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RISK MANAGEMENT AND SAFETY ANALYSIS OF THE GAS TURBINE AND ITS OPERABILITY

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ABSTRACT

A risk can produce especially serious safety problems especially in the context of technical procedures. This can also result in very high levels of economic damage. The gas turbine has to be analysed in a functional tree, where main components and their functionality within the system can be shown. This is a basic step to investigate possible failures with the method FMEA or FTA.

Key words

Risk management, Safety analysis, Gas turbine, Fault Tree Analysis, Failure Mode and Effects Analysis

1 Introduction

The term risk refers to the negative influence of an event or an action on a planned procedure. (1) This can include a business procedure such as a production procedure or even a technical procedure such as combustion in a gas turbine and its operability.
A risk can produce especially serious safety problems especially in the context of technical procedures. This can also result in very high levels of economic damage.This becomes clear using the example of aerospace engineering. A risk and the resulting damage can result in danger for life and limb, but also result in considerable financial consequences. As a result, and due to the ever-complexer composition of our industrialised world with its high technical standards, risk management has become indispensable.The earlier (for example during product development) a risk is recognised and reduced, the more successful is a product or procedure (2).
Risk management includes all measures for the recognition, analysis, evaluation, monitoring and control of risks.In 2005, ISO decided to develop a risk management standard. ISO/DIS 31000 Risk Management (Figure 1) is subdivided into the three sections Principles; Risk management framework; and Risk management process.

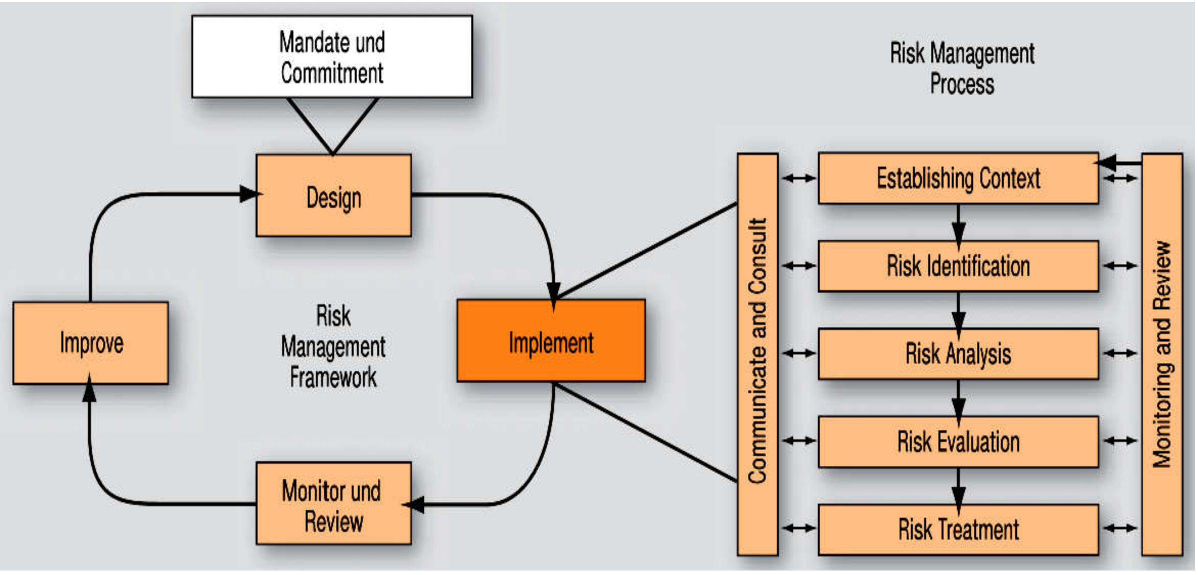

Figure 1: *Risk management in accordance with ISO 31000 (2, 3)*

The principles for risk management are (1-3):

- It creates values
- It is an integrated part of organisational processes

- It is part of the decision-making process
- It deals expressly with uncertainty
- It is systematic, structured and up-to-date
- It is based upon the best available information
- It is tailored
- It takes into account human and cultural factors
- It is transparent and comprehensive
- It is dynamic, iterative and reacts to changes
- It facilitates continual improvement and organisational strengthening

The risk management strategy includes the process of systematic and continual risk analysis (Figure 2). The information procurement stage is the most difficult phase in the risk management process, but represents a key function. The risk analysis and evaluation is performed using special methods.

