

OPTIONS FOR INTERCONNECTION OF SAFETY ASSESSMENT METHODS AND RELIABILITY CENTERED MAINTENANCE IN GENERAL AVIATION

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Keywords: *Aircraft, aviation, safety, reliability, RCM.*

Abstract

Since late 90's of the past century, the General Aviation (GA) aircraft systems have become much more complex and sophisticated. Especially in avionics, systems took a great step from mechanical instruments to adoption of multifunctional display units capable of single-pilot IFR operations. Therefore, it was necessary to significantly extend safety procedures and assessment methods and change maintenance practices already adapted for the category. The paper discusses problems of reliability/safety procedures application, current trends in maintenance and the way the systems architecture is affected. In addition, an increased effort in application of Reliability Centered Maintenance (RCM) in the small transport aircraft category is discussed and emphasized. Paper provides extension of the information given previously in [14].

1 Introduction

Theoretical approach to **safety and reliability** issues can be tracked down to 1930's. Through advances in dependability theory during World War II and in 1950's, a safety assessment with requirements defined in regulation **standards definitely took place in aviation in 1960's** of the last century. Sophisticated methods were developed and first applied on large transport airplanes in civil aviation, like Boeing aircraft developed since 60's. In Europe, first large application of safety

assessment methods is connected to the development of Concorde and Airbus A300 [13]. Simultaneous advances in reliability theory enabled more detailed (and also wider) safety analyses. Complexity of the safety assessment has grown up, partially also as a result of more complex aircraft systems.

The same increasing complexity of aircraft was also strong driver in the search for better maintenance procedures, enabling reduction of work effort and expenses in the **maintenance process**. Again, first applications were made for large transport aircraft. Result was adoption of RCM and particularly MSG-3 procedures. These procedures are based on criticality of components for the aircraft safety and also on their reliability and economic impacts of failures. Similar trends with some time delay can be found in **General Aviation (GA)** and **commuter aircraft**. However, complexity of smaller aircraft was also significantly smaller. Since 1990's, with adoption of highly complex avionic systems even for smaller aircraft, also application of safety assessment methods made a great step towards more complex and more detailed analyses. Institute of Aerospace Engineering (IAE) caught this trend and since 90's has **education in dependability of aircraft systems**. Through the last 10 years, it was also involved in the development and certification process for several GA aircraft – with Reliability/Safety assessment of numerous aircraft systems. Close cooperation with the

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Fig. 1. Simplified presentation of current aircraft categories and used safety and maintenance procedures

Whereas use of detailed safety assessment is today necessary for all aircraft categories, practical experience shows that MSG-3 procedures are still not economically feasible for small general aviation aircraft, like Cirrus SR22 – fig. (c). However, small transport aircraft with 19 seats start to be complex enough to make use of MSG-3 interesting – fig. (b). Often aircraft operators ask for utilization of MSG-3 for maintenance of such aircraft. Big transport aircraft, as Airbus – fig. (a) use MSG procedures for over 30 years.



(a) Airbus A340



(b) Let L-410



(c) Cirrus SR22

industry on practical realizations, together with own research activities forms background for education activities on this field. Fig. 1 shows in simple and easy to understand way, where is today feasible utilization of MSG-3 maintenance procedures. The information is based on long time cooperation with aircraft producers in general aviation and participation on design and certification process of numerous aircraft.

2 Reliability/Safety Assessment Process in System Design and Verification

Elementary requirements on the General Aviation aircraft¹ systems reliability/safety

¹ All types of civilian aviation other than commercial aviation (Commercial Aviation: Transportation by aircraft of passengers or cargo for hire and the ferrying of aircrafts as a commercial venture). Most general aviation aircraft were designed in compliance with CS-23 (or FAR-23) requirements and have between 2 and 19-seats.

assessment process are covered by the **Subpart F** of FAR/CS-23 airworthiness codes, and more specifically in §23.1309 of these regulations. Requirements are used in **design and certification phase** (as mandatory requirements). Even though, this paragraph is important for systems development and modifications, the requirements and recommendations involved are very general, and hence not directly applicable in the aircraft design and certification process. Therefore, for showing compliance with the paragraph, and to support certification activities in the category, an advisory circular AC 23.1309-1D, ref. [3] has been issued, as an amendment to the regulation.

