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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 simulation model based on fair assumptions of the cost structure was constructed and the cooperative strategies were tested in a game theoretic setting 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.

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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 pooling model of 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. These benefits are defined as cost savings 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

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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. 1000 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 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, US 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 (1990), 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. (2005) 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 Sections 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 MRO 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. Fig. 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

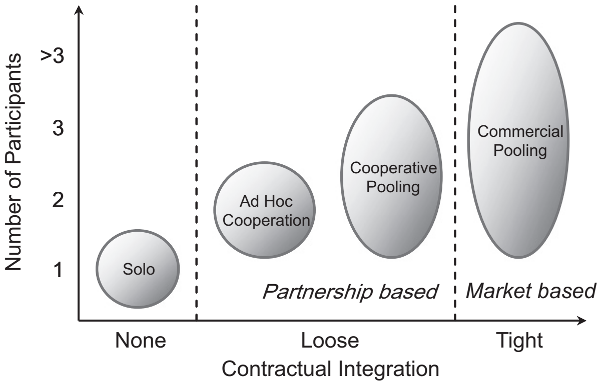

Fig. 1. Framework of cooperative strategies.

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.

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 simulation model for the availability service was created to quantify the effects of the cooperative strategies. The cooperative strategies were then analyzed in a game theoretical setting that enabled the study of conflict and cooperation between decision-makers. The focus was on the total benefit of the participating airlines, defined in this paper as cost savings relative to the solo strategy. 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 have intrinsic elements of conflict and cooperation, so they were analyzed in the game 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, i.e. cost savings, 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. This game setting can be written in strategic form as follows:

$$\Gamma = (N, (C_i)_{i \in N}, (u_i)_{i \in N}) \tag{1}$$

where N denotes the set of players in the game, C_i their respective strategy profiles and u_i their expected utility payoffs i.e. benefit. The players of the game are the 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 game result but the ratio of 1:3:6 has been used in the calculations. The benefits u_I and u_P are calculated using the simulation 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 A). The pricing alternatives of the service provider are $C_\mathrm{P} = \{\mathrm{FB, LB, LE, HE}\}$. 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 simulation model described later (the combinations are shown in Appendix B). The combination with all the airlines in the same pool is included to provide a benchmark pool with the highest benefit.

4.2. Simulation model for availability service

The pooling benefits of the cooperative strategies are calculated using a simulation 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

$$p(k) = \frac{D^k \cdot e^{-D}}{k!} \tag{2}$$

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:

$$s(k) = D \cdot (1 - \mathrm{SL}(k)) \tag{3}$$

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

$$m(k) = m(k-1) - \frac{1 - \mathrm{SL}(k)}{D}, \quad m(0) = \mathrm{TAT} \tag{4}$$

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

$$t(k) = m(k) \cdot \frac{\mathrm{TAT}}{1 - \mathrm{SL}(k)} \tag{5}$$

Using (3)–(5) 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:

$$t(k) = t(k-1) \cdot \frac{s(k-1)}{s(k)} - \frac{\mathrm{TAT}}{D}, \quad t(0) = \mathrm{TAT} \tag{6}$$

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 1–10, stage 2: days 11–30 and stage 3: days after 30) pricing policy that is commonly used within the industry:

$$f(d) = \mathrm{CP} \cdot \frac{\alpha + \sum_{n=1}^{3} \beta_n d_n}{100} \tag{7}$$

where CP is the catalog 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 catalog 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 total cost savings achieved by pooling. The annual connection cost in a commercial pool is arbitrarily set to 2% of the total cost savings.

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 cost savings achieved by pooling 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 cost savings of that pool before allocating the cost savings to the pool members and the possible service provider. The total cost savings of the membership combination is reached by adding together the cost savings achieved by each pool.

4.3. Sensitivity analysis

Changing the demand of the individual airlines in the model does not affect the game results but only the benefit distribution between the airlines. There seems to be no effect on the game result if the connection cost changes compared to the total cost savings achieved by 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 or game results in a random direction. This phenomenon is especially strong with ad hoc cooperation.

The simulation 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 simulation 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 reveal their cost afterwards.

5.2. Economies of scale in the availability service

Table 1 shows the reduced game of the pooling benefits, i.e. the game with all dominated strategies removed (all combinations are given in Appendix A). A strategy is strongly dominated if and only if it can never be the best response of the player regardless of her/his 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.

The reduced game consists of 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 B). 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 all airlines acting solo.

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 subgame of the service provider's pricing strategies is shown in Table 3, where two new pricing strategies, MP and perfect market (PM) were added to study the possible abuse of a monopolistic market position.

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),

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

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

C_I2: all airlines in a cooperative pool; C_I3: 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 3
The pricing strategies of the service provider.

C_I	C_I description				C_P			
	Solo	Ad hoc	Coop	Comm	MP	FB	LB	PM
2	{∅}	{∅}	{S, M, L}	{∅}	700,0	700,0	700,0	700,0
3	{∅}	{∅}	{∅}	{S, M, L}	0,880	660,220	718,162	880,0

C_I2: all airlines in a cooperative pool; C_I3: 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 2
Comparing the mean deviations of two pools.

MC #	Cooperative Pool 1		Cooperative Pool 2		Mean deviation	Relative pool benefit (%)
	Members	Total demand	Members	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

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 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 MP pricing strategy 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 that they would get themselves but less than they would get in the perfect market situation.

