CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Transportation Sciences

Department of Air Transport

Reliability analysis of mechanical and lubrication system of an aircraft engine

Diploma thesis

Study Programme: Technology in Transportation and Telecommunications

Study Field: Air Traffic Control and Management

Thesis Supervisor: Ing. Andrej Lališ, Ph.D.

Bc. Simona Bolčeková

Prague 2019

CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Transportation Sciences
Dean's office
Konviktská 20, 110 00 Prague 1, Czech Republic

K621..Department of Air Transport

MASTER'S THESIS ASSIGNMENT

(PROJECT, WORK OF ART)

Student's name and surname (including degrees):

Bc. Simona Bolčeková

Code of study programme code and study field of the student:

N 3710 – PL – Air Traffic Control and Management

Theme title (in Czech): **Vyhodnocení spolehlivosti mechanického a olejového systému leteckého motoru**

Theme title (in English): Reliability Analysis of Mechanical and Lubrication System of an Aircraft Engine

Guides for elaboration

During the elaboration of the master's thesis follow the outline below:

- Analysis of reliability engineering methodologies
- Analysis and description of an aircraft engine mechanical and lubrication system
- Reliability analysis of the lubrication system
- Proposal of conceptual solution to advance the reliability in terms of possible analysis automation
- Evaluation of the proposed solution

CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

Graphical work range:	as per thesis supervisor instructions
Accompanying report length:	minimum of 55 text pages (including figures, graphs and tables)
Bibliography:	Aerospace Recommended Practice ARP4754A. Guidelines For Development Of Civil Aircraft and Systems. SAE International, 2010 Guizzardi, G. Ontological foundations for structural conceptual models. 2005

Master's thesis supervisor: **Ing. Andrej Lališ, Ph.D.**

Date of master's thesis assignment: **July 27, 2018**
(date of the first assignment of this work, that has be minimum of 10 months before the deadline of the theses submission based on the standard duration of the study)

Date of master's thesis submission: **May 28, 2019**
a) date of first anticipated submission of the thesis based on the standard study duration and the recommended study time schedule
b) in case of postponing the submission of the thesis, next submission date results from the recommended time schedule

L. S.

doc. Ing. Jakub Kraus, Ph.D.
head of the Department of Air Transport

doc. Ing. Pavel Hrubeš, Ph.D.
dean of the faculty

I confirm assumption of master's thesis assignment.

Bc. Simona Bolčeková
Student's name and signature

Prague .... July 27, 2018

Declaration

I hereby declare, that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or processional qualification except as specified.

I have no serious motives against using this educational work according to the § 60 of Act of the Czech Republic No. 121/2000, on Copyright and Righs Related to Copyright and on Amendment to Certain Acts (the Copyright Act.).

In Prague, May 2019

....

Bc. Simona Bolčeková

Acknowledgements

I would like to express gratitude to my supervisor Ing. Andrej Lališ, Ph.D. for his help and support and for teaching me how to express my ideas and deal with major challenges. I would also like to thank to Ing. Zuzana Sekerešová, Ph.D. and to Ing. Oldřich Štumbauer for sharing their valuable knowledge with me and helping me to improve my work.

Finally, I would want to thank my family for their continuous support thorough my studies and for always believing in me.

Abstrakt

Cieľom diplomovej práce je analyzovať a popísať súčasnú situáciu spoľahlivostných metód využívaných v leteckom priemysle, identifikovať ich limitácie a nedostatky a navrhnúť spôsoby na ich zlepšenie. Prvé kapitoly obsahujú popis spoľahlivostných analýz, olejového systému leteckého motora a vyhodnotenie FMEA analýzy olejového systému leteckého motora vykonanej tradičnou metódou. Na základe identifikovaných nedostatkov tohto tradičného prístupu je v diplomovej práci navrhnutý ontologický model pre FMEA analýzu, pomocou ktorého je možné vykonať analýzu FMEA novým spôsobom. Navrhnutý ontologický model je expertne validovaný a môže slúžiť ako základ pre vykonávanie FMEA analýzy v spoločnosti GE Aviation Czech pomocou ontologického prístupu.

Kľúčové slová

analýza spôsobov zlyhania a ich následkov, letecký motor, motor Walter M601, ontológia, ontologický model, spoľahlivosť, spoľahlivostná analýza

Abstract

The objective of the diploma thesis is to analyze and describe current situation of reliability methodologies in the aviation industry, identify limitations and deficiencies of the reliability analysis in use and improve ways the analysis is performed. The first chapters contain description of reliability methodologies, lubrication system of turboprop engine and evaluation of traditional FMEA analysis of the lubrication system. Based on the identified deficiencies of the traditional approach of performing FMEA analysis, an FMEA ontology model for a new approach of performing FMEA is proposed in the thesis. The proposed ontology is validated by subject matter experts and provides a basis for better failure-related information management in GE Aviation Czech company.

Keywords

Failure Mode and Effects Analysis, aircraft engine, Walter M601 engine, ontology, ontology model, reliability, reliability analysis

Table of contents

List of figures

List of tables

List of abbreviations

ARP	Aerospace Recommended Practice
ATP	Advanced Turboprop engine
CCA	Common cause analysis
CS-E	Certification Specifications and Acceptable Means of Compliance for Engines
CSV	Comma separated value format
EASA	European Aviation Safety Agency
EU	European Union
FAA	Federal Aviation Authority
FAR	Federal Aviation Regulations
FHA	Functional Hazard Assessment
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FRACAS	Failure Reporting, Analysis and Corrective Actions System
FTA	Fault Tree Analysis
GE	General Electric
GE BGA	GE Business and General Aviation
GEAC	GE Aviation Czech
GUI	Graphical User Interface
HAZOP	Hazard and Operability Study
JAR	Joint Airworthiness Requirements
JPL	Jet Propulsion Laboratory
MA	Markov Analysis
MRO	Maintenance, repair and overhaul
NASA	National Aeronautics and Space Administration
OWL	Web Ontology Language
PFMEA	Process FMEA
QFD	Quality Function Deployment
RBD	Reliability Block Diagram
RCA	Root Cause Analysis
RDF	Resource Description Framework
RPN	Risk Priority Number
SAE	Society of Automotive Engineers
SPARQL	Simple Protocol and RDF Query Language

STAMP	System Theoretic Accident Model and Processes
STPA	Systems Theoretic Process Analysis
shp	Shaft horsepower
UML	Unified Modeling Language
W3C	World Wide Web Consortium
XML	Extensible Markup Language

Introduction

Risk analysis is a natural human activity. Every day we unconsciously analyze situations and take actions to minimize risks and ensure our safety, and the same concept is used also in reliability analyses in the aviation industry. The recognition of reliability is a vital factor in the development, design, production, operation and maintenance of all aircraft engine systems because as Freeman Dyson, British physicist and mathematician, said, “aviation is the branch of engineering that is least forgiving of mistakes. “All potential risk must be identified and mitigated before the engines are released to use, to ensure that every engine can perform its functions in a safe and reliable way. Predicting reliability in the early stages of a development of design provides support for reliability requirements and helps to predict potential degradation of the components during their life-time. As a result of reliability analysis, system design can be improved, over-design can be prevented in order to lower unnecessary costs, the awareness of critical components can be raised, and the overall reliability and safety can be increased by eliminating certain failure modes or taking mitigation measures.

Nowadays, there are numerous reliability analyses, however, most of them were developed in the 1940s and 1950s and since then, the way they are carried did not undergo a particular development. On the contrary, aircraft systems and aircraft engines are becoming more complex, consist of more complicated parts and electrical gadgets and continuously keep developing. The disproportion of development of systems in aviation industry and reliability methodologies causes that the traditional approach of reliability analysis requires more time to be performed and becomes less effective.

GE Aviation Czech, as many other manufacturers, is performing reliability analyses using the traditional approach and is dealing with the issue of gathering a significant amount of information in a systematic way which would allow to share or reuse the information without losing its core relationships. As the traditional approach of complex system is susceptible to human error due to system consisting of thousands of components, in collaboration with the company, this thesis aims to improve the way reliability analysis is performed using a new innovative approach. This new approach is based on using ontology model of reliability analysis, which should ensure consistency among shared and reused information, reduce time-consuming analysis processes and so improve the overall analysis efficiency and effectiveness. This way, the reliability analysis can be performed more easily, quickly and in detail and the potential hazardous failure modes can be identified, mitigated and eliminated sooner. Thus, the engines become even more reliable and safe.

1 General Electric

1.1 History of General Electric

Thomas Alva Edison was an American inventor and holder of 1093 patents whose inventions include phonograph, motion picture camera, fluoroscope, dictaphone and the famous electric light bulb. Thomas Edison was also a businessman who in 1878 established the Edison Electric Light Company that was 11 years later consolidated with all his other companies into the Edison General Electric Company. In 1892, the Edison General Electric Company merged with the Thompson-Houston Electric Company and formed the General Electric Company (GE). The company was expanding very fast and by the end of twenty century, General Electric was the producer of almost all electricity-generating and electricity-consuming devices taking part in the electrification of the United States. [1]

Thorough the years, General Electric became a multinational conglomerate and in 2012, the company was listed by Forbes Global 2000 as the fourth largest in the world. The company is currently operating across ten segments, one of which is GE Aviation.

GE Aviation is a world-leading provider of jet, turboshaft and turboprop engines for commercial and military airframes. GE engines power all categories of aircraft from the smaller regional ones like Thrush 510G to the widebody aircraft such as Boeing 787. The company also produces integrated systems for aircraft manufacturers, components for engine builders, avionics, electrical power and mechanical systems of aircraft and provides services such as product support, maintenance services, material services, digital services and data analytics, component repair and maintenance, repair and overhaul (MRO). [2]

1.2 Walter Aircraft Engines

Walter Aircraft Engines company has a distinguished history which dates to the year 1911 when Josef Walter founded the company to manufacture motorbikes, motor tricycles and cars. In early 1920’s, as a response to the growing aviation industry, the company also started to design, develop and repair aircraft engines. Its first developed engine was an air-cooled radial piston engine. The fame of the Walter engines spread abroad very quickly and by 1936, Walter aircraft engines powered air force aircraft of thirteen countries.

The last years of Walter company are tied to the M601 turboprop engine designed for use on Let L-401 aircraft. Undoubtedly, M601 engine was one of the company’s successful engines with a total of 17 million flight-hours. In July 2008, Walter Aircraft Engines were purchased by GE Aviation that continues with the production of derivates from M601- Series engines called H-Series engines. [3]

1.3 General Electric Aviation Czech

The year 2008 was a significant one for GE Aviation. In early months of this year a new organization dedicated to business and general aviation market was established under the name General Electric Business and General Aviation (GE BGA). In the same year GE BGA acquired certain assets of Walter Aircraft Engines and started development and production of turboprop aircraft engines in the Czech Republic. In consequence of this acquisition, GE GBA redesigned the M601 engine, launched a new turboprop engine called H80 and successfully entered the aviation segment of small commuter turboprop aircraft. Compared to the Walter M601, the H80 is equipped with a new compressor, blades, blisks and stators which resulted in enhanced power by 3%, higher efficiency by 8% in terms of specific fuel consumption and lower maintenance costs by more than 15%. The H80 engine shaft horsepower (shp) reaches up to 800 shp.

In 2011, the H80 engine was certified by European Aviation Safety Agency (EASA). This certification opened the European Union (EU) market to the H-80 Series and H80 engine was fitted in the Thrush 510G aircraft and the L410 aircraft. In 2012 the engine was also certified by Federal Aviation Authority (FAA). Following the success of the H80 engine, the H75 and H85 engines were developed as derivates from H80 engine with slight differences in shaft horsepower. [4]

In 2016, an investment agreement was signed between GE Aviation and Czech government for design, development, testing and production of a new advanced turboprop engine (ATP), newly named as GE Catalyst. The engine aims to deliver 1000 to 1600 shp and to increase efficiency by 20%. The engine is currently being tested and is supposed to be certified by 2020. [5]

1.4 Engine M601

The M601 is a small single-acting free turbine turboprop engine for commuter, utility, agricultural, military or trainer aircraft produced by Walter Aircraft Engines. The M601 has a two-shaft, reverse-flow design and is equipped with an axial-centrifugal compressor, annular combustor with slinger ring fuel distribution and single-stage axial turbine driving a two-stage reduction gearbox. [7] The figure 1 shows the Walter M601 engine with descriptions and the table 1 shows the main specifications of the version M601-D.

The engine M601-A was first run in 1967 and certified in 1975. Since then the M601 powered aircraft such as PZL-130 Orlik or Let L410. The M601 engine was very successful engine with a total of 17 million flight-hours. In 2008, after Walter Aircraft Engines were purchased by GE Aviation, GEAC continued with the production of derivates from M601- Series engines called H-Series engines. Currently, the biggest competitors of the H80-Series turboprop engines are Pratt & Whitney Canada PT-6 and Honeywell TPE-331. [6]

Table 1: Specifications of Walter M601-D engine [7]

Length	1675 mm
Diameter	590 mm
Dry weight	197 kg
Maximum power output	544 kW (740 hp)
Specific fuel consumption	377 g/kW.h
Fuel	Jet A,Jet A1
Power-to-weight ratio	2,76 kW/kg

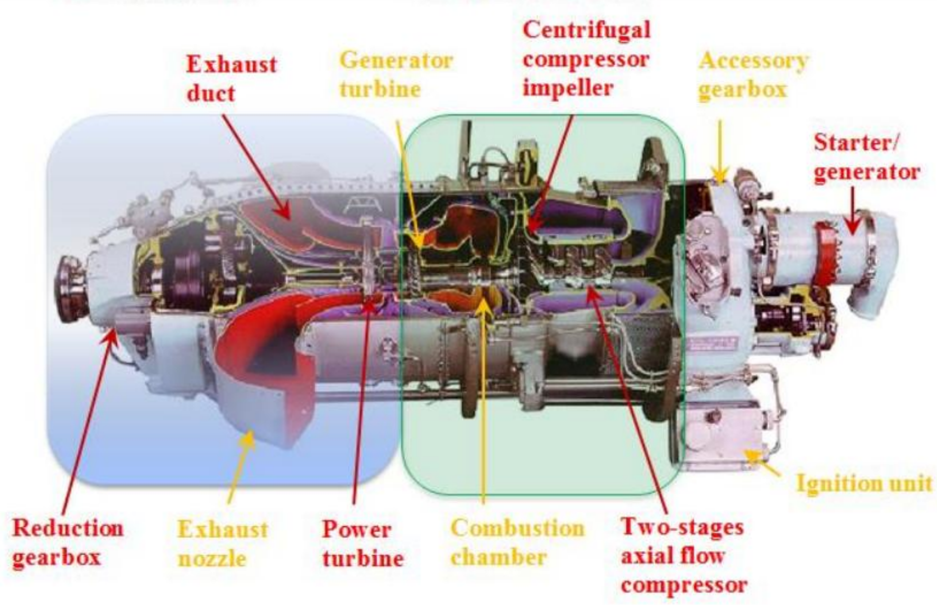

Figure 1: Walter M601 engine [7]

1.5 Reliability methodologies performed by GE Aviation Czech

Rules and regulations are the core of the European Union (EU) civil aviation system. In a matter of safety, GE Aviation Czech is tightly cooperating with the European Aviation Safety Agency (EASA). One of the EASA ‘s responsibilities that is significant for GE Aviation Czech is certification and approval of products and organizations in fields where EASA has exclusive competence, like airworthiness.

GEAC is providing and maintaining airworthiness of their engines in accordance with the document Certification Specifications and Acceptable Means of Compliance for Engines (CS-E) published by EASA which is used as demonstration of compliance with basic regulations and its implementing rules.

Although the CS-E document contains chapters like CS-E 210 Failure analysis and CS-E 510 Safety analysis, these chapters only explain that the analyses must be carried out in order to assess the probable consequence of all failures that may occur and only serve as a general guideline for meeting the safety and reliability requirements by performing safety and reliability analysis. Thus, the decision of what type of analysis will be performed is up to the organization itself. The reliability methods that are performed at GE Aviation Czech are Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Functional Hazard Assessment (FHA) and other methodologies developed by the company.

2 Reliability

Since the main objective of this work is to improve the way reliability analysis is carried in the industry reliability and its related terms will be defined first. In this chapter a theoretical overview of reliability will be presented, and several reliability methods will be described including FMEA in detail.

Undoubtedly, the recognition of reliability is a vital factor in the development, design, production, operation and maintenance of all aircraft engine systems. Predicting reliability in the early stages of a development of design provides support for reliability requirements and helps to predict potential degradation of the components during their life-time. As a result of reliability analysis, system design can be improved, over-design can be prevented in order to lower unnecessary costs, the awareness of critical components can be raised, and the overall reliability and safety can be increased by eliminating certain failure modes or taking mitigation measures.

Reliability is an age-old concept that has undergone a complex historical development. Its interpretation varies depending on context and can mean different things to different people. However, in the system engineering, the most common definition of reliability says that reliability of a component or system is the probability that the component or system will perform its intended function under specified operational and environmental conditions during a specified interval. [33]

And just like everything in engineering, reliability can be represented also mathematically. The logical definition says that reliability is the probability of failure free state under specified conditions for a specified interval. [32]

$$R(t) = 1 - F(t) = 1 - \int_0^t f(t)dt$$

where:

R(t)- probability of survival up to a given time t
F(t)- cumulative probability of failure
f(t)- density function of failure probability

To measure, predict and verify reliability of a component or system, it is important to know in what way and how often a component can fail over time. The identification of all potential failure modes and failure mechanism is a must have if we want to influence and improve the reliability of the design. This finding was the main impulse for establishment of multiple reliability methods that help us specify, analyze, evaluate, control and improve reliability of a product design. [33]

When it comes to safety and reliability, they are very often mistaken to be the same properties. Even though there is a strong dependency between them, that does not mean that they are the same. To explain, safety is a state in which you are not in danger or at risk and it can be increased by increasing component or system reliability.

2.1 Reliability engineering methodologies

The engineering field that studies, evaluates and emphasizes reliability in the life-cycle management of a product is called reliability engineering.

The main objectives of reliability engineering are the following:

- Prevention and reduction of the probability of failure or the frequency of failure
- Identification of the causes of failures and take actions to prevent them
- Determination of the mitigation actions, in case the causes cannot be fixed
- Application of methodologies for estimating reliability by analyzing reliability data

The establishment of reliability engineering organization is upon the decision of company's organizational structure, however in complex systems such as an aircraft engine it is critical to establish safety and reliability organization to ensure and support the reliability of the system.

The reliability methodologies generally define and describe reliability engineering methods and techniques used for reliability analysis which is necessary for conducting a safety assessment. Predictive reliability analyses are used mainly to analyze and predict the reliability, readiness, sustainability and safety of a system. The use of a certain reliability method is dependent upon the phase of process as shown in table 2.

