The Impact of Supportability on the Economic Viability Of a High Speed Civil Transport

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ABSTRACT

There is a significant investment being made within the design community developing tools and identifying metrics for all considerable "ilities" (manufacturability, reliability, supportability, recyclability, etc.) of design in an attempt to bring these issues into the early stages of a design process. Additionally, within the aerospace community there has been a shift in focus from a design solely for performance to a design that emphasizes the vehicle's economic viability. This shift in focus intensified the need for an accurate cost estimation in the early stages of design. In this paper these two areas are integrated through the evaluation of the impact of supportability issues on the overall economic viability of a High Speed Civil Transport. The first step involved making modifications to an aircraft cost estimation tool called Aircraft Life Cycle Cost Analysis (ALCCA). ALCCA originally contained a module that calculates the direct cost associated with line maintenance labor, material, and burden. However, the tool did not account for the cost associated with heavy maintenance visits and supporting new technologies, nor did it account for the revenue loss associated with aircraft downtime due to both preventive as well as corrective maintenance. Modules were added to the ALCCA code which represent each of these areas of supportability concerns and, using the modified version of ALCCA, the impact of supportability for the HSCT on the overall economic viability was evaluated. The results of this analysis represent an initial step towards understanding the impact of supportability on economic viability.

1. BACKGROUND AND MOTIVATION

There are three principal phases in the life cycle of a product: design, manufacturing, and maintenance. Until recently most engineers viewed these phases as totally separate stages that occurred consecutively in a product's life cycle but with little to no overlap. Even now that connections have been made between design and manufacturing and manufacturing and maintenance, virtually none have been made between design and maintenance. This means that supportability requirements are not considered when the product is being designed and developed. This "design it now, fix it later" attitude has significant, adverse effects on the affordability of the product. Looking at the long term costs of a product, 60-70% of the overall costs can be attributed to the support of the product [Blanchard, 1995]. It is extremely important to realize that the affordability of a product is not only based on the initial acquisition cost, but also the operation and maintenance costs associated with the product through out its entire life cycle.

This presents an opportunity to incorporate design for supportability considerations into the preliminary stages of design. There have been tools and methods developed to help facilitate effective maintenance decisions later in the product life cycle (after deployment). Chen and co-authors [Chen et. al., 1994] have presented an approach that can be used for developing maintenance schedules and activities for an existing industrial heavy duty gas turbine. Nottingham and co-authors [Nottingham et. al., 1997] have presented an approach to concept exploration for the engine of a High Speed Civil Transport based on maintenance and support objectives. Building upon this research, we have focused on abstracting these supportability issues into the early stages of design in order to better understand the long range impact that they have on economic viability.

The example chosen for this study is the preliminary design of a High Speed Civil Transport. Due to the technical difficulties associated with supersonic travel, there have not been significant improvements made in increasing the speed of commercial aircraft for the last 20 years. The previous generation of supersonic transports (i.e. the Concorde and the Soviet Tu-144) while technologically feasible have proven to be economically unsuccessful. Additionally, environmental noise and emission concerns for these aircraft have not been addressed. The High Speed Civil Transport (HSCT) is the United States' answer to the need for a environmentally acceptable, economically viable supersonic commercial transport. One of the greatest challenges for the HSCT will be the development of an engine technology that is capable of sustaining the rigorous demands of long range supersonic travel, while complying with noise and emission requirements. Since the engine represents a major factor of the overall acquisition and maintenance cost of the aircraft, improvements in engine reliability, maintainability and supportability can make a significant difference in reducing the operating costs of commercial engines. We believe that in addition to the direct costs associated with operating and maintaining the aircraft, the revenue loss that is associated with any downtime the vehicle experiences, will play a critical role in profitability of this supersonic program. For this reason, the impact of supportability on the overall economic viability of the HSCT is investigated in this paper.

The economic analysis code utilized for this study is referred to as the Aircraft Life Cycle Cost Analysis (ALCCA). ALCCA is a government (NASA) developed economic analysis tool that was originally developed at NASA Ames and has since been modified at the Aerospace Systems Design Laboratory at the Georgia Institute of Technology. The analysis schedule used by ALCCA is shown in Figure 1. It is within the airline analysis that the supportability modifications have been added. The original version of ALCCA had a module that calculated the direct costs associated with line maintenance labor, material and burden. However this tool did not capture the revenue loss that is associated with down time as the result of corrective or preventive maintenance, the costs associated with heavy maintenance visits, or the costs of supporting new technologies. Three modules were added to ALCCA in order to represent these issues: a *revenue loss due to failure module*, a *heavy maintenance activity module,* and a *support of new technology module*.

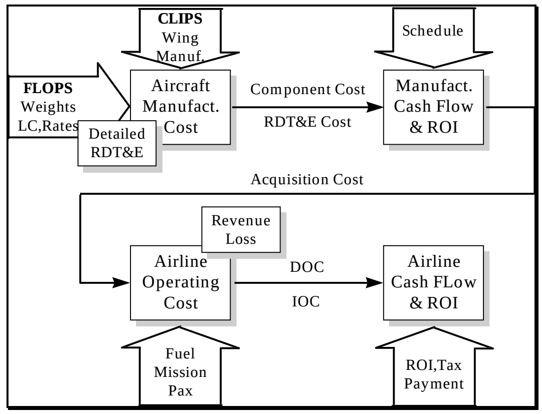

Figure 1: Aircraft Life Cycle Cost Analysis, ALCCA

2. REVENUE LOSS DUE TO FAILURE MODULE

The revenue loss due to failure module that was added to the existing ALCCA code considers four main types of failure: catastrophic, on the ground, in the air recoverable to originating airport, and in the air recoverable to alternate airport (Figure 2). The total revenue loss associated with each type of failure for a single incident of that type is calculated as a function of the ALCCA inputs. Once the total revenue loss for each type of failure is calculated, the total number of failures that the airline is expected to deal with is determined and a total revenue loss due to failure over a given period of time is determined. This total revenue loss is then distributed over the life of the aircraft as a revenue loss due to failure per trip.

