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A model-based framework for innovative Small and Medium-sized Enterprises (SMEs) in Aeronautics

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To my great grandmother Julia.

Acknowledgement

If you treat an individual as he is,
he will remain how he is.
But if you treat him as if he were what he ought to be and could be,
he will become what he ought to be and could be

Johann Wolfgang von Goethe

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Abstract

The aviation market is facing nowadays a fast growth of innovative airborne systems. Drone cargo, drone taxi, airships, stratospheric balloons, to cite a few, could be part of the next generation of air transportation. In the same time, Small and Medium-sized Enterprises (SMEs) are becoming more and more involved in designing and developing new forms of air transportation, transitioning from the traditional role of supplier to those of system designer and integrator. This situation changes drastically the scope of SMEs' responsibility. As integrators they become responsible for certification of the components and the manufacturing process, an area in which they have little experience. Certification mandates very specific knowledge, regarding the regulations, norms and standards, and dedicated procedures for certification. Certification is a mandatory process and a critical activity for the enterprises in the aerospace industry. It constitutes a major challenge for SMEs who have to take on this certification responsibility with only limited resources.

The SMEs have to face hurdles due to the high capital cost, low volumes and long gestation period of projects. They have a low experience in certification and, in a context where the regulation is not fully available, they need support to discuss with Regulation bodies. In the same time, often at the cutting edge, they may be more innovatively creative and agile than the larger enterprises.

In this thesis, we examine alternate paths, reducing the complexity and bringing one step closer to solving the problem for the innovative SMEs and other new actors in aviation industry. The objective is to provide support so that they can be more efficient to comprehend and integrate rules, legislations and guidelines to their internal processes in a more simple manner.

Two major needs are identified:

- Methodological support is not easily available for SMEs;
- Certification requirements are not easily comprehensive and adaptable to each situation.

This thesis proposes a methodological approach to support such organisation. Developed in close cooperation with a French SME in this situation, the approach is composed of a set of models (metamodel, structural, and behavioural models) covered by a certification governance mechanism. A maturity model approach completes the propositions.

Contents

List of Figures

List of Tables

List of Abbreviations

AFIS	Association Française d'Ingénierie Système (French chapter of the INCOSE)
AMC	Acceptable Means of Compliance
APU	Auxiliary Power Unit
BDD	Block Definition Diagram
BPM	Business Process Management
BPMN	Business Process Model and Notation
BPMS	Business Process Management System
CAAC	Civil Aviation Administration of China
CDR	Critical Design Review
CDI	Compliance Demonstration Item
CS	Certification Specification
CVE	Certification Verification Engineers
DAS	Design Assurance System
DO	Design Organisation
DOH	Design Organisation Handbook
DOA	Design Organisation Approval
DoDAF	Department of Defense Architectural Framework
EC	European Community
EASA	European Aviation Safety Agency
EIA	Electronic Industries Alliance
EIS	Enter Into Service
ELA	European Light Aircraft
EN	European Norm
EPF	Eclipse Process Framework
ETSO	European Technical Standard Order
EU	European Union
EUROCAE	European Organisation for Civil Aviation
FAA	Federal Aviation Agency
GM	Guidance Material
HDO	Head Design Office
HOA	Head of Airworthiness
HISM	Head of Independent System Monitoring
IATA	International Air Transport Association
IEEE	Institute of Electrical and Electronics Engineers
IBD	Internal Block Diagram
ICAO	International Civil Aviation Organization
INCOSE	International Council on Systems Engineering
IR	Implementing Rules
ISO	International Organisation for Standardisation
JAA	Joint Aviation Authorities
LOI	Level Of Involvement

LTA	Lighter-Than-Air
MBSE	Model-Based Systems Engineering
MRO	Maintenance, Repair, Overhaul
MS	Member State
NAA	National Aviation Authority
OEM	Original Equipment Manufacturer
OO	Organisation Origin
OP	Other Parties
OPM	Object Process Methodology
OPD	Object Process Diagram
ORS	Occurrence Reporting System
PDCA	Plan-Do-Check-Act (
PDR	Preliminary Design Review
PM	Project Management
PMI	Project Management Institute
PMod	Process Modeling
PO	Production Organisation
POA	Production Organisation Approval
POC	Proof of Compliance
POE	Production Organisation Exposition
QAS	Quality Assurance System
RD	Requirements Diagram
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SE	Systems Engineering
SECAM	Systems Engineering Capability and Assessment Method
SEI	Software Engineering Institute
SI	Software Implementation
SME	Small and Medium-sized Enterprise
SMS	Safety Management System
SoI	System of Interest
SoS	System of System
SPEM	Software & Systems Process Engineering Metamodel
SPICE	Software Process Improvement and Capability dEtermination
STC	Supplemental Type Certificate
SysML	Systems Modeling Language
TC	Type Certificate
TR	Technical Report
TRL	Technology Readiness Level
UML	Unified Modeling Language
VSE	Very Small Entity
V&V	Verification and Validation
WFMS	Work Flow Management System

CHAPTER 1

INTRODUCTION

CONTENTS

ABSTRACT

This chapter presents the motivations and objectives of the thesis focusing on the challenges of new enterprises aiming to enter in the aviation market.

The first section presents the general context of the aviation market with its actors, structure and constraints. A recent picture shows some noticeable changes. Particularly, the specific role of the small organisations is described, revealing a paradigm shift. Traditionally small companies are subcontractors for large groups. Recently some of them have positioned themselves on activities where large groups are traditionally leaders. Ambitious projects of completely new and largely innovative aircraft are carried out by companies with less than 250 people. These enterprises, usually categorized as Small and Medium-sized Enterprises (SMEs) are forced to be compliant with the same regulations as large companies and having to deal with the management of their supply chain which is mostly composed of SMEs. They must then take ownership of the leadership, the policy and the risks while accompanying their own subcontractors in this new approach.

The second section presents the research positioning and addresses the objectives. The analysis of the aeronautical context leads to the identification of two major needs. First the recent projects led by some SMEs highlight a need of practical methodology to support their activities of compliance to the regulation. Then whereas regulation and related elements are composed of interdependent texts, a lack of formalism is clearly identified. A more formalized framework could allow a better understanding of the expectations of the regulation.

Finally the structure of the thesis is presented in the last section, providing an overview on the six chapters.

1.1. GENERAL CONTEXT

1.1.1. The aviation market

The aviation market is facing nowadays a fast growth of innovative projects, each addressing specific areas so to reduce weight, noise, and emissions of aircraft, or to increase its autonomy, capacity and flexibility. The global trend is indeed to find new concepts to make air travel safer, greener, with more efficient aircraft. Traffic demand is expected to double in the next twenty years[1]. Airspace congestion and conflict resolution will then become a challenge for the next decades. Sustainable development now is a necessity in industry. In 2017, the International Civil Aviation Organization (ICAO) adopted a new aircraft CO_2 emissions standard which aims to reduce the impact of aviation greenhouse gas emissions on the global climate[2]. All aircraft manufacturers look for solutions to, for example, improve engines, enhance aerodynamics, or use lighter materials. Many companies study electric aircraft, hybrid engines, hydrogen fuel cells, etc. Basically any new concept to be more independent regarding the fossil fuels is analysed. Airships are also being considered again as a real alternative to passengers and cargo transportation and should enable to reduce drastically fuel consumption, and associated pollution and noise emission.

If new air transportation means open up new markets, it may well generate risks, technical, economical and societal challenges [1]. For example, drone cargos, drone taxis, airships, stratospheric balloons, to cite a few new airborne systems, could be part of the next generation of air transportation. The introduction of this kind of projects in public airspace brings along questions on air travel operations, safety and conflict resolution.

Safety is the primary concern of the aeronautics industry. Any stakeholder is concerned by safety and safety improvement. As proof, the number of fatal accidents has been drastically decreasing since the 1950's and nowadays they are at their lowest level[3]. High reliability of the aircraft and of all the systems, parts and appliances which compose the aircraft must be demonstrated through the certification process.

The certification process is a safeguard for the industry to manage a high level of safety and a low accident rate; it is an important constraint for the development of aircraft. The stake is commercial as the certificate of airworthiness is the only way to market an aircraft. It is also a societal issue as the manufacturers commit to provide safety for both passengers on-board, people on ground and infrastructures. Led by ICAO recommendations, many countries have created their own institutions to manage locally the certification process and the safety requirements, taking the responsibility to deliver the certificates of airworthiness for aircraft. In Europe, the European Aviation Safety Agency (EASA) and in United States, the Federal Aviation Administration (FAA) are major actors to monitor air travel safety. Operating any aircraft in the northern hemisphere requires a certification from at least one of these administrations. It means that the enterprises have to demonstrate that they

[1] https://www.iata.org/pressroom/pr/Pages/2018-10-24-02.aspx
[2] https://www.icao.int/Newsroom/NewsDoc2017/COM.05.17.EN.pdf
[3] https://aviation-safety.net/graphics/infographics/Fatal-Accidents-Per-Year-1946-2017.jpg

have put in place a monitoring and control of their developments. For new and innovative aircraft concepts, certification is a particular challenge because the common policy is not available and still being written.

The aviation market is highly concentrated and mostly shared by two major companies, leading the industry with civil aircraft and creating essentially a duopoly (Airbus and Boeing). Several other manufacturers propose alternatives with small regional jets or on specific niches market (ATR, Dassault Aviation, Embraer, Bombardier, Sokol …). In parallel, new actors arrive on the Asian market, for example COMAC (Commercial Aircraft Corporation of China) or Mitsubishi Aircraft. Some certification-related issues lead to significant delivery delays, but these new actors can become serious competitors in the next decades[4,5].

All these aircraft manufacturers are called OEMs (Original Equipment Manufacturers). They are working with numerous suppliers which provide systems, parts, appliances. OEMs have the final aircraft assembly responsibility and deliver directly the aircraft to their customers (mostly airlines, but also states or some non-airlines enterprises). One can identify different levels of supplier working with the OEMs, forming a typical aeronautics supply chain. The OEM is referred to as the aircraft integrator, and is usually a Large Enterprise. OEMs have to manage a few Tier 1 suppliers, themselves managing the relation with the other Tier 2 and Tier 3 suppliers. The definition of the levels is usually as follows [2]:

- Tier 1 – Tier one companies are direct suppliers to OEMs. They are sometimes called prime contractors. In aerospace industry, they are sub-manufacturers or assemblers responsible of sections or systems of aircraft, for example engines, avionics systems, aircraft interiors, landing gears etc.
- Tier 2 – Tier two companies are the key suppliers to tier 1 suppliers, without direct contact with OEMs. However, a single company may be a tier 1 supplier to one company and a tier 2 supplier to another company. In aerospace industry, they may be responsible for aero structures, subsystems, subassemblies etc.
- Tier 3 – Broader industry suppliers. They are specialized in the production of particular components, e.g. electronic components, raw materials.

This thesis is concerned mainly with initial airworthiness, and will not address continued airworthiness activities; maintenance, repair and overhaul are therefore not in scope. Within this reduced scope, many kinds of upstream and downstream flows co-exist, that may generate complexity and risks. Based on [4], we identify at least 6 kinds of flows :

- Flow of Requirements
- Flow of Information (digital or numerical, and explicit or implicit)
- Flow of Responsibilities
- Flow of Products
- Flow of Services

[4] https://www.ainonline.com/aviation-news/air-transport/2019-02-14/comac-plans-fly-three-more-c919s-year
[5] https://theaircurrent.com/industry-strategy/japan-and-mitsubishi-find-their-path-together-for-mrj-certification/

- Flow of Financial Resources

In Aeronautics, Small and Medium-sized Enterprises (SMEs)[6] are traditionally taking the role of suppliers and are strongly dependent on their relations with the integrators, the OEMs, or with other tier-1-2-3 partners. With the new arrival of aircraft concepts, some SMEs are now taking the role of OEMs and have to manage themselves the different kinds of flows as presented above. This is an important paradigm shift.

A major constraint is that the aircraft industry is governed by several rules, legislations and other guidelines. SMEs, whatever their roles in the supply chain, have to face these constraints as well. If they have the role of an OEM, they find themselves in the role of integrator and they will have to take the same roles as large companies, maintaining links with suppliers in the supply chain, supporting and supervising their work as project leader and communicating with certifying authorities. They will need to demonstrate their ability to design, produce, and operate their systems with the expected level of safety and reliability as expected by the regulation. Just as any commercial organization, SMEs have to face the usual constraints of safety, cost, time, and performance. The main difference is that they have to perform all these activities with much less resources than large companies.

1.1.2. The Small and Medium-sized Enterprises (SMEs)

SMEs are of strategic importance for the economy. The European Community has found important to better identify SMEs in order to better support them. SMEs are indeed confronted with particular issues. They have to face market environments with some more established enterprises. SMEs may be unable to access to bank finance or to invest in research and innovation as necessary. They may lack the necessary resources to comply with regulations. Additionally they may face structural barriers, such as a lack of management or technical skills, and a limited knowledge of the opportunities for growth[7].

Since 2003, date where the European Community officially provided a definition and a classification of the European SMEs (see Table 1-1), many Small Business Acts have been signed on different levels (States, Region, Federation levels) to simplify the market environment (regulation and policy), remove some barriers to their development and facilitate the access to certain markets.

Table 1 - 1 Definition of Small and Medium-sized Enterprises in Europe

Company Category	Number of Employees	Turnover	Balance sheet total
Micro	<10	< € 2 million	< € 2 million
Small	<50	< € 10 million	< € 10 million
Medium-sized	<250	< € 50 million	< € 43 millions

Source: Commission Recommendation of 6 May 2003 concerning the definition of micro, small, and medium-sized enterprises (2003/361/EC), Official Journal of the European Union, L 124/36, 20 May 2003

[6] In this thesis, small enterprises, small companies and small organisations are used interchangeably.
[7] https://op.europa.eu/en/publication-detail/-/publication/79c0ce87-f4dc-11e6-8a35-01aa75ed71a1: User Guide to the SME definition, published by the European Commission,

Some other definitions have been introduced to better support the small enterprises. For example, [5] defines Very Small Entity (VSE) as any “enterprise, organization, department, or project having up to 25 people”. They presented in [5] the premises of the future standard, the ISO/IEC 29110 series [6], international norm dedicated to the small enterprises developing a software or a system. In the same way, [7] developed a dynamic model of the Capability Maturity Model (CMM) to be applied in small organizations having less than 50 employees. They introduced new terms such as: eXtra small and eXtra eXtra small (see Table 1-2).

Table 1 - 2 Definition of Small organisations according to [7]’s classification

Variant of “Small”	Number of Employees
XXS (eXtra, eXtra Small)	1-2
XS (eXtra small)	3-15
S (Small)	16-50

This addition to the European classification is important so to cover specific issues, such as innovative systems and software development.

In Europe, SMEs represent 99.8% of the total number of companies in the European Union with 28 member states (EU-28) non-financial business sector (See Table 1-3) and employ 66.4% of the total number of European employees in the EU-28 non-financial business sector [8].

Table 1 - 3 Distribution of the SME in the EU-28 non-financial business sector

Company Category	Distribution of companies in%	Distribution of companies in thousands
Micro	93.1%	22,831
Small	5.8%	1,421
Medium-sized	0.9%	232
Total	**99.8%**	**24,484**

[8] Source: Eurostat, National Statistical Offices, DIW Econ

According to a European Commission report[8] published in 2014, SMEs represented in 2006, 80% of all European aerospace companies. According the same report, medium companies represented 9% of all aerospace companies in Europe. As an example, for the major European aircraft manufacturer, EADS (now Airbus Group), the share of smaller enterprises in the total amount of suppliers was about 76% in 2007. In France, in 2006, according Eurostat figures provided in the same report, on 392 companies, only 40 were categorised as large companies. However this result has to be balanced with the fact that in terms of purchasing volume, large groups largely dominate (79% for EADS in 2007).

[8] https://publications.europa.eu/en/publication-detail/-/publication/3fdd63c8-6d5e-4ab5-9f0d-880a6404ea88/language-en

According to a more recent report[9] published in 2018 by GIFAS[10], the French Aerospace industrials representative, SMEs represent 28% of the total supply chain turn-over in France and several supporting programs are available to support them in their development (CORAC[11], Ambition ETI-PME, etc).

In France, several competitiveness clusters (pôles de compétitivité in French) provide information, training, networks, financial and legal support to their member enterprises, in particular to SMEs. Projects may receive a label from clusters and are so recognised as of importance to the French economy development. For example, the cluster SAFE (Security and Aerospace actors for the Future of Earth) is one of the French clusters supporting innovative air transport projects. It has labelled several SMEs's projects like on-board systems, aerostats, small and large drones.

1.2. MOTIVATIONS AND OBJECTIVES OF THE RESEARCH

The civil aviation safety rules guarantee a high and consistent level of safety throughout the worldwide air transport market. For the enterprises, certification is a transverse and critical process affecting at the same time technical, economical and organisational objectives. It contributes to a societal equilibrium, but adds complexity to the development of innovative products. Addressing all the requirements for all the stakeholders of the market, from the OEMs to the Airlines and other actors throughout the supply chain, the regulation is often perceived as difficult to read for new stakeholders in the aviation sector. How to identify the necessary and sufficient regulatory requirements and how to meet them?

Although triggered by the new position of the SMEs in the aeronautical sector, this research may concern larger enterprises as well. For example, actors such as COMAC or Mitsubishi are facing similar issues as the SMEs. The common point of these actors is that they may be considered as new actors in the market compared to historical actors such as Airbus or Boeing.

In this thesis, we examine alternate paths, reducing the complexity and bringing one step closer to solving the problem for the innovative SMEs and other new actors, and how they can be more efficient to comprehend and integrate rules, legislations and guidelines to their internal processes

Some research findings lead to the identification of two major needs:

- Methodological support is not easily available for SMEs;
- Certification requirements are not easily available or adaptable to each context depending if the enterprise is an OEM, an aircraft supplier, an engine manufacturer, an equipment provider, etc….

[9] https://www.gifas.asso.fr/sites/default/files/video/gifasra20172018_definitif_copy2.pdf
[10] Groupement des Industries Françaises Aéronautiques et Spatiales
[11] Conseil pour la Recherche Aéronautique Civile, French council for research in civil aviation

1.2.1. Need of methodological support

SMEs, who are aiming to develop new concepts, have generally limited knowledge about regulation. Explanations about the certification process and support to help them implement the requirements are often requested.

As the market depends largely on a duopoly, there is a limited availability of approaches taking into account the specific needs of SMEs. The selection of appropriate methods and tools is more often large enterprise oriented. Even the existing solutions are most of the time fractionated, not answering to the full problematic.

Facing these challenges, the SMEs do not necessarily have the sufficient resources to fully read and analyse the requirements and all related documentation. They also have restricted resources to implement the required processes and a fortiori to reengineer the processes in a continuous improvement [9].

With limited resources, the availability of specific processes detailing the expected way of working and deliverables would be essential. In reality, such descriptions are not easily available, drastically complicating their role.

1.2.2. Need of formalism

Certification requirements from regulation texts are written in natural language, most often in English. This leaves space for interpretation and potential confusion on these requirements. The majority of the companies working in aeronautics usually understand the language and the implicit content; internal processes are implemented, executed, documented and improved regularly with highly competent resources since decades. The problem is more complex for new actors who have to understand the complexity of the texts in an overall glance, requiring adequate support.

One aim of this research is to introduce formalism in the certification process to provide a better comprehension of the certification objectives in a faster manner.

In particular, we identify the following key challenges:

- Certification Objectives and Systematic coverage of the certification requirements

It is important to get the major certification objectives at a glance at the beginning of the project. What are the key steps? How do the enterprises have to begin? What are the main objectives to achieve? What are the key activities that feed into the process?

If certification objectives are not well understood from the beginning and not properly taken into account, the other objectives (technical, economical and organisational) will be impacted during the project.

- Ambiguity elimination from certification requirements

It is important to eliminate redundancy from different sources of information. Where is the right information? What does it mean?

If certification requirements are not formal enough and are duplicated in different environments, the certification process will not be efficient.

- Effective measurement of the risk

Innovative SMEs have to cope with many kinds of challenges: technical, economical, societal.

The risk management process often does not consider certification issues in an integrated way, resulting in unknowingly accepting risks that could have been identified earlier.

The thesis aims at addressing these challenges, accentuated by the new situation for SMEs and other new actors.

1.3. STRUCTURE OF THE THESIS

The purpose of this section is to set forth the structure of the thesis which is organized in six chapters. Figure 1-1 illustrates the outline and provides the objective of each part. It shows the sequential link between the different parts as well.

Chapter 2 presents current regulatory constraints in aeronautics industry and the approaches available to be compliant with these mandatory requirements. First the worldwide airworthiness and the European regulation and approvals structure are introduced. The aeronautical standards express a classical way to manage a development in the aeronautics industry taking into account the certification requirements. Systems engineering is presented as an approach to develop a system in aeronautics. The chapter ends with the summary of the identified issues.

Chapter 3 presents the related work: Process, Process Modelling, Requirements Modelling, Risk Assessment and Maturity Models are discussed. The experience feedback of the use of SE in companies completes the picture to identify in a last section the major challenges for SMEs in the aviation sector.

Chapter 4 introduces the proposed framework, called “Aircraft Certification Framework (ACF)”. The ACF approach is presented with its objective, structure and architecture based on requirements and processes models. The framework governance is explained through its rules. A maturity model is proposed as well. Finally a 3-step methodology is presented, showing how the different elements of the framework are used in a coordinated manner.

Chapter 5 illustrates ACF with a real case study, coming from industry. Each step of the methodology is executed and is providing feedbacks and validation elements. All the results of the application enable at the end consideration and discussion, identifying lessons learned and potential improvements.

Chapter 6 concludes the thesis with the overview of the contributions, the identified limitations and the landscape of the perspectives for future research.

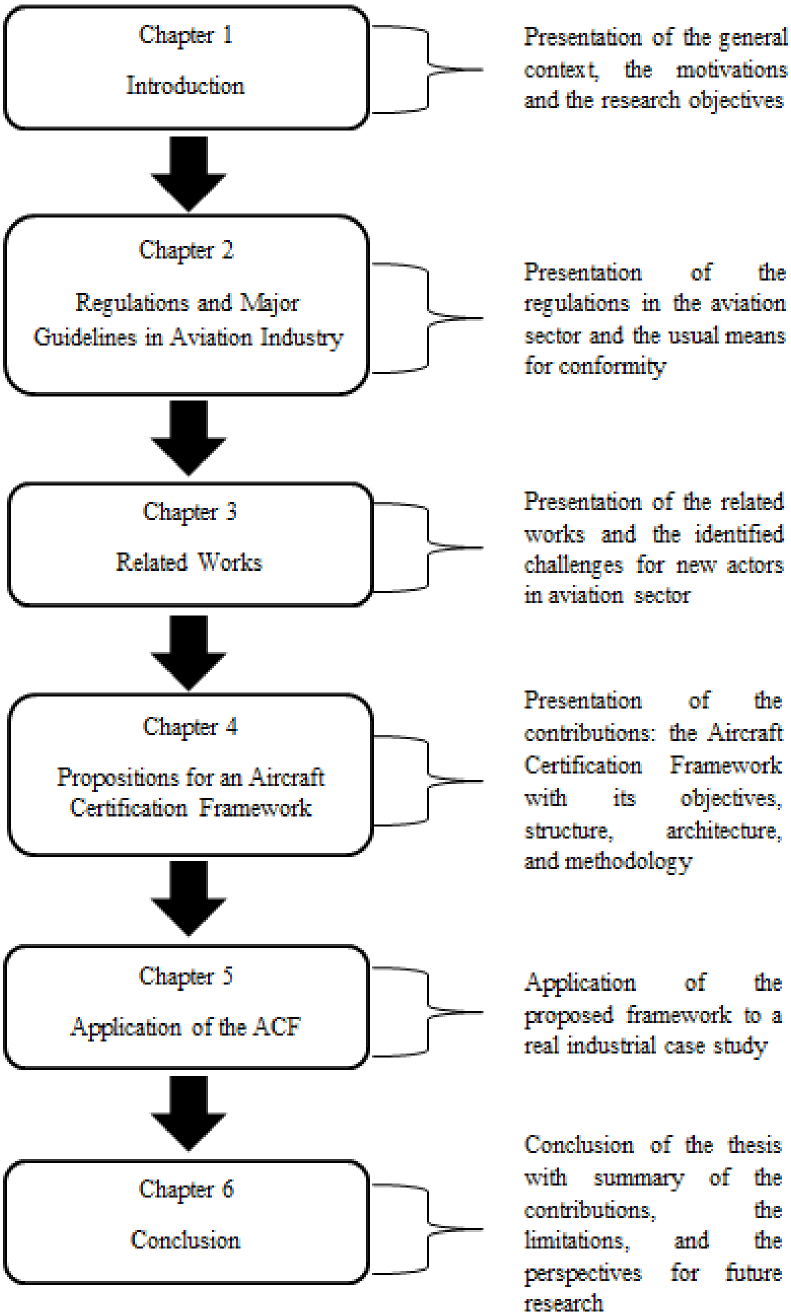

Figure 1 - 1 Outline of the thesis

CHAPTER 2

REGULATIONS AND MAJOR GUIDELINES IN AVIATION INDUSTRY

CONTENTS

ABSTRACT

This chapter presents the necessary background to understand the main concepts and the main phases of the certification process in aviation sector.

First, airworthiness is defined and the major involved institutions are presented, the main actors and the links between them described.

As the case study presented in chapter 5 has to be compliant with European regulation, the European Aviation Safety Agency (EASA) and its certification process are presented in a more detailed manner in section 2.2.

Then, in section 2.3, the available documentation used to be compliant with the regulation is described: main official guidelines are discussed. The institutions carrying these standards and their roles are detailed, as well as the structure and content of the documents. In particular, the links between ARP 4754A, ARP 4761, DO-178C and DO-254A are described to better understand their imbrication and dependencies. It is well-established that these documents allow being compliant with the international regulation. For the SMEs, it is not appropriate to focus on one document or the other. They have to understand the full picture in a quick manner and take position.

In section 2.4, Systems Engineering (SE) approach is presented. Generally accepted to be used to develop complex systems and often defined as a de-facto approach for complex aircraft development, SE combined an analytical approach and a holistic approach. Historically it is more applied in large enterprises but SMEs from aviation industry are more and more strongly advised to appropriate its principles. The available standards are reviewed in this section.

This current situation in Aeronautics industry leads to some conclusions provided in section 2.5. SMEs may face some difficulties to enter in this market. We identify two main issues we will address in the thesis.

2.1. AIRWORTHINESS CONCEPTS

In this section, we first provide a short presentation of the institutions responsible to define, disseminate and supervise worldwide the regulation and we define the terms airworthiness and airworthy.

2.1.1. Airworthiness Institutions and their Objectives

On 7 December 1944, in Chicago, the fourth International Commission for Air navigation (ICAN) concluded with the signature of a final act, known as Chicago Convention[12]. This convention is usually cited as the historical start of the international collaboration to define the air code. It contained the basic principles and arrangements for the international civil aviation and introduced normalisation and standardisation in the Industry, defining some safety limits as well. It established the **International Civil Aviation Organization** (ICAO)[13], the first and today the largest organisation dealing air regulation with 191 States members. ICAO is now the worldwide reference for air navigation principles, international air transport, international standards and recommended practices. After regular amendments, ICAO regulation consists now in 96 articles[14] completed by 19 annexes[15]. As an example, Annex 8 of ICAO regulation is dealing specifically with the “Airworthiness of Aircraft”[16] specifying uniform procedures for certification and imposing for instance:

- the initial delivery of a Certificate of Airworthiness before the enter into service of the aircraft,
- the continued validity control of the Certificate of Airworthiness,
- the necessity to get an approval of the Design,
- the necessity to control the Production.

Additionally, ICAO provides over 12,000 Standards and Recommended Practices and Procedures (SARPs) disseminated through the 19 annexes. Even if the ICAO regulation and SARPs are highly recommended to be “the basis for the development of national airworthiness regulations”[17], there is no binding mechanism with which to verify compliance and “compliance is mainly dependent on the States parties goodwill”[18].

Since 1958, the **Federal Aviation Administration** (FAA) is the aviation authority of the United States (US) regulating Civil Aviation. It is the first local organisation created just after the ICAO. It is responsible for setting up the Federal Aviation Regulations (FARs), which are binding for all flight operations in the US. The FAA also provides air traffic control services.

[12] https://www.icao.int/publications/pages/doc7300.aspx
[13] https://www.icao.int/secretariat/PostalHistory/the_chicago_convention.htm
[14] https://www.icao.int/publications/documents/7300_orig.pdf
[15] https://www.icao.int/documents/annexes_booklet.pdf
[16] https://www.icao.int/documents/annexes_booklet.pdf
[17] https://skylibrarys.files.wordpress.com/2016/07/doc-9760-airworthiness-manual.pdf, section 1.1.3
[18] http://www.europarl.europa.eu/ftu/pdf/en/FTU_3.4.9.pdf, page 1

In Europe, **JAA (Joint Aviation Authorities)** started in 1970 without any legal status of authority. As ICAO, JAA was not able to issue official certificates and provided only some recommendations to the national authorities, who agreed to cooperate by signing the “JAA arrangements” document [10].

Established on 12 July in 2002 by the European Commission, **the European Union Aviation Safety Agency (EASA)** took over the functions of the former JAA for the European Union (EU) countries and got the legal status of a real authority. The headquarters are now in Cologne (Germany) and the organisation counts 32 Member States[19]. The Agency has a standardization and oversight function for all aviation safety certification activities of Member States. The responsibilities of EASA include drafting of aviation safety legislation and providing technical advice to the European Commission and to the EU Member States, airworthiness and type certification of aircraft and aircraft parts for aircraft operating in the EU, approval of aircraft design world-wide organisations and of production and maintenance organisations inside and outside of the EU. EASA is the only example of aviation authority organised in multi-country federation.

At country level, there is usually a National Aviation Authority (NAA) which is the regulatory body responsible for aviation above the domestic territory. The NAA implements the ICAO recommendations in national legislation, as well as the rules from the institution which it might depend. It is responsible for regulatory oversight as well. Most of the countries in the world have a NAA.

For example, the **DGAC** (Direction Générale de l’Aviation Civile in French or General Directorate for Civil Aviation) is the French NAA, responsible for ensuring the safety and security of French air transport. As France is a member of the European Union, DGAC is in charge of monitoring the application of the European regulations in France under the European Union (EU) regulation and EASA authority. EASA has large responsibilities on certification process and design approval but DGAC remains responsible for approving production, maintenance, and maintenance training organizations. DGAC is required to use EASA procedures, as well as monitor and control EASA implementing rules.

2.1.2. Airworthiness and Airworthy Definitions

Airworthiness and airworthy are two fundamental concepts in aviation. We propose here some definitions shared among the main institutions.

In Annex 8 of ICAO, the “design aspects of the appropriate airworthiness requirements” is one of the main concepts of the ICAO recommendations. It regroups minimum, comprehensive and detailed requirements per class of aircraft, engine, propeller or part ensuring enough safety level. These airworthiness requirements must be established, adopted or accepted at NAA level. In the same annex, continuing airworthiness is defined as the set of processes by which an aircraft, engine, propeller or part complies with the applicable

[19] https://www.easa.europa.eu/country-category/easa-member-states

airworthiness requirements and remains in a condition for safe operation throughout its operating life.

It is useful to compare Continued and Continuing Airworthiness as they are sometimes used interchangeably. **Continued Airworthiness** is also known as Type Airworthiness [11] and is related to Initial Airworthiness [12]. **Continued Airworthiness** concerns “all the actions associated with the upkeep of a type design and the associated approved data through life.” [11], [12]. **Continuing Airworthiness** concerns “All of the processes ensuring that, at any time in its operating life, the aircraft complies with the airworthiness requirements in force and is in a condition for safe operation” [13].

According to the Federal Aviation Administration (FAA), an aircraft is considered as airworthy if it “… meets its type design and is in a condition for safe operation”[20]. This definition considers the two conditions to reach airworthiness. First the aircraft must conform to its type design, dealing with “Initial Airworthiness”. Secondly the aircraft must be in a condition for safe operation, dealing with “Continuing Airworthiness”. If either of these two conditions cannot be met, the aircraft will be considered to be *un-airworthy*.

This distinction between “Initial Airworthiness” and “Continuing Airworthiness” is essential to understand the general regulation structure. This dichotomy is used in any regulation structure.

Another definition used by the UK Defense Authority includes people on the ground. According to the MAA02 master glossary [11], “Airworthiness is the ability of an aircraft or other airborne equipment or system to be operated in flight and on the ground without significant hazard to aircrew, ground crew, passengers or to third parties; it is a technical attribute of materiel throughout its lifecycle.”

According to Australian Defence Force (ADF) [14], “Airworthiness is a concept, the application of which defines the condition of an aircraft and supplies the basis for judgement of the suitability for flight of that aircraft, in that it has been designed, constructed, maintained and is expected to be operated to approved standards and limitations, by competent and approved individuals, who are acting as members of an approved organization and whose work is both certified as correct and accepted on behalf of Defense.” Here the definition highlights the regulatory authority that will provide the airworthiness approvals.

In [10] and [14], the definition is taking into account safe conditions, possession of the necessary requirements and allowable limits. An aircraft must be operated within the limits specified in the Flight Manual (flight envelope, etc). An aircraft which exceeds any of these limits may compromise its airworthiness.

[20] http://www.faa-aircraft-certification.com/faa-definitions.html

2.2. EASA AND THE EUROPEAN REGULATION

As the research in this thesis is oriented towards European enterprises, we focus the analysis on the European regulation, we present in this section a comprehensive overview. In 2.2.1, we describe the structure of the European regulation. In 2.2.2, we detail the Initial Airworthiness and the main notions and definitions to understand the content of the Part 21. In 2.2.3, we present the overall certification process. In 2.2.4, we discuss finally three important additional concepts in the certification process: the “Privileges”, the “Proportionality” and the “Level Of Involvement” (LOI).