Reliability analysis is a process based on acquiring, identifying and organizing relevant system-specific information and information necessary for making decisions about the system and its requirements. Typically, the analysis is done at system model level with the final product in form of information about system model functions and its properties. Thus, the main objective of system reliability analysis is gathering all information about the system. [16]

There are two main methodological approaches, inductive and deductive.

- Inductive approach - bottom-up approach based on analyzing the functions and failure modes of components on local level and proceeding into analyzing the failure modes effects on a whole system, e.g. FMEA
- Deductive approach - top-down approach based on identifying the end level failure mode effect and analyzing all possible failure modes that might cause it, e.g. FTA [33]

Table 2: Reliability methods

Phase of process	Reliability methods
Identification and definition of reliability requirements	Quality Function Deployment (QFD), Markov Analysis (MA), etc.
Analysis of reliability	Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), Root Cause Analysis (RCA), etc.
Verification of design defects	Failure Modes and Effects Analysis (FMEA), Failure Modes, Effects and Criticality Analysis (FMECA), Common Cause Analysis (CCA), Failure Reporting, Analysis and Corrective Actions System (FRACAS), etc.

2.2 Guidelines for performing reliability analysis

Since safety and reliability are getting more recognition in the aviation industry and the operated systems are becoming more complex, there has been a large increase in the emergence of new safety and reliability analyses such as FMECA, Systems Theoretic Process Analysis (STPA), System Theoretic Accident Model and Processes (STAMP), Hazard and Operability Study (HAZOP), etc. Nevertheless, there are no regulations that would state which of these analyses must be performed to assure safety and reliability of aircraft or aircraft systems and to obtain and maintain the airworthiness.

Society of Automotive Engineers (SAE) is an American organization that develops standards for system engineering in various industries, including aviation industry. Currently there are 36 890 aerospace standards developed by SAE and the most-known ones in aviation safety are the ARP standards. The ARP standards were developed to provide guidelines for development of safe and reliable aircraft and aircraft systems including information about existing safety and reliability methods and analysis. In general, the ARPs are standard guidelines for development of civil aircraft and aircraft systems focused on safety.

2.2.1 ARP4761

The SAE ARP4761 “Guidelines and methods for conducting the safety assessment process on civil airborne system and equipment “describes guidelines and methods of performing the safety assessment for certification of civil aircraft and its systems. The ARP4761 is used to demonstrate compliance with 14.CFR 25.1309 airworthiness regulations published by FAA and with CS-25.1309 airworthiness regulations published by EASA. [12]

The main purpose of the ARP4761 document is to identify typical activities, documents and methods that may help to perform the safety assessment. The ARP4761 describes primary analytical methods and tools for performing safety assessment and in appendices offers its detailed description and explanation. Some of the mentioned methods are FHA, FMEA, FTA, MA, FTA or CMA.

2.2.2 ARP4754

The ARP4754 “Certification considerations for highly-integrated or complex aircraft systems “describes the certification aspects of complex aircraft systems and engine systems. The ARP4754 was developed within the Federal Aviation Regulations (FAR) and the Joint Airworthiness Requirements (JAR) Part 25.

The purpose of this document is to provide general international basis for demonstrating compliance with airworthiness requirements for complex aircraft or engine systems. For instance, the ARP4754 contains description of system development process, certification process and coordination, requirements determination, detailed safety assessment process, requirements and implementation validation and process assurance. [15]

It needs to be emphasized that the ARP standards are not safety and reliability methodologies but serve only as guidance documents.

2.3 FHA

One of the practices highly recommended by the ARP4754 document in terms of risk identification is Functional Hazard Assessment (FHA). FHA is a systematic way of identification of functions and classification of their failure conditions based on their severity. The system level FHA identifies single failures as well as combination of failures that may affect the system or aircraft functions and result in a malfunction or a complete loss of function. The FHA is the initial activity in performing the safety assessment on a brand new or redesigned aircraft system. In FHA, the severity of failure conditions is not ranked with a severity number, but it is classified as catastrophic, severe-major/hazardous, major, minor or no safety effect. Table 3 shows an example of functions and their failure conditions.

Table 3: Example of function and their failure conditions [12]

Function	Failure condition
Control flight path	Inability to control flight path
Control touch down and roll out	Inability to control touch down and roll out
Control thrust	Inability to control thrust
Control cabin environment	Inability to control cabin environment
Provide spatial orientation	Inability to provide spatial orientation
Fire protection	Loss of fire protection

The result of FHA is an FHA report that contains descriptions of functions, failure conditions, phase of operation, effects of failure conditions, classification of failure conditions, reference for supporting material and verification method. [12]

2.4 FTA

Complex systems carry a complex set of paths to failures and the Fault Tree Analysis (FTA) was created specifically to identify and organize these failure paths. FTA is a systematic, top-down method which starts by focusing on one top level event and provides a method how to determine causes that lead to this event. FTA analyzes single failures as well as combinations of failures that may possibly cause the top event. The figure 4 represents graphically an example of an FTA scheme.

The graphic representation of FTA consists of symbols of event and logic. The logic symbols include AND-gate and OR-gate symbols shown in figure 2 and the event symbols include oval, rectangle, triangle, circle or diamond symbols shown in figure 3.

Figure 2: FTA gate symbols [13]

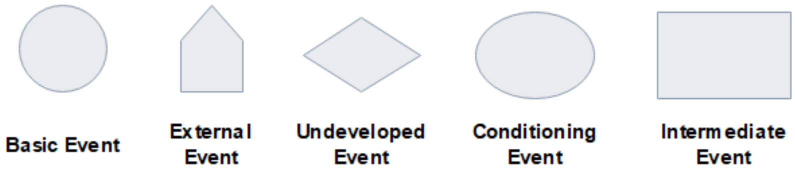

Figure 3: FTA event symbols [13]

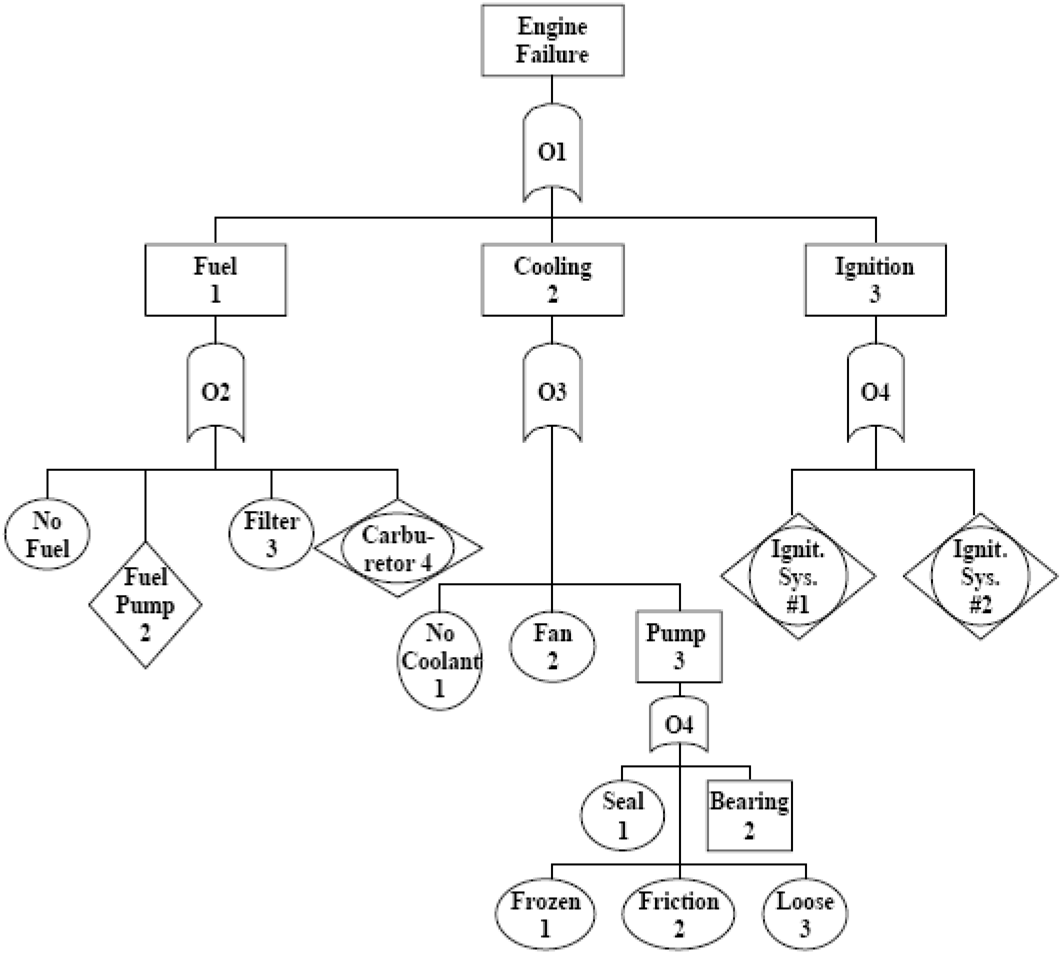

Figure 4: Example of FTA graphic representation [17]

FTA analysis provides quantitative and qualitative evaluation techniques. The qualitative FTA techniques are used to identify the common-cause potentials, whereas the quantitative techniques provide a quantitative ranking of contributions to system failure. [12]

2.5 FMEA

In the history of aviation, there were a lot of cases when a poorly designed product or process caused an accident, or, in the better case, the product had to be recalled before it could cause an accident. In ideal world, any potential failure modes would have been discovered and mitigated during the initial testing of the product or process. However, this is not how it works in a real life and that is one of the reasons why Failure Modes and Effect Analysis (FMEA) is performed.

FMEA is a systematic, bottom-up method of assessing risks associated with a certain system, item or process. The purpose of performing FMEA is to identify all potential failure modes, its effects and causes and propose mitigation measures to eliminate or reduce them. Another important feature of FMEA is the calculation of risk associated with all failure modes to prioritize issues for corrective actions. FMEA was developed at the end of 1940's by the American army and since then it is the most used technique in risk analysis.

Typically, FMEA is composed of the following information:

- Parts lists for each system, subsystem, process or components
- Potential failure modes for each system, subsystem, process or components
- Root causes of all failure modes
- Description of local/system/end level effects of all failure modes
- Severity, occurrence and detection ranking of all failure modes
- Mitigation measures for the failure modes

2.5.1 Types of FMEA

There are several types of FMEAs depending on the phase of process during which they are performed as shown in figure 5.

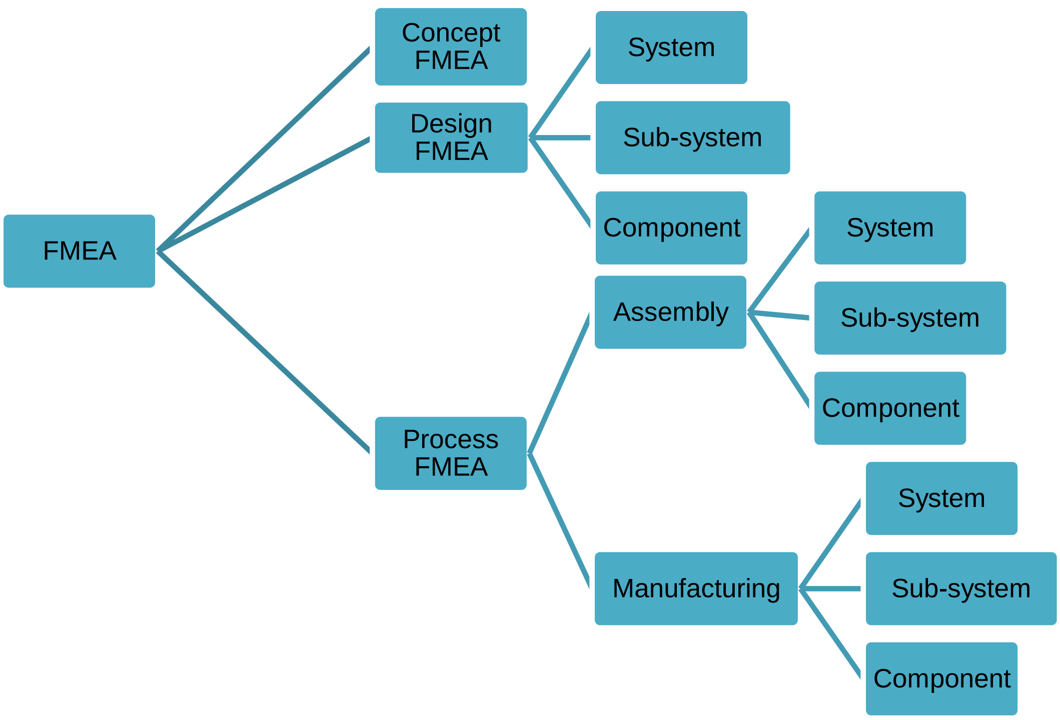

Figure 5: Types of FMEA

The scope of concept FMEA is to identify the potential failures associated with the functions of the concept proposal. Design FMEA analyses the system, sub-system or components during the early design concept stages and tries to lower any potential design failures. And the last one, process FMEA analyses assembly and manufacturing processes in terms of potential failure modes, its causes and effects.

FMEA can be also divided into functional and piece-part FMEA. A functional FMEA performs a top-down analysis at the functional level of whole system or sub-system, meanwhile a piece-part FMEA performs analysis at the piece-part level to identify failure modes of support or additional equipment and tries to verify that those failure modes cannot impact or damage functionality of the whole system or sub-system.

2.5.2 FMEA process

There are lot of variations of FMEA process, however, the basic FMEA process should consist of the following steps:

1) *Collection of information*

The first step is gathering all the necessary information for performing FMEA. This information can include part lists for each system or component, current drawings or schematics, specifications, FMEA requirements, functional block diagrams, explanatory materials like the theory of operation, list of failure rates, previous FMEA reports, any design changes or revisions, etc.

2) *FMEA header information*

In the very beginning, it is required to fill in the header FMEA information that must include project name, starting and ending date, latest revision date, organization, group and the responsible person for performing FMEA. There can be additional information such as FMEA number, system or process reference number, names of team members, etc.

FMEA should not be performed by a single person or a team, but it should be a group work among the area of design, manufacture, assembly, reliability, quality, etc.

3) *Identification of failure modes, their effects and causes*

Since there is a list of components or a list of process steps, the functions and requirements for each component or process step can be defined and keeping in mind these functions and requirements, all potential failure modes can be identified more easily. Remind that failure modes are the manners in which a component or a system could potentially fail to meet or deliver the intended function and its requirements.

After having identified the failure modes, their effects, which are consequences or results of each failure mode, can be identified and described. The effects of failure modes should be considered against the local effect, the next level or system level effect and the end level effect.

The failure modes do not appear out of nowhere, thus there must be an indication of how the failure could occur, which is called failure cause. It is important to emphasize that there can be more than just one cause for each failure mode.

4) *Severity, occurrence and detection ranking*

To calculate the risk associated with all failure modes to prioritize them for corrective actions and to divide components into a critical and non-critical one, severity, occurrence and detection ranking numbers are used so as their product called risk priority number (RPN).

Severity (S) is a ranking number associated with the most serious effect for a certain failure mode. The range of severity is usually from 1 (no effect) to 10 (hazardous effect without warning).

Occurrence (O) is a ranking number associated with the likelihood of occurrence of each failure mode. The occurrence number has a relative meaning and is not equal to the frequency of failure known also as a failure rate. The range of occurrence is from 1 (remote-failure is almost unlikely) to 10 (very high-failure is almost inevitable).

Detection (D) is a ranking number associated with the best design control to prevent the failure from occurring. Its range is also from 1 (almost certain) to 10 (absolute uncertainty).

The RPN is calculated as a product of severity, occurrence and detection ranking numbers and the range of result is from 1 to 1000 on an integer scale.

$$RPN = S * O * D$$

5) *Recommended mitigation actions*

Based on the RPN results, the next step is to recommend actions to prevent or mitigate the risk of failure which can be done either by reducing the probability of its occurrence, improving the detection method or a complete redesign of component or process.

6) *Actions taken*

After a mitigation action has been implemented, it is necessary to enter a description of the action that has been taken, revise S, O and D and calculate a new RPN.

7) Output information

The output information from FMEA is usually presented in a form of a table. The most common is a table in excel worksheet which contains information sorted in following columns: FMEA header information, components, failure modes, effects, causes, severity, occurrence, detection, RPN, recommended action, action taken, new RPN, other comments. The figure 6 shows the most common form of an FMEA worksheet. [11]

FMEA Form

Process/Product Name: ____________________

Responsible: ____________________

Process Step/Input	Potential Failure Mode	Potential Failure Effects	S	Potential Causes	O	D	RPN	Action Recommended	Actions Taken	S	O	D	RPN
Fill carafe with water	*Wrong amount of water*	*Coffee too strong or weak*	*8*	*Faded level marks on carafe*	*4*	*4*	*128*	*Replace old carafes*	*Carafe replaced 9/15*	*8*	*1*	*3*	*24*

Figure 6: Example of FMEA worksheet [9]

The described FMEA process is just a general guideline and it is up to each company to decide what kind of information do they want to include in their FMEA.

To sum up, the output from the FMEA of a system is a qualitative assessment of the level of reliability and safety in form of defining all potential failure modes, problematic areas in the design and technology and their effects on the system function.

2.5.3 FMECA

Failure Modes, Effects and Criticality Analysis (FMECA) is composed of two separate analyses, FMEA and Criticality Analysis (CA). The added value of this enhanced FMEA is that it not only identifies the failure modes, their effects and causes, but it also performs criticality calculations, ranks failure modes criticality, determines critical items and provides a foundation for qualitative safety and reliability analysis.

2.5.4 Limitations and deficiencies of FMEA

Although FMEA proved its functionality and is one of the most used reliability analyses, it can be very difficult and time-consuming to use it for complex systems with hundreds of components. As mentioned before, FMEA requires gathering of all information from various sources and work of different teams in a systematic way.

Using an excel spreadsheet for FMEA may seem to be the easiest way how to create it, however there are several commercial softwares for FMEA and FMECA that provide more functions like multiple user access support, advanced calculation of RPN, completeness checks, system hierarchy, etc.

Some of these tools are for instance XFMEA[1] software from ReliaSoft used by GEAC, FMEA-Pro[2] software by Dyadem, Item[3] software, APIS-IQ[4] and many more. Nowadays, these FMEA softwares are used by almost every bigger industrial company.

As the FMEA is usually performed by multiple persons or teams, the information they insert into FMEA softwares is not organized semantically and its interpretation can vary from person to person or team to team. Thus, even though these tools made the storage of FMEA information clearer and more organized, they are still missing the storage of information in a way that would allow it to be shared or reused without possible loss of information consistency.

[1] https://www.reliasoft.com/products/reliability-management/xfmea
[2] https://sphera.com/operational-risk/fmea-pro/
[3] http://www.itemsoft.com/fmeca.html
[4] https://www.apis-iq.com/

3 Turboprop engine

In agreement with GE Aviation Czech, the FMEA of lubrication system of turboprop engine was proposed as the reliability analysis to be performed using a new approach. The lubrication system was selected because it is one of the less complex engine systems to be manageable in this thesis, but at the same time, it is complex enough to be used for a demonstration of the new approach of reliability analysis.