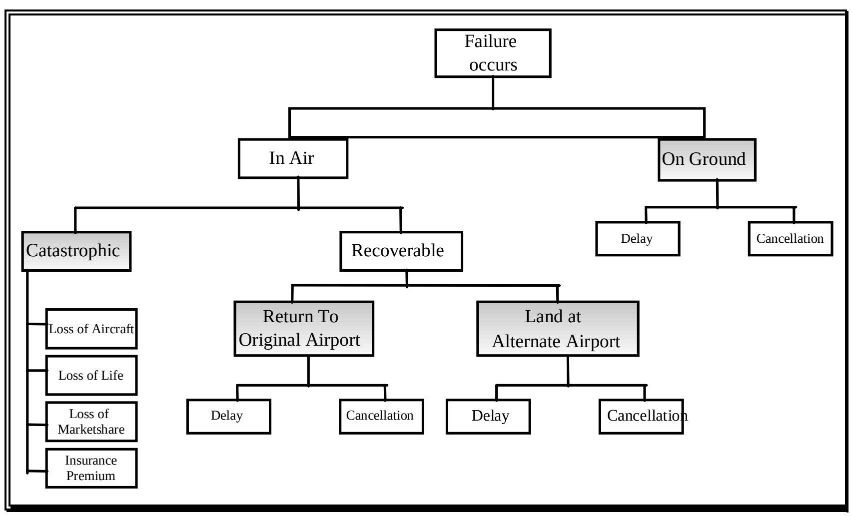

Figure 2: Four Main Types of Failure Modeled in The Revenue Loss Module Within ALCCA

Catastrophic Failure

Catastrophic failure is one in which the failure is unrecoverable, causing a total loss of life as well as aircraft. For the revenue loss module, it is assumed that when a catastrophic failure occurs it is due to a mechanical failure associated with the aircraft engines. The revenue loss associated with a catastrophic failure consists of four main components: loss of life, loss of aircraft, loss of market share, and insurance premium penalties.

The loss of life revenue loss is determined as a function of the total number of passengers, the percent of liability that the airline shares with their insurance carrier, and the monetary value associated with the loss of a life. The issue of insurance for an airline, we found through interviews with personnel at AIG Aviation, is quite complex due to the nature of the industry and the complexity of the vehicles. When an airline purchases insurance, it is handled in the manner of a commodity with different insurance carriers providing different percentages of coverage. A typical policy would cover the airline for the loss of life associated with a catastrophic failure with a $1 million dollar deductible for a given aircraft. However, due to the fact that catastrophic failures are rare, often times airlines, particularly large ones, will purchase a policy in which they share a certain percentage of the liability associated with loss of life if a catastrophic failure occurs in exchange for a reduced insurance premium. For this reason, a variable which represents the percentage of insurance liability the airline accepts was added to the ALCCA inputs. The final piece of information used to determine the revenue loss associated with loss of life is the monetary value of a life. This value will vary from airline to airline, with the insurance carrier, and over time. For this reason a variable was added to ALCCA in order to allow the user to input the most appropriate value for loss of life.

The loss of the aircraft cost is due to the fact that when a catastrophic failure occurs it is assumed that nothing can be recovered from the aircraft structure. This total vehicle loss has a monetary value associated with it equal to the value of the aircraft. For the revenue loss module, this value is assumed to be the acquisition cost that the airline incurs when purchasing the aircraft.

In addition to the revenue loss associated with shared liability, the airline also incurs a revenue loss due to increased insurance premium when a catastrophic failure occurs. According to AIG Aviation, an airline can see an almost doubling effect in their insurance premium when a catastrophic failure occurs that is the fault of the airline (excluding terrorism or pilot error). This information is reflected in the penalty that the airline receives for increased insurance premium.

Finally, the last component of the revenue loss due to catastrophic failure is associated with loss of market share. Anytime a catastrophic failure occurs there is always a significant amount of negative publicity which will cause airline to be viewed as less reliable, and therefore, a higher safety risk. This will in turn negatively affect the market share of the airline due to the fact that less people will be purchasing tickets with the airline. It is assumed within a one year period the airline will succeed in rebuilding its public image and will not see a reduced market following the first year. The percentage of market share lost as a result of a catastrophic failure is modeled using a percentage of the annual revenue for one year. This loss of market share is dependent on a number of factors including the size and reputation of the airline, how long it has been in business, the circumstances surrounding the failure, etc. Due to this fact, the percentage of annual revenue that is lost after a catastrophic failure occurs has been added as an input to ALCCA. The total sum of the revenue loss associated with loss of aircraft, loss of life, loss of market share, and increased insurance premium results in the total revenue loss due to catastrophic failure per incident.

Common Elements of Failure in Air and on Ground

While each type of failure has distinguishing circumstances that make the revenue loss associated with each incident unique there are some common elements that are found between failure on the ground, failure in the air recoverable to originating airport, and failure in the air recoverable to alternative airport. We will first discuss the common elements of these three types of failure and then will examine each failure individually discussing what distinguishes them.

Passenger related expenses include all costs relating to the handling of the passengers during a delay but it excludes costs of an overnight delay where passengers are normally put in hotels. These expenses include paying for passenger's meals and refreshments, overtime for passenger handling personnel, telephone calls, and arrangements for changes to flights where connections are missed [Kruger, 1989]. The expenditure is determined by the number of passengers, the duration of the delay and the airport where the incident occurred. The revenue loss module added to ALCCA captures the first two elements (number of passengers and delay duration) but does not capture the differences in airports. The equation used for the passenger related expenses within the revenue loss module was developed using data taken from a study performed by [Kruger, 1989] including the Boeing 747, Airbus A300, and Boeing 737.