Basically, the document [3] provides very valuable guidance and information on the reliability/ safety assessment process, and methods that are recommended in certification process for the category. In addition, the

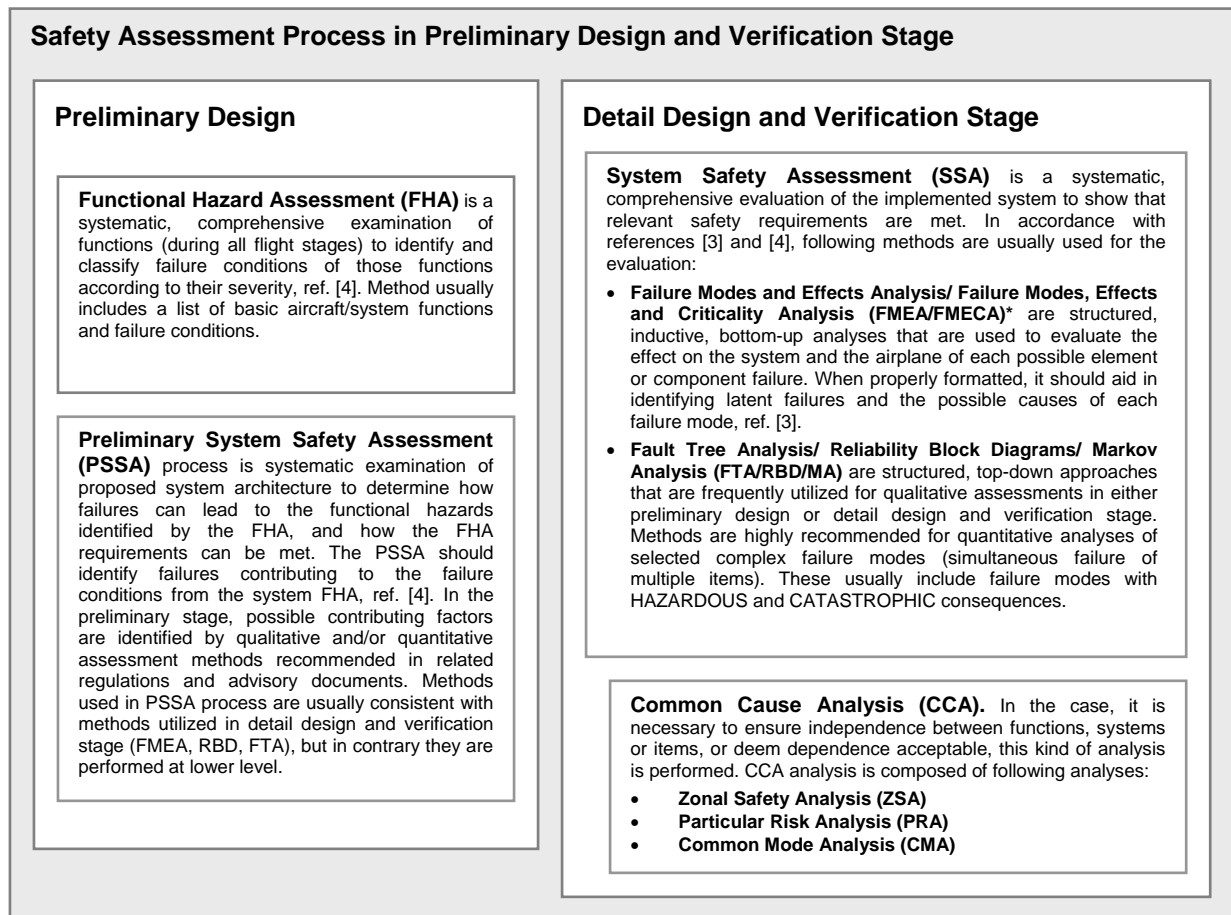


Fig. 2. Simplified overview of the Safety Assessment Process in preliminary design and verification stage (definitions partially taken from *SAE ARP4761* document, ref. [4]).

advisory circular defines operational and maintenance considerations. Although AC 23.1309-1D is an important document dealing with reliability/safety appraisal requirements and recommendations, it is not the single one. A wide range of other materials and notes exist, and may be used as a useful source for performing preliminary and detailed safety assessment process.