To perform the reliability analysis, it is necessary to describe the lubrication system, its functions and components first. Therefore, this chapter will briefly introduce turboprop engine and its lubrication system divided into four oil lines will be described in detail.

A turboprop engine is a turbine engine that has been optimized for driving a propeller. Generally, turboprop engines as gas turbine engines use air as a working fluid to provide thrust, which means that the air needs to be accelerated.

A turboprop engine consists of two main parts, the core engine and the propeller. The principle of turboprop engines is very similar to the basic turbojet engines. The main difference is that in case of turbojet engine, all the hot exhaust is expanded through the nozzle to produce thrust and in case of turboprop engines, most of the energy of the exhaust is used to turn the turbine. This turbine is attached to a drive shaft which passes through the core shaft and finally connects to the gear box which connects to the propeller. [34] There must be a reduction gearbox between the drive shaft and the propeller itself, because the relatively small revolutions of the propeller vary a lot from the revolutions produced by the turbine. The figure 7 represents the basic parts of a turboprop engine.

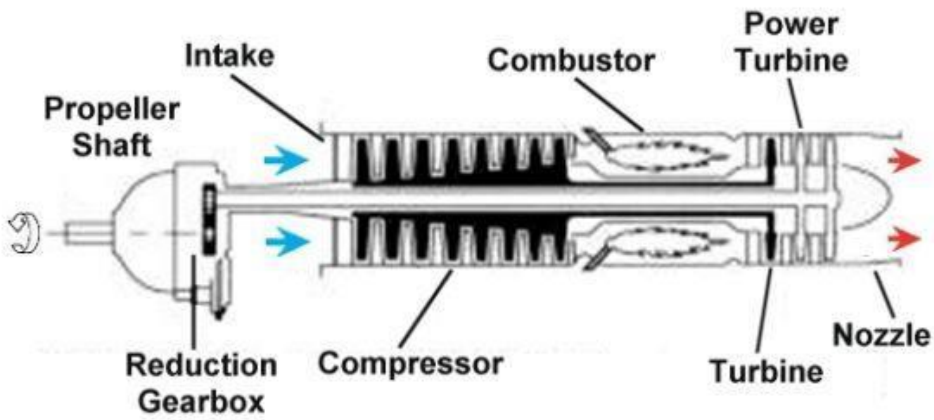

Figure 7: Parts of turboprop engine [34]

Turboprop engines are very efficient in the lower flight speed spectrum, from a Mach number of 0.2 to 0.7. They are generally used on small commuter aircraft like ATR42/72 or

Bombardier Dash 8 powered by PW150A, bush aircraft like Thrush 510 powered by GE H80-Series, business aircraft like Piper Meridian powered by PT-6-Series or military aircraft such as Tupolev Tu-95 powered by engine NK-12MV.

3.1 Lubrication system of turboprop engines

The purpose of the lubrication system of an aircraft is to supply enough lubricating oil with prescribed purity, temperature, viscosity and pressure.

The lubrication system is required to:

- lubricate parts that are in contact and have relative movement such as bearings, gears, accessory drives of splines,
- remove friction-generated heat by cooling the stressed parts that are in contact and have relative movement,
- serve as a hydraulic fluid in engine and in the variable pitch system of a propeller,
- remove the contaminants from the lubricant,
- protect internal components from corrosion,
- provide oil delivery to the torquemeter system.

The lubrication circuit starts with the pressure pump delivering the oil from the oil tank to the lubricated parts via system of ducts and tubes. Pressured oil lubricates the most stressed areas such as shaft bearings, drive bearings, gears and gear teeth and splines. The other less stressed parts are lubricated by the oil that is falling from the pressure-lubricated parts. The oil droplets flow into the collectors from where they are pumped back into the oil tank by scavenge pumps. There are also additional components such as valves, taps, coolers, filters, strainers, thermometers or pressure transmitters included in the lubrication system. [10] [14]

Two main types of lubrication systems are:

1) self-contained re-circulatory system shown in figure 8 in which the oil is distributed through the engine and scavenged back to the oil tank by pumps and
2) expendable system in which the oil is spilled overboard after performing its function.

Nowadays most of turboprop engines use the self-contained re-circulatory system.

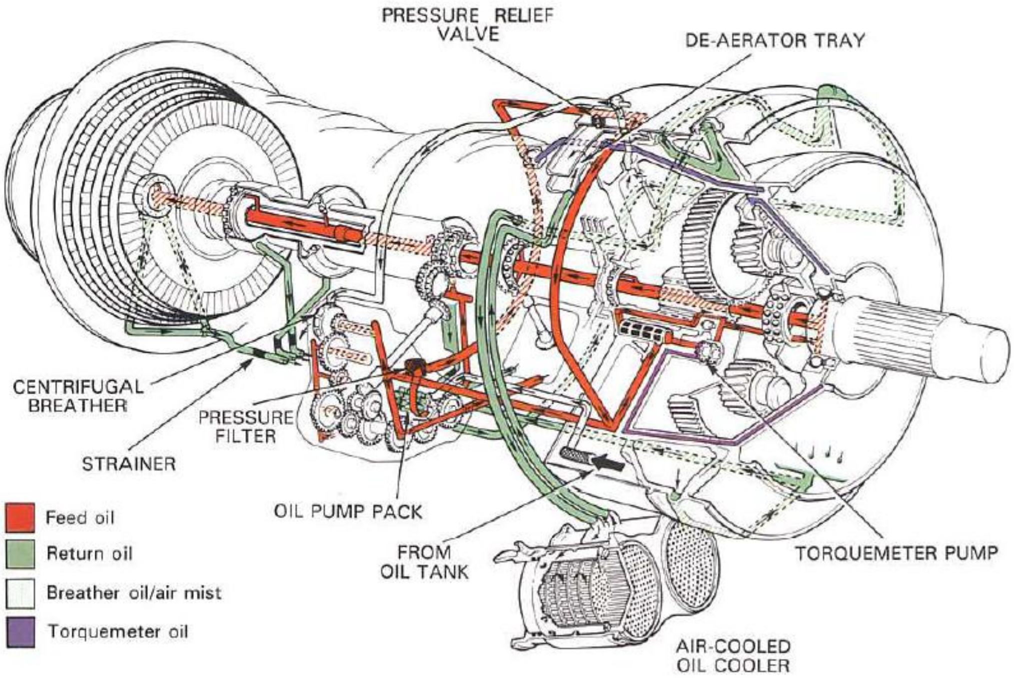

Figure 8: A self-circulatory pressure relieve valve type lubrication system [18]

3.1.1 Engine lubrication and cooling pressure oil line

The purpose of the main pressure oil line is to provide continuous supply to those parts of the engine that are in contact and have relative movement to reduce the friction. The most stressed parts are lubricated directly via tubes and nozzles and the rest of the parts are lubricated by oil droplets falling from the directly lubricated parts and oil saturated air.

The main components of the engine lubrication pressure oil line are:

- oil tank – shown in figure 9, provides storage of oil, can contain additional components such as oil dipstick, filler neck or magnetic plug,
- pressure pump – shown in figure 10, provides pressure oil delivery to the oil system,
- oil filter - provides filtering oil coming from the oil pump,
- by-pass valve - provides oil by-pass following clogging of the oil filter,
- tubes- provides oil supply,
- de-aerating device - provides removal of air from the returning oil,
- oil pressure transmitter - provides oil pressure transmission,
- oil temperature transmitter - provides oil temperature transmission,
- strainers - provide backup protection of nozzles and oil pumps against contamination,
- oil cooler - reduces heat of the oil.

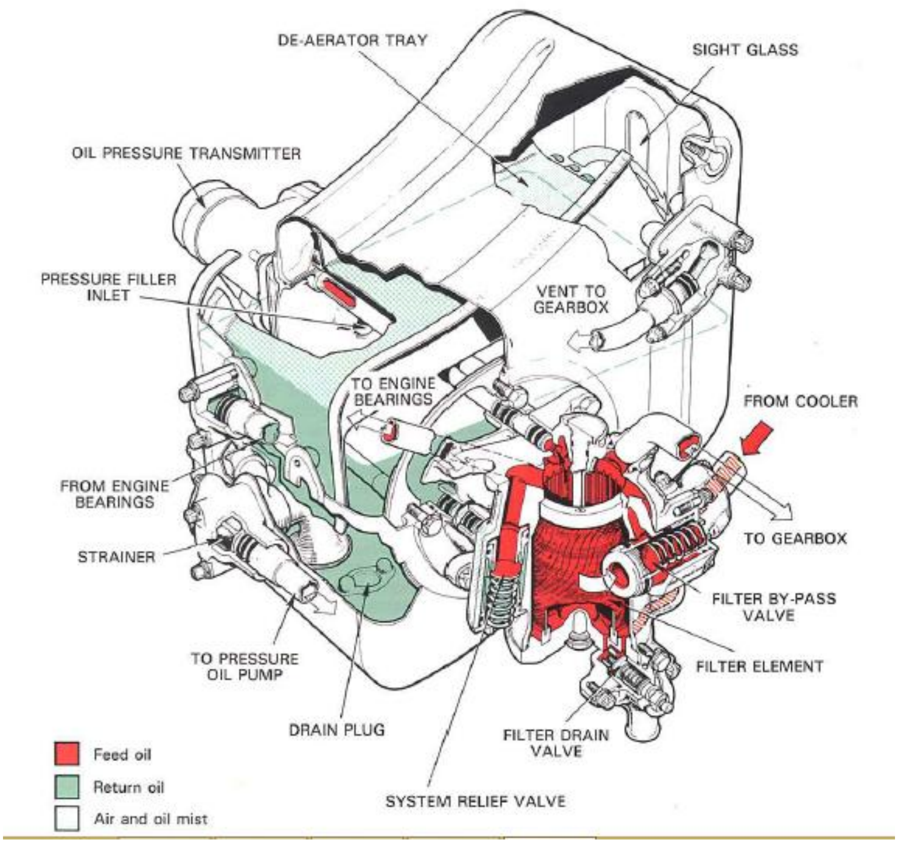

Figure 9: An oil tank [18]

3.1.2 Scavenge/returned oil line

The purpose of the scavenge/returned oil line is to return the oil from the sumps, the gearboxes and the bearing compartments to the oil tank.

The main components of the scavenge oil line are:

- scavenge pump - returns scavenge oil back to the oil tank,
- oil sump - collects oil droplets falling from lubricated parts,
- tubes - provide scavenge oil delivery to the oil tank,
- magnetic chip detector – shown in figure 11, magnet that provides collecting ferritic,
- filters and strainers – shown in figure 12, provide backup protection of scavenge pumps against contamination.

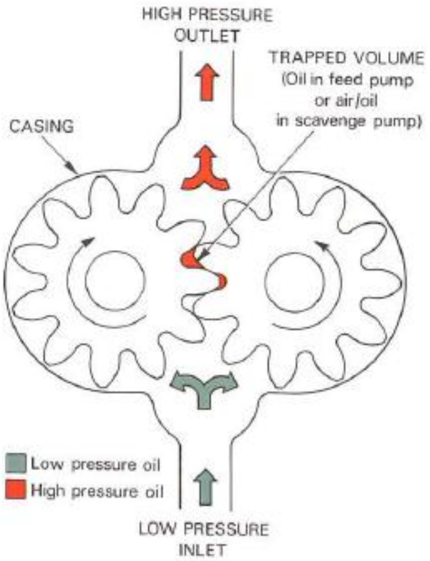

Figure 10: A gear pump [18]

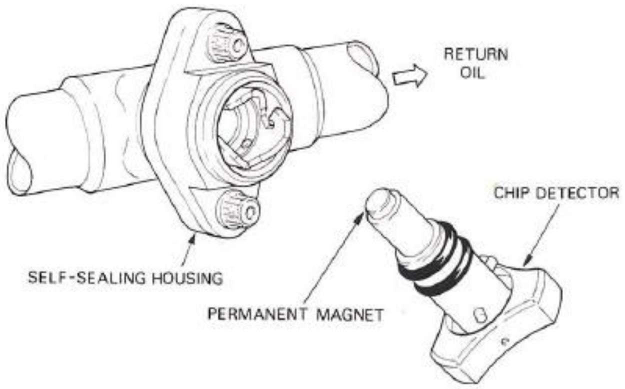

Figure 11: A magnetic chip detector [18]

Figure 12: A scavenge filter [18]

3.1.3 Torquemeter pressure oil line

The purpose of the torquemeter pressure oil line is to deliver pressured oil to the torquemeter system, so that the torque measurement of the power in the reduction gearbox can be performed. The torquemeter system works on the principle of comparing axial force on countershaft with the oil pressure.

The main components of the torquemeter pressure oil line are:

- tubes - provide oil supply to the torquemeter pump and to the torquemeter pressure transmitter,
- torquemeter pump - provides supply of pressured oil to the torquemeter,
- torquemeter pressure transmitter - provides torquemeter pressure transmission.

3.1.4 Propeller speed governor pressure oil line

The purpose of the propeller speed governor pressure oil line is to provide hydraulic regulation of the propeller speed.

The main component of the propeller speed governor pressure oil line is the tube that supplies pressured oil to the propeller. The additional valves and solenoids belong to the propeller system.

3.1.5 Lubricating oil

The lubrication system is required to supply enough lubricating oil with prescribed purity, temperature, viscosity and pressure.

In general, turboprop engines use low viscosity synthetic lubricants and oils without minerals because they can retain their lubricating properties through the whole lubrication circuit and are resistant to oxidation at high temperatures. It follows that the main characteristics of engine lubricating oil are viscosity, pour point, flash point, pressure resistance, oxidation resistance and thermal stability. [14]

4 Reliability analysis of lubrication system

As a logical sequence of second and third chapter, this chapter will provide an overview of the standard process of FMEA analysis of the lubrication system and will discuss some of the most common failure modes of the system's four main components. In the last section of this chapter will be shown an example of FMEA analysis and few findings will be presented.

A turboprop aircraft engine is composed of various systems such as inlet system, compressor, combustion chamber, fuel system, exhaust system, fire protection system, lubrication system and more. Each of these systems needs to be reliable and safe and perform its functions without endangering the functionality of the aircraft engine. Although the lubrication system of a turboprop engine is one of the less complex ones, its correct functionality is crucial for the engine performance. The lubrication system is composed of many mechanical components and failure of each of them could impact the overall functionality of the aircraft engine. For instance, the lubrication system includes gear pumps such as pressure, scavenge or torquemeter pump. One of the failure modes of the gear pumps can be a ball bearing seizure due to some material or manufacturing defect. This failure mode can result in stopping the pump and since the pump is no longer sucking the lubricating oil, there might be a leakage of oil through sealing during climb of the aircraft. As a result of the oil leakage during climb, the engine can catch a local fire causing its in-flight shut down. As seen in this example, even a minor failure mode can propagate straight to the aircraft engine and impact its functionality. This example is also intended to illustrate the importance of analysing all potential failure modes and developing mitigation actions to increase safety and reliability of the engine.

What is more, the failure modes analysis is required by the CS-E document to prove that all hazardous engine effects that may occur are extremely remote, which means that their probability is less than 10^{-7} per engine flight hour. Hazardous engine effects include a non-containment of high energy debris, concentration of toxic products in the engine bleed air for the cabin, significant thrust in the opposite direction to that commanded by the pilot, uncontrolled fire, failure of the engine mount system leading to inadvertent engine separation, release of the engine by the propeller and complete inability to shut down the engine.

4.1 Lubrication system of M601 engine

As the GE H-80 Series engines are derivates from the M601 produced by Walter Aircraft Engines, in this thesis will be described the lubrication system of M601 engine and in addition to this, an example of FMEA of its lubrication system will be described in detail. The M601 is a turboprop aircraft engine for commuter, utility, agricultural or trainer aircraft. Its lubrication system is a self-contained re-circulatory system in which the oil is distributed through the engine and scavenged back to the oil tank by pumps.

The lubrication system consists of four pressure oil lines including the main engine lubrication and cooling pressure oil line, scavenge/returned pressure oil line, torquemeter pressure oil line and propeller speed governor pressure oil line. The primary functions of the M601 engine lubrication system are identical to the functions of the general turboprop engine lubrication system described in Chapter 3. There are only a few slight differences such as types of the mechanical components, the most stressed lubricated parts or additional components.

4.2 Identification of failure modes

The identification of all potential failure modes must be carried out to assess the likely consequence of them and help to mitigate or prevent them. Identification of failure modes also helps to predict reliability of the mechanical components by determining the probability or frequency of all failure modes.

Before starting the identification of failure modes of the components of lubrication system, it is helpful to define general potential failure modes for aircraft engine domain as shown in table 4. This classification of failure modes is a good base for each detailed analysis. With further classification, it is always possible to insert more failure modes.

Table 4: Example of detailed classification of aircraft engine components failure modes

Ref.nr.	Failure mode	Ref.nr.	Failure mode
1	internal leakage	8	connection discontinuity
2	external leakage	9	does not open
3	transmitter failure	10	does not close
4	signaller failure	11	does not stay in position
5	bearing seizure	12	fracture
6	drive shaft failure	13	clogging
7	inner wear	14	limited flow

In the following sections, the potential failure modes of the four primary components of aircraft engine lubrication system will be described. It needs to be emphasized that all likely failure modes need to be included in the analysis, even if they are extremely remote.

4.2.1 Failure modes of tubes

Tubes are used to supply the lubricating oil to the most stressed parts, torquemeter or propeller system. Aircraft engine tubes are divided into internal and external depending on whether they are inside the main body of the engine or outside. Their structure is very simple, so there are only few possible failure modes as shown in table 5. As the system and engine level effects depend on the specific location of the tube, there will be listed only the failure modes and their causes. However, the main local effects of failure modes such as tube fracture or crack are oil leakage and loss of pressured oil.

Table 5: Example of failure modes of tubes

Failure modes of tubes	Cause
Fracture	Material/manufacturing/corrosion defect low-cycle fatigue, high-cycle fatigue
Crack	Material/manufacturing/corrosion defect low-cycle fatigue, high-cycle fatigue

4.2.2 Failure modes of strainers and filters

Strainers and filters provide protection from the contaminants in the lubricating oil. They are constructed as a porous filter through which the oil passes and are located in tubes leading to certain components such as pumps, gears, valves, bearings, nozzles, etc. A filter is considered to have failed when it allows the contaminants to pass through it or when it clogs. The main failure modes of strainers and filters and the conditions which lead to them are listed in table 6. In case of passing contaminants, the effects of filter failure modes depend on the components they are supposed to protect from contamination. In case of clogging, the main local effects are reduced delivery of pressured oil or complete loss of pressured oil.