Goodwill expenses encompass the loss of revenue that is incurred by the airline due to the need to compensate passengers for any inconvenience experienced. Passengers who purchase a ticket on a HSCT will be paying a higher ticket price and therefore, will be expecting a higher level of reliability and service. Any delays, even those of minor duration will result in a loss of goodwill with the customer. In order to insure that this does not negatively impact the overall reputation of the airline, compensation will need to be offered any time that a passenger is delayed. The equations used to represent the loss of goodwill expenses were developed based on heuristics and vary based on the severity of the type of failure.

Basic costs include cost elements that are related to the aircraft, excluding all passenger related costs. Major items included in this category are additional parking fees, electrical power and other services supplied to the aircraft, additional freight handling costs, and overtime payment for non-technical personnel. These costs are typically a function of the type of aircraft, and the duration of the delay. The equation for the basic costs used in the revenue loss module was derived from data found in [Kruger, 1989].

Fuel dump costs apply to the case of a return to land or diversion event during the early stages of the flight. The aircraft can not land if the aircraft mass is greater than the maximum landing weight of the aircraft. For this reason, fuel must be dumped in order to allow an emergency landing. The relationship used for the fuel dump cost was developed based on the cost of fuel , the takeoff weight of the aircraft, and the maximum landing weight of the aircraft.

Overnight costs occur whenever a daytime or evening departure is delayed to the next day. Passengers are normally put up in hotels. The cost then becomes independent of the exact duration of the delay and are largely determined by the hotel rates, meals provided and transportation costs. The total cost is a function of the number of passengers and the hotel rate.

Rerouting costs are those associated with rerouting passengers on another airline in the case that the flight is canceled. Depending on the airport and the location, this may mean rerouting passengers on subsonic flights. Typically, airlines do not charge full ticket price to other airlines that require booking on a flight due to rerouting. For this reason, the equation for the rerouting expense assumes an revenue loss of 80% of the original ticket price for each flight that is rerouted.

Finally, if a failure results in a down time of greater than 48 hours, it is assumed that no further passenger or aircraft related expenses will be incurred. Beyond 48 hours the only loss of revenue will be that associated with lost ticket sales due to the downtime of the aircraft. This cost is determined as a function of the number of flights that are lost due to the excessive down time. It is important to note that due to the unique nature of the HSCT it is assumed that an airline will not consist of a large fleet size nor will there be a spare aircraft to cover such downtime.

Delay and Cancellation Chain Model

All of these components of revenue loss are determined as a function of the delay duration that the passenger experiences. Due to the fact that ALCCA does not determine delay duration, a module for determining the delay chain/duration was developed. The scheduling of flights shows that the time of peak demand for commercial aircraft is in the mid-afternoon, around 1:00. This information was based on a typical time of the day distribution for the various days of the week for a fleet of short and long range aircraft[Kruger, 1989]. Due to the fact that the peak demand is at 1:00 PM, it is assumed that this time would also correspond to the time when there are the most aircraft flying. Accordingly, it follows that if a failure is going to occur, there is a higher probability that it will occur at this time. For this reason, it is assumed that the failure that occurs corresponds to the 1:00PM flight. In order to determine the delay duration for each flight a method of responding to downtime due to failure and the impact that this has on all of the flights effected was developed. First the number of flights effected is determined. Then, based on a schedule with the first flight occurring at 1:00, the delay duration for each flight effected is determined.

There are several assumptions that were made in developing the delay chain model used in ALCCA. Referring to Figure 3, there is an overnight down time that is accounted for. This down time is used to accommodate overnight curfews placed on the aircraft due to noise regulations as well as routine servicing and inspection requirements. It is assumed that this downtime will always start at 11 PM. The duration of the overnight downtime is a function of the daily operational availability which is input by the user into ALCCA. As previously mentioned, the passenger related expenses are restricted to a 48 hour time period. It is important to note that due to logical complexity, the difference in time zones, inherent in the operation of the HSCT, were not accounted for. The current model is based on a single time zone representation.

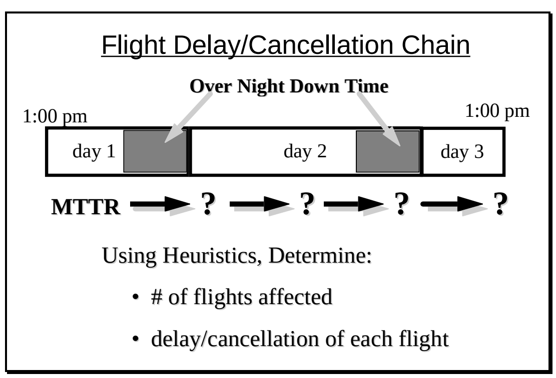

Figure 3: Flight Delay/Cancellation Chain

Given this structure of flight scheduling, there are 3 blocks of time in which the revenue loss costs discussed above are applied. These three blocks are labeled in Figure 3 as day 1, day 2, and day 3. As we discuss the framework of the logic used in the flight delay/cancellation chain, we will work through a number of examples for different Mean Time To Repair values. For each of the following examples we will assume a block time of 4 hours, ground time of 1 hour, and a daily utilization time of 16 hours, which are in general inputs to ALCCA.

If the Mean Time To Repair (MTTR) is less than ten hours (the time from the occurrence of the failure, 1:00 PM, and the start of the overnight down time 11:00 PM) then the flights effected are confined to the first day of scheduled flights. First the number of flights that will be effected is determined by dividing the ten hours that are available to schedule flights by the total time for each flight (sum of block time and ground time). Next a check is performed to determine if the MTTR will result in any cancellations of flights. As long as the delay does not exceed the amount of time from the last scheduled take off for the day to the start of the overnight time out of service, no flights will have to be delayed overnight. This time is defined as the leeway. If the MTTR is less than the leeway then the delay for each flight effected will simply be equal to the MTTR.