2.2.1. Structure of EASA Regulation

As shown in Figure 2-1, the European regulation is structured in four different levels:

- The basic regulation. Based on ICAO recommendations, it establishes common requirements for the regulation of safety and environmental sustainability in European civil aviation. This text is under European Union (EU) responsibility.
- The Implementing Rules (IR). They are composed of several texts with a different subject each and including mainly Initial Airworthiness and Continuing Airworthiness but also air operations, personnel licensing, aerodromes, air traffic management and air navigation services. These texts are under European Commission (EC) responsibility.
- Implementing rules may have Annexes which are more practical rules. For example, Initial Airworthiness IR n°748/2012 is bounded to the Annex I which is also called Part 21. Continuing Airworthiness IR n°1321/2014 is bounded to Part M, Part 145, Part 66, Part 147 and Part T. The annexes are considered to be “Hard Law” in the sense that all applicants have to be compliant with Annexes. These texts are under the EASA responsibility.
- Some practical texts are called “Soft Law”. The name of these texts comes from the fact that the applicants may negotiate the content under certain conditions. These texts are under the EASA responsibility and consist in three main kinds of documents:
    - *Acceptable Means of compliance (AMCs)*, strong recommendations provided by EASA to enable applicants to be compliant with the Hard Law. Companies may propose alternative means of compliance but it may be more difficult to make them validate by EASA instead of following the proposed AMCs;
    - *Guide Materials (GMs)*, additive information to help companies to find the right mean of compliance according their organisation;
    - *Certification Specifications (CSs)*, the adopted code related to “design aspects of the appropriate airworthiness requirements”. EASA adopted CS-25 is for Large Airplane, CS-23 for large rotorcraft, etc…

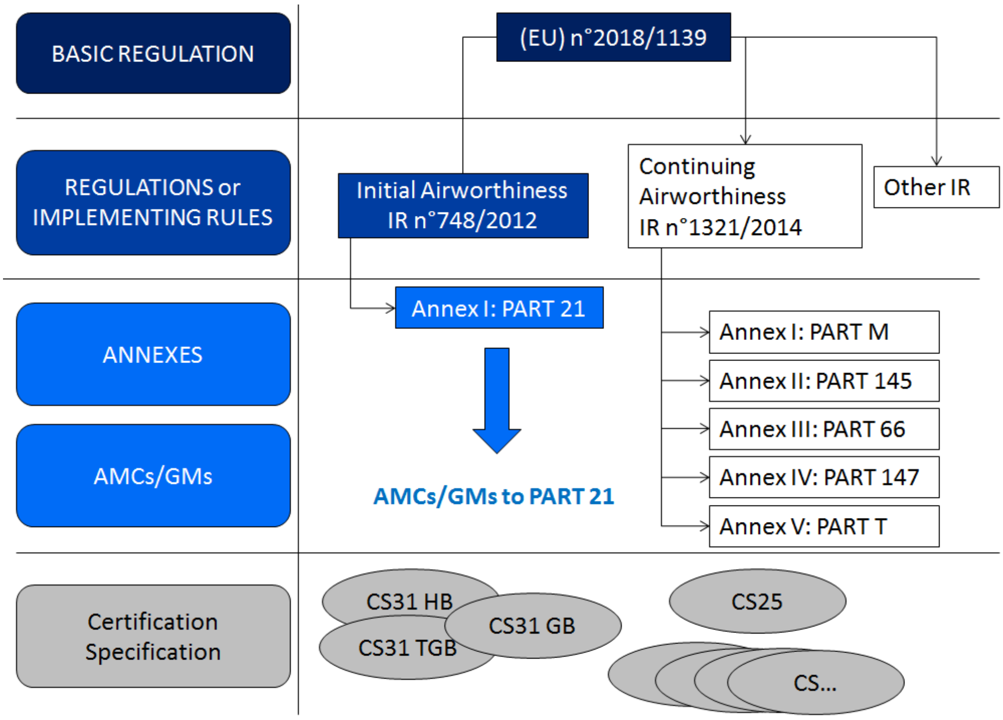

Figure 2 - 1 European Regulation structure

EASA publishes also Good Practices for information purposes only. They must not be considered as formally adopted by the EASA. Good Practices do not introduce new or modified rules and do not constitute any legal obligation or right for the Agency or the organisations. Moreover EASA is responsible for distributing Airworthiness Directives (ADs) for aircraft subject to European regulations. An AD is a formal communication which mandates some corrective actions.

Under the EASA regulation, numerous definitions have to be understood. Here a focus is done on the main concepts: what is a product, what are parts and appliances and what are the aircraft concerned by the EASA regulation.

In accordance with Annex 8 of ICAO, Regulation (EU) No. 2018/1139 [15] and [16] defines '**product, parts and appliances**' as follows:

- '**product**' shall mean "an aircraft, an engine or a propeller";
- '**parts**' shall mean "any element of a product, as defined by that product's type design"; and
- '**appliances**' shall mean any "non-installed equipment", i.e. "any instrument, equipment, mechanism, apparatus, appurtenance, software or accessory carried on board of an aircraft by the aircraft operator, which is not a part, and which is used or intended to be used in operating or controlling an aircraft, supports the occupants' survivability, or which could impact the safe operation of the aircraft".

Under European legislation, the EASA has responsibility for the airworthiness to the majority of the civil aircraft registered in the Member States of the European Union. However, the Regulation also stipulates that certain aircraft are subject to national regulations. Each aircraft type is categorised as either:

- "EASA aircraft", aircraft that is subject to European airworthiness regulations; or
- "Non-EASA aircraft", aircraft that is subject to national airworthiness regulations.

In the past EASA provided in the Annex II the list of products excluded from EASA's responsibility but this file has been removed[21]. Now the determining factor to exclude a given aircraft from the scope of the Basic Regulation is the concrete nature of the operation performed – not the aircraft itself nor its registry, its owner nor its operator. Also the responsibility for determining whether a certain operation falls within the scope of the Basic Regulation belongs fully to the Member States. However, article 1(2) of Basic Regulation excludes formally from the EASA's scope any aircraft involved in the execution of military, customs, police, search and rescue, firefighting, coastguard or similar activities or services[22].

Under the IR No 748/201, some "EASA Aircraft" may beneficiate of derogation regarding the objectives of the certification. It is the case for some European Light Aircraft (ELA) classified as ELA 1 and ELA 2 that may have lighter certification process without negotiation with EASA (see Appendix B for detailed definitions of ELA1 and ELA2).

2.2.2. Initial Airworthiness

Regulation (EU) N°748/2012 is the European transcription of the ICAO recommendations dedicated to Initial Airworthiness. Table 2-1 provides an overview of the content by presenting the titles and a summary of the 12 articles. This regulation is a high level specification and explains the main objectives of the Initial Airworthiness.

Traditionally referred to as Part 21, the Annex 1 of Regulation (EU) N°748/2012 constitutes the real core of the aircraft certification. Part 21 is composed of 2 sections:

- **Section A** describes the Technical Requirements addressed to the certification applicant. This section is composed of 14 applicable Subparts (from A to Q);
- **Section B** describes the procedures for competent authorities, basically EASA or NAA (Same Subparts).

The composition of the 14 Subparts (in both sections) is presented in the Table 2-2. Some Subparts refer to approval or certificate but not systematically. Subparts A, F and Q are not concerned by an approval or a certificate.

[21] https://www.easa.europa.eu/document-library/product-certification/type-certificates/easa-product-lists
[22] https://www.easa.europa.eu/faq/19236

Table 2 - 1 The Regulation (EU) N°748/2012 Structure

ARTICLE	ARTICLE TITLE	SUMMARY OF CONTENT
Article 1	Scope and definitions	This Regulation specifies the different certificates. Some definitions are provided.
Article 2	Products, parts and appliances certification	Products, parts and appliances shall be issued certificates.
Article 3	Continued validity of type-certificates and related certificates of airworthiness	The products shall have a type-certificate issued in accordance with this Regulation. The design of an individual aircraft and its basic type design shall be part of a type-certificate. All changes to this basic type design shall be approved. A certificate of airworthiness issued with a type-certificate shall comply with this Regulation.
Article 4	Continued validity of supplemental type-certificate	Supplemental type-certificates or changes to products shall be issued under this Regulation.
Article 5	Continued operation of certain aircraft registered by Member States	Article deleted by Regulation 69/2014.
Article 6	Continued validity of parts and appliances certificates	Approvals of parts and appliances issued by a Member State and valid on 28September 2003 shall have been issued in accordance with this Regulation.
Article 7	Permit to fly	Aircraft which did not hold a certificate of airworthiness or restricted certificate of airworthiness issued under this Regulation, are deemed to have a Permit to Fly at least.
Article 8	Design organisations	An organisation responsible for the design of products, parts and appliances or for changes or repairs thereto shall demonstrate its capability in accordance with Annex I (Part 21).
Article 9	Production organisations	An organisation responsible for the manufacture of products, parts and appliances shall demonstrate its capability in accordance with the provisions of Annex I (Part 21)
Article 10	Agency measures	The Agency shall develop acceptable means of compliance (hereinafter called "AMC") that competent authorities, organisations and personnel may use to demonstrate compliance with the provisions of the Annex I(Part 21) to this Regulation.
Article 11	Repeal	Regulation (EC) No 1702/2003is repealed.
Article 12	Entry into force	This Regulation shall be applicable in all Member States from 20/08/2012

Table 2 - 2 The Part 21 Structure (14 Sub-Parts for A and B)

SUB-PART	TITLE	APPROVAL/CERTIFICATE?
A	General Provisions	
B	Type Certificates and Restricted Type Certificates	X
D	Changes to Type Certificates and Restricted Type Certificates	X
E	Supplemental Type Certificates	X
F	Production without Production Organisation Approval	
G	Production Organisation Approval for Products, Parts and Appliances	X
H	Certificates of Airworthiness and Restricted Certificates of Airworthiness	X
I	Noise Certificates	X
J	Design Organisation Approval	X
K	Parts and Appliances	X
M	Repairs	X
O	European Technical Standard Order Authorisations	X
P	Permit to fly	X
Q	Identification of Products, Parts and Appliances	

In accordance with ICAO regulation and (EU) No. 2018/1139 [16], an important concept of Part 21 is that it addresses three kinds of elements that can be certified through approvals:

- **Products**, which may be the aircraft or the engines;
- **Appliances**; and
- **Parts**.

Figure 2-2 shows (in SysML notation[23]) the implicit interactions between these three kinds of elements considered in Part 21. Any Product may be composed of Parts and Appliances or even other products. It is the case of the Aircraft. If a Product is composed of only parts and appliances it is necessary an engine or a propulsion system. Any appliance may be composed of several parts as it is the smallest elements managed by Part 21. The top level system under consideration is the aircraft, called Product. It is composed of Parts, Appliances and Products (Engines and propulsion systems are actually the only components considered as Products). Aggregation links are used in Figure 2-2. Composition links could have been used as well but it would be a stronger relation.

[23] http://www.omgsysml.org/

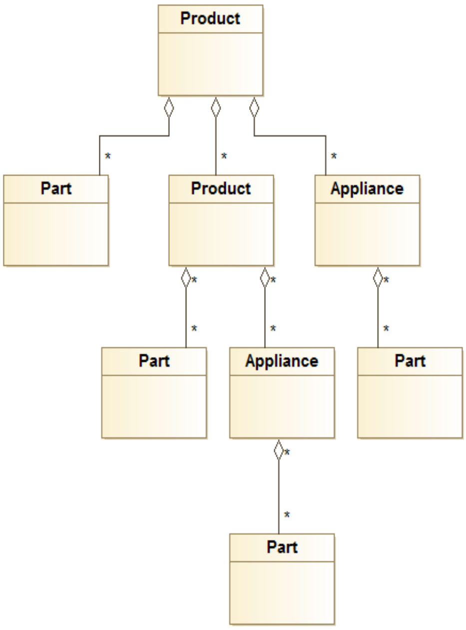

Figure 2 - 2 Product hierarchy of an aircraft system as suggested by the Part 21 (in SysML notation)

As a basic principle, any product, any part, and any appliance may be certified according to Part 21. But there in practice some limitations. Figure 2-3 shows the scope and the limits of the certification. Three kinds of elements are actually excluded from the EASA certification and are not considered for approvals according Part 21 rules, even they are included in the applicable design data and process:

- Standard parts,
- Raw materials and
- Consumable materials.

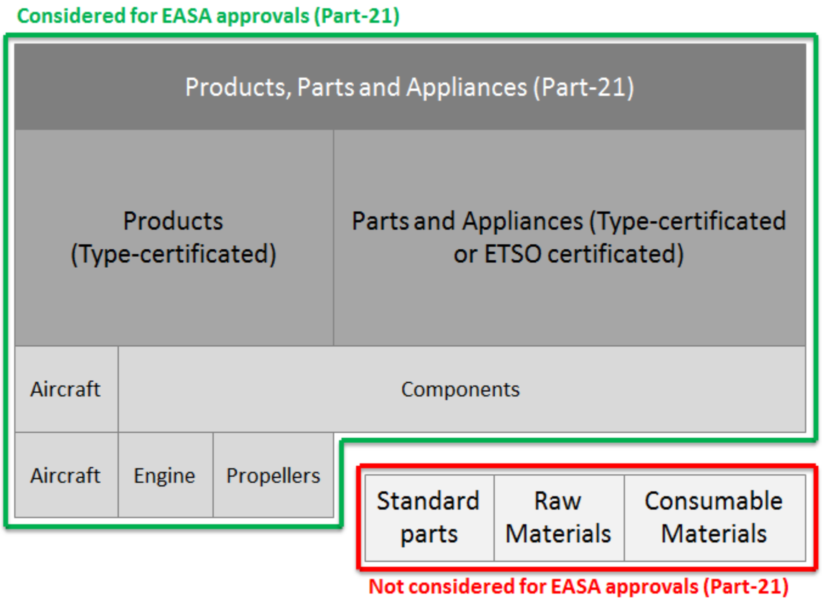

Figure 2 - 3 Scope and limits of the Part 21

Another major concept of the Part 21 is that inherent requirements may concern different kinds of enterprises with different objectives: an OEM, aiming to produce a new aircraft, a manufacturer of a propeller, engine system or a supplier designing and/or manufacturing a part or an appliance. Different contexts co-exist in Part 21. Depending on the situation, the organisation will need to address different kinds of subsets of requirements of Part 21. A particular organisation is most of the time not concerned by the full requirements.

As an example for an “aircraft”, a manufacturer has to go through a certification process sequenced by four main kinds of applications:

- a Design Certificate, taking into account a proposed design, a formal “type design”, and the followed process. It is usually the Design Organisation Approval (DOA, Supart J), but it may also be the Alternatives Procedures to DOA (APDOA) too (included in SubPart J),
- a Production Certificate, taking into account the production facility based on the DOA scope. It is usually the Production Organisation Approval (POA, Subpart G), but it may be the Production without POA too (Subpart F),
- a Type Certificate (TC, Subpart B), considering the approved “type design”, and under condition of issuing a Design Certificate and a Production Certificate first,
- a Certificate of Airworthiness (CoA, Subpart H), ensuring that the assembly of the aircraft is conformed to the original approved “type design” with respect to the expected operational conditions.

A Type Certificate (TC) attests that the generic product, defined by a Type Design (TD), complies with the relevant technical airworthiness requirements. The certificate is issued by EASA, and once issued the design cannot be changed, unless a new TC is applied for. The certificate reflects that the aircraft is manufactured according to an approved design, and that the design ensures compliance with airworthiness requirements. The regulating body compares design documents and processes to determine if the design meets requirements established for the type of equipment. The Design Approval (DOA) is then an important first approval before applying for the TC.

These four applications are mandatory for each “type design” of aircraft that any OEM wants to market. “Type design” comprises all of the drawings and the specifications that define the original aircraft to certify, enabling to build the certification basis of the first produced aircraft and to show compliance of all subsequent airplanes in accordance with the initial approved “type design”.

As Table 2-1 shows, there exist other approvals/certificates in Part 21. The manufacturers of parts/appliances may request an ETSO (European Technical Standard Orders) if they want to keep the responsibility of the design, in the place of the OEM. As shown in Figure 2-3, the engine and propulsion systems are considered as specific parts and the motorists shall be entitled to have a TC instead of an ETSO. Usually, the OEMs also have to apply to Noise Certificate, Permit to Fly and Flight Conditions approvals. They may apply as well to some ETSOs for strategic reasons. Depending on the company strategy, the certification requirements might change. Depending on the operational conditions of the system, the certification requirements may change too from full certificates to restricted ones. Restricted certificates are delivered particularly when the use of the aircraft is limited by certain conditions of operations.

Part 21 is dealing with Initial Airworthiness, but in reality Initial and Continuing Airworthiness cannot be completely separated. Initial Airworthiness has to be implemented thinking in advance about Continuing Airworthiness facilitating the general methods and procedures ensuring the continuity of airworthy conditions of any part, and the full aircraft [6].

2.2.3. Typical Aircraft Certification Process

This section will detail the typical aircraft certification process divided in four major inter-dependent phases:

- Design Organisation Approval (DOA);
- Production organisation Approval (POA);
- Type Certificate (TC);
- Certificate of Airworthiness (CoA).

To obtain a CoA, an aircraft manufacturer needs a TC, which, in turn, requires a DOA and a POA. Unlike an engine manufacturer, usually concerned by the three approvals TC-DOA-POA, part manufacturers may only be concerned by the POA.

A. Certificate of Airworthiness (CoA) and Type Certificate (TC)

The Certificate of Airworthiness (CoA), the last step of the aircraft initial airworthiness certification process, can only be issued if Type Certificate has already been issued in accordance with Part 21. In contrast, Restricted Certificate of Airworthiness will be issued to aircraft conformed to a Restricted Type Certificate only.

A Certificate of Airworthiness is issued under the compliance with the subpart H. A Type Certificate is issued under the compliance with the subpart B. The competent authority responsible to issue a CoA is usually the NAA whereas EASA usually manages the issuance of the TC. The main challenges are on the TC activities and issuance of the CoA is mainly the result of the good execution of the TC issuance process.

The TC procedure is divided in four phases and can start once an application for a TC has been accepted and an initial certification team established:

- **Phase I** – Technical familiarisation and establishment of the Type Certification Basis.
  The objective of this phase is to provide all technical information about the project to the EASA designated team of experts, so to enable definition and agreement on the initial EASA Type Certification Basis.
- **Phase II** – Agreement of the Certification Program
  The objective of this phase is the definition and the agreement on the proposed means of compliance with each paragraph of the Certification Basis and the identification of the Team involvement.

- **Phase III** – Compliance determination
  The objective of this phase is the demonstration of compliance with the Certification Basis and the acceptance of the compliance demonstration.
- **Phase IV-** Final Report and issue of a Type Certificate
  The objective of this phase is the establishment of a final report recording details of the type investigation and, based on approval of the final report by the responsible Certification Manager, the issue of the EASA Type Certificate.

According to the phases listed above, the phases on the applicant side are detailed in Figure 2-4 with eight sequential steps in the type certification process. The following main certification activities have to be implemented by the applicant, using the adequate forms provided by the EASA[24].

1. Application for TC
2. Eligibility checks
3. Preparation of project technical familiarization
4. Proposal of certification basis
5. Proposal of certification program
6. Compliance Demonstration
7. TC Issuance
8. Certification of Airworthiness issuance

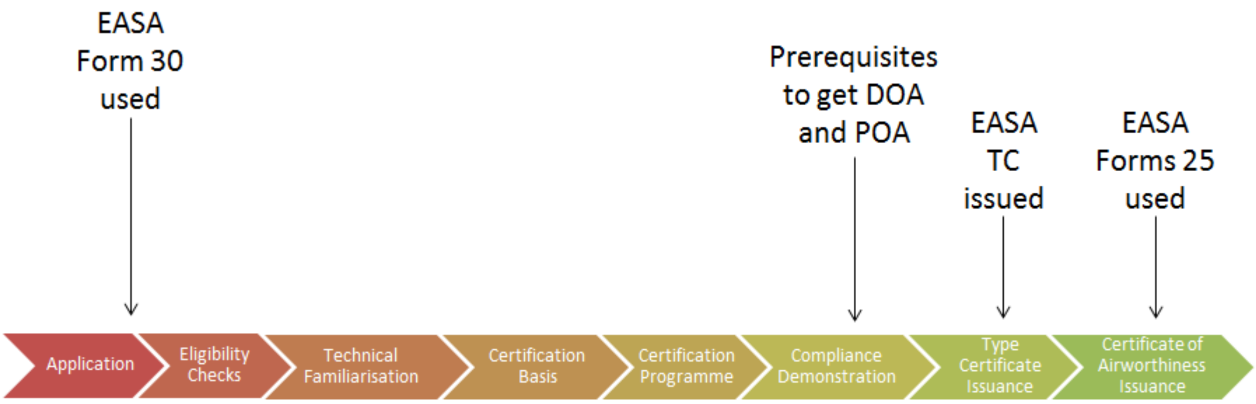

Figure 2 - 4 Type-certification and Certificate of Airworthiness sequence

The duration of each of these phases has to be negotiated with EASA and mostly depends on the product complexity and on the experience and expertise of the aircraft manufacturer.

This procedure is generally timed (EASA decision) between 18 months and 5 years. The maximum timing for a Type Certification procedure is 5 years because of the resource allocation and the regulation evolutions. If a certification program needs more than five years to comply with standards, the authority considers that the applicant is not ready to be certified and the certification program must be restarted (new application), and based on the latest

[24] https://www.easa.europa.eu/sites/default/files/dfu/PR.TC.00001-002%20Type%20certification.pdf

released regulation. For complex aircraft, this risk has to be mitigated in order to comply with the five-year timeframe. The longer the certification procedure is, the higher the certification program cost will be.

In parallel to the application to the Type Certificate for a product, the manufacturer must apply for different agreements in order to comply with quality standards so to demonstrate to the authority that the manufacturer has structured, organized its company to ensure an acceptable level of quality and expertise. Those agreements are:

- Design Organization Approval (DOA)
- Product Organization Approval (POA)

Those agreements are prerequisites to the Type Certificate validation. The DOA is issued by EASA whereas the POA is generally issued by the NAA on behalf of EASA. In order to comply with those agreements, specific procedure must be followed and two manuals, a Design Organization Handbook (DOH) and a Product Organization Exposition (POE), must be provided to authorities. Those manuals describe the general organization of the company on design and/or product activities, detailing staff sizing, allocation, formation and general management process in order to comply with aeronautic quality standards.

B. Design Organisation Approval (DOA)

All companies involved in designing aeronautical products, parts, appliances, designing changes, designing repairs must demonstrate their capabilities. This demonstration is usually done through Design Organisation Approval (DOA). The DOA is issued when compliance with subpart J to Part 21 has been demonstrated to EASA.

The application to a DOA is related to a product type certification. Organizations involved in design of aeronautical products are mandated to demonstrate they have put in place a real Design Assurance System (DAS) which implies a detailed monitoring and control of their developments. The purpose of such request is to guarantee that the design manufacturers have qualified staff, quality control and organization structure that allow them to design and demonstrate to the authorities, compliance of their products with the applicable certification specification.

Although DOA approval under subpart J is the standard way to demonstrate design capability, the regulation allows alternative ways to demonstrate the organization design capability. The Alternative Procedures to DOA (called APDOA) enable to lighten the constraints and the certification requirements. In general such alternatives are linked with more simple designs or temporary procedures before being in capacity to answer to the complete DOA requirements.

Usually, a Design Organization Approval application is timed to 18 months, but EASA may accept a timing between 6 months and 18 months, depending on the complexity of the project and the aeronautical experience of the applicant.

Figure 2-5 details the DOA process and illustrates 5 necessary phases:

1. Application for DOA
2. Eligibility checks
3. Investigation phase
4. Closure of Findings
5. DOA Issuance

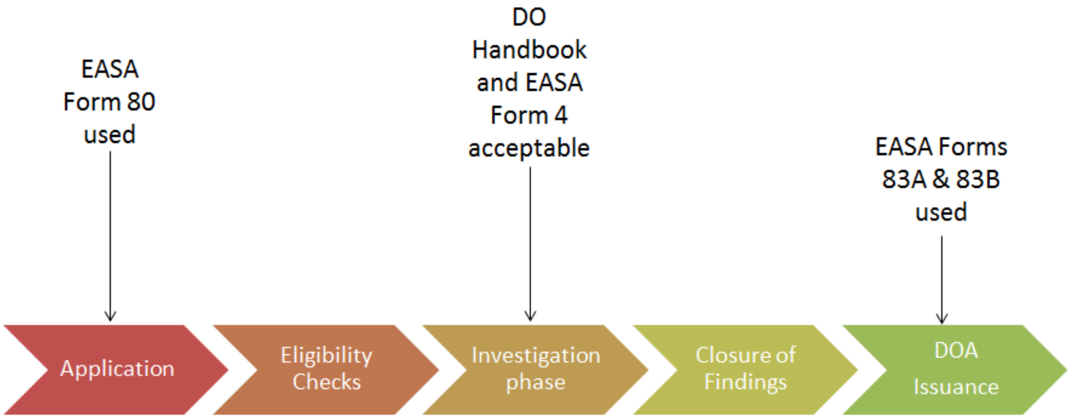

Figure 2 - 5 EASA DOA process

C. Production Organisation Approval (POA)

All companies involved in manufacturing aeronautical products, parts, appliances, designing changes, designing repairs must demonstrate their capabilities, and one of proposed ways to do that is by holding a Production Organisation Approval (POA). The POA is issued when compliance with subpart G to Part 21 has been demonstrated to EASA.

As for the design approval, organizations involved in aeronautical products production must demonstrate to the authorities that they have qualified staff, quality control and organization structure to manufacture products, parts and appliances in conformity with an approved design data.

The standard way to demonstrate production organization capability, is by complying with Part 21 subpart G, but as an alternative way, in case of infrequent or low volume of production, simple technology or very small organization, an approval according under the subpart F may be proposed.

The normal time frame to process a Part 21 subpart G approval is about 18 months from the allocation date; however the amount of time taken is largely dependent on the ability of the applicant to produce the documentation required and to rectify any non-conformity that may be identified during the certification process.

EASA and DGAC confirm a process timing of 6 months in minimum and 18 months in maximum, depending on the complexity of the project and the aeronautical experience of the project leader.

Figure 2-6 details the POA process and illustrates 6 necessary phases:

1. Application for POA
2. Eligibility checks
3. Investigation phase
4. Closure of Findings
5. Identification of gaps
6. POA Issuance

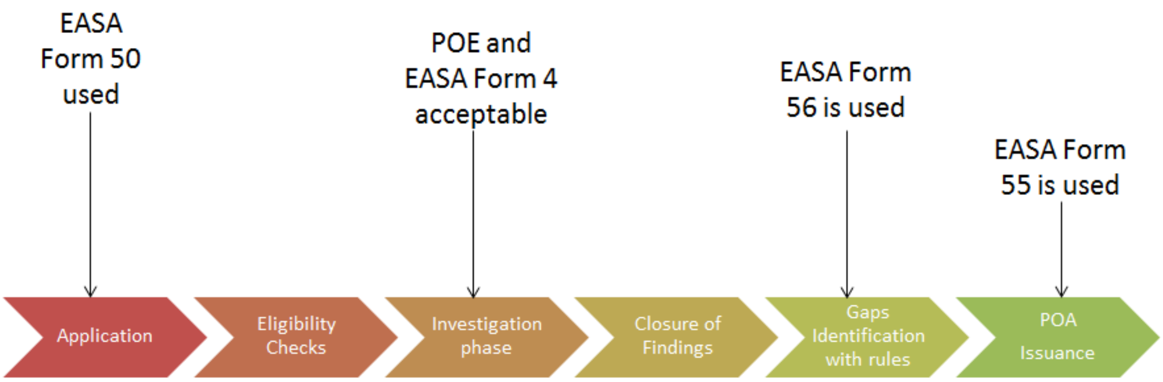

Figure 2 - 6 EASA POA process

D. Enterprise organisation

The European regulation imposes that some functions have to be properly assigned to persons in the organisation. The following roles are defined in the Part 21:

(a) The Chief Executive
(b) An Office of Airworthiness with
- *the Chief of the Office*

(c) A Design Organisation with
- *the Head of the Design Organisation*
- *a Chief of the independent monitoring function of the Design Assurance System (DAS),*
- *a staff dedicated of Certification Verification Engineers (CVEs) responsible for checking compliance with applicable requirements*

(d) a Quality Manager
(e) an Accountable Manager

These roles are detailed in Part 21 with assigned functions, as summarized in Table 2-3. Additionally, Part 21 describes the Office of Airworthiness objectives with 23 different tasks (See Appendix C to get the detailed list of objectives).

The organisation is significantly constrained by the regulation, Part 21 provides some alternatives for organisational structures. Six possibilities have been extracted from initial airworthiness and associated guide materials:

- The functions of Chief Executive and Head of the design organisation may be performed by the same person (see GM No1 to 21.A.239(a) Design assurance system).
- Accountable Manager function may be carried out by the Chief Executive or by another person in the organisation, nominated by him or her to fulfil the function provided his or her position and authority in the organisation permits to discharge the attached responsibilities (see GM 21.A.145(c)(1) Approval requirements – Accountable manager)
- Accountable Manager function may be carried out by the Chief Operating Officer
- Quality Manager and Head of Independent Monitoring may be performed by the same person.
- There are situations where a Quality System, including independent monitoring and continuous internal evaluation functions, is not justified and /or feasible. Subpart F may apply in case of very small organisation, implying individual inspection by the Authority.
- For an SME, the Quality Manager may also perform "airworthiness control" tasks in addition to those of quality assurance. The actual division of duties will vary with the particular organisation.

Table 2 - 3 Generic Functions and Roles according EASA regulation [12]

Function	**Role**
Chief Executive	a. provide the necessary resources for the proper functioning of the design organisation. b. sign the handbook.
Chief of the Office of Airworthiness	a. act as the focal point for co-ordinating airworthiness and environmental protection matters. b. reports directly to the Head of the design organisation or is integrated into an independent quality assurance organisation reporting to the Head of the design organisation.
Chief of the independent monitoring function of the DAS	a. Continuing evaluate (system monitoring) the design assurance system in order to ensure that it remains effective. Ensure that all responsibilities of the DAS are properly discharged, proposing corrective and preventive measures for continuous effectiveness. b. The system monitoring may be undertaken by the existing quality assurance organisation when the design organisation is part of a larger organisation. c. always reports to the head of Design Organization.
Head of the Design Organisation	a. sign the handbook. b. responsible for the design of the product, for design of minor changes to type design, minor repairs to products and for compliance of the organisation with Part 21Subpart J. c. sign a declaration of compliance with the applicable CS and environmental protection requirements after verification of satisfactory completion of the Type Investigation.
Quality Manager	a. responsible for ensuring that the quality system is implemented and maintained. b. responsible for monitoring the organisation's compliance with Part 21 Section A Subpart G and requesting remedial action as necessary by the other managers or the accountable manager as appropriate. c. report to the accountable manager. d. responsible for the monitoring and amendment of the Exposition, including associated procedures manuals, and the submission of proposed amendments. e. responsible for establishing an independent quality system to monitor compliance with EASA requirements. f. responsible for implementing a quality audit programme in which compliance with all maintenance procedures is reviewed at regular intervals, in relation to each type of aircraft (or component) maintained, and any observed non-compliances or poor standards are brought to the attention of the person concerned via his/her manager. g. assess sub-contractors for extension of the quality system, and maintaining the expertise necessary to be able to do so, to the satisfaction of EASA/NAA. h. assess suppliers of new and used components, and materials, for satisfactory product quality in relation to the needs of the organisation. i. preparing standard practices and procedures for use within the organisation, derived from approved sources, and keeping them up to date. j. analyse defects in respect of aircraft undergoing maintenance so that any adverse trends are identified and responded to promptly.
Accountable Manager	a. responsible for ensuring that all production work is carried out to the required standard. b. responsible for ensuring compliance with the requirements for initial grant and subsequent maintenance of the production organisation approval. c. responsible for ensuring that all necessary resources are available and properly used in order to produce under the production approval in accordance with Part 21 Section A Subpart G. d. demonstrate that he or she is fully aware of and supports the quality policy and maintains adequate links with the quality manager.
Certification Verification Engineers (CVE)	a. responsible for checking and signing all the documents of compliance with the applicable requirements. b. may work in conjunction with the individuals who prepare compliance documents, but may not be directly involved in their creation (this is to ensure independent checking).

2.2.4. Three important additional concepts

In addition, three concepts applied that strongly impact the certification process are presented in this section: Privileges, Proportionality and Level of Involvement.

Privileges – At the start of the DOA and POA process, specific privileges may be granted to the concerned organizations, based on their specific experience and expertise. Such privileges can be granted by EASA only, and allow for some approvals or document issuance by the organisations, without any further verification by EASA. The privileges granted to the approved organisation and the scope of the approvals is specified in the terms of approval documents.

Proportionality - In the beginning of February 2019, EASA introduced new Acceptable Means of Compliance (AMCs) for Part 21, which complement the existing AMCs. The objective is to provide a more proportionate approach for small, non-complex organisations that produce lower-risk products and the parts installed on these products. The new AMCs shift the focus on the output of the process, instead of the detailed step-by-step documentation of the process; a more product-oriented approach, releasing the administrative application of regulations for SMEs. The AMC can be used by small companies that design and produce low-risk general aviation (GA) aircraft within the current Part 21. The AMCs also allow experience to be gained for a possible future combined (design and production) company approval.

Level Of Involvement - In June 2019, the European Commission has published a new text amending Regulation (EU) No 748/2012 with a new risk-based compliance verification approach in the certification process referred to as “Level of Involvement (LOI)”. The LOI corresponds to a new process which enables EASA to select in a more deterministic manner than before the compliance demonstration activities and data that the Agency will investigate. The process enables also to determine the depth of the investigation during the certification process per each Compliance Demonstration Item (CDI), integral part of the compliance demonstration dossier. This concept of LOI introduced 4 criteria for the purpose of risk class determination:

- For each CDI, the level of novelty: novel or not novel
- For each CDI, the level of complexity: complex or not complex
- At organisation level, the DOA holder performance: low, medium, high
- Criticality: critical or non-critical

These 4 criteria are used for the determination of EASA LOI, in the following risk assessment. Composed of two steps as illustrated by Tables 2-4 and 2-5, this approach enables to EASA to identify the level of risks of the projects and to adapt its support and engagement.

- Step 1 enables to identify the likelihood of an unidentified non-compliance;
- Step 2 determines the class of risk.

The approach is done at CDI level and enables to refine the awareness of the projects. The two steps will be detailed below.

Step 1: likelihood of an unidentified non-compliance identification

The likelihood of an unidentified non-compliance should not be confused with the likelihood of occurrence of an unsafe condition as per AMC 21A.3B(b). The likelihood of an unidentified non-compliance expresses the confidence level that the applicant addresses all the details of the certification basis for the CDI concerned, and that a non-compliance will not occur.

The likelihood of an unidentified non-compliance is established in four categories (very low, low, medium, high) depending on the applicant's relevant performance level for the CDI as assessed by EASA, and on whether the CDI is novel or complex (see Table 2-4).

Table 2 - 4 Step 1 of EASA LOI Determination

Step 1 Likelihood of an unidentified non-compliance			
CDI / Performance level of the organisation	No novel aspects and No complex aspects	No novel aspects but complex ones; Or Novel aspects but no complex ones;	Novel aspects and Complex aspects
High	Very low	Low	Medium
Medium	Low	Medium	High
Low or unknown	Medium	High	High

Step 2: class of risk identification

The second step enables to determine the risk class of a CDI (See Table 2-5). The risk class is the result of a combination between the level of the potential impact of an unidentified non-compliance (vertical axis of Table 2-5) and the likelihood of the unidentified non-compliance (horizontal axis of Table 2-5 and main result from step 1).