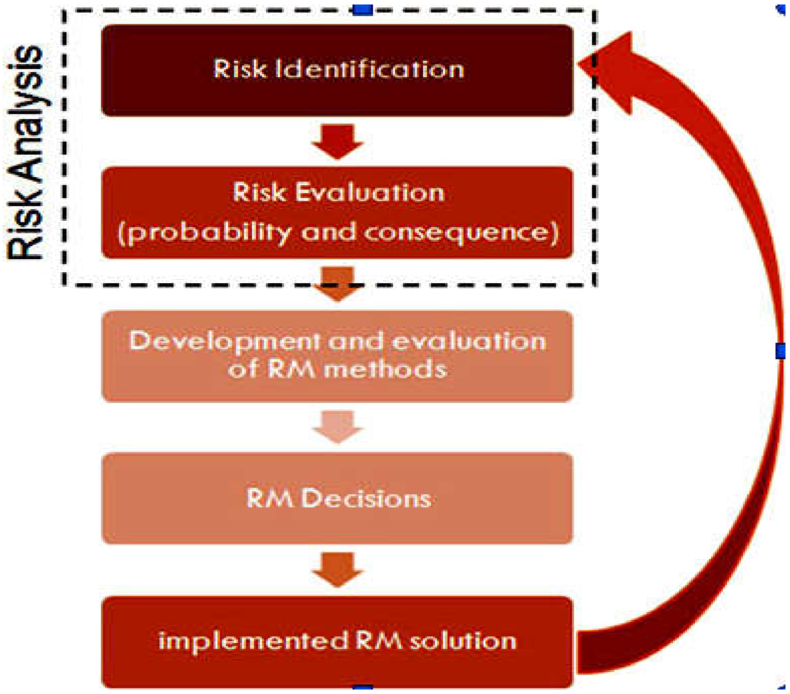

Figure 2: *The Risk Management Process (4)*

The technical background of this investigation means that it shall also consider the concept of safety analysis; the term risk analysis is often used in conjunction with Management Economics considerations.
The aim of the safety analysis is the recognition of dangers and their causes. This involves consideration of every system unit and the associated danger potential. As already indicated, there exists a large number of methods with which to conduct the analysis and evaluation. The automobile industry prefers the Failure Mode and Effects Analysis (FMEA). The aerospace engineering industry developed the Fault Tree Analysis (FTA) whilst the chemicals industry often uses the Hazard and Operability Study (HAZOP). In many cases, the best results are obtained using a combination of a number of methods of analysis. (5)
DIN EN ISO 14121-1 defines a risk as the combination of the probability of the incidence of damage and its extent. A large number of procedures exist with which to analyse these factors. In general, we differentiate between two basic types of risk analysis. A deductive procedure starts with an event and analyses its causes. An inductive procedure assumes the existence of possible deviations in a process or a system and analyses its effects (3,1).

2 Safety analysis procedures
2.1 Fault Tree Analysis

Suited to conducting reliability and safety analyses, the FTA uses a system analysis to determine component connections and subsystem failures which can result in an undesired event, known as a top event. The FTA enables depiction of the functional system structure as a causal failure effect chain and above all to calculate the probability of system failure based on the failure probabilities of basic events.

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A functional analysis is used to depict the functional failure performance of a system as a causal chain of events. The figure 3 shows which failures produce an undesired event. A test of prevention measures can be performed to this end. Systematic investigation of the system for Minimal Cut Set MCS, which depict the smallest possible failure combinations of basic elements show how the system can be optimised. In doing so, make special note of critical minimal cuts (MCS 1 order), which can only be triggered by a basic event.
A quantitative analysis is used to calculate the probability of occurrence of the events up to an undesired event and compares it with the target specifications. The basis for this is knowledge or a qualified estimation of the failure probability of all basis events.
We differentiate between the following categories of component failure:

- Primary failure (component failure with normal operation conditions)
- Secondary failure (component failure resulting from secondary damage from a primary failure or resulting from extreme operating conditions)
- Command failures (component failure resulting from faulty operation, misuse or the failure of a required source)

The fault tree is drawn up as a pictogram, which emphasise the system connections. Figure 9 shows an example of different pictograms and events with the top event "hot water heater explodes"

