INTEGRATION OF “DESIGN TO SUPPORT” AS PART OF AIRCRAFT DEVELOPMENT

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Abstract

To enhance in-service performances, it is necessary to understand the domain and scope of supportability. In fact, it facilitates leveraging the intuitive “cause and effect” relationship between design and support, and ultimately affordability.

This paper addresses the problem of defining models to jointly drive the system design and its support towards better supportability. The study deals with trade-off analyses regarding performances such as operating costs and availability.

1 General Introduction

Aircraft design has evolved from the traditional design for functional performance to design for affordability (cost effectiveness) and quality. This paradigm shift implies good reliability, maintainability, low operating costs and above all, a product designed with the operational environment in mind (including maintenance activities). Failing to give appropriate attention to product support at the design stage is a missed opportunity.

To meet these airline’s expectations, the aircraft manufacturer must keep focusing on early decisions having significant impacts on operational performances and costs. Decisions taken at the design stage strongly determine the efficiency of the aircraft support system.

The supportability describes the ability of a system to sustain in-service operational needs under certain economical limits. The supportability engineering within Airbus participates integrally in the concurrent design of a product. It plays a major role in driving the design to meet customer expectations.

The aim is to deliver a product with minimum operating cost to the operator, whilst ensuring optimum availability and operational reliability. We are looking for affordability. Affordability is not the lowest cost. It is a measure of value balancing a product’s effectiveness against its associated cost and risk.

Today, Airbus has developed and implemented a model to predict the global supportability performance of their products, based on design features, economical data and aircraft utilization.

Safety analyses are not part of this study. Safety remains of course a top driver in design. Other processes, with different priorities, exist to produce safe aircrafts. Here the objective is not to enhance safety, but rather to improve operating efficiency without degrading safety.

The paper is organized as follows. In the next section, we set out the notations used throughout the rest of the paper. In section 3, we present the enablers to improve supportability performances. Section 4 describes the trade-off challenge and our modelling technique. We then explain the criteria to make decisions in section 5. Finally, we summarize the results and conclude with directions for further researches.

2 Nomenclature

DMC	Direct Maintenance Cost
CSDD	ATA Common Support Data

	Dictionary
GSE	Ground Support Equipment
LRU	Line Replaceable Unit
MEL	Minimum Equipment List
MMEL	Master Minimum Equipment List
MPD	Maintenance Planning Document
MSG-3	Maintenance Steering Group – 3
MTBF	Mean Time Between Failures
MTBUR	Mean Time Between Unscheduled Removals
MTTR	Mean Time To Repair
NFF	No Fault Found

3 Enablers to Improve Supportability Performances

Through their activities, supportability engineers have to work on how to:

- Reduce the occurrence of function loss at the least cost;
- Increase function recovery at the least cost.

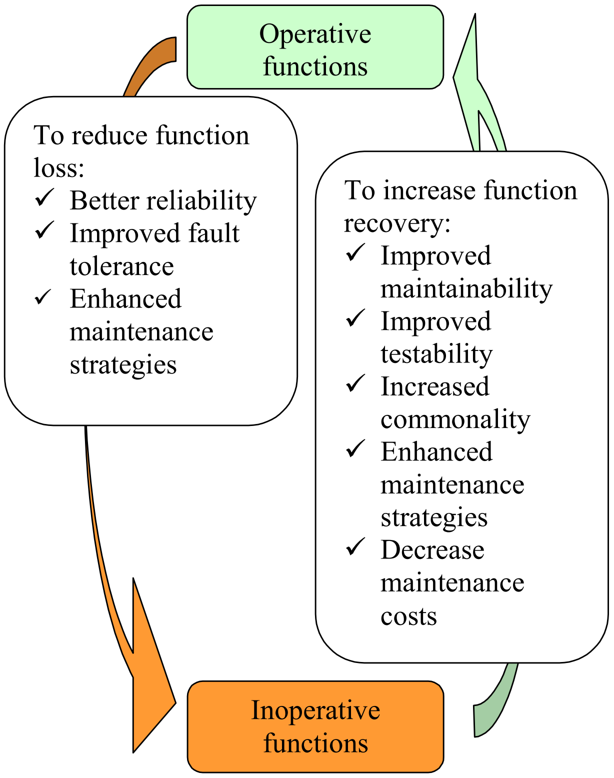

Fig.1 Potential Supportability Activities.