The potential impact of a non-compliance with part of the certification basis is considered either critical or non-critical on product safety or in the environment.

Table 2 - 5 Step2 of EASA LOI Determination

Step 2 Risk classes determination				
Likelihood / Criticality of an unidentified non-compliance	Very low	Low	Medium	High
Non-critical	Class 1	Class 1	Class 2	Class 3
Critical	Class 1	Class 2	Class 3	Class 4

EASA’s compliance verification activities are directly linked to the class determination. The involvement of EASA will follow the following rules:

- Risk Class 1: No EASA involvement in verifying compliance data and activities performed by the applicant to demonstrate compliance at the CDI level;
- Risk Class 2: EASA’s LOI is typically limited to the review of a small portion of the compliance data; there is either no participation in the compliance activities or participation in a small number of compliance activities (witnessing of tests, audit, etc.);
- Risk Class 3: In addition to the LOI defined for Risk Class 2, EASA’s LOI typically comprises the review of a larger amount of compliance data, as well as participation in some compliance activities (witnessing of tests, audit, etc.); and
- Risk Class 4: In addition to the LOI defined for Risk Class 3, EASA’s LOI typically comprises the review of a large amount of compliance data, the detailed interpretation of test results, and the participation in a large number of compliance activities (witnessing of tests, audit, etc.).

Privileges and LOI are two interdependent concepts. As much the organisation will have privileges, the EASA LOI will be lower than for an organisation without privileges.

2.3. SAFETY AND AERONAUTICS STANDARDS

To help enterprises in their development to be compliant with regulation, numerous guidelines exist and have to be considered. These guidelines are not mandatory to follow. However as the main regulatory bodies (ICAO, EASA and FAA) acknowledge their compliance to the regulation, they became the main references and are now de-facto standards. Reducing noticeably the quantity of knowledge to understand the certification process, their dissemination has spread over the community in aeronautics.

In this section, first the main institutions responsible of the guidelines authoring are presented, followed by an overview of the standards.

2.3.1. The aeronautic Institutions

The **Radio Technical Commission for Aeronautics (RTCA)** is an American non-profit organization that develops technical advice and consensus-based recommendations for the use of regulatory authorities and aeronautics industry regarding communications, navigation, surveillance, and air traffic management system issues. RTCA functions as an advisory committee for FAA policy, program, and regulatory decisions. RTCA is recognized and utilized worldwide as well.

The **Society of Automotive Engineers (SAE International)** is an American non-profit organization originally active in automotive industry only, but gradually covering broader industries such as aerospace. SAE International coordinates the development of technical standards based on best practices identified and described by SAE committees and experts.

European Organisation for Civil Aviation Equipment (EUROCAE) is a European non-profit organisation developing performance specification and guidance documents for the aviation community. EUROCAE has published many ED (EUROCAE Documents) in parallel and in collaboration with SAE and RTCA.

EUROCAE, RTCA, SAE International are not regulatory bodies. Still they are playing a substantial role in the international regulation as they publish acknowledged standards in the aviation industry. They are supporting the main regulatory bodies (ICAO, EASA and FAA) in their missions and activities. They are working jointly to issue standards which are worldwide recognized. In Aeronautics, the main standards are issued by these three organisations.

2.3.2. The Aeronautical standards for the certification

In the Aeronautics sector, a certification target is achieved by being compliant with a list of well-known guides which the five most important are:

- **ARP4754A / ED-79A** [17]: Certification Considerations for Highly-Integrated or Complex Aircraft Systems
- **SAE AIR6110** [18]: Contiguous Aircraft/System Development Process Example
- **SAE ARP4761** [19]: Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment
- **RTCA DO-178C / ED-12C** [20]: Design Assurance Guidance for Airborne Software
- **RTCA DO-254 / ED-80** [21]: Design Assurance Guidance for Airborne Electronic Hardware

These guides all represent a consensus for the aviation community and can be considered as best practices in this industry. Moreover, they are recognized by both EASA and FAA. They are applicable at different levels of the aircraft development, and thus they are highly interdependent. The guidelines and methods provided in the 4 documents are intended to be used in conjunction with the material provided by the certification administrator (EASA, etc…). These four documents, other guidelines and their relationships will be detailed below.

A. ARP4754A / ED-79A

ARP4754A / ED-79A [17] “Certification Considerations for Highly-Integrated or Complex Aircraft Systems” was published in 1995 by SAE and EUROCAE and addresses the total life cycle of systems that implement aircraft level functions. ARP4754A / ED-79A [17] “discusses the certification aspects of highly-integrated or complex systems installed on aircraft, taking into account the overall aircraft operating environment and functions”. It is the reference for an aircraft development, addressing the total life cycle for systems that implement aircraft-level functions but excluding detailed design processes regarding systems, software and hardware.

No specific guidance regarding the substantiation work, regarding the structure of the applicant’s organisation and the distribution of the certification’s activities are provided in these documents. However, ARP4754A / ED-79A [17] provides a generic development roadmap and the list of the expected activities and tasks per development phase. It provides the following definitions:

- ‘Airworthiness’ - “the condition of an aircraft, aircraft system, or component in which it operates in a safe manner to accomplish its intended function.”
- ‘Certification’ - “the legal recognition that a product, service, organization or person complies with the applicable requirements. Such certification comprises the activity of technically checking the product, service, organization or person, and the formal recognition of compliance with the applicable requirements by issue of a certificate, license, approval or other document as required by national laws and procedures.”

The current version of ARP4754A / ED-79A [17] is a second version of ARP4754. Historically ARP4754 / ED-79:1996 [22]'s objective was to centralise in one unique document the generic, high level aspects of certification, providing more comprehensive understanding of the airworthiness requirements. In addition to the first version, ARP4754A / ED-79A [17] includes the list of documentation and data that an organization has to provide for certification purposes. It furnishes a list of processes as (See Figure 2-7).

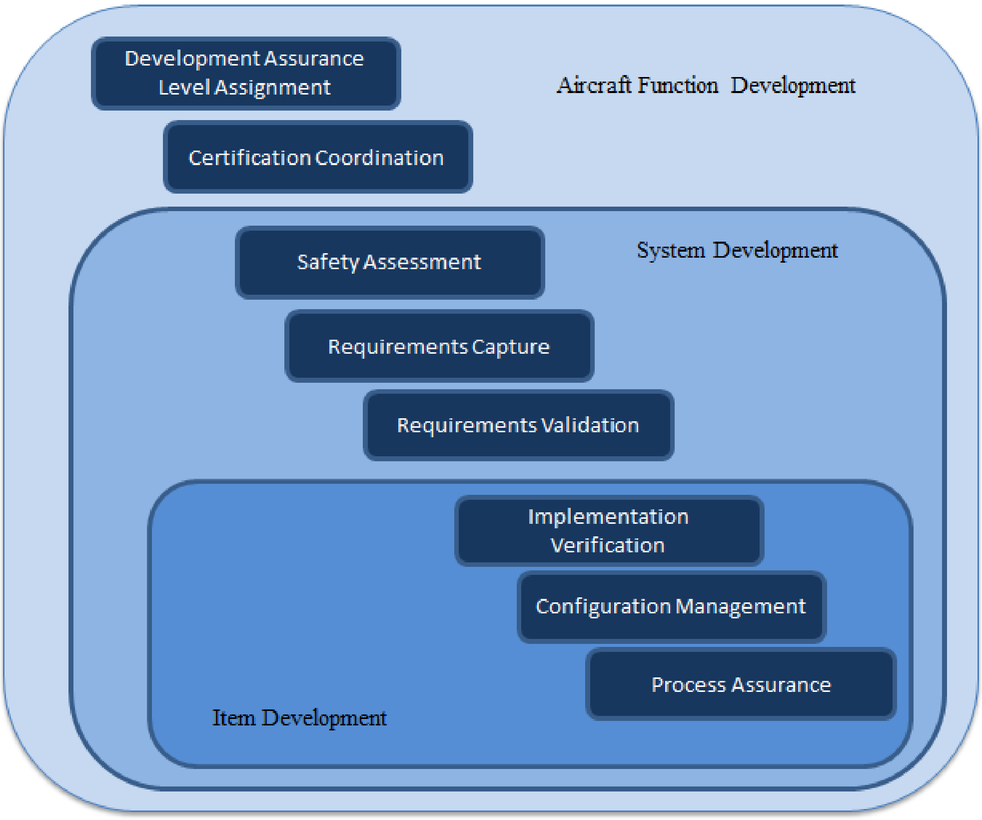

Figure 2 - 7 ARP4754A Processes (based on [16])

ARP4754A / ED-79A defines guidelines for development of civil aircraft and systems with an emphasis on safety aspects which are developed in detail in the SAE ARP4761 [19]. A summary of the recommended practice defined through the two standards are illustrated in the Figure 2-8.

B. SAE ARP4761

The Safety Assessment Process, the core process implied in the systems developments, is described in the SAE ARP4761 [19].

It is shown in Figure 2-8 how the Safety Assessment activities are interacting with the System Development Process. ARP4754A / ED-79A is to be applied in conjunction with SAE ARP4761 [18] which detail the Safety Assessment Process.

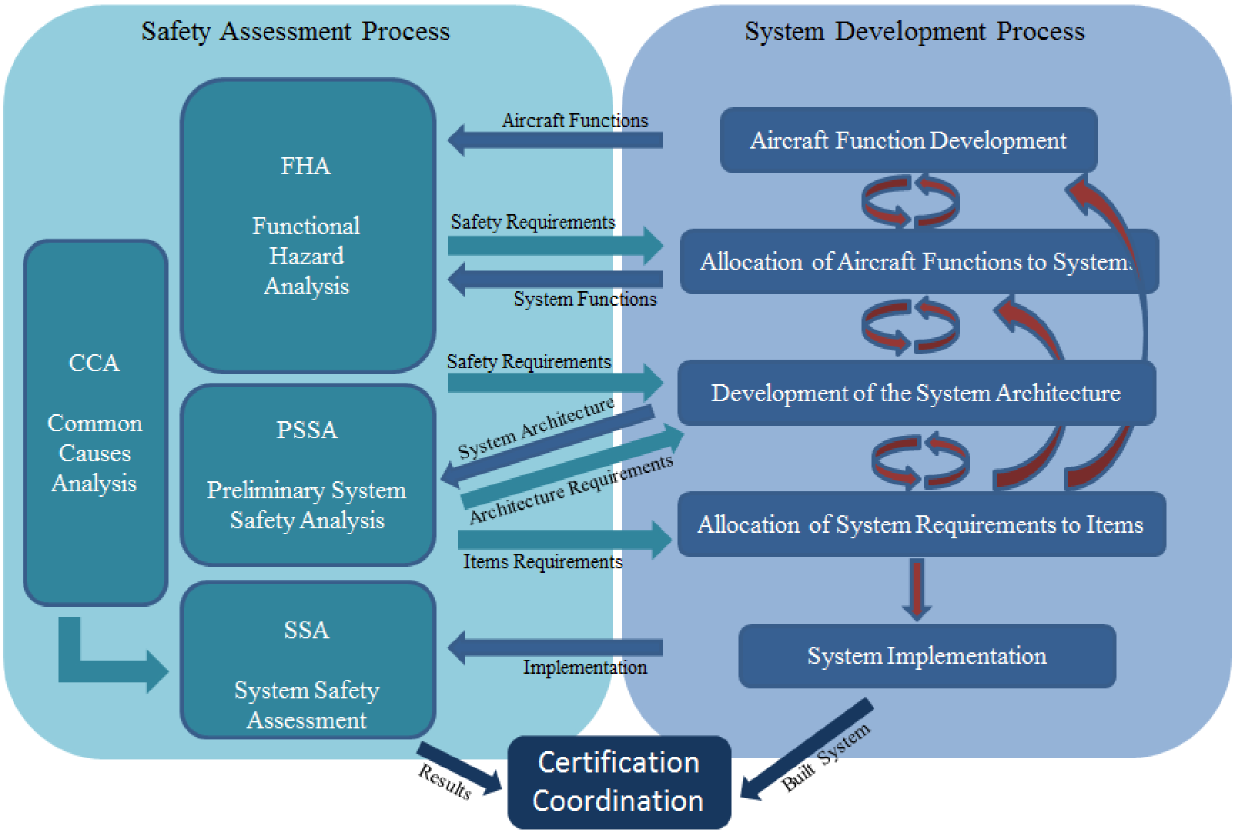

Figure 2 - 8 System Development Process according ARP4754A (based on [16] and [19])

C. SAE AIR6110

Additionally, SAE AIR6110 [18] provides a detailed example of the aircraft and systems development of a hypothetical S18 aircraft, reducing the exercise to only one system, the braking system, and only one function, Decelerate Aircraft on Ground.

D. RTCA DO-178C / ED-12C

The RTCA DO-178C / ED-12C [20] is the detailed reference for Software design processes and is widely recognized as an objectives-prescriptive standard. It provides recommendations for design assurance of embedded software. Clarification and guidance material of DO-178C are provided through RTCA DO-248C [23]. This one contains frequently asked questions (FAQs), discussion papers (DPs) and rationale.

E. RTCA DO-254 / ED-80

The RTCA DO-254 / ED-80 [21] is the detailed reference for Hardware design processes. It provides recommendations for design assurance of electronic equipment onboard, such as they are performing safely with the expected functions in specified environments.

F. Other guidelines

Additional documents have been created by other organisations such as Commercial Aviation Safety Team (CAST) which provides some Position papers (CAST-27 to CAST-33). To clarify ambiguities coming from these documents, FAA and EASA published also their own documents, for example:

- EASA Certification Memorandum - SWCEH – 001
- FAA AC 20-152
- FAA Order 8110.105A

Many other guidelines also exist to clarify some specific approach linked to certification, for example:

- RTCA DO-160G / ED-14G - Environmental Conditions and test Procedures for Airborne Equipment.
- RTCA DO-333 - Formal Methods Supplement to DO-178C and DO-278A
- RTCA DO-278A - Software Integrity Assurance Considerations for Communication, Navigation, Surveillance and Air Traffic Management Systems.

Figure 2-9 illustrates the link and the hierarchy between the guides.

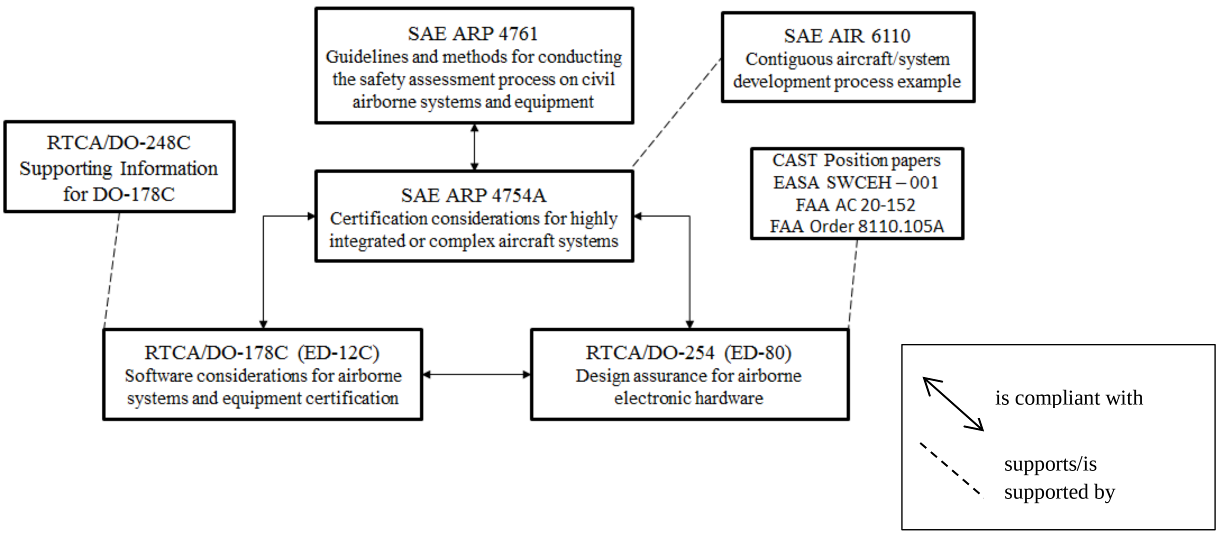

Figure 2 - 9 Safety-related Standards for certifying safety-critical systems

2.4. SYSTEMS ENGINEERING APPROACH

2.4.1. Systems and Systems Engineering

The Systems Engineering (SE) discipline emerged at the middle of the last century to improve the quality of the industrial developments as the systems to develop and produce were becoming more and more complex [24]. The Apollo program in the 1960's is a very interesting example to illustrate the complexity and the challenges faced with new high technology projects in the post-war period. This program had to combine both political, institutional, managerial, societal and technological ambitions [25]. A retrospective analysis from NASA highlights that "one of the fundamental tenets of the program management concept was that three critical factors--cost, schedule, and reliability--were interrelated and had to be managed as a group"[25]. NASA Managers, at this specific period, were coming from Air Force ballistic missile program where Systems Engineering principles had been developed and tested. From the top management, SE knowledge was spread inside the entire Apollo program and it is probably one of the key factors for Apollo's success [26]. It is indeed recognized today that the Apollo program was at the same time a technical, political and societal success, thanks mostly to the management model integrating complex technological and organisational dimensions [27].

From that period, as systems complexity was continuously growing decade after decade, the need to apply good practices increased as well. Today it is well recognized that Systems Engineering practices improve projects results, although it remains still difficult to measure its real efficiency. Honour explores, in [28] and [29], the quantitative relationships between systems engineering and program success. He highlights that there is a positive correlation factor between the level and quality effort to apply systems engineering during a program and the success of the program. He adds also that there is an optimal effort to provide. According to [30], the optimum amount of effort for a program is between 8% and 19% of the total expenditure of the program, depending on the program characteristics. It emphasises that the median value could be at 14.4% of the total expenditure of the program.

Systems theory and systems thinking are at the basis of Systems Engineering. Many propositions exist to define a system. It may be defined as « any process that converts inputs to outputs" [31]. The ANSI/EIA-632:2003 standard [32] proposes a more detailed definition: "a system is one or more end products and sets of related enabling products that allow end products, over their life cycle of use, to meet stakeholder needs and expectations". This standard adds that the engineering of a system combines a set of processes and a multidisciplinary team of people. Then from this standard, four main characteristics can be extracted:

1- A system is a combination of **products**, **processes** and **people**;
2- A system presents a kind of hierarchy between different kinds of products that we can categorize between **end products** and **enabling products**;

[25] https://history.nasa.gov/Apollomon/Apollo.html

3- A system provides intended **functions** answering to **requirements** expressed by identified **stakeholders**;
4- A system has **limited life duration** to be identified, analysed and monitored.

According a consensus among INCOSE fellows, "a system is a construct or collection of different elements that together produce results not obtainable by the elements alone" [26]. It means that a system has two important features:

1- The sum of the interrelated elements which compose the system is not sufficient to describe the system; indeed the addition of each function of each element (or each sub-system) is not sufficient to describe the entire functions of the system; it means that there are necessary **emergent functions** coming from the combination of the sub-systems.
2- The interactions between the components of the systems impose to provide an important effort on the **interfaces analysis, the flows and the dependencies management**.

In ISO 24748-1:2018 - Systems and Software Engineering - Life cycle management (Part 1: Guidelines for life cycle management) [33], the importance to define the boundaries is highlighted. A system may be closed or open depending on the quality of the interactions with the environment. The standard adds that "a system can be viewed as an isolated entity (that is, a product), or as an ordered collection of functions capable of interacting with its surrounding environment, (i.e. a set of services)". The standard mentions also the importance to build a life cycle model, segmented by stages, from its initial conceptualization to its eventual retirement.

In ISO 15288:2015 Systems and Software Engineering - System Life Cycle Processes [34], a system is defined as "a combination of interacting elements organized to achieve one or more stated purposes". The standard completes the definition adding that "a complete system includes all of the associated equipment, facilities, material, computer programs, firmware, technical documentation, services and personnel required for operations and support to the degree necessary for self-sufficient use in its intended environment".

Taking into account the different concepts of the three previous definitions [32]–[34], the following definition to describe a system is retained.

Definition 2. 1 (System)

A system is a combination of sub-systems and more simple elements interacting properly together in an identified environment. The system provides some intended functions over an identified life cycle of use, while simultaneously controlling the emergent functions.

[26] https://www.incose.org/about-systems-engineering

Systems Engineering (SE) is a discipline often associated to complex systems. In most industries, especially in aerospace, it is well recognized that using the principles of SE is appropriate to develop properly a complex system. SE would be an appropriate way to manage complexity [35], [36]. The literature in SE field often associates complex systems theories to System of System (SoS) management [37]. A SoS is composed of several interrelated systems. This facet compels to the necessary analysis of the environment where each system will be integrated and will interact. A SoS will have more concerned stakeholders, more intended functions, more emergent functions and additional performance objective to take into account.

According to [38], a complex System is “a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change”.

In ARP4754A-1996 [22], ‘complex systems’ refer to “systems whose safety cannot be shown solely by test and whose logic is difficult to comprehend without the aid of analytical tools”.

Brazier et al in [39] defined complex systems as “systems that display behaviour that is unexpected, emerging, and/or unpredictable.”. The authors added that characteristics of a complex system typically include:

- “a large scale of applications,
- many parts, and many dependencies between parts and with the environment,
- the involvement of many stakeholders with different, sometimes conflicting, interests and goals, requiring extensive cooperation and coordination throughout the system’s lifecycle,
- decision-making by stakeholders on the basis of uncertain, incomplete, inconsistent, or ambiguous information,
- in case of a networked system: autonomous sub-systems with different norms and values, rules of engagement and agreement, communication architectures, and requirements for trust,
- continuous change that may span many years;
- not one unique objective measure to determine the quality of a design.”

If complex system is one way to describe SE, it is not the only one. Blanchard, in [40], identifies five characteristics of good Systems Engineering:

- A top-down approach, viewing the system as a whole and coupled with a bottom-up approach;
- A life-cycle orientation, addressing all phases;
- An important effort on identification of requirements;
- An interdisciplinary collaborative effort;
- A good interface management, for highlighting problems.

In addition, the INCOSE defines Systems Engineering as an “interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Cost & Schedule, Performance, Training & Support, Test, Manufacturing and Disposal". [24]

ISO/IEC/IEEE 15288:2015 - Systems and Software Engineering – System Life Cycle Processes [34] provides the following definition: it is an "interdisciplinary approach governing the total technical and managerial effort required to transform a set of stakeholder needs, expectations, and constraints into a solution and to support that solution throughout its life".

These two last definitions are quite complete and highlight the major concepts of the discipline. However it does not mention the iterative quality of the activities like Eisner did in [41] and [42]: "Systems Engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near-optimal manner, the full range of requirements for the system."

From all these definitions, the following major concepts are retained: iterative, collaborative, interdisciplinary, life cycle, needs and requirements:

Definition 2. 2 (Systems Engineering).

Systems engineering (SE) is a sociotechnical, interdisciplinary, iterative and collaborative approach aiming to realize successful, reliable and sustainable systems during their entire life cycle. SE is considering both business and technical needs and requirements of all identified stakeholders.

2.4.2. Systems Engineering Standards

Since the beginning, Defence, Space and Aeronautics have been the main contributors to make evolve the Systems Engineering discipline. Each sector has developed its own norms in adequacy with its specificities and now numerous standards exist [43]. Most of them are published by the International Organization for Standardization (ISO), the International Electro-technical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE), the American National Standards Institute (ANSI) and the Electronic Industries Alliance (EIA).

This thesis concentrates on Aeronautics field. In literature three standards are generally studied [43]–[46]:

- ISO/IEC/IEEE 15288:2015 - Systems and Software Engineering – System Life Cycle Processes [34];
- ANSI/EIA 632:1998 - Processes for Engineering a System [32];
- IEEE 1220:2005 Application and Management of the Systems Engineering Process [47].

Standard IEEE 1220 [47] has been superseded in 2005 by ISO/IEC 26702:2007 - Systems engineering - Application and management of the systems engineering process [48], withdrawn in 2016 and replaced by ISO/IEC/IEEE 24748-4:2016 - Systems and Software Engineering – Life Cycle Management (Part 4: Systems Engineering Planning) [49]. This last standard can be used as a guideline to plan SE activities, in conjunction with the standard ISO/IEC/IEEE 15288.

Figure 2-10 synthetizes the relationships between the SE standards, providing an up-to-date landscape. Even if ISO/IEC 12207:2008 - Systems and software engineering - Software life cycle processes [47] is not properly a SE standard, but Software standard, it is cited to highlight its links with the SE standards. Indeed ISO/IEC/IEEE 15288 [34] and ISO/IEC 12207 [47] share both the same alignment process.

ISO/IEC/IEEE 15288 and ANSI/EIA 632 [32] are now considered as the two main SE standards. The main differences between ISO/IEC/IEEE 15288 [34] and ANSI/EIA 632 [32] are the scope and the detail of the activities. These norms may be considered as complementary having each appropriated features, even if ISO/IEC/IEEE 15288 [34] is the most cited in literature.

ISO/IEC/IEEE 15288 and ANSI/EIA 632 and additional references will be detailed below.

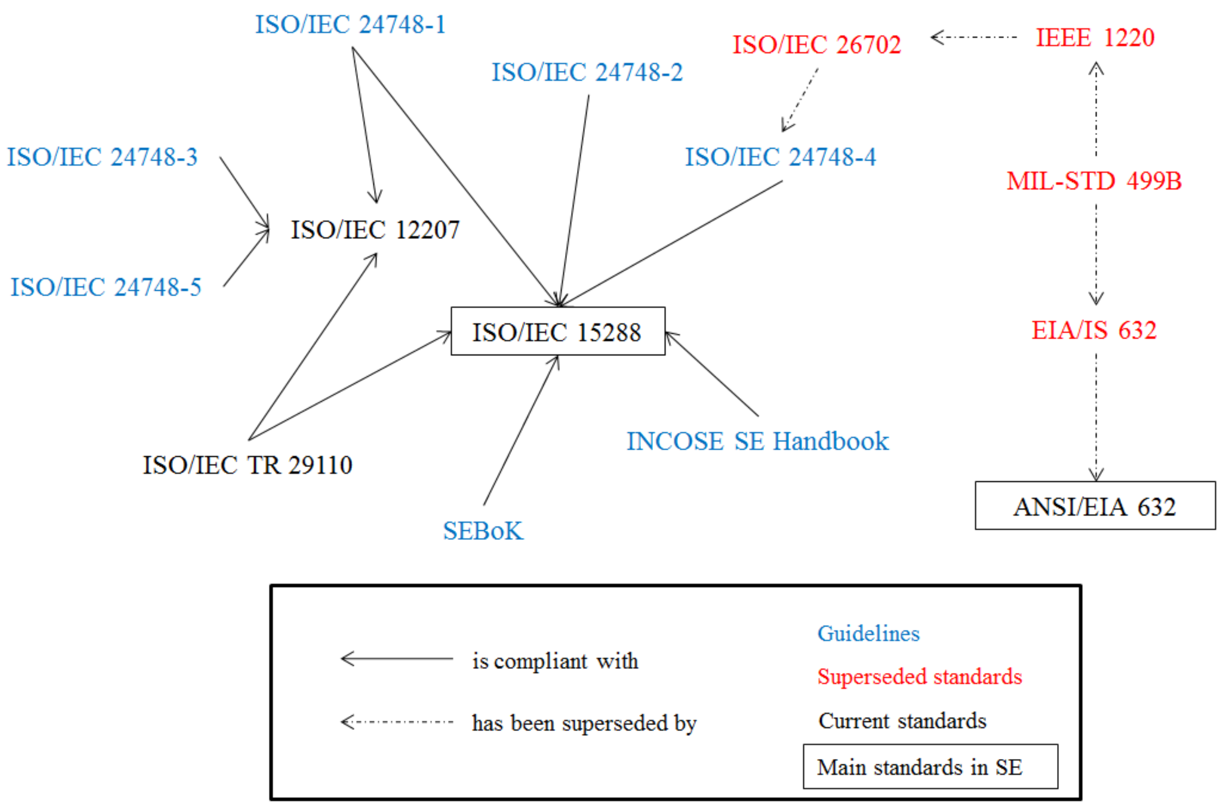

Figure 2 - 10 Overview of the standards and guidelines landscape in the context of SE

A. ISO/IEC/IEEE 15288:2015

ISO/IEC/IEEE 15288:2015 Systems and Software Engineering – System Life Cycle Processes [34] provides generic top-level process descriptions to support SE, describing the full life cycle of the system [50] from the Concept stage to Retirement (See Figure 2-11).

ISO/IEC/IEEE 15288:2015 [34] consists of 30 processes organised in 4 process groups (see Figure 2-12 to identify the main links between the processes):

- Technical processes, those related to the realisation of the project;
- Technical management processes, those related to the project management to conduct the realisation of the product;
- Organizational project-enabling, those related to the general management of the organisation which will conduct the project;
- Agreement processes, those related to the contractual relationship between a customer and a supplier.

In this standard, each process is described with the same outline: purpose presentation, outcome expectations and activities and tasks definition.

ISO/IEC/IEEE 15288:2015 [34] does not prescribe a specific life cycle model, but provides a process for defining, approving, and managing a life cycle model. More information on life cycle concepts can be found in ISO/IEC TR 24748-1:2018 - Systems and Software Engineering - Life cycle management (Part 1: Guidelines for life cycle management) [33] which provides life cycle models that can be used within the frameworks of ISO/IEC/IEEE 15288:2015 [34]. This document also provides guidance for tailoring the life cycle, introducing the concept of stages and the decision points determining that the system is ready to progress through subsequent stages (See Figure 2-11). At each decision gate, different option may happen: continue the current stage, go to a previous stage, go and execute next stage, hold project activities or terminate project.

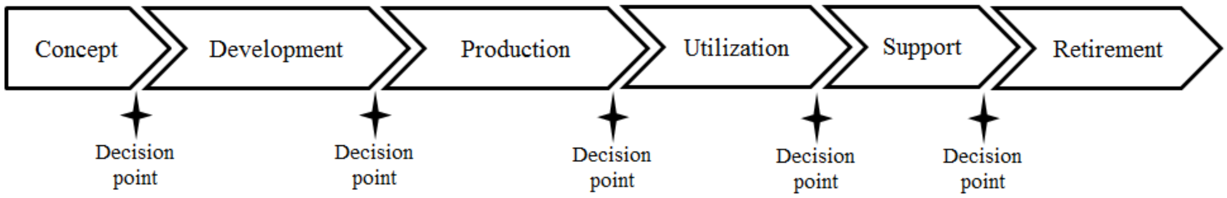

Figure 2 - 11 System Life Cycle model as proposed in ISO/IEC TR 24748-1:2018 [33]

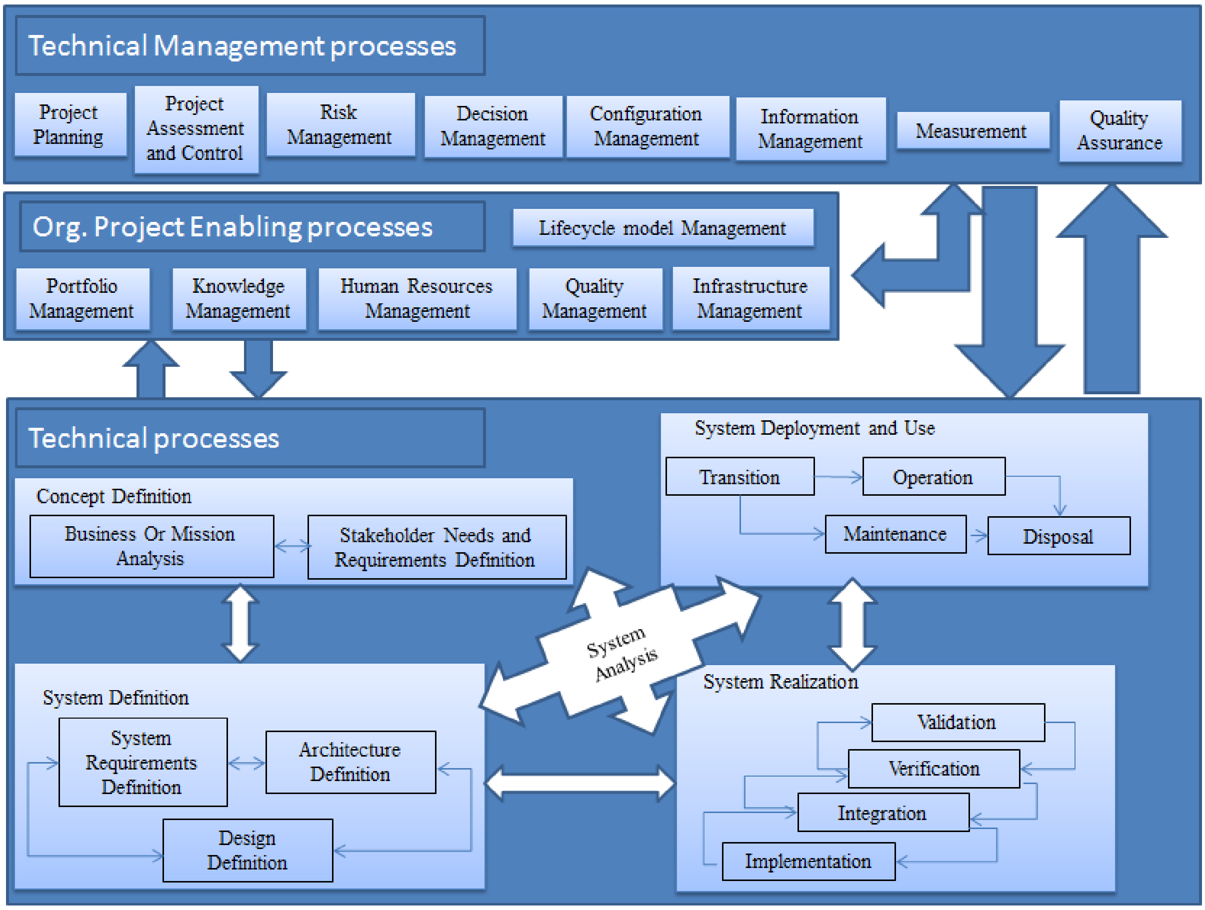

Figure 2 - 12 Relationship between processes in ISO/IEC/IEEE 15288:2015 (based on [51])

B. ANSI/EIA 632:1998

ANSI/EIA 632:1998 Processes for Engineering a System [32] provides a set of integrated processes for developing or re-engineering a system [50].

