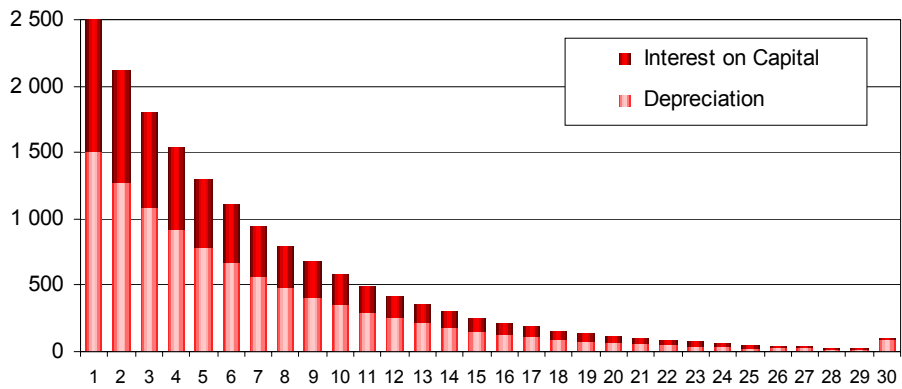


Figure 1 Annual cost of ownership using accelerated depreciation

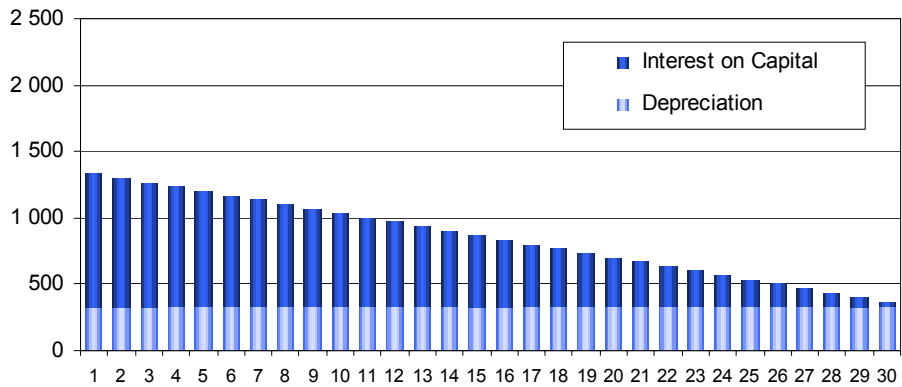


Figure 2 Annual cost of ownership using straight-line depreciation

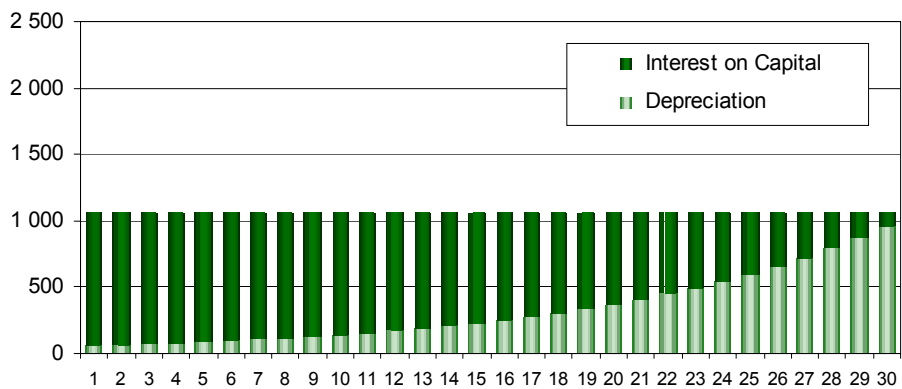


Figure 3 Annual cost of ownership using EAA approach

As can be seen in the figures, the distribution of the annual cash flows differs significantly between the methods. As they are in effect three different residual income schedules of the same investment, all of them have the same present value of US\$10 000 (e.g. Peasnell, 1982, p. 377). The differences become evident when looking, for example, at the first five years of the schedules. The present value of this early period is US\$7 245 using accelerated depreciation, US\$4 826 using straight-line depreciation and US\$4 021 with the annuity method. This means that accelerated depreciation shows 80 per cent higher cost and straight-line depreciation 20 per cent higher cost than the annuity method.

As a result, it is evident that the worst alternative for a company is to use accelerated depreciation in the valuation of rotatable spare parts. This makes the ownership costs during the first years of the service life appear significantly higher than they actually are. After that they appear lower, especially during the later half of the service life.

3.3 Allocating the cost of ownership

To have the desired effect on decision-making, the cost of ownership of a rotatable spare part has to be allocated to a correct cost object. The allocation of the ownership cost of a piece of production equipment is usually straightforward. Assuming that the asset is an aircraft, a typical cost object to allocate this cost to would be a fleet of aircraft. For the purposes of management decision-making, the average cost of available seat kilometre (ASK) of the aircraft fleet in question includes the cost of owning this particular aircraft.

If the rotatable spare part only supports one piece of equipment, its cost of ownership can be easily allocated. Commonly, when the spare part supports several pieces of equipment, it is necessary to find a cost driver to allocate the cost with. When a suitable cost driver has been identified, it can be used to divide the cost of ownership between the fleets of equipment supported by the spare part. For aircraft components, there are two suitable cost drivers, number of flight hours and number of landings accumulated by the supported aircraft. Depending on the function of the component, one of them can be chosen. For example, number of landings is clearly a more suitable driver for landing gears than number of flight hours would be. It is quite the opposite with an air conditioning unit.

An example illustrates the use of cost drivers in the cost allocation process. Let there be an airline with two fleets of aircraft, 14 Boeing 757 narrow-bodies and 8 Boeing 767 wide-bodies. The 757s operate short-haul with each aircraft accumulating 1200 cycles (landings) per year. The 767s operating long-haul accumulate half of that amount. Both aircraft types use the same type of fictional component to assist the pilots with instrument landings. The component is triplicated for safety reasons, which means that each aircraft has three units installed. 8 spare units are needed to support the 66 units installed in these aircraft. Among others, Kilpi and Vepsäläinen (2004, p.139) have presented a method of calculating the number of spare units needed to support a fleet of aircraft.

Let the original purchase price of the component be US\$28 000 with a second-hand factor of 15 per cent. If the annual interest rate is 9 per cent and the duration of the annuity is 30 years, the annual cost of ownership of US\$2 317 per unit can be calculated using Equations (1) and (2) above. For all 8 units together the annual cost of ownership is US\$18 533. This cost is then divided between the fleets with the same ratio as the total cycles accumulated. The results of the example can be seen in Table 2.

Fleet	# of A/C in Fleet	Average Cycles per Annum	Total Cycles per Annum	Share of the Spares Cost	Spares Cost per Annum
757	14	1 200	16 800	77.8%	\$14 414
767	8	600	4 800	22.2%	\$4 118
	22		21 600	100.0%	\$18 533

Table 2 Results of the cost allocation example

It is also possible to allocate *values* of rotatable spare parts to fleets of equipment to determine the distribution of capital tied up to support the fleets. The cost drivers can be used in exactly the same way in this calculation as they are used in allocating the cost of ownership. In contrast to the cost of ownership, the allocated value changes every year.

4. An illustrative example of rotatable spare part valuation

An example of rotatable spare part valuation is presented here to illustrate the effect of the ownership costs in decision-making. In the example the cost of ownership is calculated using both the annuity method and the accelerated depreciation method.

The decisions which the cost of ownership most substantially affects deal with outsourcing the rotatable spare part availability service. The question for the management

is basically whether to own the spares to support a fleet of production equipment or subcontract the availability service. In an outsourcing setting, the service provider owns the spare units and is responsible for providing sufficient availability to support the customer's fleet of equipment. It is also possible for the management to offer availability service to other companies in addition to supporting the company's own fleet.

4.1 A subcontracting decision of aircraft spare component availability

In this illustrative example there is an airline operator with a fleet of 12 aircraft and a service provider offering availability service to support the fleet with an inventory of a component Z. In each aircraft there are three units of component Z installed, and 7 spare units are needed to support the fleet. The aircraft in the fleet are 5 years old and will be operated by the airline for 5 more years. Regarding that five-year period the airline is making a decision of whether to own the spare components or subcontract the availability service to the service provider.

The airline purchased 4 spare units of component Z 5 years ago and is able to use them as spares in this setting. Two units are available in the second-hand market and the final unit has to be purchased new. If the airline decides to subcontract the service, the service provider is willing to purchase the 4 units for their fair market value.

This example shows how the outsourcing decision has a different result depending on the valuation method the airline uses. Two alternatives are presented, one with the annuity method and one with accelerated depreciation.

4.2 Results of the example

The original purchase price of component Z 5 years ago was US\$10 000 with a second-hand factor of 15 per cent. The current price of a new unit is US\$11 037. If the annual interest rate is 10 per cent and the duration of the annuity is 30 years, an annual cost of ownership of US\$902 per unit can be calculated using Equations (1) and (2) above. An annuity factor A of 9.077 can be calculated for year 5 using the expression in brackets in Equation (1). Using Equation (3) it is possible to see that the value and fair market price of one spare unit in year 5 is US\$8 187.

The service provider offers the availability service to the airline with a price of US\$29 500 to be paid upfront. As the total market price of the 4 units the airline sells to

the service provider is US\$32 748, the service provider actually pays US\$3 248 to the airline at the beginning of the service period.

If the airline uses the annuity method, its original 4 units are valued at the market price. These units and the 2 units the airline purchases from the second-hand market add up to a total value of US\$49 122. The airline also buys one new unit for a price of US\$11 037, of which US\$2 850 is immediately written off, as all the rotatable spare parts of the same type have the same value by definition. The total value of the 7 units is therefore 7 times US\$8 187 or US\$57 309. The resulting annual distribution of ownership costs can be seen in Table 3. The present value of the annual costs (equals the sum of discounted annual costs) is US\$26 785, which is well below the upfront cost of the subcontracted service.

Year	Value 1	Cost 1	Discounted cost 1	Value 2	Cost 2	Discounted cost 2
5	\$57 309	\$2 850	\$2 850	\$51 031	\$0	\$0
6	\$56 728	\$6 314	\$5 740	\$45 928	\$10 206	\$9 278
7	\$56 091	\$6 314	\$5 218	\$41 335	\$9 186	\$7 591
8	\$55 384	\$6 314	\$4 744	\$37 201	\$8 267	\$6 211
9	\$54 607	\$6 314	\$4 313	\$33 481	\$7 440	\$5 082
10	\$53 753	\$6 314	\$3 920	\$30 133	\$6 696	\$4 158
		\$34 420	\$26 785		\$41 795	\$32 320

Value 1: Value with Annuity method

Cost 1: Annual costs with Annuity method

Discounted cost 1: Present value of annual costs with Annuity method

Value 2: Value with Accelerated depreciation

Cost 2: Annual costs with Accelerated depreciation

Discounted cost 2: Present value of annual costs with Accelerated depreciation

Table 3 Results of the valuation example

If the airline uses accelerated depreciation instead, the figures are different. Using an annual depreciation rate of 10 per cent, each of the 4 units owned is worth US\$5 905 at the beginning of the contract period. The purchased units are valued at their purchase prices, US\$8 187 for the 2 second-hand units and US\$11 037 for the new unit. The total value of the 7 units of US\$51 031 is then depreciated for five years with the results showing in Table 3. The present value of the annual costs is now US\$32 320.

The ownership cost of US\$32 320 seems high enough to make the service provider's offer of US\$29 500 appear economical. Looking at these numbers the management would accept the offer satisfied with the savings of US\$2 820. Additionally, the

managers would perhaps congratulate each other for making a profit of US\$2 282 per unit by selling the 4 spare units for over their book value.

This example shows that using accelerated depreciation may lead to results significantly different from the annuity method. In an unlucky situation, as in this example, this difference would result in an uneconomical management decision. It is by no means so that the accelerated depreciation would always favour the subcontracted service. It may as well be the other way around.

When a large variety of different settings are constructed by altering the parameters of this example, certain conclusions can be drawn. If the age of the supported fleet is increased, the difference between the methods decreases and, at some point, accelerated depreciation begins to show lower costs than the annuity method. Increasing the depreciation rate causes the point of equal total cost to move backwards in time. If the spare units are all purchased second-hand, accelerated depreciation always shows higher cost.