Supportability specialists have to consider:

- Product design and quality;
- Potential maintenance strategies;
- Possible aircraft utilizations.

3.1 Product Design and Quality

3.1.1 Reliability, Testability and Commonality

System robustness and sustainability are essential to achieve better in-service results. Supportability specialists influence supplier‘s selection on the basis of their ability to meet challenging contractual requirements.

One aspect of design that has a critical impact on affordability is reliability. In fact, it impacts aircraft downtime, maintenance and spare parts. Indicators of reliability used are Mean Time Between Unscheduled Removal (MTBUR) used to identify all unscheduled removals and Mean Time Between Failure (MTBF), which reflect confirmed failures.

Testability is the property of an item to allow rapid confirmation of its own functional integrity. Cost-effective testability enables, for example, the reduction of:

- Aircraft downtime;
- Erroneous removal of serviceable Line Replaceable Unit (LRU);
- Shop test and repair cost.

Measurement of testability is often given by No Fault Found (NFF) rate:

$$NFF = 1 - MTBUR/MTBF\ .$$

To clarify NFF meaning, after a failure has been reported, troubleshooting will attribute the failure to a LRU. This LRU is removed and sent to the repair station for test. If the suspect LRU passes the test, then it is returned to service. The failure has not been confirmed in shop. In this case, the removal is counted as a NFF.

When selecting a LRU, it is necessary to consider the resulting amount of commonality on the aircraft.

It can directly influence maintenance easiness and operating cost. The lack of equipment commonality requires multiple lines of spare parts, specialized tools and support equipment.

3.1.2 Fault Tolerance

On the other hand, supportability performances can be improved by exploiting fault tolerance. In fact a fault tolerant aircraft increases deferred maintenance to optimize flexibility for aircraft availability.

A system is redundant if one failure of any of its components does not affect the system's purpose. Redundancy or back-up mechanisms will enhance the fault tolerance of a system. However, actual decision for the system redundancy must also be dictated by complexity and cost constraints.

The official system fault tolerance, relevant to all evident failures, is defined by Airbus in Master Minimum Equipment List (MMEL). It is then customized by airlines in Minimum Equipment List (MEL). The MEL includes the MMEL, specific airline's requirements and local regulations.

The MMEL lists all the safety-related items for which revenue flights are permitted, even if the items are inoperative at departure. Systems are attributed a 'GO', 'GO IF' or 'NO GO' status, depending on their impact on the safety of a flight. These attributes are defined as follows:

- 'GO' items can remain inoperative for a limited period of time;
- 'GO IF' items can remain inoperative conditionally for a limited period of time;
- 'NO GO' items prevent the dispatch of the aircraft.

The MMEL ensures a safe dispatch. It is a major contributor to operational reliability and may represent a way for operators to significantly reduce operating costs. Therefore, there is a great benefit of designing with the MEL in mind. In our model, it impacts:

- The risk of operational interruption. It is lower for system architectures and equipments that give the greatest flexibility for dispatch with fault present.
- The stock level of spare parts. In the same way, the desired availability of spare parts (as modeled) depends on item criticality.

3.1.3 Maintainability

Another indicator of design quality is its maintainability. Poor maintainability will adversely impact Direct Maintenance Costs (DMC) and/or operational reliability.

Maintainability deals with maintenance issues at the product design stage, time to troubleshoot, access, remove, install and test. Thus, it impacts on how quickly maintenance may be conducted but it has no effect on the frequency of failure occurrence. The maintainability ensures that an aircraft and its support elements can be maintained:

- In the least time;
- At the least cost;
- With the minimum expenditure of support resources;
- Without adversely affecting performance.

Maintainability is considered through the mean time to fix a visible defect. It is affected by inherent design, accessibility, faultfinding and ease of removing, installing or deactivating a LRU.

3.2 Maintenance Strategies

Free maintenance design often proves impossible, as a result the products have to be designed for effective and efficient maintenance and support. To ensure customer satisfaction, product support is essential. Moreover, it has a strong influence on aircraft sales.