Regarding the life cycle definition, the standard defines 3 main phases

- Conception, consisting of the Pre-System Definition
- Creation, consisting of the System Definition, Subsystem Design, and Detailed Design
- Realization, consisting of the End Product Physical Integration, Test, and Evaluation

Regarding the processes, the standard defines 13 fundamental processes organised in 5 group processes (See Figure 2-13 to see the links between them):

- Acquisition and Supply
- Technical Management
- System Design
- Product Realization
- Technical Evaluation

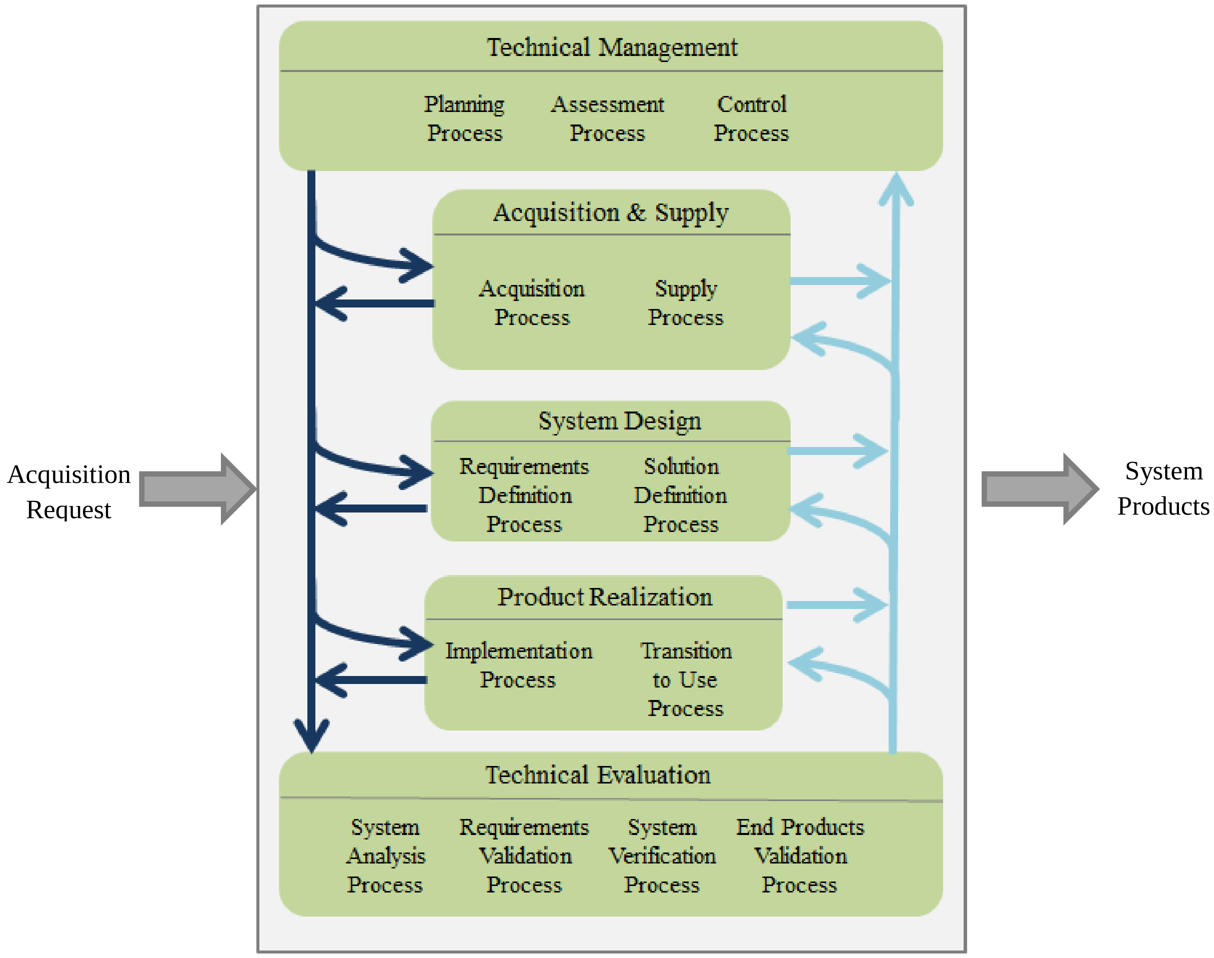

Figure 2 - 13 Relationship between processes according to ANSI/EIA 632:1998

The standard introduced two important concepts. First, the composition of the system to develop in two main categories: the end products and the enabling products (see Figure 2-14);

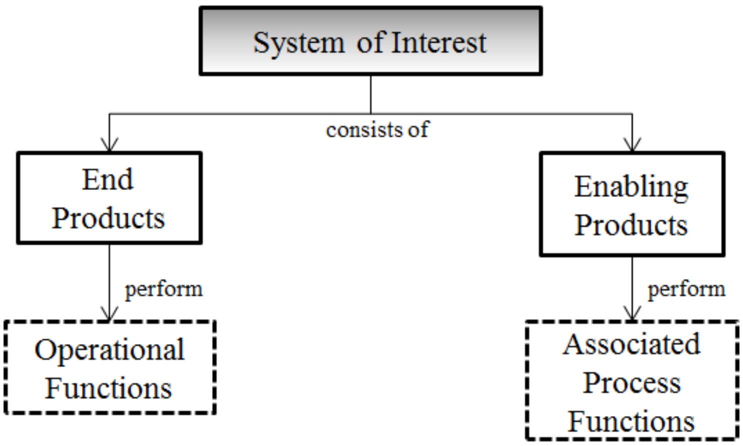

Figure 2 - 14 Relationship between the system elements according to the ANSI/EIA 632

Then the layer development approach through the building blocks hierarchy thanks to what any subsystem of the main system can be considered as a system of interest for a part of the stakeholders (see Figure 2-15).

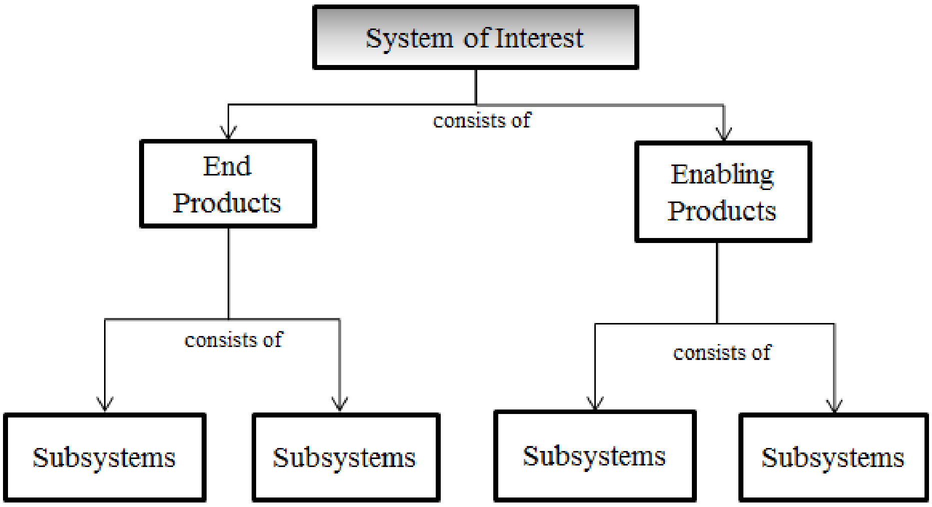

Figure 2 - 15 Building blocks hierarchy approach

ANSI/EIA 632:1998 [32] provides a methodology for implementing the standard. The organisation should:

(1) decide which of the processes apply to their enterprise;
(2) decide which requirements from this Standard apply for the processes selected;
(3) establish appropriate policies and procedures that govern project implementation;
(4) define appropriate tasks for each of the selected requirements; and
(5) establish the methods and tools to support task implementation.

This standard is not considering strictly speaking the stage of transition, maintenance and disposal. However the document highlights that the processes are applicable at any point in a product's life cycle. The processes may be considered as useful to design product improvements during use phase, to reengineer the products and to correct any enabling product design anomaly for the retirement or disposal process. ANSI/EIA 632:1998 [32] was the standard used for engineering the A380 program [52].

C. SEBoK and INCOSE Handbook

The Guide to the Systems Engineering Body of Knowledge (SEBoK)[27], created by the Body of Knowledge and Curriculum to Advance Systems Engineering (BKCASE) project is an

[27] https://sebokwiki.org/wiki/Guide_to_the_Systems_Engineering_Body_of_Knowledge_(SEBoK),

alternative to understand the discipline. It is a major, peer-reviewed addition to the systems engineering literature, regularly updated and currently available at version 2.1. It provides a list of 249 primary references where the INCOSE Handbook and ISO/IEC 15288 [34] are the most heavily internally cited [53].

The INCOSE Handbook [24] aims to provide a detailed comprehension of the SE discipline, in compliance with the content of ISO/IEC 15288. It details each process, clarifying concepts and objectives coming from the norm. It covers also some usual practice of SE, sharing a common understanding of the discipline within the community of practitioners.

D. ISO/IEC 29110 series

ISO/IEC 29110 series - Systems and Software Engineering – Lifecycle Profiles for Very Small Entities (VSEs) [6] provide generic top-level process descriptions to support, in particular but not only, SE for specific small enterprises defined in the standard as VSEs, enterprises having up to 25 people.

To address the identified issue of SE for SMEs, the “ISO/IEC 29110 series - Systems and Software Engineering” [6] aim to provide a lightweight solution for Very Small Entities (VSEs). The norm differentiates different targets according the context of the VSE. Four categories are characterized by four “Profiles” (see Table 2-6): “Entry Profile”, “Basic Profile”, “Intermediate Profile” and “Advanced Profile”.

Table 2 - 6 ISO/IEC 29110 series Profiles Description [6]

PROFILE	TARGET
Entry	Start-up VSEs (less than three years of operation) or SMEs working on small project (less than six person-months)
Basic	VSEs developing a single application by a single work team (external or internal contract)
Intermediate	VSEs involved in the development of more than one project in parallel with more than one work team
Advanced	VSEs aiming to sustain and grow as an independent competitive system and/or software development business

ISO/IEC 29110 series [6] are currently the only guide available for Systems Engineering certification at company level. It is partly published and publicly available at no cost from the ISO website. Practical documentations called “Deployment Packages” (DPs) are provided additionally to the guidelines. DPs are the name of the artefacts designed according to the standard recommendations. It deals with templates, manual, process documents, procedures, etc, useful for implementing the standard practices. For the moment, DPs are only available from the author's public site[28] and from INCOSE web site for members only. It is foreseen that all the documentation (Guidelines, and DPs) will be available from a new platform in the future[29]. Some DPs were developed to facilitate the implementation of the two processes of the two profiles "Entry" and "Basic". The DPs for the two other Profiles "Intermediate" and "Advanced" are not fully available yet[30]. A summary of material concerned by this standard is listed in Appendix D.

Regarding the content, this Systems Engineering standard is quite different from the ISO/IEC/IEEE 15288 [34] and the ANSI/EIA 632 [32]. ISO/IEC 29110 series [6] are more practical, furnished with a lot of guides and examples, and moreover enables the companies to be certified. Numerous papers exist providing the positive reasons to be certified [54]–[56]. Despite a great potential, ISO/IEC 29110 series [6] present, in its current form, three weaknesses regarding our problematic:

- ISO/IEC 29110 series [6] apply for non-critical systems development projects. Safety and security requirements are indeed not treated as specific requirements.
- The "Intermediate" and "Advanced" profiles are not fully complete neither for Software nor Systems part, even if Software Intermediate and Advanced Profile guides have been published in 2017 and 2018 respectively and Systems Intermediate Profile guide has been published in September 2019.
- As the standard does not address the regulation issue or even address the safety assessment therefore ISO/IEC 29110 series [6] do not answer to support new SMEs in the Aeronautics market.

[28] https://profs.etsmtl.ca/claporte/english/vse/
[29] http://29110.olea.org *(Warning: this website was still incomplete and in active development on 10/12/2019)*
[30] The last check has been done on 10/12/2019

2.5. CONCLUSIONS FOR NEW ACTORS

From this section, the current situation on legislation, regulations standards and guides in the aeronautics industry has shown to be complex to understand, particularly for SMEs, new on the market.

Numerous guidelines exist; each of them may also be difficult to understand. From these recommended guides, all process-based standards, a list of necessary and required processes may be extracted and implemented in a company. Applying all available documents, being the official references and validated by the international regulators, constitutes a necessary but not sufficient approach. Part 21, central document of the European regulation, is more than the aggregation of these guidelines.

The enterprises from aerospace industry are used to apply Systems Engineering to manage large and complex programs. It is recognized that this approach enables to reduce cost and time overrun even if it is quite difficult to measure the real profit in detail. For SMEs, it may be difficult to implement properly Systems Engineering processes. Several standards exist with various definitions, processes. They have different level of abstraction (See Figure 2-16) and remain subject to interpretation. Furthermore they only provide high level recommendations. The standards usually do not specify the details of “how to” implement process requirements for engineering a system. The implementation of the necessary and sufficient processes is always the responsibility of the organisation through its policies and own procedures. There is no generic method guiding the deployment of the SE processes and companies are forced to create theirs from scratch [57].

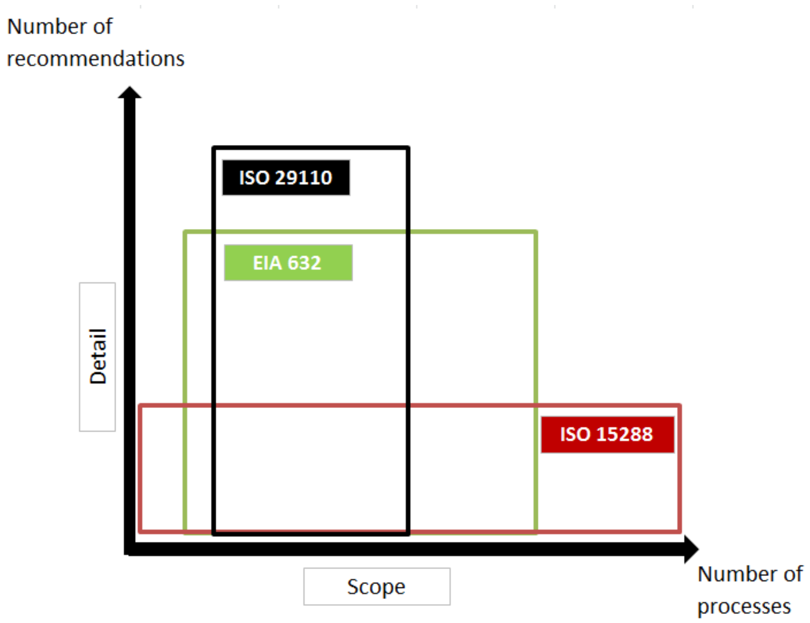

Figure 2 - 16 ISO/IEC 29110 compared to usual SE Standards (based on [50], [58])

As a consequence, the following hypotheses may be proposed:

1. As regulation is process oriented, the breakdown of certification rules in processes, objectives and activities will facilitate its implementation and monitoring.
2. The use of process modelling is adapted to the perspective of certification and will facilitate the verification of the compliance to the applicable rules.
3. Processes modelling implemented according to well-established guidelines ensures a full development description and adequate result.

The objective of this work is to provide a more comprehensive understanding of the airworthiness requirements in complementary to the traditional documentary support. Additionally SMEs need progressive solutions to manage the inherent risk of the critical certification process.

A solution is needed to transform the implicit knowledge of the regulation into explicit knowledge, addressing the following questions:

- How to make the content of the regulation more formal?
- How to extract the right information from the regulation?
- How to propose a progressive solution?

The next section will endeavour to answer these questions by discussing the following disciplines: Process, process modelling, requirements modelling, knowledge management, maturity models, and SE engineering industrial feedback.

CHAPTER 3

STATE OF THE ART AND RELATED WORKS

CONTENTS

ABSTRACT

This chapter presents a state of related works addressed during this thesis.

The study of the context leads to identify the major stakes for the SMEs from the Aeronautics. At the end of the previous section, three questions have emerged:

- How to make the content of the regulation more formal?
- How to extract the right information from the regulation?
- How to propose a progressive solution?

Being the reference for managing complex projects in aerospace, Systems Engineering (SE) was the first studied area in this thesis. The purpose of SE is to increase a system's probability of success and reduce the risk of failure. The objectives of the analysis were to extract the best practices in SE and find out what could be applied to the new SMEs in the aviation sector.

Next, trying to answer to the first question and taking into account that all the norms, SE included, describe the processes to implement in the organisation, process and process modelling have been studied.

The second question led the research towards the decision-making area, searching a support to classify and extract right data from the regulation.

Finally, since aeronautics is a sector where investments are quite significant and over the long term, continuous and progressive solutions should be offered to SMEs which do not immediately have all the necessary resources. Maturity and capability models have been then study to find progressive solutions.

This chapter is organised as following:

- In section 3.1, Systems Engineering (SE) has been studied from the point of view of experts applying SE principles and through their lessons learned. Model-Based Systems Engineering (MBSE) and Knowledge Engineering are identified as two disciplines that require special attention;
- In section 3.2, Process, process modelling and modelling languages are investigated;
- In section 3.3, Knowledge Engineering is discussed, highlighting two particular inductive methods: decision tree classifiers and expert systems;
- In section 3.4, Capability and Maturity Models are presented. They could be an alternative approach to model the growth of new and innovative enterprises in aeronautics sector;
- In section 3.5, trying to answer to the questions identified in the previous section, the different and complementary research paths are imagined to be combined in one unique approach.

3.1.SYSTEMS ENGINEERING PRACTICE

The previous chapter presented the main concepts of Systems Engineering (SE) and the related standards. The SE approach is multiple and is mainly founded on the practices from companies and industrialists. The purpose of this section is to show the importance of SE in the context of the Small and Medium Enterprises (SMEs). The upward trend in SE relates to the system modelling and analysis, key activities in model based systems engineering (MBSE).

3.1.1. Feedbacks from Industry

A. General Observations in Industrial Projects

Numerous examples show that projects can fail causing considerable losses. Some are famous and are considered now as case studies, for example:

- In 1986, the space shuttle Challenger exploded 73 seconds after the launch, because of a booster failure, killing the seven crew members [59];
- In 1991, the MIM-104 Patriot missile defense system failed to track and intercept an incoming Iraqi Scud missile, because of a wrong time calculation and rounding errors, causing the death of 28 soldiers and many other injuries[31];
- In 1996, the maiden flight of the Ariane 5 failed just 40 seconds after its lift-off because of a software error in the inertial reference system, costing $7 billion [60];
- In 1999, the NASA Mars Climate Orbiter failed to take the expected orbit around Mars, because mainly of a wrong route calculation, causing the loss of the probe [61].

It is not easy to have a clear and complete vision of the landscape of all projects in the world without considering the specifics of the projects, the countries where these projects are carried out and the sizes of organization. However, several reports show how difficult it is to achieve a project with the expected results. According to the Chaos Report from Standish Group[32], considering the period 2011-2015 in Europe, only 25% of IT projects reach successfully the initial objectives. Around 56% have only a relative success and 19% fail. In another report published in 2011 and questioning people from only French projects[33], 55% of respondents estimate that between 16% and 50% of their strategic projects are purely and simply abandoned. According a study conducted by PMI (Project Management Institute) in 2011 and based on feedbacks from international representative industrials, in organization with low maturity level, only 53% of projects met original goals and business intent [34].

[31] https://sdqweb.ipd.kit.edu/publications/pdfs/saglam2016a.pdf
[32] https://www.standishgroup.com/sample_research_files/CHAOSReport2015-Final.pdf
[33] http://www.blog-gestion-de-projet.com/wp-content/uploads/2012/03/Rapport-observatoire-des-projets-2011.pdf
[34] https://www.pmi.org/-/media/pmi/documents/public/pdf/learning/thought-leadership/pulse/pulse-of-the-profession-american-english-2012.pdf?v=52c063b2-6a10-4a50-92fe-e23a11166d95

If the criteria to assess the success of a project could be discussed, it seems that traditional approach to conduct a project is not enough to reach the initial expectations and some progress margins can be found. Systems Engineering is generally mentioned to reduce significantly the risk of project failure. The next section will present some observations from projects practicing SE recently in Europe.

B. Observations in European Industry applying Systems Engineering

The evolution of Systems Engineering (SE) within SMEs is of high interest for working groups of industrialists and academics within associations like INCOSE. The French chapter of INCOSE (Association Française d'Ingénierie Système, AFIS) and the German one (Gesellschaft für Systems Engineering, GfSE) are both working actively on the promotion and expansion of SE in European SMEs, as the following examples illustrate. Here are presented the results of reports from these two institutions.

AFIS Observations

Recently, a French guidebook was published to provide the SE key concepts to SMEs [62]. Based on the ISO/IEC 29110 standard, the book proposes a didactic approach for the purpose of SMEs who aim to implement the SE approach in their organisation. In particular a deployment approach of the two main processes: system realization and associated project management is explained.

In parallel, AFIS has supported the PISOC experience (PIlot initiative for the deployment of Systems engineering within SMEs in OCcitanie) whose goal was to assist six SMEs deploying the SE in their organisation. The project took as an objective the ISO / IEC 29110 standard and tested the recommendations of the guide. The results of the project, presented in [63] and [64], showed that SMEs are motivated to learn about new approaches and to change their current practice if they have the potential to better manage their risks.

The feedbacks from PISOC showed in particular that SE implementations enable:

- a structural effect on the organisation;
- a better integration of product changes;
- an increased responsiveness capacity;
- a better control on configuration management, requirements management, risk management and defect management processes.

But SMEs seem to face a lot of barriers to fully implement all the principles. Among other identified good practices, the initiative showed the necessity to:

- Make aware the SMEs through a short and adequate training;
- Adapt the recommendations with the business objectives of the organisation; and
- Promote concrete prospects of gain in the short or medium term.

These results of these two AFIS initiatives clearly show the need to increase support for SMEs in their Systems Engineering application.

GfSE Observations

Similarly, a study, conducted on behalf of GfSE [65] and based on interviews within different sectors and enterprise sizes, reported several barriers to the use of Systems Engineering. Ordered by importance, the main obstacles are as follows:

- Benefits and return on investment (ROI) would be not enough quantifiable;
- Investment cost could be a show stopper since the introduction of new methods seem to require significant provisions;
- Skilled systems engineers are still rare and organisations recognize insufficient expertise to expand SE efficiently;
- Some respondents say they are not concerned; methods and best practices become then secondary.

The study highlights six areas of interest where the organisations should provide important efforts. For each area, the experts of the study report the current barriers to apply the SE tenets in the organizations and particularly in SMEs. The six following areas are extracted for the purpose of this thesis.

1. <u>Requirements management</u> is an area particularly difficult to manage for SMEs, that usually apply tools such as MS Office for the documentation of requirements. Dedicated software tools such as IBM Rational Doors are used in large companies but the challenge still exists in the reuse of requirements specifications, the consistency, the control and supervision of numerous requirements and numerous changes.
2. <u>Domain-spanning system architecting</u>, creating the system model, is still considered as too expensive and unmanageable. The tools are sometimes too rigid and increase the complexity of the domain-spanning system architecting application. Successful application still requires further development when it comes to methods and supporting tools.
3. <u>Model-based systems engineering (MBSE)</u> is hindered by a lack of continuous tool chains and established standards to enable model consistency. Tool interfaces play an important role here. Consistent simulation is complicated due to a lack of standardised formalisms. The necessity is however recognised for further work on this topic; particularly with increased system complexity.
4. <u>Virtual verification and validation</u> is, for SMEs, still very much based on real prototypes. The aspect of virtual product development is acknowledged as a precursor, but not yet as an equivalent. Only a small proportion of the interviewees classify V&V in the early phases of product conception and focus on virtual, model-based validation. There is still a lack of trust in the models and simulations

5. Process tailoring is a way to adjust development processes but is often driven-based on the experience of project managers rather than on clearly defined criteria. There is often a lack of objective criteria.
6. Product Life Cycles is not always recognized as important, except from the maintenance point of view.

In particular, the report presents several challenges for SMEs. First the Systems Engineering practice is often depending on the expertise of one person within the organisation. Also the diversity of norms and guidelines seems too large and the associated processes too rigid, and therefore unsuitable for the context of SMEs. As an exception, process tailoring seems to provide some opportunities to apply SE processes. More obviously, SE practice may become relevant for SMEs when their products reach a certain level of complexity.

From this report, like from AFIS and PISOC experience, a strong need to adapt and support the SE practice within SMEs emerges.

Consensus on Grand Challenges for Systems Engineering

In [66], analysing the industrial practice, the author identified a set of seven Grand Challenges for Systems Engineering, defining a research agenda for short, medium and long term needs. According to the author, the **Information and Knowledge Management** is one of the main challenges of Systems Engineering research of the next generation, so as **Modelling and simulation**. The author highlights the need to represent the total system in one integrated model which takes into account fully the human factors. **Model-Based Systems Engineering (MBSE)** is well identified to answer to this challenge but the article argues that the discipline unfortunately lacks of available tools to fully achieve all the objectives. System verification, validation and assurance need robust, scalable and adaptable techniques and tools.

Taking into account this analysis and the seven INCOSE challenges presented in [67], a consensus is clearly identified on the MBSE approach. Considered as an important pillar for Systems Engineering practice, this approach will therefore be deepened in the next section.

3.1.2. Model-Based Systems Engineering

In the previous section, Model-Based Systems Engineering (MBSE) has been identified, by different sources, as one of the main stakes for Systems Engineering evolution. As seen in section 2.4, Systems Engineering promotes a holistic approach. The idea is to provide different views on the system to develop to better anticipate the emergence of new non expected properties. It is one of the objectives of the model Based System Engineering.

In this section, MBSE is presented through its different facets highlighting the strengths and weaknesses of this approach.

A. Context and Definitions

Numerous books and papers exist on the application of MBSE, proposing several definitions [68]–[74]. In [65], MBSE is a way to communicate in an explicit and unambiguous way and a way to create knowledge models. In [69], Model-Based Systems Engineering (MBSE) is considered as the most critical component of systems engineering. The author proposes insights and guidelines for architecting and design of complex systems through the use of formal models. In [74], MBSE is opposed to the traditional Document-Based Systems Engineering, generating documents and artefacts. In [70], MBSE must be enforced by a structured approach which establishes a clear separation between the needs identification phase and the solutions phase (Logical and Physical architectures). The authors argue that MBSE is based on the three following pillars: a language, a method and a tool.

A definition of MBSE is proposed by INCOSE [75]: MBSE "… is the formalized application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases."

In this thesis, the following definition is retained largely inspired by the INCOSE definition [75]. It introduced the fact that MBSE may be used through any SE activity and not only through those cited in the INCOSE definition.

Definition 3.1 (MBSE)

Model-Based Systems Engineering (MBSE) is the formalized application of modelling to support Systems Engineering activities, beginning in the conceptual design phase and continuing throughout development and later life cycle phases.

It is identified that MBSE brings invaluable assets [76]-[77]. Three of them are emphasized in this thesis and will be detailed in this section: physical properties analysis, inter-communication solutions and assessment and evaluation means.

B. Physical properties analysis

Among the assets of modelling, the first one relates to the characterisation of system properties [76]. This is mainly relevant for complex systems where unpredictable or uncertain behaviour is addressed. In this case, the physics of the system and its environment laws are represented in order either to identify a certain number of parameters, or to control the system behaviour, or to predict it [81]–[84]. These continuous models are often based on mathematical principles. They rely on differential equations to be solved, which allow simulation for their validation and better understanding of phenomena or behaviour.

C. Inter-communication solutions

Another class of models tends to describe the system for the sake of communication between stakeholders, by sharing a vision. Most of these discrete models given by MBSE methods serve this necessary purpose [78] and [79]. All stakeholders have to describe the same system from their viewpoints. These individual viewpoints are of the utmost importance so as to set up the requirements as a baseline for design and development [87]. Texted-based requirements are an elementary informal shape of the virtual system. To model them instead of doing textual statements has many advantages: re-usability, simplification in terms of number of requirements, thorough analysis, early validation, and cost-effectiveness [88], [89]. It is here a model-centric engineering approach as compared to former document-centric approaches. Therefore, communication becomes a crucial asset if one knows how to make it efficient. The justification is amendable when the communication is clear and understandable. In the next chapter, we will discuss our contribution including the requirement modelling for the communication sharing in SMEs.

D. Assessment and evaluation means

The last class of models emphasized here is the set of models for assessment and evaluation, where the purpose is to output measured indicators for decision-making. A large range of these kinds of models consists of a discipline called MDAO (Multi-Disciplinary Analysis and Optimization) [78]–[80]. The approach mainly focuses on optimal design based on models from several skills or disciplines. This optimization may rely on the geometry analysis, the performance analysis, and even the cost analysis. Aspects, such as dependability, can be targeted relating to the safety analysis and assessment. Several modelling solutions for qualitative and quantitative safety requirements can be found in literature (AltaRica, Figaro, SAML to cite a few [90]–[92]).

E. Knowledge management and decision support

In [77], the authors highlights that when using MBSE the necessary cooperative aspects of the activities are not sufficiently taken into account. They propose to enhance the approach with two new organisational components: **knowledge management and decision-making process**.

MBSE standards are available but MBSE theory and ontologies remain to be defined to reach a distributed and secure model environment crossing multiple domains [75]. This result is in concordance with the lessons learned from [65].

Knowledge management and decision support will be detailed in the next sections as well.

F. Models and metamodels

Models are central objects of the MBSE discipline. There are many ways to describe a system, according to many different views. The purpose of a model may have different objective as well. A typology of models may be developed as proposed by AFIS[35] :

- Cognitive models;
- Normative models (prescriptive or constructive);
- Predictive models (formal or analytics);
- Shared models for reuse and knowledge management mostly.

According the SEBoK[36], models can be classified in two different groups:

- physical models versus;
- abstract models which can be either descriptive, analytical or hybrid models.

For this thesis, the following definition is retained, inspired by [93] and the works of the OMG[37]:

Definition 3.2 (Model).

A model is a representation of a system in order to analyse it and optimize it. A model requires several points of view to be able to answer to different questions. A model needs to respect the substitutability principle and, in that sense, have to be necessary and sufficient to enable to answer to specific questions about the real system.

From this definition, the two major relations between the model and the system are highlighted. A model *represents* the system and should be a *relevant* representation, allowing to answer to some questions instead of the system itself. This definition do not explicit the language used to represent the system. Modelling languages will be treated in the next section on a process point of view. It is highlighted here that the language definition for a model may be also a model, called metamodel. The metamodelling approach is the approach proposed by the OMG (Object Management Group) to ensure the development of consistent and complete models. It is a standardization work, breaking down the modelling approach into 4 levels where:

- level M0 is the lowest level of modelling with the creation of instances;
- level M1 is the level of the definition of the models;
- level M2 is the level of the definition of the metamodel;
- level M3 is the highest level with the definition of the meta-metamodel.

The aim of this approach is to ensure that each level conforms to the next level. The OMG provides a single meta-metamodel, the MOF (Meta-Object Facility), which is self-defining. Several metamodels are proposed by the OMG, such as:

[35] https://www.afis.fr/nm-is/Pages/Modélisation/Typologie des modèles.aspx
[36] https://sebokwiki.org/wiki/Types_of_Models (v. 1.9.1, released 16 October 2018)
[37] The Object Management Group (OMG): https://www.omg.org/

- Product-oriented metamodels, for example those for UML or SysML;
- Process-oriented metamodels, for example SPEM metamodel (Software & Systems Process Engineering Metamodel [94]) or the BPDM (Business Process Definition Metamodel [95]);
- Transformation-oriented metamodels for example the metamodel supporting the languages for QVT (Query, View and Transformation [96]), etc…

All these M2 level metamodels are then MOF compliant. Models produced at M1 level by conforming to the M2 level metamodel ensure that they are well structured and consistent. Similarly, the instances produced at level M0 by conforming to a model at level M1, itself conforming to level M2, ensure that they are well structured and consistent.

Some other metamodels have been developed by other organizations than OMG. For example, the OPF metamodel (Open Process Framework, 2005) proposed by the OPEN Consortium (Object-oriented Process, Environment and Notation) has opened up a field of research which has made it possible to provide other proposals such as the EPF (Eclipse Process Framework) or OpenUp. The OPF has the advantage of being compatible with several formalisms (UML, OML, Object-Z ...). The main disadvantage is that it does not always differentiate well the limit between each level of modelling, in particular between metamodel and model. In addition, the OPF does not provide any meta-metamodel. For this thesis, the following definition is retained for a metamodel:

Definition 3.3 (Metamodel).

A metamodel is a model that defines the language of expression of a model.

3.2. PROCESS AND PROCESS MODELLING

Practical experience on MBSE and the invaluable assets of modelling need to be taken into account. In this thesis, the chosen point of view is focused on the enterprise and its processes. The system to model is not the product to develop, but rather the necessary organisation to develop the product. This section is focused on the internal processes of the organisation and the modelling aspect of the processes.

3.2.1. Process Approach and Process Management

A. Concepts of process and definitions

The concept of process has been widely spread thanks to the emergence of quality standards, and particularly due to the ISO 9000 suite[38], published for the first time in 1987. The main idea of this norm is that the business processes are reproducible and can be so formalized. It is then possible to describe all the activities, all the necessary steps for the process orchestration. According to the ISO 9000 norm [97], the introductive and explicative norm to the ISO 9000 family, a process is:

"a set of interrelated or interacting activities that use inputs to deliver an intended result".

In this definition:

- the "intended result" of a process may be an output, a product or a service depending on the context;
- the "inputs" and "outputs" may be tangible (e.g. materials, components or equipment) or intangible (e.g. data, information or knowledge); and
- the "inputs" to a process are generally the "outputs" of other processes.

For EIA 632[32] a process is "a set of interrelated tasks that, together, transform inputs into outputs".

For ISO 15288 [34] a process is "a set of interrelated or interacting activities that transforms inputs into outputs".

In ISO/IEC/IEEE 24748-2 [98], a process is defined as "an integrated set of activities that transform inputs (for example a set of data such as requirements) into desired outputs (for example a set of data describing a desired solution)". A process can be controlled by organizational directives, constraints, governmental regulations or laws, and can be supported, by enabling mechanisms such as:

- resources that performs the tasks;.
- other resources such as the facilities, equipment and funds;
- tools, methods, procedures and techniques.

[38] https://www.iso.org/iso-9001-quality-management.html

Figure 3-1 illustrates these concepts which are used trough the major SE standards such as ISO/IEC/IEEE 24748-2, ISO 15288:2015 and SE Handbook as well.