4.3 Managerial implications

In this example, using the accelerated depreciation leads to an annual loss of only US\$543. Taking into account that there are easily 1000 different components in an aircraft to be supported by similar services and, that component Z with a list price of US\$11 037 is reasonably inexpensive, the magnitude of the problem becomes evident.

The benefits of subcontracting derive from the scale economies and will be realised if the service provider supports other similar fleets with the same pool of spare components. Similarly, the airline may utilise the scale economies by offering availability service or pooling its spare components with other operators (Kilpi and Vepsäläinen, 2004).

If the management decides to offer availability service of rotatable spare parts to other companies, the importance of the accurate valuation increases. Now the risk is not only about selecting higher cost alternatives, but it is about initiating loss making business activities.

Apart from subcontracting and service providing decisions, there are also other kinds of management decisions related to rotatable spare part values and their ownership costs. Service levels of spare part inventories are set to minimise the sum of production

equipment downtime cost and the cost of spare part ownership. Too high service level increases the cost of spare parts while too low service level increases the cost of downtime. If the management knows the actual cost of ownership, it will succeed in setting the service level correctly.

As the cost of rotatable spare part ownership is eventually allocated to fleets of production equipment, the method of calculation also affects the cost of the production process itself. Regarding an airline, the cost of rotatable spare part ownership appears as a small factor in the average cost of available seat kilometre (ASK) of an aircraft fleet. This way it has a minor effect on all the decisions based on the ASK cost of the fleet.

In 2002 the aviation supply chain was estimated to hold over US\$50 billion worth of spare part inventory (McDonald, 2002, p.48). Because of the easy availability of the information, it is most probable that this figure is based on the financial accounting values reported to taxation authorities by the industry. These values are usually calculated using accelerated depreciation. Bearing in mind that financial accounting typically accelerates the depreciation and makes the values on the average appear lower than they actually are, the figure could easily be over 30 per cent higher, ending up to over US\$65 billion. This example shows that a careless use of the financial accounting values seems to underestimate the problem of accumulating inventories.

5. Conclusions

In today's business life, there is an increasing trend towards outsourcing. Outsourcing even extends to functions like manufacturing or research and development previously considered as core competences. Following the trend is quite appropriate if there are foreseeable benefits available in doing so. In contrast, following the trend without really knowing the results is not recommended.

The purpose of this study was to provide help in making better judgements in outsourcing decisions concerning rotatable spare part availability. It has been shown here that taking into consideration the special characteristics of the rotatable spare parts and using the EAA approach in calculating their values as well as the costs of their ownership, actually results in more reliable estimates than other methods of valuation which might be considered.

It may not be just aircraft, trains, computer systems and paper mills that will be depending on rotatable spare parts in the future. It is possible and easily imaginable that advances in technology, increasing environmental awareness and higher requirements of availability will bring the rotatable spare part ideology to the consumer sector some day soon. The most complex consumer products like automobiles, personal computers, home entertainment centres as well as central heating and cooling systems could be fixed on-site or while-you-wait by replacing the faulty component with a spare unit.

As can be seen in the annuity calculations in the previous sections, the application of EAA is rather straightforward. It has not been the intention here to make any contribution by showing how it works, even if a lot of space is used to illustrate how it can be applied in the valuation of rotatable spare parts. The intended main contribution of this study can be found in section 2.1. It is to distinguish rotatable spare parts from other production assets in the financial sense based on the differences between their functional roles. This includes the rules of treating the rotatable part in its revenue generating role as a common production asset, in its insurance-like role as a spare part and while it is changing from one role to the other.

It would be interesting to study how volatile inflationary conditions could be taken into account in the annuity calculations. This study assumes low and stable inflation rates, which is a reasonable assumption regarding most of the Western economies. Globalisation and offshoring initiatives may lead to situations in which the rotatable spare parts are produced and owned by companies in the third world, where the inflation rates may not be so stable. As the payback periods of rotatable spare parts are long, high or volatile rate of inflation would definitely have an effect on their valuation.

One evident issue of utilising the EAA approach is the availability of necessary input data (e.g. discount rate, payback period, periodic cash flows). It would be interesting to study more thoroughly how the input data may be obtained.

The value of rotatable spare part is one factor affecting the outsourcing decision of its availability service. Another study would be needed to cover the other factors that have an effect on it.

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Kilpi, Jani; Vepsäläinen, Ari P.J., 2004. Pooling of Spare Components Between Airlines. *Journal of Air Transport Management*, Vol. 10. Iss. 2. pp. 137-146

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PAPER III

Pooling of Spare Components Between Airlines

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Pooling of spare components between airlines

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Abstract

The purpose of providing component availability service is to maximize aircraft utilization by keeping spare units ready to be installed whenever needed. Since the size of the fleet supported by the spare component inventory is the most important driver behind the inventory cost, inventory pooling among a number of airlines is an intuitive way of exploiting the scale economies of availability services. This study demonstrates the savings potential of balanced inventory pooling arrangements among various airlines. Managerial implications of successful cooperation are discussed.

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Keywords: Inventory pooling; Aircraft components; Airline management

1. Introduction

An important driver of airline performance is the high utilization of aircraft. While reliable and modular components increase utilization, fast replacement service is paramount in case of failure. Keeping functional replacement units at hand shortens the delay of the service and allows the repair work to be performed later on. The costs of this component availability service are caused mainly by the capital tied up in the spare components. In this study, managing the number and location of spare components is considered as availability service, which can be produced in-house, purchased from subcontractors or offered to external customers. These three alternatives constitute a make–buy–sell decision for the maintenance organization regarding every component type it supports. Maintaining in-house capability is an alternative that sustains sovereignty but also ties up valuable capital in a property that is steadily losing its value. Subcontracting component availability replaces capital costs with a constant cash flow, increasing business flexibility. This alternative also increases transaction costs and possibly lead times. Providing availability service to external customers is normally an eligible addition to providing service to one's own organization.

This study considers a fourth alternative of providing availability service, which helps to decrease the spare parts inventory by means of pooling the aircraft components among several airlines. The idea here is to combine the best features of the make–buy–sell decisions of several airlines into a cooperative effort of pooling the inventories of certain spare components. Here it does not matter where or by whom the repair work and other maintenance operations on the components are performed. Inventory pooling is a method of utilizing economies of scale. Fig. 1 shows an example of how economies of scale work in the component availability service. The graphs in the figure have been produced using the model presented below, in section 2.1. with typical parameter values. The number of aircraft in the fleet does not mean the whole fleet of the airline, but just the fleet of one aircraft type or family operated by the airline.

As can be seen in Fig. 1, the more aircraft there are in the fleet, the lower is the spare component need per aircraft. Spare needs are random by nature because they are initiated by a random phenomenon, aircraft component failure. The law of large numbers reduces variation when the number of random events increases. Considering a cooperative setting between airlines it is evident that participants with relatively small fleets have much more to gain than their larger counterparts.

Antti Wäre, Vice President of system business at Nokia Investment Company China, has said (Morais, 2001, p. 104) that ‘there is no point transferring your

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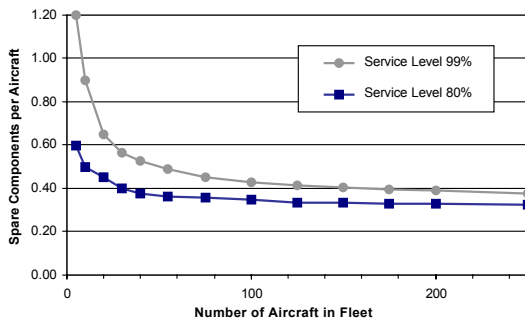


Fig. 1. Economies of scale in component availability service.

inventory to a supplier, because it will then have the inventory cost, and you will see it showing up sooner or later. But if you can reduce the whole chain's inventory, it will make you more competitive'. This study is not merely suggesting that the airlines rid themselves of the spare unit inventories, it suggests a way of lowering the total amount of tied up capital considering the whole value chain.

1.1. Pooling opportunities in the aviation industry

In the aviation industry there has been a constant strain of driving down the number of spare units. It has even been said that the potential for savings through tighter management of spares in the supply chain is greater than any existing revenue opportunities in the airline business (McDonald, 2002). It was estimated in 1995 that the aviation supply chain held US\$45 billion in inventory, nearly 80% of which was owned by the operators (Flint, 1995). Despite a lot of serious talk about reducing inventory levels, the figure was estimated to be over US\$50 billion in 2002 (McDonald, 2002).

If the inventory value of the aviation supply chain is considered per aircraft in operation, the dollar amount has actually dropped from about US\$3.75 million per aircraft in 1995 to about US\$3.35 million per aircraft in 2002. This is because the global airline fleet has increased from about 12,000 to about 15,000 aircraft during that period. New aircraft taken into operation lately represent new technology which means considerably lower need for spare parts than industry average. On the other hand the new technology parts are more expensive than their low technology predecessors. So it is unclear whether the spare inventory glut has actually increased or decreased.

In 2002 the expenditure in commercial aircraft maintenance was estimated to be US\$34 billion, 52% of which was accounted for by work on engines and other components (Flint, 2002). Compared to this figure the holding cost of the US\$50 billion worth of spares inventories seems quite remarkable. Of the total

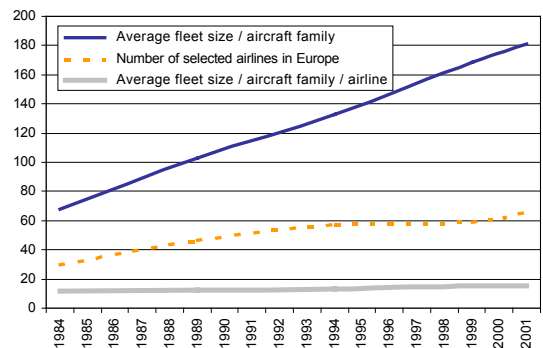


Fig. 2. Trends in the fleet composition of selected European airlines. The airline selection behind the trends has been made as follows. First of all, it only includes aircraft designed and manufactured outside the former Soviet Union area. It excludes all the so called regional jets, i.e. jet aircraft that are mainly designed for thin and reasonably short routes. Thirdly, it only includes European commercial airlines which at some point during the 17 year period operated at least 10 aircraft fulfilling the criteria above. The empirical data behind the trends is based on the World Airline Reports published every year by the Air Transport World magazine. The report is published every summer, and reports from the following issues have been used here: May 1985, June 1990, June 1995, July 2000, July 2002.

operating costs of an airline, maintenance costs typically represent some 10–15% (Seristö, 1995).

Fig. 2 shows some trends in the fleet composition of selected European airlines from the year 1984 to 2001. More new jet aircraft were taken into use during that period than ever before, as the total fleet increased from under 1100 to over 2700 aircraft. The average total fleet of an aircraft family increased even more rapidly than the number of aircraft in use. As the number of airlines has more than doubled during the period, the average fleet of an aircraft family per airline has increased relatively slowly.

The setting in the industry is such that the real potential of utilizing economies of scale to reduce costs is beyond the reach of most individual airlines. Continuously growing total fleets of different aircraft families ensure that the cost reduction potential keeps increasing. A cooperative arrangement between two or more airlines operating common aircraft family is one way of utilizing the potential.

The idea of cooperative pooling is in no way new to the air transport industry. In the 1960s there was a lot of fleet commonality between European airlines, which provided a foundation for two maintenance consortiums called KSSU and Atlas (Lombardo, 2000). KSSU was a joint effort of KLM, SAS, Swissair and UTA while the airlines behind Atlas were Air France, Alitalia, Iberia and Lufthansa. Lufthansa and Air Canada are also planning to extend their cooperation regarding the component maintenance of the CRJ aircraft to the

pooling of spare component inventories (Flint, 2000). It is significant that these cooperative efforts have this far been isolated exceptions to the general rule of each airline maintaining its own inventories.