Table 6: Example of failure modes of filters and strainers

Failure modes of filters and strainers	Cause
Partial clogging	Contamination
Complete clogging	Contamination
Channelling	Cyclic flow/material or manufacturing defect
Crack	Cyclic flow/material or manufacturing defect

4.2.3 Failure modes of valves

Valves regulate the pressure or the lubricating oil flow. They are composed of various smaller components, thus there are more possible ways in which they can fail over time. The effects are very dependent on the type of valve, its function and location. For instance, in the case of a by-pass valve, the failure effect of a permanently open valve can be contamination of the lubricating oil. The most common failure modes and its causes are listed in table 7.

Table 7: Example of failure modes of valves

Failure modes of valves	Cause
Does not open	Wear, contamination, loss of lubrication
Does not close	Wear, contamination, loss of lubrication
Does not stay in position	Wear, contamination, loss of lubrication
Seal leakage	Wear, surface damage, manufacturing defect

4.2.4 Failure modes of gear pumps

Pumps are one of the most common mechanical components and there are lots of categories of them depending on its structure. There are three basic gear pumps in the lubrication system of an aircraft engine, the main pressure pump, scavenge pump and torquemeter pump. As in the case of valves, gear pumps are also composed of multiple components and their most common failure modes are listed in table 8. Usually, all these failure modes result in stopping the pump. The failures of these three types of gear pumps differ in the system effect. For instance, the main pressure pump's system effect is no delivery of pressured oil. The failure modes of scavenge pump result in leakage of oil because of reduced scavenging and the torquemeter pump failures result in loss of power control due to loss of torque indication. Even though they have different system and engine failure effects, they usually happen because of the same causes.

Table 8: Example of failure modes of gear pumps

Failure modes of gear pumps	Cause
Drive shaft failure	Material/manufacturing defect
Bearing seizure	Material/manufacturing defect
Gears inner wear	Material/manufacturing defect

4.3 Example of FMEA of lubrication system

The lubrication system of the M601 engine consists of around 30 components and each of them can possibly fail in multiple ways, which have multiple causes and effects. Thus, the FMEA of the whole lubrication system would be too extensive to be included in this work. To demonstrate how the traditional FMEA is created, the torquemeter pressure oil line was selected, which consists of five components, pressured oil tube to torquemeter pump, pressured oil tube to torquemeter pump strainer, torquemeter pump, pressured oil tube to torquemeter transmitter and torquemeter transmitter as shown below in figure 13.

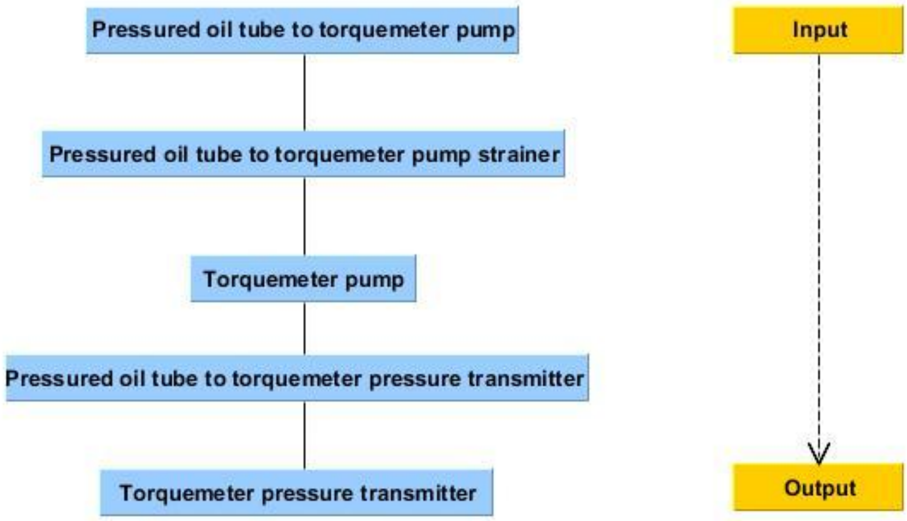

Figure 13: Torquemeter pressure oil line

The following table 9 shows FMEA of the torquemeter oil pressure line of the lubrication system of the M601 engine. The FMEA worksheet includes information such as component name, function, failure mode, local effect, next (system) level effect, engine (end) level effect, cause and severity. Other information like component reference number, occurence, detection, frequency of failures, RPN and mitigation actions are excluded due to their confidential character.

The potential failure modes, effects and causes included in the FMEA of torquemeter pressure oil line were discussed by various team members of the GE Aviation Czech company, ranging from design, manufacturing and assembly to quality, reliability and customers. As can be seen in the table, there are small differences in the interpretation of the same failure effects and a few typos are present. As a result of having to insert manually such an extensive amount of information into a commercial software (XFMEA), it is challenging to maintain the information up to date.

In the past these issues could be solved easily by defining and applying general procedures and establishing a common glossary. There are various works that propose few techniques to make the process of creation of FMEA more efficient such as the book Effective FMEAs by Carlson [37]. However, with such a substantial amount of information these recommendations do not seem to be effective enough anymore and there have been new attempts how to solve this issue.

One of the most modern approaches is using ontologies for knowledge representation. The use of ontologies ensures a common understanding of information by determining the structure of the relationships between the concepts and it provides additional values like verification of the correctness of the inserted information by using a reasoner. What is more, most of the issues mentioned in section 2.4.5. could be solved by using the ontology approach. In the last years, there have been several attempts to support FMEA analysis by developing FMEA ontology. In [45], authors proposed FMEA ontology to support lead free soldering process. Ontology model proposed in [38] focuses on failure analysis and fault behaviour and ontology in [39] was developed specifically for process FMEA. One of the latest approaches of developing FMEA ontology is from NASA ‘s JPL. Their Fault Management Ontology [31] was first published in 2016 and has been continuously developing an approach to capture failure information in a modelling environment using ontologies with significant results so far. Following the results from the mentioned works, the ontology approach is very promising and can be one of the possibilities how to improve reliability analysis.

Table 9: FMEA of torquemeter pressure oil line of lubrication system

ComponentName	Function	FailureMode	LocalEffect	NextLevelEffect	EngineLevelEffect	Cause	Severity
Pressurized oil tube to torquemeter pump	Provides oil supply to torquemeter pump	tube fracture	Leakage of inlet oil	Loss of tube oil delivery to the torquemeter pump	Loss of power control due to loss of torque indiaction	Manufacturing defect	major
						Material defect	
Pressurized oil tube to torquemeter pump strainer	Protects torquemeter pump against contamination	Partial clogging of the strainer	Reduced delivery to the torquemeter pump	Loss of tube oil delivery to the torquemeter pump	Loss of power control due to loss of torque indiaction	Contamination	major
		Strainer complete clogging	Stopped delivery to the torquemeter pump	Loss of tube oil delivery to the torquemeter pump	Loss of power control due to loss of torque indiaction	Contamination	major
Torquemeter pump	Provides oil delivery to the torquemeter	Drive shaft failure	Torquemeter pump stopped	Torquemeter pump failure	Loss of power control due to loss of torquemter indication	Manufacturing defect	minor
						Material defect	
		Drive gear fragmentation of the ring gear of tooth	Torquemeter pump stopped	Torquemeter pump failure	Loss of power control due to loss of torquemter indication	Manufacturing defect	minor
						Material defect	
		Ball bearings seizure	Torquemeter pump stopped	Torquemeter pump failure	Loss of power control due to loss of torquemter indication	Manufacturing defect	minor
						Material defect	
						Overloads	
		Ball bearings seizure/pitting	Torquemeter oil pressure delivery fluctuations	Torquemeter inlet pressure fluctuations	Loss of power control due to fluctuations of torque indication, posssible overtorque	Manufacturing defect	minor
						Material defect	
		Pump gears inner wear	Reduced pressure to torquemeter	Possible inaccuracy of torquemeter measurement	Loss torque indication accuracy, posssible overtorque	Manufacturing defect	minor
						Material defect	
Pressurized oil tube to torquemeter pressure transmitter	Provides oil supply to the torque transmitter	Tube fracture	Oil pressure leak	Loss of tube oil delivery to the torque pressure transmitters	Loss of power control due to loss of torque indiaction	LCF (Low-cycle fatigue)	minor
						HCF (High-cycle fatigue)	
						Manufacturing defect	
						Material defect	
			Oil pressure leak in the proximity of hot parts	Possible oil fire in proximity of hot parts	Local engine fire	LCF (Low-cycle fatigue)	major
						HCF (High-cycle fatigue)	
						Manufacturing defect	
						Material defect	
Torquemeter pressure transmitter	Provides torquemeter oil pressure transmission	Transmitter failure	Loss of torque indication	Loss of power control due to loss of torque indication	Loss of power control due to loss of torque indication	Manufacturing defect	minor

5 Ontology

The core of the FMEA analysis proposed in this diploma thesis are ontologies and this chapter will cover the history of ontology, the understanding of the term ontology in information sciences and detailed explanation of a methodology that will be later used for the development of an FMEA ontology.

5.1 History of ontology

The word ontology is compound of two greek words- ontos, which means “being “and logia which means “the study of “. If we look at ontology as a philosophical study of being, its history goes back to Plato and Aristotle. However, historically, the term ontology as we know it nowadays was first published in two works by Rudolf Gockel [25] and Jacob Lorhard [26] in 17th century. Since then, the ontology has undergone a significant development and lately has been receiving more attention from information and computer sciences. [19]

The definition of the term ontology depends on the context where it is used and can be understood in various ways. According to the Webster dictionary [27], the philosophical term ontology can be defined as:

- a branch of metaphysic concerned with the nature and relations of being;
- a theory about the nature of being or the kinds of existents;
- a theory concerning the kinds of entities and specifically the kinds of abstract entities that are to be admitted to a language system.

In general, the ontology ‘s aim is to build theories about the identity, classification, relations, causality, axiomatization, properties and others. Ontology is trying to find answers for general questions such as: What entities do exist? What are the differences between objects and events? What are the relationships between objects and events? What kinds of properties does a thing have? etc. [19]

5.2 Ontology in information science

Ontologies in information science and philosophy are based on the same idea of representing the entities, events, their properties and relations between them in a systematic way. Applied ontologies are the successor of the prior philosophy ontology. The need to apply ontologies into information and computer science for a better information sharing arose in the mid-seventies due to the research and development of artificial intelligence. [20]

The information and computer science define the term ontology as:

- a way of specifying content-specific agreements for the sharing and reuse of knowledge among software entities,
- a naming, definition and formal representation of the entities (classes, categories), their properties and relationships between the concepts that substantiate one or more domains.

5.2.1 Ontology development

The development of an ontology is an iterative process. According to [28], there is no right or wrong way to build ontologies. In the last years, new methodologies for building ontologies [35] [28] or reusing general ontologies [36] were established. In this thesis, the methodology from Natalya F. Noy and Deborah L. McGuinness [28] was selected because of its clear and understandable, yet detailed description and explanation. To develop ontology, the methodology suggests following these steps:

1) *Determine the domain and the scope of the ontology*

In this step, the following questions should be answered:

- Why do we want to create the ontology?
- What will be the domain of the ontology?
- What will be the use of the ontology?
- Who will be using and possibly upgrading the ontology?
- What information would the ontology cover?

2) *Do a research about already existing ontologies in a certain domain and consider reusing them*

After determining the domain of the ontology, it can be worthy to do a research on the domain of the developed ontology to find out if there are any already existing ontologies that could be used a base for the developed domain ontology. These reusable ontologies can be found for example in ontology libraries such as DAML [29] or Ontolingua library [30].

3) *Determine, name and describe principal terms in the ontology*

The most creative step of the ontology development is the actual determination and description of principal terms that form the base of the proposed ontology. It can be helpful to answer questions like: What exactly will the ontology be about? What details would we like to know about these terms? etc. The result of this step should be a list of the most important terms and the properties that should be added to them.

4) Identify the classes and the class hierarchy

The fourth step is one of the most important for the ontology development itself. Based on the list of ontology terms, the classes needed to be included in the ontology are identified and defined. The hierarchy of classes can be developed by using two approaches, the bottom-up and the top-down approach. The top-down approach starts with defining the most general concepts and then continues with further categorization of these general concepts. The bottom-up approach is opposite of the top-down one, thus it starts with the definition of the specific classes and continues with grouping them into general concepts.

5) Define the class properties and its facets

The list of the most important terms of the ontology should consist of nouns, adjectives as well as verbs. In this step, the main focus will be put on the adjectives to select the properties of the classes and concepts in general. It needs to be mentioned that all subclasses of a certain class will inherit its properties, so the properties should be chosen wisely. During this step the properties of the properties should be also defined, for example the cardinality and type of value.

6) Define the object properties

The remaining verbs from the list of the important terms are usually object properties. The object properties define the relationship between two or more concepts. The domain and range of the object property as well as its characteristics should be defined. The characteristics of the object properties can be, for example, functional, symmetric, asymmetric, transitive, etc.

7) Create instances

The very last step consists of creating and inserting the instances (individuals) into the developed ontology model. It must be chosen which class does the instance belongs to, fill in its property values and assert some of the object properties (relationships).

For facilitating the ontology analyses, there are ontology editors such as Protégé[5] or Hozo[6]. To encode the ontology with these tools, the Ontology Web Language (OWL) is used. It is an ontology language built by W3C based on the Resource Description Framework (RDF).

[5] https://protege.stanford.edu/
[6] http://www.hozo.jp/

5.2.2 Benefits of using ontologies

In the past, one of the biggest issues in the information and computer sciences was the actual storage of a huge amount of information. Nowadays there can be terabytes of data stored very easily, but the new issue is the actual storage of data in a systematic and semantically correct way, so that the data can be shared and reused. Modern problems require modern solutions and using ontologies can be one of the solutions for a better data management.

What is more, since the ontologies have the relationships between concepts built into them, their automated reasoning function can infer some information and check the inconsistencies.

Another feature of ontologies is that they are easy to extend without having an impact on the basic structure, so that the ontology model can evolve and grow with a further development over time.

Finally, ontologies can be represented in both structured and unstructured data formats which provides easier data integration as well as user friendly data representation.

6 Proposal of FMEA ontology model

The issue with information consistency, shareability and reusability in FMEA analysis has been outlined in Section 2.5.4 (Limitations and deficiencies of FMEA) and using ontologies was proposed as one of the possible solutions for a better information management. In Section 4.3 are already mentioned few developed ontologies applicable for FMEA domain such as [31], [38], [39] and [45]. However, neither of these ontologies fit directly the purpose of aircraft engine reliability analysis. Therefore, in this chapter, the already developed FMEA ontologies will be analysed, the most suitable one for FMEA analysis of aircraft will be selected and customized for the use case of aircraft engine FMEA and then applied. The FMEA analysis based on FMEA ontology should ensure that the input information is consistent and semantically organized and prevent misleading output information.

6.1 Process of development of the model

The methodology of ontology development described in Section 5.2.1. will be applied for the development of the FMEA ontology and all process steps of the FMEA ontology development will be described in detail. The process steps are following:

1) *Determine the domain and the scope of the ontology*

As the main objective of this work is to propose an ontology for performing FMEA reliability analysis of turboprop engine, the domain of the proposed ontology is FMEA reliability analysis of aircraft engine. FMEA analyses can differ depending on the companies they are performed at, thus, the scope of the ontology model is to model only the common basis of FMEA analysis, which could be possibly extended by additional concepts, as needed.

What is more, risk analysis methods are usually based on similar concepts, thus the FMEA ontology proposed in this diploma thesis may also serve as a base for other risk management ontologies.

2) *Consider reusing existing ontologies*

While doing a research on already existing ontologies related with risk failure analysis, FMEA or failure management, three suitable ontological models were found. The first one called Risk analysis model [38] was presented at INCOSE Chicago Symposium 2010, the second one called Fault Management ontology was developed by NASA's JPL [31] and the last one is PFMEA ontology model proposed by Z. Rehman and C.V. Kifor in their work [39].

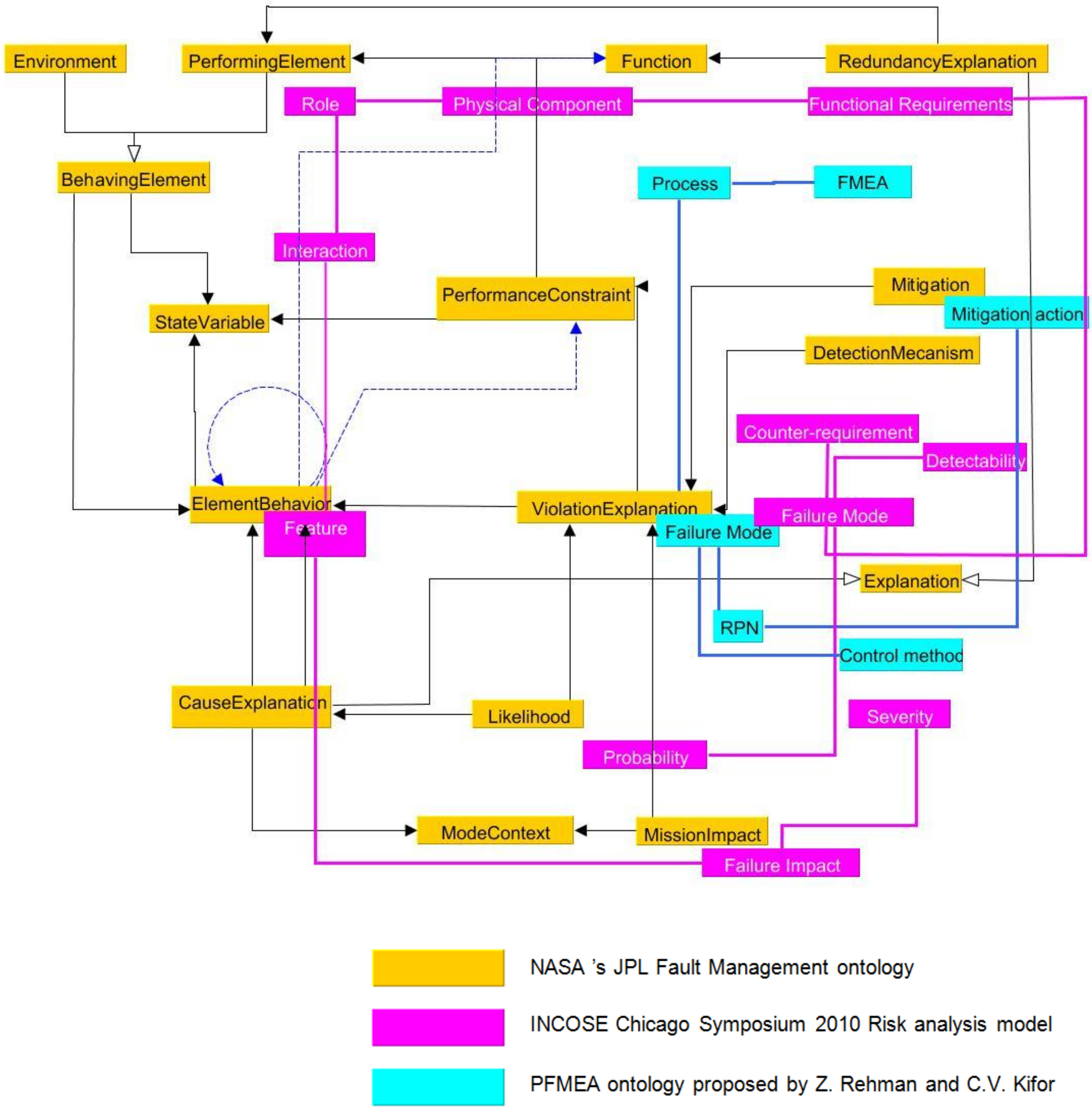

Figure 14: Comparison of three failure analysis-related ontologies in Unified Modeling Language (UML)

Figure 14 shows a comparison of the three mentioned ontologies. The comparison is based only on comparing the main concepts (classes, entities) included in each ontology. For the sake of practicality and readability, the attributes and relations are omitted. As seen in the figure, the basic concepts of FMEA such as component, failure mode, cause, etc. are part of each ontology. The differences between them are the additional concepts and type of analysis. The PFMEA ontology is very brief and focuses on processes, their failure modes and mitigation of risk. The Risk analysis ontology is focused on failure modes, fulfilment of requirements and fault behaviour. The JPL's Fault Management ontology is the most robust one and covers concepts from the traditional FMEA model to the fault behaviour.

