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Abstract

Rail transport industries are currently experiencing higher demand on rolling stock performance, capacity and service quality. As a result, higher levels of resilience against failure, robustness and availability at reduced cost are expected. This necessitates development and implementation of an applicable and effective maintenance planning and scheduling system. With increasing awareness of the benefits of Condition-Based Maintenance (CBM), employment of this maintenance strategy has become a focus of rolling stock companies all over the world, setting ambitious and challenging issues.

Over the past decades, significant improvement has taken place in the development of an applicable and effective Condition-Based Maintenance. One of the major developments has taken place by the aviation industry with the introduction of on-condition inspection/condition based maintenance through the Maintenance Steering Group (MSG-3) concept. MSG-3 methodology implicitly incorporates the principles of Reliability Centered Maintenance (RCM) to justify task development and incorporates an efficient maintenance decision logic for the selection of an applicable and effective maintenance program. This methodology is a combined effort by the manufacturers, regulatory authorities, operators, and Air Transport Association (ATA) of USA (ATA). In the commercial aviation industry, increasing emphasis is now being placed on using the MSG-3 methodology for development of scheduled maintenance tasks and intervals for modern commercial aircraft. MSG-3 is a common means of compliance for developing scheduled maintenance requirements in the framework of the manufacturer's instructions for continued airworthiness promulgated by most of the regulatory authorities.

The aim of this report is to introduce the proven experience gained through the application of MSG-3 methodologies, in the development of scheduled CBM based aircraft maintenance program. In particular, the objective is to evaluate the potential benefit of a system such as MSG-3 to the railway industry for the development of an effective and efficient rolling stock maintenance programme. To achieve the purpose of this research, literature studies has been conducted and empirical data and information have been collected through document studies, interviews, questionnaires, and observations from the aviation industry, combined with the published best practices from the aviation industry.

The report describes the evolution of scheduled CBM methodology within the aviation industry and provides an overview of the "aircraft maintenance program development". The underlying concept, principles and processes of MSG-3 are presented and the details of each maintenance strategy is discussed with a specific focus on inspection/functional check. In continuation, the current practices in the rolling stock industry for development of maintenance programs is discussed and an assessment of current use of CBM in European train operating companies is provided.

Based on the results obtained through this study, it is highly recommended that a task force to be established within the railway industry to harmonize the regulations among stakeholders and railway authorities, for development of rolling stock's Inspection/CBM programs. In this process, the study also suggests that rolling stock stakeholders should establish a Maintenance Review Board to develop a specific maintenance program and share their data and experience. Special attention should be given to the identification of Maintenance significant items, definition of applicability and effectiveness criteria, and determination of maintenance intervals. It is also vital to implement a "maintenance reliability and surveillance programme" to evaluate and control the effectiveness of maintenance program.

Contents

List of abbreviation and acronyms

AIAA	American Institute of Aeronautics and Astronautics	MRBR	Maintenance Review Board Report
ALS	Airworthiness Limitation Section"	MSG	Maintenance Steering Group
APU	Auxiliary Power Unit	MSG-3	MSG-3 Airline/Manufacturer Maintenance Program Planning Document
ASM	Ageing Systems Maintenance	MSI	Maintenance-Significant Item
ATA	Air Transport Association of USA	NAVAIR	U.S. Naval Air Systems Command
CBM	Condition Based Maintenance	NDE	non-destructive examination
CCS	Control Command and Signaling	NDT	Nondestructive testing
CDM	Condition Directed Maintenance	NoBo	notified body
CM	Condition monitoring		
CMR	Certification Maintenance Requirements	OC	On-condition
DET	Detailed Inspection	PBS	Product Break down Structure
EMSG	Engineering and Maintenance Standing Group	PRM	Accessibility for people with reduced mobility
ETA,	Event Tree Analysis	QoS	Quality of Service
FAA	Federal Aviation Administration	RAMS	Reliability, Availability, Maintainability, Safety
FAL	Fuel Airworthiness Limitations	RCM	Reliability-Centered Maintenance
FCU	Fuel Control Unit	SAE JA1012	A Guide to the Reliability-Centered Maintenance RCM Standard
FMEA	Failure Mode and Effect Analysis	SDI	Special Detailed Inspection:
FTA	Fault Tree Analysis	SJ	Statens Järnvägar
GVI	General Visual Inspection	SPA	special protection area
HAZOP	Hazard and Operability	SRT	Safety in Railway Tunnels
HT	Hard Time	S-SHM	Scheduled Structural Health Monitoring:
LCC	Life Cycle Cost	TBM	Time-based maintenance
LOC&PAS	Locomotives and passenger units	TC	Type Certification
MIL-STD-2173	Military Standard: Reliability-Centered Maintenance requirements for naval aircraft, weapons systems and support equipment	P-F interval	interval between the potential failure and the functional failure
MPDs	Maintenance planning documents	TSI	European Technical Specifications for Interoperability
MRB.	Maintenance Review Board	WPMS	Wheel Profile Measurement Systems

1 Introduction and background

1.1 Overview

Rail transport is a large, integrated, and partly automated system, in which significant improvements in technology, safety and services have taken place over the past decades. However, governments, passengers and freight customers have rising expectations and aspirations for the rail system. There is a constant pressure to drive up availability and reliability, and to drive down costs, while assuring and improving safety. Passengers and freight users also still expect a more affordable, convenient and on time service (Candfield, 2011). When dealing with the technical systems involved in the rolling stock, the consequences of unreliable services become critical and may include a loss of capacity, incidents, exposure to accidents and a high cost of operation. Unreliable services may also create serious problems regarding the company's marketplace position. To this end, improving rolling stock operability have become a major requirements and a strategic issue for both manufacturer and operators.

Obviously, identification and implementation of an appropriate maintenance policy will enhance rolling stock operability. It also reduces premature replacement costs, maintains stable production capabilities, and prevents the deterioration of the system and its components (Vineyard et al., 2000). With increasing awareness of the fact that maintenance not only ensures a high level of safety, reliability, and availability of the system, but also creates value in the business process, approaches to maintenance have become a focus of the strategic thinking of many companies all over the world (Kumar and Ellingsen, 2000).

1.2 Maintenance

Maintenance is the combination of technical, administrative, and managerial actions carried out during the life cycle of an item which intend to retain it in, or restore it to, a state in which it can perform the required function (SS-EN 13306).

Over the past decades, significant improvement has taken place in the development of an applicable and effective Condition-Based Maintenance (CBM) program. Currently, CBM as a preventive maintenance tool is the most popular maintenance strategy discussed in the literature (Ahmad and Kamaruddin 2012; Dieulle et al., 2001; Han and Song, 2003; Moya, 2004). CBM is a maintenance program that recommends maintenance decisions based on the information collected on the asset status (Jardine et.al. 2006). In CBM, the condition of a component or system can be evaluated based on various parameters, such as vibration levels, crack size, corrosion level, temperature, contaminants, or other parameters extracted by other Nondestructive testing (NDT) methods. The measurement process can also include evaluations based on human senses (e.g. visual inspection) to measure or evaluate component condition, such as degree of dirtiness and abnormal color. The motivation of using CBM is that 99% of failures are preceded by certain signs, conditions, or indications that a failure is going to occur (Bloch and Geitner, 1983). The heart of CBM is the ability of measuring and assessing these signs either by testing, inspection or condition monitoring (CM). The purpose of the measurement process is twofold: first, it collects the condition data (information) of the component and secondly, it can increases the knowledge of the failure causes and effects and trends in the deterioration patterns of component. The measurement process can be carried out in two ways: on-line and off-line. On-line processing is carried out during the running state of the equipment (operating state), while off-line processing is performed when the component or system is not running. In addition, the measurement can be performed either periodically or continuously. Typically, periodical measurement is carried out at certain intervals, such as every hour or at the end of every working shift, with the aid of portable indicators, such as hand-held meters, acoustic emission units, and vibration pens. As for continuous monitoring, as its name suggests, monitoring is normally performed continuously based on special measurement devices, such as vibration and acoustic sensors (Ahmad and Kamaruddin 2012).

The two main limitation of continuous monitoring include: it is associated with an additional cost since measurement devices are needed for the monitoring. In addition, it requires larger data storage capabilities, post processing and data management. Therefore, specific attention also has been given by industry on how to develop an applicable and effective CBM program using just an off-line monitoring approach.

1.3 Other industries

In this regard, several attempts have been made by different industries. One of the major development has taken place by the aviation industry with the introduction of on-condition (OC) inspection through Maintenance Steering Group (MSG) concept. OC inspection in the aviation industry is a scheduled task to detect a potential failure condition (MIL STD 2173, 1986), so that action can be taken to prevent the functional failure or to avoid the consequences of the functional failure. (Moubray, 1997). This concept has been evolved since the introduction of MSG-1 (1968) for a specific application on Boeing 747. The efficacy of the systematic MSG-1 methodology applied to Boeing-747 was considered to justify a generic solution, which could be applied to other new aircraft. This resulted in the publication of a second document by ATA in 1970 as MSG-2: “Air-line manufacturer maintenance program planning document”. This document was used to develop the maintenance programs for aircraft such as the Fokker-28, Boeing 727, L-1011 and DC-10. (Smith and Hinchcliffe, 2004).

A decade after MSG-2 was published, MSG-3 (1979) made a major departure from MSG-2. The major driver to develop MSG-3 included the development of a new generation of aircraft, new regulations and new damage tolerance rules for structures, which had a heavy influence on maintenance program development. In addition, the introduction of Reliability-Centered Maintenance (RCM) by Nowlan and Heap (1978), provided the basis for the development of a new, improved “Airline/Manufacturer Maintenance Program Planning Document MSG-3”, published by ATA in 1980. (Transport Canada, 2003; ATA, 2005). MSG-3 incorporated a more efficient maintenance decision logic, and clarified the distinction between economics and safety category of failures, as well as considering the treatment of hidden functional failures, at its heart.

This methodology was a combined effort by the manufacturers, regulatory authorities, operators, and Air Transport Association of USA (ATA). As mentioned, MSG-3 methodology implicitly incorporated the principles of RCM to justify task development, but stopped short of fully implementing reliability-centered maintenance criteria to audit and substantiate the initial tasks being defined (Transport Canada, 2003).

MSG-3 methodologies had a major departure heading from traditional time-based (TBM) maintenance, overhaul and replacement, towards the employment of a CBM program. Based on traditional TBM concept, there was a widespread belief that all failures could be prevented by age-based overhaul. Hence, TBM became the norm for Preventive Maintenance. This kind of approach motivated the indiscriminate use of overhaul or preventive replacement for all items included in a Preventive Maintenance program (Tsang, 1995). However, according to the reliability investigations conducted by United Airlines, no more than 11% of the items would benefit from a limited operating age or scheduled overhaul. In fact, there is seldom a strong relationship between the items operating time and failure probability. Thus, for the remaining 89% of the items, these were inappropriate maintenance measures, which contributed to unnecessary maintenance efforts and non-beneficial downtime. These failures were one of the main sources of unscheduled corrective maintenance, sudden aircraft unavailability, and disturbed operation (Ahmadi et. al. 2007). As a result, the concept of on-condition maintenance has been developed within aviation industry to tackle the non-age related failure modes. On-condition maintenance is defined as a scheduled inspection that is designed to detect a potential failure condition, so that action can be taken to prevent the functional failure or to avoid its consequences. (Moubray, 1997; Nowlan and Heap, 1978; MIL-STD-2173, 1986). On-condition tasks are well known because, the item, which are inspected, is allowed to be left in service “on the condition”, as long as they continue to meet specified performance standards until a potential failure is detected (Moubray, 1997). In other words, these tasks required repair or removal of specific components “on the condition” when they do not meet specified performance standards. Here, the decision maker has to consider the technical performance limits of the component, failure mechanism and degradation process, as well as the failure rate to judge whether immediate corrective action is required or if it is profitable to do some more inspection or to consider some issues, and extend the operational life of the component or system. On-condition maintenance is also known as Condition Based Maintenance (CBM) and Condition Directed Maintenance (CDM) (Moubray, 1997; Tsang, 1995), because the need for corrective or consequence avoiding action is based on the assessment of the condition of the item. On-condition tasks discriminate between the units, which require maintenance to prevent a functional failure, and those that will probably meet required performance and could survive to the next inspection. In some cases, the time of the next inspection depends on the result of previous inspection. If the inspection exposes that the system is in early stage of degradation, the next inspection interval could be adjusted i.e. reduced (Welte, et.al, 2006) so that the degradation process is under control and maximum life could be achieve. Therefore, each serviceable item remains in service and will be inspected or tested at regular intervals until its failure resistance falls below a defined level. This discrimination permits all items to achieve most of their useful life (Nowlan and Heap, 1978). The process of "on-condition" maintenance is applied to items on which a determination of their continued airworthiness can be made by visual inspection, measurements, tests or other means without disassembly inspection or overhaul.

1.4 Current practice

In the commercial aviation industry, increasing emphasis is now being placed on using the MSG-3 methodology for development of scheduled maintenance tasks and intervals for modern commercial aircraft. MSG-3 is a common means of compliance to develop scheduled maintenance requirements in the frame of the instructions for continued airworthiness promulgated by most of the regulatory authorities. The biggest advantage of MSG methodology is the application of on-condition inspection/condition based maintenance, and to introduce a risk-based approach to define maintenance requirements. Similarly, there are other available approaches for developing maintenance plans in other sectors including automotive construction and mining.

In the railway industry, the current maintenance strategies are generally characterised by a combination of both corrective (condition-based) and scheduled (interval-based) maintenance. However, the selection of an optimum strategy can often be subjective with little reference to scientific or statistical proof. The selection of an appropriate strategy will have a significant impact on the life cycle costs and benefits to the system and should be analyzed in a scientific manner. Therefore, techniques and methods to find the optimum solutions has to be implemented in order to improve the maintenance of railway systems. According to the proven experience gained through the application of MSG-3 methodologies, the aim of this task is to study the aviation best practices in the use of CBM approaches in the development of *scheduled aircraft maintenance program*, which may be applied in the future to rolling stock maintenance.