The most important ones, also referred in the advisory document are ARP 4754 [4] and ARP 4761 [5]. Documents describe detailed guidelines and methods for performing the reliability/safety assessment process. An overview of certification and verification process as well as methods utilized for the category (in accordance with *ARP 4761* document) is presented in figure 2.

Nowadays, **Institute of Aerospace Engineering (IAE)** is involved in many safety/reliability related activities on the field of the **General Aviation**. Besides large international projects as PPLANE or CESAR², the crucial part of activities includes close collaboration and co-operation with Czech aerospace industry. As a result, significant contribution to design and development of a new generation aircraft systems has been achieved, through the assessment processes; these include safety/reliability appraisals

² **PPLANE** – Personal Plane: Assessment and Validation of Pioneering Concepts for Personal Air Transport Systems;
CESAR - Cost Effective Small Aircraft.

performed at various levels³, and for different aircraft classes⁴. As an example of analyses done in the past on different aircraft systems, a short list is provided:

- Safety/reliability assessment of electric-power distribution system
- Safety/reliability assessment of avionic system
- Safety/reliability assessment of Pitot-static system
- Safety/reliability assessment of engine control system
- Safety/reliability assessment of trim system
- Safety/reliability assessment of flaps extension/retraction system



Fig. 3. VUT100 Cobra

Compared to civil transport aircraft category, the assessment methods utilized for the GA aircraft systems have their own specifics. Thanks to the increased complexity in recent years, certification and verification processes of such systems became much more complex; especially electric/electronic and avionic equipment complexity have grown-up.

However, forasmuch as the manufacturers in the category are small and medium sized enterprises with very limited resources, appropriate level of simplification is recommended for modeling of complex or/and highly integrated aircraft systems. Basic simplifications that are fully acceptable and adequate for certification and verification purposes within the category are defined in SAE ARP 4761 [4]; apart of these, the level of adequate simplification should be also dependent on the class, in which the particular aircraft is categorized (in accordance with an aircraft division in AC 23.1309-1D ref. [3]).

In the past, IAE practically applied safety assessment procedures (including testing of simplifications) on its **VUT100 Cobra** airplane, at the beginning designed at IAE under the lead of prof. Pistek and later developed in close cooperation with EVEKTOR Company. Many systems of this 5-seater aircraft were analysed and design changes were made (based on safety assessment). The cooperation later continued with EVEKTOR **EV55 Outback** project – twin-engine turboprop 10-seater aircraft. Different aircraft class brought also different procedures applied in safety assessment. IAE also developed an experimental aircraft **VUT 001 Marabu**. Together with other aircraft, wide range of systems in different classes of GA aircraft were analysed on IAE. Experience is also supplemented by **national projects** (like Aerospace Research Centre) and **EU projects** (like CESAR and PPLANE) held at the institute. Typical assessment methods for the selected aircraft systems and general recommendations on the systems architecture to meet the regulation requirements are given in table 1.

³ Preliminary System Safety Assessment/ System Safety Assessment (see figure 2).

⁴ The institute, has an extensive experience with **Class I** (typically single reciprocating engine and max. weight under 6000 lb.) and **Class III** (typically single or multiple reciprocating or turbine engines max. weight equal or over 6000 lb.) aircraft safety/reliability assessment (the definition of classes is in accordance with advisory circular AC 23.1309-1D, ref. [3]).

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Tab. 1. Examples of typical systems, where safety assessment is required