Like any other supportability element, maintenance has to be considered where possible to influence design during aircraft development.

Maintenance deals with actions to reduce the likelihood of failure and to restore a failed item to an operational state. Maintenance is categorized as either preventive or corrective.

Preventive Maintenance is sub-divided into:

- Scheduled maintenance (periodic), i.e. tasks performed at defined intervals, listed in the Maintenance Planning Document (MPD);
- Predictive maintenance (unscheduled) based on inspection and automatic monitoring techniques.

Corrective maintenance is sub-divided into:

- Deferred maintenance;
- Immediate corrective actions.

Preventive maintenance is about avoiding situations that could impact safety or have serious operability or economical consequences. On the contrary, corrective maintenance does not reduce the consequences of future failures. It only puts the system back into operation.

In the model, scheduled maintenance tasks concern only evident and hidden failures. A second event or failure is required to identify a hidden failure. In fact a hidden failure concerns a function normally:

- Active, and its cessation will not be evident to the operating crew during performance of normal duties;
- Inactive, and its readiness to perform, prior to it being needed, will not be evident to the operating crew during the performance of normal duties.

The predictive maintenance implies the capability to make appropriate decisions about emerging defects (degradation) based on diagnostics or prognostics information. The predictive maintenance plays an important role, if:

- The airline wants to avoid failure occurrence;
- The capability of detection is reliable;
- The false detection is minimized.

All these aspects are considered through input data.

Corrective maintenance entails all actions performed when degraded mode is no longer accepted. This type of maintenance is reduced by scheduled tasks and by the failure anticipation thanks to predictive maintenance.

Regular line maintenance and associated organizations are not modeled. It includes the regular short haul inspections of aircraft between their arrival and subsequent departure from an airport.

3.3 Airline Operations

To have valuable estimates of the future operational and support costs, it is necessary to consider the way a fleet is operated and supported.

This is one of the difficulties since low-costs, charters and major companies could operate Airbus aircrafts in very different manners. As a result the aircraft have to be adapted to the way they will be operated by airlines types.

The airline philosophy is considered through:

- Acceptance of functional degradation, considering airline policy and pilot decision;
- Spare management;
- Aircraft operational profile.

The aircraft operational profile is characterized by:

- Annual use;
- Flight length;
- Mean time between two successive flights;
- Mean exposure time to fault evidence in flight and on ground.

4 Trade-Off Models

Through their analyses the supportability specialists appreciate the dependency between design and support. They work to reach a good compromise between performance and cost.

4.1 Challenge Description

Today an increasing cost is being allocated to operations and support. As a result, it becomes necessary to explore "cause and effect" relationships between design decisions and their operational and support related impacts.

Designing for future support would benefit from models that provide engineers with quantitative arguments.

Permanently, supportability specialists perform trade-offs associated to different design alternatives and maintenance strategies. They challenge the relations between aircraft design and the possible airline organizations. The aim is to drive the design to meet the operational needs.

In common practice, we believe that the impact of aircraft design on the support system and its cost-effectiveness does not receive enough attention. Moreover, a valid quantitative analysis would minimize the risks in decision-making.

To illustrate, in comparing possible design alternatives, associated maintenance costs must be taken into account and balanced against the gains resulting from increased aircraft availability.

Even if adding redundancies improves operational reliability, it often increases maintenance costs. A compromise has to be found.

Adding scheduled maintenance tasks increases aircraft scheduled downtime, but it may sometimes be beneficial to the overall operating costs. In fact, it can avoid the potential cost of an unscheduled removal, which could induce delays, high repair costs and aircraft unscheduled downtime.

In the aviation industry, the approach to maintenance policy is most of the time a subjective approach, based on sound engineering judgment, previous evidence of successful maintenance regimes and safe escalation in agreement with the authorities.

An empirically grounded approach is not relevant to assess the impact of maintenance policies. In fact, representative historical data reflecting the performance of an item subject to different policies are rarely available.

Consequently, mathematical models can offer an invaluable help. However deterministic or probabilistic support models are rarely used in practice. Models often lack the simplicity necessary for evaluation.