The remainder of this report is constructed as follow. In Section 2, the evolution of scheduled CBM methodology within aviation industry is described. In Section 3, an overview on aircraft maintenance program development is provided. In Section 4 the underlying concept, principles and processes of development of an aircraft maintenance program for system and on-wing engine is presented in detail. In this section the details of each maintenance strategy is discussed with a specific focus on inspection/functional check. The current practices in the rolling stock industry for development of maintenance program/plan is discussed in Section 5 and an assessment of current use of CBM in European train operating companies is provided in Section 6. The report ends with the discussion and conclusion in Section 7.

2 Evolution of Condition-Based Maintenance within MSG[1] methodology

United Airlines started a research program in 1965, to substantiate the outcomes of the FAA task force and to provide a generally applicable systematic review of aircraft design. This research concluded that in the absence of operational experience, the best maintenance process should still be utilized through a structured logical decision tree. In June of 1967, T.D. Matteson and F.S. Nowlan presented a paper on the use of this methodology at an aircraft design and operations meeting of the American Institute of Aeronautics and Astronautics (AIAA). As a result, rudimentary decision logic was created and over the next few years, it was developed with the cooperation of airlines, manufacturers, and FAA. The methodology was used to develop the Boeing-747 initial maintenance program document. This document was published on 10 July 1968 by ATA under the title “Boeing-747 Maintenance Steering Group (MSG) Handbook: Maintenance Evaluation and Program Development (MSG-1)” (Nowlan & Heap,

[1] Maintenance Steering Group

1978). This was the first attempt at applying reliability-centred maintenance concepts when developing an aircraft maintenance program.

MSG-1 was a ‘bottom-up’ approach to the Boeing-747 systems, in which components were the highest level to be considered. Hence, MSG-1 focused on a component such as the Fuel Control Unit (FCU) in a system and analysed which part of that component might fail. Then, it was determined what kind of maintenance action was required to prevent the failure. Through MSG-1, the potential maintenance measures for each maintenance strategy were selected and evaluated from criteria based on operating safely or essential hidden function protection. The remaining potential maintenance tasks were evaluated to determine if they were economically viable. MSG-1 introduced three broad processes to classify the scheduled maintenance requirements, i.e. Hard Time (HT), On-Condition (OC), and Condition Monitoring (CM). OC requires an item to be periodically checked or tested, against an appropriate physical standard to determine whether the item can continue in service or not (Nakata, 1984).

The efficacy of the systematic MSG-1 methodology applied to Boeing-747 was considered to justify a generic solution, which could be applied to other new aircraft. This resulted in the publication of a second document by ATA in 1970 as MSG-2: “Airline manufacturer maintenance program planning document”. This document was used to develop the maintenance programs for aircraft such as the L-1011 and DC-10. (Smith & Hinchcliffe, 2004). The objective of the two MSG methodologies was to develop scheduled maintenance programs that assured maximum safety and reliability of the system, at the lowest possible cost. MSG-1 and MSG-2 both followed the same process, but MSG-2 was a generic document, and non-aircraft type-related (Nowlan & Heap, 1978). Subsequently, in 1972, United Airlines used the idea of MSG-2 under the US Department of Defence (DOD) contract to develop the P-3A and S-3A maintenance programs, and the F-4J program in 1974. (Smith & Hinchcliffe, 2004). An enhanced document was also prepared in Europe, called EMSG-2. It was used to develop maintenance program requirements for such aircraft as the Airbus A-300 and Concorde. MSG-2 and EMSG-2 continued to use a ‘bottom-up’ approach to aircraft systems and were ‘maintenance process oriented’, whereby the integrity of components in sub-systems was considered before those of the overall system.

The most important advantage of MSG-1 and MSG-2 was the application of On-Condition (OC) maintenance, which made them unique. The introduction of OC began an era of new thinking. It was permissible to let an aircraft pass an immediate maintenance check with known deterioration, degradation or wear, and postpone the required maintenance action until the next earliest opportunity, as long as the appropriate physical standard and pre-scribed limitations were met. This approach helped the operators to have fleets with increased availability and made planning more flexible. Moreover, since the cost of correcting potential failures is often far less than the cost of correcting functional failures, OC maintenance reduced the maintenance costs. Furthermore, OC maintenance strongly reduced the number of irrelevant scheduled overhauls, which was the main source of ‘infant mortality’ and unreliability. In addition, by avoiding premature removals of items that were still in a satisfactory condition, the required spare part volumes were reduced. Depending on the operating context of the asset, warning of incipient failure enables the users of a system to reduce or avoid consequences in a number of ways (Moubray, 1997):

1. Down time: corrective action can be planned at a time that does not disrupt operations.
2. Maintenance costs: the user may be able to take actions to eliminate the secondary damage, which would be caused by unanticipated failures. This would reduce the downtime and the maintenance costs associated with the failure.
3. Safety: warning of failure provides time either to shut down an item before the situation becomes dangerous, or to move people out of harm's way.

Today, OC tasks are well known because the inspected items are allowed to be left in service 'on condition' as long as they continue to meet specified performance standards (Moubray, 1997), until a potential failure is detected. For example, as many as 400 items that might have required scheduled overhaul prior to MSG-1/MSG-2/EMSG-2 were reduced to about 10 afterwards. In 1975, NAVAIR rewrote the MSG-2 procedures, to apply an 'analytical maintenance program' to naval aircraft and engine programs, which resulted in "NAVAIR Systems Command (NAVAIR 00-25-400)". This was applied to in-service naval aircraft and the manual was utilized to revise the preventive maintenance requirements for most of the Navy's in-service aircraft. (MIL-STD-2173). The MSG-2 methodology revolutionized Navy procedures for developing preventive maintenance programs; but there were still aspects to consider for further development of both MSG-2 and NAVAIR 00-25- 400 documents. For example, they did not cover the procedures for developing inspections intervals and for refining the initial analysis. (MIL-STD-2173)

Moreover, the effectiveness criteria for different maintenance strategies and failure consequences were not considered and there was still a problem of balancing the requirements of cost and dependability. In addition, there was still pressure to decrease maintenance costs. In fact, the incentives to reduce the cost were changed from technical and engineering issues during design to economical issues and costs associated with effective maintenance during operation. As a result, the industry constructed a framework that incorporated cost-effective maintenance strategies. This led to the development of the third generation of MSG-3 methodology within aviation industries. The concept and process of MSG-3 and Aircraft maintenance planning is discussed in detail the next chapter.

3 An overview on aircraft maintenance planning development

The maintenance and inspection requirements of an aircraft are defined by "Maintenance planning documents" (MPDs) developed by aircraft manufacturers. Two processes are used to support the development of the initial MPDs, which are known as "*Type Certification" (TC)* and "*Maintenance Review Board" (MRB)* processes.

Maintenance requirements defined through the TC process are intended to ensure that the design of the aircraft meets the defined safety standards and design goals. The TC maintenance requirements are tabulated into a specific document entitled "Airworthiness Limitation Section (ALS)". The ALS comprises the Fuel Airworthiness Limitations (FAL) document, the Certification Maintenance Requirements (CMR) document (Systems), and the Ageing Systems Maintenance (ASM) document. It includes also the Safe Life Airworthiness Limitation Items (the Life Limited Parts document) and Damage Tolerant Airworthiness Limitation Items (the ALI document for Structure document). The ALS is the source for standalone documents where all above-mentioned documents will be processed for approval independently (See Fig. 1).

Through the MRB process the initial scheduled maintenance and inspection requirements for new aircraft are developed. The review board includes fleet stakeholders e.g. manufacturers, operators (potential operator in case of new aircraft), vendors and regulatory authorities, etc. (See Fig. 1). The maintenance and inspection requirements that result from MRB analysis are detailed in a document called "MRB Report" (MRBR). The MRBR is intended to be used as a basis for each operator to develop its own continuous airworthiness maintenance programme, subject to the approval of its regulatory authority. After approval, the requirements outlined in the MRBR become a framework around which each air carrier develops its own individual maintenance programme.

For development of an MRBR, the Maintenance Steering Group methodology (MSG-3) is used due to the fact that it is a common means of compliance for the development of minimum scheduled maintenance requirements within the framework of the instructions for continued airworthiness promulgated by most of the regulatory authorities. MSG-3 has been developed through a combined effort by the manufacturers, regulatory authorities, operators, and the Air Transport Association (ATA) of the USA. The MSG-3 methodology implicitly incorporates the principles of Reliability-Centered Maintenance (RCM) to justify task development, but stops short of fully implementing RCM criteria to audit and substantiate the initial tasks being defined (Transport Canada, 2003). The working portions of MSG-3 are divided into four sections, i.e. system and power plant; including components and the Auxiliary Power Unit (APU), aircraft structure, zonal inspection, and lightening/high intensity radiation field (ATA MSG-3 2007). Since its original publication in 1980, MSG-3 has been revised several times, with the latest revision having been made in 2015. In the following sections, available failure management strategies and the maintenance task development process as offered by MSG-3 are discussed.

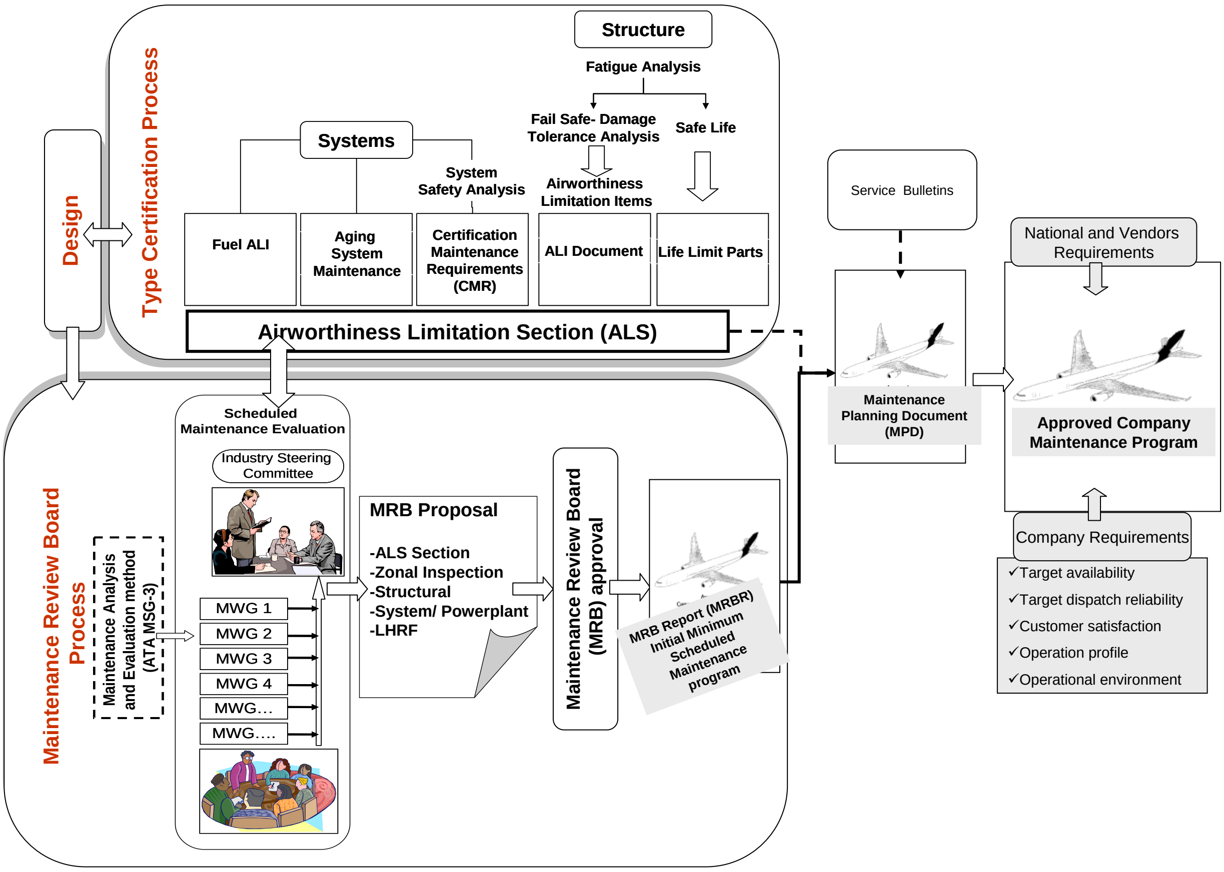

Figure 1: Aircraft maintenance program development process (Ahmadi et. al, 2010)

4 Maintenance Steering Group-3 (MSG-3) methodology

The aim of MSG-3 methodology is to facilitate the development of initial scheduled maintenance tasks and intervals for development of an MRB report, to be acceptable to the stakeholders including regulatory authorities, the operators, and the manufacturers. As stated by ATA MSG-3 (2007), the objectives of efficient scheduled maintenance of aircraft are as follows:

- To ensure realization of the inherent safety and reliability levels of the aircraft.
- To restore safety and reliability to their inherent levels when deterioration has occurred.
- To obtain the information necessary for design improvement of those items whose inherent reliability proves to be inadequate.
- To accomplish these goals at a minimum total cost, including maintenance costs and the costs of resulting failures.

The MSG-3 outlines the decision process for determining the scheduled maintenance requirements initially projected to maintain the inherent safety and reliability levels of the aircraft, at reduced cost. The maintenance and inspection tasks developed through this process will become the foundation to develop airline's own customised maintenance program (See Fig. 2). As operating experience accumulates, additional modifications may be made by the operator to maintain efficient scheduled maintenance ATA MSG-3 (2007).

MSG-3 implicitly incorporates the principles of RCM to justify task development. It involves a top-down, system-level, and consequence-driven approach in which maintenance task justification should be based on applicability and effectiveness criteria. The analysis steps include:

1. Selection of the Maintenance-Significant Items (MSI),
2. The MSI analysis process (identification of functions, functional failures, failure effects, and failure causes),
3. Selection of maintenance actions using decision logic, which includes:
   - Evaluation of the failure consequence (level 1 analysis)
   - Selection of the specific type of task(s) according to the failure consequence (level 2 analysis).