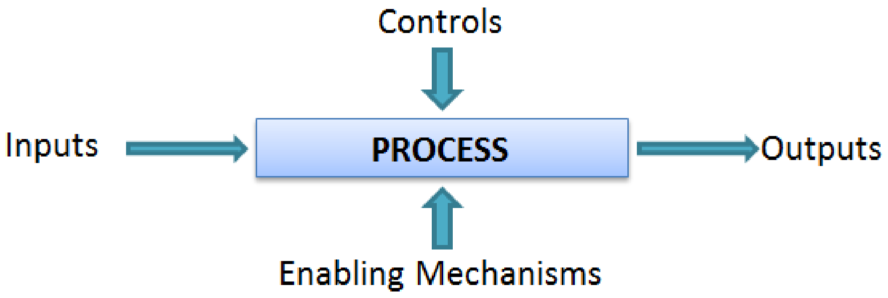

Figure 3 - 1 Process concept presented in ISO/IEC/IEEE 24748-2 (based on [98])

In the Business Process Model and Notation (BPMN) proposed by the OMG[39], a process is defined as "a graph of Flow Elements, which are a set of Activities (atomic and non-atomic), Events, Gateways, and Sequence Flow ….". An atomic activity is called a task which will be performed by an end-user, an application, or both.

Based on these different sources, we identify six important concepts: objective, activity, task, role, resource and event.

According to the norm ISO 9000 family, processes are classified in three categories:

- Realization,
- Support,
- Management.

This classification is largely reused in literature and in the other norms.

According to [50] and [97], a process is a logical sequence of tasks performed to achieve a particular objective.

For this thesis, we propose the following definition for process:

Definition 3.4 (Process)

A process is a combination of activities interacting together to answer to a determined objective. Each activity is composed of at least one task, each performed by an end-user, an application, or both. The execution of the process is always under the responsibility of defined roles, using resources to transform inputs into outputs under certain conditions and events. It is classified in three categories: Engineering processes, Enabling processes, Project Management processes.

[39] From 2013, BPMN is an ISO norm: ISO/IEC 19510 [99].

Processes as proposed in the available norms and guides and presented in this report describe the task to perform but do not describe how to perform them. This is usually the purpose of the methods, methodologies and tools. To complete and clarify, the terms method and methodology are clarified here.

A method provides support for a process by proposing a way of carrying out a task or a set of tasks. According [100], SE methods may consist of, for example, :

- Observation;
- Analysis;
- Synthesis;
- Documentation;
- Communication.

For this thesis, we propose the following definition for method:

Definition 3.5 (Method)

A method is a set of techniques, practices and procedures for performing a task or a set of tasks.

A tool, applied to a particular method, will facilitate the performance of the tasks. A methodology will combine processes, methods and sometimes tools to provide a kind of roadmap to reach particular objective.

For this thesis, we propose the following definition for methodology:

Definition 3.6 (Methodology)

A methodology is a combination of processes, methods and tools.

B. Process Approach

The process approach is a quality management strategy which incorporates the plan-do-check-act cycle (PDCA cycle) called also Deming wheel and a risk-based thinking [101] to build and improve continuously the processes within an organisation. Figure 3-2 illustrates the PDCA cycle and shows the continuous objective for process improvement. For each cycle, the organisation needs to:

- define and classify the necessary processes and the necessary activities and tasks,
- determine required process inputs and expected outputs,
- determine required enabling and control mechanism,
- assign responsibilities and authorities for processes,
- identify risks and opportunities for processes,
- define the conditions for updating cycles.

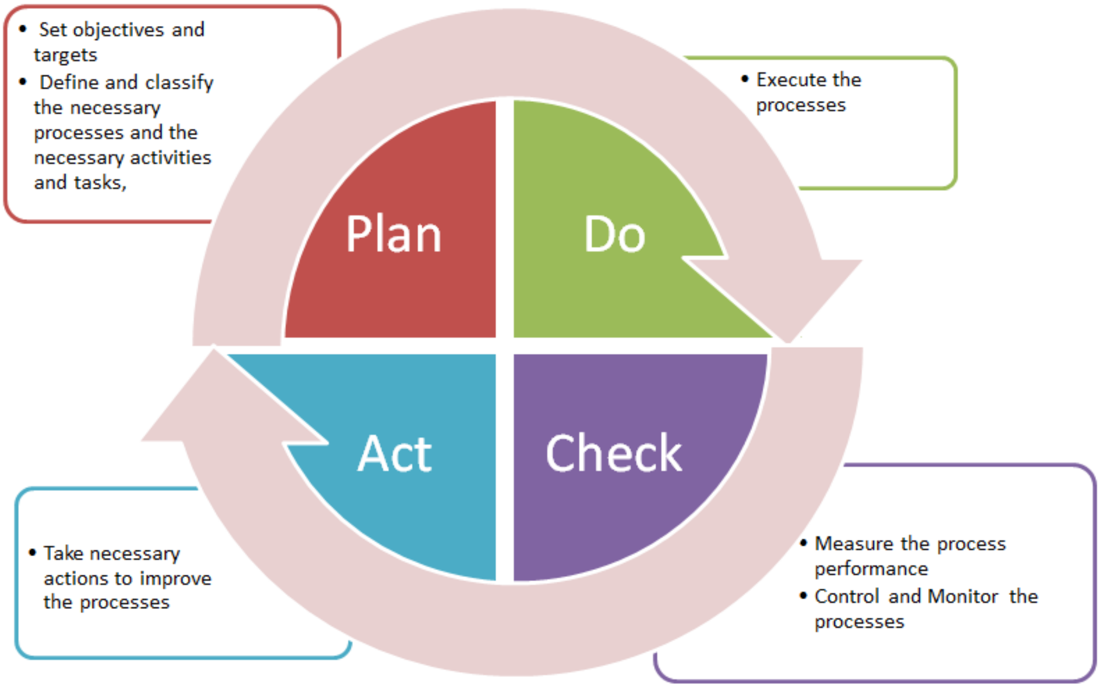

Figure 3 - 2 PDCA cycle

C. From Process Approach to Process Management

Over the last decades, Business Process Management (BPM) has become progressively a mature discipline, combining knowledge from information technology, management sciences and industrial engineering with the purpose of improving business processes [102]–[104]. BPM evolution is strongly linked with the Information Systems history (see Figure 3-3).

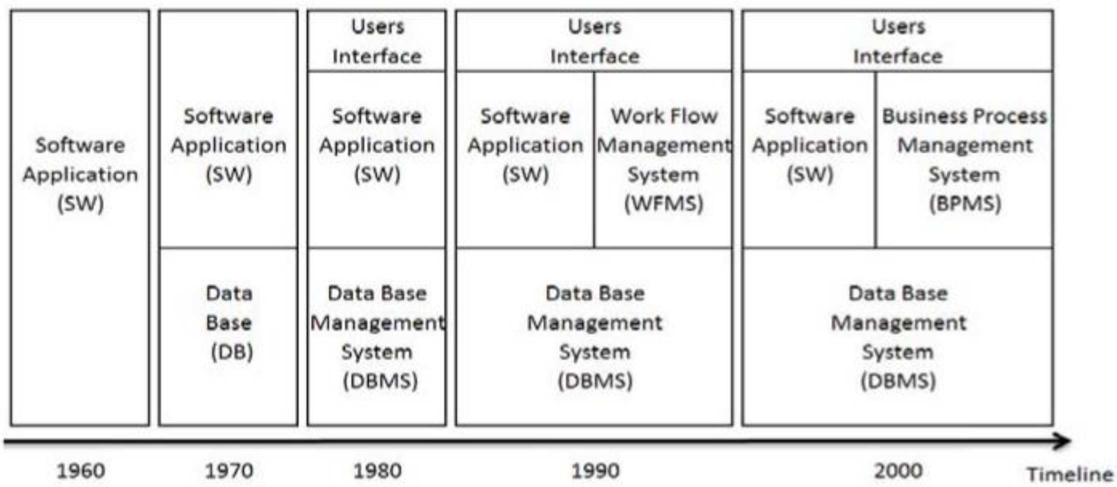

Figure 3 - 3 Historical view of Information Systems (based on [105])

The origin of BPM could be dated with the emergence of computer sciences and technologies [104] and it is a part of process science [106]. In the 1990's, Enterprise Resource Planning systems (ERPs) enable to automate a set of tasks and give birth to what we called the Work Flow Management. Work Flow Management Systems (WFMS) enabled for the first time to model the processes. Business Process Management Systems (BPMS) arrived just after the 2000's, becoming more powerful than WFMS where there are embracing all the activities of Business Process Management from modelling and analysis to simulation and enactment.

In the next sections, process modelling and process modelling languages will be discussed.

3.2.2. Process Modelling

The goal of process modelling is mainly to understand, improve and support a process [107]. Models of processes are useful to communicate. Graphical notations may be used to enhance textual or verbal communication, providing stakeholders a support for discussion. Some organizations may use only informal process models to structure discussions and to document procedures [108]. In all cases, process modelling allows to abstract and reason on the structure of work within organisations [109].

A. Business process modelling

Business process modelling is the particular activity of representing the processes of enterprises. There are different ways to model the enterprises, for instance 4EM method [110], TOGAF[40], DoDAF[41]. There are also several enterprise architecture modelling languages (ArchiMate[42], Zachman[111], …). But there is no consensus between them, especially regarding model elements and enterprise artefacts [112], making things complicated for SMEs.

In this thesis, the following business process modelling definition is kept.

Definition 3.7 (Business Process Modelling)

Business Process Modelling is the activity of modelling the processes of an enterprise with the aim to answer to a business objective.

[40] https://www.opengroup.org/togaf
[41] https://dodcio.defense.gov/library/dod-architecture-framework/
[42] https://www.opengroup.org/archimate-forum/archimate-overview

No unique kind of model enables to represent the full vision of the enterprise. Modelling and a fortiori Business process modelling requires making choices. Process modelling may enable several but different activities for the enterprise:

- processes management and control,
- documentation of the enterprise activities,
- analysis and the re-engineering of processes,
- conformity analyse of executed activities,
- performance estimation thanks to simulation,
- business risk management,
- enterprise architecture framework,
- workflow management.

B. Systems Engineering Process Modelling

Process modelling in Systems Engineering is generally used through the MBSE activities to analyse the conceptual design of a product, to perform simulation, to better control the system behaviour in operational context and optimize it [113]. Process modelling is then most of the times used to analyse the system under development.

Some initiatives exist to use modelling for systems engineering processes themselves. In [114], the authors explore a modelling approach to support innovative development taking into account, at the same time, the requirements from the product, the design process and the organisation. Based on the Vee-cycle, the approach aims to provide a mechanism of arbitration between technical, organizational and cognitive contradictions in innovative design. Similarly, [115] proposes to model the ISO processes by using SysML notation. Various static diagrams are used such as block diagrams mainly. But the behavioral views of processes are absent in the modelling, along with the justification of the adopted models.

In this thesis, the following process model definition is kept.

Definition 3.8 (Process model)
A process model is a representation of a process, describing its structure and its behaviour. A process model will show how the elements of its composition, the activities and the tasks, interact together, sequentially or in parallel, to achieve a common goal. It may embed the roles of people, the generated and updated documents, as well.

The next section will deal with the topic of the modelling language used for the process models.

3.2.3. Process modelling languages

Any language may be characterized according two attributes: the syntax and the semantics. The syntax defines the objects which can be manipulated and the semantics is the meaning brought by the objects.

Two criteria are generally retained to differentiate the syntax of different languages. On one hand they are either textual or graphical. On the other hand, they are either natural (informal) or formal. Thus four groups of languages can be distinguished:

- Natural/Informal and textual languages (mother tongue languages);
- Formal and textual languages (machine or computer languages);
- Formal and graphical (musical notations);
- Natural/Informal and graphical languages (e.g. flowcharts)

The different types allow more or less flexibility in communication and interpretation. Whatever the choice regarding the syntax type, inside an organisation, a process model, must follow a common notation to be shared and understood by all. Several notations or languages exist to model processes. In this thesis, BPMN, OPM, UML and SysML are considered, covering the major use for research and industrial projects. Other languages exist: EPC (Event-Driven Process Chain), Petri-Nets, Workflow Networks, YAWL, etc. The use of one or the other is mainly driven by modelling needs. Information regarding these languages and comparison between them are provided in [113], [114].

A. BPMN

BPMN (Business Process Model and Notation) is an activity-oriented graphical and informal language. It is often considered in the literature and in industry to be the de-facto standard for business process modelling [116] and [117]. BPMN is supported by the Object Management Group (OMG) since 2006. It is comprehensible, easy to use and can be read and understood by persons with diverse backgrounds and without a long training [104].

The current version BPMN 2.0.2 specification [118] provides four different types of diagrams:

1. Process diagram, describing the ways in which operations are carried out to accomplish the intended objectives of an organization;

2. Collaboration diagram, presenting how processes interact together;

3. Conversation diagram, which specifies the logical relation of message exchanges;

4. Choreography diagram, defining the expected behaviour between two or more interacting business participants in the process.

B. OPM

Object–Process Methodology (OPM) model integrates structural, functional and behavioural aspects of a system in one single type of diagram, called Object–Process Diagram (OPD). The ontology comprises three different types of entities:

- Objects;
- Processes; and
- States.

An OPM model consists in a set of different OPDs with a different abstraction level. Based on formal mathematical foundations of graph grammars and a subset of natural language, OPM enables to represent graphically a system and auto-generates natural language text specifying the inherent requirements [119]. Since 2015, OPM is now recognized through the ISO norm 19450[43].

C. UML

With the development of computer science, Model-Based Engineering (MBE) approaches emerged for control software development. The Unified Modelling Language (UML) [120] is one of the most wide-spread languages and is often considered as a de-facto standard [121] as well but more used for modelling software. Like BPMN, the object-oriented UML is an OMG standardized language. UML is historically used to analyse, model and design object-oriented software systems. However it may also be used for process modelling as proposed in the Software and Systems Process Engineering Metamodel (SPEM) [94] that aims to provide guidance material for meta-process modelling. Characteristics and components of a system are hardly expressed in UML diagrams [122].

D. SysML

SysML, a UML-based profile, commonly used in Systems Engineering [86], is one of the pillars of Model-Based Systems Engineering (MBSE) [123]. It is used to support interdisciplinary system development [124]. SysML has facilitated awareness and adoption of MBSE, but it still needs substantial functional enhancements (essentially to improve integration), a better display with differentiated kinds of visualisation (text, diagram, tables, interactive display, model differencing, …) and the necessary mechanism for tools interoperability [125]. As UML, it is structured around different kinds of diagrams, describing the different aspects of a system, allowing multiple views of a system. There is no standard method associated to SysML, nor with UML and BPMN. Methods need to be defined to make the use of the diagrams explicit, and to express a dedicated methodology conforming to the

[43] https://www.iso.org/standard/62274.html

approach deployed. Among the nine SysML diagrams proposed to model a system, theoretically five can be used to represent the structural aspects and four can be used to represent the behavioural aspects (see table 3-2). It is recommended by OMG to use both aspects to describe a system. The main drawback of this language is that consistency between diagrams must be demonstrated to get confidence in the modelled system [115] as the different diagrams and objects from diagrams are not systematically linked.

Table 3 - 1 The nine SysML Diagrams

Five Structural Diagrams	Four Behavioural Diagrams
Package Diagrams	Use Case Diagram
Block Definition Diagram	Sequence Diagram
Internal Block Diagram	State Machine Diagram
Requirement Diagram	Activity Diagram
Parametric Diagram	

The fact that there is no method can be seen either as a great strength or a big drawback. It may be a strength as it allows to adapt the language to the specific context of the system. At the contrary, for SMEs in particular, it may be difficult to appropriate it without specific technique to use it.

3.3. KNOWLEDGE MODELLING

As seen in section 3.1, knowledge is an important resource in organisations and knowledge management is an important discipline to explore [126]. It constitutes a competitive advantage for any enterprise and particularly for innovative companies [127] and [128]. Despite an increasing interest, there is no common and accepted definition of what knowledge and knowledge management are. According to [115] and [116], knowledge management is defined as a set of four types of activities:

- **acquisition of knowledge**, process of creation and knowledge-building;
- **conversion of knowledge**, how the knowledge is stored and distributed or made available to people in the organisation;
- **application of knowledge**, how the knowledge is used;
- **protection of knowledge**.

Within organisations, collective knowledge may rely a lot on individual knowledge. If the management of knowledge is not taken into account in the organization and promoted as a strategic reality, the organization takes the risk of losing its knowledge with the departure of its employees [130]. Common and capitalised knowledge are of strategic importance.

Knowledge management can be used also for problem-solving methods or as a decision making support. Particularly knowledge modelling has emerged as a cognitive discipline to help formally to take the right decision in a highly complex environment. Several approaches exist. In this thesis we have explored two main approaches constructing knowledge by inductive methods: the decision tree classifiers and the expert systems.

3.3.1. Decision Tree Classifiers

Decision tree classifiers are one of the basic techniques for data classification and multistage decision making [131], [132]. Their construction is simple and easy to understand. They are usually powerful in terms of accuracy as well. They are used both to find out the appropriate factors influencing a particular situation and to discover a solution to a particular question. They are well suited to categorize problems according attributes or features [133]. In a multistage approach, the final and complex decision is broken up into a set of simpler decisions, simplifying the decision making. However, decision tree classifiers can become large, may undergo an excessive complexity and can become therefore incomprehensible or unusable [134].

Decision tree classifiers are used in many diverse areas such as medical diagnosis, radar signal classification [131], [135]. In particular, they are largely used in aerospace safety assessment and fault diagnosis.

In this thesis, the focus is done on Directed Acyclic Trees (DAT), satisfying the following properties:

- A DAT is a tree with no cycle and in which we can find the four following types of components (see figure 3-4):
  - a unique root
  - internal nodes
  - edges
  - leaf nodes
- A DAT is traditionally composed of several paths, each defined from the root to a leaf node. Each path is a unique sequence of nodes and edges, leading to a particular leaf node. Each path constitutes a rule decision such as “IF-THEN” rule.
- The internal nodes are labelled by attributes or features, determining the intermediate decision steps and describing splitting criteria. Each splitting criteria creates a new logical “AND” in the “IF part“ and the leaf node constitutes the “THEN part” [132].
- The internal nodes show a pair of edges: entry and exit edges. The root is the only node with no entry edge. The leaf nodes have no exit edges.
- The depth of a path in a DAT is the length of the path from the root to leaf node. Each path may have a different depth.

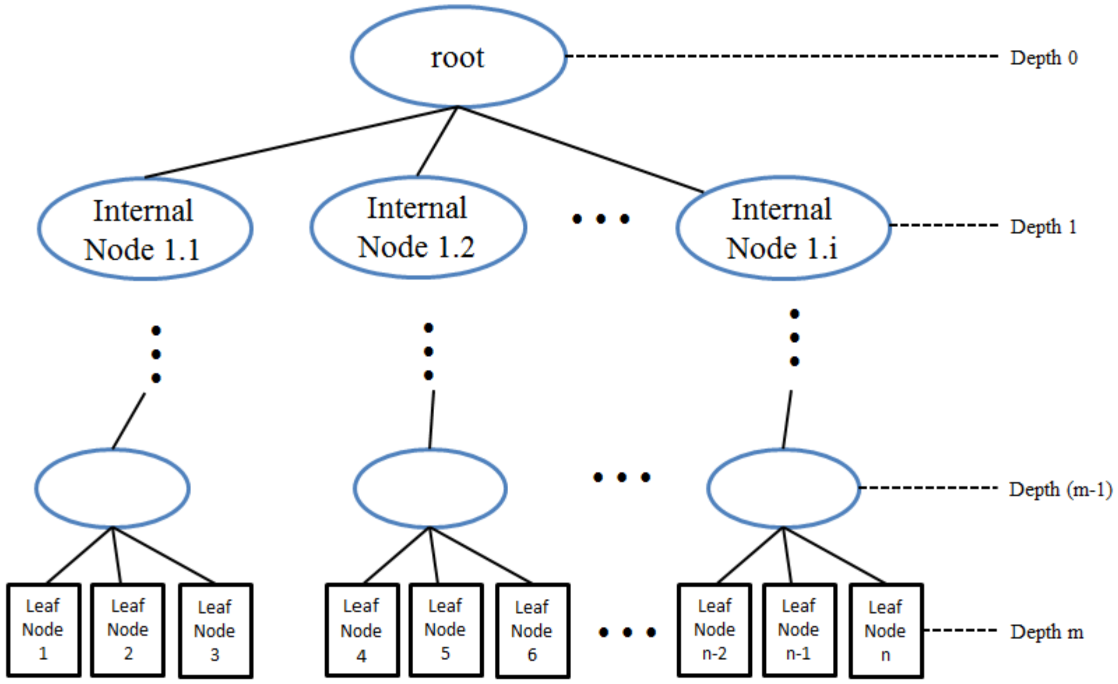

Figure 3 - 4 Example of a directed acyclic decision tree (based on [131])

Decision tree classifiers may be attractive for the following reasons [131]:

1) Complex decisions can be constructed by the union of simpler local decisions.

2) In contrast to conventional single-stage classifiers where information is tested against all features, decision trees are multi-staged classifiers. It means that information is tested against only certain subsets of features, thus eliminating unnecessary analysis.

3) In single stage classifiers, one subset of features may be used for discriminating among all features. This features subset is usually selected by a globally optimal criterion. In decision tree classifiers different subsets of features at different internal nodes of the trees may be chosen. This flexibility can provide a potential performance improvement.

On the other hand, some drawbacks of decision tree classifiers can be identified [131]. The following three situations are identified as potential problems that may occur:

1) Overlap between different branches can increase the number of terminals and reduce the optimization.

2) Errors may be accumulated from level to level in a large tree. It is pointed out in [136] that it is difficult to optimize simultaneously the accuracy and the efficiency.

3) The performance of a decision tree classifiers strongly depends on its design quality

Finally, research literature identifies four approaches for construction of a decision tree [131]:

- Bottom-Up approach starting from the different available decisions;
- Top-Down approach starting from the root node, defining splitting rules;
- Hybrid approach, using both a bottom-up procedure to direct and assist a top-down procedure;
- Tree growing-pruning approach.

In this thesis, only the first three approaches will be used.

3.3.2. Expert systems or knowledge-based systems

Expert systems can be linked to the evolution of Artificial Intelligence in parallel with the construction of intelligent computers and the development of Knowledge Engineering [137]–[139]. The term “expert” refers to the goal to develop programs built on knowledge of experts to solve problems. The terms expert systems and knowledge-based systems are often used interchangeably.

An expert system is traditionally composed of two main parts (see Figure 3-5):

- The **knowledge base**, consisting in both factual and heuristic knowledge and representing a domain of expertise;
- The **inference engine**, leading to the solution of the problem by building reasoning on the basis of the available knowledge.

Knowledge representation formalizes and organizes the knowledge for use by the inference engine [128]. It means that two steps are needed to build an expert system:

1. Choose the adapted technique to organise and formalise the available knowledge;
2. Choose the adapted inference mechanism to reason the knowledge.

Depending on the knowledge representation, several kinds of Expert Systems can be distinguished, for example case-based and rule-based expert systems. When the knowledge is represented as a set of rules, such as IF-THEN rules, the system is called “Rule-Based Expert System”. In such an Expert System, the knowledge base contains two main elements:

- the base of facts; it deals with logical statements such as, for example,
$$p \vee not\ q$$
- the base of rules; it deals with assumptions between the facts such as, for example,
$$(p \vee q) \rightarrow r$$

Knowledge engineers have the role to acquire and represent knowledge and have to encode the expertise of a particular domain. The main objective of the expert system is to provide the user an answer equivalent to the expert knowledge.

In case of Rule-Based Expert System, the inference mechanism involves chaining of IF-THEN rules. Two kinds of method based on a reasoning chain are usually discussed: forward chaining and backward chaining [137], [139]–[141]. Using both the rules and the facts to generate new knowledge, the problem considered and the hypotheses available will lead to choosing one or the other method. Different environments are available for these two methods. PROLOG (for PROgrammation LOGique in French) is an example of environment with a built-in backward chaining inference engine [140]. CLIPS (C Language Integrated Production System) is an example of environment with a built-in forward chaining inference engine [141].

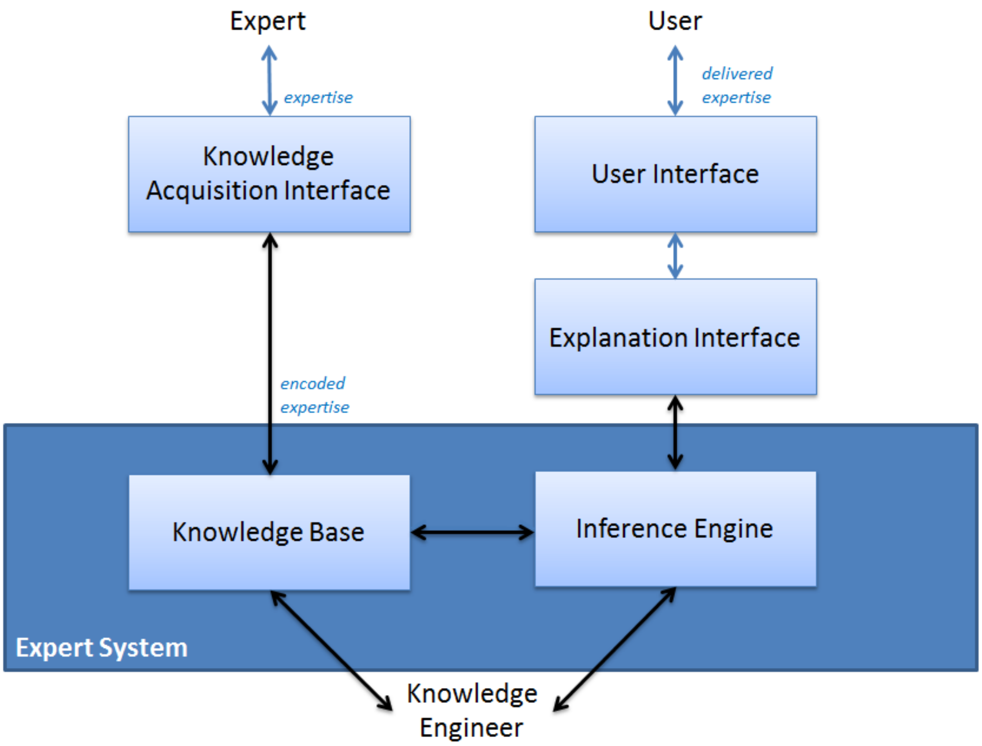

Figure 3 - 5 Basic structure of an Expert System (based on [137])

3.4. CAPABILITY AND MATURITY MODELLING

One major source for the concept of maturity stages as known today is the quality management process maturity grid [142]. At that period, best practices according maturity stages and measurement categories are introduced to better manage processes in organisations. In the 1990's, when the concepts of quality and process improvement, were growing, numerous maturity models appeared [143]. Capability Maturity Model Integration (CMMI) is the most recognized today [144]. Additionally to CMMI, some other maturity models have been studied. This section will cover this specific area, providing a short overview of the available models.

3.4.1. CMMI, SECM and SPICE models

This section will present the specificities of three major maturity models: CMMI Development, SECM and ISO/IEC 15504 also known as SPICE.

A. CMMI Development

CMMI Development V2.0 [145] is composed of 25 processes called Practice Areas (PAs) regrouped in Capability Areas (CAs), themselves regrouped in four categories such as: Doing, Managing, Enabling or Improving. Appendix E shows the list of PA per CA and Category. This maturity model proposes two kinds of representation of processes: the continuous and the staged representation. The continuous representation of the processes usually refers to a Capability model whereas a staged representation of the processes usually refers to a Maturity Model. Capability models and maturity levels are generally not used in parallel. Capability Models provide process capability levels which are a means for incrementally improving the processes one by one and enable to classify their performance in the context of the organization. Maturity Models, on the other hand, provide company maturity levels which enable to classify the organisations according to their ability to control a list of identified processes. The organization is evaluated as a whole and can reach each maturity level according to different objectives. CMMI Development V2.0 [145] proposes for both representation (Capability models and maturity levels), five levels as follows:

- **Level 1 – Initial.** Work gets completed but it is often delayed and over budget;
- **Level 2 – Managed.** Projects are planned, performed, measured and controlled;
- **Level 3 – Defined.** Organization provides guidance across projects;
- **Level 4 – Quantitatively Managed.** Organization is data-driven;
- **Level 5 – Optimizing.** Organization is focus on continuous improvement.

CMMI is regularly updated by the CMMI Institute.

B. SECM

EIA/IS 731 SECM [146] proposes a capability model to support the development and improvement of systems engineering capability. It intends to provide complete coverage for EIA 632, Processes for Engineering a System [32], one of the Systems Engineering standard presented in section 2.4.2. EIA/IS 731 SECM is a tool that organizations can use to evaluate the capability of their implemented Systems Engineering process. It can be used also as a guide for developing or improving a Systems Engineering process [147]. EIA/IS 731 SECM is composed of 19 processes called Focus Areas (FAs). They are organised in three categories: Technical, Management and Environment (See Appendix F). Additionally, EIA/IS 731 SECM provides a tool to evaluate the capability of 19 processes or FAs according six capability levels:

- **Level 0 – Not performed.** Use of empirical practices.
- **Level 1 – Performed informally.** Use of defined practices.
- **Level 2 – Planned and tracked.** Plan defined procedures, schedule and monitor their execution.
- **Level 3 – Well defined.** Define a formalized and standardized process and systematically implement it.
- **Level 4 – Quantitatively controlled.** Establish measurable quality objectives, indicators and pilot their monitoring.
- **Level 5 – Continuously Improving.** Improve organizational practices and increase the efficiency of the process.

Last version of SECM was provided in 2002.

C. ISO/IEC 15504 or SPICE

ISO/IEC 15504 [148] also known as SPICE (Software Process Improvement and Capability dEtermination) proposes a process management model, as well as a set of requirements for the evaluation and improvement of these processes. Each process is evaluated according six levels of capability:

- **Level 0 – Incomplete.** There are no easily identifiable work products.
- **Level 1 – Performed.** Specific Practices are performed informally and performance is not rigorously planned and tracked. Execution is dependent upon individual knowledge.
- **Level 2 – Managed.** The activities are planned and tracked. The process is documented. Work products, placed under version control, are reviewed and corrective actions are taken when needed.
- **Level 3 – Established.** A standard process is rigorously documented and used within the organization. Performance of practices is assessed. Information related to the use of the processes is traced and used for planning and managing them.
- **Level 4 – Predictable.** Measurable quality goals are established and detailed measures of the performance are collected and analysed to identify potential improvements.
- **Level 5 – Optimizing.** Process effectiveness goals are established based upon business goals of the organization. The process undergoes continuous refinement based on quantitative feedback.

This norm is currently being revised within the framework of the activities for the ISO/IEC 330xx family of standards [149].

3.4.2. Maturity Models in Literature

Numerous publications can be found on maturity models propositions, for example [143], [144], [150]–[154]. Most of the models are based on traditional maturity models, such as CMMI or SPICE. In particular [151] compares 16 different maturity models and identifies the main characteristics to select a maturity model or to design a new one. As another example, [154] compares 15 capability/maturity models tracking the measurement framework, the process reference model, the usage support and how they have been developed/validated. Also, [153] proposes a tool to select the right business process maturity model among 69 models through a questionnaire of 14 questions. In [155], a criteria grid is proposed to assess the level of maturity of a company regarding the implementation of SE processes. It could be an efficient tool to promote and apply SE principles but in reality it does not provide a clear deployment method. [152] proposes a complete procedure to develop a maturity model and [155]–[159] are proposing new maturity models. All these maturity models in literature are based on maturity levels that represent different states through which an organization is transformed. Its processes are improved, evolving from poorly defined and inconsistent practices (generally level 0 or 1) to repeatable practice and predictable processes until process innovation and optimization (generally level 5 or 6). Achieving each maturity level also entails satisfying all the requirements of the lower levels.

[160] points out that maturity models may be useful to manage complexity in project management and can be used as a decision-making support. The authors present the management complexity maturity model which assesses the maturity of the organization regarding the management of the complexity. This model presents 4 levels of maturity:

- Level1: Lack of active complexity management;
- Level2: Opportunistic complexity management;
- Level3: Continuous complexity management;
- Level4: Systematic complexity management.

With capability/maturity models, SMEs could beneficiate of an adequate support which would be a tool used for a ramp-up strategy. Unfortunately, capability/maturity models, and especially the CMMI, may often be considered as too complex to deploy and too expensive for SMEs, even if 76% of appraised units (of 18 000 apparaisals) have 100 or fewer employees[44]. As Systems Engineering standards their objective is to provide good practices without imposing how to implement them [44]. They are often judged as too theoretical to be implemented in a SME.

[44] CMMI Adoption Trends 2019 Mid-Year Update, https://cmmiinstitute.com/resource-files/public/cmmi-adoption-trends-2019-mid-year-update

3.5. CONCLUSION

This chapter discussed the status of the following approaches:

- Systems Engineering application;
- Process Modelling;
- Knowledge Modelling;
- Capability and Maturity Modelling.

First, we learned that Systems Engineering is a discipline difficult to apply easily and particularly in SMEs. MBSE is one of the main challenges we identify. Even large enterprises are demanding methodical approaches and tool support to spread its implementation. Organisational features, such as knowledge management and decision-making process, should be integrated more systematically for a better efficiency.

Modelling the system and its inherent processes is a way to provide another comprehension on the objectives and to give a more formal view on the expected system requirements. Taking the organisation as the system to model, the processes must be identified and the right language to model them.

Knowledge modelling is another challenge. This section introduced the fact that some complex problems are difficult to solve without adapted solving strategies, especially when the information show strong inferential relationships. Two particular methods have been discussed with their main advantages and drawbacks: Decision Tree Classifiers and Expert Systems.

Maturity and Capability Modelling is an approach with the aim to help organisation to assess their internal maturity. It can be used as well to help the organisation to evolve through different states corresponding to different levels of maturity of its processes.

After analysis of these different and complementary approaches, combining them, a new framework has been built. It will be presented in the following chapter.

CHAPTER 4

PROPOSITIONS FOR AN AIRCRAFT CERTIFICATION FRAMEWORK

CONTENTS

ABSTRACT

This chapter describes an approach to address the issues identified in sections 2.5 and 3.5. The objective is to provide methodological support to innovative enterprises in the aviation sector during their certification process. Using the lessons learned from Systems Engineering, process management, process modelling, knowledge management and maturity models, a solution is built with a strong organisational point of view. Relying on the European certification objectives (presented in chapter 2), a framework is proposed, called **Aircraft Certification Framework (ACF)**.

The framework ACF is composed of several parts:

- a metamodel (see section 4.1.3);
- functional, structural and behavioural models (see section 4.2);
- a governance approach (see section 4.3);
- a practical methodology to support the certification process implementation (see section 4.4).