Here we propose an easy method that enables to explore and utilize the dependency between supportability performances. As a result the model considers the interactions of:

- Reliability;
- Testability;
- Fault tolerance;
- Maintainability;
- Economical factors;
- Spare management;
- Maintenance policies.

An evaluation of aircraft systems must be based on detailed system-specific parameters. The model is developed to compare potential solutions. The inputs needed are often estimated on average and can be inaccurate. Thus, in this case, the value of the model is limited to comparisons and should be used with caution when investigating absolute values.

The methodology demands expert judgments. If little or no experience exits within the organization, it becomes difficult to get relevant inputs for the method. These estimates are mainly based on:

- Data collected from in-service Airbus fleet;
- Knowledge of the current design and information coming from others skills (safety specialists, system designers…) or organizations (e.g.: equipment suppliers…);
- Knowledge of future operations and support (aircraft mission attributes, types of major airlines customers, airports of departure and arrival…).
- Traced assumptions validated by design team, program management and airlines.

The model has the ability to combine engineering and financial information, like:

- Repair and test costs, sum of the labor and material cost;
- Cancellation and delay costs;
- Spare related costs.

4.2 Calculation Strategies

To compute supportability performances, two ways of modeling are necessary:

- A reliability grouping, based on system architecture;
- A maintenance grouping, based on scheduled task.

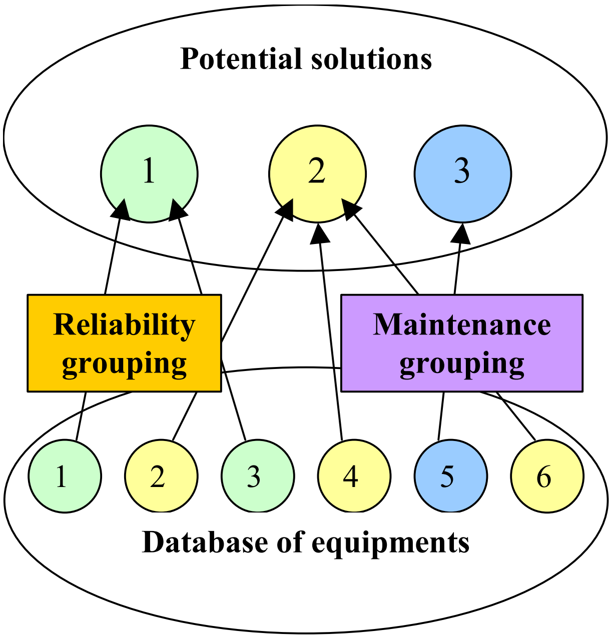

Fig.2 Calculation Strategies

4.2.1 Maintenance Grouping

A scheduled task is related to function(s). So in the model, we have a functional approach for the scheduled interval attribution.

This avoids recounting the time to perform the scheduled task if several items checked during the same task are analyzed.

On the other hand, having a functional approach provides consistency with:

- Safety analyses;
- MMEL status;
- Alarm philosophy;
- And particularly scheduled maintenance determination.

The method for determining the scheduled maintenance tasks and intervals for systems and power plants is based on a progressive logic diagram laid down in the Maintenance Steering Group-3 (MSG-3) document. It establishes a logical breakdown of the aircraft into functional areas.

In order to determine the appropriate maintenance tasks, the specialist first identifies the functions. Next, for each function, the analysts determine the possible failures that could occur to prevent the item from performing its intended function. Then, for each functional failure, the analysts determine the possible effects that could result from the failure. According to the operational and economical consequences, a task may be selected.