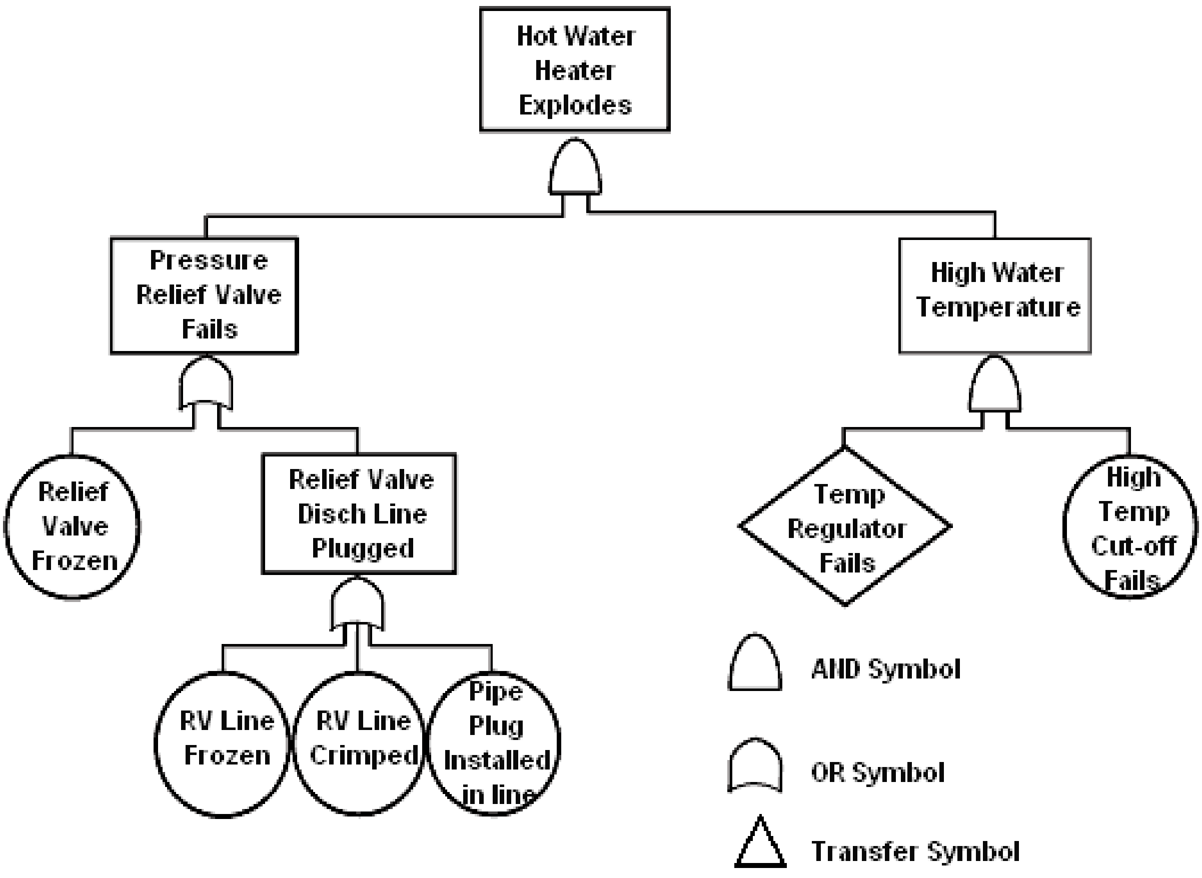

Figure 3: *Fault tree pictogram (6)*

Basis events have only a single output. A top event can only have one input. The important factor is the nature of the connection. Whilst the OR combination of two inputs is sufficient to trigger an output, the AND connection requires both inputs in order to trigger an output.
The following work steps are required for the generation of a fault tree:

- A system and function analysis
- The definition of the undesired event (top event)
- Determination of the reliability command variable with a time interval
- Determination of the failure modes and categories
- Depiction of the failure performance in the fault tree up to the basic events

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- Determination of the critical and other minimal cuts
- Evaluation of the basis events from input data (failure rates, times)
- Probabilistic evaluation of the fault tree (calculation of the top event)
- Results, target/actual comparison, measures
- Fault tree analysis of the improved system

Working on the basis of the results, it is possible to determine the most effective measures for eliminating weak points and optimising reliability and safety.