1.2. Decreasing spare component inventories

Aircraft components are complex high level modules consisting of dozens or hundreds of parts. The life span of a component may exceed two decades, during which it is probably repaired or overhauled more than a dozen times. These issues, accompanied by the usual aviation specialties like authority requirements for certification and traceability, as well as reliability and safety issues increase the cost of obtaining and keeping aircraft components. Since the majority of the inventory value in aviation supply chain is tied up in spare components, they represent the primary target for inventory value reduction.

There are four factors affecting the cost of providing availability service: reliability of the component, turnaround time (TAT) of the component repair process, required service level of the spares supply, and the number of units supported by the spares.

Improved component designs with higher reliability have been introduced to extend the time between failures. This goal has been shared by the numerous studies in the area of preventive maintenance. Decreasing turnaround times of the repair processes has been addressed in several studies especially as a method of lowering the value of spare part inventories (e.g. Cobb, 1995). Higher service levels lead to fewer stock out occasions at the cost of higher inventory levels. In spare parts optimization the service levels are set, commonly by utilizing information systems, so as to balance the cost of stock outs against the inventory costs. Two examples of commercial spare parts optimization software are OPUS10 and Xelus (Alfredsson and Eriksson, 1998; McDonald, 2002). Proprietary systems developed by airlines include CMAM by Scandinavian Airlines (Reed, 1989) and CIMLINK by Delta Airlines (Henderson, 2000).

The economies of scale associated with the number of units supported can be seen in Fig. 1, since this factor depends directly on the number of aircraft in the fleet. Possible ways to affect the number of units supported include standardizing the fleet composition, subcontracting the availability service and inventory pooling. The connection between an airline's fleet composition and maintenance related costs has been pointed out by Seristö (1995) and Seristö and Vepsäläinen (1997). The effective number of units supported can be increased by subcontracting the availability service to an organization that already enjoys economies of scale or, by offering the availability service to other organizations. Possible subcontracting partners include Original

Equipment Manufacturers (OEMs), independent service providers as well as those airline maintenance organizations (e.g. Hill, 2002; Reed, 1992) that offer component availability as an auxiliary service of their maintenance services. Some caution is advisable regarding outsourcing from OEMs even if they control the highest economies of scale in the industry. Keeping a significant share of the business on the airline side prevents OEMs from gaining a market position too close to a monopoly. Active presence in the maintenance business also helps airlines to dampen the effects of fluctuations in passenger demand, as it is inherently less cyclical and more profitable than the core airline business.

In the basic case of inventory pooling all the inventory locations belong to a single organization, for example, a company or military force. In this case the pooling can be considered successful if the total benefit is positive. In cooperative pooling the inventory locations belong to several different organizations. An arrangement like this is successful only if every participant benefits from it. Additionally, the benefits should be reasonably evenly distributed between the participants, if the cooperation is going to last. Even if these conditions are fulfilled, managing a pooling arrangement can still be challenging, as is the case with any inter-firm cooperation.

Concerning aircraft component availability a mutually beneficial arrangement would distribute the provision of the availability service evenly between the partners, instead of one airline selling the availability service of all the components to the other cooperating airlines. As regards one component the arrangement would be unbalanced, but regarding all the components under the cooperative effort, there would be a balance.

2. Modeling availability

The purpose of this study is to show the possibilities of lowering the number of spare components through inventory pooling. A rather standard statistical model of component availability is used and the results are verified by computer simulations. The focus is on the spare units needed to cover unscheduled removals assuming that all the components follow the principle of 'fly until fail'. Inventory needs for any scheduled removals can be handled independently.

2.1. Basic model of component availability

The basic model illustrates the relations between the four factors of availability (reliability, turnaround time, service level and the number of units supported) and the number of spare units needed.

In the aviation industry the most widely used measure of reliability is the mean time between unscheduled removals (MTBUR). If it is known only as a meter

value, the average utilization of the component also needs to be known for converting the MTBUR into calendar time. Repair TAT is measured as the elapsed time between the event when a failed component is removed from an aircraft and the moment when it is stored after the repair and ready to be used as a spare unit. The required service level of the spares supply is measured as the share of the number of times the request is fulfilled on a certain component when this very component is requested from the supply. The number of units supported is measured as the total number of the components in question that are installed in all the aircraft in the airline's own fleet as well as in other fleets supported by the inventory.

According to Palm's theorem the stationary distribution for the number of units in the pipeline is a Poisson process with an assumption that the interval between the arrival of units in the pipeline is negative exponentially distributed (Palm, 1938). The theorem has been acknowledged widely in the area of queuing theory (e.g. Baccelli and Brémaud, 1987). For example, Takács (1962) and Jardine (1973) have applied Palm's general idea in studies of maintenance and system reliability. Alfredsson (1997) has clearly stated that the theorem is suitable to be applied when studying aircraft components. Airbus Industries (2002) apply the same theorem for average demands up to 10 but suggest Gauss distribution to be used instead of Poisson when demand exceeds that value. Using Gauss distribution would not change the results significantly as far as the service levels are higher than 75%.

For the component failure process to be a Poisson process it is assumed that the failure process is independent of the number of spare units available. This assumption is typically violated if there are shortages in the system, since shortages momentarily reduce the number of operational units thus decreasing the demand of spare units. Nevertheless, this assumption is commonly acknowledged when the expected number of shortages is small compared to the number of units in the spares supply (Graves, 1985).

Using Poisson distribution it is possible to calculate the probability for a certain number of unscheduled removals occurring during a certain time period (Alfredsson, 1997). If the time period is set equal to Repair TAT, the formula is as follows:

$$p(k) = \frac{D^k e^{-D}}{k!}, \quad (1)$$

where D equals the expected demand of spare units during TAT, k equals the number of unscheduled removals during TAT, e equals the base for the natural logarithms and $p(k)$ equals the probability of exactly k unscheduled removals to happen during TAT.

As $p(k)$ is the probability of exactly k unscheduled removals happening during the repair TAT, it is by

definition also the probability of exactly k units to be in repair at any given moment. It can also be seen that $p(k)$ equals the probability of exactly $u-k$ spare units being left in the spares supply at any given moment, where u stands for the total number of spare units and $u \geq k$.

The demand is caused by the unscheduled removals that occur during the repair TAT. So the expected demand D also means the expected number of unscheduled removals during the repair TAT. It can be calculated as follows:

$$D = \frac{\text{TAT}}{\text{MTBUR}_{\text{ct}}} \text{QTYU}, \quad (2)$$

where TAT equals repair TAT of the component, MTBUR_{ct} equals the MTBUR of the component in calendar time, QTYU equals the number of units supported by the spares and D equals the expected demand of spare units during TAT.

At this point it is necessary to introduce two new concepts. They are the expected risk of shortage and the expected confidence of no shortage. The expected risk of shortage $r(u)$ concerning a spares supply with u units, gives the share of the number of times a shortage is expected on a certain component when this very component is requested from the supply. It is assumed that the service discipline (Walrand, 1988; Baccelli and Brémaud, 1987) of the shortage queuing system is plain FIFO. This means that, in case of a shortage, every unit coming from repair is delivered to fulfill the shortage that occurred first, i.e. the one that has been waiting for the longest time. Some references use the term priority rules instead of service discipline (Jardine, 1973).

The expected confidence of no shortage or just expected confidence $c(u)$ concerning a spares supply with u units, is the inversion of the expected risk of shortage $r(u)$. Since both $c(u)$ and $r(u)$ are relative measures, this means that $c(u) + r(u)$ equals 1. The measures $c(u)$ and $r(u)$ are usually expressed as percentages.

It can be seen that the expected confidence of a spares supply with k units $c(u)$ equals the probability of less than u units being in repair at any given moment. Similarly the expected risk of shortage $r(u)$ equals the probability of exactly u or more units being in repair at any given moment. The corresponding formulas for values of $u > 0$ are as follows:

$$c(u) = \sum_{n=0}^{u-1} p(n), \quad (3)$$

$$r(u) = \sum_{n=u}^{\infty} p(n) = 1 - c(u), \quad (4)$$

where u equals the number of units in spares supply, $p(k)$ equals the probability of exactly k units to be in repair at any given moment, $c(u)$ equals the expected confidence of no shortage with u units in spares supply and $r(u)$

Table 1
Results of a basic availability example

k/u	Probability $p(k)$	Expected confidence $c(u)$ (%)	Expected risk of shortage $r(u)$ (%)
0	0.681430	0.00	100.00
1	0.261370	68.14	31.86
2	0.050126	94.28	5.72
3	0.006409	99.29	0.71
4	0.000615	99.93	0.07
5	0.000047	99.99	0.01
6	0.000003	100.00	0.00

equals the expected risk of shortage with u units in spares supply.

With zero units in spares supply, the expected confidence of no shortage $c(0)$ equals zero, since there cannot be any fulfilled requests with no spares. Consequently, the expected risk of shortage $r(0)$ equals one.

An example illustrates the application of the formulas above. If the repair TAT of a component is 14 days, its MTBUR is 730 days and the number of units supported is 20, the average demand of 0.38356 can be calculated for it using (2). Using Eqs. (1), (3) and (4) it is possible to calculate the expected confidences and risks of shortage for this demand with different number of spare units. The results can be seen in Table 1.

When describing the formulas, it was assumed that the service discipline of the shortage queuing system is FIFO. If this assumption is held, the service level of the spares supply $s(u)$ equals the expected confidence $c(u)$. With this observation the formulas described above form a basic model, using which it is possible to explore the effects of the four initial factors on the number of spare units needed.

2.2. The impact of the factors on inventory levels

The basic model is first used to produce graphs picturing the relative effect of each factor on the number of spare units needed. A suitable relative measure for comparing the factors is the number of spare units needed per each unit supported by the spares supply. The following figures present this measure as a function of each of the four factors. In each figure two factors remain constant and one factor is given three different values, while the factor under examination is given a selection of values.

Fig. 3 shows that it is possible to decrease the need of spares by increasing the reliability of the component. As the reliability of an aircraft component is heavily dependent on the quality of its design and manufacturing, an advisable situation for an airline to affect this factor is an initial provisioning process of a new aircraft type or another occasion, including selection of new

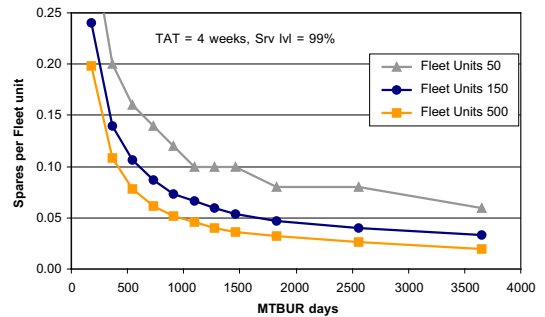


Fig. 3. Spares per fleet unit as a function of MTBUR days.

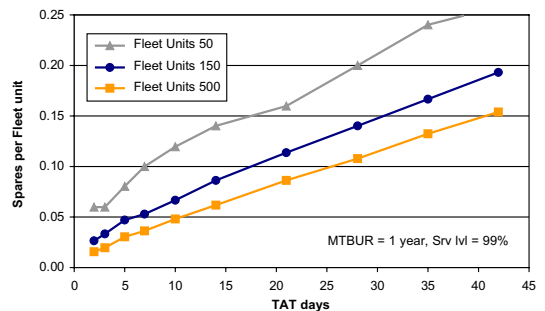


Fig. 4. Spares per fleet unit as a function of the repair TAT days.

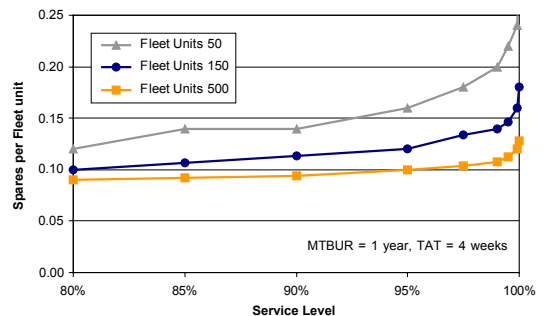


Fig. 5. Spares per fleet unit as a function of the service level.

components. Concerning components already in use, there are maintenance related means to increase the reliability, like applying optimal inspection, overhaul and replacement intervals (Jardine, 1973).