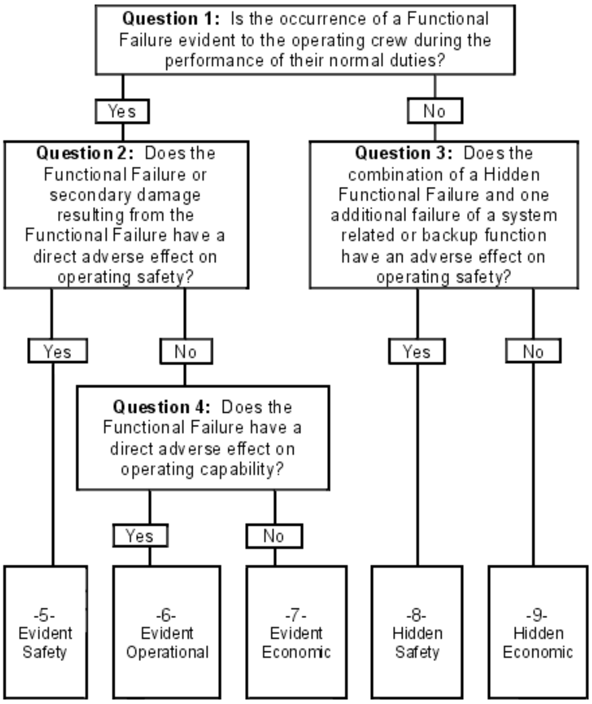

Fig. 3. MSG-3 Logic to Categorize Functional Failure Effects.

4.2.2 Reliability Grouping

Reliability grouping is necessary to predict operational interruption rate. Supportability engineers often need to work with systems having elements connected in parallel and/or series.

To calculate the system operational reliability, it is necessary to use a method, like the fault tree method, to analyze dependent and independent failure modes.

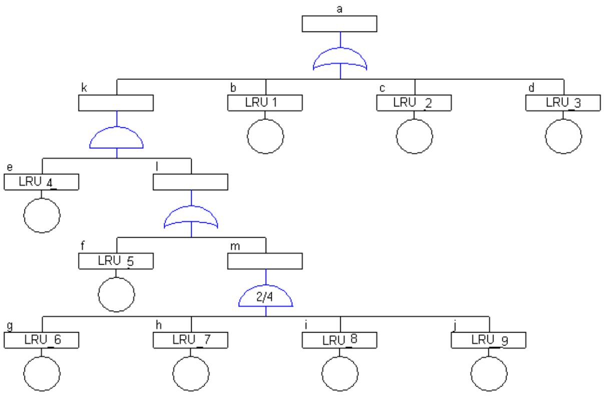

Fig. 4. Example of Fault Tree Diagram.

5 Decision Criteria

The method proposed makes predictive values available during concepts phases. At this stage, it is possible to take advantage of the design freedom available. The design process is immersed in uncertainty that decreases with time as knowledge increases about the system behavior. In fact, design freedom decreases very quickly and makes it difficult and costly to change the design once full-scale development has been initiated.

The dilemma is depicted in the figure below. The abscissa is the design timeline; design knowledge and freedom populate the ordinate. Knowledge is information about the object of design and the process embedded. Freedom is the degree to which changes in the product/process are feasible.

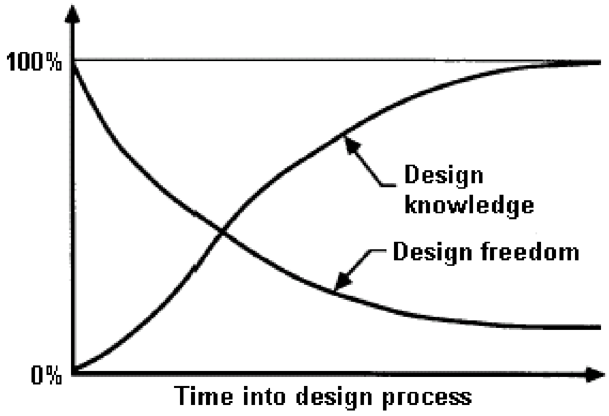

Fig. 5. Design Leverage.

Supportability engineering, implemented early enough in the design process, contributes to better aircraft operability. It can influence the design to focus on customer's values.

The model provides an analytical mean to assist supportability engineers in their decision-makings:

- Choice of a given solution for a given maintenance concept;
- Choice of maintenance type and frequency for a given design solution with a general maintenance concept.

The supportability performances of the system studied are given in cost. Considering economical implications caused by specific system ensures to:

- Have a common unit to integrate all supportability performances;
- Establish relationships between different elements of costs;
- Quantify potential economical risk area;
- Give supportability contribution to global aircraft performances (weight…).