2.2 Failure Mode and Effects Analysis FMEA

FMEA was developed in the NASA space programme in 1959/60. The terms "quality" and "safety" are closely related in aerospace engineering. (9,7)
FMEA serves the investigation of potential weaknesses in design and production plans in the planning stage. It thus assumes a preventative character. A particular characteristic is the basic rule stating the requirement to locate, evaluate and if possible eliminate all possible causes for a potential fault. (1)
FMEA is thus an inductive analysis procedure. A significant character of the FMEA is the determination of risk priority numbers (RPN), which provide a statement about the urgency of a possible fault. This method provides a qualitative evaluation. (2)

RPN is defined as follows (1):

$$S \times O \times D = RPN$$

S (Severity) stands for the probability of incidence of a cause of a fault; O (Occurrence) represents the meaning of the fault; whilst D (Detection) represents the probability of the discovery of the cause of a fault. A large number of evaluation aids are available for the rating the numbers S, O and D. The RPN serves the decision-making in terms of the necessity of optimisation. RPN 40 represents a low risk, (no measures), 40 RPN 100 represents a moderate risk (measures required with safety components) whilst RPN 100 is classified as an intolerable risk (measures required). (1)

Careful preparation of the FMEA is decisive to its success. The following preparation steps are important (1):

- Generate a system structure and function tree
- Select the object of analysis (potential malfunctions)
- Draw up a work plan (team composition, moderator, tasks, timetable
- Compile fault data (failure data, experiment results)
- Prepare documents (design drawings, production plans, specifications)
- Prepare components (test parts, models)

An important step in FMEA is system modelling. The system model is developed by dismantling the overall system into main components, components and system elements. This is followed by a functional analysis of the system elements. The interplay of the system elements is depicted in a function tree. Every function is checked for possible risks.The resulting list of potential malfunctions provides the basis for performing the FMEA. (1)
A central element of FMEA is the corresponding form as shown in figure 4.

Potential Failure Mode & Effects Analysis

Process/Product:	Stock Inventory
FMEA Team:	
Responsibility:	
Prepared By:	

Row Number Sort	Process Steps or Product Functions	Potential Failure Mode	Potential Effects of Failure	Severity (1-10)	Potential Cause(s) of Failure	Occurrence (1-10)	Current Controls	Detection (1-10)	Risk Priority Number (RPN) Sort
	Process								
1	Stock Inventory	Stock in wrong location	Unable to locate Stock	5	Correct location is full	7	Stock checked twice a year	9	315
2	Stock Inventory	Damaged	Insufficient	7	Supplier Defect	3	Incoming	8	168
3	Stock Inventory	Damaged	Insufficient product	7	Handling Error	5	Standard Operating	9	315
4									

Figure 4: *FMEA form (example) (1,7,3)*

2.3 HAZOP

One method of risk analysis often used is the Hazard and Operability Study, HAZOP. This method was developed by the British chemicals industry in the 1960s. Working in teams, individual components of a process are their connections are checked for possible deviations using guide words. (8) Typical guide words are "no", "more", "fewer" "backwards" etc. This seeks to develop conceptual approaches to deviations and identify hazards.

The analysis can start very early with the system conception and is then continued during the development process. The effectiveness of the procedure depends strongly on the quality and exactness of the system conception and the technical knowledge of the team members, in order to recognise potential deviations and evaluate risks. (8)

HAZOP consists of the following work steps (8):

- Selection of a process step
- Attribution of the process step (e.g. speed, tension)
- The combination of every attribute of a process component with guide words (no, more)
- Risk identification for every attribute
- A discussion of possible causes and outcomes
- Development of any necessary remedial action
- Continuation of the analysis with another guide word, attribute or process component

HAZOP is a recognised standard procedure for the analysis of deviations. It is highly complicated in terms of personnel requirements, as it requires the assembly of a team which meets regularly for discussion. This is associated with high costs. The success of the procedure depends strongly on the knowledge of the team members. Both the HAZOP study and the FMEA analysis use tables as a tool. (9)

6. Test methods

The gas turbine has to be analysed in a functional tree, where main components and their functionality within the system can be shown. This is a basic step to investigate possible failures with the method FMEA or FTA. Figure 11 shows an example of a gas turbine functional tree.