After consideration, the Fault Management ontology was selected to be a basis for the ontology presented in this thesis. This ontology was developed by a team of professionals from NASA and it aims to define general vocabulary for fault management domain (FMEA and FTA domain) to represent problematic behaviour including failure modes, its effects, causes and failure propagation. What is more, the Fault Management ontology includes most of the concepts necessary for the FMEA of aircraft engine domain and its functionality has been recently proven by a team of people from Tietronix Software, Inc. and the NASA's JPL [43]. However, the ontology is suited for fault management of a space mission, so the vocabulary differs from the one used in FMEA analysis of aircraft engine.

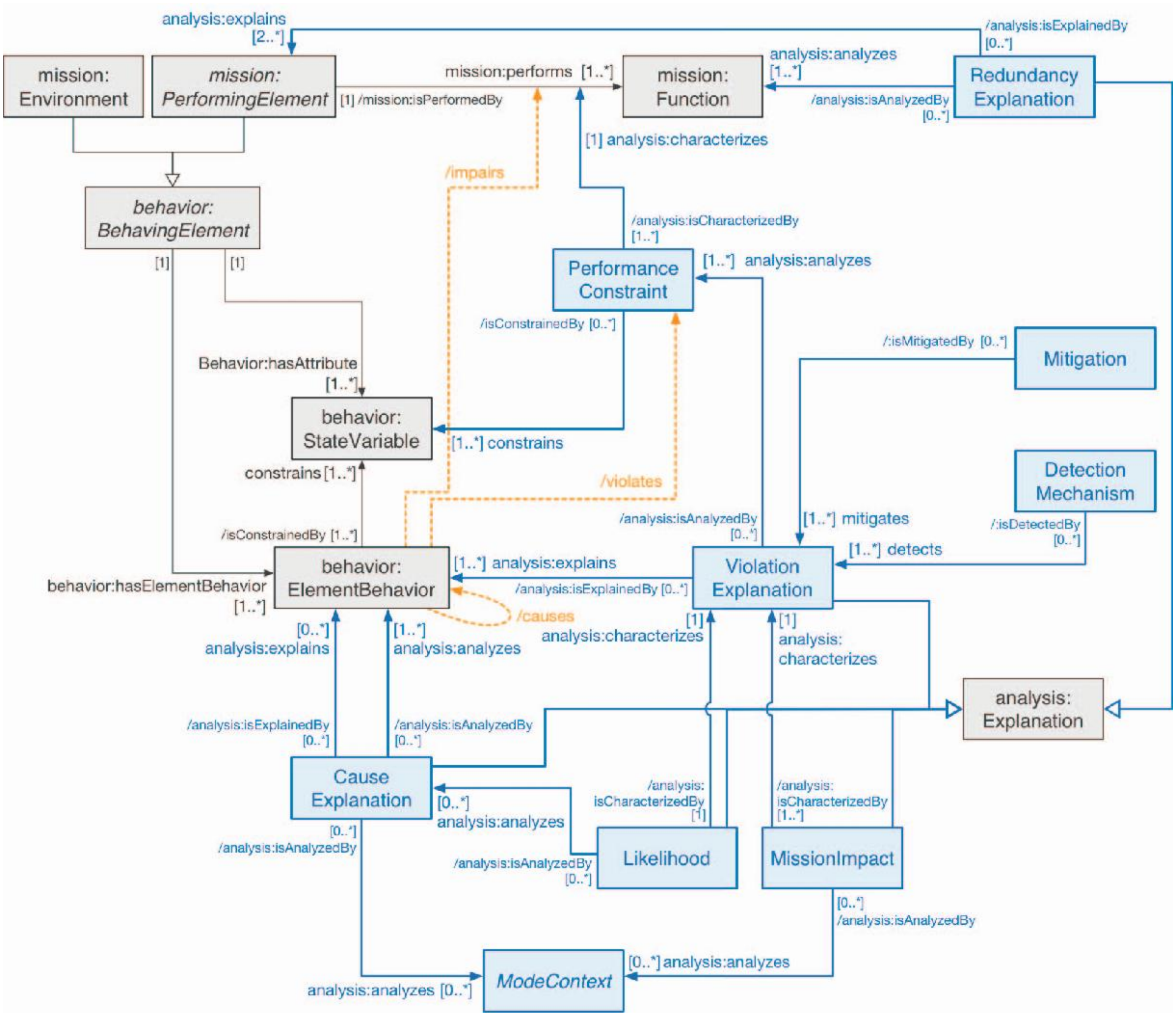

Figure 15: NASA JPL's Fault Management ontology [31]

Figure 15 shows the Fault Management ontology. It consists of two parts – the blue boxes illustrate the basic fault management concepts and the additional black boxes illustrate fault behaviour concepts. The Fault Management ontology includes no attributes of the concepts (classes) and defines seven basic relationships that are: analyses (opp. is analysed by), performs (opp. is performed by), characterizes (opp. is characterized by), explains (opp. is explained by), constrains (opp. is constrained by), mitigates (opp. is mitigated by) and detects (opp. is detected by).

In the new proposed FMEA ontology will be reused mostly the fault management concepts in blue, including Violation Explanation, Cause Explanation, Mission Impact, Likelihood and Detection Mechanism. Violation Explanation in the model stands for indication of a failure mode. Violation Explanation is associated with Component that have at least one Function. Cause Explanation explains the cause of the failure mode and Mission Impact captures the end level effect of a failure mode. In case of FMEA analysis, concept Likelihood stands for occurrence or failure rate and Detection Mechanism stands for detection.

3) *Determine, name and describe principal terms in the ontology*

After answering questions such as: What part of reality will the ontology describe? What details would we like to know about the concepts? or What are the relationships between the concepts? a list of the most important terms was written. This list of FMEA-related terms includes terms such as FMEA, component, function, failure mode, cause, effect, local effect, next level effect, engine level effect, severity, occurrence, detection, RPN, FMEA team, FMEA leader, starting date of FMEA, ending date of FMEA, compensating provision, actions taken, revised RPN, failure rate, reference number, description, hazardous effect, major effect, minor effect, no effect, to have, to be part of, to cause, to be a function/effect/cause of, to examine, to violate, and more.

4) *Identify the classes and the class hierarchy*

Based on the important FMEA-related terms and the Fault Management ontology, in this step the classes and the class hierarchy will be identified and defined. The top-down approach will be used, and the identification of classes will start by defining the most general concepts and then continue with further categorization. The basic classes of the FMEA ontology will be equivalent to the columns of FMEA worksheet and will include component, function, failure mode, cause, effect, RPN and compensating provision. All these classes are subclasses of a top class named Thing and are sibling classes among each other, which means they are on the same level in the class hierarchy. The class Effect will be further categorized into subclasses named Local Effect, Next Level Effect and Engine Level Effect. The basic class hierarchy in UML is shown in figure 16.

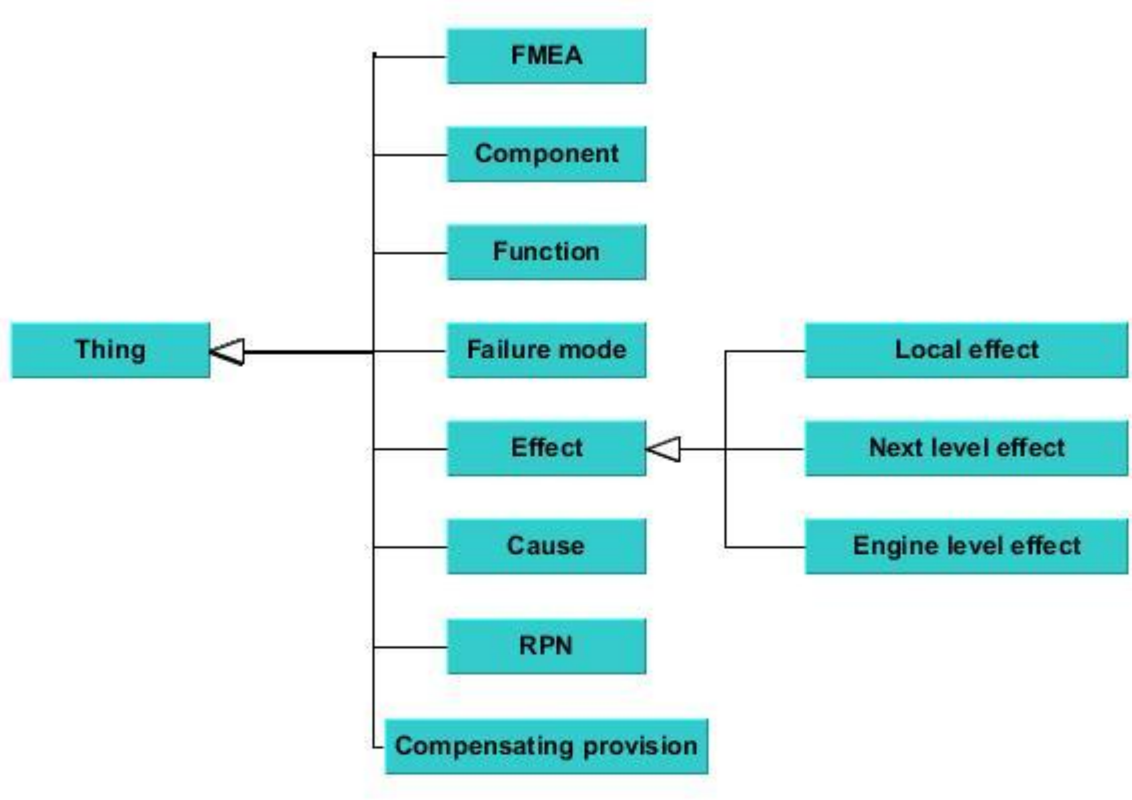

Figure 16: Class hierarchy in UML

5) *Define the class properties and its facets*

The definition of class hierarchy and class properties are tightly intertwined because during both steps the nouns and adjectives from the FMEA-related terms list are analysed and identified either as a class or as a class property. In some cases, some of the terms are omitted. For example, the terms severity, occurrence and detection were defined as properties of the class RPN and not as a separate class as it is in the Fault Management ontology. It needs to be emphasized that sometimes not all the necessary classes and their properties are included in the list of the most important terms and they can be identified later during the process of further development. Few examples of such class properties are: cause description, local effect description, compensating provision description, etc. The properties of the class properties such as the cardinality and type of value should be also defined. The class properties associated with certain classes and their type of value are shown in table 10. The cardinality of the classes will be shown later in the proposed FMEA ontology model graphically represented in UML.

Table 10: Class properties

Class	Class property	Type of value
FMEA	FMEA name	String
	FMEA number	String
	FMEA leader	String
	FMEA starting date	Date
	FMEA ending date	Date
Component	Component name	String
	Component reference number	Integer
Function	Function description	String
	Function reference number	Integer
Failure Mode	Failure mode description	String
	Failure mode reference number	Integer
Cause	Cause description	String
Effect	Effect description	String
Local Effect	Local effect description	String
Next Level Effect	Next level effect description	String
Engine Level Effect	Engine level effect description	String
Compensating Provision	Compensating provision description	String
RPN	RPN number	Integer
	Severity number	Integer
	Occurrence number	Integer
	Detection number	Integer

6) Define the object properties

The object properties define the relationship between two or more classes. The remaining verbs in the list of important terms, defined in the first step, name general relationships such as possession, examination or causality. Even though object properties should be as general as possible, they should also ensure that all classes and their related instances have that specific object property they are attached to. In this case, there are eight object properties derived from the verb to have, for instance: has function, has failure mode, has cause, has local effect, etc. All object properties included in the FMEA ontology, their domain, range and characteristics are shown in table 11. The defined object properties (relationships) are the major difference between the FMEA ontology proposed in this thesis and the Fault Management ontology by NASA's JPL. The FMEA ontology includes more specific relationships unlike the Fault Management ontology which uses mostly general relationships such as "analyses" and "explains".

Table 11: Object properties

Object property	Domain	Range	Characteristics
Examines	FMEA	Component	Asymmetric, irreflexive
Is examined by	Component	FMEA	Asymmetric, irreflexive
Has function	Component	Function	Asymmetric, irreflexive
Is function of	Function	Component	Asymmetric, irreflexive
Has failure mode	Component	Failure Mode	Transitive
Is failure mode of	Failure Mode	Component	Transitive
Has local effect	Failure Mode	Local Effect	Transitive
Is local effect of	Local Effect	Failure Mode	Transitive
Has next level effect	Local Effect	Next Level Effect	Transitive
Is next level effect of	Next Level Effect	Local Effect	Transitive

Object property	Domain	Range	Characteristics
Has engine level effect	Local Effect, Next Level Effect	Engine Level Effect	Transitive
Is engine level effect of	Engine Level Effect	Local Effect, Next Level Effect	Transitive
Has cause	Failure Mode	Cause	Transitive
Is cause of	Cause	Failure Mode	Transitive
Has compensating provision	Failure Mode	Compensating Provision	Asymmetric, irreflexive
Is compensating provision of	Compensating Provision	Failure Mode	Asymmetric, irreflexive
Has RPN	Failure Mode	RPN	Asymmetric, irreflexive
Is RPN of	RPN	Failure Mode	Asymmetric, irreflexive
Violates	Failure Mode	Function	Asymmetric, irreflexive
Is violated by	Function	Failure Mode	Asymmetric, irreflexive

7) Create instances

The instances of FMEA of lubrication system of turboprop engine are specific components, their associated functions, possible failure modes, their causes, effects, etc. When identifying an instance of a class, first, the class needs to be chosen, then the instance of that class is created, and its class data properties are filled in. Finally, the object properties are asserted. For example, the class Component contains an instance named "torquemeter pressure transmitter". The torquemeter pressure transmitter has a component reference number 5 and component description "torquemeter pressure transmitter". Its asserted object properties are "has function: provides torquemeter oil pressure transmission", "has failure mode:

torquemeter pressure transmitter failure”, etc. This way, the instances can be added to the ontology one by one.

What is more, the use of ontology avoids multiple assertion of the same information, which means that a certain data property or object property assertion between two classes can be done only once. This results in reduction of the amount of manually inserted information and increase of the overall effectiveness.

6.2 Ontology model and mapping to the concepts

After completing all steps of the process of development an ontology, the next logical step is to represent the developed ontology model graphically. In this thesis, the FMEA ontology model will be graphically represented in class diagram in UML. UML was selected as a modelling language because it provides a standard way of visualization of a system design, which in this case is the developed FMEA ontology. The new proposed FMEA ontology is shown in figure 17.

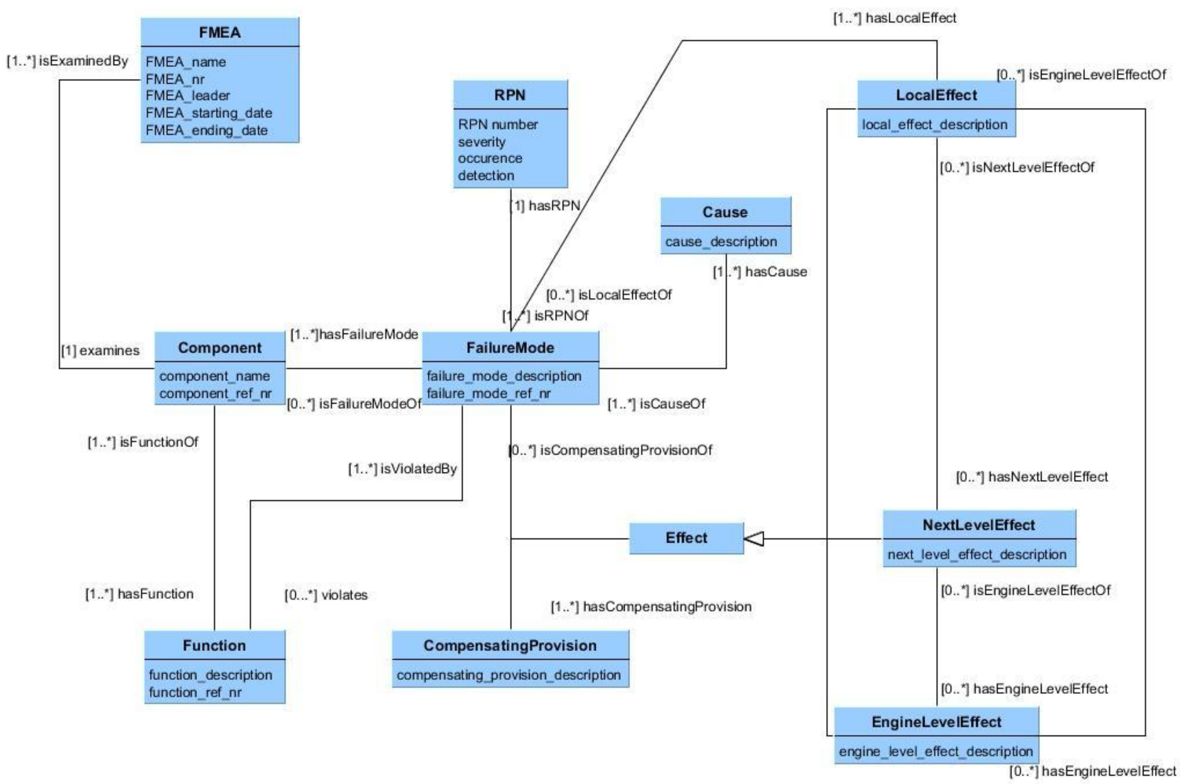

Figure 17: Proposed FMEA ontology in UML

The ontology model comprises eleven classes that have multiple datatype properties (attributes) and object properties (relationships). The basic hierarchy of classes and their properties had been proposed in Section 6.1. These classes and their properties match the standards of the traditional FMEA table and their detailed explanation is described in the following.