The paper does not attempt to address whole life cycle cost or direct operating cost. We focus on the costing issues directly relevant to the supportability aspects. This assumption satisfies the needs of the supportability specialists. As a result, we do not consider here:

- Acquisition costs (aircraft price, documentation, training or infrastructure…);

- Indirect maintenance costs such as administration, training and airline engineering;
- Utilization costs (fuel, navigation and airports taxes, insurance…);
- Withdrawal costs (obsolescence).

As we want to design for the operational environment, the performance predicted must show us if we satisfy the need:

- To sustain commercial operations without interruption;
- To minimize operating, maintenance and support costs.

The model capabilities enable us to simulate several costs, based on agreed assumptions, for trade-off analyses:

- The direct cost of operational interruptions (e.g. cancellations, delays, diversions);
- The Direct Maintenance Cost (DMC) and Ground Support Equipment (GSE) cost;
- The costs of time not serviceable, which refers to preventive and corrective maintenance ground-time;
- And lastly the spare costs.

These performance measures will be the basis for decision support.

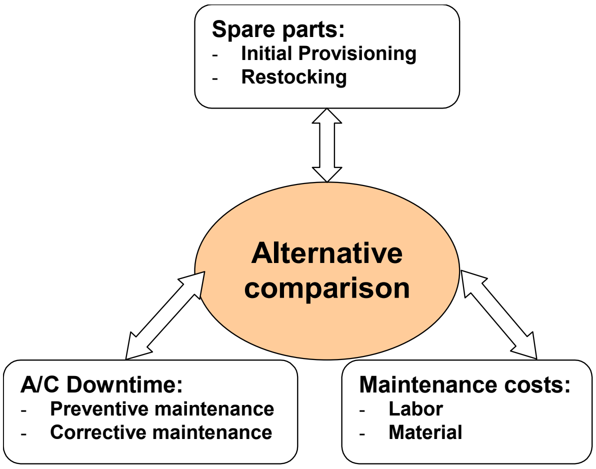

Fig. 6. Simplified Sketch of the Model.

All modeled costs are consolidated into a global supportability operating cost for comparing different design alternatives. Thus, we combine these separate contributions unambiguously by calculating their economical implications.

5.1 Operational Interruption Costs

Operational reliability measures the punctuality of aircraft operations against failure occurrence. It is the percentage of scheduled flights, which depart and arrive without incurring a chargeable (technical) operational interruption. It remains a top priority for all operators given its strong commercial impact, punctuality being a major cause for dissatisfaction.

Delays and cancellations are the most frequent results of disruptive events.

Technical delays occur when the malfunctioning of equipment, related checking and required corrective action causes the aircraft's departure to be delayed by more that a specified time after the scheduled departure time (usually 15 minutes of delay). When talking about aircraft performance, only delays linked to aircraft design are considered. The delays not taken into account in the modeling are those due to:

- Weather;
- Air Traffic;
- Personnel availability (strikes);
- Passengers' delays;
- Accidental damages…

A cancellation occurs if a scheduled revenue flight is cancelled after being delayed or, if a too long delay is expected.

The impact of operational interruption ranges from real revenue losses to customer dissatisfaction. On top of the negative impact on customer satisfaction, delays are expensive. Air Transport Association estimates that, for 2004, 86.5 million ATC delay minutes drove an estimated $4.8 billion in direct operating costs for U.S. airlines.

An operational reliability tool [1] has been developed within Airbus to predict the in-service behavior of a given design regarding delay and cancellation rate. The operational interruption, due to specific equipments, is a stochastic event. Its probability is usually between 10^{-7} and 10^{-4}.

In our study, we use this tool to assess operational interruption rate and we then convert it into costs.

5.2 Maintenance Costs

Maintenance costs can be split into several categories, mostly indirect (material handling, supplies) and direct (labor and materials) costs.

During aircraft life, accumulated maintenance costs are in the order of magnitude of the aircraft acquisition costs.

As an aircraft manufacturer, major cost parameter that can be influenced is the Direct Maintenance Cost (DMC). Direct Maintenance Costs (DMC) are defined in the ATA Common Support Data Dictionary (CSDD) [2] as maintenance labor and material costs directly expended in performing maintenance on an item.