SYSTEM	THE WORST FAILURE CONDITION BY FHA	TYPICAL ASSESSMENT METHOD	RECOMMENDATION/ INFLUENCE ON THE SYSTEM ARCHITECTURE
Avionic electronic system	CATASTROPHIC (IFR ⁶ operations)	Detailed safety/ reliability assessment consisting of qualitative and quantitative analysis. Verification of independencies or identification of specific dependencies between systems. Specific failure modes are usually proven by tests.	Back-up of critical attitude, altitude and heading information. Particular indicators are usually connected to electric-power system as essential loads. Maximum possible safety/reliability is achieved by appropriate distribution of single devices to different sources of el. power.
	Total loss of primary flight information necessary for continued safe flight and landing		
Pitot-static system	HAZARDOUS/ CATASTROPHIC (IFR ⁶ /icing operations)	Safety is often proved based on similarity to existing (and certified) system with satisfactory service experience. (In accordance with AC 23.1309-1D, 15c(1)). In some special cases, it may be required to establish independence and isolation of the channels via qualitative methods. Alternatively, detailed safety assessment may be used.	Back-up of static pressure sensor for all IFR ⁶ aircraft. The commuter aircraft (as well as large transport aircraft) must have, in accordance with regulation requirements two independent Pitot-static systems.
	Loss of airspeed and altitude information.		
Trim system	CATASTROPHIC	Detailed safety/ reliability assessment consisting of qualitative and quantitative analysis. Alternatively, prove of safety based on similarity to existing system.	Critical components with failure leading to release of trim tab from control surface (particularly mechanical components and connections) must be backed up.
	Release of the trim tab connection to control surfaces; since the trim tab is often not aerodynamically and mass balanced, there is a high probability that flutter occurs.		

2.1 FMEA / FMECA

According to ref. [6], in the risk related applications, such as military, automotive industry or medical equipment, where failure of the system, may eventuate in very serious consequences the qualitative analyses are usually evaluated during preliminary and certification stages. The situation is similar in aerospace applications where the **FMEA (Failure Modes and Effects Analysis) or FMECA (Failure Modes, Effects and Criticality Analysis) analysis is usually necessary** for showing compliance with the requirement ‘*No Catastrophic Failure Condition should result from the failure of single component⁵*’. In this case, the reliability/safety assessment usually consists of appropriate combination of qualitative and quantitative analyses. However, mentioned application is not the only one; for the failure

conditions resulting in less substantial consequences, the analysis may be used to show the isolation between the redundant system channels or to support other assessment methods (tests, similarity, etc.).

Definition of FMEA/FMECA is given in fig. 2. The principle of the analysis is to consider each failure mode of every component of a system and to ascertain the effect on system operation.

FMEA/FMECA analysis may be used very effectively to identify safety or reliability critical components, failure modes and their effects on the overall system; moreover, particular recommendations on the system architecture improvements are part of this qualitative assessment. Outputs from FMEA/FMECA typically include:

- *Recommendations for design changes*
- *Recommendations for flight manual/checklists*
- *Recommendations for maintenance*
- *A list of critical components*

⁵ Also, no single failure should result in the loss of a function that causes a Hazard Failure Condition, in compliance with AC 23.1309-1D document, ref. [3].

⁶ Aircraft capable of IFR flights (Instrument Flight Rules) – aircraft able to fly under adverse weather conditions and at night using only instruments onboard for flight control and navigation.

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Tab. 2. An example of piece-part FMEA analysis (modified ARP 4761 form for FMEA)

FAILURE MODES AND EFFECTS ANALYSIS (FMEA)		
System: Hydraulic system	FMEA Description: Aircraft XY hydraulic system	Date: 15.9.2008
Subsystem: Primary System		Sheet 6 of 39
Item Gamma: 29	FTA References: FTA 29-001	File: Hydraulics_0X
Function:	Author: Andrej Weisman	Rev: 1

PART No.	PART TYPE	FAILURE MODE	FAILURE CAUSE	FLIGHT PHASE	FAILURE EFFECT	FAILURE EFFECT ASSESSMENT	COMMENTS
A01	Relief Valve A01	No operation on demand	Stuck, mechanical failure, defective spring	All flight phases	Increase of the pressure (signalized to pilots on MFD); Function is performed by Relief Valve A04.	MINOR	<i>Maintenance action:</i> Exchange or repair of defective valve.
		Spontaneous operation	Mechanical failure		Hydraulic fluid is flowing directly into reservoir; loss of pressure in primary hydraulic circuit. Pressure is supplied by standby line. Together with loss of pressure in standby line - HAZARDOUS	MAJOR	<i>Maintenance action:</i> Replacement of the valve.
		Leakage	Seal failure		Hidden failure; limited leakage of hydraulic fluid.	MINOR	<i>Maintenance action:</i> Exchange of defective sealing.