The framework ACF is structured according to known standards to ensure continuity and durability. The main objective of the ACF is to provide a formalized approach combining process modelling and organisation assessment. Depending on the context of the enterprise, only the suitable requirements from the certification regulations are selected. Appropriate processes that result are provided, textually and graphically. A general view of the development process is built and the communication both inside and outside is improved. As a shared repository, the framework aims to capitalize information and facilitate re-use as well.

This chapter is organised as following:

- Section 4.1 will first provide an overview on the ACF;
- Section 4.2 will describe the main models proposed within the ACF Design Engineering part;
- Section 4.3 will describe the governance approach;
- Section 4.4 will describe the methodology, linking together the different parts of the ACF approach;
- Section 4.5 will summarise the contributions.

4.1. FRAMEWORK PRESENTATION

4.1.1. Objectives of the Framework

As shown, available guidelines are not sufficient to answer to all airworthiness requirements. It is proposed to turn back to the source requirements of the guidelines and study the regulation texts mainly constituted by Part 21. Based on the identified issues, the research project addresses the following questions:

- Q1. How to formalize the regulations and the expected and informal requirements coming from diverse institutions and standards?
- Q2. How to provide appropriate support for innovative SMEs in the aerospace sector?
- Q3. What kind of knowledge do organisations need to enter into the certification process?
- Q4. What are the necessary processes, activities and roles to implement in the organization in order to be compliant with the certification regulations?
- Q5. What are the recommendations to SMEs before entering the certification process?
- Q6. What is the gap between the regulations and the current standards? Is there headroom to provide SMEs a kind of leeway, another path than the one described in the standards?
- Q7. Can we identify a critical path for SMEs?

The main objective is to provide a new reference framework with associated structural and behavioural models, adaptable to the situation (i.e aircraft and enterprise). The Aircraft Certification Framework (ACF) is then proposed.

4.1.2. General Approach

Like in most Systems Engineering approaches, we may consider organisations as a combination of three types of entities: people, processes and products. In this research, the proposed model-based approach focuses on the processes and the roles within an enterprise (engineers for example and those as expected by the regulation). Considering the organisation as a system, a Systems Engineering approach and its techniques are applied. The system is described through its processes and the necessary people assigned to the activities and tasks. The products themselves are outputs of the processes, called artefacts. The system of interest is therefore not the system under development but the organization, responsible for its development, its integration and its subsequent certification. In this thesis, the focus is in particular on the certification process in aeronautics industry.

Taking into account the concepts explained in section 3.1, Model-Based Systems Engineering (MBSE) and Process Modelling are combined in one approach to graphically represent requirements, processes and roles of the enterprise. The approach aims to create a new framework, called **Aircraft Certification Framework (ACF)**. Figure 4-1 depicts a general point of view on this approach, incorporating the three main parts of the framework: Design Engineering, Governance and Tooling.

Design Engineering, core of the ACF, will be detailed in section 4.2 whereas Governance will be described in section 4.3. Tooling is a transverse proposition which will be treated through the sections 4.2 and 4.3.

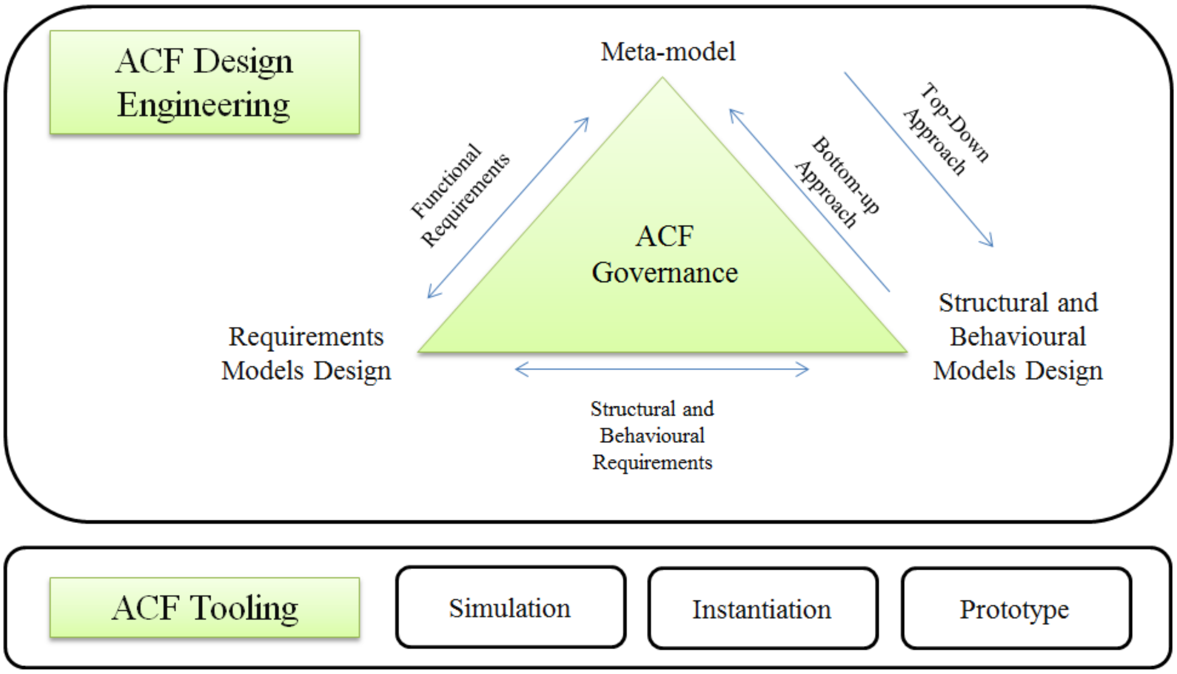

Figure 4 - 1 Overview of the ACF framework

The Design Engineering part is composed of three main components:

- A set of Functional, or Requirements Models (see section 4.2.2), representing graphically the certification Requirements. Applying the classification presented in Table 4-1, the Part 21 requirements are structured and modelled in a graphical manner;
- A set of Structural and Behavioural Models (see section 4.2.3 and 4.2.4), describing the structural and behavioural requirements;
- A Metamodel (see section 4.1.3) describes the concept definitions of the methodological approach.

Table 4 - 1 The Requirements Classification according [39], [161]

REQUIREMENTS CATEGORY	OBJECTIVE
FUNCTION	The purpose of a system
BEHAVIOUR	The way a system acts
STRUCTURE	The components of a system and their relationships

The requirements models and the processes are built with a free, open source SysML editor called TTool [162]. TTool includes a diagram editor, a simulator, complementary verification modules (model checking, verification by abstraction), and several code generators. The Tooling part offers the capability to perform simulations on behavioural diagrams, so to verify the models and particularly to identify potential bottlenecks that might have to be removed. Moreover, simulations provide a means to instantiate, test or evaluate the models with data from an SME currently involved in the development of innovative airborne systems.

The feedbacks provided by data and stakeholders are used to improve the models and the metamodel and to validate the general approach. Some instantiations will be presented in Chapter 5 through the application of the ACF to a case study.

Both simulation and instantiations are used as verification and validation technics for the completeness and the consistency of the models.

In addition a prototype has been developed to test the feasibility to centralize the data of the framework in one unique environment (see Appendix G for a short description of the prototype).

4.1.3. Structure of the Framework

The **Aircraft Certification Framework (ACF)** is inspired by the four-layer model hierarchy proposed by the OMG[45] and proposes an architecture with three layers (see Figure 4-2):

- A layer with a metamodel (M2);
- A layer with a set of models (M1);
- A layer with real data coming from SMEs (M0).

The idea is to achieve coherence between models. As illustrated in figure 4-2, it is possible to trace a concept from its definition (M2 level), through the modelling (M1 level) and finally to its actual use (M0 level). This three-layer architecture is a structuring mechanism that helps to reason on our models and classifications.

[45] https://www.omg.org/ocup-2/documents/Meta-ModelingAndtheMOF.pdf

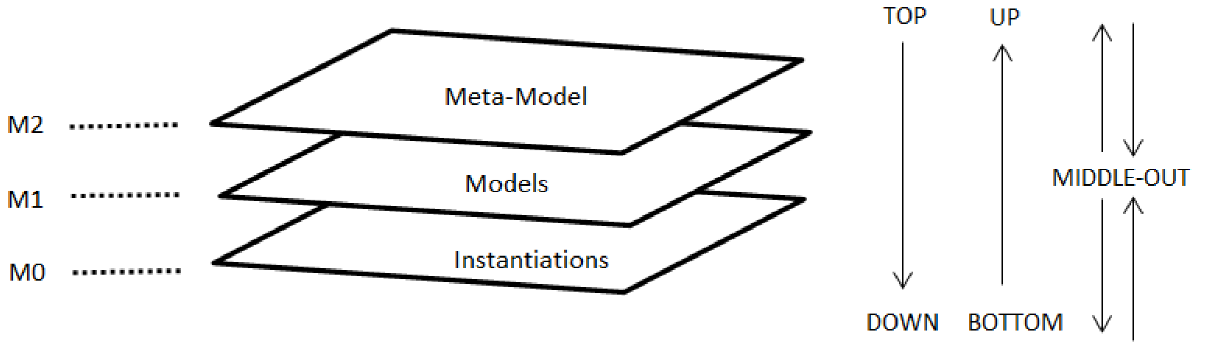

Figure 4 - 2 Top-Down, Bottom-Up and Middle-Out approaches of ACF approach

In this approach, the three layers are coherent and consistent, building a reliable representation of the organisation. In addition, the modelling approach was conceived using three steps, working together concurrently:

- A « Top-Down » approach,
- A « Bottom-Up » approach,
- A hybrid approach called « Middle-Out » approach.

The « Top-Down » approach constitutes one type of analysis of process modelling. The construction of the layer M2 is the starting point of this kind of analysis. M2 synthetizes the framework concepts and supports the building of the next layers M1 and M0.

The « Bottom-Up » approach constitutes another type of analysis of process modelling, starting from the data and experience coming from the SMEs (M0). This approach allows to identifying the need from the industry and building the adapted processes development (M1). It enables to make evolve the metamodel (M2).

« Top-Down » and « Bottom-Up » approaches are complementary and improved through **the « Middle-Out » approach**. The M1 layer is built initially according to identified scenarios and are updated in return thanks the two other approaches.

Based on the assessment of the available languages to model processes (Cf. section 3.2), SysML has been chosen for its ability to represent requirements, processes and make the link between. Among the nine SysML diagrams available to represent a system, the framework uses only six diagrams:

- Three Structural Diagrams (see section 4.3.3 for further details)
  - Package diagrams
  - Block Definition Diagram
  - Requirement Diagram
- Three Behavioural Diagrams (see section 4.3.4 for further details)
  - Use Case Diagram
  - State Machine Diagram
  - Activity Diagram

4.2. PROPOSAL FOR DESIGN ENGINEERING

4.2.1. Context and Use Cases

In this thesis, the context of modelling is focused on certification activity and requirements coming from regulation. Use case diagrams enable to represent the context of the modelling approach. they are central in modelling using SysML [115]. It enables to identify quickly:

- The boundaries of the modelling;
- The use cases;
- The actors; and
- The relations between use cases and actors.

The Figure 4-3 illustrates the main scenarios of the use case “Initial Airworthiness – Part 21” for the process of “Certification Management” for either an aircraft manufacturer, an engine manufacturer or a part/appliance manufacturer (see section 2.2.3, part D, as well as Table 2-3). As shown, three kinds of actors are involved in the certification process:

- The different roles inside the Enterprise as expected by the regulation;
- The Certification Authorities positions;
- The Suppliers.

The central “Initial Airworthiness – Part 21” is described with the different possible scenarios: <<include>> mentions specific cases, <<extend>> indicates extensions on the use case. This “Initial Airworthiness – Part 21” includes, in any case, the following two scenarios:

- “General Provisions - Subpart A”;
- “Identification of Products, parts and Appliances - SubPart Q”;

Then according to the context, three different use cases may be identified:

- “Certificate Airworthiness - Subpart H”, basically for an aircraft manufacturer;
- “TC Application - SubpartB”, basically for an engine manufacturer;
- “ETSO Application - Subpart O”, basically for a part/appliance manufacturer.

In case of an aircraft manufacturer, “Certificate Airworthiness - Subpart H” is referred to and then additional use cases are included:

- “Noise Certificate - Subpart I”;
- “TC Application - SubpartB” including itself:
  - “Change Management - SubPart D”;
  - “Repair Management - Subpart M”;
  - “Design Agreement - Subart J”;
  - “Production Agreement”.

Additionally, “Certificate Airworthiness - Subpart H” may be extended by the use case “Permit to Fly - Subpart P”. For example, it is the case if the organisation has not been granted of any privilege to issue the permit to fly by itself.

“TC Application - Subpart B” may be extended by:

- The use case “ETSO Application - Subpart O” if the organisation has the strategy to certify some sub-parts of the aircraft as well or by the use case; or
- The use case “Supplemental TC - Subpart E”.

For simplification, the Figure 4-3 does not detail the use cases for the engine, parts or equipment manufacturers, but the logic remains the same.

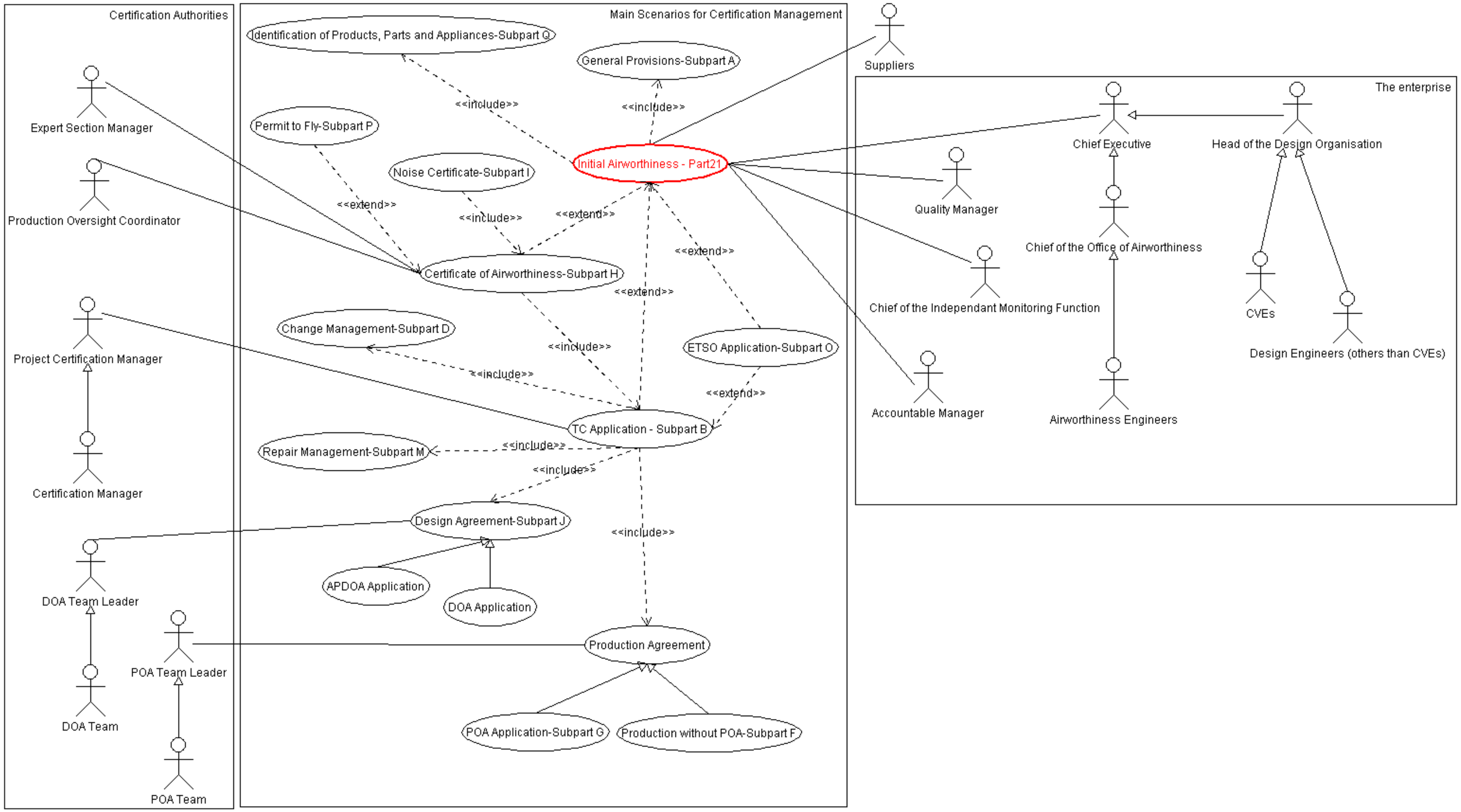

Figure 4 - 3 Description of the Use case “Initial Airworthiness”

4.2.2. Metamodel

The Metamodel (See Figure 4-4) represents the concepts definitions of the methodological approach for certification in one model.

The requirements are considered as an important concept of the metamodel. Acceptable Means of Compliance (AMCs, see section 2.1) are proposition to demonstrate that the requirements are implemented. AMCs are provided by EASA and are part of the regulation. The Means Of Compliance (MOC) are the means chosen by the enterprise to demonstrate that all tasks and activities have been carried out. Proofs of Compliance (POCs) are evidence that the requirements have been implemented through the processes. Justifications are part of the analysis of the requirements and the construction of the Acceptable Means of Compliance (AMCs). To simplify assumptions and arguments are not taken into account in this metamodel.

Each process, by its structure and its behavioural design, focuses on at least one objective and is compliant with the relevant certification requirements. Some certification requirements may be associated with AMCs. The enactment of each process results in at least one Proof Of Compliance (POC) with the certification requirements as discussed in section 2.1. Each process is composed of at least one activity. Each activity, with at least one task, is linked to a role which is either inside (internal role in the enterprise) or outside the company through a customer or supplier role (Tier 1-3). Additionally, some activities and/or tasks can be executed by more than one role.

The Figure 4-4 focuses on the certification process. It can be stated that assessing the realisation, management and support processes result in similar representation. For those processes the approach remains the same.

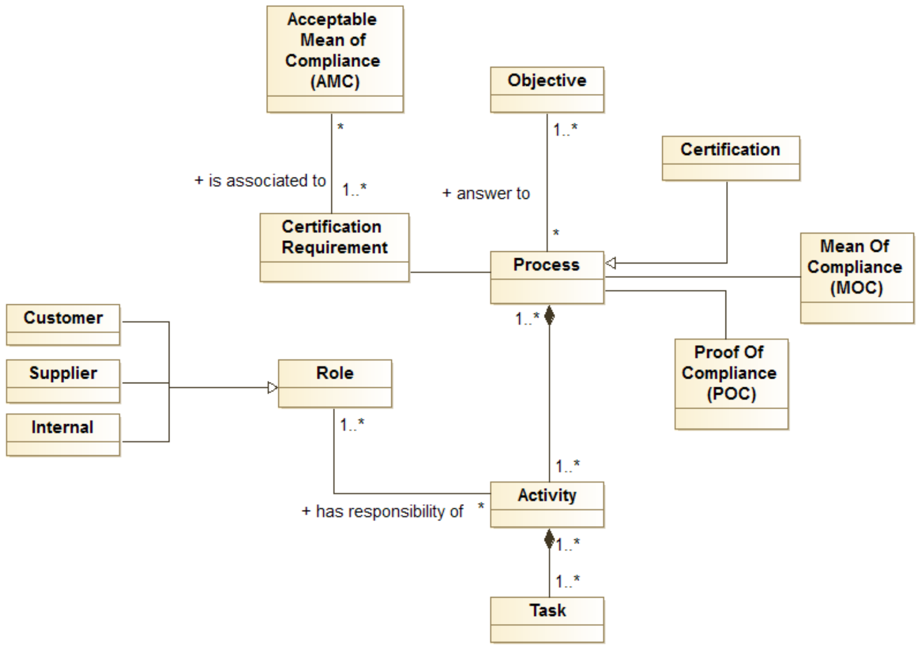

Figure 4 - 4 Metamodel supporting the framework for certification purposes

4.2.3. Process Requirements and Requirements Diagrams

SysML Requirements Diagrams (RDs) enable to represent the requirements graphically, focusing on the relations between them and with some other elements coming from other SysML Diagrams. According to [115], six types of relationships exist in SysML RDs:

- Derive → Design purpose
- Nesting → Requirements Composition
- Satisfy → Traceability and coverage
- Trace → Requirements Association
- Refine → Design purpose
- Verify → Traceability, verification and coverage

Nesting type of relationships allows detailing the hierarchy between the requirements whereas Trace type of relationships allows being less specific. Enabling to link Test cases and System blocks, traceability, verification and coverage with the system elements are embedded with this kind of representation. Derive and Refine relationships allow adding more details about the system description. Derived requirements are requirements not explicitly stated in the requirements baseline but introduced during the requirements management process due to necessity for the design, the architecture, or any decision making process. A refinement should bring clarification to the requirement context.

Figures 4-5, 4-6 and 4-7 constitute examples of RDs. These figures are based on section 2.2.2, Table 2-2. They illustrate the high-level requirements from Part 21, using only nesting relationships. The different subparts of the Part 21 are more comprehensively shown and the links between the different subparts of Part 21 are highlighted.

Figure 4-5 shows the requirements diagram for an aircraft manufacturer. The "Top requirement" subpart is Certificate of Airworthiness (CoA) and Restricted Certificate of Airworthiness (RCoA), "CoA and RCoA" (subpart H) in Figure 4-5. Additionally one main subpart can be identified: Subpart B, for a Type Certificate (TC) and Restricted Type Certificate (RTC), "TC and RTC" in Figure 4-5. It is a product oriented certificate.

In Figure 4-6, the requirements diagram for an engine manufacturer shows the same main subpart but in this diagram it constitutes the "Top requirement" subpart.

In Figure 4-7, the requirements diagram for a part/appliance manufacturer shows that the "Top requirement" subpart is Subpart O, for a European Technical Standard Order (ETSO), "ETSO" in Figure 4-7, which is part and appliance oriented certificate.

The three diagrams show that the "Top requirement" subparts have a nesting link with subparts A and Q. Also they show that Subpart B requires compliance with more subparts than Subpart O. Figures 4-5 and 4-6 have been simplified as ETSO is part of them but remains optional. This requirement refers to Figure 4-7.

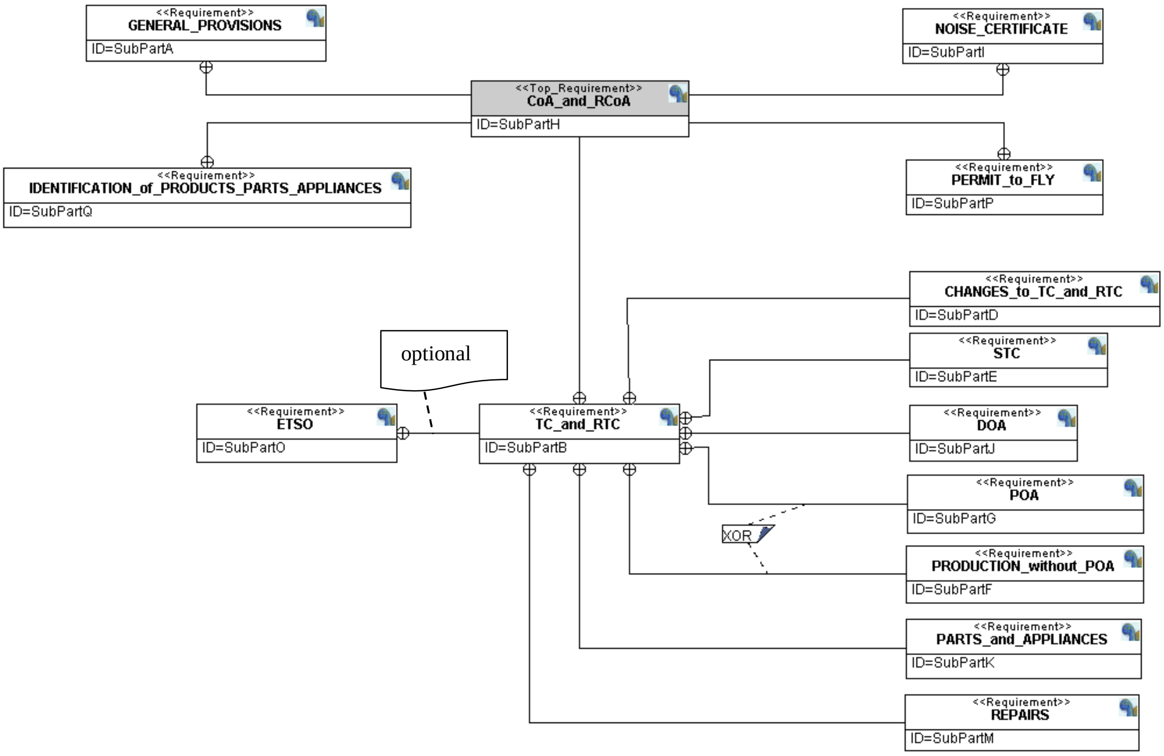

Figure 4 - 5 Certification Requirements Diagram for an aircraft manufacturer

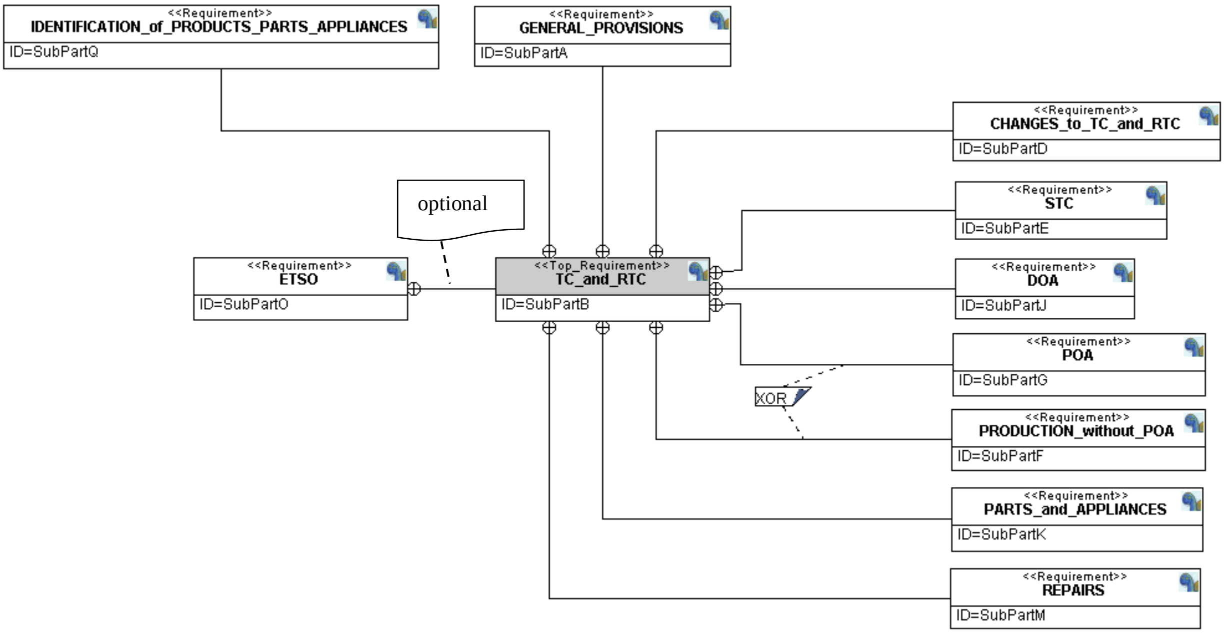

Figure 4 - 6 Certification Requirements Diagram for an engine manufacturer

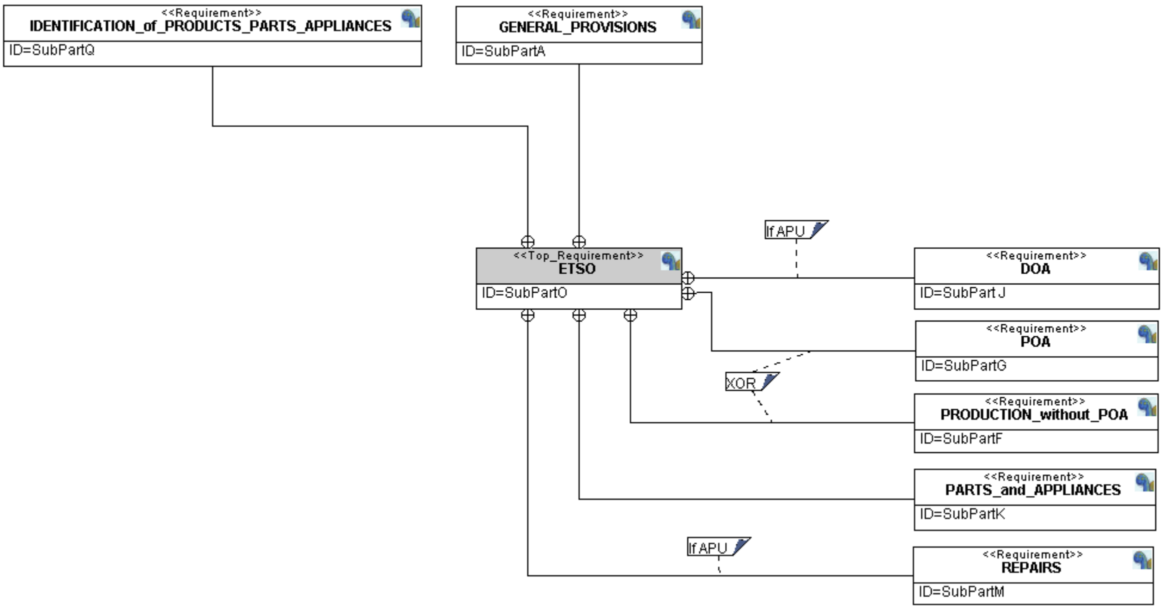

Figure 4 - 7 Certification Requirements Diagram for a part/appliance manufacturer

The critical requirements from Subpart J (see section 2.2.3) are defined mainly in Part 21, article 21.A.239 with the constitution of a Design Assurance System (DAS) for the control and supervision of the design and design changes. The DAS shall include the following activities:

- Control the design;
- Assess compliance with any applicable requirements;
- Independently check the compliance;
- Liaise with the Agency;
- Continuously evaluate the design organisation;
- Manage subcontractors, including assess the process and design assurance quality against the contract.

Figure 4-8 shows these requirements in a requirements diagram, highlighting the different aspects to be taken into account.

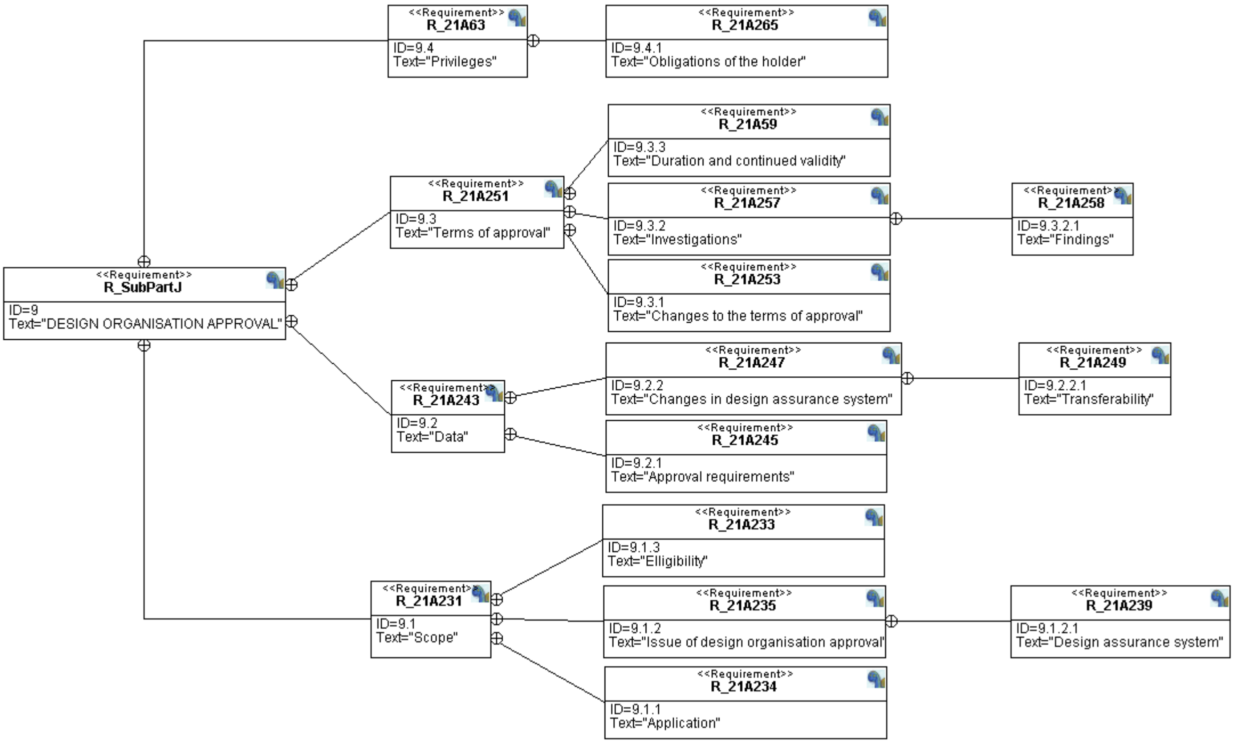

Figure 4 - 8 Requirements Diagram for Part 21-SubPart J

The critical requirements from Subpart G (see section 2.2.3) are defined mainly in Part 21, article 21.A.139 with the constitution of a Quality Assurance System (QAS) for the control and supervision of the production and production changes. The QAS shall include the following activities:

- Control the production;
- Assess compliance with the design;
- Independently check and monitor the compliance;
- Liaise with the Agency;
- Continuously evaluate the production organisation;
- Manage subcontractors, including assess the process and product quality against the contract.

Following the same logic, Figure 4-9 illustrates these requirements.