FMEA- FMEA class represents the header information of FMEA analysis. It has attributes such as a leader of FMEA, starting and ending date and other required information about the performed analysis. Each functional FMEA analyses failure modes of system or components, therefore the object property "examines" connects the class FMEA and Component. As seen in figure 19, an FMEA can examine multiple components, but a component can be examined by only one FMEA to avoid duplicity of information.

Component- Component class represents a certain component. Its attributes are a component name and reference number. Each component is examined by an FMEA through the "is examined by" object property, has associated at least one function through the "has function" object property and can have associated failure modes through the "has failure mode" object property.

Function- Function class represents different functions of system or components. Its attributes are function description and function reference number. The Function class is related to the Component class through the object property "is function of" and also to the class Failure Mode through the object property "is violated by".

Failure Mode- class Failure Mode indicates presence of a failure mode of a certain component. It has properties such as failure mode description and reference number. Failure Mode is associated with the Component class through the object property "has failure mode". In addition to this, failure mode can be associated to a certain function using the object property "violates". Each failure mode has asserted an RPN number using the object property "has RPN" and it needs to have associated at least one cause through the "has cause" object property. Certain failure can have a local effect which indicates the propagation of failure through the system and this relationship is represented by the object property "has local effect". The last object property associated with the Failure Mode class is "has compensating provision" property which indicates the potential ways of mitigation of the failure mode.

Effect- Effect class is the only that is further divided into subclasses named Local Effect, Next Level Effect and Engine Level Effect. This class indicates the propagation of a failure mode and merges all its subclasses into one general Effect class.

Local Effect- Local Effect class represents a local effect of a certain failure mode and its attribute is local effect description. This class is related to the Failure Mode class through the object property "is local effect of" and the classes Next Level Effect and Engine Level Effect using the object properties “has next level effect” or “has engine level effect”. In case of these object properties, the cardinality starts at 0, which means that the local effect does not need to have next level or engine level effect.

Next Level Effect- Next Level Effect class indicates that a failure mode propagates through the system and causes some system level effect. This class has one attribute which is next level effect description. The Next Level Effect class can be associated with the class Local Effect through the object property “is next level of” or with the class Engine Level Effect through the object property “has engine level effect”.

Engine Level Effect- Engine Level Effect class indicates that a failure mode can propagate to the engine and possibly cause its malfunction. Its attribute is engine level effect description. The Engine Level Effect is associated with the class Local Effect and Next Level Effect through the object property “is engine level effect of”. As in the case of classes Local and Next Level Effect, the cardinality starts at 0, so there does not need to be an engine level effect of certain failure mode and the propagation of the failure mode can be prevented, for example, at local effect.

Cause- Cause class represents the cause of a failure mode. Its attribute is cause description. Each failure mode needs to be associated with at least one cause through the object property “has cause”.

RPN- RPN class represents the RPN number which is a product of severity, occurrence and detection ranking number. It serves for the prioritization based on the risk which failure mode represents. Thus, the RPN class is associated with the Failure Mode class through the object property “is RPN of”.

Compensating Provision- Compensating Provision class represents the compensating provisions for mitigation of hazardous failure modes. It has attribute compensating provision description and is associated with a certain failure mode through the object property “is compensating provision of”.

This detailed explanation and description of classes, their attributes and relationships among them illustrates how the classes interact with each other and how an FMEA table is built from the gathered information using the proposed ontology.

6.3 Ontology model representation

In this section, the new developed FMEA ontology will be represented using the Web Ontology Language (OWL) in open-source ontology editor Protégé, so that the knowledge from the ontology model can be further exploited by computer programs, for instance, to verify the consistency of the information or just to extract it.

6.3.1 OWL

OWL is Web Ontology Language developed by W3C [41] to standardize the formal expression of an ontology and to make it machine-readable. In this thesis the OWL 2 published in 2009 by W3C OWL Working Group will be used for expressing the proposed FMEA ontology. The ontologies expressed in OWL 2 can be shared via the Web documents and provide classes, data and object properties, individuals and data values. To store and share ontologies, a concrete syntax is needed. There are various syntaxes suitable for OWL 2 such as RDF/XML, OWL/XML, Manchester Syntax or Turtle, however the primary one is RDF/XML syntax which will be used as a syntax for the new FMEA ontology in this work.

6.3.2 RDF

For expressing the ontology information in the Web, the Resource Description Framework (RDF) is used. The basic structure of an expression in RDF is a triple of subject, predicate and object in Extensible Markup Language (XML) format. This triple is call RDF graph and is shown in figure 18. [44]

Figure 18: RDF graph structure [44]

The assertion of an RDF triple defines a relationship (object property) between two concepts (classes or individuals). For instance, the statements “torquemeter pressure transmitter provides torquemeter oil pressure transmission” can be expressed in an RDF graph having following structure: subject: *component= “torquemeter pressure transmitter”* predicate: *“has function”* object: *function= “provides torquemeter oil pressure transmission”* or vice versa: subject: *function= “provides torquemeter oil pressure transmission”* predicate: *“is function of”* object: *component= “torquemeter pressure transmitter”.* Graphic representation of the previous example is shown in figure 19 and 20.

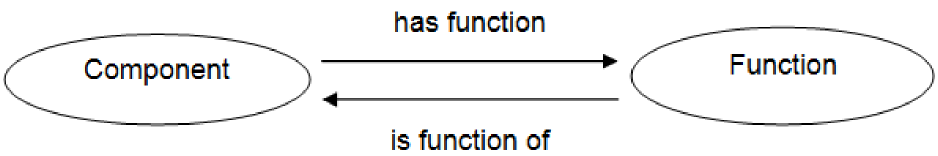

Figure 19: RDF triple example

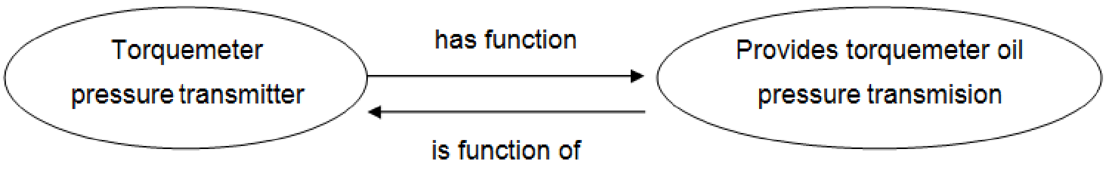

Figure 20: RDF triple instance example

6.3.3 Protégé

For converting the new developed FMEA ontology into OWL with RDF/XML format, an ontology editor will be used. Currently, there are tens of ontology editors developed. The requirements for the ontology editor used in this thesis are open-source software, supporting OWL, RDF and Simple Protocol and RDF Query Language (SPARQL), user friendly and allowing users to input ontology instances. After consideration, Protégé ontology editor was selected and, in this section, will be used to describe the representation of the proposed FMEA ontology.

As mentioned before, Protégé is an open-source ontology editor for knowledge representation. Nowadays, it is one of the most used ontology editors with more than 300 000 users registered. It was developed at Stanford University and the first version of Protégé was released already in 1999. [42] In this thesis will be used one of the latest Protégé versions, version 5.5.0.

In the following figures will be shown how classes, data properties, object properties, general class axioms and instances of the developed FMEA ontology are expressed in Protégé.

Figure 21 shows the class hierarchy of the FMEA ontology. As can be seen, it is equivalent to the class hierarchy in figure 16. In figure 21, the class Failure Mode was selected as an example and its usage and description is shown in detail. In the description part are defined some general rules known as general class axioms, which, in this case, define the object properties assertions and at the same time restrict some domain properties assertions to ensure the information consistency and avoid misalignment of information.

Figure 22 shows data properties asserted to certain classes. The domain defines the class which the data property describes, and the range represents the type of value. For instance, class Component has data property named component_name. The range of component_name data property is string, which means that the type of value is a sequence of characters, e.g. text.

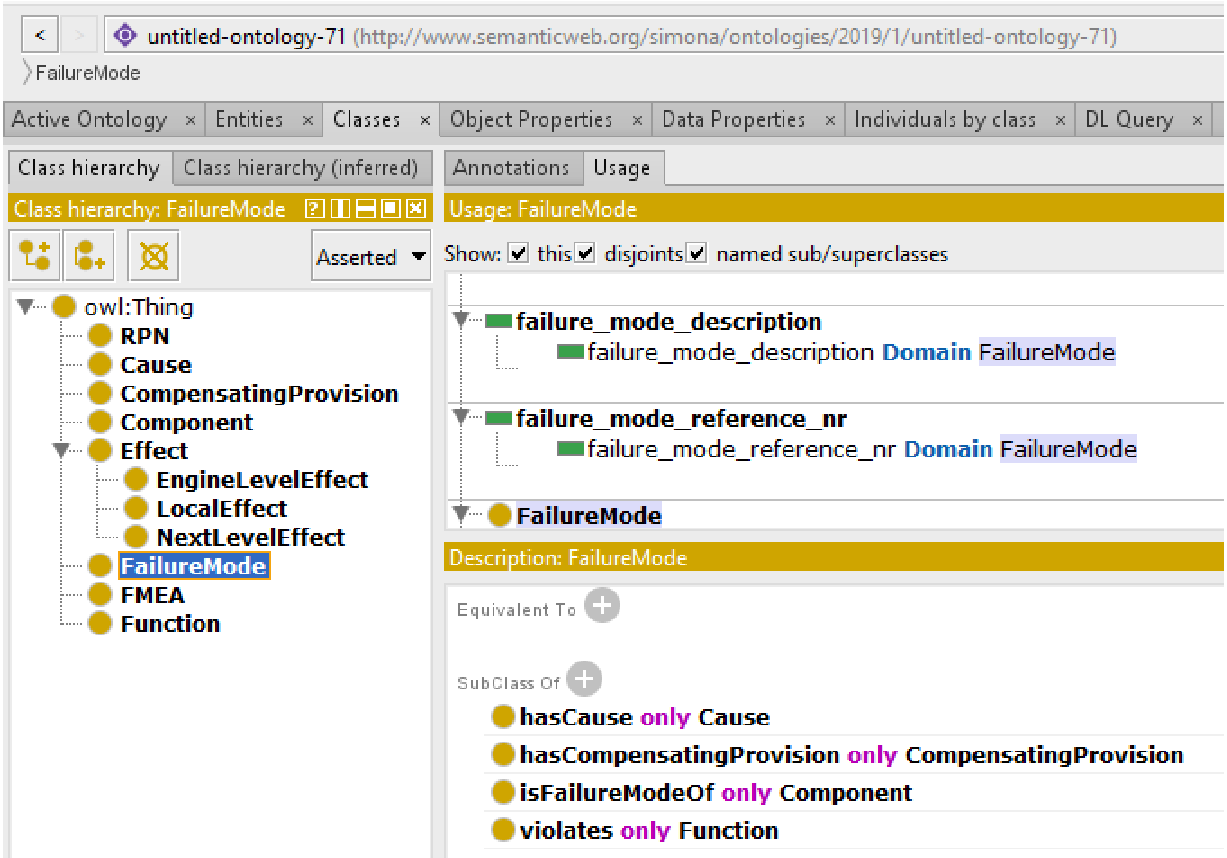

Figure 21: Class hierarchy in Protégé

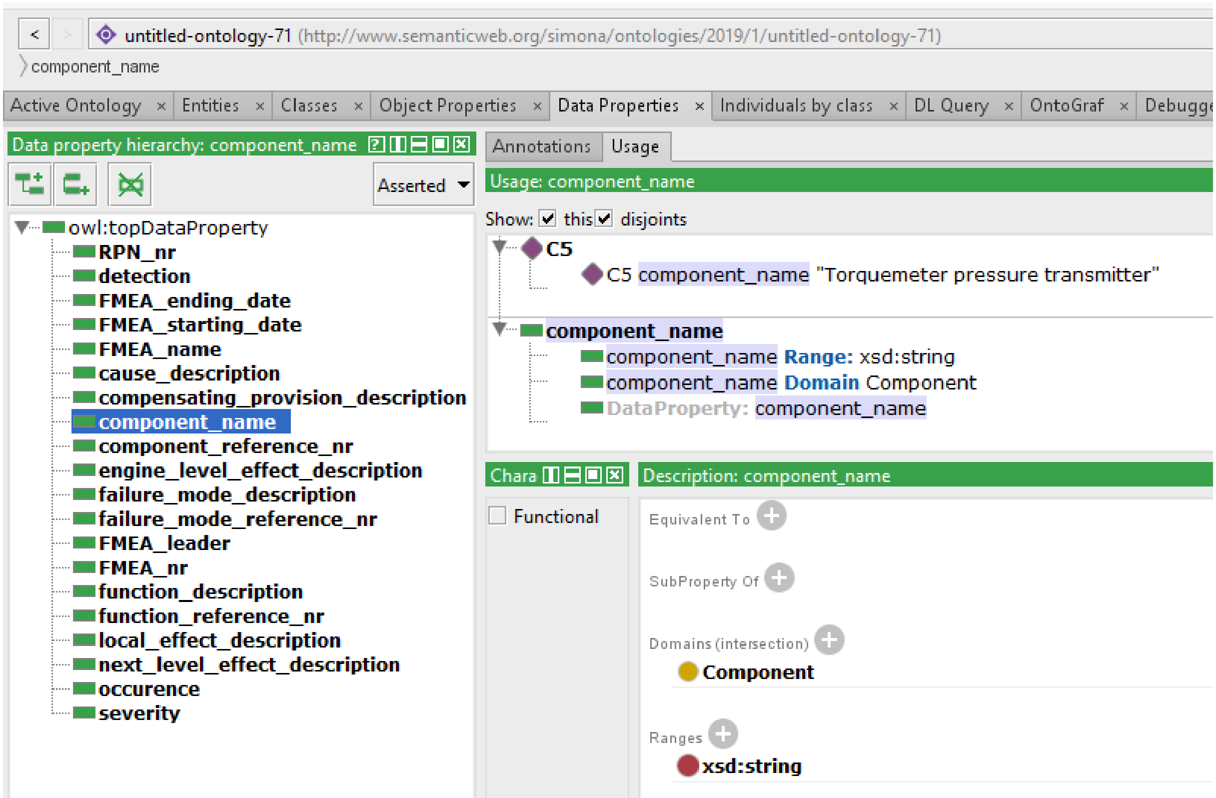

Figure 22: Data properties

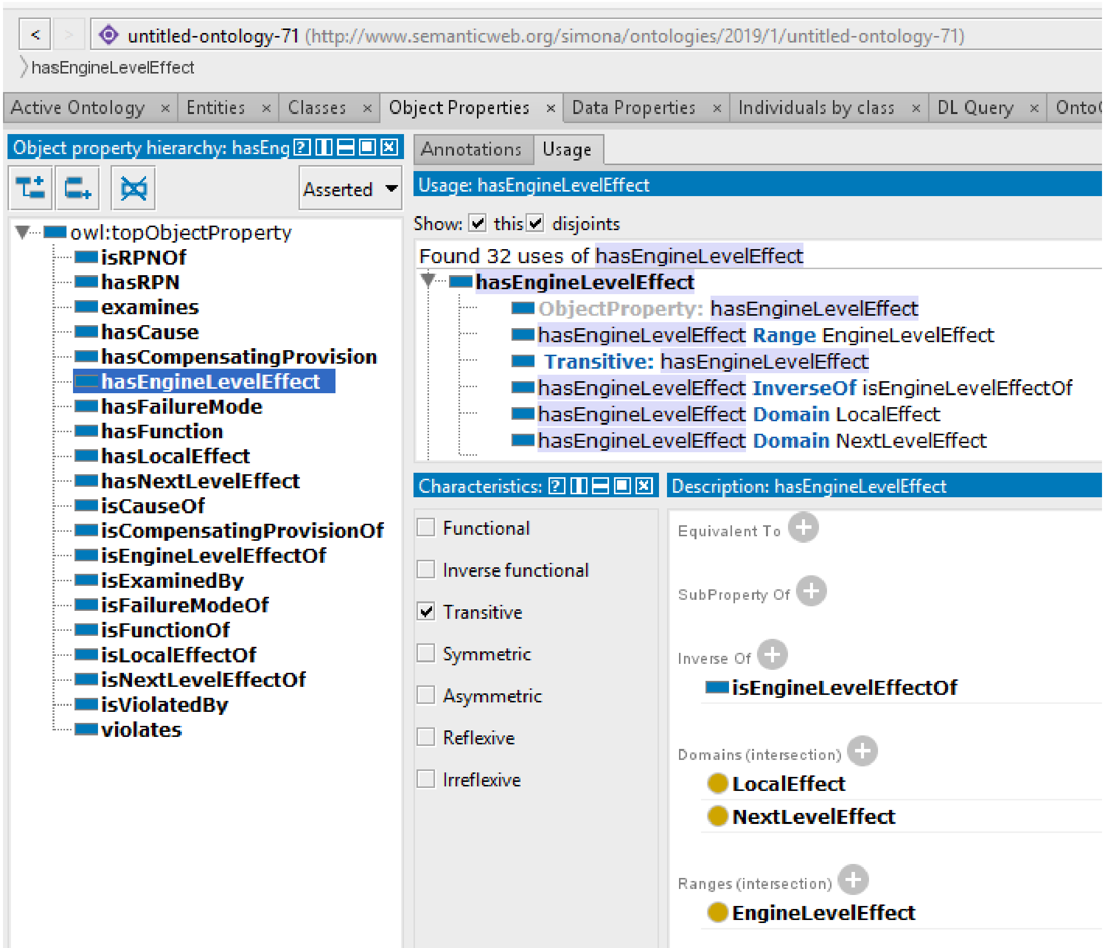

Figure 23: Object properties

Figure 23 shows object properties of the FMEA ontology and their characteristics. As can be seen, the object property “hasEngineLevelEffect” has domain Local Effect and Next Level Class and its range is class Engine Level Effect. It is inverse object property of “isEngineLevelEffectOf” and has transitive characteristics, which means that if A is instance of B and B is instance of C, A is also instance of C.

Finally, figure 24 shows that instances can be inserted directly into the ontology in Protégé. In this case, there are five instances of Component class and the component C3 with component name “Torquemeter pump” has asserted six object properties. These properties are either asserted manually or generated automatically from previous information by using a reasoner.

In figure 25, the FMEA ontology is represented graphically and it is shown how the classes are connected with each other.