As a practical example of the qualitative safety/reliability process significance and impact on aircraft system architecture, the **MASTER switch** may be taken (see Figure 3); design of this switch must ensure release of all sources of the electric energy in the case of extremely adverse



Figure 4: Typical configuration of MASTER switch (Cessna C-172)

operating conditions (as emergency landing, etc.). On the contrary, in the case of the switch failure (spontaneous release), it **must not** allow to detach all these sources (with catastrophic consequences for IFR aircraft). Therefore, the switch is physically divided into two independent parts and able to fulfill all the airworthiness standard requirements.

Results of FMEA/FMECA are not strictly connected only to safety related applications. Accordingly, the method can play a significant role in implementation of Reliability Centered Maintenance. More detailed description of the relationship between RCM and FMEA/FMECA methods will be subject of the next chapter.

3 Application of MSG-3 on Aircraft Systems

The idea of MSG-3 application on Czech GA aircraft established from the cooperation with Czech aircraft producers. The application of this method gives an advantage to our producers and their customers against competition (saving of maintenance costs, operational improvement of an aircraft). Furthermore, development in MSG-3 methods went so far that even operators of existing aircraft in small transport aircraft category push producers to introduce MSG-3 maintenance programs for given type to save operational costs.

3.1 MSG-3 History

Before the MSG logic, up to the early 1950s and early 1960s, all aircraft maintenance was

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based on the theory of preventive replacement or restoration, commonly referred to in the industry as “hard-time”. Fixed lives for all parts or tasks were written into the maintenance schedule and adhered to when planning the work. They were not efficient and cost-effective, because they do not take into account the parts reliability, effects of failures and the maintenance time consumption.

Development in maintenance methods led to introduction of MSG. The Federal Aviation Administration (FAA) and the airline industry formed a Maintenance Steering Group (MSG) to develop the new approach for establishing initial scheduled maintenance plans for aircraft.

In July 1968, MSG-1 was applied for Boeing 747. New maintenance plans MSG-2 and EMSG-2 were applied to other types of airplanes. MSG-3 was introduced in 1980.

3.2 Implementation of MSG-3

The first step in MSG-3 implementation is to define systems and subsystems of the aircraft.

For example in compliance with ATA iSpec 2200.

For each component of systems, subsystems and parts, it is necessary to review the available technical data, (reliability and maintainability characteristics and description, operation documentation). The next step is the determination of the “maintenance significant items” (MSIs) for each component by answering the questions about its detectability, safety, operational and economic impact. If the answer to any of these questions is yes, then according to the MSG-3 guidelines, the item needs specific analysis to determine the maintenance tasks, if any, that will be applicable and effective to detect and/or prevent failure.

In order to determine the appropriate maintenance tasks for each MSI, the next step is to identify the functions, failures, causes and effects.

In this step FMEA (Failure Modes and Effects Analysis) or FMECA (Failure Modes, Effects and Criticality Analysis) can be used.