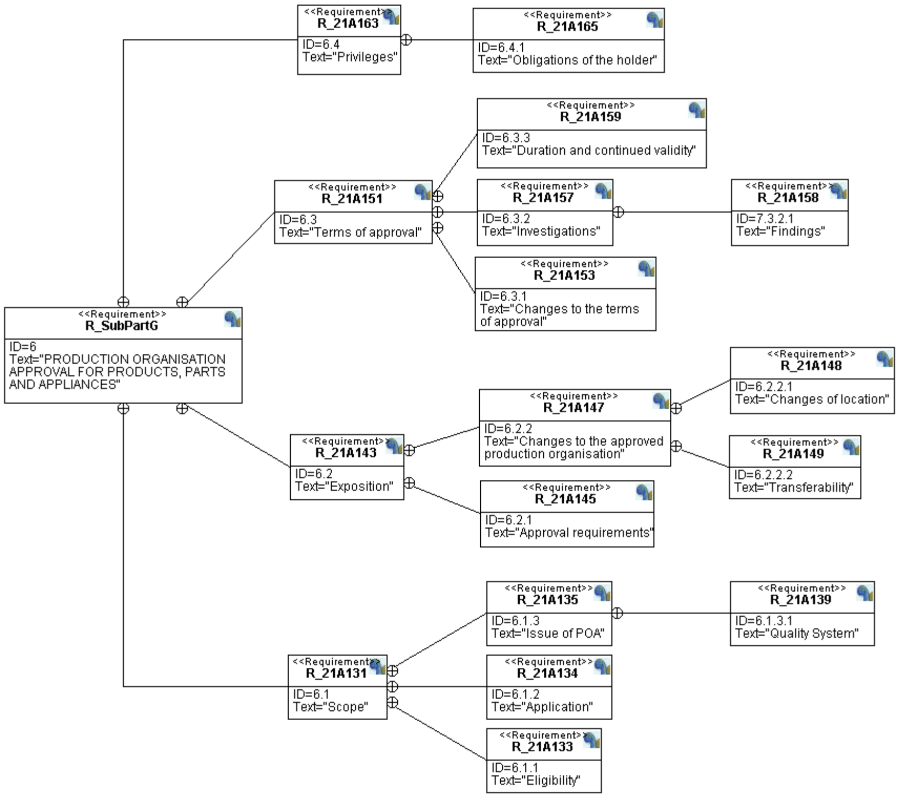

Figure 4 - 9 Requirements Diagram for Part 21-SubPart G

This modelling of the requirements of all 14 subparts needs to be done so to have a better overview of the requirements to be addressed. This section has merely shown some of those requirements diagrams.

4.2.4. Structural Process Models

So to go more in detail on the contents of the framework, for the organisation (the system of interest), use is made of SysML's Block Definition Diagrams (BDDs), so to represent the structure of the system from an external point of view, and of Internal Block Diagrams (IBDs), so to represent the internal structure of the system blocks. BDDs and IBDs describe the system hierarchy providing a static description of the system, a structural representation of the necessary processes. The structural diagrams produced in this research depict the necessary and sufficient processes needed for compliance with Part 21 and their composition and represent graphically the structure of the organisation.

Inspired by the OMG BPMN approach and the definition of process from [50] and [97], four different types of element are created to describe the composition of the organisation:

- Package for Process Groups;
- Process for Elementary Processes;
- Activity to describe the processes elementary elements; and
- Task to describe the composition of the activities.

Figure 4-10 illustrates this approach and figure 4-11 provides an example. At the highest level, each process group is composed of a set of processes which can be described internally with some intrinsic parts, called activities that in turn are composed of different tasks. The Tasks are the lowest level of description of the organisation.

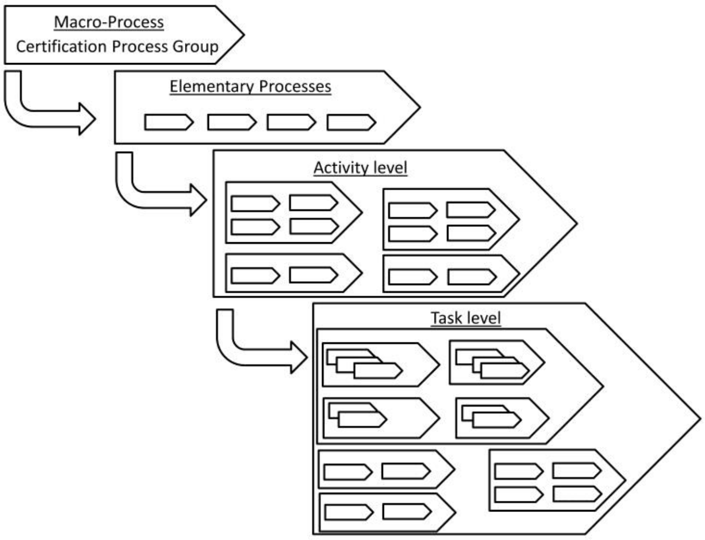

Figure 4 - 10 Structural approach for certification processes package

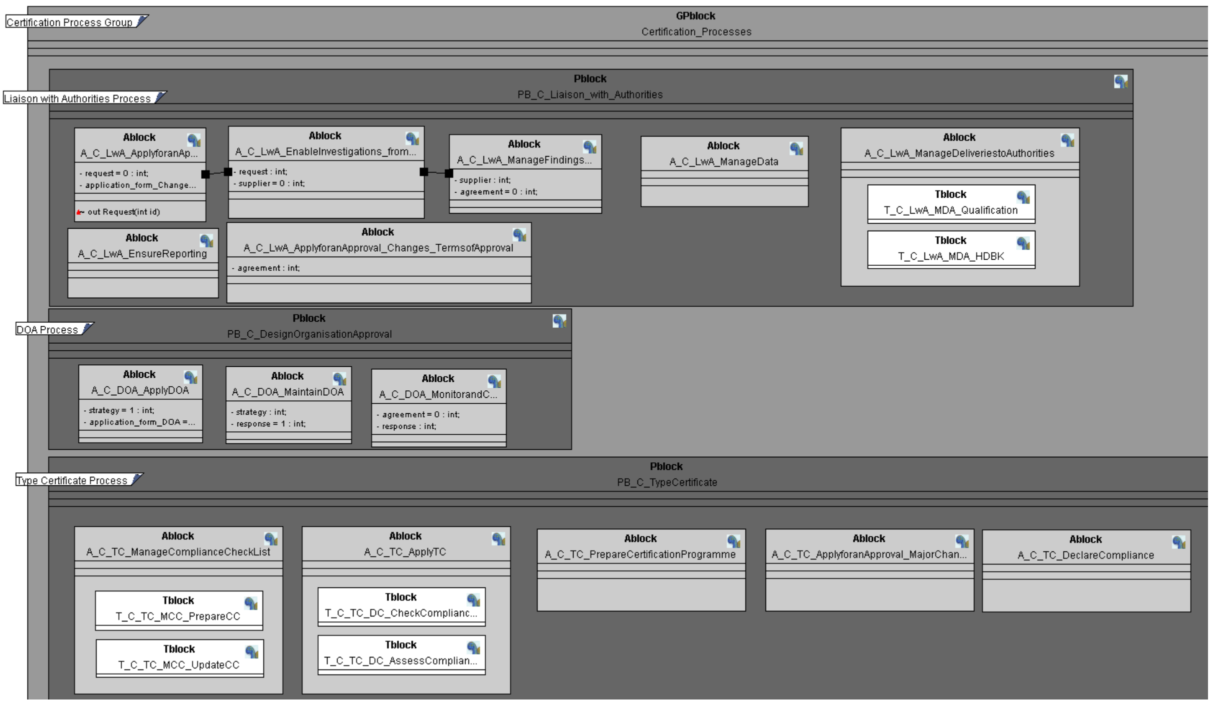

Figure 4 - 11 BDD of Subpart J (extract)

TTool (the tool used in this research) makes no distinction between BDDs and IBDs, only BDDs exist. TTool BDDs enable to analyse the coverage of the system requirements and ensure the traceability between the system elements allowing a part of verification activities on the system design. Figures 4-12 and 4-13 represent two examples of RDs updated with coverage of the requirements with BDDs elements.

4.2.5. Behavioural Process Models

Behavioural Models provide a dynamic description of the organisations' activities, their ordering and dependencies. SysML activity diagrams and SysML state machine diagrams are used to model the system behaviour. As illustration, Figures 4-14 and 4-15 represent two examples of behavioural diagrams with behavioural aspects of the certification requirements. Figure 4-14 represents an extract of the Generic Development Process from the Identification of Aircraft Level functions to Design of System Architecture. Figure 4-15 represents the overview of the Type Certification process.

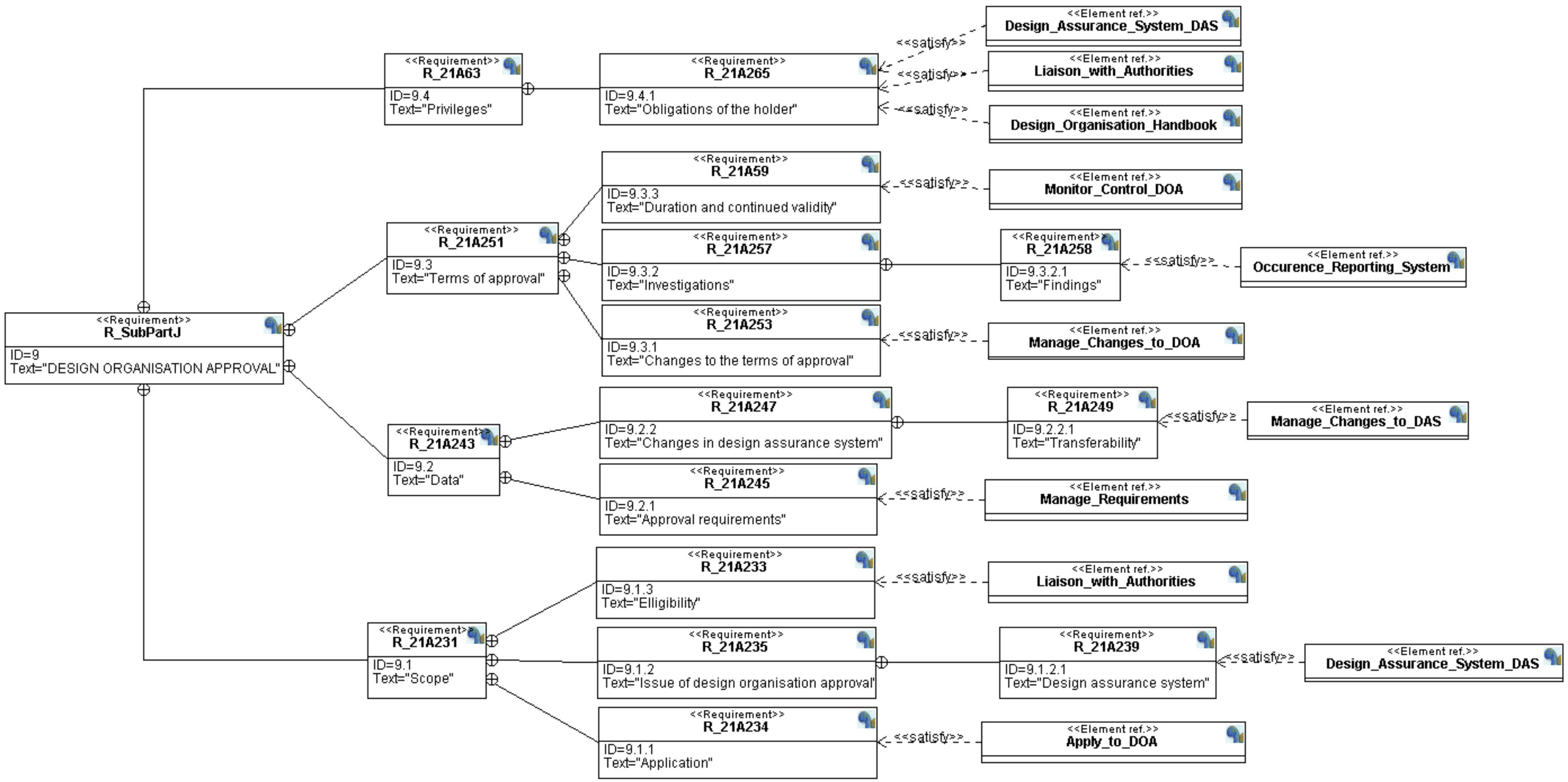

Figure 4 - 12 RD representing subpart J with BDDs coverage (TTool)

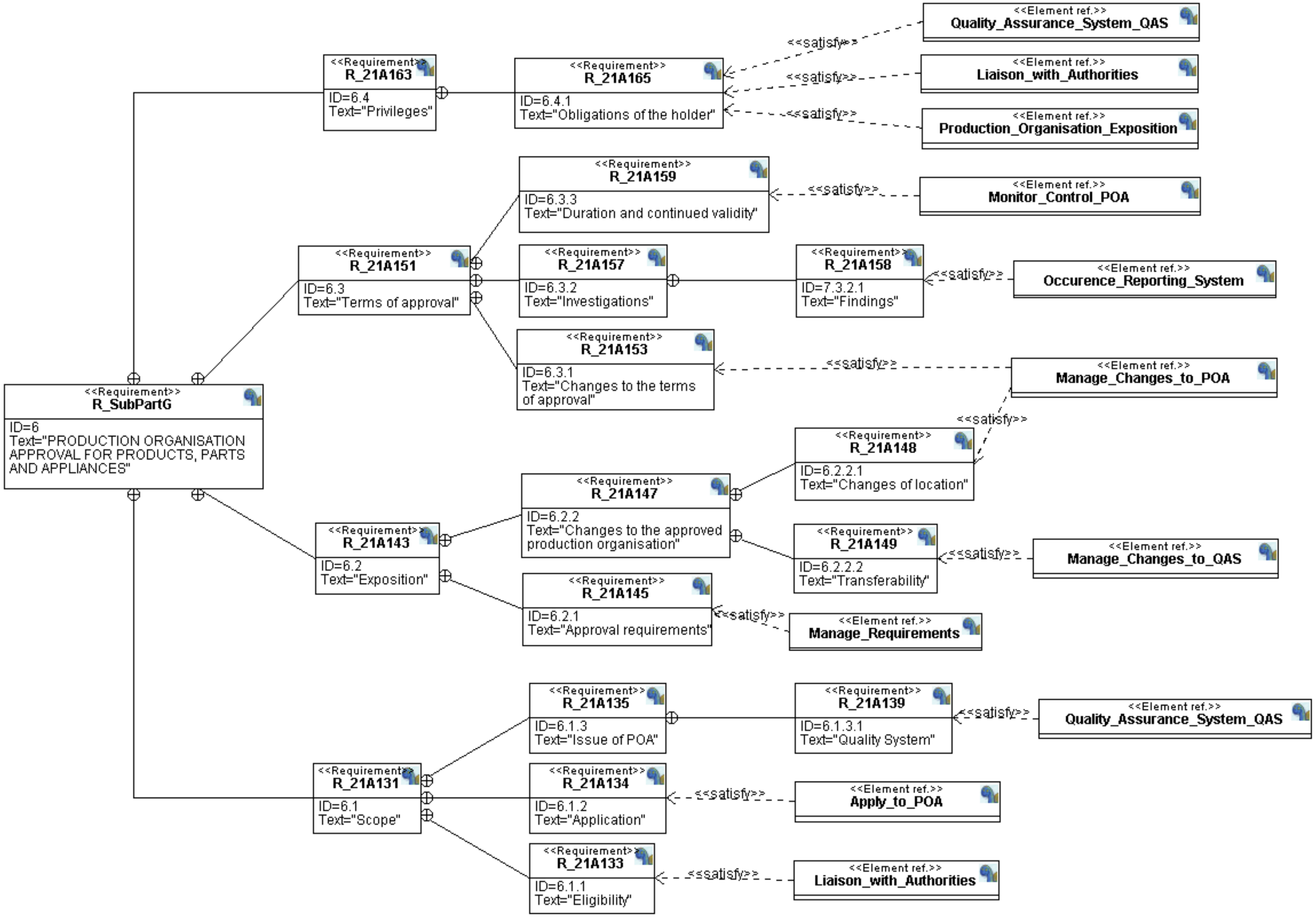

Figure 4 - 13 RD representing subpart G with BDDs coverage (TTool)

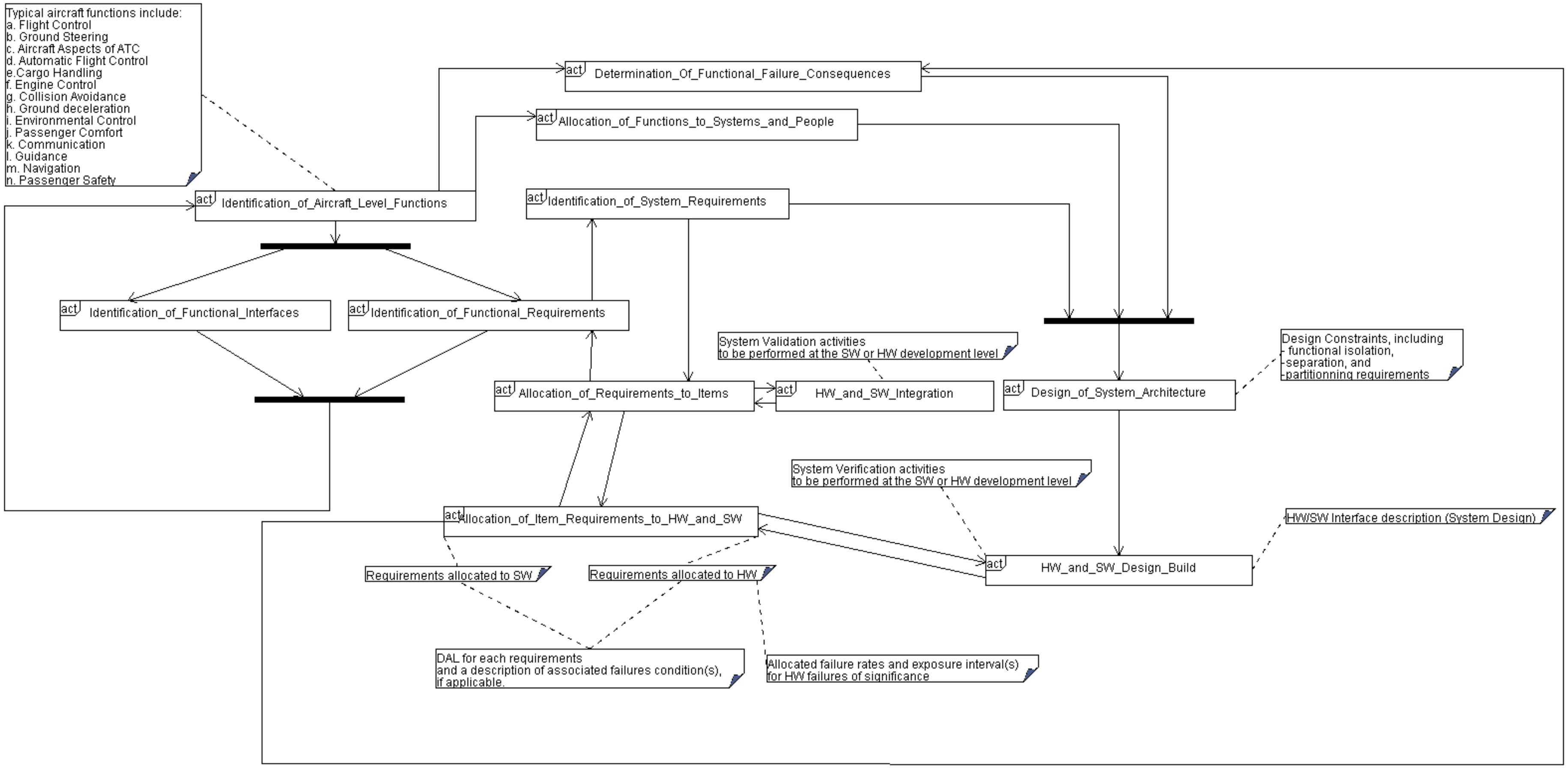

Figure 4 - 14 Activity Diagram of the Generic Development Process (TTool)

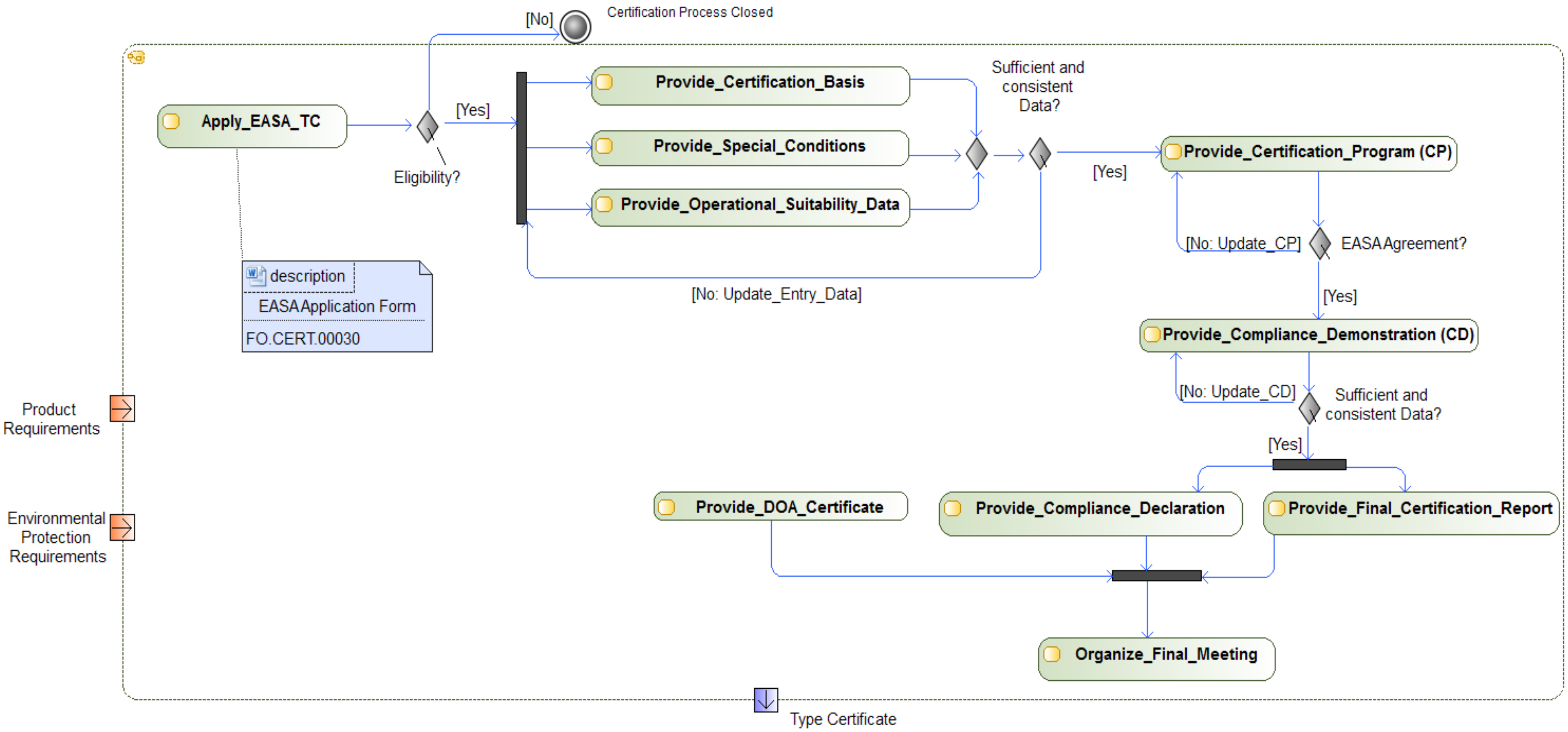

Figure 4 - 15 Activity Diagram representing the Type Certification Process

4.3. PROPOSAL FOR GOVERNANCE

4.3.1. Introduction

In Part 21, some certificates are linked, depending on each other or on the contrary are mutually exclusive. In this last case, applying for one certificate may exclude applying for another one. Thus, an organisation aiming to comply with Part 21 will not need to comply with all aspects described in the text. We assume that an organisation first has to identify its eligibility for a potential application for compliance to each subpart (see Table 2-2).

Section 2.2 underlines that Part 21 allows different objectives for certification. As an example, Table 4-2 shows the available options to demonstrate design capability according to a specific type of design. According the design of the project, the certification strategy and the effort for the organisation will be different.

Table 4 - 2 Demonstration of capability[46]

	Demonstration of capability			
Type of Design	DOA	AP DOA	CP	None
Aircraft Type certificate				
-All Aircraft	Yes			
-ELA2	Yes	Yes		
-ELA1	Yes	Yes	Yes	
Engine Type Certificate				
-All Engines	Yes			
-Piston Engine	Yes	Yes		
-Engine installed in ELA2 Aircraft	Yes	Yes		
-Engine installed in ELA1 Aircraft	Yes	Yes	Yes	
Supplemental Type Certificate (STC)				
-All STC’s	Yes			
-STC Group 1 [47]	Yes	Yes		
-STC Group 2 [48]	Yes	Yes		
-STC on ELA1 or its engine or propeller	Yes	Yes	Yes	
Minor changes	Yes	Yes	Yes	Yes
Repairs				
-Minor	Yes	Yes	Yes	Yes
-Major	Yes	Yes		
-Major on ELA1 or its engine or propeller	Yes	Yes	Yes	
ETSO		Yes		

For well-established OEMs with a strong foundation and experience in certification activities, the list of certification requirements may be more stable than for a new entrant. In SMEs, often the general manager of a company is responsible for the decision to apply for certification, and bears sole responsibility for the process. This thesis proposes a way to

[46] https://www.easa.europa.eu/easa-and-you/aircraft-products/design-organisations
[47] For definition, see GM No 1 to 21.A.112B
[48] For definition, see GM No 1 to 21.A.112B

accelerate the certification process, supporting strategic decisions for each step of the certification.

Governance is a way to manage the enterprise's decision to apply for certification, but it is much more than project management. Governance determines both the organisational and business strategies [39]. Following section 3.3, a decision support for the enterprises is needed, so to enable them to select the right approach to the certification process. In this section, a proposal is made for the implementation of such a decision support.

4.3.2. Structure of the Governance

Certification Governance is introduced (see figure 4-16) and is defined as a decision-making process starting from the analysis of a specific context (the inputs), that constitutes a set of knowledge needed to generate a decision (the output) composed of a dedicated certification strategy, some certification requirements, and specific process-oriented objectives.

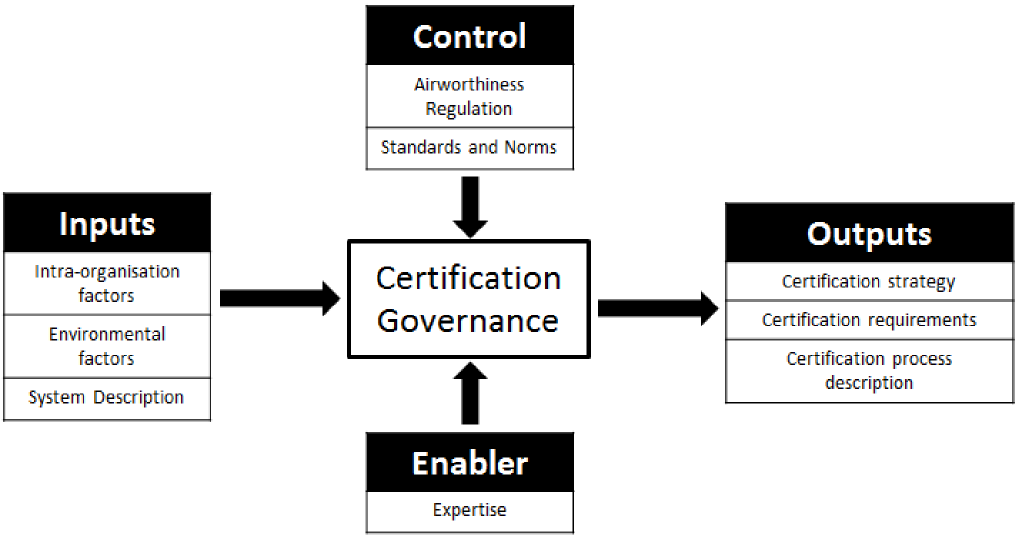

Figure 4 - 16 Certification Governance Principles

Expertise in certification domain is identified as the main enabler in our context (experience, rules of thumb …). Documentation of the certification process may be one of the resources resulting from expertise. Control is coming mainly from aviation regulation. Guidelines, more or less imposed to the enterprise, may impact the decision process as well. The necessary knowledge to develop a new airborne system is accounted for as "Inputs". The Certification Governance requires knowing:

- Intra-organisation factors, characteristics of the organisation itself like the size of the enterprise (total number of employees), the types of activity of the enterprise, its market strategy;
- Environmental extra-factors, characteristics of the system to be developed such as the type of aircraft, its weight, or its operational conditions;
- System description.

The Certification Governance first generates the certification strategy: a list of certificates fitted to the situation and the context of the enterprise. Then the choice of strategy will result in the necessary certification requirements and a certification processes description with adequate certificates objectives (Structural diagrams and behavioural diagrams as described in sections 4.2.3 and 4.2.4).

4.3.3. Rules of the Governance

Certification Governance aims to help organisations during transition, anticipating the strategic decision needed to acquire the necessary regulatory certificates. A first approach is to see the problem space as a decision tree, explored by the decision maker. The decision is then enabled by a simple deterministic tool (See Figure 4-17). Each final decision is composed of a set of several decisions to apply for different certificates, defining a general strategy for the organisation. The last leaf of each branch of the tree is then defined as one particular strategy.

This approach has many advantages. It is simple enough to be understood by an organisation without any specific training. It enables a better understanding of the relations between the different subparts and the different certificates required by regulation. However, this representation has the disadvantage of being static. Moreover, any missing information might lead to a bottleneck in the reasoning process. Each question at each of the nodes requires an answer to identify the best strategy.

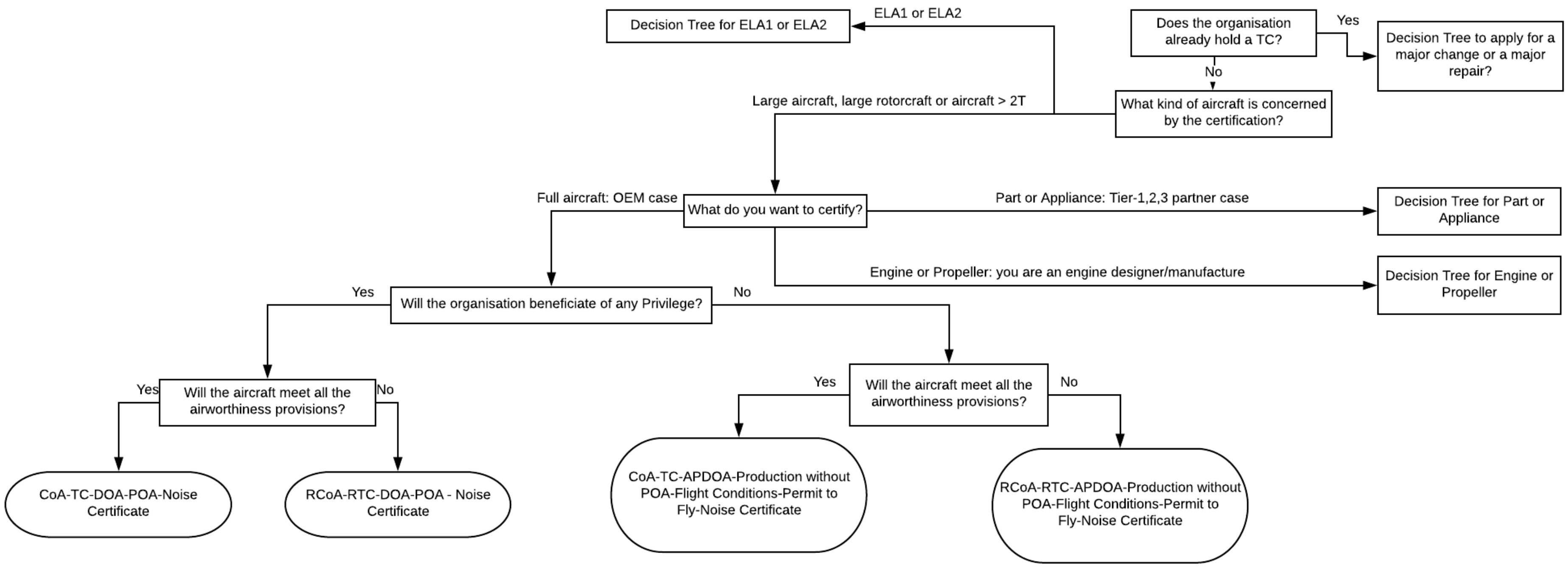

Figure 4 - 17 Extract of the decision tree as suggested by Initial Airworthiness (Part 21)

An alternative approach is proposed, with the use of expert system technologies [163], integrating the requirements as decision rules. A rule-based system allows to taking into account the time dimension, the potential conflicts between the solutions to be managed, as well as partially available information. A decision rule constitutes a mapping from a set of conditions to an outcome. Certification Governance may be seen as an inference engine managing a knowledge base and a set of facts to generate a certification strategy. The knowledge base is then a set of rules defined in the following form: IF <conditions> THEN <actions list>. The behaviour of the expert system's inference engine then allows a reasoning process leading to a recommendation on the strategy to be adopted. Table 4-3 shows an extract of rules that are included in the expert system built in the CLIPS environment.

Table 4 - 3 Decision Rules for Certification Governance (extract)

ID	Rule content	Rule Meaning
Rule 1	{|If Aircraft='>2T' and Organisation='OEM' Then MainStrategy='CoA'.|}	An integrator aiming to market an aircraft over 2T shall request for a Certificate of Airworthiness.
Rule 2	{|If MainStrategy='CoA' Then MainCertificate='TC'.|}	An organisation applying to a Certificate of Airworthiness shall apply to a Type Certificate.
Rule 3	{|If MainCertificate='TC' Then DesignCertificate='Y'.|}	An organisation applying to a Type Certificate shall apply to a design approval.
Rule 4	{|If MainCertificate='TC' Then ProductionCertificate='Y'.|}	An organisation applying to a Type Certificate shall apply to a production approval.
Rule 5	{|If MainCertificate='TC' and AirworthinessProvision='Yes' Then ValidatedCertificate='TC'.|}	An organisation applying to a Type Certificate and demonstrating enough Airworthiness provision can validate its request for a Type Certificate.
Rule 6	{|If MainCertificate='TC' and AirworthinessProvision='No' Then ValidatedCertificate='RTC'.|}	An organisation applying to a Type Certificate and failing to demonstrate enough Airworthiness provision shall request for a Restricted Type Certificate instead of a Type Certificate.
Rule 7	{|If MainCertificate='TC' and Privilege='Yes' Then FC='No' and PtF='No'.|}	An organisation applying to a Type Certificate and having privileges will not have to request for a Permit to Fly or Flight Conditions.
Rule 8	{|If MainCertificate='TC' and Privilege='No' Then FC='Yes' and PtF='Yes'.|}	An organisation applying to a Type Certificate and having no privileges will have to request for a Permit to Fly and Flight Conditions.
Rule 9	{|If MainCertificate='TC' Then NoiseCertificate='Yes'.|}	An organisation applying to a Type Certificate will have to request for a Noise Certificate.
Rule 10	{|If Aircraft='>2T' and Organisation=Subcontractor and Part<>'propeller' and Part<>'engine' Then MainStrategy='ETSO'.|}	An integrator aiming to market an equipment for an aircraft over 2T shall request for an ETSO if the part is neither an APU, a propeller nor an engine.