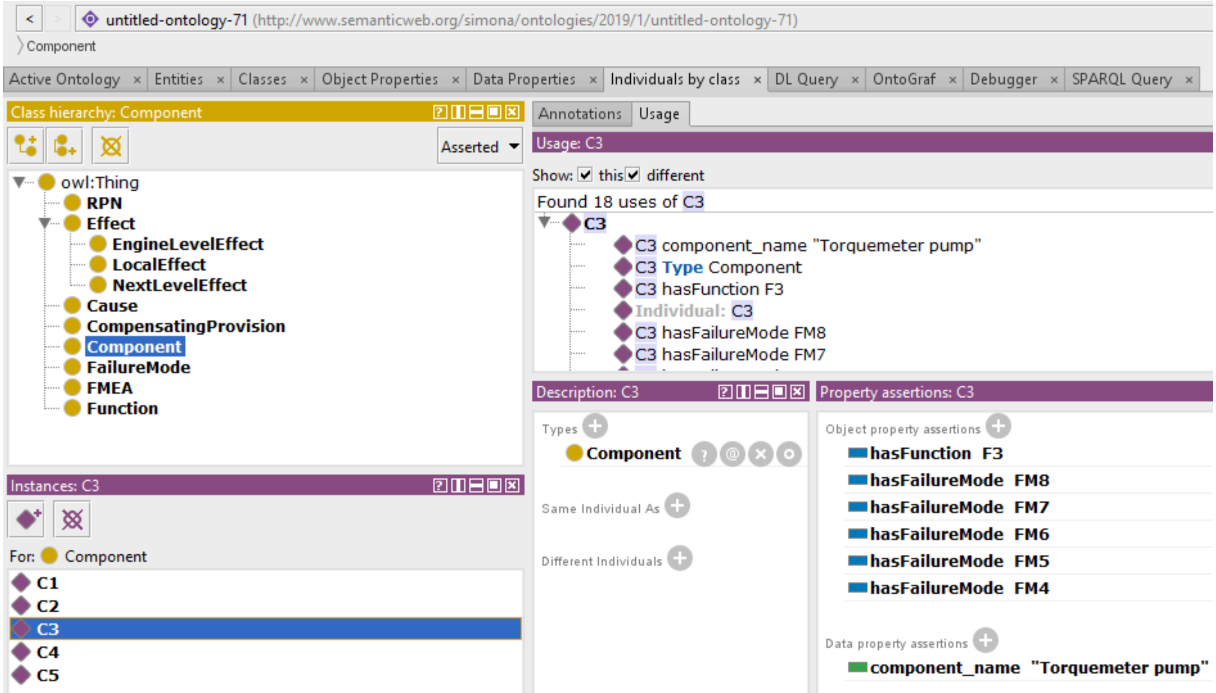

Figure 24: Example of instances

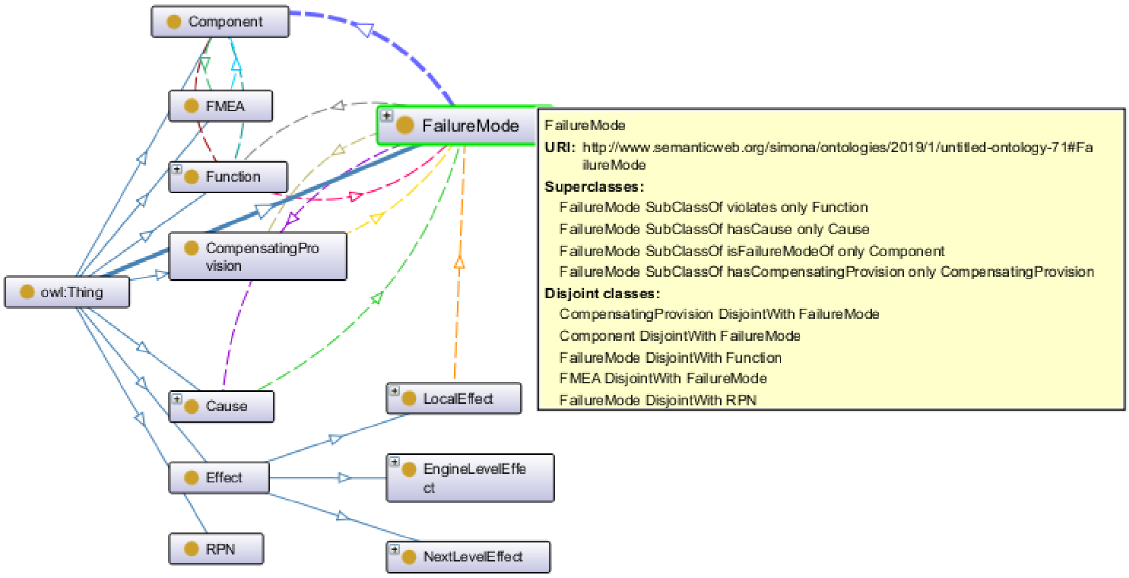

Figure 25: Representation of ontology in OntoGraph

Protégé editor supports many formats and in this diploma thesis, the proposed FMEA ontology was extracted as an OWL script with data stored in RDF triples. This way, the information can be uploaded to other softwares which allow to work with the data stored in RDF triples and retrieve it in a format suitable for common end users.

7 Ontology model verification and validation

In order to verify the functionality of the proposed FMEA ontology model, the FMEA of torquemeter pressure oil line of a turboprop engine lubrication system will be performed using the new ontology approach. The traditional FMEA of torquemeter pressure oil line is shown in Chapter 4, Section 4.3. In this chapter, the gathered failure-related information about torquemeter pressure oil line will be mapped to the developed FMEA ontology model and the traditional FMEA table will be created by querying needed information. After obtaining the FMEA table by the innovative ontology approach, this effectiveness of the new approach and the traditional FMEA approach will be compared regarding the time-consumption, information correctness and consistency.

7.1 Data retrieval from the model information

In this section, the failure-related information of torquemeter pressure oil line will be mapped to the proposed ontology model and the process of data retrieval from the model information will be described.

The information can be mapped to the ontology model in Protégé manually or uploaded from relational database, xlsx or csv spreadsheet or xml document. In this case, the information was inserted into Protégé manually as instances of classes, and 39 object properties were asserted.

Ontology editor Protégé is very useful when developing ontology, inserting class axioms and even instances. However, it fails to export the inserted data in a format easily readable by end users such as xml or xslx format. For this purpose, a Tomcat[7] web application called Apache Jena Fuseki[8] will be used.

7.1.1 Apache Jena Fuseki

Apache Jena Fuseki is a Java web application that can run on Tomcat servlet. Tomcat servlet is an open-source Java servlet and in this thesis will be used the version Tomcat 9. The used version of Apache Jena Fuseki is the version 3.10.0. Apache Jena Fuseki was selected due to its user-friendly Graphical User Interface (GUI) which provides means to mount ontologies on web server as datasets under a selected name and then manage them. [46] It also provides data retrieval by querying information using SPARQL 1.1. The results can be downloaded in multiple formats one of which is Comma-Separated Values (CSV) format which can be viewed in a CSV viewer or simply converted to xls or xlsx format and open as an Excel file.

[7] https://tomcat.apache.org/
[8] https://jena.apache.org/documentation/fuseki2/

Figure 26 shows a dataset named fmea mounted to Apache Jena Fuseki. This fmea dataset contains the proposed FMEA ontology including instances in XML/RDF format.

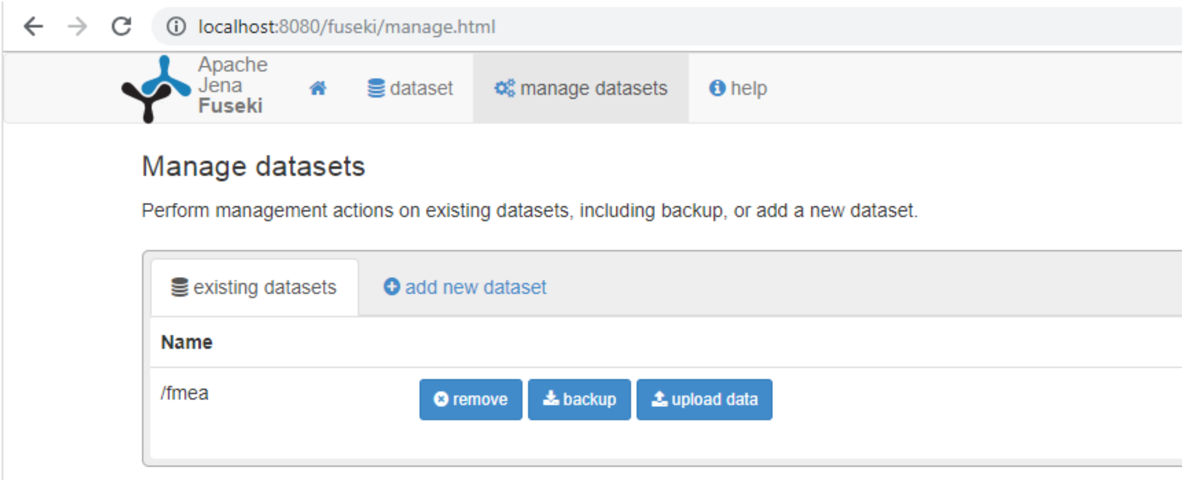

Figure 26: Apache Jena Fuseki

7.1.2 SPARQL

After uploading the fmea dataset, the web app allows retrieving the queried information using SPARQL. SPARQL is a semantic query language designed especially for databases that is able to retrieve and manipulate data in RDF format. [44] Figure 27 shows how the information is queried in Apache Jena Fuseki application.

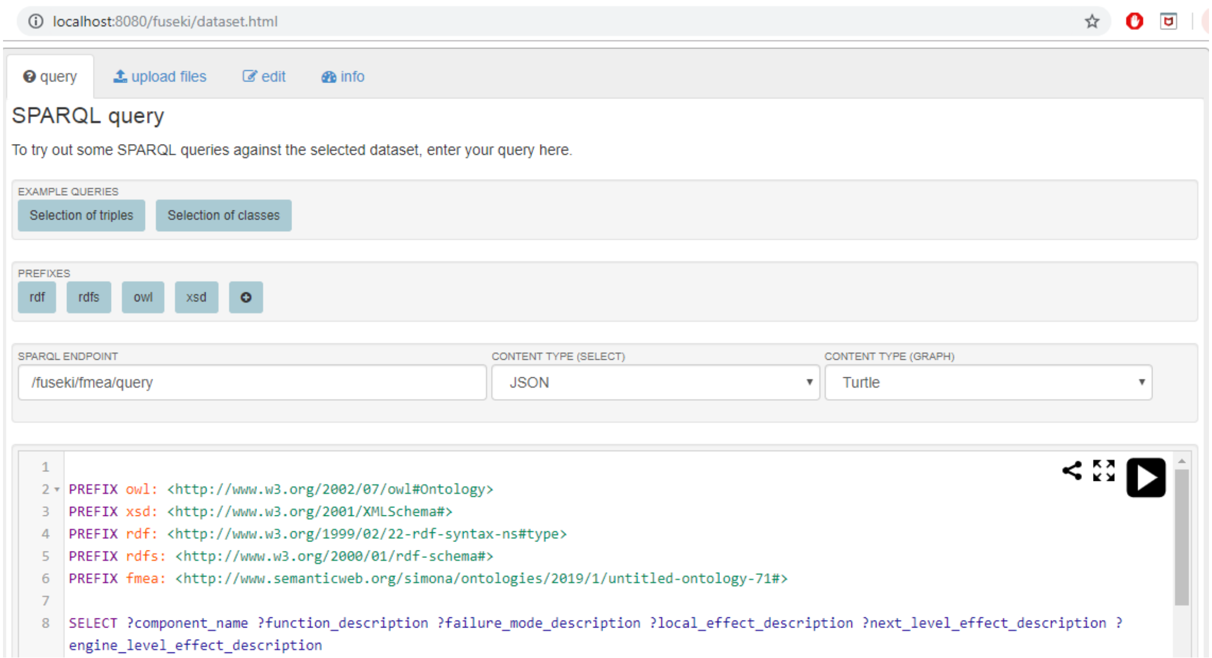

Figure 27: Apache Jena Fuseki- SPARQL query

In order to extract the information about failure modes and effects of components of torquemeter pressure oil line in a lubrication system and obtain results in form of a traditional FMEA worksheet, the following SPARQL query, shown in figure 28, was used.

```
PREFIX owl: <http://www.w3.org/2002/07/owl#Ontology>

PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#type>

PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>

PREFIX fmea: <http://www.semanticweb.org/simona/ontologies/2019/1/untitled-ontology-
71#>


SELECT ?component_name ?function_description ?failure_mode_description
?local_effect_description ?next_level_effect_description ?engine_level_effect_description

WHERE

{ ?Component fmea:component_name ?component_name.

  ?Function fmea:function_description ?function_description.

  ?Component fmea:hasFunction ?Function.

  ?FailureMode fmea:failure_mode_description ?failure_mode_description.

  ?Component fmea:hasFailureMode ?FailureMode.

  ?LocalEffect fmea:local_effect_description ?local_effect_description.

  ?FailureMode fmea:hasLocalEffect ?LocalEffect.

  ?NextLevelEffect fmea:next_level_effect_description ?next_level_effect_description.

  ?LocalEffect fmea:hasNextLevelEffect ?NextLevelEffect.

  ?EngineLevelEffect fmea:engine_level_effect_description
?engine_level_effect_description.

  ?NextLevelEffect fmea:hasEngineLevelEffect ?EngineLevelEffect.

}
```

Figure 28: SPARQL query to display FMEA information

The first five lines contain prefixes that are necessary to declare the used ontology, the language it is encoded in, its syntax and schema. The “SELECT” part contains queried information, which in this case is: component_name, function_description, failure_mode_ description, local_effect_description, next_level_effect_description and engine_level_effect_ description. The “WHERE” part defines the requirements for the selected information.

After running the SPARQL query in Apache Jena Fuseki, a table with the query results shows and can be downloaded in various formats. For the purpose of this diploma thesis, the output query was downloaded in CSV format and converted to xls format to get a table identical to the traditional FMEA table shown in table 8.

Table 12 shows the information queried from the instances added to the proposed FMEA ontology in Protégé. This information includes name of the component, its function, potential failure modes and their local effect, next level effect and engine level effect. As can be seen, the new approach of performing FMEA using ontologies can provide the same results as the traditional way of FMEA analysis.

7.2 Validation and evaluation of proposed ontology model

In this section, the proposed FMEA ontology model will be validated based on the results of the ontology-based FMEA analysis. The results of ontology-approach FMEA analysis in form of an FMEA table will be evaluated and compared with the traditional FMEA table in table 8. Later, the new and the traditional approach will be compared in terms of time-consumption, information correctness and information consistency.

The correctness of the information in the resulting FMEA (table 12) was examined and confirmed by authorized person from GE Aviation Czech. The evaluation of the information correctness consisted in examining whether the information such as component, potential failure modes and their effect are complete and assigned correctly. The correct FMEA results proved that the developed FMEA ontology model fulfilled its function and is valid.

Regarding the effectiveness of the new ontology approach to perform FMEA analysis, the traditional and the new approach will be compared.

Firstly, although the traditional FMEA table 9 and FMEA table 12 acquired by using ontology approach are both complete and correct, they are not identical. The differences consist in the written interpretation of the same concepts or in some cases the difference is caused by a typo. Following table 13 shows the identified differences in next level failure effects.

Table 12: FMEA information of torquemeter oil line of lubrication system extracted using the proposed FMEA ontology

component_name	function_description	failure_mode_description	local_effect_description	next_level_effect_description	engine_level_effect_description
Pressurized oil tube to torquemeter pressure transmitter	Provides oil supply to the torque transmitter	Pressurized oil tube to torquemeter pressure trasmitter fracture	Oil pressure leak	Loss of tube oil delivery to the torque pressure transmitters	Loss of power control due to loss of torque indication, possible overtorque
Pressurized oil tube to torquemeter pressure transmitter	Provides oil supply to the torque transmitter	Pressurized oil tube to torquemeter pressure trasmitter fracture	Oil pressure leak in the proximity of hot parts	Possible oil fire in proximity of hot parts	Local engine fire
Torquemeter pump	Provides oil delivery to the torquemeter	Torquemeter pump gears inner wear	Reduced pressure to torquemeter	Possible innacuracy of torquemeter measurement	Loss of torque indication accuracy, possible overtorque
Torquemeter pump	Provides oil delivery to the torquemeter	Torquemeter oil pump drive gear fragmentation of the ring gear of teeth	Torquemeter pump stopped	Torquemeter pump failure	Loss of power control due to loss of torque indication, possible overtorque
Torquemeter pump	Provides oil delivery to the torquemeter	Torquemeter pump drive shaft failure	Torquemeter pump stopped	Torquemeter pump failure	Loss of power control due to loss of torque indication, possible overtorque
Torquemeter pump	Provides oil delivery to the torquemeter	Torquemeter pump ball bearings initial seizure/pitting	Torquemeter oil pressure delivery fluctuations	Torquemeter inlet pressure fluctuations	Loss of power control due to fluctuations of torque indication, possible overtorque
Torquemeter pump	Provides oil delivery to the torquemeter	Torquemeter pump ball bearings seizure	Torquemeter pump stopped	Torquemeter pump failure	Loss of power control due to loss of torque indication, possible overtorque
Pressurized oil tube to torquemeter pump strainer	Protects torquemeter pump against contamination	Pressurized oil tube to torquemeter pump strainer complete clogging of the strainer	Stopped delivery to the torquemeter pump	Loss of tube oil delivery to the torquemeter pump	Loss of power control due to loss of torque indication, possible overtorque
Pressurized oil tube to torquemeter pump strainer	Protects torquemeter pump against contamination	Pressurized oil tube to torquemeter pump strainer partial clogging of the strainer	Reduced delivery to the torquemeter pump	Loss of tube oil delivery to the torquemeter pump	Loss of power control due to loss of torque indication, possible overtorque
Pressurized oil tube to torquemeter pump	Provides oil supply to torquemeter pump	Pressurized oil tube to torquemeter pump fracture	Leakage of inlet oil	Loss of tube oil delivery to the torquemeter pump	Loss of power control due to loss of torque indication, possible overtorque

Table 13: Semantic differences in two FMEA tables

Traditional FMEA approach	Ontology FMEA approach
Loss of power control due to loss of torque indication	Loss of power control due to loss of torquemeter indication
Loss of power control due to loss of torquemter indication	Loss of power control due to loss of torquemeter indication
Loss torque indication accuracy, possible overtorque	Loss of torquemeter indication accuracy, possible overtorque

As can be seen in the table 13, the FMEA table created by the traditional approach includes typos and some of the same effects are written in different way. This happens because in case of the traditional FMEA softwares, the majority of the information is inserted manually, and it can be difficult to keep such an amount of information consistent and semantically correct. In case of the ontology FMEA approach, each instance such as component, failure mode or effect and their characteristic attributes are inserted manually only once, and each inconsistency of an inserted instance, data and object property is detected by a reasoner. What is more, the reasoning function can also infer some information automatically. That is why the ontology approach ensures a common understanding of information and information consistency even if various people collaborate on the FMEA.