In Fig. 4 it is clearly visible that the relative spare need is directly proportional to the repair TAT as the curves are upward sloping and more or less linear. Thus it is possible to decrease the relative need of spares by squeezing the repair TAT.

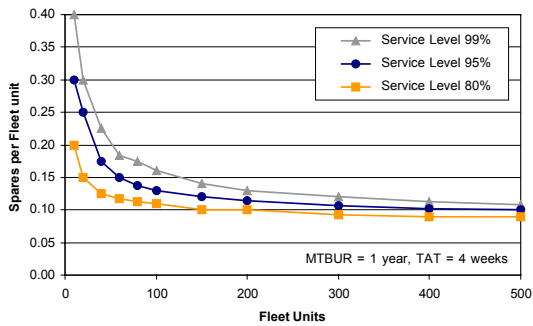


Fig. 6. Spares per fleet unit as a function of the number of fleet units.

Fig. 5 shows that it is possible to decrease the relative need of spares by decreasing the required service level. As can be seen in the curve, there is a considerable increase in the need of spares above the service level of 95%. The closer the service level gets to 100%, the more extra spares are needed per each fraction of a percentage unit.

In Fig. 6 it is clearly visible that increasing the fleet size decreases the relative need of spares. As can be seen from the steepness of this curve compared to the others, this factor has a very strong effect on the spare need. It is the number of fleet units in particular which can be affected by the make–buy–sell decisions of the component availability.

3. Fictional example of airline cooperation

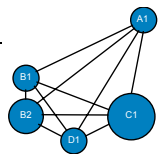
To illustrate the effects of cooperation in component availability, it is necessary to present a fictional example. In this example there are four airlines (A, B, C and D) operating the same aircraft type from five different bases in the same geographical area. These airlines have decided to cooperate in providing availability of one commonly used aircraft component Z. Their plan is to pool their spare component inventories in effort of reducing the total number of spare units needed and effectively lowering the capital tied into owning them.

Airline B operates the aircraft type from two different bases (B1, B2). Each of the other three airlines operates from a single base (A1, C1, D1). The component Z in the example has been chosen so that there are four identical units of Z installed in each aircraft. The fleets of each airline are shown in Table 2. Beside the table there is a figure showing the fleet sizes and geographical locations of each base.

The component manufacturer provides the mean time between unscheduled removal (MTBUR) of 6570 flight hours for component Z. It is assumed in this example that the four airlines all have an equal level of aircraft

Table 2
The fleets and geographical setting of the example

Airline	Base	Fleet aircraft	Fleet units
A	A1	20	80
B	B1	45	180
	B2	15	60
C	C1	60	240
D	D1	25	100



utilization and fly their aircraft on the average nine flight hours each calendar day. This produces an effective MTBUR of two years or 730 calendar days for component Z.

Even if in theory there is an equal chance per each flight hour and landing for a component to fail, most of the component removals are actually performed in the airline’s own base. This is because most of the component failures do not compromise flight safety or require immediate actions. The costs of replacing a component in a foreign location are also very high in form of expenses associated with return flight delay as well as transportation of service personnel and required parts. In this example it is assumed that all the component removals are performed in each airline’s own base.

In this example the repair TAT for component Z is assumed to be three weeks or 21 calendar days regarding each of the four airlines. Although it is not significant here where or by whom the repair work is performed, it is necessary to notice that after repair the component always returns to the same base where it was removed after failure.

3.1. Modeling an inventory pool

Different inventory models for repairable items have been introduced by a number of authors. Among those models Lee (1987) and Dada (1992) consider the idea of inventory pooling. With certain restrictions these models can be used to approximate transactions and stocking levels in inventory systems that include pooling. Here the basic model of component availability is applied to illustrate how cooperating airlines can pool their spare component inventories. The initial situation before pooling is that each airline holds its own inventory in its base. The basic model can be used to calculate how many spares each base needs to maintain acceptable service level.

In a pooling arrangement the combined inventory of all the participants can be treated like one spares supply even if it is located in five different bases. This observation was also made by Lee (1987). The basic model can now be used to calculate how many units the cooperating airlines together need to maintain the same

acceptable service level as before. This total number of spares they may distribute between the bases as they please.

Since the bases of the cooperating airlines in this example are located apart from each other, the pooled inventory cannot serve them as quickly and effortlessly as an unpooled inventory could. If the spare unit request cannot be fulfilled from local inventory, an emergency transshipment from another base is performed. The whole idea of pooling separate inventories depends on emergency transshipments, because they offer means for one base to exploit an inventory that is located in another base. For the basic model of component availability to work, it is assumed that every emergency transshipment is sooner or later returned. This means that when the receiving base of the emergency transshipment later on regains units in its inventory, it sends one unit back to the sender of the emergency transshipment.

Even if all reasonable means are used to hasten emergency transshipments, they are always slower than deliveries from the local inventory. This means that the airlines have to accept logistics delays regarding the spares deliveries from other bases than their own. The maximum logistics delays of the emergency transshipments between the bases are shown in Fig. 7. The delays in the figure are fictional but could easily represent a typical European setting.

The logistics delays between two different bases range from 5 to 12 h. In addition to the actual flight time and

waiting for the flight to depart, the delay consists of locating the unit, packing, loading, unloading and finally receiving and unpacking it. A1 and D1 form the only pair of bases with the longest delay of twelve hours. One-hour delay is assumed in the most common case when the request for spare unit can be fulfilled in the base where it was made.

Component Z is assumed to have an important role in the aircraft dispatch reliability, so its service level requirement is relatively high. It is assumed that all the airlines in the cooperation agree on the service level requirement of component Z being at least 99% without pooling. In the pooling arrangement the service level requirement is set so that it should be at least 99% regarding the combined inventory. It is also important not to totally compromise the internal service level in any of the bases. Because of that the service levels provided by the local inventory in each base should exceed 75%.

3.2. Results of the example

In Table 3 there are the spare units and service levels of the separate bases in an initial situation, when there is no cooperation between the airlines. 12-hour service level in the right hand column means the service level that is achieved with a maximum of 12-hour logistics delay. As can be seen in the table, inventory pooling is already used by airline B between its own two bases.

Regarding airlines A, C and D, the basic model of component availability is applied to their fleets separately. As a result the number of spare units that offers a service level of at least 99% is found. For airline B the model is first applied to the combined fleet of bases B1 and B2 in effort of determining the total number of spares offering the acceptable 12-hour service level. The spares of airline B are then divided between the two bases by applying the model to the separate fleets and finding as equal service levels as possible.

Considering the airline cooperation setting, the model is first applied to the combined fleet in effort of determining the total number of spares offering the acceptable 12-hour service level. The total number of spares is then divided between the five bases by applying

		Destination				
		A1	B1	B2	C1	D1
Origin	A1	1	11	10	9	12
	B1	11	1	5	7	8
	B2	10	5	1	6	6
	C1	9	7	6	1	6
	D1	12	8	6	6	1

Fig. 7. Maximum logistics delays between bases (in hours).

Table 3
Spare units and service levels without cooperation

Airline	Base	Fleet units	Spare units	Service level 1 h (%)	Service level 12 h (%)
A	A1	80	7	99.06	99.06
B	B1	180	10	96.12	99.49
	B2	60	5	96.87	99.49
C	C1	240	15	99.49	99.49
D	D1	100	8	99.05	99.05
		660	45	98.12	99.32

Table 4
Spare units and service levels with cooperation

Airline	Base	Fleet units	Spare units	Service level 1 h (%)	Service level 12 h (%)	Spares down (%)
A	A1	80	4	79.91	99.31	43
	B1	180	8	84.74	99.31	20
B	B2	60	4	90.29	99.31	
	C1	240	10	84.01	99.31	33
D	D1	100	5	83.55	99.31	38
		660	31	84.50	99.31	31

the model to the separate fleets and finding as equal service levels as possible. This is done keeping in mind that the service levels provided by the local inventory in each base should exceed 75%. In Table 4 there are the spare units and service levels of the separate bases in a cooperative situation.

As can be seen by comparing Tables 3 and 4, the total number of spares needed has decreased by over 30% by sacrificing 10–20 percentage units of one-hour service level. Every participant has gained in inventory carrying costs, small ones relatively more than large ones. If the one-hour service levels in the bases seem arbitrary, it is because each base can only accommodate whole spare units and adding or subtracting one unit significantly changes the service level. In an optimal situation, however, the one-hour service levels are equal among the bases. If the cooperation is expanded to concern a large number of components, the deviations between one-hour service levels of different components balance each other.

Even if the one-hour service levels are considerably lower in the cooperative setting, it very seldom takes full 12 h to satisfy a spare need. Actually only bases A1 and D1 may experience delays that long. It is easy to see that a centrally located base generally experiences shorter logistics delays than a remote base.

One-hour service levels are achieved by using local inventories. Emergency transshipments are performed to achieve 12-hour service levels. There are a number of possible sourcing rules to be used when selecting the supplying base of an emergency transshipment. Some usable sourcing rules are presented in the following list:

- Select randomly between the bases with sufficient inventory;
- Select the base with shortest logistics delay and sufficient inventory;
- Select the base with relatively highest available inventory; and
- Select the base with sufficient inventory according to preset priorities.

The sourcing rules can also be combined so that one is selected as a primary rule and another as a secondary rule to be used if the primary one results in a tie.

The random selection is probably the least biased one towards any of the cooperating airlines in the long run, since no base will be preferred at any time. The second alternative minimizes the logistics delay, but clearly favors remote bases. The third alternative minimizes the harm that could be caused for the availability in the supplying base. Regarding this alternative it is for obvious reasons important to use relative inventory measures instead of absolute ones. The sourcing rules could also be set so that they favor one or other base in a premeditated way. As airlines with relatively large fleets gain less from the cooperation than their smaller partners, it is possible to compensate them by making the sourcing rules more favorable for them. It seems that the models of Lee (1987) and Dada (1992) would be suitable for determining the effects of different sourcing rules.

After applying the model to various different cooperation settings certain conclusions can be drawn. It can be seen that the savings potential of the cooperation is directly proportional to the number of its participants, assuming that the participants' fleets are reasonably similar in size. On the contrary, the one-hour service levels are inversely proportional to the number of the participants in the cooperation. It is possible to see that there is a saturation point in the number of cooperation participants when the one-hour service levels approach the 75% limit.

The cost level achieved by the participants is determined quite intuitively by the total fleet size of the cooperation. It also seems that, the smaller the airline's fleet is in comparison to the total fleet size of the cooperation, the higher is the savings potential for that particular airline. On the other hand, the more similar the sizes of the cooperating airlines are, the higher is the savings potential of the total cooperative effort. Even two airlines with fleets of equal size can realize considerable savings by cooperating with each other.

3.3. Managerial implications of inventory pooling

In practice a cooperative effort like the one illustrated in this example requires certain prerequisites to be fulfilled. The most important one is a common forum, some event or working group that makes it possible to

start planning cooperation. In today's environment in the aviation industry the alliances are gathering airlines around the same table. Between alliance partners it is easier to initiate a cooperative effort like this than it would be between separate airlines possibly competing against each other in various business areas.

Doz and Hamel (1998) have stated that the playing field in alliances is generally very unstable and turbulent. Today's partner may be tomorrow's rival. In another study they have emphasized that successful companies should never forget that their partners' aim may be to disarm them (Hamel et al., 1989). This uncertainty leads into avoiding such cooperative arrangements that could be damaging if the relationship abruptly changes. Kleymann and Seristö (2001) have concluded that one challenge in an alliance relationship is to learn to balance the cooperative benefits and the loss in flexibility and sovereignty. Gulati (1995) has stated that mutual trust between partners counteracts fear of opportunistic behavior, thus reducing the transaction costs associated with the relationship. These challenges of cooperation need to be addressed before entering into inventory pooling arrangement.

A major obstacle between isolated spare inventories and cooperative setting is that airlines with relatively large fleets have less incentive to participate in cooperation than airlines with smaller fleets. In absolute terms all the players achieve the same cost level but smaller participants descend from much higher level. This contradiction leads to cooperation between reasonably equally sized participants or, in the case of unequal sizes, to some method of compensation from relatively small partners to their larger counterparts. Future research needs to examine how the differences in participants' incentives affect the composition of the cooperative arrangements.