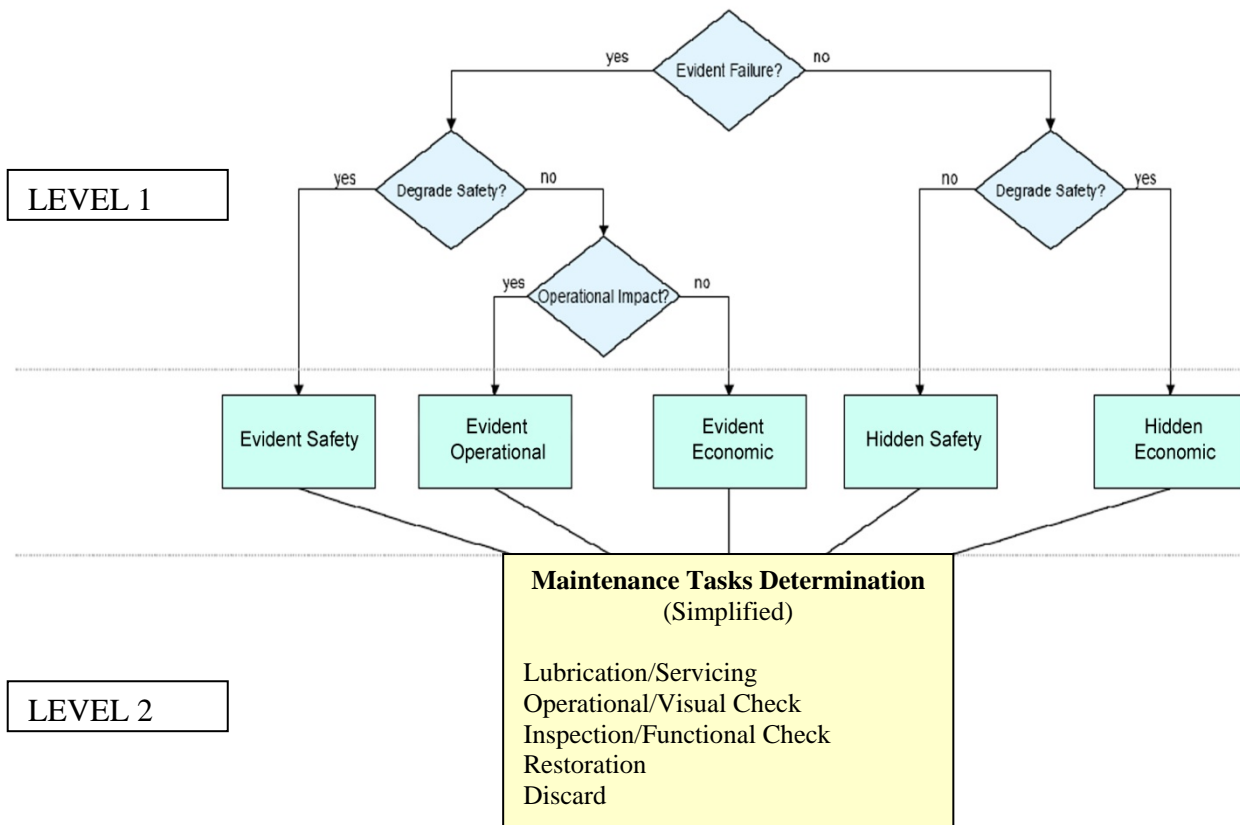


Fig. 5. MSG-3 logic

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MSG-3 guidelines provide logic designed to assign each functional failure effect to one of five categories: *Evident Safety, Evident Operational, Evident Economic, Hidden Safety, Hidden Economic*. This is also referred as “level one analysis” and the decision-making logic is presented in fig. 5.

For each potential failure, the MSG-3 guidelines provide logic, referred to as “level two analysis,” to determine the appropriate scheduled maintenance tasks. There are five types of tasks that can be performed: *Lubrication / Servicing, Operational / Visual Check, Inspection / Functional Check, Restoration and Discard*.

In the real maintenance tasks assigning step are assigned real maintenance tasks with a description and intervals to MSG LEVEL 2 maintenance tasks. Reliability or economic data can be used for interval optimization or field experience with the operation of similar airplanes part.

MSG Analysis Report contains a list of parts, maintainability and reliability data, MSIs,

functions, failures, effects, causes, maintenance tasks and intervals that has been identified for each MSI. It is used for creation of the final maintenance plan. Systems/Powerplants, Structure, Zonal, L/HIRF Maintenance Tasks are grouped to bigger maintenance blocks, consistent with operator operations and capabilities, to accomplish scheduled maintenance tasks. There are a number of approaches to develop this final maintenance plan (Block, Segmented, Phased, Continuous maintenance Visit, etc.).

3.3 Relationship between Reliability Analyses and MSG-3

MSG-3 analyses utilize, as the input, PFHA (Preliminary Functional Hazard Assessment) and FHA (Functional Hazard Assessment) for all aircraft systems and parts. Also FMEA can be used as valuable source of data for MSG-3. These analyses can be applied to define system functions, failures, causes and effects and to answer MSG-3 LEVEL 1 questions.

Tab. 3. Interconnection between FMEA and RCM

Classification applied by AC 23.1309 (typically used in FMEA)	EFFECTS (RCM LEVEL 1 categories)	
	Evident Failure (Evident)	Hidden Failure (Hidden)
No Safety Effect	No Safety Effect / Evident Economic Effect	No Safety Effect / Hidden Economic Effect
Minor	Evident Operational Effect (optionally Evident Safety Effect) ^{***}	Hidden Economic and Operational Effect (optionally Evident Safety Effect) ^{***}
Major	Evident Safety Effect	Hidden Safety Effect
Hazardous	Evident Safety Effect	Hidden Safety Effect
Catastrophic	Evident Safety Effect	Hidden Safety Effect

Note*: FMEA (safety assessment) is focused only on safety related issues, but it does not cover economic or operational issues. Failure can have no safety effect; however, it can cause large damage with high repair costs. Sometimes, repair can be more expensive than preventive maintenance.