A sample of MSG-3 application for system maintenance development is provided in appendix 1.The sample is based on the example database of ACME, for a Turbofan 77, dealing with an aero engine fire extinguishing system maintenance analysis, and follows US Black & White Standard Template.

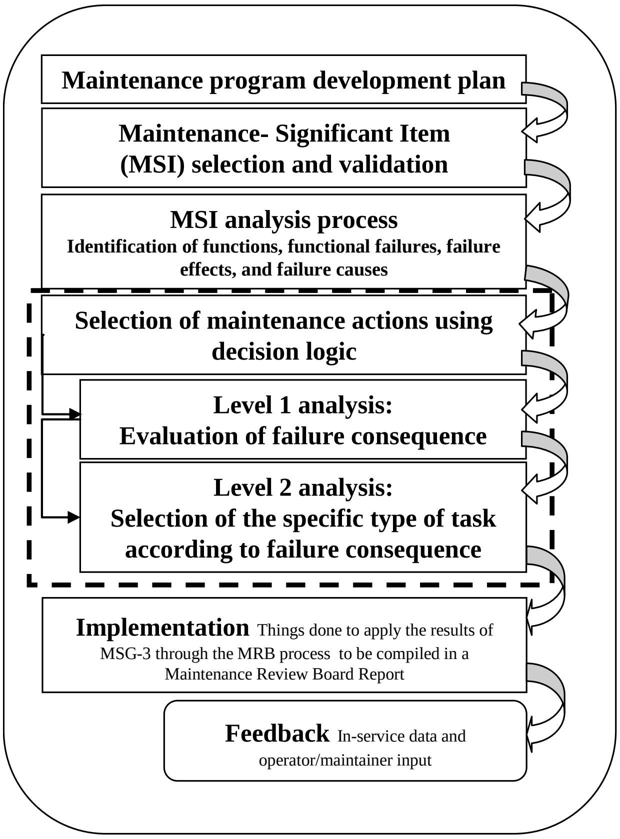

Figure 2: Steps of MSG-3 process for Aircraft maintenance analysis

4.1 MSG-3 failure management alternatives

The available failure management strategies offered by MSG-3 consist of specific scheduled maintenance tasks selected based on the reliability characteristics of the components, and they are performed at fixed, predetermined intervals. The objective of these tasks is to prevent deterioration of the inherent safety and reliability levels of the system. The maintenance tasks suggested by MSG-3 includes:

1- Servicing /lubrication task:
2- Inspection/functional check (On-condition inspections)
3- Operational checks and Failure finding tasks (for hidden failure consequence)
4- Restoration
5- Discard
6- Combination of tasks

Regardless of the method that we use to develop a scheduled maintenance program, the key question is whether the selected maintenance task is able to fulfil its objectives or not. Therefore, maintenance task selection needs to have overriding criteria to recognize the fulfilment of these objectives.

In order to justify a specific task within MSG-3, "applicability and effectiveness criteria" have been developed for each specific maintenance strategy, as used in RCM methodology. This criteria is an essential part of the analysis to identify whether the selected maintenance task is able to fulfil its objectives or not. The applicability of a task depends on the reliability of the item (Rausand & Van, 1998), the item's failure characteristics and the type of task (SAE JA1012, 2002; MIL-STD-2173, 1986; Nowlan and Heap, 1978). In other words, a task is applicable if it eliminates a failure or at least reduces the probability of occurrence to an acceptable level or reduces the impact of failures (Rausand & Van, 1998). The effectiveness of a task is a measure of the result of the fulfilment of the maintenance task objectives, which is dependent on the failure consequences (MIL-STD-2173, 1986; Nowlan and Heap, 1978). In other words, the maintenance task's effectiveness is a measure of how well the task accomplishes the intended purpose and the extent to which it is worth doing (Rausand & Van, 1998). In general, a maintenance task must reduce the expected loss to an acceptable level, to be effective (Rausand and Hoyland, 2004). Hence, the discussion about the effectiveness criteria of each type of failure management strategy should be related to each type of failure consequence (See Fig 3). The basic preventive maintenance and inspection strategies offered by MSG-3 including their applicability and effectiveness criteria are as follows (ATA MSG-3, 2007):

A) **Lubrication/Servicing:**

According to ATA MSG-3, 2007, it is defined as "Any act of Lubrication or Servicing for maintaining inherent design capabilities". To be applicable, the replenishment of the consumable must reduce the rate of functional deterioration. The evaluation criteria for identification of scheduled restoration effectiveness are as follows:

- Safety category of failures: The task must reduce the risk of failure.

- Operational category of failures: The task must reduce the risk of failure to an acceptable level.
- Economic category of failures: The task must be cost-effective.

B) **Operational/Visual Check (for hidden failures)**

This is a scheduled task used to determine whether a specific hidden failure has occurred. ATA MSG-3, 2007 defines an operational check as "a task to determine *whether* an item is fulfilling its intended purpose". *This type of task* "does not require quantitative tolerances. A visual check is also defined as "an observation to determine that an item is fulfilling its intended purpose". The objective of an Operational/Visual Check within MSG-3 methodology is "to detect a functional failure that has already occurred, but is not evident to the operating crew during the performance of normal duties". MSG-3 (2007) defines the applicability criteria for operational and visual checks as: "Identification of failure must be possible."

According to (SAE JA1012) a failure-finding task shall satisfy the following additional criteria to be applicable:

- The basis upon which the task interval is selected shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.
- The task shall confirm that all components covered by the failure mode description are functional.
- The failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.
- It shall be physically possible to perform the task at the specified intervals.

The evaluation criteria for identification of Operational/Visual Check effectiveness are as follows:

- Safety category of failures: Identification of failure must be possible.
- Operational category of failures: The task must ensure adequate availability of the hidden function to reduce the risk of a multiple failure.
- Economic category of failures: The task must ensure adequate availability of the hidden function in order to avoid economic effects of multiple failures and must be cost-effective.

C) **Inspection/Functional Check (Scheduled Condition Based Maintenance/Inspection):**

The main purpose of this scheduled task is to detect a potential failure condition (MIL STD 2173, 1986), so that action can be taken to prevent the functional failure or to avoid its consequences of the functional failure. (Moubray, 1997). A functional check is a quantitative check to determine if one or more functions of an item performs within specified limits. Functional checks should be performed in accordance with the manufacturer's instructions.

Potential failure is defined as “a defined identifiable condition that indicates that a degradation process is taking place that will lead to a functional failure.” Functional failure also is define as “a failure of an item to perform its intended function within specified limits.” Figure 3 shows a typical failure process. As shown, failure starts to occur at point, “A” which is not necessarily related to age, continue deterioration to point “B”, at which potential failure can be detected and if it is not managed, functional failure will occur at point “C”.

In addition to the potential failure, one needs to consider the amount of time/cycles which elapses, between the point at which it becomes detectable, and the point where it deteriorates in to functional failures. This interval is known as P-F interval. The P-F interval is known as lead time to failure, or failure development period. In practice, task interval must be selected so that , to ensure the inspection or checking will detect the potential failure before functional failure occurs, while providing a reasonable amount of time to do something about it. By definition, the minimum interval likely to elapse between the discovery of potential failures and the occurrence of the functional failure, is known as Nett P-F interval. (Moubray, 1997; MIL-STD-2173, 1986).

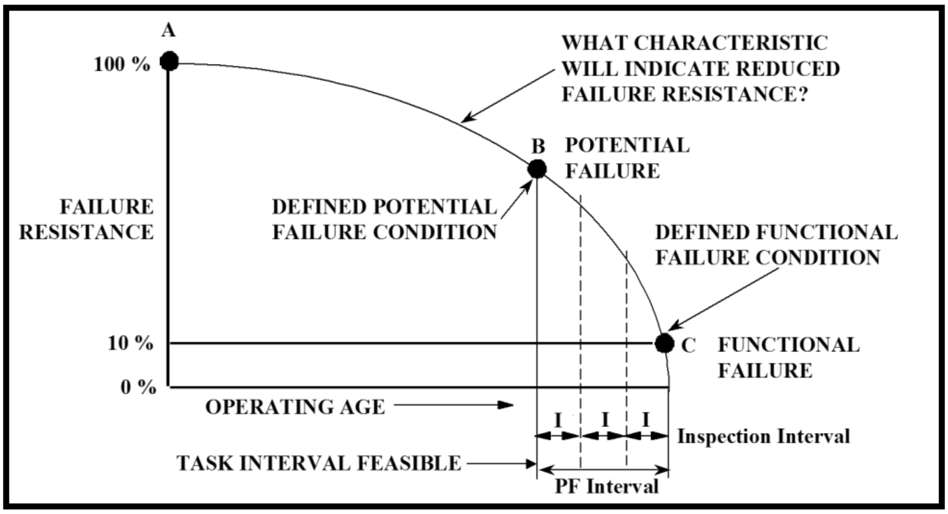

Figure 3: P-F Curve (NAVAIR 00-25-403)

Inspection/Functional Check can result in repair or removal of specific components “on the condition” when they do not meet specified performance standards. Therefore, each unit remains in service and is inspected at regular intervals until its failure resistance falls below a defined level, or when a potential failure is discovered. On condition tasks discriminates between units that require corrective maintenance to prevent a functional failure and those that will probably survive to the next inspection. This discrimination permits all units of the item to realize most of their useful lives (Nowlan and Heap, 1978). On condition tasks includes inspections for symptoms of failure at organizational, intermediate or depot level for all type of equipment (MIL STD 2173, 1986).

This type of preventive maintenance program has a number of advantages, because on condition tasks identify individual unit at the potential failure stage. Particularly Inspection/Functional Check is effective in preventing specific modes of failure and in reducing failure and operational consequences. They also reduce the average cost of secondary damage caused by a functional failure is avoided. It avoids the premature removal of units that are still in satisfactory condition. In addition, the cost of correcting potential failure is often far less than the cost of correcting functional failures. Each unit realizes almost all of its useful life. The number of removals for potential failures is only slightly larger than the number that would result from an actual functional failure. Thus, repair costs and the number of spare units needed to support repair process are kept to a minimum.

These tasks are similar to time-based maintenance in a sense that the task should be performed at a pre-defined interval. However, unlike time-based tasks, it does not normally involve an intrusion into the equipment and the actual preventive action is taken only when it is believed that an incipient failure has been detected. It should be noted that, even when a time-based task is applicable, an Inspection/Functional Check may still be a better option because it eliminates the possibility of premature removal of the item from service for PM action (Tsang, CBM tools and Decisions).

Three main methods has been proposed by MSG-3 as follows (ATA MSG-3, 2007):

General Visual Inspection (GVI): A visual examination of an interior or exterior area, installation or assembly to detect obvious damage, failure or irregularity. This level of inspection is made from within touching distance, unless otherwise specified. A mirror may be necessary to enhance visual access to all exposed surfaces in the inspection area. This level of inspection is made under normally available lighting conditions such as daylight, hangar lighting, flashlight or drop-light and may require removal or opening of access panels or doors. Stands, ladders or platforms may be required to gain proximity to the area being checked. Basic cleaning may be required to ensure appropriate visibility (see ATA MSG-3, 2007 for details).

Detailed Inspection (DET): An intensive examination of a specific item, installation or assembly to detect damage, failure or irregularity. This could include tactile assessment in which a component or assembly can be checked for tightness/security. Available lighting is normally supplemented with a direct source of good lighting at an intensity deemed appropriate. Inspection aids such as mirrors and magnifying lenses may be necessary. Surface cleaning and elaborate access procedures may be required (see ATA MSG-3, 2007 for details).

Special Detailed Inspection (SDI): An examination of a specific item, installation, or assembly making use of specialized inspection techniques such as Non Destructive Testing (NDT) and/or equipment (e.g. boroscope, video-scope, tap test) to detect damage, failure or irregularity. Intricate cleaning and substantial access or disassembly procedure may be required. Classification of a task as an SDI does not define the required qualifications for the person performing the task (see ATA MSG-3, 2007 for details).

Scheduled Structural Health Monitoring (S-SHM): The concept of checking or watching a specific structural item, detail, installation or assembly using on board mechanical, optical or electronic devices specifically designed for the application used. SHM does not name any specific method or technology.

MSG-3 defines the applicability criteria for an inspection/functional check as: reduced resistance to failure must be detectable, and there exists a reasonably consistent interval between a deterioration condition and functional failure (See Fig. 5). SAE JA1012 explains the applicability criteria for such tasks and defines five criteria which an inspection/functional check (on-condition task) must satisfy:

- There shall exist a clearly defined potential failure.
- There shall exist an identifiable interval between the potential failure and the functional failure (the P-F interval), or failure development period.
- The task interval shall be less than the shortest likely P-F interval.
- It shall be physically possible to perform the task at intervals less than the P-F interval.
- The shortest time between the discovery of the potential failure and the occurrence of the functional failure, (the P-F interval minus the task interval) shall be long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.

The evaluation criteria for identification of Scheduled Inspection/Functional Check effectiveness are as follows:

- Safety category of failures: The task must reduce the risk of failure to assure safe operation.
- Operational category of failures: The task must reduce the risk of failure to an acceptable level.
- Economic category of failures: The task must be cost-effective; i.e. the cost of the task must be less than the cost of the failure prevented.

D) **Scheduled restoration (rework or hard time restoration):**

According to ATA MSG-3, 2007, a scheduled restoration is defined as “the work necessary to return the item to a specific standard. Restoration may vary from cleaning or replacement of single parts up to a complete overhaul.” It is a scheduled task that restores the capability of an item at or before a specified age limit to a level that provides a tolerable probability of survival to the end of another specified interval. A stated by ATA MSG-3, 2007, the applicability criteria for a scheduled restoration is defined as: “The item must show functional degradation characteristics at an identifiable age, a large proportion of units must survive to that age, and it must be possible to restore the item to a specific standard of failure resistance.”

SAE JA1012 further describes the applicability criteria for such tasks and defines the following three criteria that must be satisfied for applicability:

- There shall be a clearly defined (preferably a demonstrable) age at which there is an increase in the conditional probability of the failure mode under consideration.
- A sufficiently large proportion of the occurrences of this failure mode shall occur after this age to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.
- The task shall restore the resistance to failure (condition) of the component to a level that is tolerable to the owner or user of the asset.