If the MTTR is greater than the leeway then there will be flights that are canceled and therefore, passengers that are delayed overnight. If this is the case, then the number of flights that result in an overnight delay is calculated based on the difference between the MTTR and the leeway. If all of the flights are delayed overnight, it is assumed that the passengers will be rerouted on the first flight in the morning. Therefore, the delay for each flight simply becomes the time starting at the scheduled departure time and ending at the departure time for the first flight the next day.

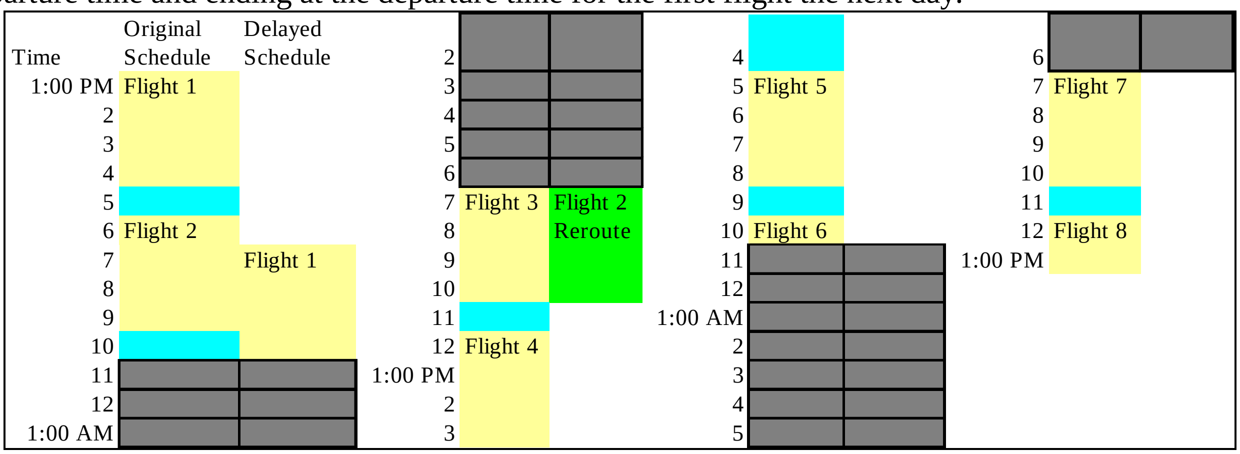

Figure 4: Example of Day 1, Overnight Flight Rescheduling: Block Time = 4 hrs, Ground Time = 1 hr, Daily Utilization = 16 hrs, MTTR = 6 hrs

If the MTTR is of a smaller duration such that it is possible to have some flights delayed with a same day departure, then the delay for each of these flights is calculated. Figure 4 shows an example of the flight rescheduling for a MTTR greater than the leeway (MTTR = 6 hours) with split between same day and overnight delays.

It is important to note at this point that the way that the code was written was such that the earliest scheduled flights would be rerouted first, moving along in sequential order. It may be noted that this is not the only possible scenario and, in fact, each airline on a case by case basis may respond differently to these types of delays. However, as a first approximation we chose the simplified method as discussed to model this scenario. Further development in this area could lead to a more inclusive rescheduling model.

A similar logic is used to determine the number of flights effected and the delay each flight will incur if the MTTR carries over to day 2. The flights that are scheduled during the first ten hours (day 1) of the failure downtime are assumed to be delayed overnight and rerouted in the morning. The number of flights effected during day 2 of the downtime is determined by calculating the number of hours of the MTTR that carry over into day two. If the number of hours of the MTTR that carry over into day two is less than the leeway, then the delay for each flight is simply equal to the MTTR that carries over. However, if the carried over MTTR is greater than the leeway, then a number of checks are performed. First of all, the number of flights that would be required to be delayed overnight is determined. There are two possible scenarios that are modeled in the code. Scenario 1 represents the case where more than half of the total number of flights effected in day 2 would have to be delayed overnight, Scenario 2 otherwise. If the number of flights that are delayed overnight for the second day is greater than half the total number of flights effected for day 2, then it is assumed that half of the flights that should be delayed overnight (rounded down) will be rerouted on another airline on the same day as they were originally scheduled. An example of this can be seen in Figure 5 which shows the rescheduling that occurs for a MTTR equal to 28 hours. As can be seen in this figure, there are eleven hours of the MTTR that carry over to day two. This means that only one flight will be able to take off on this plane during day two and three flights should be delayed overnight and rerouted the next day. However, since this exceeds half the total number of flights effected (4 flights), one of these flights will be rerouted on another airplane on the last possible flight that day. As a result, Flight 3 is delayed 11 hours, Flight 4 is rerouted on another airline on day 2, and Flights 5 and 6 are delayed overnight and rerouted in the morning.

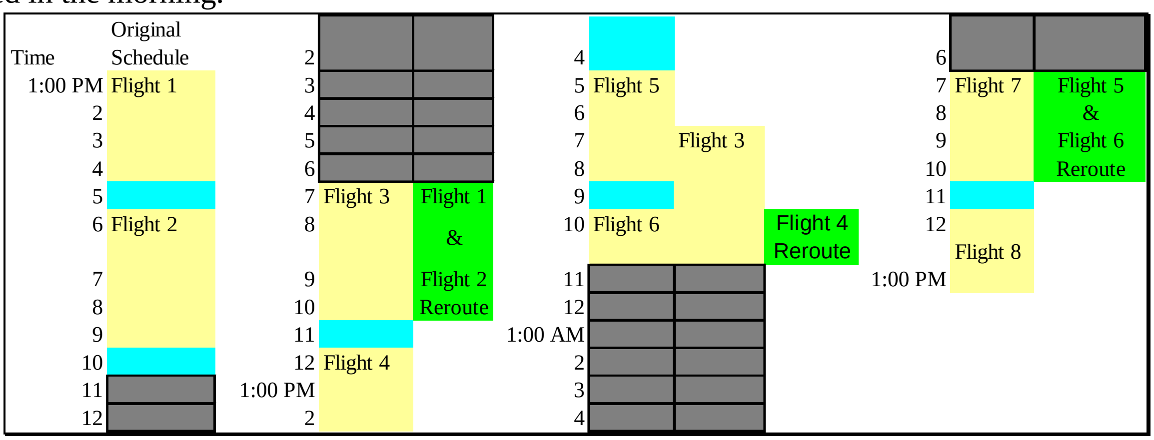

Figure 5: Example of Day 2, Overnight Flight Rescheduling: Block Time = 4 hrs, Ground Time = 1 hr, Daily Utilization = 16 hrs, MTTR = 28 hrs