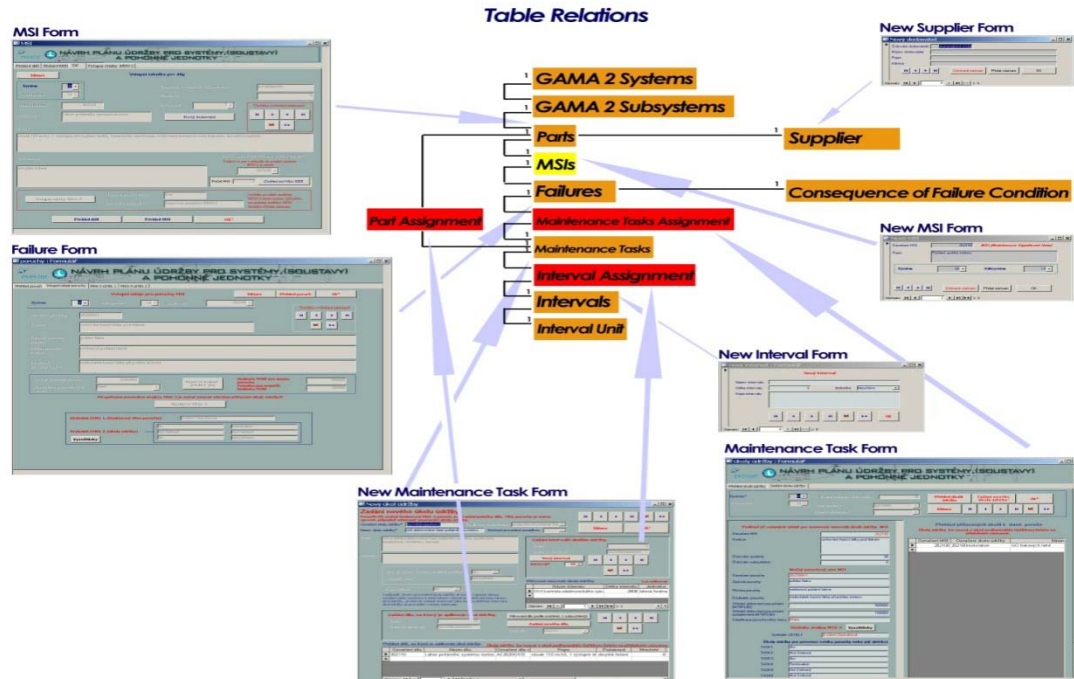
Since economic effects form important part of the maintenance plan, “No safety effect” classification (AC23.1309) uses several categories from RCM Level 1 (No Effect / Evident Economic)

Note**: FMEA analysis lists only failures of single components. However, to assess effects of Hidden failures, classification for simultaneous failure of primary and the back-up system is used.

Note***: Failures classified as MINOR (in accordance with AC 23.1309) often result in small reduction of safety margins or in emergency procedures. Based on particular case, classification may be i.e. “operational” or “safety”.

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Glossary

- 1 Relations between tables are 1-n type. It means, that n entries in a table belong to the entry in another table, what is signed 1 for this relation.
Example: N failures belong to one MSI, but n MSIs don't belong to one failure.
- Tables for creation of n-n relations
Example: One failure belongs to n maintenance tasks and one maintenance task belongs to n failures.
- Directing table
Example: N parts and n failures belong to one MSI.

Fig. 6. Structure of Database for Aircraft Systems and Powerplants Maintenance

Major drawback of common safety and reliability analyses is their focus only on safety related issues. Failure effects are split into several categories – *No Safety Effect, Minor, Major, Hazardous and Catastrophic*. In contrary, MSG-3 uses classification focused on safety, but also on operational economy and diagnostics. Outputs from RCM Level 1 include following classification - *Evident Safety, Evident Operational, Evident Economic, Hidden safety and Hidden Economic*.