MSG-3 defines a restoration as “that work necessary to return the item to a specific standard”. It summarizes the applicability criteria for a scheduled restoration as: “The item must show functional degradation characteristics at an identifiable age, a large proportion of units must survive to that age, and it must be possible to restore the item to a specific standard of failure resistance.” This, in addition to the reasonable guidance given in the “Task interval se-lection criteria” section, fulfils the criteria mentioned by SAE JA1012.

The evaluation criteria for identification of Scheduled restoration effectiveness are as follows:

- Safety category of failures: The task must reduce the risk of failure to assure safe operation.
- Operational category of failures: The task must reduce the risk of failure to an acceptable level.
- Economic category of failures: The task must be cost-effective: i.e., the cost of the task must be less than the cost of the failure prevented.

E) **Scheduled discard:**

A scheduled discard task entails discarding an item at or before a specified age limit regardless of its condition at the time. Discard tasks are normally applied to so-called single celled parts such as cartridges, canisters, cylinders, engine disks, safe-life structural members, etc.. To be applicable, the item must show functional degradation characteristics at an identifiable age and a large proportion of units must survive to that age (ATA MSG-3, 2007).

The evaluation criteria for identification of Scheduled discard effectiveness are as follows

- Safety category of failures: A safe-life limit must reduce the risk of failure to assure safe operation.
- Operational category of failures: The task must reduce the risk of failure to an acceptable level.
- Economic category of failures: An economic-life limit must be cost-effective: i.e., the cost of the task must be less than the cost of the failure prevented.

F) **Combination of tasks (for safety categories):**

This strategy is offered in the cases where it may not be possible to find a single task which on its own is effective in reducing the risk of failure to an acceptable level. In these cases, it may be necessary to define a “combination of tasks” such as a “scheduled discard” after a series of “operational check” or

"Inspections". In practice, a combination of tasks is seldom used, and it is considered as a stoppage measure, pending redesign of the affected part (Nowlan and Heap, 1978).

The evaluation criteria for identification of Scheduled Combination of tasks effectiveness are as follows

- Safety category of failures: The task must reduce the risk of failure to assure safe operation.
- Operational category of failures: The task must reduce the risk of failure to an acceptable level.
- Economic category of failures: The task must be cost-effective; i.e., the cost of the task must be less than the cost of the failure prevented.

G) **Redesign (for a safety effect):**

If no maintenance tasks are found to be applicable and effective, default strategies are introduced, which include:

- Redesign: In cases where the failure has a safety effect and there is no form of effective scheduled maintenance task, 'redesign" is mandatory. In other cases where the failure may produce a significant cost, a trade-off analysis identifies the desirability of redesign (Nowlan and Heap, 1978). In fact, the decision ordinarily depends on the seriousness of the consequences. Hence, if the consequences entail a major loss, the default action is redesign of the item to reduce the frequency of failures and their consequences.
- No scheduled maintenance (run to failure): When it is technically unfeasible to perform an effective scheduled maintenance task, and when a failure will not affect safety, or may entail only a minor economic penalty, the "no-scheduled-maintenance" or "run-to-failure" option will be accepted. Selection of the "no-scheduled-maintenance" option means that the consequence of failure is accepted.

4.2 Maintenance-Significant Item (MSI) selection and validation

As stated earlier, MSG-3 is a risk driven approach where any kind of decision should be based on the consequence of the failures. Depending on the consequence of the end item, it may have several functions with different importance. As an example, the importance of a function can range from "crucial for safety" to "nice to have but can do without". The methodology of MSG-3 dictates that the maintenance analysis should only consider those items whose functions are significant enough to proceed (deserve) with further analysis and apply the maintenance decision logic to them. The criteria for selecting the "Significant items" include "the item whose failure could affect operating safety and a have major operational or economic consequences". Hidden function items are also subjected to the same intensive analysis as MSI, i.e. if the failure of an item could be undetectable or not likely to be detected by the operating crew during normal duties. Using engineering judgment, this analysis is a quick, approximate, but conservative identification of a set of significant items in the development of a scheduled maintenance programme using MSG-3. See Nowlan and Heap (1978) and Ahmadi et al (2010) for more details. An example of MSI selection process is provided in appendix 1, pp.1.

4.3 Maintenance-Significant Item (MSI) analysis process (identification of functions, functional failures, failure effects, and failure causes)

Similar to other approaches to reliability and risk based maintenance management, MSG-3 includes the identification of risk, the objects that could be harmed, and controls for reducing the frequency or consequence of unwanted events. Similar to other risk based approaches, the results of the risk assessment are used to determine the need for a failure management strategy and, if one is needed, the risk provides a means to assess the effectiveness of the failure management strategy (Conachey et al., 2003). Hence, risk identification forms the core part of the analysis. In the MSG-3 procedure, the fundamentals of Failure Mode and Effect Analysis (FMEA) are implicitly incorporated in the analysis. The process requires the definition of function(s), functional failure(s), failure effect(s), and failure cause(s), and establishes the cause-and-effect relationships among them, which aims at determining possible system states under the assumption of the presence of certain failures. However, in this adaptation of FMEA by MSG-3, some changes have been made, in that the term “failure mode” has been changed to “failure cause” (i.e. why the functional failure occurs). Moreover, “failure effect”, which is defined by SAE JA1011 as “what happens when a functional failure occurs”, is defined by MSG-3 as “what is the result of a functional failure”. The latter is used to address the question of what the occurrence of failure means to the aircraft as a whole. For example, if a fan were to fail to blow air inside avionics ducting, the failure effect would be that the blower fault warning light would come on: “extract fan inoperative”. In fact, these two definitions are slightly different (Ahmadi et. al. 2010).

Prior to applying the MSG-3 logic diagram to an item, a preliminary work sheet will be completed which clearly defines the MSI and its function(s), functional failure(s), failure effect(s), and failure cause(s) (ATA MSG-3, 2007). (See Appendix 1 for an example). An example of identification of functions, functional failures, failure effects, and failure causes process is provided in appendix 1, pp.2-8.

4.4 Selection of maintenance task using MSG-3 decision logic

In order to select the applicable and effective maintenance task, MSG-3 provides a decision diagram logic, which includes two levels of analysis. In the first level the type of failure and its consequences will be evaluated, i.e. evaluation of the failure consequences. In the second level, the available maintenance strategies will be evaluated to identify the applicable and effective maintenance task (s).

4.4.1 Level 1 analysis: evaluation of failure consequences

Evident and hidden failures:

In order to determine if a preventive maintenance task can reduce the undesirable consequences to an acceptable level, it is necessary to determine whether the failure itself will be evident or hidden, to the crew while they are performing their normal duties. The classification of failures into hidden or evident failures is vital for the evaluation of protective devices, since their failures are not detectable per se during normal operation. A failure, which, by itself, is obvious to the crew during the normal duties, is classified as an evident failure. All evident failures are analyzed as single failures. Failures that are not evident to the operating crew while they are performing their normal duties are classified as hidden failures. The hidden failures will be analyzed as part of a multiple failures (Nowlan and Heap, 1978). A multiple failure is defined as "a combination of a hidden failure and a secondary failure (or event) that makes the hidden failure evident". Specific attention will be given to the hidden failures during design stage to determine whether they have any effect on safety and operation.

Identification of the consequence of failure

When either an evident or hidden failure has been selected as the nature of the failure, the next step is to analyze the consequences of failure. Three major categories considered by MSG-3 for classification of failure consequences are safety, operational and economic consequences. Accordingly, the following five failure effect categories are defined:

- Evident Safety
- Evident Operational
- Evident Economic
- Hidden Safety
- Hidden Non-safety

Regarding the operational effect of hidden failures, it should be mentioned that hidden failures within MSG-3 are analyzed as parts of multiple failures, and such failures on their own do not have any consequences. Here the aim of preventive maintenance is to assure the availability necessary to avoid the effects (consequences) of multiple failures on safety, operation, or economy. An example of level 1 analysis is provided in appendix 1, pp 9.

4.4.2 Level 2 analysis: selection of a specific type of task(s) according to failure consequence

For safety category failures, a rigorous approach is taken in which all maintenance alternatives must be analysed, and the most effective task or a combination of tasks must be selected. This approach for safety category of failures encourages a consideration of all the applicable failure management strategies for a given failure mode and provides a comparison of maintenance alternatives (e.g. inspection, restoration, etc.) and to select of the most effective maintenance alternatives among all the applicable choices. In cases where there is no form of applicable and effective scheduled maintenance task (because any available task would be technically unfeasible or not worth doing), selecting "redesign" is mandatory to satisfy the applicability and effectiveness criteria.

In the case of operational and economic consequences, a decision diagram approach (binary approach with Yes/No answers) is used. In this approach, it is assumes a preferred order in the selection of the type of the maintenance alternatives, i.e. on-condition inspection first, restoration second, discard third, failure-finding inspection fourth, and a combination of tasks as the fifth one. If no applicable and effective maintenance task are found, the option of "redesign may be desired" is the decision. Here the assumption is that, the characteristics of the tasks themselves suggest a strong order of preference based on their overall effectiveness as preventive measures (Nowlan and Heap, 1978). Likewise, SAE JA1012 states that, in most of the RCM-based decision diagram approaches, there are two key assumptions, which form the preference hierarchy for the failure management policies. The first assumption is that some categories of failure management policies are inherently more cost-effective than others. The second assumption is that some are inherently more conservative than others. In the first approach, if one of the earlier tasks in the preference order is deemed to be applicable and effective, it is selected and the analysis continues with the next failure mode. Otherwise, the second failure management strategy should be evaluated, and so on until the end of the decision diagram has been reached. It should also be borne in mind that the use of decision diagrams may introduce an element of sub-optimization to the failure management policy selection process, from the cost point of view (SAE JA1012, 2002).

It should be noted that most of the RCM standards adapt the decision diagram approach to select appropriate maintenance strategies (See e.g. SAE JA1012, 2002, Defence Standard 02-45 (NES 45), 2000). However, NAVAIR 00-25-403 incorporates a rigorous approach to select maintenance strategies, for all types of failure effect categories. Obviously, MSG-3 employs a combination of these two approaches (See Fig. 4).

As is evident in Figure 4, Servicing/lubrication tasks are evaluated first because they relate directly to the design and operation of the equipment. As discussed above, the next choice is on-condition inspection/functional check (as a CBM approach) particularly if it can be performed without removing an item from the equipment. As mentioned earlier, this strategy has a number of advantages .The next choice is restoration tasks if no applicable and effective “inspection/functional check” can be found. Scheduled restoration of a component leads to a marked reduction in the overall failure rate of items that have a dominant engineering failure mode. This type of task may be cost effective if the failure has major economic consequences. A restoration task usually permits the remanufacture and reuse of time expired units. Thus, material costs are lower than they would be if the entire unit were discarded. Similarly, Scheduled discard is economically the least desirable of the preventive tasks. However, it has a few desirable features. A safe life limit on simple component can prevent critical failures. A safe life limit on a component can prevent critical failures caused by certain engineering failure modes. Similarly, an economic life limit can reduce the frequency of functional failures that have major economic consequences. However, the discard task is in itself quiet costly. The average life realized by an item subject to a safe life limit is only a fraction of its potentially useful life. The average life of an item subject to an economic life limit is much less than the useful life of many individual units. In addition, a discard task involves the cost of replacement. New items or parts must be purchased to replace the time expired units. A life limit usually does not permit remanufacture and reuse. For safety related consequences, “combination of tasks” are evaluated as final alternative. A combination tasks is an alternative to redesigning the equipment to satisfy the safety failure consequences. An example of level 2 analysis is provided in appendix 1, pp 10-11.

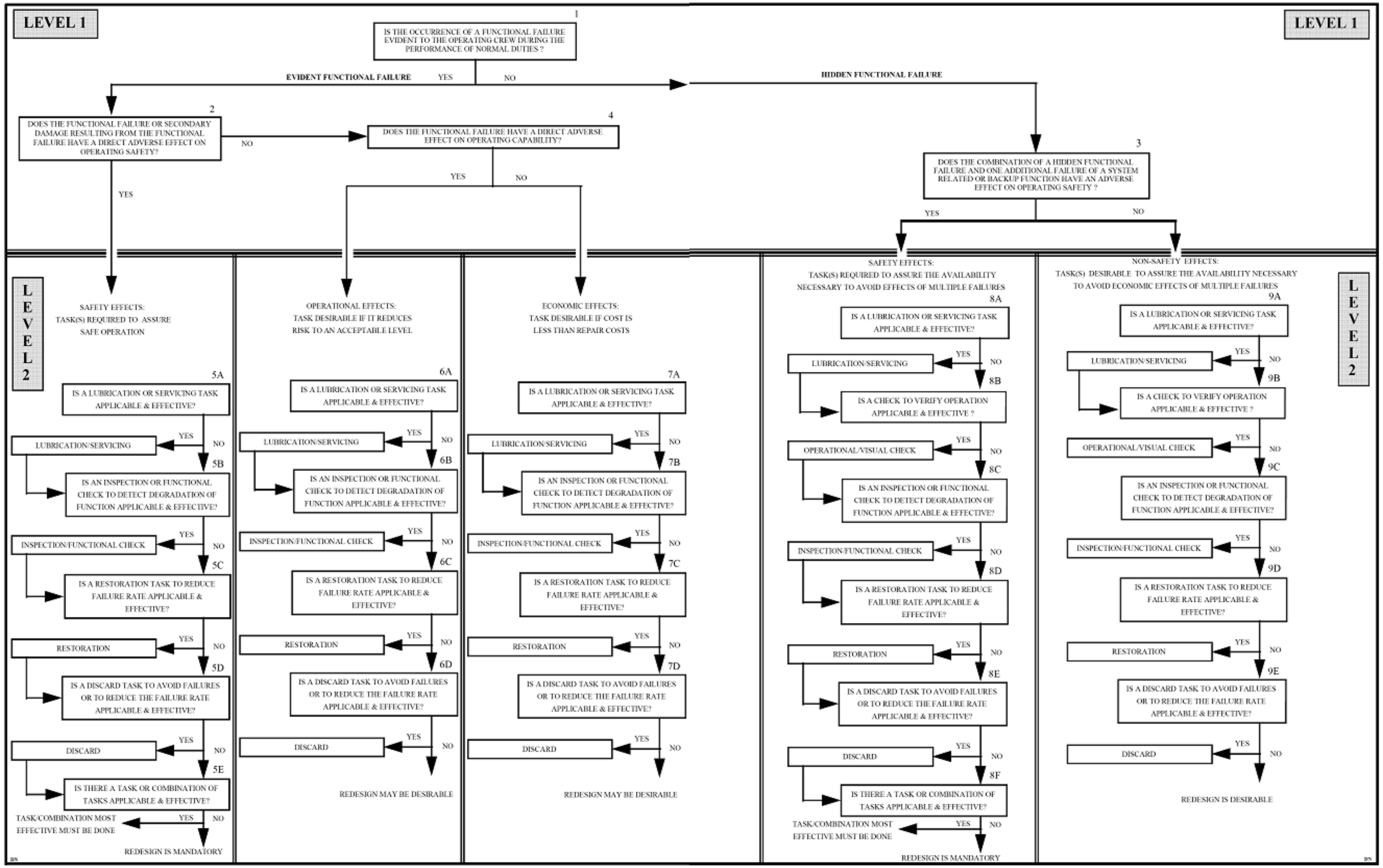

Figure 4: MSG-3 Logic Diagram for Systems and Power plant (ATA MSG-3, 2007)