Secondly, concerning the input information, in case of the traditional FMEA approach using a commercial software like XFMEA by ReliaSoft, most of the information such as component name, failure mode, failure effects and causes is inserted manually or selected from predefined values. Given the table 8 and its columns ComponentName, Function, FailureMode, LocalEffect, NextLevelEffect and EngineLevelEffect, there are 53 cells filled in. That means that 53 assertions were done. In case of using the new ontology approach, the same assertions can be done only once and cannot be duplicated. This way, the ontology is able to automatically predict a failure propagation path if the local, next and engine level effect are repeating. Given the table 11 and its columns component_name, function_description, failure_mode_description, local_effect_description, next_level_effect_description and engine_level_effect_description, there are 53 cells filled in as well, but only 39 assertions were done. The following table 12 shows the comparison of FMEA results concerning the assignment of relationships. In the table is also included comparison of the results of scavenge pressure oil line of lubrication system, even though they are not demonstrated in this thesis due to its explicit content and confidential character.

Table 14: Comparison of FMEA results of scavenge and torquemeter oil line using traditional and new approach

	XFMEA	Protégé	Difference
Relationships assigned in FMEA of torquemeter pressure oil line	**53**	**39**	**26%**
Relationships assigned in FMEA of scavenge and torquemeter pressure oil line	**176**	**115**	**35%**

As can be seen in the table, the difference is significant and has increasing trend with increasing amount of information. In the beginning of the development of an ontology and inserting new individuals, each relationship has to be defined. However, with increasing amount of inserted information, some of the relationships such as components with the same function or next level effects resulting in the same engine level effects start repeating and the ontology assigns these relationships automatically. That is one of the reasons why ontologies can be efficient in failure mode analysis of complex systems consisting of lots of components such as aircraft engine.

Finally, using the ontology approach ensures that the input information is semantically correct and stored in a systematic way. Currently, in the FMEA in table 9 can be seen that there are multiple same engine level effects described differently. This means that not all failure modes, that can cause a certain engine level effect, can be found out by querying that specific engine level effect since it has various interpretations. Using ontologies can solve this issue, because a certain engine level effect is inserted as an individual and cannot be duplicated. Thus, for instance, if someone wants to have list of all failure modes that can result in engine level effect "loss of power due to loss of torque indication", failure modes thereof can be easily queried from the failure-related information because this specific engine level effect has only one interpretation allowed.

Given the validation of ontology by GE Aviation Czech and three demonstrated benefits of using ontology-based FMEA, the proposed FMEA ontology can be pronounced valid and used for FMEA analysis.

8 Discussion

The correct results of reliability analyses are very important and valuable for all manufacturers. Based on the results, potential hazardous failure modes can be prevented, system design can be improved, or the awareness of critical components can be emphasized. Concerning the traditional approach of reliability analyses, the reliability engineer needs to gather all necessary information for performing the analysis and this information is usually documented by other engineers. As the design evolves, the continuous gathering of information based on day-to-day communication among engineers on the project can become inefficient and seem interminable. Moreover, the passing of information through a chain of persons can result in worse quality of the information and its correct understanding.

The need to apply ontologies into information and computer science for a better information sharing arose in mid-seventies and in recent years, the term ontology became more and more searched by industry manufacturers, which are trying to improve their information management. The use of ontology approach for performing reliability analyses is one of the possibilities how to improve the way reliability analyses are carried nowadays and this thesis aimed to apply the innovative ontology approach on FMEA analysis of lubrication system of a turboprop engine. This approach consists of developing an ontology suitable for FMEA analysis and mapping the failure-related information to the concepts. The ontology approach ensures that the information, stored in a knowledge repository, is semantically correct and each concept has only one correct understandable interpretation.

When comparing with the traditional approach, the use of ontology approach to perform reliability analysis provides a large scale of benefits. The first significant benefit is the quality of data which are stored in databases as instances of ontology concepts. This approach ensures that the data are stored in a systematic way, are semantically correct and consistent, thus can be shared or reused in future. The ontology approach allows to insert each instance such as component, failure mode or effect and their attributes only once and each inconsistency of an inserted instance, data and object property is detected by a reasoner and some information are even inferred automatically. This way, the ontology approach ensures a common understanding of information and information consistency and avoids misalignment of information. Moreover, since each instance can be inserted only once, the amount of manually inserted information is significantly decreased and there is less chance that typographical error will occur. To sum up, the reliability analysis performed using ontology approach can provide better, more consistent and trustful results.

Another feature of ontologies is that they are easy to extend without having an impact on the basic structure, so that the ontology model can evolve and grow with a further development over time and the classes can be categorized into more subclasses in a detailed way. In a way, the ontology approach enables ontology auto-population of knowledge and reliability analyses. In the beginning of the process of storing the information as instances of ontology concepts, a knowledge base including different types of components, their functions, possible failure modes, etc. must be inserted. As the number of instances grows, the relationships start repeating themselves, for instance the same types of components have the same function, or the same local effects result in the same engine level effects, so this information is asserted automatically by inference engine. The more robust the ontology is, the higher the level of automation it provides, which again, is very beneficial for complex systems such as aircraft engines.

What is more, the ontology proposed in this thesis can serve as a basis for a system which would be able to extract failure-related information from different documents, store it and retrieve the requested information for reliability analysis. The purpose of the ontology in this system is that it can provide a machine-readable information about concepts, attributes and relationships that are stored in a systematic structure of the reliability analysis domain. This feature is closely intertwined with the possibility of creating a common knowledge repository including all information about products stored as instances of ontology and easily extract the information necessary for performing reliability analysis without having to rely on engineer-to-engineer communication.

One of the qualitative characteristics of FMEA is an FMEA team comprising adequately trained members which participate on performing the analysis. The knowledge and experience of team members is vital when identifying and defining all likely failures that can occur. A person highly experienced in performing FMEA analysis can define failure modes, relationships and connections more easily, correctly and make their definitions more understandable for others than someone less skilled in this area of reliability analysis. In addition to this, the basic rules of assigning failure modes to components or effects to failure modes, also known as general class axioms, can be defined in the ontology model by FMEA experts with more experience and thus prevent misleading or hard to understand assignment of information by someone less skilled. The person performing FMEA would be able to see the predefined failure modes for components of the same type (for instance, the class transmitter or strainer) and decide if all of the failure modes apply to that certain component or if some of them need to be added or excluded. To sum up, the ontology model with predefined relationships and class axioms can help to perform the FMEA analysis more easily and make the results more refined even if someone less knowledgeable is performing the analysis. What is more, human error is a part of creation of FMEA which is hard to avoid and it can happen even to the most professional and experienced person. In this case, if someone clicks wrongly and assigns a failure to incorrect component, the information mapping to the ontology model can prevent inaccurate assignment of information and the software based on ontology model will show a warning of inaccuracy of information. The results of FMEA analysis performed by the new ontology approach would be more exact and consistent, and each other FMEA analysis of derivate or similar engine system would require less and less time to be carried, since the information mapped to the ontology can be shared and reused more easily.

Mainly in the aviation industry, any change to be implemented requires a difficult process of approval by the authorities. For instance, if GE Aviation Czech decides to start performing FMEA analysis using the ontology approach, more extensive research would have to be done and the approach would have to be tested on more than just lubrication system of a turboprop engine. This process of testing and possible implementation would require a certain amount of time and need to train reliability engineers for using the new system, which would certainly result in additional costs. On the other hand, in consideration of all mentioned potential benefits of ontologies, the new ontology approach for reliability analysis can be eventually compensating for the additional costs related to its implementation. Even though it is obvious that the ontology approach for reliability analyses has potential and can bring a significant value for work of reliability engineers, the approach is still relatively new to the aviation industry and it is currently under research and development of several research groups.

The proposed FMEA ontology was already verified and validated using data provided by GE Aviation Czech and significant results were demonstrated so far. Considering all mentioned advantaged and disadvantages of using ontology approach for FMEA analysis, the use of this relatively new approach has potential of improving the FMEA analysis and should be considered for implementation at GE Aviation Czech.

Conclusion

The aim of this thesis is to propose a way how to improve the process of reliability analysis and for this purpose, following the work of NASA JPL, an innovative ontology approach was selected.

This work was done in collaboration with GE Aviation Czech. The company provided failure-related information about lubrication system of turboprop engine M601, thus the practical part of the thesis is based on real data application. After carrying the traditional FMEA and identifying its limitations and deficiencies, a new approach to FMEA analysis was proposed and implemented in order to improve the way FMEA is performed and address some of the issues it is currently dealing with. Most of these deficiencies were related with the lack of semantic organisation and misinterpretations.

The use of ontologies ensures a common understanding of information by determining the structure of the relationships between the concepts and it provides additional values like verification of the correctness of the inserted information by using a reasoner and, what is more, one of the additional values of ontologies is decrease of time-demanding nature of the FMEA process.

The FMEA ontology model proposed in this thesis was developed from already existing Fault Management ontology by customizing it to the aircraft engine FMEA domain. The classes, attributes and relationships in the proposed FMEA ontology were modelled specifically to fit the standards of the FMEA analysis performed at GE Aviation Czech and provide an equivalent result in form of FMEA table.

In order to verify the functionality of the proposed FMEA ontology model, the information necessary for performing FMEA analysis were mapped to the ontology model in ontology editor Protégé. To retrieve the information in a form of a FMEA table, the proposed FMEA ontology model in Protégé along with the mapped information were converted to RDF/XML format and mounted to the web application Apache Jena Fuseki as an fmea dataset and then queried by using SPARQL query. The output information was presented in form of standard FMEA table and compared with the results of traditional FMEA method. After comparing the traditional FMEA approach and the innovative ontology FMEA approach, it was proven that the ontology approach resulted in better efficiency regarding the time-consumption, information correctness and consistency. Given the validation of ontology by GE Aviation Czech and demonstrated benefits of using ontology-based FMEA, the proposed FMEA ontology was pronounced valid and used for FMEA analysis with considerable results, which met the expectations of this thesis.

The ontology approach applied in this thesis, however, faces also some limitations. The model was developed only for FMEA analysis, so in case of reusing it for other reliability analysis ontologies, it must be extended by other missing concepts. Another limitation is that the ontology approach was applied only on the lubrication system of a turboprop engine, thus before possible implementation it would have to be applied and tested also on other aircraft engine systems.

As a vision for the future, based on the new ontology approach and the proposed FMEA ontology, an ontology-based software for performing FMEA analysis can be developed and used at GE Aviation Czech providing results in a standard FMEA table in more effective and less time-consuming way.

As a vision for the more distant future, this new ontology approach and the FMEA ontology model can serve as a basis for future development and augmentation of the proposed ontology by further categorization into subclasses and create a robust reliability analysis ontology for aviation industry domain in general. Human brain likes to classify things and create structures, because it makes the knowledge more easily understood. An ontology, consisting of thousands of disseminated boxes, could be able to simulate this function of human brain. Thus, a system which would use this robust reliability analysis ontology, would be eventually able to create a reliability analysis automatically, based on its knowledge base and previous situations. This way, a “virtual mind” could perform reliability analyses and since human factor is number one of the frequently present contributory factors in all aviation accidents, this step towards artificial intelligence could be a possibility how to increase reliability and safety in aviation.

References

1. Company-histories.com. General Electric Company-Company History [online]. Date accessed: March 03, 2019. URL:http://www.company-histories.com/General-Electric-Company-Company-History.html
2. GE Aviation. Aviation History [online]. Date accessed: March 03, 2019. URL: https://www.geaviation.com/company/aviation-history
3. KELLNER, Tomas. GE reports. Czech This Out: Like the Wright Flyer, GE's Turboprop Business Was Born in a Bike Shop - GE Reports [online]. Date accessed: March 03, 2019. URL:https://www.ge.com/reports/czech-this-out-like-the-wright-flyer-ges-turboprop-business-was-born-in-a-bike-shop/
4. History | GE Aviation. Building on 100 years of innovation. [online]. Date accessed: March 05, 2019. URL: https://www.geturboprops.com/company/history
5. GE Aviation. GE and Czech Republic finalize investment agreement to build new turboprop headquarters to support Advanced Turboprop development program. 2016. [online]. Date accessed: March 05, 2019. URL:https://www.geaviation.com/press-release/business-general-aviation/ge-and-czech-republic-finalize-investment-agreement-build
6. D-436 (LeteckeMotory.cz). H80. [online]. Date accessed: March 05, 2019. URL: http://www.leteckemotory.cz/motory/h80/
7. Walter M601 turboprop engine maintenance training manual. Praha. GE AVIATION CZECH s.r.o., 2008.
8. EASA. ED Decision 2003/9/RM. 2003.[PDF]. Date accessed: March 12, 2019. URL: https://www.easa.europa.eu/sites/default/files/dfu/decision_ED_2003_09_RM.pdf
9. GoLeanSixSigma.com. Failure modes & Effects Analysis (FMEA)- Template & Example. 2018. [online]. Date accessed: March 12, 2019. URL: https://goleansixsigma.com/failure-modes-effects-analysis-fmea/
10. POLIKOVSKIJ, Vladimir. Letadlové hnací skupiny. Translated: Rudolf Bartoš, Zděněk Hlávka. Praha SNTL. 1956
11. Society of Automotive Engineers, Aerospace Recommended Practice, ARP 4754. Recommended Failure Mode and Effects Analysis (FMEA) practices for non-automobile applications. 2001.
12. Society of Automotive Engineers, Aerospace Recommended Practice, ARP 4761 Guidelines and Method for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment. 1996.

13. TQM Diagram - Professional Total Quality Management Diagram Software. What is Failr Tree Analysis (FTA)?- The Beginner's Guide. [online]. Date accessed: March 12, 2019. URL: https://www.edrawsoft.com/what-is-fault-tree-analysis.php
14. ADAMEC, Josef and KOCÁB, Jindřich. Letadlové motory. Vyd. 2. Praha: Corona, 2008. ISBN 978-80-86116-54-9.
15. Society of Automotive Engineers, Aerospace Recommended Practice, ARP 4754 Considerations considerations for highly-integrated or complex aircraft systems. 1996.
16. DODSON and NOLAN. Reliability Engineering Handbook. New York: Marcel Dekker. 1999
17. Six Sigma Safety. Fault Tree Analysis. [online]. Date accessed: March 12, 2019. URL: https://www.oshatrain.org/notes/2bnotes12.html
18. The Jet Engine. The Technical Publication department. Rolls-Royce plc. 5th edition. 1996. ISBN 0902121 235
19. DEVAUX, Michaël and LAMANNA, Marco. The Rise and Early History of the Term Ontology (1606–1730). Quaestio.Yearbook of the History of the Metaphysics. 2009. pp. 173-208
20. GUIZZARDI, Giancarlo. Ontological Foundations for Structural Conceptual Models [online]. 2005. Thesis for: PhD. Universidade Federal do Espírito Santo.
21. W3C Semantic Web activity. World Wide Web Consortium *(W3C).* 2011. Date accessed: March 20, 2019. URL: https://www.w3.org/2001/sw/
22. W3C Semantic Web activity. World Wide Web Consortium *(W3C).* Date accessed: March 20, 2019. URL: https://www.w3.org/2007/03/layerCake.png
23. SHAMER, Peter and SKIPPER, Joseph. Toward a Framework for Modeling Space Systems Architectures. Archived 2009-02-27 at the Wayback Machine. NASA, JPL.
24. ŘEPA, Václav. Vývojové trendy vývoje informačních systému- výzva BPR.. [online] Date accessed: March 20, 2019. URL: http://nb.vse.cz/~repa/veda/EurOpen99%20Paper.pdf
25. GOCKEL, Rudolph. Lexicon philosophicum quo tanquam clave philosophiae fores aperiuntur. 1915.
26. Ogdoas Scholastica, continens Diagraphen Typicam artium: Grammatices (Latinae, Graecae), Logices, Rhetorices, Astronomices, Ethices, Physices, Metaphysices, seu Ontologiae, Sangalli : Apud Georgium Straub, 1606.
27. Merriam-Webster Dictionary, [online:www.m-w.com], Date accessed: March 21, 2019.
28. NOY, Natalya and MCGUINESS, Deborah. Ontology Development 101: A guide to creating your first ontology. Stanford University, Stanford, CA, 94305. 2001.
29. [online] URL: http://www.ksl.stanford.edu/software/ontolingua/
30. [online] URL: http://www.daml.org/ontologies/

31. CASTET et al., “Fault Management Ontology and Modeling patterns,“ in AIAA SPACE 2016, AIAA SPACE Forum, Long Beach, CA, 2016. Doi: http://doi.org/10.2514/6.2015-1115.
32. MIL-STD-785B- Reliability Program for Systems and Equipment Development and Production
33. HOLUB, R.; VINTR, Z. Spolehlivost letadlové techniky : elektronická skripta. Brno : VUT FSI, 2001. pp. 233
34. NASA. Glenn Research Center. Turboprop Thrust. Date accessed: March 12, 2019. URL: https://www.grc.nasa.gov/www/k-12/airplane/turbprp.html
35. FALBO, R.A. SABiO: Systematic Approach for Building Ontologies, in: G. Guizzardi, O. Pastor, Y. Wand, S. de Cesare, F. Gailly, M. Lycett, C. Partridge (Eds.), Proceedings of the 1st Joint Workshop ONTO.COM / ODISE on Ontologies in Conceptual Modeling and Information Systems Engineering, Rio de Janeiro, Brazil, 2014.
36. FERNANDEZ-LOPEZ, GOMEZ-PEREZ, SUREZ-FIGUEROA. Methodological guidelines for reusing general ontologies, Data Knowl. Eng., 86 (2013) 242-275.
37. CARLSON, Carl. Effective FMEAs: Achieving Safe, Reliable, and Economical Products and Processes Using Failure Mode and Effects Analysis. Hoboken, N.J.: John Wiley & Sons, 2012.
38. SCHINDEL, William. Failure Risk Analysis: Insights from Model-Based System Engineering. INCOSE Chicago Symposium 2010. [online] Date accessed: March 20, 2019.URL:http://www.omgwiki.org/MBSE/lib/exe/fetch.php?media=mbse:patterns:pbse_wg_meeting_dec_17_2014_attachment_2.pdf
39. REHMAN Z. and KIFOR, S. An Ontology to Support Semantic Management of FMEA Knowledge. International Journal of Computers Communications and Control. 2016. ISSN 1841-9836
40. CASTET,Jean-Francois; BAREH, Magdy; NUNES, Jeffery; OKON, Shira; GARNER, Larry; CHACKO, Emmy; IZYGON, Michel. Failure Analysis and Products in a Model-Based Environment. 2018 IEEE Aerospace Conference. DOI: 10.1109/AERO.2018.8396736
41. [online] URL: https://www.w3.org/TR/owl2-primer/
42. [online] URL: https://protege.stanford.edu/about.php
43. [online] URL: https://jena.apache.org/documentation/fuseki2/
44. [online] URL: https://www.w3.org/TR/sparql11-http-rdf-update/
45. MOLHANEC, M. et al (2010); The Ontology based FMEA of Lead Free Soldering Process, International, Spring Seminar on Electronics Technology - ISSE, DOI:10.1109/ISSE.2009.5206998,1-4.