Airlines have a long history of customizing their aircraft (Feldman, 2000), thus providing the industry with a huge variety of differently configured planes all looking the same from the outside and almost the same from the inside. There has been an ongoing argument among the airlines and aircraft manufacturers about the standardization and its potential benefits, but so far not much has changed. This means that it is a major challenge for airlines to find common components to cooperate with, even if they are operating the same aircraft type. In the long run the cooperating airlines could give in to some level of standardization when configuring new aircraft or planning modifications to the existing fleets.

Historically airlines are quite suspicious about each other's maintenance philosophies and the quality of their maintenance work. Before starting to cooperate, the airlines should agree on common standards concerning all maintenance related issues of the components in question.

To provide reliable and stable delivery times between every base in the cooperation, a streamlined logistics system is needed. A commonly accessible IT system is required for providing transparent real-time information about the stock levels in the bases. If the airlines actually cooperated in providing availability for only one component, the cost of logistics and IT systems could be prohibitive. It is, however, assumed here that real life cooperation would concern such a large number of components that the cost of maintaining logistics and IT systems would be negligible in comparison to the inventory savings.

The bases of the cooperating airlines are tightly connected with their own flights, which can normally transport one or two components at very short notice and with not much extra cost. For the logistics system to work it needs procedures for issuing and receiving spare components efficiently. Like many other industries, the aviation industry is also building electronic marketplaces such as Cordiem and Aeroexchange in the internet (Mecham, 2002a, b). These marketplaces are beginning to offer services like inventory listing with near-on-line updating and partner specific viewing rights, which would be quite adequate for supporting inventory pooling.

4. Concluding remarks

Based on the scale economies in the component availability service, a conclusion can be made that even relatively large airlines should stay away from the pure make alternative in the make–buy–sell decision. Preferred options include subcontracting (buy), service providing (sell) and inventory pooling (buy and sell combined).

It has long been known that inventory pooling between airlines in the area of spare components would be a source of definite savings. It has been shown here that in a perfectly feasible pooling arrangement the inventory levels can be decreased by over 30% by making a minor sacrifice in short time service levels. Furthermore, proactive replenishments and new repair priorities can compensate for this sacrifice. Transshipments from bases with available inventory could replenish the stock before it reaches zero, thus reducing the need for emergency transshipments. Service disciplines other than FIFO, that has been reported here, can be used not only to improve service levels but also to reduce costs with the same number of spare components.

The combination of the undeniable awareness of the beneficial effects of cooperation and reluctance of exploiting its potential is a situation with long history but reasonably short foreseeable future. In today's highly cost sensitive and competitive business

environment it should not take too long for airlines to start overcoming the obstacles and adding the pooling of spare components into their widening selection of cost reduction methods.

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PAPER IV

Cooperative Strategies for the Availability Service of Repairable Aircraft Components

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Cooperative Strategies for the Availability Service of Repairable Aircraft Components

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Abstract

This paper specifies cooperative strategies for the availability service of repairable aircraft components and finds out which factors contribute to the emergence of a particular cooperative strategy. The strategies ad hoc cooperation, cooperative pooling and commercial pooling were specified and compared to the alternative of acting alone, i.e. solo strategy. A spreadsheet model based on fair assumptions of the cost structure was constructed and the cooperative strategies were tested both from the viewpoint of total efficiency and from the perspective of each participant. Despite the explicit focus on aircraft components, the findings should be relevant to any industry using a closed-loop maintenance process with repairable spare parts.

Keywords:

Inventory pooling; Repairable spare parts; Aircraft maintenance

1. Introduction

This paper specifies cooperative strategies for the availability service of repairable aircraft components and finds out which factors contribute to the emergence of a particular cooperative strategy. We extend the model of the pooling benefits with repairable aircraft components by Kilpi and Vepsäläinen (2004) and apply the extended model to an analysis of the specified ad hoc cooperation, cooperative pooling and commercial pooling strategies used to realize the pooling benefits. The strategies are also compared to acting alone, which is called solo strategy. The total benefit of all participants and the individual benefit of each participant are accounted for.

The analysis and results of this study were motivated by the airline industry where the scale economies are strong in the maintenance, repair, and overhaul (MRO) services. The intuitive way of accumulating the demand for spare units would be to pool the inventories together and use the pool to satisfy the demand from several aircraft fleets operated by different airlines. Nevertheless, this pooling does not seem to take place in the real world to such a high degree as could be expected. Neither have the alternative cooperative strategies and the factors that contribute to their emergence been extensively elaborated in research. We believe that the conclusions can be generalized to other industries in which the equipment utilization requires a stock of repairable and replaceable spare components. When repairable spare components are used in a closed-loop material flow, the environmental load of the maintenance process is generally also lower than with disposable spare components discarded after use. As environmental awareness increases, some industries currently relying on consumable spare components might well adopt the usage of repairable components. Östlin et al. (2008) discuss the closed-loop relationships within a broader scope of remanufacturing while Chung and Wee (2008) focus on a semi-closed supply chain and green product design.

The availability service of repairable aircraft components secures aircraft utilization by providing a supply of functional spare units to back up the critical functions of the aircraft. These easily replaceable modules of the aircraft are called Line Replaceable Units (LRUs) or aircraft components. At any given time at any location within the flight network, any one of the ca. 1 000 components may fail. The failures themselves may take weeks to fix but the failed component can usually be identified quickly. As flight

delays are expensive, it is justified to stock spare units and repair the failed units off-line. The availability service, part of the aircraft maintenance, repair, and overhaul (MRO) services, is responsible for providing a supply of those spare units as economically as possible.

There has been a trend of increasing cooperation between airlines and subcontracting MRO services during the last decades. For example, U.S. major airlines outsourced USD 241 million worth of MRO services in 1985 and USD 2.4 billion in 1999 (Canaday, 2000, p. 28). The worldwide MRO market of commercial jet aircraft, excluding the spare part inventories, was USD 38.3 billion in 2005, of which 49 % was in-house expenditure (Jackman, 2006). The worldwide fleet of about 17,000 commercial jets were supported by a total supply of spare parts worth USD 44 billion of which USD 26.8 billion was held by the airlines in 2006 (Harrington, 2007, p. 78). Assuming that the annual inventory holding cost is 17 % and there are no other costs in the availability service, the total market of the aircraft spare part availability was USD 7.5 billion. Thus, each commercial jet was supported by USD 2.6 million of inventory.

The issue of spare part availability without cooperative elements has been discussed in literature both specifically concerning aircraft components (e.g. Taylor and Jackson, 1954; Shaunty and Hare, 1960; Johnson and Fernandes, 1978; de Haas and Verrijdt, 1997; Mabini and Christer, 2002; Ghobbar and Friend, 2003) and generally, as the literature reviews by McCall (1965), Pierskalla and Voelker (1976), Sherif and Smith (1981) and Kennedy et al. (2002) show. Cohen and Lee (1990) in turn present pooling, in descriptive terms without modeling, as a policy of improving spare part inventory control. Wong et al. (2004) present an analytical model for determining spare parts stocking levels in case of inventory pooling motivated by an airline operator's repairable spare parts inventory problem. Carter and Monczka (1978) construct a model to study spare part pooling as a commercial service as well as pool implementation. Weng (1999) studies risk-pooling over demand uncertainty. There are also studies with advanced mathematical models but limited managerial analyses, in which pooling is achieved by emergency or priority shipments between the pool stocks and the point of need (e.g. Lee, 1987; Axsäter, 1990; Dada, 1992; Tagaras and Cohen, 1992). Supply chain coordination in general was reviewed by Arshinder et al. (2008).

This paper suggests that among the cooperative strategies commercial pooling is more efficient than ad hoc cooperation or cooperative pooling if the service provider is willing to share enough pooling benefits with the members, and the members are ready to trust a mission critical service to an outside party. Ad hoc cooperation is feasible when the airline is cautious about subcontracting the availability service and there is a cooperating airline nearby with close enough fleet composition. A cooperative pool is feasible with a limited number of members under conditions where there is no commercial service provider available or the existing service provider's pricing is unreasonably high.

Going deeper under the general level of contributing factors, the demand structure and the benefit sharing criteria stand out from the other factors. For a cooperative pool the paper suggests benefit sharing criteria that drive the demand structure towards a dynamic equilibrium.

This paper is structured so that the concept of availability service regarding repairable aircraft components is discussed in section 2, and section 3 continues by presenting a framework of cooperative strategies. The quantitative model used is explained in section 4 together with the conditions of applicability. The results are presented in section 5. Finally, the paper ends with discussion.

2. Availability service of Aircraft Components

2.1 Components in Aircraft Maintenance

To maximize aircraft utilization, the most critical functions in aircraft are designed to be quickly repairable so that there is a collection of compact functional components that can easily be replaced between flights if necessary. Every time a failed component is removed from an aircraft, a similar functional component has to be installed in the aircraft. Thus, the component failure causes the demand of a spare unit in the spares supply. The airline operators try to maximize aircraft utilization by stocking spare units to be installed whenever needed. Loan arrangements are commonly used if there is a need for a spare unit but none left in the spares supply.

After being removed from an aircraft the failed component is sent to a workshop. Depending on the reason of its removal, a number of maintenance, repair or overhaul

operations are performed on it. When it is fully functional, it is certified and sent back to the spares supply. With the certification the component becomes airworthy, i.e. it can be installed in an aircraft. Spare units are identical in function to units installed in the aircraft but have an insurance-like role compared to the revenue generating role of the installed units. In time, installed units fail and the roles change and, if the rotation is working well, all the units take turns in being in revenue generating role and being a spare.

2.2 Availability Service

The implementation of component availability services is affected by the airline operator's flight network's complexity and its fleet composition. There are two general types of carriers: hub-and-spoke and origin-and-destination. Hub-and-spoke carriers connect a large number of destinations to each other by offering transfer services through the hub. Since these carriers command a limited number of hubs that also act as aircraft bases, the operative volume per base is relatively high. On the contrary, origin-and-destination carriers connect a limited number of destinations to each other by offering non-stop services between them; i.e. there are numerous bases, each of them with relatively low operative volume.

From the viewpoint of availability service, the most important factors in the network complexity are the number of aircraft bases and the distribution of the operational volume between them. The number of destinations in the network is less significant, as the majority of component support needs materialize in the bases.

Although the aircraft manufacturers are consolidating and there are fewer competitors than before, the variety of aircraft types available has been constantly increasing and also utilized by the airlines (Kilpi, 2007, p. 83). Because most of the components are suitable for one fleet or family of aircraft, every aircraft family practically requires its own supply of spare components.

In addition to the economies of scale and the required official authority certificate, there are few barriers of entry into the component availability service market, whose main function is to bring together business volume. Since business volume means the demand for spare units, the intuitive way of accumulating it is to pool inventories together and

use the pool to satisfy the demand from several aircraft fleets. There are two types of these pools: *commercial pools* and *cooperative pools*.

In *commercial pooling* there is one service provider and several customers that buy availability services from the service provider. In *cooperative pooling* there are several equal members that share their spare units between each other according to a mutual agreement, whose scope can vary from an ad hoc cooperation with loose loan arrangements to relatively tight cooperation. Thus, in a cooperative pool, every member has connections to all other members in that pool, and in a commercial pool every member has a connection only to the service provider and the service provider has a connection to all the members. In a cooperative pool with n members, there are $n*(n-1)$ connections in total, while in a commercial pool of n members, there are $2*n$ connections respectively.

An average airline operator sources all the maintenance of its fleet from its own MRO department that subcontracts parts of it to external service providers. It is common to include the availability service of aircraft components within a general component support agreement.

2.3 The Cost of Availability Service

Carter and Monczka (1978, p. 28) identify three cost elements in MRO inventory pooling as follows: inventory holding, ordering, and back-order costs. In order to bring out the differences between the cooperative strategies, ordering costs need to be further divided into handling and transfer costs. Similarly, back-order costs have to be divided into loan-in and wait costs. In addition, interface costs represent the annual fixed costs of maintaining relationships between the cooperating parties.

Inventory holding cost is the prevailing item including the cost of capital and all storage costs. Regardless of the size of spare components inventory, there will be shortages that are usually solved by borrowing the required spare units from external loan provider leading to loan-in costs.