TASK	APPLICABILITY	SAFETY EFFECTIVENESS	OPERATIONAL EFFECTIVENESS	ECONOMIC EFFECTIVENESS
LUBRICATION OR SERVICING	The replenishment of the consumable must reduce the rate of functional deterioration.	The task must reduce the risk of failure.	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective.
OPERATIONAL OR VISUAL CHECK	Identification of failure must be possible.	The task must ensure adequate availability of the hidden function to reduce the risk of a multiple failure.	Not applicable.	The task must ensure adequate availability of the hidden function in order to avoid economic effects of multiple failures and must be cost effective.
INSPECTION OR FUNCTIONAL CHECK	Reduced resistance to failure must be detectable, and there exists a reasonably consistent interval between a deterioration condition and functional failure.	The task must reduce the risk of failure to assure safe operation.	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective; i. e., the cost of the task must be less than the cost of the failure prevented.
RESTORATION	The item must show functional degradation characteristics at an identifiable age, and a large proportion of units must survive to that age. It must be possible to restore the item to a specific standard of failure resistance.	The task must reduce the risk of failure to assure safe operation.	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective; i.e., the cost of the task must be less than the cost of the failure prevented.
DISCARD	The item must show functional degradation characteristics at an identifiable age and a large proportion of units must survive to that age.	The safe life limit must reduce the risk of failure to assure safe operation.	The task must reduce the risk of failure to an acceptable level.	An economic life limit must be cost effective; i.e., the cost of the task must be less than the cost of the failure prevented.

Figure 5: MSG-3 Applicability and Effectiveness criteria for task selection (ATA MSG-3, 2007)

5 Current practices in rolling stock maintenance program development

In many countries, the railway industry has historically been operated and controlled by the national government. This situation has gradually transformed into a multi-stakeholder environment were a number of different companies are present. Sweden is an example of this where the previously governmentally controlled Statens Järnvägar (SJ) owned the trains and the railway infrastructure, operated the trains, maintained the trains and the infrastructure, educated the railway staff, manufactured railway parts etc. The deregulation of the Swedish railway sector started in 1998 saw SJ split into two branches for infrastructure and rolling stock. The rolling stock remained in SJ as well as the management of train operations. The infrastructure was taken over by a new governmentally owned organization; Banverket. In year 2001 SJ was further split into smaller entities. The ownership of all stations and buildings was redirected to Jernhuset. A company called Green Cargo was founded and took over the responsibility of the cargo transportation. The Rolling stock maintenance was also placed in a separate company Euromaint. SJ was now a purely a train operating company. Since then, there are more than 30 companies in Sweden competing for the transportation of passengers. Many of the new operators leased their rolling stock fleet and contracted the maintenance company Euromaint or other companies like Swemaint to maintain their rolling stock fleet.

The infrastructure side is managed by Banverket was also subjected to further deregulation in 1998. Banverket was divided in two main parts. One part owning the infrastructure, responsible for ordering new infrastructure projects, maintenance actions, and initiating renewals. The execution of these actions was located in a company called Banverket production (later called Infranord) and Banverket projektering (later called Vectura). Gradually these companies were subjected to external competition from new companies like VT-track, Balfour Betty, Structon, Speno, Sperry etc. Additionally to this, a new set of consultant companies focusing on railway were establishing them self in Sweden e.g. SWECO rail who later on in 2013 bought the production company Vectura. The remaining part of Banverket was merged with similar agencies responsible for sea and road transportation to form the current infrastructure manger Trafikeverket.

To exercise the control of the railway system safety a special agency was founded in 1988; Järnvägsinspektionen which now is called Transportstyrelsen. This authority was responsible of granting permits for infrastructures (railway and metro) and rolling stock to be used in traffic. It also investigated accidents and incidents in the railway system.

Due to the deregulated market, the responsibility of maintaining the railway system is spread out among the different companies. As an example, a company manufacturing steel, which is transported by rail, could rent a cargo wagon from a wagon owner, which will provide the maintenance intervals of the wagon e.g. the bogies. The wagon manufacturer prior to this provided the maintenance intervals to wagon owner. The operation of the cargo transport is handled by a third party who provides locomotives and train drivers. A maintenance company contracted by the cargo operating company performs the maintenance of the locomotive and a second maintenance company could carry out the wagon maintenance. Additionally, to this, a third maintenance company can be responsible for performing the wheel grinding (Lathe reprofiling). To complicate the situation this should be synchronized with the infrastructure maintenance of e.g. rail grinding and renewal to provide an optimal wheel-rail contact to ensure safety and minimize wheel and rail wear. Typically this is not done effectively as the infrastructure maintenance is divided in a similar way which adds more companies to the equation.

For sustainable performance of railways over its life span, effective maintenance plans are required. Effective maintenance plan is required to meet strategic and regulatory requirements in terms of quality, safety, reliability, maintainability, availability, capacity and QoS (Famurewa, S. M., 2015). It entails quantifying maintenance needs or identifying maintenance tasks and determining the resources required for these tasks (CENELEC EN 60300-3-14, 2004; Márquez, A. C., 2007).

The development of maintenance plan in the rolling stock industry has evolved over time based on the available technology, business strategy, maintenance budget, culture, risk perception and need for competition. Based on experience of operating current or similar fleets, some of the practices over the years include:

- Implementing manufacturers' recommendations provided in the maintenance and operation manual.
- Adapting personal or organisational experience with the asset or similar assets.
- Studying and analysing technical documentation of the asset, such as drawings, diagrams and technical procedures.
- Considering regulatory and/or mandatory requirements, such as safety conditions of item operation and environmental regulations for item.
- Using inspection reports
- Using maintenance engineering techniques such as FMECA, ETA, FTA, HAZOP etc.
- Using RAMS and LCC analysis
- Health monitoring and predictive analytics.

A common maintenance practice in the rolling stock industry is the use of predetermined maintenance interval. Maintenance works are scheduled at a fixed interval (kilometre-, calendar-, time-based, mission-based or usage intensity-based interval). Example, of such actions is manual inspection by maintenance personal, wheel reprofiling at specified vehicle kilometre. Renewal intervals usually last between three and six years, while component maintenance is often kilometre-based, see Table 1. During a maintenance check, preventive maintenance is carried out and the functionality of the rolling stock subsystem/items are restored. Generally, for freight wagon maintenance, wheel maintenance takes the biggest costs. Wheel maintenance can amount up to 50% of the total maintenance (Lagnebäck, 2007).

Table 1: Typical maintenance interval for various wagon component from a Swedish operator/maintenance workshop (Palo, 2014)

Component	Maintenance action	Interval (km)
Wagon	Inspection	80 000
Drawgear	Control	250 000
Frame	Control	500000
Brake system	Control	75000
Wheel	Control	30000
Drawgear	Overhaul	75000
Bearing box	Overhaul	800000
Bogie	Overhaul	1000000
Brake system	Overhaul	1000000
Wheel	Overhaul	200000

There is a paradigm shift in the rolling stock industry towards proactive and data-driven approaches for the development of a maintenance plan. Basically, many stakeholders are now implementing the last mentioned approaches (e.g. FMECA, RAMS and LCC analysis techniques) in the development of their maintenance plans. This is simply because these approaches are reliable and can be used to address various problems.

A state of the art approach to rolling stock maintenance is predictive maintenance with effective condition monitoring systems. The condition monitoring systems of rolling stock can be divided into two types based on the principle and philosophy of their operation; reactive or predictive. The reactive systems are used to detect and identify component in its faulty state after failure occurrence. The predictive system gives indications of impending failure of a component and provide possibilities for predictive analytics and proactive maintenance. This makes it easier to plan maintenance activities ahead and to utilize the equipment in a more efficient manner. Some examples of such systems and detector technologies are: acoustic bearing detector, vehicle performance monitoring, wheel condition monitoring, non-destructive examination (NDE) technologies and vision technologies.

5.1 Regulatory and Authority requirements (National, European)

This section defines the safety requirements for Rolling Stock, which are in place to ensure a vehicle is safe to operate (e.g. derailment risk, gauging) and in some cases will not generate excessive forces which will degrade the infrastructure. According to the Swedish regulations, a new vehicle should be authorized by the Swedish Transport Agency before entering into service. This is also the case of upgrading or renewal of an existing authorized vehicle. The authorization means that a subsystem is allowed to be used and operated in Sweden. The Swedish Transport Agency has regulations on approval of railway subsystems, these regulations contain different rules that the operating companies have to follow when they are responsible for operating a railway vehicle. For example, an application for approval of railway vehicles shall, in the event that the Transport Board has previously approved the technical design of the rail vehicle and shall contain documentation certifying the railway vehicle's safety-related interaction with the railway infrastructure. The documentation must include a report containing information on: (Retrieved from: Transport Styrelsen, Technical authorization)

- Detectability in terms of signal safety
- Interaction with the train protection systems
- The railway infrastructure scanning for defective railway vehicles
- Communication between the railway vehicle and traffic management
- Dynamic interaction with the track
- Dynamic and static gauging profile
- Electromagnetic compatibility with the surroundings, excluding the energy system
- Current collection and interaction with the energy system of the infrastructure, and
- Towing, lifting/rescue.
- The application shall, when requested by the Swedish Transport Agency, be supplemented by additional documentation to supplement the safety case.

The safety certificate shows that the operating company has a safety management system that satisfies the Swedish safety requirements and has rolling stock that is either approved in Sweden and/or fulfils the EU interoperability requirements and has sufficient liability insurance. The Swedish Transport Agency check regularly that the operating companies have functioning safety control, we can say that the operating companies realize and correct their own shortcomings by themselves.

In the national regulations, there is exemptions from approval requirement for certain railway vehicles. For example, approval is not required for rail vehicles which operate at no more than 20 kilometers per hour and which are not engaged for the carriage of passengers, if the rail vehicle: (Retrieved from: Transport Styrelsen, Technical authorization)

1. is used within an A-SPA (special protection area closed to traffic due to work in progress);
2. is used within an area where other traffic is conducted exclusively by low-speed cautious movement;
3. does not have rail-mounted wheels with significance for propulsion or braking; or are towed.

Railway vehicles authorized in a foreign country, under the international agreements on mutual recognition, may be used without Swedish Transport Agency approval.
The Swedish Transport Agency may authorize a subsystem when the important requirements on interoperability, safety, health, environment, reliability and availability are met. This means that the new system should be at least as safe as equivalent subsystem that is in operation at the time of the application. The Authorization shall also ensure that the subsystems are interoperable and can be operated together (vehicle-signaling system-infrastructure).

In May 2016, a new directive on the interoperability of the rail system within the European Union, EU 2016/797, was approved. It states that from June 2019, the European Union railway agency located in Valenciennes will authorize new and modified railway vehicles. The authorization will be valid for traffic within a region which can include railway network in several member states including Norway and Switzerland. The vehicles will fulfil the relevant TSIs of the European Union and a limited number of national rules. The operating company has the responsibility to ensure that the vehicles fulfil the technical requirements of the TSIs. The so called notified body (NoBo) should assess that the requirements are fulfilled. Table 2 represents the regulation documents for authority requirements for different systems for rolling stock (National, European): (Retrieved from: Transport Styrelsen, Technical authorization).

Table 2. Regulation documents for authority requirements for different systems for rolling stock (Retrieved from: Transport Styrelsen, Technical authorization)

TSI	Valid version	Amendments
Control Command and Signalling (CCS)	EU 2016/919	Replaces 2012/88/EU changed by 2012/696/EU, 2015/14/EU
Wagon (WAG)	321/2013	1236/2013, 924/2015
Locomotives and passenger units (LOC&PAS)	1302/2014	
Noise (NOI)	1304/2014	
Accessibility for people with reduced mobility (PRM)	1300/2014	
Energy (ENE)	1301/2014	
Infrastructure (INF)	1299/2014	
Safety in Railway Tunnels (SRT)	1303/2014	

There are different requirements national and European should be meet by the operating companies before put the vehicles in service. These requirements depends on the type of vehicles.