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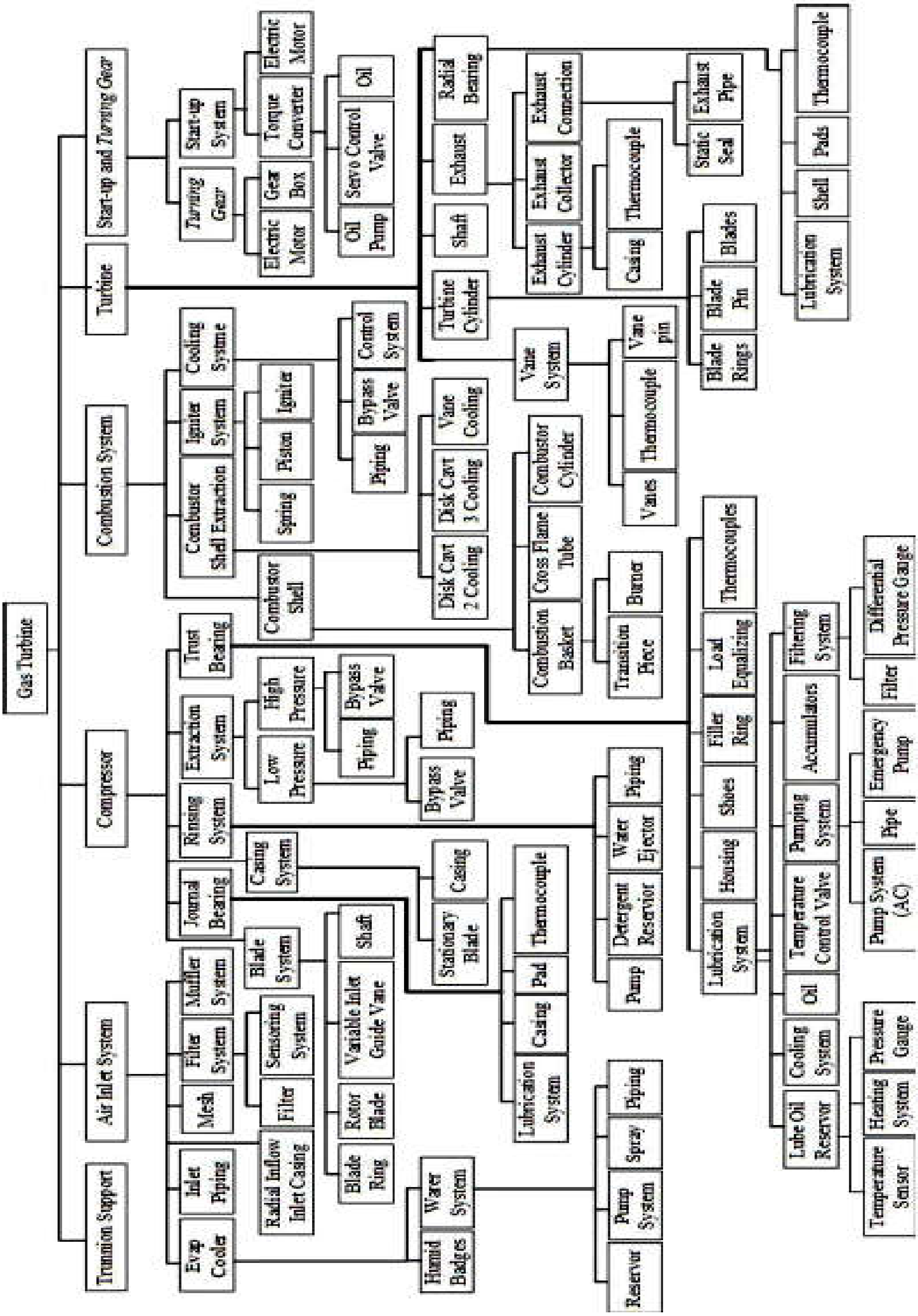

Figure 5: *Gas turbine functional tree (9)*

The next step is the e.g. FMEA analysis for each component of the gas turbine in order to find critical parts. A worksheet with the components will be completed in 3 steps.

First the severity assessment for each failure mode should be defined as shown in table 1.