The same type of logic is used to account for the delays during day 1 and day 2 when the MTTR carries over to day 3 but is less than 48 hours. Due to the 48 hour limited time period, day 3 only consists of the time between 7 AM and 1 PM. For this reason, any part of the MTTR that carries over to the third day simply becomes the delay duration for the flights effected on day 3. Anything beyond 48 hours is assumed to be accounted for by internal rescheduling and will not result in any further passenger related delays. The only revenue loss associated with a MTTR greater than 48 hours is that which accounts for loss of potential sales from flights that will not be scheduled due to the down time.

Having discussed the common elements of revenue loss for non-catastrophic we now turn our attention to the differences between the elements of revenue loss for each type of failure. The revenue loss associated with a failure on the ground consists of passenger handling expenses, loss of goodwill expenses, basic expenses, overnight expenses, loss of sales expense, and rerouting expenses as described previously. The revenue loss associated with a failure in the air that is recoverable to the originating airport consists of the same elements as a failure on the ground with the addition of fuel dump costs and increased goodwill costs. Due to the fact that a failure that occurs in the air will result in an emergency landing, we feel that a higher level of compensation will be required in order to maintain the customer's confidence in the airline. The revenue loss associated with a failure in the air, recoverable to an alternate airport is similar in its components to that of a failure in the air, recoverable to the originating airport. However, due to the fact that this type of failure is more serious, and requires a landing at an airport that is not affiliated with the airline, there are additional revenue losses that will be experienced. The revenue loss associated with a failure in the air, recoverable to an alternate airport consists of all costs previously discussed with the addition of a difference in labor rate expense, increased basic expense, increased passenger related expenses, and increased overnight expense. The difference in labor rate revenue loss is associated with the increase in maintenance labor rate that will result from having to out-service the repairs that must be made to the aircraft. The basic cost and passenger related expenses are increased by 30% over that the other types of failure due to the fact that the aircraft will be at an airport where the airline does not have facilities and therefore, these services will also have to be out-sourced.

Once the revenue loss for a single occurrence for each type of failure is determined, the next step is to calculate the total revenue loss for the airline over a given period of time. This is done by applying probabilities of likelihood to each failure type and determining the total number of each type of failures that will occur for a given time period. This time period within ALCCA is the economic life over which all of the cash flow calculations are performed which the user inputs. The probability of a catastrophic failure , the probability of failure in the air recoverable to originating airport, and the probability of failure in the air recoverable to an alternate airport have been added as ALCCA inputs as well. Using the MTBF, annual utilization, and the economic life the total number of failures over the life of the aircraft can be determined. Applying the probabilities of each type of failure to the total number of failures, we are able to determine the total number of each type of failure that will occur during the life of the aircraft. Taking the sum total of the total number of failures for a single type times the revenue loss per incident of that type results in the total revenue loss due to failure over the economic life of the aircraft. Finally, this value is divided by the total number of flights over the economic life in order to give a total revenue loss due to failure on a per trip basis.

3. HEAVY MAINTENANCE VISITS AND MID-VISITS MODULE

In addition to the revenue loss due to failure modifications made to ALCCA a direct operating cost module for heavy maintenance visits and mid-visits was created and added. Both modifications were made in the direct operating cost calculations subroutine within ALCCA. While ALCCA includes the cost of line maintenance (routine maintenance that has a high frequency, is less extensive, and requires a lower down time duration) it did not capture the cost of heavy maintenance (preventive maintenance that occurs less frequently but quite extensive resulting in a longer downtime duration). The heavy maintenance that was evaluated consists of a Heavy Maintenance Visit and a Mid-visit. In order to model the costs of these two types of maintenance activity we relied on data provided by Delta Airlines for the Boeing 767. A Mid-visit (MV) occurs every 4 years for the 767 with a maximum of 5 years, 8125 cycles, or 25000 hours (which ever occurs first). A Heavy Maintenance Visit consists of heavy structure refurbishment which occurs every 8 years, 13000 cycles, or 40000 hours (which ever occurs first) and includes all Mid-visit tasks. The data provided by Delta Airlines consists of maintenance summary reports for HMVs and MVs performed on individual 767 aircraft.

Each report summarizes the down time required to perform the maintenance activity, the tasks performed, the time required for each task, and the material expenditure. The maintenance tasks performed are broken down into three categories: routine maintenance, non-routine maintenance, and engineering orders. Routine maintenance consists of those tasks that are set forth by aircraft manufacturer and are approved by the FAA as the minimum required maintenance that must occur for the given time frame. Non-routine maintenance consists of any tasks that are not planned to occur during the visit but are performed as the result of unanticipated flaw detection. Engineering orders are not directly related to the maintenance of the aircraft and consist of modifications or additions that are mandated from the aircraft engineering department. Each category of maintenance tasks has a material cost associated with it. Using this data, we were able to determine a relationship for the material cost of each category as a function of the number of hours required. It is important to note that the data set that we used to establish these relationships was limited and therefore, while we do feel that we have captured the trends, more data should be gathered to improve on the established relationships for the heavy maintenance material cost.