The handling costs cover the on-site per transaction costs that arise when a spare unit is needed. This includes picking and transportation costs within one base. The handling costs are the same should the unit come from the local stock or from a remote site. In

the latter case, the handling costs include identifying the unit in the goods receiving area instead of picking it from the stock.

The transfer costs incur when the unit is not stored in the customer's home base or when units need to be transferred between sites for stock balancing. These costs cover all the per transaction costs of the transfer.

In those cases when the spare unit is not available at the home base, there is a risk of flight delays. Sometimes it is possible to avoid or at least postpone the flight delay by utilizing the scheduled downtime. This arrangement involves some costs. Wait costs include both arrangement costs and flight delay costs.

The interface costs are the annual transaction costs between two parties involved in the availability service. These costs are proportional to the interface complexity between the two parties and include the annual costs of maintaining the relationship as well as the amortization of the initial negotiation costs.

3. Cooperative Strategies

There are several cooperative strategies for component availability services which airlines can practice. Figure 1 illustrates a strategy framework that accounts for the number of participants involved and the tightness of the contractual integration. The most traditional strategy is to perform the availability service in-house so that the airline provides the service only for its own fleet. This is called solo strategy.

Neighbor airlines that have some fleet commonality easily drift into a loose form of cooperation by providing a loan unit against a fee when there is an aircraft on ground needing it. If the relationship and trust between parties gets stronger, there is an opportunity of utilizing economies of scale without outright pooling. Assuming that the parties are roughly equal in demand volume and that there are efficient logistics connections between their bases, both parties could lower their home base stocks and rely on loans from the other party. This type of cooperative is called *ad hoc cooperation* as there is no contractual commitment and each party pays standard fees for the loans. Both parties gain from lowering their stocks, and assuming that they are approximately the same size their loan payments tend to nullify each other in the long run.

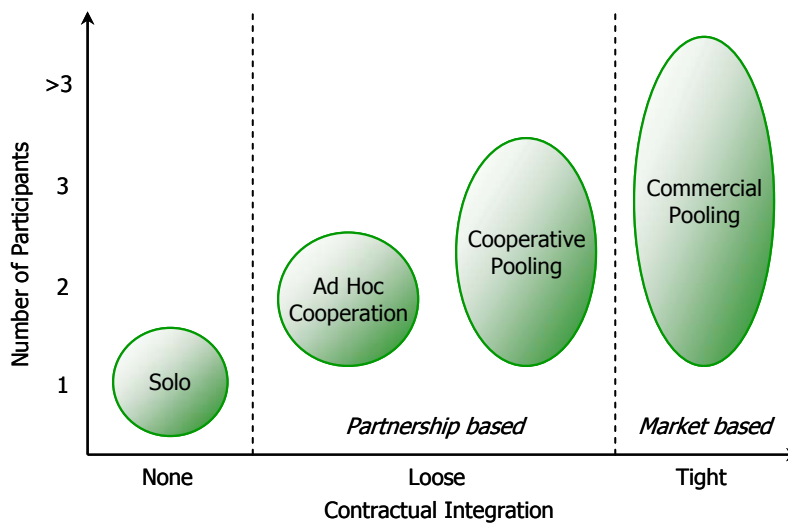


Figure 1 Framework of cooperative strategies

In cooperative pooling two or more airlines with fleet commonality formally agree upon a set of rules to share their spares inventories of certain aircraft component. Within the rules there are clauses that determine the benefit sharing principles, response times to spares needs, logistics arrangements between the parties, and inventory distribution between the affected bases, as well as the priorities in the stock-out situations. When a member replaces a failed unit with a spare unit out of the pool, it becomes responsible for delivering the failed unit back to the pool after it has been repaired.

Contrary to the partnership based strategies, commercial pooling is market based. In this strategy an airline subcontracts the availability service to a company offering the service on the market. Against a fixed annual fee the airline gets spare units from the service provider when it needs them. There is a formal agreement between the service provider and the airline which covers service fees, delivery lead times and liability in delay situations, in addition to the general clauses covered by the cooperative pool agreements.

A large airline with uniform fleet structure may by itself have the same potential for utilizing scale economies as well as enjoy some coordination and operational advantages compared to a same size pool of smaller airlines. As a result, if these airlines of different sizes are compared to each other, the solo strategy of the large airline can be regarded as efficient. However, if the business alternatives of the large airline are

compared to each other, the solo strategy does not seem efficient because, by joining the pool of its smaller peers it may further decrease its availability costs and achieve a higher level of efficiency than with the solo strategy.

4. Research Design

4.1 Modeling Cooperative Strategies

The modeling of the cooperative strategies was performed using a simplistic but illustrative case of one large international base, like London Heathrow (LHR) or Los Angeles International (LAX), where many operators need availability service of a particular component. This setting leads to a situation where transfer and wait costs as well as interrelations between different kinds of components need not be considered. Based on these assumptions, a spreadsheet model for the availability service was created to quantify the effects of the cooperative strategies. The cooperative strategies were then analyzed in a setting that enabled the study of conflict and cooperation between decision-makers. The focus was on the total benefit of the participating airlines. Different demand combinations and alternative benefit sharing criteria between the cooperative airlines were also tested. The total benefit of the participants was analyzed together with the individual participants' benefits to find a most efficient dynamic equilibrium.

The cooperative strategies were analyzed in a setting where there are several airlines with a support need for a particular component type, and one service provider that has set up a commercial pool to provide availability services for the same component type. Each airline has an option of acting solo, starting an ad hoc cooperation with another airline, setting up a cooperative pool with another airline or subcontracting the availability service to the service provider. Because every airline can choose to act solo and this strategy has no potential for pooling benefits, it was used as the base case relative to which the benefits of the other cooperative strategies were calculated.

The number of strategy combinations depends on the number of airlines as well as the limitations in the number of parties that could join in a certain type of cooperation. The chosen setting includes a service provider (P) and three airlines (Small, Medium and Large) together (I), all located at the same base. The distribution of the demand volume

between the airlines does not affect the model result but the ratio of 1:3:6 has been used in the calculations. The benefits u_l and u_p are calculated using the spreadsheet model for the availability service described later.

The strategy alternatives of the airlines are described as membership combinations (the complete list of the combinations is shown in Appendix I). The pricing alternatives of the service provider are $C_p = \{FB, LB, LE, HE\}$. Fair share of the Benefit (FB) and Lower share of the Benefit (LB) illustrate the cases where the service provider takes either more or less benefit than it brings to the pool. With FB the benefit of the service provider is set equal to the average benefit of the airlines in the commercial pool and with LB the service provider offers its customers 10 % extra benefit compared to the benefit of a similar cooperative pool. Because the service provider cannot necessary estimate the pool demand correctly before setting the prices, the pricing alternatives Low Estimate (LE) and High Estimate (HE) were chosen to test the result of inaccurate estimates. Thus, they are not deliberate pricing strategies but more like errors in its pricing process where service provider estimates the pool demand to be 90% (LE) or 110% (HE) of the actual demand.

The dynamics of pooling and the benefit division are explored by creating another pool setting where there are five airlines. The individual levels of demand are chosen to illustrate the benefit sharing between fleets of different sizes as well as to cover the typical spectrum of real life fleets based in a large international airport. The total demand of 740 spare units per year is distributed between the airlines as follows: ($D = 300, 200, 120, 80, 40$). The airlines are denoted respectively. Airlines 300 and 200 are in fierce competition for passengers and thus reluctant to participate in the same pool.

For simplicity, the only cooperative strategy considered in this setting is cooperative pooling. The interface costs are excluded from the calculations, as it is not necessary to compare cooperative strategies to each other. This setting is explored by calculating the pooling benefits for the applicable membership combinations using the spreadsheet model described later (the combinations are shown in Appendix II). The combination with all the airlines in the same pool is included to provide a benchmark pool with the highest benefit.

4.2 Spreadsheet model for Availability Service

The pooling benefits of the cooperative strategies are calculated using a spreadsheet model for demand and costs. The unit of the availability service is the expected annual demand of spare units of a certain component type. In commercial pooling this means that an airline purchases availability service for an expected demand of spare units per year and the service provider delivers spare units against an agreed annual charge to satisfy that demand.

The demand part of the model is derived from the model of Kilpi and Vepsäläinen (2004, pp. 141-142) that assumes Poisson demand and calculates the expected demand based on component reliability, repair turnaround time, and the number of units supported. Thus, the probability of exactly k unscheduled removals occurring during the repair turnaround time is:

$$p(k) = \frac{D^k \cdot e^{-D}}{k!} \quad (1)$$

where D equals the expected demand of spare units in the repair turnaround time and e equals the base for the natural logarithms. $p(k)$ is the probability of exactly k units to be in repair at any given moment. Calculating and cumulating $p(k)$ for a certain expected demand D and each possible k gives a demand specific service level for every possible number of spare units in the system.

This demand model was extended by including a loan-in process that secures the pool stock shortage situations from an external loan-in stock which is assumed to be infinite. In effect, this process encapsulates the availability service to provide a 100 % service level. The expected number of pool shortages $s(k)$ is effectively the same as the number of loans required per repair turnaround time:

$$s(k) = D \cdot (1 - SL(k)) \quad (2)$$

where $SL(k)$ equals the service level for k spare units in the system. The mean wait time of all spare unit issues $m(k)$ is:

$$m(k) = m(k-1) - \frac{1 - SL(k)}{D}, m(0) = TAT \quad (3)$$

The expected wait time of a shortage equals the expected loan-in time per loan $t(k)$ and is calculated as follows:

$$t(k) = m(k) \cdot \frac{TAT}{1 - SL(k)} \quad (4)$$

Using (2), (3) and (4) the expected loan-in time per loan $t(k)$ can be calculated recursively, based on the expected number of shortages $s(k)$, repair turnaround time TAT and expected demand D :

$$t(k) = t(k-1) \cdot \frac{s(k-1)}{s(k)} - \frac{TAT}{D}, t(0) = TAT \quad (5)$$

Finally, the optimal spare unit count is derived by minimizing the sum of the cost elements.

Of the cost elements, the annual inventory holding cost is assumed to be 17 % of the spare unit's market value, which represents reality within the industry. The handling costs are calculated by multiplying the number of spare unit issues by a constant dollar value. The handling costs are assumed to be the same regardless of whether the unit is issued from the airline's own stock or from the pool. If the unit is loaned, the handling costs are higher. The loan-in costs are calculated by summing up the loan fees of the expected loans over one year. The loan fees $f(d)$ are calculated according to a three stage (stage 1: days 1 to 10, stage 2: days 11 to 30 and stage 3: days after 30) pricing policy that is commonly used within the industry:

$$f(d) = CP \cdot \frac{\alpha + \sum_{n=1}^3 \beta_n d_n}{100} \quad (6)$$

where CP is the catalogue price of the component, α is the loan start-up fee, β is the loan fee for the loan stage n and d is the number of loan days during the loan stage n . The ratio between the catalogue price, market price, loan handling fee and issue handling fee has an effect on the model result. The selected ratio used in all calculations is 200:170:5:1, which represents reality within the industry.

The interface costs are calculated by multiplying the annual costs per connection by the number of connections in the pool. The connection cost is assumed to be symmetrical

between two parties; i.e. A's connection cost towards B is equal to B's connection cost towards A. Based on reasonable assumptions of the industry, the connection cost in a cooperative pool is set 150 % higher than in a commercial pool. Based on the sensitivity analysis, the results are not sensitive to the ratio between the connection cost and the pooling benefit. The annual connection cost in a commercial pool is arbitrarily set to 2 % of the gross pooling benefit.

Considering ad hoc cooperation the airline needs to specify the minimum service level that it requires to be satisfied by its own inventory. Hereafter this is called risk level. Based on sensitivity analysis, a 90 % risk level seems to maximize the benefits of ad hoc cooperation at lower demand levels, so it is used in the calculations.

To evaluate the pooling benefit of a cooperation the inventory holding, handling, and loan-in costs of each member airline are first added together and then subtracted from the total costs of the baseline strategy where all the airlines act solo. The interface costs of the pool are then subtracted from the gross benefit of that pool before dividing the net benefit between the pool members and the possible service provider. The total benefit of the membership combination is reached by adding together the benefits of each pool.