On-aircraft DMC are originated by labor and material costs on aircraft structures and installed systems (equipment). Off-aircraft DMC are originated by labor and material costs for both test and repair of an item removed from aircraft and send to repair shops on a scheduled or unscheduled basis.

The DMC of LRU can be added up to that of a subsystem and subsequently to a system. This methodology has traditionally been used by Airbus in the bottom up calculations of DMC.

On the other hand, DMC does not include those indirect maintenance labor and material expenditures which contribute to the overall maintenance operations, line station servicing, administration, record keeping, supervision, tooling, test equipment, facilities, etc. These indirect costs are called Indirect Maintenance Cost (IMC) or overheads.

In the model, the DMC triggered by scheduled maintenance include check cost and, in case of finding, repair cost (on and off aircraft).

The DMC triggered by predictive maintenance include the prognostic and diagnostics cost and, in case of findings repair cost (on and off aircraft).

The DMC triggered by corrective actions include trouble-shooting, test and repair cost (on and off aircraft). In this case, the manpower cost is not only impacted by test and repair time, but also by mean time to apply MMEL procedure, if relevant.

5.3 Spare Costs

Spare parts are also an important factor for the effectiveness of a support system. In fact, the provision and maintenance of an appropriate stock of spares is decisive for the support cost and availability of a system. In fact, the lack of spare can induce long time out of service.

Maintenance and repair tasks are delayed if too few spare parts and assemblies are purchased. On the other hand, if too many spares are bought, the cost of storage rises and the capital is tied up in inventory.

The increasing airline competition demands for intelligent methods of spare quantification taking into consideration both technical and economical requirements. Spare management is complex because linked to:

- Item criticality (operational impact, passenger comfort);
- Spare price;
- Fleets and categories;
- Multi locations;
- Seasonality;
- Item obsolescence.

Even if spare cost is quite specific to each operator, a generic mean spare cost can be calculated assuming an average fleet size and spare policy, for example.

In this model, the main input parameters to assess spare part quantities are:

- The fleet size;

- The aircraft utilization;
- The variation of protection level according to item criticality;
- Reliability;
- Spare turn around time (transit time, shop processing time, lead time and administrative time);
- Specific airline parameters (number of maintenance stations, type of operations).

The spare costs include:

- Initial provisioning costs, i.e. a non-recurring cost spent by the operator at aircraft delivery. In the model, the initial provisioning investment has been spread over a given amortization period of several years using an interest calculation formula.
- Spare restocking costs, linked to removal rate.

5.4 Downtime Costs

Keeping aircraft downtime to a minimum is key when discussing flexibility. Today maintenance has to be very fast, because large losses of profit can be attributed to downtime.

Low cost airlines, in particular, are seeking to reduce the downtime required for aircraft maintenance.

Rather than talking about compulsory maintenance ground time, airlines often talk about aircraft unavailability defined by the time the aircraft is not available for commercial operation. Aircraft unavailability for commercial utilization is split between:

- Planned downtime (scheduled maintenance)
- Unplanned downtime (breakdowns).

Reducing maintenance downtime comes down to:

- Reducing frequency of preventive and corrective maintenance;
- Reducing time to restore a function, to apply MMEL procedures, to perform a scheduled task or restore pax comfort related functions.

This output is given in cost by using the Revenue Passenger Kilometer (RPK) and average load factor.

6 Conclusion

Today Airbus has developed and implemented a first model to predict the global supportability performance of its products. It is envisaged to enhance the model and take into account a global extended enterprise point of view (e.g. system suppliers).

Moreover further research will be conducted to take into account new concepts like health monitoring. The objective is to integrate appropriately the assessment of such capabilities within the model.

7 References

[1] Hugues E, Saintis L and Cabarbaye A. ORA, model and tool for predicting Operational Reliability within Airbus. *Congrès Maîtrise des Risques et Sûreté de Fonctionnement (Lambda-Mu 14)*, Bourges, pp. 448-451, 2004.

[2] Air Transport Association. ATA Common Support Data Dictionary, 2005.

[3] Mavris Dimitri N, DeLaurentis Daniel A. A probabilistic approach for examining aircraft concept feasibility and viability. *SO Aircraft Design (1369-8869)*, Vol. 3, No. 2, pp. 79-101, Jun 2000.