The labor costs for the MV and HMV are calculated as a function of the total man hours required for the visit. The total man hours are simply the sum of the routine, non-routine, and engineering order man hours. Additionally, the burden costs for each type of visit are calculated. The burden cost is determined as a percentage of the total labor costs incurred for the particular visit. Typically, the burden associated with maintenance activity is 200% of the total labor cost, however, this value is a user specified variable within ALCCA. The values for labor, material, and burden costs of HMVs and MVs are all added into the overall direct operating cost of the aircraft which is used in the overall economic viability calculations.

4. SUPPORT OF NEW TECHNOLOGIES MODULE

The final modification made to ALCCA was the addition of cost penalties associated with new technologies that are being used on the aircraft. The two technologies that were included in these modifications are the Hybrid Laminar Flow Control and Circulation Control. While it is anticipated that both of these technologies will lead to increased aircraft performance, we feel that there will be a economic penalty associated with the maintenance and service of these two technologies. Both of these technologies require a source of blown air that will most likely be linked with the aircraft air-conditioning system. It is for this reason that the support penalty associated with maintenance of these technologies was added as a complexity factor to the air-conditioning maintenance that is currently modeled in the detailed airframe maintenance model of ALCCA. The modification consists of a flag for each technology which enables the user to specify whether these technologies are being used or not. Additionally, the user specifies the economic penalty as a percentage of the normal air-conditioning maintenance.

5. DEVELOPING SUPPORTABILITY MODELS

As a result of the modifications discussed in the previous sections the reliability, maintenance and support parameters listed in Table I are now available for the user within ALCCA. It is also indicated which variables represent new additions to the ALCCA input file and what range they were examined at for this study. As stated previously, the main objective of making the ALCCA modifications was to enable a more realistic and detailed analysis of the economic impact of supportability on the viability of the HSCT. With this as our motivation, we wanted to determine the support parameters that had the most significant impact on the economic viability of the HSCT.

Additionally, we were interested in evaluating the effect that these parameters would have over specified ranges on support cost.

Table I: ALCCA Supportability Variables and Ranges

Variable	New(N) or Existing (E)	Range
Ground Time	E	0.5 - 4 hours
Maintenance Burden	E	100% - 200%
Mean Time Between Failures	E	1000 - 15000 hours
Mean Time To Repair	E	2 - 96 hours
Value associated with loss of life	E	$1 Mil - 3 Mil
Percentage of liability airline assumes for catastrophic failure	N	0 - 50%
Percentage of annual revenue lost after catastrophic failure	N	5% - 40%
Probability of Catastrophic Failure	N	1E-10 - 1E-7 incidents/flight hour
Probability of failure in the air, return to originating airport	N	1E-6 - 1E-3 incidents/flight hour
Probability of failure in the air, land at alternative airport	N	1E-8 - 1E-5 incidents/flight hour
Airline Fleet Size	N	1 - 250
% difference in labor cost due to out-service of labor at alternative airport	N	10% - 50%
Mean Time Between Mid-visit	N	1 - 4 years
Mid-visit Routine Man-hours	N	2400 - 5000 hours
Mid-visit Non-Routine Man-hours	N	500 - 5000 hours
Mid-visit Engineering Order Man-hours	N	500 - 5000 hours
HMV Routine Man-hours	N	5000 - 10000 hours
HMV Non-routine Man-hours	N	6400 - 10000 hours
HMV Engineering Order Man-hours	N	2200 - 10000 hours
Hybrid Laminar Flow Control Support Complexity Factor	N	100 - 300%
Circulation Control Technology Factor	N	100 - 300%

Given the support parameters and their ranges, a screening test was conducted. The purpose of a screening test is to identify the most significant factors and thus, if possible, reduce the number of variables needed to allow *efficient* higher order modeling. The experimental design used for the screening in this study was a Fractional Factorial Design for the variables listed in Table I. This design allows to estimate the significance of the main effects of each variable (i.e. first order only). Note that from the screening a linear relationship could be established between the responses and the variables. If the response depends on the variables linearly and the fit is acceptable, then this model could be used as the response surface equation. However, in our case we are using the results of this experiment to identify the most significant parameters which will then be used in a *higher order response surface model*.

A Pareto plot, which represents the fractional effect of each control factor on the output for a particular response, was generated for each response. Two of the resulting Pareto plots can be found in Figure 6 and 7 for $/RPM and Total Operating Cost respectively. From these plots it is possible to select the most significant factors for each response. $/RPM, average yield per revenue passenger mile, is used as an objective here, since it captures best as a metric the interests of all parties with an economic interest in the HSCT: manufacturer, airline, and passengers.

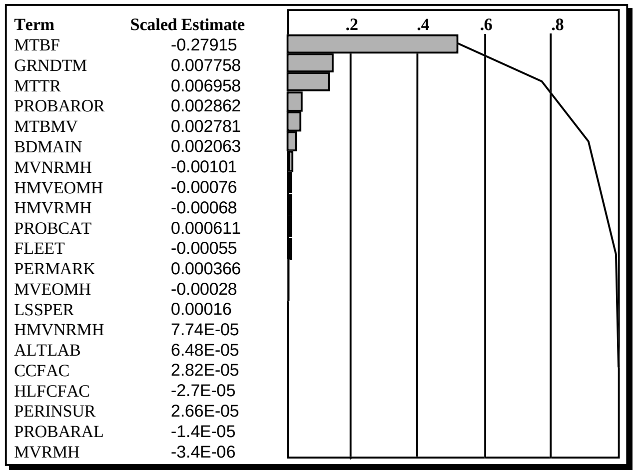

Figure 6: Pareto Plot For $/RPM Response

The first six parameters, Mean Time Between Failure (MTBF), Ground Time (GRNDTM), Mean Time To Repair (MTTR), Probability of Failure in the Air, Recoverable to Originating Airport (PROBAROR), Mean Time Between Mid-Visit (MTBMV), and Maintenance Burden (BDMAIN), have the dominating effects on both responses, representing about 92% of the total response. They should be used as the variables in the response surface equation, while the remaining supportability parameters are held constant at their most likely values. The same procedure was employed yielding similar results for the screening of supportability variables with respect to the indirect and direct operating costs.