Classifications used in safety assessment and in MSG-3 have so strong similarities that it clearly offers interconnection. One of possible approaches to standardize interconnection between reliability analyses and MSG-3 is presented in tab. 3.

3.4 Software Application for Maintenance of Aircraft Systems and Powerplants

MSG-3 analysis can be done without the software application, but human faults do occur, this analysis is very extensive and it is difficult to handle great amount of data. The software created at Institute of Aerospace Engineering is GA maintenance oriented and its application is cheaper and more suitable for this category. It works with available data gained through the airplane design, certification and service. The big advantage is that the maintenance plan can be updated through the service and data of this database can be used for the solving of failure causes and effects in the service. The contact with customers and operators of aircraft can be performed through the internet portal that is connected with this database. This contact is very important, because the aircraft producer

can optimize the maintenance plan in accordance with operator requirements.

This software is used for easier, more effective and faster application of MSG-method for the creation of maintenance plans for systems and powerplants of small aircraft. This user-friendly database application was created in Microsoft Access 2003. Programming in Visual Basic and SQL was used during development.

The software-user interface has the logical structure. There are forms for data input for parts and MSIs, failures and RCM analyses, maintenance tasks and intervals and forms for output reports. The MSG-3 process is fully integrated. There are cells for data input that serve to the identification and better description of parts, MSIs, failures, tasks and intervals. The software environment and the structure of this database is shown on Figure 6.

3.5 Practical Application of MSG-3

Meantime, there is significant demand for application of MSG-3 procedures for small transport aircraft. Since, there is an increasing complexity in systems for such aircraft, MSG-3 can offer significant savings in maintenance. One of current practical realizations is application of MSG-3 during L-410 UVP maintenance plan innovation. L-410 (Figure 7) is the legendary Czech turbo-propeller aircraft for 19 passengers. Many versions of L-410 have been operated for many years. It is produced by Aircraft Industries a.s. Requirements of operators led to search for possible application of MSG-3 in current modernization process. Steps that have to be done before MSG-3 application include:

- *Evaluation of the L-410 current maintenance programme and its problems.*
- *Formulation of maintenance goals, (required maintenance costs and time consumption).*
- *Available data assessment.*

- *Development of the narrow cooperation with operators and Civil Aviation Authority.*
- *Training of maintenance specialists.*



Fig. 7. L-410 aircraft (2-engine turboprop, 19-seats)

IAE already started the cooperation with Aircraft Industries a.s. The first phase of MSG-3 methodology testing is in progress. MSG-method was applied to selected parts of L-410 systems. It wasn't possible to utilize complete MSG-3 process in the first step, because of limited extend of the task (serving rather as a testing sample). Availability of input data, as well as procedures for MSG-3 application were tested. It was proved that even in this aircraft category, it is possible to apply MSG-3 methodology to all aircraft systems.

4 Conclusions

The paper presents recently growing field of safety/reliability assessment in the general aviation. Modern trends connected with introduction of new avionic systems force producers to adopt more complex development methods including detailed safety assessment of systems. On the other hand, the need to reduce operating costs creates pressure on adoption of RCM methods for maintenance also in GA and commuter aircraft categories. RCM slowly penetrates to commuter aircraft and its application in smaller GA aircraft can also bring reduction of operating costs (especially for aircraft with complex avionic equipment).

The trend towards introduction of MSG and its close connection to safety assessment offers improvements for future GA aircraft. Some of the related activities are presented in the paper. **Table 3** provides guidelines for **interconnection of safety assessment process** (part of development and certification) **and MSG-3 maintenance**.

IAE-BUT (Institute of Aerospace Engineering - Brno University of Technology) closely cooperates with the industry and helps to practically apply (and further develop) latest knowledge available on this field. An example is own software application supporting creation of MSG maintenance programmes, see chapter 3.4. These activities should help Czech (and European) industry improve competitiveness on the world market.

Acknowledgment

Some of the presented activities were partially supported by Czech Ministry of Education, Youth and Sports (in the frame of Aerospace Research Centre), by Ministry of Industry and Trade (in the frame of grant projects FI-IM/038 and FI-IM4/041).

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