5.1.1 Requirements on trams, metros and local trains (National technical requirements)

Trams, metro vehicles and local trains shall be safe and interoperable with the lines. The vehicles shall fulfill following requirements (Retrieved from: Transport Styrelsen, Technical authorization):

- New vehicles shall be at least as safe as the existing vehicles running in the same type of operation.
- The vehicles shall be able to be detected by the train detection system of the infrastructure.
- The vehicles have to be interoperable with the train protection system of the infrastructure (if any). In addition, the on board train protection system has to be interoperable with the brake and traction system of the vehicle.
- There shall be radio system in driver´s cab for communication with the traffic control center.
- The running dynamics of the vehicle shall be acceptable on the infrastructure. The standard EN 14363 is adequate for demonstration of this requirement).
- The gauge of the vehicle shall fit into the free space of the infrastructure.
- The vehicle shall not send harmful electromagnetic interference to the environment. (The standards EN 50121, EN 50500 and EN 62311 are adequate for demonstration of this requirement).
- The vehicle shall be interoperable with the energy system of the infrastructure.
- Vehicles out of order and derailed vehicles shall be able to be towed, jacked and rerailed.
- The vehicle shall be reliable, especially when operated in winter environment where it's intended to be used.
- There shall be driver´s manuals available in Swedish. The manuals shall give the operational characteristics and limitations of the vehicle (e.g. vehicle gauge, maximum design speed, axle loads, brake performance, rescue and towing, etc.).
- There shall be instructions for lifting, jacking and towing of a vehicle.
- There shall be a rescue service card for the rescue service team for the specific type of vehicle.
- There shall be a maintenance plan and maintenance instructions in Swedish.
- The manufacturer shall have an acceptable quality system, demonstrating that all vehicles of same type are manufactured according to the same design.

In the UK requirements for trams and metros are regulated by the Office of Rail and Road (ORR). This includes the adoption of the German BOStrab guielines to ensure safe operation. However, these guidelines provide no specific maintenance requirement, but safety should be assired through the life of the vehicle. BOStrab guidelines can be found at: http://orr.gov.uk/__data/assets/pdf_file/0018/5076/ttgn5-bostraben-main.pdf

5.1.2 Requirements on locomotives and passenger units

New passenger and locomotives units shall be authorized. This mean that the passenger and locomotives units shall fulfil the requirements according relevant TSIs (European Technical Specifications for Interoperability) and national requirements regarding open points and specific cases in the TSIs. The Swedish Transport Agency (the national safety authority of Sweden) also applies the new approach in the authorization process. This means that a notified body assesses the passenger and locomotive units fulfilment of the TSI requirements (Retrieved from: Transport Styrelsen, Technical authorization)

Valid TSIs

New passenger and locomotives units shall normally fulfil the following TSIs for the authorization: (Source: Transport Styrelsen, Technical authorization)

- TSI Locomotives and passenger rolling stock, Commission regulation (EU) no. 1302/2014.
- TSI Noise, Commission regulation (EU) no. 1304/2014.
- TSI Accessibility for persons with reduced mobility, Commission regulation (EU) no. 1300/2014, not applied for locomotives.
- TSI Control-command and signaling (2012/88/EU, amended by 2012/696/EU and 2015/14/EU).

5.1.3 Requirements for wagons

New, upgraded and renewed wagons shall normally be authorized according "The new approach". This mean that the wagons shall fulfil the requirements according relevant TSIs and national requirements regarding open points and specific cases in the TSIs. The Swedish Transport Agency also applies "The new approach" in the authorization process. This means that a notified body assesses the wagons fulfilment of the TSI requirements (Retrieved from: Transport Styrelsen, Technical authorization).

Valid TSIs

New wagons shall normally fulfil the following TSIs for the authorization:

- TSI Wagon, Commission regulation (EU) no. 2013/321, amended through regulations (EU) no. 1236/2013, and regulation (EU) no. 924/2015
- TSI Noise, Commission regulation (EU) no. 1304/2014

5.2 Available Standards used for development of maintenance program and RAMS, risk and LCC analysis

The maintenance program is decided based on maintenance engineer's judgements, previous experience and RAMS standards. Rolling stock manufacturers are required to provide a maintenance plan which includes the preventive maintenance intervals for the train's systems and sub-systems. This is provided to the rolling stock owners and operating companies. The Manufacturing companies follow standards when they design the maintenance plan/inspection intervals and some of these standards are listed in Table 3 below.

Table 3. Standards use by Rolling Stock manufacturers to design the maintenance plan

Identification		Title	Status
[1]	**EN 15380-2**	Railway applications - Classification system for railway vehicles - Part 2: Product groups	2006
[2]	**EN 15380-5**	Railway applications - Classification system for railway vehicles - Part 5: System structure	2014-11
[3]	**EN 50126**	Railway applications - The specification and demonstration of reliability, availability, maintainability and safety (RAMS)	2000-03 2006-09

[4]	**EN 50126-3**	Railway applications – The specification and demonstration of reliability, availability, maintainability and safety (RAMS) – Part 3: Guide to the application of EN 50126-1 for rolling stock.	2008
[5]	**EN 50128**	Railway applications - Communications, signalling and processing systems - Software for railway control and protection systems	2001-11 2011-03
[6]	**EN 50129**	Railway applications - Communication, signalling and processing systems - Safety-related communication in transmission systems	2011-04
[7]	**EN 60812**	Analysis techniques for system reliability - Procedure for failure mode and effects analysis (FMEA)	2006
[8]	**EN 61025**	Fault Tree Analysis	2007
[9]	**MIL-HDBK-2155**	Failure Reporting, Analysis and Corrective Action Taken	1995
[10]	**TSI-LOC&PAS**	Commission Regulation (EU) No 1302/2014, of 18 November 2014, concerning a technical specification for interoperability relating to the 'rolling stock- locomotives and passenger rolling stock' subsystem of the rail system in the European Union	2014-11
[11]	**EN 60300-3-11**	Dependability management. Application guide. Reliability centred maintenance	2010-01
[12]	**EN 60300-3-12**	Dependability management. Application guide. Integrated logistic support	2011-07
[13]	**Regulation 445-2011-EU**	COMMISSION REGULATION (EU) No 445/2011 of 10 May 2011 on a system of certification of entities in charge of maintenance for freight wagons and amending Regulation (EC) No 653/2007	2011-15
[14]	**Rail Industry Standard RIS-2004-RST**	Rail Vehicle Maintenance	2016

For the national level, there are different Reliability, Availability, Maintainability and Safety (RAMS) and risk standards that the companies are follow when they do RAMS, risk and LCC analysis. The first standard called SVENSK STANDARD SS-EN 50126, which is based on the EUROPEAN STANDARD EN 50126:1999. The Technical Committee CENELEC TC 9 X, Electrical and electronic applications in railways prepared this European Standard. This European Standard provides the railway support industry and Railway Authorities, throughout the European Union, with a process that will enable the implementation of a consistent approach to the management of RAMS. Processes for the specification and demonstration of RAMS requirements are cornerstones of this standard. This European Standard can be applied systematically by railway support industry and a railway authority, throughout all phases of the lifecycle of a railway application, to develop railway RAMS requirements and to achieve compliance with these requirements. The systems-level approach defined by this standard facilitates assessment of the RAMS interactions between elements of complex railway applications. This standard promotes co-operation between railway support industry and a railway authority, within a variety of procurement strategies, in the achievement of an optimal combination of RAMS and cost for railway applications. This European Standard incorporates by dated or undated reference, provisions from other publications. For dated references, subsequent amendments to or revisions of any of these publications apply to this standard only when incorporated in it by amendment or revision. For undated references, the latest edition of the publication referred to applies (Retrieved from: Transport Styrelsen, Technical authorization).

EN ISO 9001- 1994	Quality systems – Model for quality assurance in design, development, production, installation and servicing
EN ISO 9002- 1994	Quality systems – Model for quality assurance in production, installation and servicing
EN ISO 9003- 1994	Quality systems – Model for quality assurance in final inspection and test
ENV 50129- 1998	Railway applications - Safety related electronic systems for signaling
IEC 60050- 1990	International electro technical Vocabulary Chapter 191: Dependability and quality of service
IEC 61508	series Functional safety of electrical/electronic/programmable electronic safety-related systems

The second standard called SVENSK STANDARD SS-ISO 31000:2009, the standard was designed for risk management. Risk management refers to the architecture (framework, process and principles) for managing risks effectively. Railway industry (manufacturers and operating companies) face internal and external factors and influences that make it uncertain whether and when they will achieve their objectives and plans. The effect this uncertainty has on an organization's objectives is "risk". Risk management can be applied to an entire organization, at its many levels and areas, at any time, as well as to specific functions and activities. Although the practice of risk management has been developed over time and within many sectors to meet various needs, the adoption of consistent processes within a comprehensive framework can help to ensure that risk is managed efficiently and coherently across an organization. In this International Standard, a generic approach is described to provide principles and guidelines for managing any form of risk in a systematic and credible manner and within any scope and context. Accordance with this international standard, the management of risk enables an organization to, for example (Retrieved from: Transport Styrelsen, Technical authorization):

- fulfil with relevant regulatory requirements and international norms;
- improve stakeholder confidence and trust;
- create a reliable basis for decision making and planning;
- improve operational effectiveness and efficiency;
- improve loss prevention and incident management; and
- minimize losses.

6 Assessment of current use of CBM in European train operating companies and metro systems.

Maintenance is the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (EUROPEAN SRANDARDS CSN EN 13306). Hence, it can include many types of actions at many levels of an organisation. However, sometimes maintenance actions can be labelled as operational actions even though it falls under the maintenance definition. Operation is defined as "a combination of all technical, administrative and managerial actions, other than maintenance actions, that result in the item being in use". This definition implies that the maintenance actions has to be defined before the operational actions can be established. When looking at the maintenance definition the key aspect is the "required function". The required function is "a combination of functions, or a total combination of functions of an item which are considered necessary to provide a given service" To defining a maintenance action one has to connected it to a specific required function with associated limits of the state of the function e.g. failure limit defining when a "failure" occur. The failure is an event in time, which is constituted by the functional state passing the failure limit. The state after the failure event is then called the "fault state" where the "failure mode" is a way of defining how a specific failure event or a fault state can be perceived. It is worth mentioning that different failure causes or failure events can have the same the same failure mode. E.g., the failure mode "no light" of a light bulb could have different causes or failure evens. The state prior to the failure event is called the "operating state" or "up state". The functional state can of course vary during this state depending on the system. E.g. for functions with a degrading property, the state is called a "degraded state". When the state is to be considered as degraded is dependent on the system at hand.

6.1 Maintenance strategies

Maintenance activities can be divided into two main categories, corrective (repair) and preventive (scheduled and controlled) maintenance. The two groups are divided into subgroups where corrective maintenance can be either deferred or immediate, depending on the severity of failure. Preventive maintenance can be divided into scheduled maintenance and condition based maintenance (CBM) are two types of, see Figure 6. Scheduled maintenance is as the name indicates maintenance performed according to a schedule. The schedule is usually derived based on previous experiences, failure statistics, calculations or tests. CMB is on the other hand dependent on the condition of the system or more specifically the adequacy of the system to carry out a required function.

6.2 Condition based maintenance (CBM)

CBM is a preventive maintenance strategy focusing on the actual condition rather than a predefined maintenance schedule and it "include a combination of condition monitoring and/or inspection and/or testing, analysis and the ensuing maintenance actions. The condition monitoring and/or inspection and/or testing may be scheduled, on request or continuous."

The advantage with this strategy is that maintenance actions can be performed when needed. Unnecessary actions can be avoided while necessary actions can be executed. This strategy is however dependent on the possibility to measure the state of the required function at hand. As indicated by the definition of CBM above, this strategy includes and requires many steps. These steps can be summarised by the following points.

- Domain knowledge: By the use of the domain knowledge, the required functions subjected to the CBM strategy should be defined together with appropriate alarm or failure limits.
- Measurements: Measurement methods should be able to measure different phenomena's reflecting the status of the required functions of the asset.
- Feature extraction: From the measurements different features representing the status of different functions of the asset are generated.
- Analysis: In this stage, the trends of the features are being analysed.

- RAMS, RISK and LCC optimisation: Based on the asset's status different maintenance scenarios can be tested and a decision can be made optimising the availability, risk and LCC. (Note: LCC analysis includes both cost and income (benefits))
- Execution: The final step of CBM is the maintenance execution. By finalising this step, following the other steps, a complete CMB process has been executed.

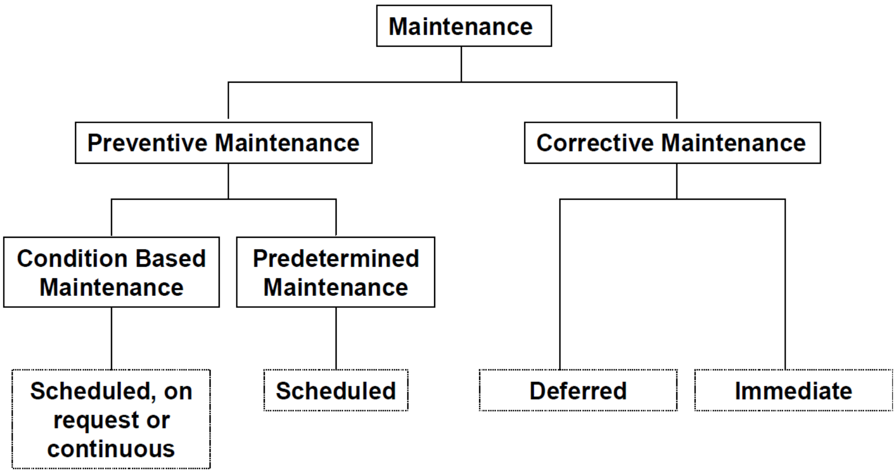

Figure 6. Maintenance types (EN 131306:2010)

6.3 CBM for rolling stock

The required functions which maintenance aims to retain and restore is associated with different systems/units or components. A suitable maintenance plan should then be implemented for each function. If CBM is selected the status of the functions must be possible to measure. Normally the status of different units or components are measured in order to control the status of the function. Hence the technical structure with associated functions has to be defined. The following section describes an example of a product breakdown structure. The product breakdown structure (PBS) for a railway vehicle locomotive, multiple unit, metro, light rail, coaches, etc. consist of nine systems as follows (INTERNATIONAL STANDARD IEC 60300-3-3):

1. Car body
2. Bogies and running gear
3. Power supply
4. Propulsion
5. Auxiliaries
6. Braking
7. Interiors
8. Control and communication
9. Specials

Each system consist of many subsystems as follows:

1. Car body consist of seven subsystems as follows:
   i) Body structure
   ii) Exterior aesthetics
   iii) Exterior doors/steps
   iv) Couplers
   v) Gangways

vi) Window units
vii) Body additions

2. Bogies and running gear consist of five subsystems as follows:
   i) Bogie structure
   ii) Suspension
   iii) Wheel (set)
   iv) Traction line
   v) Bogie additions
3. Power supply consist of three subsystems as follows:
   i) Line voltage system
   ii) Engine system
   iii) Generator
4. Propulsion consist of four subsystems as follows:
   i) Propulsion
   ii) Electric
   iii) Electric power cond.
   iv) Electric power conv.
5. Auxiliaries consist of four subsystems as follows:
   i) Air supply system
   ii) Hydraulic system
   iii) Battery system
   iv) Auxiliary electric system
6. Braking consist of two subsystems as follows:
   i) Braking control
   ii) Brakes
7. Interiors consist of seven subsystems as follows:
   i) Interior architecture
   ii) Heat, ventilation and air conditioning
   iii) Interior doors
   iv) Water services
   v) Catering
   vi) Ticketing
   vii) Lighting
8. Control and communication consist of five subsystems as follows:
   i) Infrastructure train control system
   ii) Train and vehicle control
   iii) Fault diagnostics
   iv) Data communications
   v) Information systems
9. Specials consist of two subsystems as follows:
   i) Tilt system
   ii) Snow protector de-icing

6.4 Schedule inspection and measurement methods for rolling stock

To implement CBM, of a specific product break down structure of a railway vehicle, different measurement systems has to be identified and implemented. The following section describes different philosophies and measurement systems implemented in the European railway system. Inspection and condition monitoring systems of railway vehicles can be divided into two different types based on their placement, e.g. wayside monitoring systems and on-board monitoring systems. Further, they can be classified either as reactive or predictive based upon the principle and philosophy of their operation (Lagnebäck, R., 2007). The reactive systems are used to detect and identify a component in its faulty state after failure occurrence. They give lagging indications for non-performance or performance deviation of different components. The predictive systems give leading indications of impending failure of a component. For the implementation of condition-based maintenance, focus should be laid on the predictive systems, since this would provide possibilities for predictive analytics and preventive maintenance. Most of the condition monitoring systems for railway vehicles are focused on wheelsets and bogies since these are the critical parts that have the largest impact on the overall vehicle performance and are the major cost drivers, although recent developments have seen introduction of technology to detect changes in other systems such as image recognition.

6.4.1 Reactive systems

Reactive systems detect faults that has already happened in the vehicles; many of these faults are hard to predict or are sudden in nature, i.e. they have a short potential-functional failure interval. In most cases, the information from these systems is suitable for reactive actions and not for simple trending or advanced predictive analytics, but it is of importance to protect the equipment from further damage. Some examples for reactive systems are (Lagnebäck, R., 2007):

- Dragging Equipment Detector: The dragging equipment detector is used to detect equipment that is hanging below the vehicle. There are simple mechanical detectors with a vertical standing beam located between the rails and on the outside of the rails to trigger an alarm when they are knocked off. Other advanced system include accelerometers installed in steel boxes and advanced vision technology to trigger an alarm when hit by a passing item.
- Hot Box Detector and Hot/Cold Wheel Detector: The hotbox detector detects the heat emitted from the failing bearing. The hot/cold wheel detector is similar to a hotbox detector. It detects the heat radiation from the wheel. The technology is used to detect skidding wheels or wheels with inadequate breaking performance. By measuring, the temperature of the wheels at places where the brakes are applied and comparing the readings between wheel sets it is possible to identify wheels that have too much or too little breaking force.
- Sliding wheel detector: They are designed to detect wheels that are sliding or skidding due to the fact that they are not rolling as fast as they should compare with the velocity of the whole vehicle. Mechanical failures or human errors can cause sliding or skidding wheels to occur and if undetected, they can result in derailments. These can be monitored using: the hot/cold wheel detector, infrared camera that is used to detect sliding wheels, digital image processing system and automatic sliding wheel detection system.

6.4.2 Proactive systems

Proactive systems are capable of measuring, recording and trending the ride performance of vehicles and condition characteristics of railway vehicles. It is possible to analyses the condition of the equipment to predict possible failures that may occur in a near or distant future. This makes it easier to plan maintenance activities ahead and to utilize the equipment in a more efficient way. Some examples of such systems and detector technologies are (Lagnebäck, R., 2007):

- Acoustic bearing detector: The development of the acoustic detectors arose out of the limitations of the Hot Box Detector and a need for a more predictive system to monitor the health of the bearings. There are a number of systems using a set of microphones that are located at the side of the track. These systems used to detect and record the acoustic signature of the axle bearings on vehicles passing at normal track speeds.

- Vehicle performance monitoring: There are systems that are used for monitoring the performance of the vehicles, bogies and the individual wheel sets on the track and for detecting defect such as lateral displacement, hunting and excessive angle of attack. There are contact measurement systems and non-contact measurement systems. The contact systems are based on strain gauges and/or accelerometers, and can measure the forces (lateral and vertical) that the vehicles induce into the track and the wheel/rail force. This makes it possible to identify vehicles with a high lateral-vertical force (L/V) ratio and are at risk of causing a derailment. The non-contact systems often use lasers and vision technology. An example of non-contact technology is Truck/Bogie Optical Geometry Inspection. The system uses an optical monitoring system, laser and a camera to measure the position of the wheel sets, the angle of attack, hunting behaviour and the lateral position of the wheels in relation to the rail.
- Wheel condition monitoring: The significant impact of a wheel-rail interface on the entire performance of railway systems makes the monitoring of wheel condition very important. Wheel condition monitoring includes assessment of wheel profiles, wear, cracks and other anomalies. Wheel profile monitoring can be done using a contact system such as MiniProf or automated Wheel Profile Measurement Systems (WPMS). A typical WPMS consists of four units one on each side of each rail. These units contain a laser, a high-speed camera, and an electronic control system. When a train passes the units, the wheel triggers a sensor, and the protection cover opens, the laser beam starts to shine, and then the camera takes pictures of the laser beam projected onto the surface of the passing wheels. These pictures are thereafter processed and the different profile parameters indicating the conditions of the wheel are estimated. For wheel damage detectors, a camera and laser used to measure the wheel profile and the brake pads. The measuring system performs a condition assessment of the wheel profile as well as brake pads. It calculates the extent of wear and identifies components that no longer meet what is required by standards. The measuring system scans the wheel's path by laser scanning and image capture. The system will then automatically identify different types of damage to the wheel rim (Retrieved from: http://www.gotchamonitoringsystems.com/WDD.php).
- For brake damage, the measuring system uses cameras to take high-resolution images on brake shoe when wheeled. The software then analyzes the images and can measure the wear rate on brake shoe and calculate the period until replacement is required based on normal decomposition rate. For hot spring detectors, the measuring system detects noise emitted from the wheel bearing and can identify possible defects at an early stage (Retrieved from: http://lynxrail.com/uploads/REF-ENG-010%20Brake%20Pad%20Examiner%20White%20Paper%201.0.pdf).
- For vehicle load characteristics detectors, the measuring system uses optical fiber sensors that are clamped to the rail. It detects track forces in vertical and lateral direction. The measuring system measures both static load (wheel, bogie, trolley, train) and identifies possible wheel defects. (Retrieved from: http://www.gotchamonitoringsystems.com/WIM.php). For vehicle's suspension and damping system detectors, the measurement system uses cameras to identify defects or missing components in the bogie. This includes:
  - Missing or defective in springs / dampers
  - Missing end caps for the wheel bearing
  - Friction separators out of position

The images taken by the respective booklet are analyzed in the software and any defects or missing components are automatically recorded. If a critical defect is found, an alarm is sent to the traffic management center.
There is another vehicle load characteristics detectors, for example, the measuring system uses weight sensors to measure wheel load, axel load, total truckload and trainload. The measuring system can identify critical loads such as overload or oblique load distribution. The measurement method includes special concrete slats with mounted weight sensors. This type of abrasive can have characteristics other than the other abrasive types on the track, which results in the traceability of the distance traveled from the remaining part of the track. Measurement is done by special concrete slats with mounted weight sensors. The advantage of using this method are

  - It can identify vehicles that can damage the track due to excessive dynamic forces or overload.
  - It can identify critical loads that exceed the line classification.

(Retrieved from: http://www.schenckprocess.com/products/wheel-diagnosis-wheelscan).

- Non-destructive examination (NDE) technologies: Non-distractive examination methods, such as ultrasonic, eddy current testing, magnetic particle testing, die penetration testing can be used to identify cracks (surface and sub-surface) and defects in vehicle components. Mainly ultra sound scanning is useful in identification of fatigue cracks in under frames and axels.
- Vision technologies: Vision technology can be used for monitoring in a large amount of applications such as break pad inspections to get an automated inspection process. It can also be used for detecting faulty springs, axles, missing end cap bolts, faulty handbrakes, under frame cracks and deficiencies, buffer faults, air pipe connection faults and coupler faults.
- For passenger wagons doors is one of the most important aspects to avoid delays in traffic. Doors consists of many moving parts and can often cycle many times during a day depending on the rout. Failing doors which will not open will disrupt the passenger flow and can halt the train until passengers has been evacuated resulting in delays. In metro systems with tight schedules, failing doors can echo in the system and render in large disruptions in the traffic. During recent years many companies has developed monitoring systems of this critical item. By analyzing eg. the power consumption when operating a door a deteriorated state of the door functions could be detected and preventive maintenance actions can be executed to avoid disturbing failures.

The preventive maintenance and inspection schedules are based on expert information and standard practices for brakes and wheels. The preventive replacement of brakes and wheels are based on the recommended interval/lifespan from the manufacturing companies and are carried out when the train is in the workshop for corrective maintenance. The manufacturing companies use the following inspection and measurement systems for CBM of brakes and wheels during the warranty period and by train operators:

- General inspection: A visual inspection of an interior or exterior area, assembly or installation to detect irregularities, damages and failures. This can be done from within touching distance, unless otherwise specified. A mirror may be necessary to enhance visual access to all exposed surfaces in the inspection area. This level of inspection is made under normally available lighting conditions such as hangar lighting or daylight and may require removal or opening of access panels.
- Detailed inspection: An intensive inspection of a specific item, assembly or installation to detect irregularities, damages and failures. Mirrors inspection aids as may be necessary, surface cleaning is required.

- Functional check: An inspection used to detect degradation of subsystem's function. A functional check is a quantitative check to determine if one or more functions of performs within specified limits. Functions of brake control, brake shoes, pneumatic components for the activation of the brake cylinders and wheel-slide protection due to the required basic conditions are required for function check during the preventive maintenance at the workshop.
- Wheel profile measurements: The interaction between wheels and rails is one of the key factors on the dynamical behaviour of rolling stock, and consequently, on the safety and comfort of railway vehicles, so it´s necessary to detect with high accuracy and frequency the different parameters of wheels, and in particular, the contact wheel profile. There are five wheel parameters can be measured, wheel flange height, wheel flange thickness, qR factor, back-to-back distance and wheel diameter. Wear and dimensional parameters of wheel profile is an important measurement used by operating and manufacturing train companies. Most companies used non-contact measurement devices. These devices work based on laser light technology to ensure high accuracy measured data. The most important measured wheel profile variables appear on the sensors and can be compared to individual limit values for wheel profile. The wheel profile measurements cover the essential flange measurements of (cross dimension, thickness and height) and wheel width.
- Non-destructive Testing: Non-destructive testing is used when visual inspections are inadequate, non-destructive inspection methods may use to detect fatigue damage during appropriate scheduled preventive maintenance tasks. Manufacturing companies estimate the inspection intervals for train cost driver subsystems use non-destructive testing such as numerical dynamical simulations and structural finite-element analyses.

6.5 Assignment of inspection interval

Inspection and condition monitoring of railway vehicles has been a major focus of safety, efficiency and cost effectiveness since the 1980s. This is based on the fact that it can decrease the operational risk, enhance the performance and in the long run contribute to cost reduction of rolling stocks. Railway vehicle's condition monitoring either in the form of inspection or monitoring is considered to be essential activities in vehicle maintenance (Matthias A., 2016). They aim at collecting information on a condition of different systems, sub-systems or items of the vehicle. Vehicle inspection entails checking for conformity by observing, testing or gauging the relevant characteristics of the vehicle. On the other hand, vehicle monitoring includes all continuous or periodic activities to measure the actual state of vehicle and to evaluate any changes in its physical parameters with time. This is normally carried out with the item in operation, in an operable state and in few instances when it is out of or removed from operation.

Based on information from the manufacturing and operating companies of trains inside and outside Sweden (Europe region) the inspection and preventive maintenance interval is decided based on experts/maintenance engineer's judgements and maintenance standards used by the manufacturing companies. Manufacturing companies decide the maintenance intervals plan for train's systems and send it to the operating companies. For example, **one manufacturing company** uses their own method for optimizing the assignment of the interval for preventive maintenance and inspection of train's sub-systems. **This company** develops their own maintenance program/plan for their trains based on the component's supplier recommendation, RCM standards, FMEA (Failure Mode and Effects Analysis) and their engineering expert judgement. They identify the train's critical components based on FMEA and their engineering judgment, so they do not use the MSG-3 approach to select the critical components.

This company uses condition based maintenance methods to update their maintenance plans for the whole train sub-systems. They follow the TSI (EU technical specifications for interoperability) guideline to do their maintenance program, especially for safety inspection for rolling stock. **This company** as a train manufacturer has manuals for maintenance tasks/intervals for all subsystems (boggies, braking, wagons, etc.) of rolling stock provided from the sub-system's supplier. They merged them to develop a maintenance plan for the whole system (train). This means that the analysis of train systems and components integrated in one maintenance manual. **This company** did many CBM tasks, for example, Lubrication/Servicing, Operational/Visual Check, and Inspection/Functional Checks for the trains that they responsible for. **They** select the type of inspection based upon two things: the criticality of the component and how it is easy to do the inspection.
In summary, the manufacturing and operating companies have maintenance system based on regular checks on a trolley's status, combined with a flat-rate replacement and a flat rate reprocessing of some key components (cost driver subsystems). They do different types of inspections, for example:

6.5.1 Security inspections

In the government regulations for the industry, the term "security inspection" is defined. With regard to security inspections, specific authority requirements are imposed on the performance of these and those who perform the work. The operating company service system applies the following principles:

- **Planned security inspection:** Inspection should be done with an interval determined by time and/or distance.
- **Targeted security inspection:** Inspection should be performed when maintenance, conversion or unforeseen events caused intervention in essential functions. A targeted security inspection should also be performed if suspicions exist that significant functions have been affected for other reasons. The functions that should be taken into account consist of the systems and components covered by the planned security inspection. Targeted security inspection should be carried out in applicable parts. This means that targeted security inspection only needs to include the systems and components affected by an operation. Checklist for scheduled security inspection shall be used in applicable parts.