In general, the subgame shown in Table 3 is a prisoner's dilemma where the Nash equilibrium indicates that the airlines should always select cooperative pooling (strategy 2). However, if this is considered a repeated game with 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 game 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.

Table 4
The effect of demand estimates.

C_I	C_I description				C_P		
	Solo	Ad hoc	Coop	Comm	FB	LE	HE
2	{∅}	{∅}	{S, M, L}	{∅}	700,0	700,0	700,0
3	{∅}	{∅}	{∅}	{S, M, L}	660,220	539,341	743,137

C_I2: all airlines in a cooperative pool; C_I3: 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.

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.

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 (ERS) from joining the pool, and according to relative incremental pool contribution (RPC). The volume based criterion seems like an intuitive way of sharing pooling benefits.

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.

Table 5
Benefit sharing criteria in cooperative pooling.

Benefit sharing criterion	MC #	Solo	In cooperative pool	Relative cost				
				D300 (%)	D200 (%)	D120 (%)	D80 (%)	D40 (%)
VOL	2	{∅}	{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	{∅}	{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	{∅}	{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.

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 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 benefits were defined as cost saving compared to acting alone, i.e. the solo strategy. 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 also 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.

Appendix A. 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}	{∅}	{∅}	{∅}	0,0	0,0	0,0	0,0
2	{∅}	{∅}	{S, M, L}	{∅}	700,0	700,0	700,0	700,0
3	{∅}	{∅}	{∅}	{S, M, L}	660,220	718,162	539,341	743,137
4	{M, L}	{∅}	{∅}	{S}	−20,−20	−20,−20	−20,−20	−20,−20
5	{S, L}	{∅}	{∅}	{M}	−20,−20	−20,−20	−20,−20	−20,−20
6	{S, M}	{∅}	{∅}	{L}	−20,−20	−20,−20	−20,−20	−20,−20
7	{L}	{∅}	{∅}	{S, M}	190,95	285,0	95,190	247,38
8	{M}	{∅}	{∅}	{S, L}	223,112	335,0	124,211	278,57
9	{S}	{∅}	{∅}	{M, L}	323,162	485,0	235,250	414,71
10	{L}	{∅}	{S, M}	{∅}	265,0	265,0	265,0	265,0
11	{M}	{∅}	{S, L}	{∅}	315,0	315,0	315,0	315,0
12	{S}	{∅}	{M, L}	{∅}	465,0	465,0	465,0	465,0
13	{∅}	{∅}	{S, M}	{L}	245,−20	245,−20	245,−20	245,−20
14	{∅}	{∅}	{S, L}	{M}	295,−20	295,−20	295,−20	295,−20
15	{∅}	{∅}	{M, L}	{S}	445,−20	445,−20	445,−20	445,−20
16	{L}	{S, M}	{∅}	{∅}	189,0	189,0	189,0	189,0
17	{M}	{S, L}	{∅}	{∅}	279,0	279,0	279,0	279,0
18	{S}	{M, L}	{∅}	{∅}	380,0	380,0	380,0	380,0
19	{∅}	{S, M}	{∅}	{L}	169,−20	169,−20	169,−20	169,−20
20	{∅}	{S, L}	{∅}	{M}	259,−20	259,−20	259,−20	259,−20
21	{∅}	{M, L}	{∅}	{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,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 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 B. 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}	{∅}	{∅}	0.00
2	{∅}	{300, 200, 120, 80, 40}	{∅}	20.99
3	{200}	{300, 120, 80, 40}	{∅}	14.09
4	{∅}	{300, 120, 80}	{200, 40}	13.72
5	{∅}	{300, 120, 40}	{200, 80}	13.55
6	{300}	{∅}	{200, 120, 80, 40}	13.50
7	{∅}	{300, 80, 40}	{200, 120}	13.46
8	{∅}	{300, 120}	{200, 80, 40}	13.46
9	{∅}	{300, 40}	{200, 120, 80}	13.43
10	{∅}	{300, 80}	{200, 120, 40}	13.42
11	{200, 40}	{300, 120, 80}	{∅}	10.26
12	{40}	{300, 120}	{200, 80}	9.78
13	{300, 40}	{∅}	{200, 120, 80}	9.74
14	{40}	{300, 80}	{200, 120}	9.71
15	{200, 80}	{300, 120, 40}	{∅}	9.15
16	{80}	{300, 120}	{200, 40}	8.84
17	{300, 80}	{∅}	{200, 120, 40}	8.70
18	{80}	{300, 40}	{200, 120}	8.69
19	{200, 120}	{300, 80, 40}	{∅}	8.47

20	{120}	{300, 80}	{200, 40}	8.18
21	{120}	{300, 40}	{200, 80}	8.10
22	{300, 120}	{∅}	{200, 80, 40}	8.08
23	{200, 80, 40}	{300, 120}	{∅}	5.38
24	{300, 80, 40}	{∅}	{200, 120}	4.99
25	{200, 120, 40}	{300, 80}	{∅}	4.72
26	{300, 120, 40}	{∅}	{200, 80}	4.40
27	{200, 120, 80}	{300, 40}	{∅}	3.69
28	{300, 120, 80}	{∅}	{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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