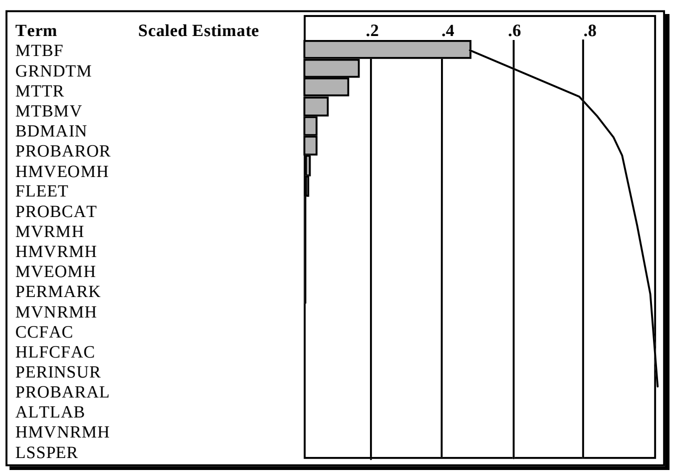

Figure 7: Pareto Plot For Total Operating Cost Response

The reduction in the number of variables through a screening test allows a larger number of experiments to be run efficiently to include higher order effects and interactions between factors in the response surface model. The design used in this latter part of the study is a central composite design (CCD) that evaluates main and quadratic effects as well as two-factor interactions. Second order models have been found to be a sufficiently accurate approximation for economic responses over a moderate range of interest for the factors in this problem. If the range is too large, the quadratic approximation may not yield a sufficient prediction and a higher order model needs to be employed. After running the experiments using the modified version of ALCCA, a regression analysis is conducted (using a statistical package called JMP) to evaluate the fit of the resulting response surfaces. Each response surface is a polynomial that maps the six input factors to each of the economic responses. The resulting equations take on the following form:

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_{ii}^{2} + \sum_{i=1}^{k} \sum_{j=1}^{k} b_{ij} x_{ij} \quad i < j \quad [1]$$

where R is a response ($/RPM, Total Operating Cost, etc.)
b_o... is the intercept
b_i ...are the regression coefficients for the linear terms (main effects)
b_{ii} ...are the coefficients for the pure quadratic terms
b_{ij} ...are the coefficients for the two-factor interactions
x_i, x_j ...are the design factors and $x_i x_j$ denotes the interactions between two factors.

For this study, second order response surfaces were found to be sufficient as indicated by the high R^2 values for all four responses listed in Table II. The R^2 value is an indicator as to how well the response surface equation predicts the data. A perfect prediction would result in an R^2 of 1. These response surface equations were used further for evaluating the impact of variation in the supportability parameters over their given range. Each range was selected in order to realistically reflect possible improvements or deterioration in the area of support.

Table II: Statistical Results for the Response Surface Equations

Response	$\mathbf{R^2}$
$/RPM	0.999626
Total Operating Cost	0.999788
Indirect Operating Cost	0.999417
Direct Operating Cost	0.99981

6. IMPACT OF ALCCA MODIFICATIONS

In order to evaluate the impact of the new modifications to ALCCA, several cases were run where all the reliability, maintainability, and supportability parameters were held at their most likely values and the MTBF was allowed to vary. The MTBF is perhaps the most prominent measure of reliability, maintainability, and supportability, as indicated by the Pareto plots, and is therefore of particular interest. The purpose of evaluating the responses as a function of MTBF is to see what type of effect improvements (increased MTBF) would have on the overall economic metrics. Evaluating first the impact of MTBF on $/RPM we refer to Figure 8. As can be seen in this figure, increasing the MTBF has a significant effect on the $/RPM for a range of 1000 to 15000 hours MTBF. Much of this can be attributed to the fact that an increase in MTBF will result in an increase in Utilization as seen in the graph also. The points labeled with a star and a diamond in Figure 8 correspond to the values of $/RPM and Utilization that result from a MTBF equivalent to that which is typical for a subsonic transport and the Concorde, respectively. This gives a feel for the amount of improvement in supportability the HSCT must realize over the Concorde in order to truly be competitive with subsonic transports.