4.3 Sensitivity Analysis

Changing the demand of the individual airlines in the model does not affect the model results but only the benefit distribution between the airlines. There seems to be no effect on the model result if the connection cost changes compared to the gross benefit of pooling. However, if the connection cost in a cooperative pool decreases towards the connection cost in a commercial pool, the efficiency advantage of commercial pooling diminishes.

Changing the total demand of the model has only a minor effect on the results but random fluctuation appears with lowest levels of demand. The natural cause of this phenomenon is the discontinuous nature of the size of the spares supply. You can only have one unit or two units even if the optimal number would be 1.5 units. With low demand these borderline cases may bias the model results in a random direction. This phenomenon is especially strong with ad hoc cooperation.

The spreadsheet model was found to be sensitive to the ratio between the component prices, loan handling fees and issue handling fees. Pooling benefits are generally higher when the component prices are relatively high compared to the handling fees as the benefits come from the ownership costs, not handling costs. If the loan handling fee decreases towards the issue handling fee, the ad hoc cooperation becomes more attractive as it utilizes loans more heavily than the cooperative and commercial pooling strategies do.

The benefit of ad hoc cooperation is moderately sensitive to the risk levels chosen by the cooperating airlines. The benefit is maximized when the chosen risk levels result in a total spare unit count that equals the optimal count in a corresponding pool. The benefit distribution between the parties in ad hoc cooperation is sensitive to their respective risk levels. The airline that takes higher risk loses compared to its risk adverse partner. For the ad hoc cooperation to be beneficial, the parties should have a mutual understanding of the optimal risk level and a trust that the other party is not changing its risk level on purpose to gain more benefit.

The spreadsheet model is also sensitive to imperfections of the spares market. In optimal conditions any party may acquire or sell a number of spare units at a fixed market price, thus being able to treat the ownership cost as a fixed cost. If there is no market for the spares, their market values become arbitrary and the calculations based on those values provide unreliable results. The spares ownership cost is at least partially sunk, when decreasing the number of spares becomes an unattractive option. In practice the spare component market works reasonably well regarding aircraft types that are commonly used by the top 50 or so airlines, as the authority certification secures a certain level of quality in the second hand units.

5. Analysis of Cooperative Strategies

5.1 Cost Comparison

All cost elements except inventory holding costs differ significantly between the cooperative strategies. Inventory holding is practically the same with all except the solo strategy.

In case of ad hoc cooperation the contractual integration and the resulting interface costs are low. Thus, zero interface costs are assumed. On the contrary, the contractual arrangements in cooperative and commercial pooling lead to higher interface costs. As the degree of conflicting interests is expected to be higher between two competing airlines than between an airline and an independent service provider, and the resulting interface complexity of cooperative pooling is higher, a higher cost per connection in cooperative pooling than in commercial pooling is assumed. There are also more connections in a cooperative pool with four or more participants than in a commercial pool of the same size.

Ad hoc cooperation requires a higher number of loans to work affecting both loan-in and handling costs. If the ad hoc cooperation works at the optimal inventory level, the loan-in fees to external loan providers are the same as with the cooperative and commercial pooling strategies. As the handling fee of an inventory issue is lower than the handling fee of a loan, ad hoc cooperation has generally higher handling costs than the other strategies. The distribution of the loan-in fees between the cooperating airlines affects their individual benefits but not the total benefit.

From the perspective of a member there is also a cost related difference, since only commercial pooling offers foreseeable availability cost. This is because the benefit sharing in commercial pooling is based on service pricing while the other strategies only reveal their cost afterwards.

5.2 Economies of Scale in the Availability Service

Table 1 shows a setting where all the dominated strategies have been removed (all combinations are given in Appendix I). A strategy is strongly dominated if and only if it can never be the best response of the player regardless of his/her beliefs of the other player's strategies (Myerson, 1991, p. 57). Two non-dominated strategies for the airlines exist as follows: a cooperative pool between each other (strategy 2 in Table 1) or a commercial pool offered by the service provider (strategy 3 in Table 1).

In the notation P stands for the service provider and I designates the three airlines together. The strategy alternatives for the airlines are $C_I = \{\text{Solo, Ad hoc, Coop, Comm}\}$ signifying the four cooperative strategies compared in this study. The pricing strategies for the service provider are C_P with more detailed descriptions shown in the

table footer. Table 1 shows the relative pooling utility, i.e. benefit of I and P (u_I, u_P) respectively. The unit of the benefit is 1/1000 of the gross benefit of an ideal pool with no interface costs. The interface costs used in the calculations are 50 units per connection in a cooperative pool and 20 units per connection in a commercial pool. The same applies to Tables 3 and 4 as well.

C_I	C_I Description				C_P			
	Solo	Ad hoc	Coop	Comm	FB	LB	LE	HE
2	{ $\emptyset$ }	{ $\emptyset$ }	{S,M,L}	{ $\emptyset$ }	700,0	700,0	700,0	700,0
3	{ $\emptyset$ }	{ $\emptyset$ }	{ $\emptyset$ }	{S,M,L}	660,220	718,162	539,341	743,137

C_2 : All airlines in a Cooperative Pool
 C_3 : All airlines in a Commercial Pool
 S,M,L: Small, Medium, Large airline
 FB: Fair share of the pooling Benefit
 LB: Lower share of the pooling Benefit
 LE: Low demand Estimate
 HE: High demand Estimate

Table 1 The non-dominated strategies for cooperative and commercial pooling

The non-dominated strategies include the two alternatives where all three airlines pool their demand together. This is because the scale economies are strong in the availability service and the most effective way of building scale is to form as large a pool as possible. The ad hoc cooperation strategy is also dominated by the cooperative and commercial pooling strategies. However, independence from contractual partners and service providers is an immediate advantage of ad hoc cooperation, which is hard to measure in dollars. This might well explain why it is used by several airlines in the real world.

An illustrative example of the causality between the demand distribution and total pooling benefits is given in Table 2 (all membership combinations are shown in Appendix II). In this example, the average demand of the two pools is 370 in each case but the mean deviations are 50, 50, 30 and 10 respectively. The pooling benefit is slightly higher with higher deviation than with lower deviation. Membership combinations MC #7 and MC #8 have the same mean deviation resulting in equal pooling benefits. In general, if a particular demand is distributed between one or more pools, the total cost of all these pools is directly proportional to how equally the demand is distributed between them. Thus, the highest benefit is achieved by distributing the demand as unequally as possible, i.e. all of it in the same pool. On the contrary, dividing the demand into an increasing number of equally sized pools decreases the efficiency towards the baseline case of every airline acting solo.

MC #	Cooperative Pool 1		Cooperative Pool 2		Mean Deviation	Relative Pool Benefit
	Combination	Total Demand	Combination	Total Demand		
7	{300, 80, 40}	420	{200, 120}	320	50	13.46%
8	{300, 120}	420	{200, 80, 40}	320	50	13.46%
9	{300, 40}	340	{200, 120, 80}	400	30	13.43%
10	{300, 80}	380	{200, 120, 40}	360	10	13.42%

Table 2 Comparing the mean deviations of two pools

In Table 2 the members of Pool 1 and Pool 2 are shown in braces with the individual demand signifying each member. The total demand of each pool is also shown. The mean deviation of the total demand per membership combination is the focal issue in the table. The relative pool benefit equals the total savings created by the two pools in comparison with the membership combination in which all airlines have selected the solo strategy.

5.3 Benefit Sharing and Monopoly Threat in Commercial Pooling

By now it seems that the most efficient way of serving multiple sources of demand is to set up one joint pool. If all the demand is met by one commercial pool, the service provider might abuse its monopolistic market position. However, a company in monopoly position is vulnerable to the threat of incursions by market entrants (Baumol et al, 1982, p. 222) and a mere possibility of a challenge in a form of a cooperative pool or another commercial pool should limit the service provider's utilization of monopoly power.

A comparison of the service provider's pricing strategies is shown in Table 3, where two new pricing strategies, Monopoly Power (MP) and Perfect Market (PM), have been added to study the possible abuse of a monopolistic market position.

C _i	C _i Description				C _p			
	Solo	Ad hoc	Coop	Comm	MP	FB	LB	PM
2	{Ø}	{Ø}	{S,M,L}	{Ø}	700,0	700,0	700,0	700,0
3	{Ø}	{Ø}	{Ø}	{S,M,L}	0,880	660,220	718,162	880,0

C₂: All airlines in a Cooperative Pool

C₃: All airlines in a Commercial Pool

S,M,L: Small, Medium, Large airline

MP: Monopoly Power

FB: Fair share of the pooling Benefit

LB: Lower share of the pooling Benefit

PM: Perfect Market

Table 3 The pricing strategies of the service provider

The benefit division of a commercial pool is determined by the service provider's pricing. If the service provider sets the prices high, the benefits of the airlines are low

and vice versa. The service provider's benefits also depend on the airlines' actions, since they have an option to set up a cooperative pool of their own (strategy 2), which would decrease the service provider's benefits to zero. This strategy would lead to a benefit of 700 but the same demand in a commercial pool would create a benefit of 880 because of the lower interface costs of commercial pooling. The difference of 180 between these figures can be seen as the extra benefit of commercial pooling versus cooperative pooling.

The service provider's pricing strategy Perfect Market (PM) represents a situation, where competition has shaved off all benefits from the service provider and the airlines receive all of them. In contrast, using the Monopoly Power pricing strategy (MP) the service provider acts as if it commanded a total monopoly power and sets the prices so that there is no pooling benefit left for the airlines. Between these extreme cases, there are pricing strategies that divide the benefits more equally. The strategy Fair Benefit (FB) gives airlines less benefit than they would get themselves by setting up a cooperative pool. By using the strategy Lower Benefit (LB), the service provider gives the airlines more profit than they would get themselves but less than they would get in the perfect market situation.

The comparison shown in Table 3 resembles a prisoner's dilemma where the Nash equilibrium indicates that the airlines should always select cooperative pooling (strategy 2). However, if the setting is repeated for unknown number of forthcoming rounds, there would be a different equilibrium. If the expected number of future rounds is at least six, the service provider would benefit more from repeatedly selecting strategy LB than trying strategy MP once. Knowing this the airlines would be willing to take a one-time risk of losing the benefit of 700 and select commercial pooling (strategy 3). If the service provider cooperates the airlines would gain an additional benefit of 18 per round compared to cooperative pooling. If the service provider does not cooperate, the airlines would get zero profit from one round and change to cooperative pooling. The service provider would get zero profit from all rounds thereafter. The result of the repeated setting is valid as long as the airlines' benefit in the cooperative pool is higher than it would be in a commercial pool but increasing the airlines' benefit also increases the required number of expected future rounds.

Aside from the service provider's intentional strategies, the involuntary choices in its pricing have a significant effect on the benefit sharing. The outcomes of strategies LE and HE shown in Table 4 reveal the importance of accurate demand estimates in the service provider's pricing process.

C _i	C _i Description				C _p		
	Solo	Ad hoc	Coop	Comm	FB	LE	HE
2	{Ø}	{Ø}	{S,M,L}	{Ø}	700,0	700,0	700,0
3	{Ø}	{Ø}	{Ø}	{S,M,L}	660,220	539,341	743,137

C₂: All airlines in a Cooperative Pool
 C₃: All airlines in a Commercial Pool
 S,M,L: Small, Medium, Large airline
 FB: Fair share of the pooling Benefit
 LE: Low demand Estimate
 HE: High demand Estimate

Table 4 The effect of demand estimates

If the demand is estimated to be even slightly lower than it actually is, the service provider sets the prices too high and the service offering is not competitive. On the other hand, a few per cent too high demand estimate leads to lost profits as a result of too low prices. As inaccurate demand estimates are likely, perhaps a suitable pricing strategy would be to be optimistic and proceed with a somewhat low pricing when it is possible to attract more demand and raise the margins later on.

5.4 Benefit Sharing in Cooperative Pooling

In cooperative pooling, the members may decide upon the benefit sharing scheme among themselves. There are three typical benefit sharing criteria as shown in Table 5: according to the annual demand volume (VOL), equal relative savings from joining the pool (ERS), and according to relative incremental pool contribution (RPC). The volume based criterion seems like an intuitive way of sharing pooling benefits.