Severity	Criteria	Ranking
None	No discernible effect.	1
Very minor	Fit and finish/squeak and rattle item do not conform. Defect noticed by discriminating customers (less than 25 %).	2
Minor	Fit and finish/squeak and rattle item do not conform. Defect noticed by 50 % of customers.	3
Very low	Fit and finish/squeak and rattle item do not conform. Defect noticed by most customers (greater than 75%)	4
Low	Vehicle/item operable but conform/convenience item(s) operable at a reduced level of performance. Customer somewhat dissatisfied	5
Moderate	Vehicle/item operable but conform/convenience item(s) inoperable. Customer dissatisfied	6
High	Vehicle/item operable but at a reduced level of performance. Customer very dissatisfied	7
Very high	Vehicle/item inoperable (loss of primary function)	8
Hazardous with warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves non-compliance with government regulation with warning	9
Hazardous without warning	Very high severity ranking when a potential failure mode affects safe vehicle operation and/or involves non-compliance with government regulation without warning	10

Table 1: *Failure mode severity (9)*

The ranking helps to prioritize failure modes and their effects within the system.

The next step is the occurrence ranking as shown in table 2. The frequency of occurrences is based on documented experienced failure modes and processes.

Failure mode occurrence	Rating	Frequency	Probability
Remote: Failure is unlikely	1	≤0.010 per thousand vehicles/items	$\leq 1\times10^{-5}$
Low: Relatively few failures	2	0.1 per thousand vehicles/items	1×10^{-4}
	3	0.5 per thousand vehicles/items	5×10^{-4}
Moderate: occasional failures	4	1 per thousand vehicles/items	1×10^{-3}
	5	2 per thousand vehicles/items	2×10^{-3}
	6	5 per thousand vehicles/items	5×10^{-3}
High: repeated failures	7	10 per thousand vehicles/items	1×10^{-2}
	8	20 per thousand vehicles/items	2×10^{-2}
Very high: Failure is almost inevitable	9	50 per thousand vehicles/items	5×10^{-2}
	10	≥100 in thousand vehicles/items	$\geq 1\times10^{-1}$

Table 2: *Failure mode occurrence (10)*

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The third step is the detection ranking also based on experienced tests or inspections etc.
Table 3 shows the Failure mode detection evaluation criteria.

Detection	Criteria	Ranking
Almost certain	Design control will almost certainly detect a potential cause/mechanism and subsequent failure mode.	1
Very high	Very high chance the design control will detect a potential cause/mechanism and subsequent failure mode	2
High	High chance the design control will detect a potential cause/mechanism and subsequent failure mode	3
Moderately high	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode	4
Moderate	Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode	5
Low	Low chance the design control will detect a potential cause/mechanism and subsequent failure mode	6
Very low	Very low chance the design control will detect a potential cause/mechanism and subsequent failure mode	7
Remote	Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode	8
Very remote	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode	9
Absolutely uncertain	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode: or there is no design control	10

Table 3: *Failure mode detection evaluation criteria (10)*

As shown in chapter 2.2 the three rankings enable the calculation of the Risk Priority Number (RPN).

Tables 4 and 5 show an example of a risk analysis of a gas diffuser liner failure in a V94.2 Siemens gas turbine.

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Potential failure mode	Potential cause(s)	Potential effects of failure	Failure mode number
Circumferential Cracking on the weld seam connecting the diffuser liner and casing liner	Changing the clearance between diffuser liner and diffuser outer casing	Increasing the liner clearance (6+2 clearance) and consequently gas escapes to space between liner and expansion joint and finally reduction of expansion joint life	FM 1
		Increasing the liner clearance (6+2 clearance) and consequently gas escape to space between liner and expansion joint and finally increasing the exhaust casing temperature	FM 2
		Increment of turbine absolute vibration due to contact of diffuser liner and diffuser outer casing	FM 3
		Contact of diffuser liner and diffuser cone and increment of vibration and consequently reduction of life of welding joints of diffuser outer casing	FM 4
	Exhaust gas leaks from the crack of weld joint into space between diffuser liner and diffuser outer casing	Exhaust gas escape in space between diffuser liner and diffuser outer casing and consequently reduction of expansion joint life	FM 5
		Exhaust gas escape in space between diffuser liner and diffuser cone and consequently increment of the exhaust casing temperature	FM 6
	Increasing the diffuser liner vibration and consequently increase of diffuser outer casing vibration	Increase of absolute vibration of Turbine	FM 7
Detachment of first liner of diffuser	Collision of liner with thermocouples which are measuring the temperature of exhaust gas	Thermocouples are damaged and consequently the control and monitoring system is failed	FM 8
	Emerging turbulence in turbine outlet flow	Reduction of turbine performance	FM 9
	Hot turbine exhaust flow is directed towards the gas diffuser outer casing	Reduction of expansion joint life	FM 10
		The temperature of exhaust casing increases and it is deformed due to temperature increase	FM 11
	Liner vibrations are transmitted to the stationary turbine parts	Increment of absolute vibration of Turbine	FM 12