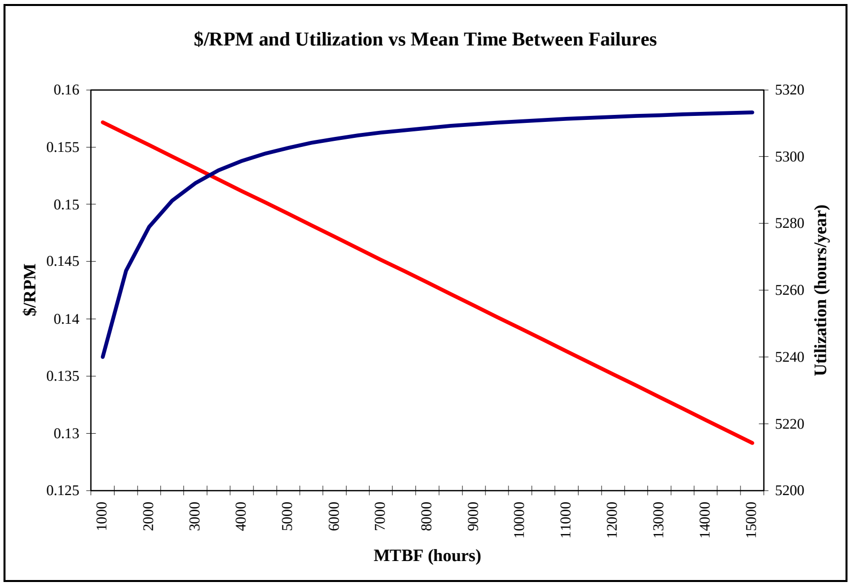

Figure 8: $/RPM and Utilization versus Mean Time Between Failures

Using the response surface equations for the operating costs (indirect, direct, and total) we also evaluated their behavior with improvements in MTBF, displayed in Figure 9. While an improvement in MTBF (increase) does not significantly impact the direct operating cost, it has a large influence on the indirect operating costs. This can be attributed in part to the fact that the indirect operating cost includes the new revenue loss module. The less frequently there is a failure, the less revenue loss due to failure that will be observed. Observe also, that the indirect operating cost is greater than the direct operating cost for poor MTBF, but as MTBF improves a cross over point is reached and the indirect operating cost is decreased beyond operating cost.

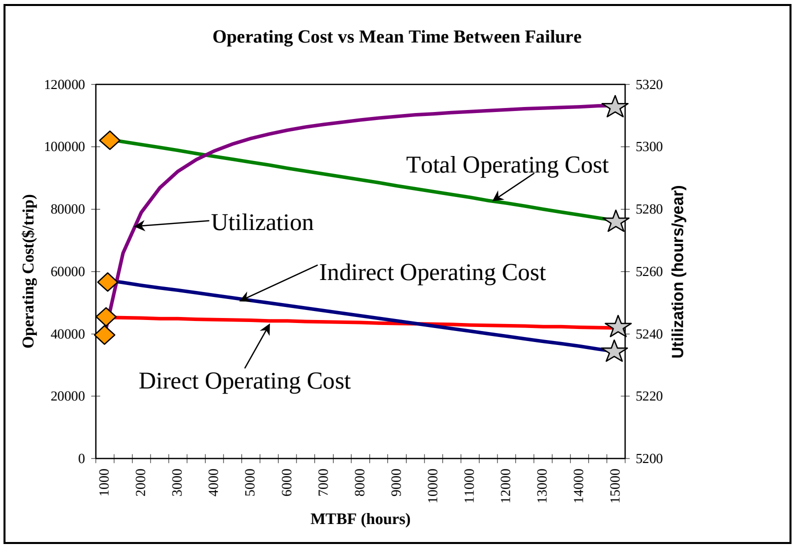

Figure 9: Operating Cost Versus Mean Time Between Failure

Consequently, the observation to be made from Figure 9 is the decrease in the total operating cost with improved MTBF. This result helps to justify improvement claims for the supportability of the aircraft in order to achieve overall economic targets.

To assess the impact of the modifications made to ALCCA (revenue loss module, HMV and MV operating costs, and new technology support), the impact of the supportability parameters on the economic metric of $/RPM with and without the modifications is compared. Thus, the original version of ALCCA was run first with all the support parameters set at their least desirable settings (worst case scenario) and then at their most desirable settings (best case scenario). The new version of ALCCA was then run with the worst and best case scenario settings. The results of this analysis are summarized in Figure 10. As can be seen, there is a significant difference in the impact that the support parameters have on $/RPM with the modifications turned on. The support parameters in the modifications made to ALCCA introduce an approximately 47% increase in $/RPM with respect to the value from ALCCA without the modifications.

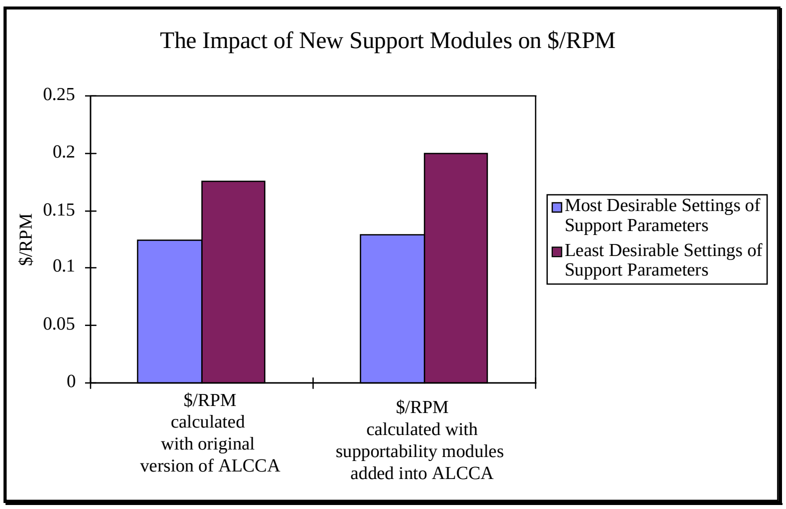

Figure 10: Impact of Support Module on $/RPM

7. CLOSURE, FUTURE WORK, AND RECOMMENDATIONS

While we have been able to show that the modifications made to ALCCA have influenced the impact that the support parameters have, there are still areas that need to be further evaluated and elaborated on before a more complete and accurate analysis can be performed. We acknowledge that we have only touched the surface with regards to the support of new technologies. There is room for improvement in capturing all of the support expenses associated with circulation control and hybrid laminar flow control. Also, there are proposed technologies (e.g. engine noise reduction technologies) that we have not evaluated with respect to support expenses at all. With respect to the HMV and MV, as stated previously, we feel that we have been able to capture the trends that these costs will follow, but lack of sufficient amounts of data prohibited the development of a more accurate model. Even in light of the areas that will require future work, we have been able to show that the support parameters do impact the overall economic viability metrics of the HSCT. This shows that improvements made in reliability whether through design improvements or through more effective maintenance and support will contribute to a more economically viable HSCT. We have been able to establish a foundation upon which future research and development within the area of design for supportability can occur.

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