Benefit Sharing Criterion	MC #			Relative Cost				
				D300 %	D200 %	D120 %	D80 %	D40 %
VOL	2	{Ø}	{300, 200, 120, 80, 40}	100.0	100.0	100.0	100.0	100.0
	6	{300}	{200, 120, 80, 40}	130.6	97.7	98.0	98.2	98.6
ERS	2	{Ø}	{300, 200, 120, 80, 40}	100.0	100.0	100.0	100.0	100.0
	6	{300}	{200, 120, 80, 40}	126.6	99.7	99.7	99.7	99.7
RPC	2	{Ø}	{300, 200, 120, 80, 40}	100.0	100.0	100.0	100.0	100.0
	6	{300}	{200, 120, 80, 40}	117.3	104.2	104.4	104.7	105.2

VOL: According to the annual demand volume

ERS: Equal relative savings from joining the pool

RPC: According to relative incremental pool contribution

Table 5 Benefit sharing criteria in cooperative pooling

If the benefits are divided according to the annual demand (VOL), the high demand members gain slightly more benefits compared to the low demand members. The main incentive problem with this benefit sharing criterion is that it encourages each individual member to pool with as small partner as possible. If this criterion is used, there is a demarcation point after which a large new member would take more benefit out of the pool than it would bring in the pool. This incentive problem remains if the benefit sharing criterion Equal Relative Savings (ERS) is applied. The high demand members still gain slightly more benefits compared to the low demand members.

A dependency between the number of pool participants and the maximum attractive size of a new pool member can be identified in case of VOL. This demarcation point may create barriers to the pool growth as illustrated in the VOL row of Table 5 where all airlines but D300 enjoy lower costs by being in a four member pool than collaborating with D300. With further analyses it turns out that the demand level 220 is a break-even point from attractive to unattractive new member in this particular case.

The criterion that drives the pool arrangement towards a dynamic equilibrium and the most cost efficient setting is based on the relative incremental pool contribution of the member (RPC). This criterion seems to encourage the individual members towards those membership combinations that are more efficient in total. Thus, every member's individual benefit is also at the maximum when they all join in the same pool (MC #2). Interestingly, according to this criterion the benefits of a two member pool should always be divided equally.

6. Discussion

This study presents a framework of cooperative strategies (solo, ad hoc cooperation, cooperative pooling, and commercial pooling), in which the potential of each strategy to capture pooling benefits in the availability service of repairable aircraft components was analyzed against a variety of external conditions. The results suggest that the pooling benefits are generally higher with more demand for one component type served by one pool. However, there are conflicting interests that complicate the emergence of efficient pools. This might partly explain why pooling is not being used to such a high degree as could be expected on the basis of evident benefits.

The use of a closed-loop maintenance process with repairable components compared to the use of consumable spare parts is a relatively rare choice in various other industries. However, the rising environmental awareness is likely to promote the use of repairable components and the increasing complexities of a closed-loop process need to be dealt with. The models in this study were designed specifically for the closed-loop process. In addition to increased complexity, there will be reservations about the use of second-hand spare units compared to new ones and, as a result of this increased quality concern, the closed-loop process requires more trust between the trading partners. In the aviation industry, this requirement is backed up by the tight control of authority regulations and certification. Other industries need to find their own way.

In general, the analyses show that commercial pooling tends to prevail when the service provider is willing to deliver pooling benefits to the members and the members dare to subcontract this critical service. If the airline is cautious about doing that and there is a cooperative airline located nearby, ad hoc cooperation is a feasible alternative. This might at least partially explain why especially in North America ad hoc cooperation is popular although other cooperative strategies might be more efficient in terms of total benefit. All these strategies are widely used by airlines and there are even airlines using them all at the same time for different component types.

The analyses imply that commercial pooling would be more efficient than cooperative pooling in most cases. This means that, as there is an increasing supply of availability service at most of the commercial airports, cooperative pools will probably remain few and far between. Even if two airlines decide to cooperate in the component support of a common fleet, they are more likely to set up a joint venture to run a commercial pool than establish a cooperative pool (see e.g. Buyck, 2007). This arrangement has lower interface costs and includes an opportunity of attracting other airlines as external customers. However, the possibility of cooperative pooling is a potential challenge to a service provider without competitors who might consider exercising monopoly pricing.

When applying the strategy of cooperative pooling, there are multiple ways to share the pooling benefits to the members, e.g. according to the annual demand volume, equal relative savings from joining the pool, or according to relative incremental pool contribution. Interestingly, the intuitive way to share benefits on the basis of the volume

seems to favor smaller pools. At some demarcation point it makes large entrants unattractive to the current members, thus issuing an implicit limit for the pool size. This might partially explain why in the real world there is a tendency towards multiple pools where one large pool would be more efficient in terms of total benefit. Nevertheless, there are also other limitations to the pool size caused e.g. by the distance between airline bases and differences between their fleet compositions. Although the criterion of incremental pool contribution is relatively complex compared to the volume based criterion, it should result in larger and more efficient pools. This is also an interesting finding from the viewpoint of commercial pooling because it generally implies the use of the volume based criterion.

As to the future research on availability services, there are at least two areas with special potential for valuable results. One is to investigate the cooperative strategies more extensively using game theory and to build a general framework that describes them according to the theory of industrial organization. Another interesting area is to determine an optimal geographical structure for a multibase pool taking into account the transfer and wait costs.

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Appendix I: Complete set of strategy alternatives

C_I	C_I Description				C_P			
	Solo	Ad hoc	Coop	Comm	FB	LB	LE	HE
1	{S,M,L}	{ $\emptyset$ }	{ $\emptyset$ }	{ $\emptyset$ }	0,0	0,0	0,0	0,0
2	{ $\emptyset$ }	{ $\emptyset$ }	{S,M,L}	{ $\emptyset$ }	700,0	700,0	700,0	700,0
3	{ $\emptyset$ }	{ $\emptyset$ }	{ $\emptyset$ }	{S,M,L}	660,220	718,162	539,341	743,137
4	{M,L}	{ $\emptyset$ }	{ $\emptyset$ }	{S}	-20,-20	-20,-20	-20,-20	-20,-20
5	{S,L}	{ $\emptyset$ }	{ $\emptyset$ }	{M}	-20,-20	-20,-20	-20,-20	-20,-20
6	{S,M}	{ $\emptyset$ }	{ $\emptyset$ }	{L}	-20,-20	-20,-20	-20,-20	-20,-20
7	{L}	{ $\emptyset$ }	{ $\emptyset$ }	{S,M}	190,95	285,0	95,190	247,38
8	{M}	{ $\emptyset$ }	{ $\emptyset$ }	{S,L}	223,112	335,0	124,211	278,57
9	{S}	{ $\emptyset$ }	{ $\emptyset$ }	{M,L}	323,162	485,0	235,250	414,71
10	{L}	{ $\emptyset$ }	{S,M}	{ $\emptyset$ }	265,0	265,0	265,0	265,0
11	{M}	{ $\emptyset$ }	{S,L}	{ $\emptyset$ }	315,0	315,0	315,0	315,0
12	{S}	{ $\emptyset$ }	{M,L}	{ $\emptyset$ }	465,0	465,0	465,0	465,0
13	{ $\emptyset$ }	{ $\emptyset$ }	{S,M}	{L}	245,-20	245,-20	245,-20	245,-20
14	{ $\emptyset$ }	{ $\emptyset$ }	{S,L}	{M}	295,-20	295,-20	295,-20	295,-20
15	{ $\emptyset$ }	{ $\emptyset$ }	{M,L}	{S}	445,-20	445,-20	445,-20	445,-20
16	{L}	{S,M}	{ $\emptyset$ }	{ $\emptyset$ }	189,0	189,0	189,0	189,0
17	{M}	{S,L}	{ $\emptyset$ }	{ $\emptyset$ }	279,0	279,0	279,0	279,0
18	{S}	{M,L}	{ $\emptyset$ }	{ $\emptyset$ }	380,0	380,0	380,0	380,0
19	{ $\emptyset$ }	{S,M}	{ $\emptyset$ }	{L}	169,-20	169,-20	169,-20	169,-20
20	{ $\emptyset$ }	{S,L}	{ $\emptyset$ }	{M}	259,-20	259,-20	259,-20	259,-20
21	{ $\emptyset$ }	{M,L}	{ $\emptyset$ }	{S}	360,-20	360,-20	360,-20	360,-20

S: Small Airline
 M: Medium Airline
 L: Large Airline

FB: Fair share of the pooling Benefit
 LB: Lower share of the pooling Benefit
 LE: Low demand Estimate
 HE: High demand Estimate

This table shows the complete set of strategy alternatives that are possible for three airlines of different sizes with a selection of all four different cooperative strategies for each airline and one service provider with a selection of four different pricing strategies. In the notation P stands for the service provider and I designates the three airlines together. The strategy alternatives for the airlines are $C_I = \{\text{Solo, Ad hoc, Coop, Comm}\}$ signifying the four cooperative strategies compared. The pricing strategies for the service provider are $C_P = \{\text{FB, LB, LE, HE}\}$ with more detailed descriptions shown in the table footer. The table shows the relative pooling utility, i.e. benefit of I and P ($u_{I,up}$) respectively. The unit of the benefit is 1/1000 of the gross benefit of an ideal pool with no interface costs. The interface costs used in the calculations are 50 units per connection in a cooperative pool and 20 units per connection in a commercial pool. The distribution of the demand volume between the airlines does not affect the model result but the ratio of 1:3:6 has been used in the calculations.

Appendix II: Pool benefits for different membership combinations

MC #	Membership Combination Description			Relative Pool Benefit
	Solo	Cooperative Pool 1	Cooperative Pool 2	
1	{300, 200, 120, 80, 40}	{Ø}	{Ø}	0.00 %
2	{Ø}	{300, 200, 120, 80, 40}	{Ø}	20.99 %
3	{200}	{300, 120, 80, 40}	{Ø}	14.09 %
4	{Ø}	{300, 120, 80}	{200, 40}	13.72 %
5	{Ø}	{300, 120, 40}	{200, 80}	13.55 %
6	{300}	{Ø}	{200, 120, 80, 40}	13.50 %
7	{Ø}	{300, 80, 40}	{200, 120}	13.46 %
8	{Ø}	{300, 120}	{200, 80, 40}	13.46 %
9	{Ø}	{300, 40}	{200, 120, 80}	13.43 %
10	{Ø}	{300, 80}	{200, 120, 40}	13.42 %
11	{200, 40}	{300, 120, 80}	{Ø}	10.26 %
12	{40}	{300, 120}	{200, 80}	9.78 %
13	{300, 40}	{Ø}	{200, 120, 80}	9.74 %
14	{40}	{300, 80}	{200, 120}	9.71 %
15	{200, 80}	{300, 120, 40}	{Ø}	9.15 %
16	{80}	{300, 120}	{200, 40}	8.84 %
17	{300, 80}	{Ø}	{200, 120, 40}	8.70 %
18	{80}	{300, 40}	{200, 120}	8.69 %
19	{200, 120}	{300, 80, 40}	{Ø}	8.47 %
20	{120}	{300, 80}	{200, 40}	8.18 %
21	{120}	{300, 40}	{200, 80}	8.10 %
22	{300, 120}	{Ø}	{200, 80, 40}	8.08 %
23	{200, 80, 40}	{300, 120}	{Ø}	5.38 %
24	{300, 80, 40}	{Ø}	{200, 120}	4.99 %
25	{200, 120, 40}	{300, 80}	{Ø}	4.72 %
26	{300, 120, 40}	{Ø}	{200, 80}	4.40 %
27	{200, 120, 80}	{300, 40}	{Ø}	3.69 %
28	{300, 120, 80}	{Ø}	{200, 40}	3.46 %

This table shows the members of Cooperative Pools 1 and 2 as well as the airlines that have selected the solo strategy in braces with the individual demand signifying each member. The relative pool benefit equals the total cost savings created by the two pools in comparison with the topmost membership combination in which all airlines have selected the solo strategy.

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