Table 4: *Potential failure modes of gas diffuser liner failure (10)*

Failure Mode Number	Severity	Occurrence	Detection	RPN
FM 1	2	1	7	14
FM 2	3	3	6	54
FM 3	5	6	2	60
FM 4	3	3	8	72
FM 5	2	2	7	28
FM 6	3	1	7	21
FM 7	5	2	4	40
FM 8	9	1	2	18
FM 9	7	2	3	42
FM 10	6	1	4	24
FM 11	4	1	7	28
FM 12	7	1	3	21

Table 5: *FMEA worksheet for risk analysis of gas diffuser liner failure (10)*

This risk assessment allows to create a critical matrix as shown in figure 12.

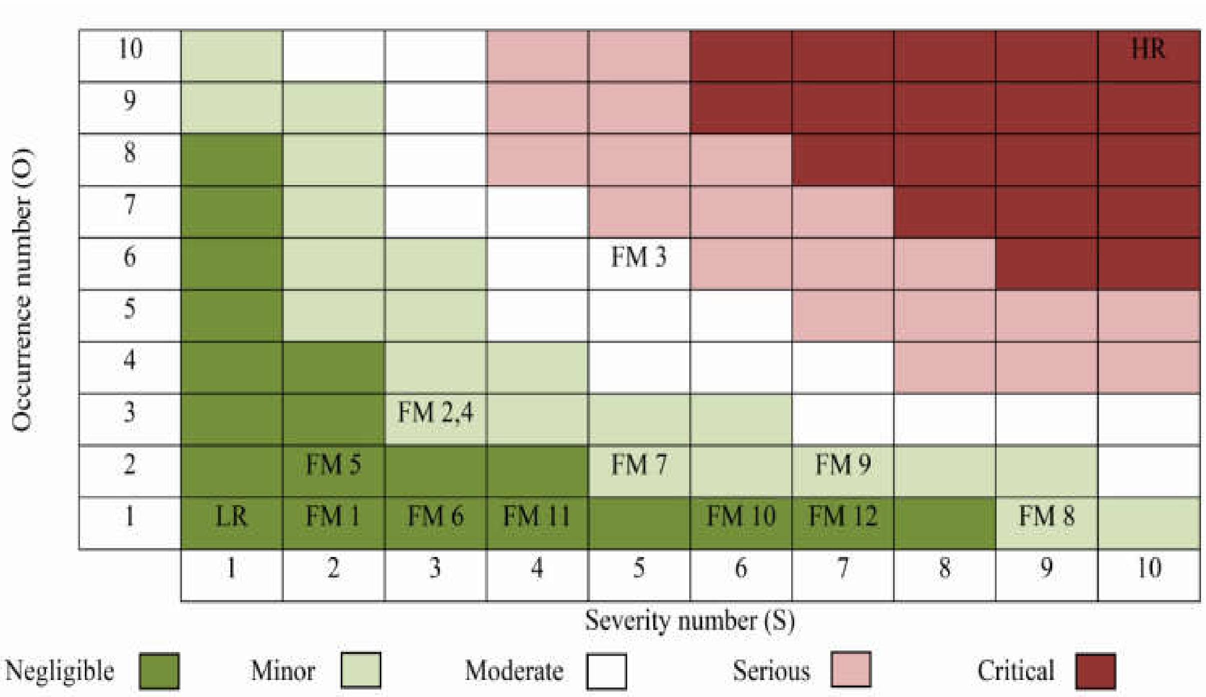

Figure 6: *Critical matrix (10)*

Conclusion

The risk assessment shows possible failures and their effects with a ranking which can be used in order to tolerate failures or to improve the system. The analysis of each component ensures the completeness of failures.

This procedure also allows conclusions about maintenance, reliability and availability of a system. It is a necessary tool to find potential improvements in order to increase the efficiency of stationary gas turbines.

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