6.5.2 Other periodic inspection

For periodic inspections other than safety inspection, these can be controlled by time and / or distance / gross tonnage. For example, maintenance intervals for wheel pairs shall be determined based on the use of the trolley and the type of wheel pairs and bearings. There are sets of limits for **security inspection** and **other periodic inspection** (although revising pairs of wheels may also be set shorter intervals). If the intervals for an action are exceeded, the carriage will be given a driving ban.
Other periodic inspections shall be performed in conjunction with security inspection. After one security inspection, all other periodic inspections should have such a long time limit until the next action opportunity (i.e. that they do not need to be remedied before the next security inspection).

7 Discussion and conclusion

Rail transport is one of the fastest growing mass transportation system in which governments, passengers and freight customers have rising expectations of railway operation and performance. This constantly requires the associated stakeholders to drive up RAMS performance of rolling stock at reduced cost, while continuously improving safety. As a result, more effective maintenance programs are expected to be established, to offset the failure and degradation process and to eliminate the consequences of failure or reduce them to a level, which is acceptable to the stakeholders. Condition Based Maintenance (CBM) strategies have become a focus of many companies for development of an applicable and effective maintenance program. One of the major developments in the implementation of CBM has taken place in the aviation industry with the introduction of on-condition inspection through the Maintenance Steering Group (MSG-3) concept.

The aim of this study is to introduce the proven experience of aviation expanded through the application of MSG-3 methodologies, in the development of scheduled CBM based aircraft maintenance program. In particular the objective is to evaluate the potential benefit of a system such as MSG-3 to the railway industry for the development of an effective and efficient rolling stock maintenance programme. To achieve the purpose of this research, literature studies, have been carried out and the empirical data and information have been collected through document studies, interviews, questionnaires, and observations, combined with the published best practices from the aviation and railway industry. The findings of the study were twofold; first of all it deals with the common rules and regulations governing the maintenance program, and then it compares the MSG-3 practices with the railway experience.

The study showed that the effectiveness and success of scheduled inspection/CBM strategies in the aviation industry is due to two major facts. At the beginning, the development of aircraft maintenance schedules is highly regulated. These regulations are internationally harmonized and coordinated between all countries. In this process, the recommendation and regulations provided by Federal Aviation Administration (FAA) of the USA and the European Aviation Safety Agency (EASA) are strongly considered. This means the definitions, principles and underlying concepts of any maintenance and inspection program developed and managed by the manufacturer and operator are the same, with very little difference from country to country. As an example, FAR 25/JAR 25 regulation require manufacturers to provide instructions for Continued Airworthiness as a part of aircraft certification and FAR 121/JAR OPS regulation require operators to maintain an approved maintenance program.

The other important factor in the development of an aircraft Maintenance and inspection/CBM program is the use of Maintenance Review Board concept where, manufacturers, regulatory authorities, vendors, operators, and industry work together; to develop the initial scheduled maintenance / inspection requirements for new aircraft and/or on-wing power plant. This provides a unique opportunity where, all stakeholders will be engaged in the process, and share/combine their knowledge and experience for development and management of the maintenance program. Through this process, different operational environments will be considered and the uncertainty of the decision-making will be reduced. The MRB procedure requires the establishment of a Maintenance

Review Board to approve the work, a Joint Manufacturer/Airline Steering Committee to direct the work, and a Joint Manufacturer/Airline Working Groups (MWG) to develop requirements and task analysis. MSG-3 methodology refers as a common means of compliance for defining the maintenance requirements and development of Maintenance Review Board Report (MRBR) by MRB stakeholders, e.g. manufacturer, authorities, operators.

The Maintenance Review Board Report (MRBR) outlines the Initial minimum scheduled maintenance / inspection requirements to be used in the development of an approved continuous airworthiness maintenance program for the airframe, engines, systems and components of a given aircraft type. It is generated as an expeditious means of complying in part with the maintenance instruction/requirements of developing Instructions for Continued Airworthiness, as required by Appendix H to 14 CFR part 25. It is intended that the MRB Report will be used as a basis for each operator to develop its own continuous airworthiness maintenance program subject to the approval of his regulatory authority. After approval of the MRBR by the FAA/EASA, the requirements become a base or framework around which each air carrier develops its own individual maintenance program.

In the railway industry, manufacturers and operators do not currently follow common international standards or guidelines, as a common means of compliance for the development of rolling stock maintenance program. In general, manufacturers use variety of available standards and guidelines (e.g. RCM and EN standard, etc.). In most of the cases, the potential operators and stakeholders are not engaged in the analysis and development process of the maintenance program.

Another important factor of a successful Maintenance and inspection/CBM program development within aviation industries, is the establishment of a mandatory reliability program by the operator. Since adjustments of the maintenance program are necessary, the operator's maintenance reliability program must be established, to suit specific types of operation, and to facilitate this requirement. According to "AMC M.A.301-4 Continuing airworthiness tasks", the air operator should have a reliability assessment program, to analyze the effectiveness of the maintenance programme, with regard to spares, established defects, malfunctions and damage, and to amend the maintenance programme accordingly. The purpose of a reliability programme is to ensure that the aircraft maintenance programme tasks are effective and their periodicity is adequate. The reliability programme may result in the escalation or deletion of a maintenance task, as well as the de-escalation or addition of a maintenance task. A reliability programme provides an appropriate means of monitoring the effectiveness of the maintenance programme.

In the aviation industry, the manufacturer provides the initial minimum maintenance program for the whole aircraft and associated systems, and the operator is responsible for updating the maintenance program when the operation is matured. In this process, the manufacturer plays an important role and must support the operator with recommendation and analysis procedure for the whole life of the product. In addition, the manufacturer conducts a maintenance steering group where the maintenance program of a specific aircraft type is reviewed, and the updates are introduced for the operator (i.e. from the top to the bottom). Operators are mandated to get the new version of the maintenance programme approved by the local aviation authority. The analysis procedure requires that the System breakdown structure developed by Air Transport Association of the USA is followed. The basis for these analyses are the Reliability program.

In the railway industry, the manufacturer has manuals for maintenance tasks/intervals for all subsystems (bogies, chassis, wagons, etc.) of rolling stock provided from the subsystem's supplier. The manufacturer merged these manuals to develop their maintenance plan/program for the whole system (i.e. train). This means that the analysis of train systems and components is integrated in one maintenance manual. However, the railway industry does not conduct a maintenance steering group like the airline system. Thus, to setup industry steering group for railway industry, these group should consist of specialist from the authority, operators and from the manufacturer.

After delivery of the vehicle to the operator, several scenarios may exist depending on the contract between manufacturer and operator. In one of the studied scenarios, the manufacturer takes the responsibility of updating the maintenance program for the train during the warranty period. After the warranty period, the operators have the responsibility to update their own maintenance plan without going back to the manufacturer except for safety issues where the operator must follow the relevant authority standards. However, in general, it is widely believed in the railway industry that after delivery of the vehicle to the operator, it is their own asset and they need to take care of the life cycle maintenance program. Depending on the type of the rolling stock, either cargo or passenger vehicle, the maintenance for systems and components (bogies, chassis, wagons, etc.) might not always follow a harmonized process. This is because the maintenance program of a wagon might be developed by company A, while the train maintenance program is developed by Company B. In some cases, the operator develops their own maintenance program/plan for their rolling stock based on their engineering expert judgement.

The study shows that the operator rarely communicates with the manufacturer and suppliers regarding the maintenance program and there is no formal procedure for feedback from operator to the manufacturer. However, operators are mandated to follow safety instruction provided by the authorities. The manufacturer is solely responsible for the whole maintenance program development, and mostly relies on the supplier recommendation. The suppliers do not have operational experience and therefore their recommendation is very conservative. The manufacturer collects recommendation form the suppliers and develop a maintenance plan. Most of the time the recommendations are adjusted according to the experience of the manufacturer.

As a best practice in the aviation industry, MSG-3 uses a process flow chart and guides the analyst on how to employ any kind of available maintenance strategies. This includes assessment of the failure effect category (safety, operational, economic), type of failures (evident or hidden), applicability and effectiveness of maintenance tasks as well as definition of the associated interval.

As stated earlier, MSG-3 is a risk driven approach where any kind of decision must be based on the consequence of the failures. Depending on the final consequence, it may have several functions with varying importance. As an example, the importance of a function can range from "crucial for safety" to "nice to have but can do without". The methodology of MSG-3 dictates that the maintenance analysis should only consider those items whose functions are significant enough to proceed (deserve) with further analysis and apply the maintenance decision logic to them. The criteria for selecting the “Significant items” include “the item whose failure could affect operating safety and a have major operational or economic consequences”.

In the railway industry, there is no specific guideline for the definition of the “Maintenance Significant Items” (MSI). The critical items are judged based on their engineering expert judgement and the results obtained for failure criticality assessment through FMECA. It should be noted that the identification of MSIs are the first most important step in the development of and effective and efficient maintenance program. In railways the safety limits and criteria drive the MSIs in general. However, each stakeholder defines their own criticality criteria based on their individual business case where, cost benefits are taken into consideration. Normally cost driver items and items, which disturb their operation, are considered as critical. However, there is no evidence that operational and economic effect of failures are considered for an item to list as MSI.

The study shows that there is no guideline or standard in the railway industry dedicates the development of a rolling stock maintenance program following the MSG-3 concept as used in the aircraft industry. In general, assessment of the failure effect category (safety, operational, economic), type of failures (evident or hidden), applicability and effectiveness of maintenance tasks as well as definition of the associated interval are not part of a harmonized guideline. Some manufactures and operators use an RCM methodology where they are mostly use the FMECA philosophy for the items and according to the criticality, will identify if the items are significant for maintenance. It should be mentioned that having a maintenance review board system increases the effectiveness of FMECA analysis because stakeholders share data.

Concerning the methodology of developing a maintenance program, the most important step in the definition of a scheduled CBM program is to get an idea of the reliability characteristics and risk of failures. In fact, having a constant, decreasing or increasing failure rate provides valuable input for the development of a CBM task. In order to control the efficiency and effectiveness of a maintenance task during the operation phase, establishment of “operator reliability program” is necessary.

Within the study, it was also found that an established method for identification of maintenance significant items (MSI) does not exist in the railway industry. The MSI selection method should include defined criteria that indicates the significance of a failure mode. As an example, whether the failure affects the safety of passengers, the health of the vehicle, passenger comfort and by how much. Moreover, establishment of a criteria for identification of applicability and effectiveness of a maintenance task, including CBM tasks, are vital. This is required to ensure that selected inspection/CBM tasks are able to reduce the risk of failures. In addition, it helps to identify how well the task can fulfil the objectives.

7.1 Recommendations for rolling stock industries

Based on the outcome of the study, the following conclusions and recommendations are provided in relation to the application of MSG-3 methodology within the rail industry and specifically for rolling stock maintenance:

1. The concept of a "Continuous Track Worthiness" Maintenance Program needs to be established at a European level, to support the development of a combined program of Inspection and maintenance that fulfils the maintenance needs of rolling stock. Track Worthiness is applied as a measure of the rolling stock's suitability for safe operation on track. Similar to aviation industry, "Certification of Track Worthiness" can be conferred by a certification audit by the national railway authority of the state of rolling stock's registry, and will be maintained by performing the required/defined inspection maintenance requirements.
2. In this process, the responsibility of the manufacturers, suppliers and operators need to be clearly defined in order to fulfil the 'Continuous Track Worthiness' requirements of rolling stock through its whole life cycle. In this concept, the responsibility of the manufacturers is held through a defined life of the vehicle, not just for the period of Guaranty/warranty.
3. To improve the effectiveness of an inspection and maintenance regime, it is highly recommended that a European task force is created to harmonize and coordinate the regulations and procedures of maintenance program development among authorities and stakeholders.
4. The concept of a "Maintenance Review Board" (MRB) needs to be established within railway industry, specifically for rolling stock maintenance, where manufacturers, regulatory authorities, vendors, operators and industry collaborate to develop the initial scheduled maintenance / inspection requirements for new vehicles and associated systems. A typical MRB may include a steering committee to direct the working process and several Maintenance Working Groups, to perform the maintenance need analysis per system. Having this process in place enables the industry to engage all stakeholders and employ their knowledge and experience in determining the most effective inspection and Condition Based Maintenance program.
5. Development of harmonized guideline based on the Maintenance Steering Group (MSG-3) methodology for rolling stock will enhance the decision making process through assessment of the maintenance needs and program development. The specific issues that need to be considered in the guideline includes:
   - Identification of maintenance significant items (MSI)
   - Definition of the failure effect category (e.g. safety, environment, passenger comfort, operational, economic), and their measures,
   - Development of applicability and effectiveness criteria of maintenance tasks selection
   - Description of the procedures and methodologies for determination of tasks interval.
6. The rolling stock operators should establish a reliability assessment program, to analyze the effectiveness of the maintenance programme, with regard to defects, malfunctions and damage, to suit specific types of operation and to facilitate this requirement. Obviously, the outcome of a reliability programme may result in the adjustment of the maintenance task, i.e. escalation or deletion of a maintenance task, as well as the de-escalation or addition of a maintenance task, to ensure the effectivity of maintenance program.

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Appendx 1: An example of MSG-3 application for system maintenance development

Note:

This appendix provides an example of MSG-3 implementation. Since most of the manufacturers didn't allow to use their analysis, the partners have added the following example which is available for public.