4.3.4. Maturity Model

Referring to sections 2.2 and 3.4, the necessity of a dedicated maturity model to certification objectives was established. Such a model will impact the rules in the expert system. In this thesis, a model with different levels of maturity has been developed, addressing only OEMS objectives. This model will allow guiding SME's overtime in their evolution, to adapt the strategy with an increased maturity.

Recalling that the system of interest is the organisation, Figure 4-18 shows the organisation evolution over time for an aircraft manufacturer. For example, with some initial experience, a "level 1" can be reached at the end of the Preliminary Design. In this maturity model, five levels are defined. Figures 4-18 shows how the five levels are sequenced during the aircraft development timeframe.

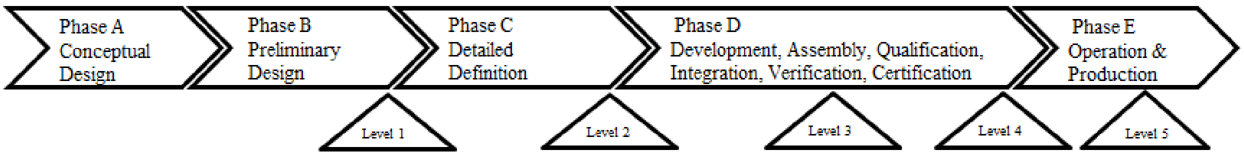

Figure 4 - 18 Development cycle and Maturity Gate for an aircraft manufacturer

For each "Level", some specific objectives are associated:

- Main objective of Level 1 is to put in place the necessary processes to prepare the EN 9100 certificate. A Quality Management System (QMS) and its processes are required.
- Main objective of Level 2 is to put in place the necessary processes to get the Design Organisation Approval. A Design Assurance System (DAS) and its processes are required by EASA.
- Main objective of Level 3 is to put in place the necessary processes to get the Production Organisation Approval. A Quality Assurance System (QAS) and its processes are required by EASA.
- Main objective of Level 4 is to put in place the necessary processes to get the Type Certificate and the Certificate of Airworthiness. A full Safety Management System (SMS) and its processes are required by EASA.
- Main objective of Level 5 is to put in place the necessary processes to cover the continued airworthiness. Continuing Airworthiness and concerned Parts such as ¨Part-M, Part-145, Part-66, etc are not the purpose of this report. The update of the SMS (SMS+) and its processes are required.

D. Level 1 : Quality Management System (QMS)

This level is reached thanks to the EN 9100 objectives. Each element of a Quality Management System (QMS) helps to achieve the overall goals of meeting the customers' and organization's requirements. The requirements for this Level 1 include:

- the definition of the organization's quality policy and quality objectives;
- the definition of the QMS and its processes and instructions;
- the management of the QMS records;
- the customer satisfaction follow-up;
- the QMS monitoring and control;
- the continuous QMS improvement;
- a risk-based thinking;
- the necessary performance indicators;
- the non-conformity management.

Inspired by the PDCA cycle (see Figure 3-2), the objectives of the level 1 help the organisation to structure itself before being able to answer to the EASA certification requirements.

E. Level 2 : Design Assurance System (DAS)

This level is reached by being compliant to the Subpart J requirements. The requirements for this Level 2 include a Design Assurance System (DAS) (see section 2.2.3 and 4.2.2).

F. Level 3 : Quality Assurance System (QAS)

This level is reached by being compliant to the Subpart G requirements. The requirements for this Level 3 include a Quality Assurance System (QAS) (see section 2.2.3 and 4.2.2).

G. Level 4 : Safety Management System (SMS)

This level is reached by being compliant to the all subparts necessary to get the TC and the CoA, establishing a real Safety Management System (SMS) in the organisation and the necessary conditions for the entry into service of the aircraft. The requirements for this Level 4 include requirements from subparts A, B, D, E, G, H, I, J, K, M, O, P, Q.

H. Level 5 : SMS+

This level is reached by ensuring a continuous improvement of the Safety Management System (SMS) whatever the events after entry into service of the aircraft.

In addition, for each "Level", the evolution regarding Systems engineering, project management, the integration between these two approaches and the MBSE knowledge are developed and exposed in Table 4-4.

Table 4 - 4 Proposed Maturity classification (inspired by [155])

LEVEL	OBJECTIVE	SYSTEMS ENGINEERING KNOWLEDGE (SE)	PROJECT MANAGEMENT KNOWLEDGE (PM)	INTEGRATION OF SE AND PM	MBSE KNOWLEDGE
1	QMS	Not known	Not known	There is no Systems Engineer in the organisation.	Not known
2	DAS	Unknown, or known and misunderstood.	Unknown, or known and misunderstood.	Systems Engineer and Project Manager are working independently without mutual discussion.	Unknown, or known and misunderstood.
3	QAS	Generally known in the entire organisation but cannot be fully deployed (lack of resources).	Generally known in the entire organisation but cannot be fully deployed (lack of resources).	Systems Engineer and Project Manager are discussing together. Tasks are done in parallel and several tasks are done twice.	Generally known in the entire organisation but cannot be fully deployed (lack of resources).
4	SMS	Generally known in the entire organisation. Its relevance is accepted locally and it is applied.	Generally known in the entire organisation. Its relevance is accepted locally and it is applied.	Systems Engineer and Project Manager are working together sharing same indicators. Some tasks are still done in parallel and sometimes twice.	Generally known in the entire organisation. Its relevance is accepted locally and it is applied
5	SMS+	Its relevance is accepted, understood and used in any relevant project.	Its relevance is accepted, understood and used in any relevant project.	Systems Engineer and Project Manager are working in symbiosis.	Its relevance is accepted, understood and used in any relevant project.

4.3.5. Risks and opportunities management tool

A framework for risk assessment able to support the decision making in the certification process is proposed, so to assess the internal situation in the organisation and particularly to categorize the certification risks and opportunities. The approach is used to assess the situation in the organisations. Tables 4-5 and 4-6 provide respectively the risk impact levels definitions (in this case, reaching the Type Certificate as example) and the categories of the risk occurrence during certification.

Table 4-5 presents the risk impact classification to the achievement of the Type Certificate as planned and in accordance with the resources and the agreements with EASA. Low level risks do not require any change in organization or TC planning but provide a temporary additional pressure on the teams. Medium level risks require a modification to the planning but not additional resources and no new agreement with EASA. Any potential planning delay may be absorbed in the global planning. High level risks have a huge impact on the organisation as they require new resources and a new agreement with EASA. Very high level risks have a huge impact on the TC issuance and may provoke the end of the project or a redefinition of the agreement with EASA with the examination of a complete new TC. For other certificates, similar categorisation can be made.

Table 4 - 5 Risk impact definition

	IMPACT			
	Low	**Medium**	**High**	**Very High**
Planning	Additional team effort but no Impact on the TC Planning	Additional team resources required to accommodate the TC Planning	Additional team resources required and agreement with EASA to accommodate the TC Planning delay	TC not achievable, or new TC application is required
Costing	↑ up to 10%	]10% - 20%]	]20% - 30%]	↑ over 30%

Table 4-6 presents the risk occurrence probability modelled with a rating system based on four categories: unlikely, possible, likely and nearly certain. It is assumed that “unlikely” risks are improbable risks during the certification life cycle. They may occur only rarely. “Possible” risks are more probable and expected to occur sometimes during the certification life cycle. “Likely” risks may occur at least once during the certification life cycle as they are highly probable. They may be experienced several times. We assume that “Nearly certain” risks are almost sure to occur. They have high probability to be experienced several times or even continuously during the certification life cycle.

Table 4 - 6 Risk occurrence probability definition

PROBABILITY			
Unlikely	**Possible**	**Likely**	**Nearly Certain**
<= 25%	]25% - 50%]	]50% - 75%]	> 75%

Combining tables 4-5 and 4-6, a new view can be obtained, simplifying the readability (see table 4-7). This approach, for the assessment of the risks, defines a new scale of four categories to assess the level of each identified risk with respect to the project objectives to achieve successfully the certification targets:

- Low risks (in green, rated between 1 and 2) are acceptable, manageable easily inside the development team and require no specific escalation;
- Medium risks (in yellow, rated between 3 and 6) are shareable inside one team or may be transferable to another team if necessary;
- High risks (in brown, rated between 8 and 9) require a high monitoring and control through a good prevention and mitigation plan and escalation is required.
- Very high risks (in red, rated between 12 and 16) require precise prevention and mitigation measures to control them and escalation is required.

Table 4 - 7 Risk assessment

		IMPACT			
		Low (1)	Medium (2)	High (3)	Very High (4)
PROBABILITY	Nearly Certain (4)	4	8	12	16
	Likely (3)	3	6	9	12
	Possible (2)	2	4	6	8
	Unlikely (1)	1	2	3	4

A similar approach has been developed to assess the opportunities of the projects. Tables 4-8 and 4-9 provide respectively the positive impact levels classification and the definitions of the four occurrence probability categories of the opportunities which may provide an advantage to the certification process.

The opportunities to improve an existing planning/organisation for a development are classified with respect to the expected positive impact of an opportunity (here Type Certificate is used as an example). Table 4-8 presents the four levels of positive impact: Low, Medium, High and Very high. Each level is defined with two dimensions of assessments: planning and costing. Each positive impact of opportunities is assessed according a time benefit or a financial gain.

Table 4 - 8 Opportunity positive impact definition

	IMPACT			
	Low	**Medium**	**High**	**Very High**
Planning	Early TC delivery < 1 week	early TC delivery < 1 month	early TC delivery < 2 months	early TC delivery > 2 months
Costing	↑ up to 10%	]10% - 20%]	]20% - 30%]	↑ over 30%

Table 4-9 presents the opportunities occurrence probability modelled with a rating system based on four categories: unlikely, possible, likely and nearly certain. Table 4-9 is similar to table 4-7. The similar logic is followed.

Table 4 - 9 Opportunity occurrence probability definition

PROBABILITY			
Unlikely	**Possible**	**Likely**	**Nearly Certain**
<= 25%	]25% - 50%]	]50% - 75%]	> 75%

Combining again tables 4-8 and 4-9 leads to a new view on the opportunities (see table 4-10).

Table 4 - 10 Opportunity assessment

		IMPACT			
		Low (1)	Medium (2)	High (3)	Very High (4)
PROBABILITY	Nearly Certain (4)	4	8	12	16
	Likely (3)	3	6	9	12
	Possible (2)	2	4	6	8
	Unlikely (1)	1	2	3	4

The presented risks and opportunities management approach is complementary to the risk management approach provided by EASA (Section 2.2.4). The latter uses Compliance Demonstration Items (CDIs) as input, so to enable the Level Of Involvement (LOI) of EASA in the certification process. These CDIs depend on the organisation and are not known a-priori. Certification Memorandum (published in July 2019)[49] provides some insights. For example, the use of new technology, new operations, new kind of installations, the use of new requirements or the use of new means of compliance can induce that a CDI is novel or not. Also, a first implementation of the ARP 4754 or a first implementation of the ARP 4761 is interpreted as novel. The introduction of a complex work-sharing scheme with system / equipment suppliers is interpreted as complex in the same document. Additionally, it is considered as “critical”, any reference to: CS-23 commuter, CS-25, CS-29, RPAS or any other complex innovative products.

[49] https://www.easa.europa.eu/sites/default/files/dfu/CM-21A_21.B-001.pdf

4.4. THE ASSOCIATED METHODOLOGY

4.4.1. Structure of the methodology

The Aircraft Certification Framework (ACF) relies on a methodology aiming to organise and structure the way to operate the different parts together for the ACF approach.

The methodology includes the following three successive steps (See Figure 4-19):

1. **Enterprise Analysis**: Through this step 1, the company investigation enables to assess the current internal organisation and process and to determine the Level Of EASA Investment (LOI). The parameters values of the methodology are identified;
2. **Certification Requirements Elicitation**: Through this step 2, knowing the parameters values, the applicable rules are automatically triggered and enable to elicitate the adapted certification requirements. The associated SysML requirements diagrams are generated to propose a graphical representation of the elicitated requirements;
3. **Process and Organisation Definition**: Through this step 3, elicitation of adapted certification requirements enables to generate compliant processes and organisation. The associated SysML diagrams for processes and organisation are provided.

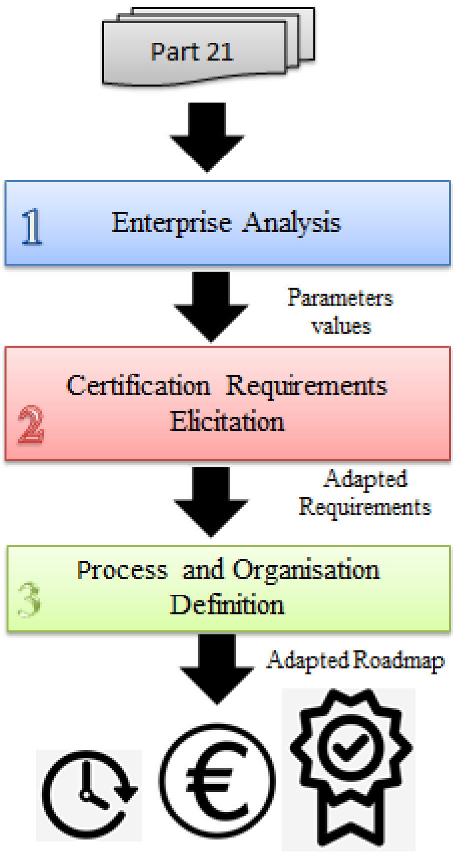

Figure 4 - 19 The three-step ACF methodology

4.4.2. Step 1 of the ACF methodology

This section aims to detail the different activities of the first step of the ACF methodology. At the end of this step, company-specific value settings are identified (see table 4-11). In the Figure 4-20, the process of the Enterprise Analysis is detailed and three main sub-steps are defined:

A. Enterprise investigation: based on internal information analysis;
B. Risk Assessment: based on the ACF risk assessment tool (see section 4.3.5);
C. LOI determination: based on the EASA LOI determination tool (see section 2.2.4).

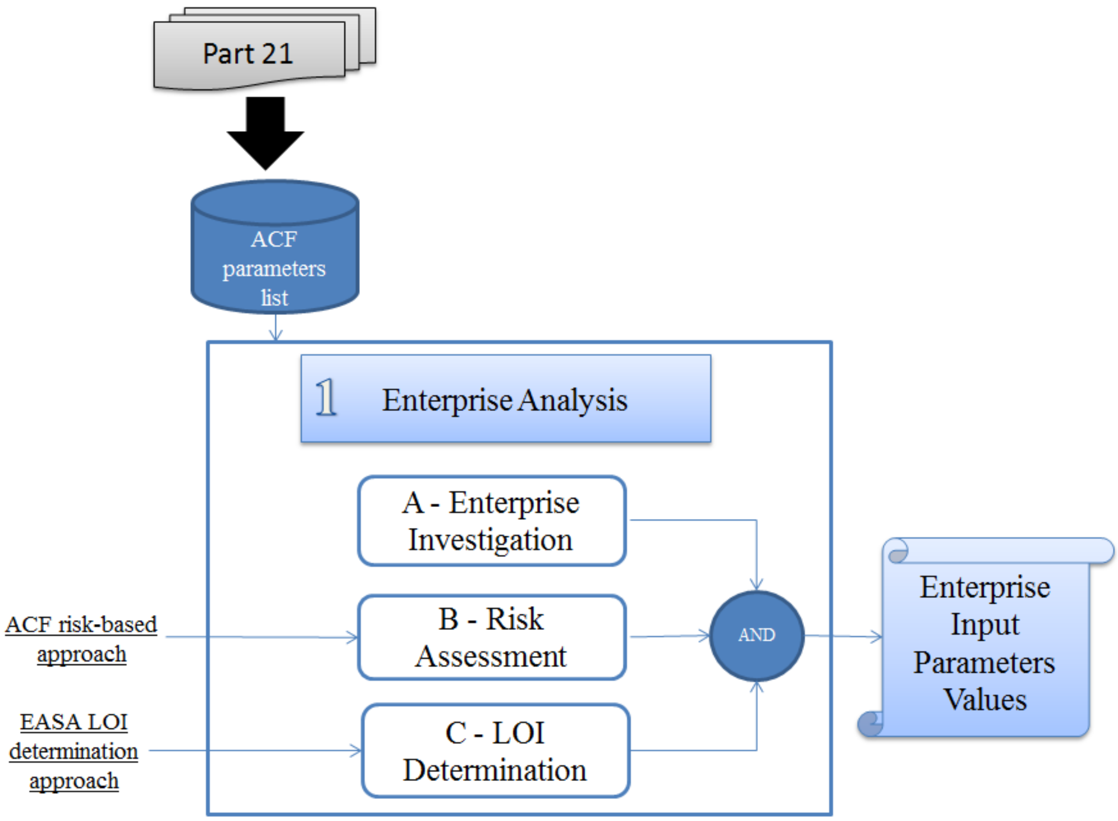

Figure 4 - 20 ACF Methodology Step 1

Based on the results of its three sub-steps, Step 1 enables to identify the values associated with each of the ACF parameters necessary to feed the rules of the expert system defined in section 4.3.3. Information such as the type of organization, the type and weight of the developed aircraft, the rate of production, etc, are gathered and values of input parameters are identified. As can be seen in Table 4-11, which shows the main ACF Input parameters, each parameter is defined by a name, potential values and a meaningful description.

Table 4 - 11 List of the main ACF Input Parameters

Input Parameter Name	**Input Parameter Expected Values**	**Input Parameter Description and Meaning**
Organisation	OEM, Subcontractor	An organization is considered to be either an Original Equipment Manufacturer (OEM) or a supplier (subcontractor).
OO (Organisation Origin)	MS, NotMS	The organization having their principal place of business in a Member State (MS) will have the attribute MS otherwise NotMS.
Maturity	High, Medium, Low	An organization will be assessed with one of three maturity levels.
PPA (Product, Part, Appliance)	Pr, Pa, A	The certification process is dealing with either a Product (Pr), a Part (Pa) or an Appliance. (A)
Product	Aircraft, Propeller, Engine	A Product is considered to be either an Aircraft, a Propeller or an Engine
Aircraft	ELA1, ELA2, >2T	An Aircraft is considered to be either an ELA1, an ELA2, or with a maximum take-off weight superior to 2T
PA (Part, Appliance)	APU, StandardPart, Other, None	A Part or an Appliance (PA) will follow the same certification process except in case of APU or "Standard Part". The concerned company may not be involved for a Part or an Appliance certification (PA=None).
Complexity	Yes, No	An aircraft is considered to be complex or not complex.
Privilege	Yes, No	The company may beneficiate of privileges or not.
Production	Regular, SmallSerie	The rhythm of production has an impact on the certification process depending on the number of produced series. Regular means that the production is planned to be in a quite large timeline with the creation of a real supply chain. SmallSerie means that only few aircraft will be produced.
EIS (Enter Into Service)	Yes, No	The final product is already in service (EIS=Yes) or not (EIS=No).
Airworthiness_Provision	Yes, No, NoRestriction	Default value is 'NoRestriction'. 'Yes' will mean that there is no particular conditions and 'No' means that there are some. This two values are not considered at the beginning of the certification process.

Step 1-A enables to identify the main characteristics of the organisation, and the product to develop. The values of the following parameters are established:

- Organisation;
- OO (Organisation Origin);
- PPA (Product, Part, Appliance);
- PA (Part, Appliance);
- Product;
- Aircraft;
- Complexity;
- Production;
- EIS (Enter Into Service);
- Airworthiness_Provision.

Following the approach in section 4.3.5, step 1-B enables to identify the following parameter: Maturity. Similarly, following the approach in section 2.2.4, step 1-C enables to identify the following parameter: Privilege.

4.4.3. Step 2 of the ACF methodology

The main objective of this step is to extract the requirements adapted to the organisation configuration. Figure 4-21 illustrates Certification Requirements Elicitation through the following three main sub-steps:

A. Automatic selection of applicable rules (see section 4.3.2);
B. Elicitation of applicable subparts (see section 4.3.2);
C. Adapted requirements diagram generation (see section 4.2.2).

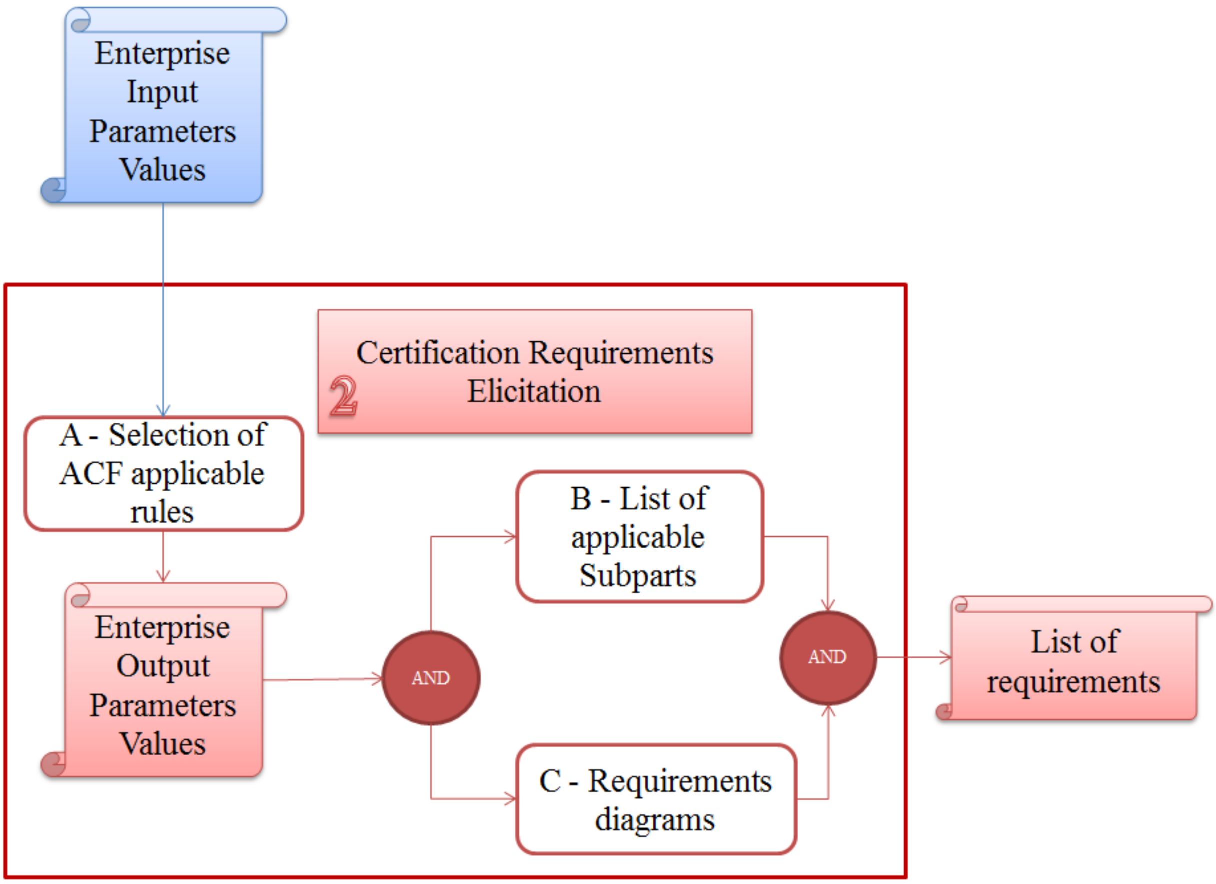

Figure 4 - 21 ACF Methodology Step 2

Step 2 enables to identify the values associated with company-specific parameters (see list in Table 4-12) describing a particular strategy for the organisation. Then based on this identified strategy, a list of the applicable subparts is characterised and a set of requirements diagrams is proposed. Finally, a reduced and adapted list of requirements is identified for the specific context of the enterprise.

Table 4 - 12 ACF Output Parameters list

Output Parameter Name	**Output Parameter Expected Values**	**Output Parameter Description and Meaning**
MainStrategy	CoA, TC, ETSO	Three main Strategies exist depending if the organization aims to certify an aircraft, an engine, a part or an appliance.
MainCertificate	TC, ETSO, POA, wPOA, DOA	Considering the main Strategy, a main certificate is identified.
DesignCertificate	Y, N	Depending on the Main Strategy, a design certificate has to be considered or not.
ProductionCertificate	Y, N	Depending on the Main Strategy, a production certificate has to be considered or not.
FC (Flight Conditions)	Yes, No	FC will inform about the necessity or not to apply for Flight Conditions approval.
PtF (Permit to Fly)	Yes, No	PtF will inform about the necessity or not to apply for a Permit to Fly.
NoiseCertificate	Yes, No	NoiseCertificate will inform about the necessity or not to apply for a Noise Certificate.
DesignApproval	DOA, APDOA, CP	Three different kinds of design Approval exist.
ProductionApproval	POA, wPOA	Two different kinds of production Approval exist
ValidatedCertificate	TC, RTC	When possible, for an aircraft or an engine, the main certificate is assessed considering the airworthiness provisions.
ValidatedStrategy	CoA, RCoA	When possible, for an aircraft or an engine, the main strategy is assessed considering the airworthiness provisions.

Thanks to the input parameters values identified during the step1, and following the rules of the expert systems presented in section 4.3.2, step 2-A enables to identify the high level strategy of the organisation. The values of the following parameters are established:

- MainStrategy
- MainCertificate
- DesignCertificate
- ProductionCertificate
- FC
- PtF
- NoiseCertificate
- DesignApproval
- ProductionApproval

Knowing the high level strategy of the organisation, the applicable subparts and the applicable requirements are identified. Also step 2-B highlights the concerned subparts whereas step 2-C generates the associated requirements diagrams.

4.4.4. Step 3 of the ACF methodology

Based on the list of requirements obtained from the step 2, the requirements are first refined to be in accordance with the organisation case. Then adapted processes and adapted organisation are defined and are both represented graphically in diagrams. Figure 4-22 details the objectives of this step through its main sub-steps, called A, B, C as follows:

A. Requirements Refinement;
B. Selection of adapted processes and associated diagrams generation;
C. Selection of adapted organisation and associated diagrams generation.

At the end of step 3, an adapted roadmap is provided. Taking into account the main characteristics of the enterprise, this roadmap is describing the acceptable delay for DOA, POA and TC.

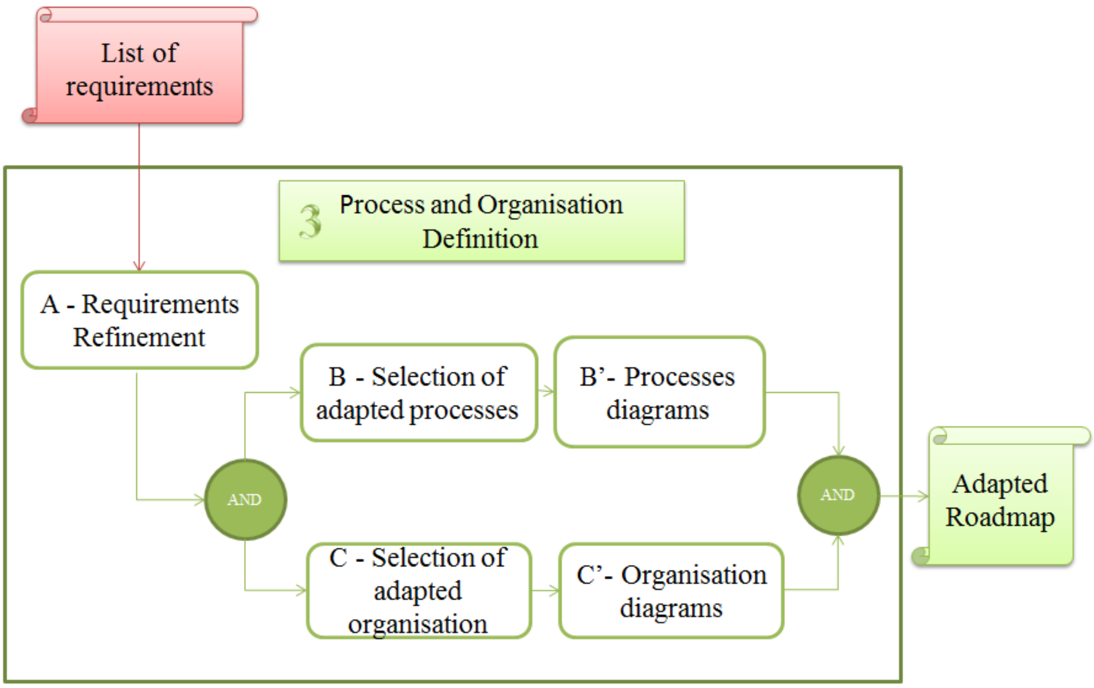

Figure 4 - 22 ACF Methodology Step 3

Step 3-A aims to refine the list of selected requirements. The requirements from Part 21 do not always carry functional content. To avoid confusion and clarify the objectives of the organisation, some requirements are removed from the reference list. Based on the refined requirements, Step 3-B selects the adapted processes and step 3-C selects the adapted organisation. Then associated diagrams are proposed in steps 3-B' and 3-C'.

4.5. SUMMARY OF THE PROPOSITIONS

In this section, we have presented a new reference framework based on:

- the Part 21 rules;
- the Systems engineering recommendations;
- the current aeronautical context; and
- the SMEs needs.

This reference framework called **Aircraft Certification Framework (ACF)** is composed of several elements:

- a modelling approach with:
    - a metamodel establishing the different modelled concepts;
    - functional requirements diagrams;
    - structural process diagrams;
    - behavioural process diagrams;
- a governance approach with:
    - a risk-based solution;
    - an expert system to determine the adapted certification strategy;
    - a maturity model;
- a methodological approach composed of three steps.

ACF aims to answer to the problematic presented in section 2.5.

The next chapter will present an application to a specific case study: an airship manufacturer.

CHAPTER

5

APPLICATION OF THE AIRCRAFT CERTIFICATION FRAMEWORK

CONTENTS

ABSTRACT

The trigger of this research is coming from the development of new airborne systems with the issue of certification. Lighter-Than-Air aircraft (LTA) or aerostats are again in the aeronautics landscape and are becoming new alternatives to conventional aircraft. Some of them are being developed by SMEs facing at the same time technological, societal and economical challenges. Certification is probably the main stake for these organisations as the regulation is not yet fully available.

In this chapter, we propose to apply the Aircraft Certification Framework (ACF) to a specific SME aiming to develop a LTA. The objectives of this chapter are to:

- Illustrate the framework implementation;
- Demonstrate the benefits to use the framework;
- Identify some leverages;
- Identify the limitations of the approach; and
- Characterize potential future research.

To do so, the following sections are proposed:

- In section 5.1, LTA concepts and history are presented, as well as the LTA particularities on a certification point of view;
- In section 5.2, the case study itself is presented, a French SME that aims to develop a 60T airship to transport heavy loads. The methodology proposed in section 4.4 is then applied step by step;
- In section 5.3, the results will be discussed, opening up to potential research avenues.

5.1. LIGHTER-THAN-AIR CONCEPTS AND THEIR CERTIFICATION

This section introduces the general concepts related to the Lighter-than-Air (LTA) aircraft and the specificities of their certification process.

5.1.1. LTA definitions, history and basic structure

A. Definitions

Conventionally aircraft are composed of two kinds of families (see Figure 5-1):

- The Aerodynes or Heavier-Than-Air" vehicles (HTAs);
- The Aerostats or Lighter-Than-Air" vehicles (LTAs).

The name of aerostat is coming from the fact that this kind of aircraft operates mainly thanks to the aerostatic lift (buoyant force) instead of the aerodynamic lift for aerodynes. The specificity of the LTAs is that they derive their lift mostly from the buoyancy of surrounding air rather than from aerodynamic motion like do the HTAs. The family of aerostats is divided into two parts:

- non-motorized aerostats, also called balloons;
- motorized aerostats, also called airships.

The common feature between motorized and non-motorized aerostats is that they are both inflated with a gas that is lighter than air, for example hot air, helium, or hydrogen. The main difference between airships and balloons is that balloons fly without any power supply, whereas airships are powered and have steerable systems.

A summary of these different categories is illustrated in the Figure 5-1. It is usual to distinguish:

- airships with a rigid envelope;
- airships with a semi-rigid envelope;
- airships with a flexible envelope, usually called blimps; and
- hybrid airships, which mix aerostatic lift and aerodynamic lift.

Like airships, different kinds of balloons exist as well. It is usual to separate the three following categories:

- the free balloons, the most common and known;
- the tethered balloons, additionally composed of a ground system which prevents the balloon from drifting; and
- the stratospheric balloons, used mainly for climatic studies.

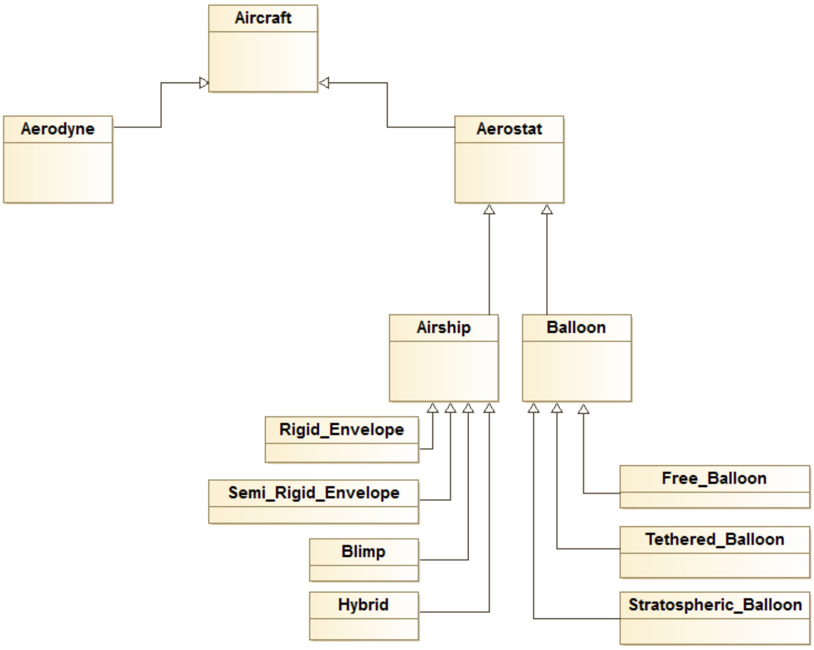

Figure 5 - 1 Aircraft classification (in SysML notation)

B. History

The first demonstrated flight of a hot-air balloon took place in France in 1783. The Montgolfier brothers used animals for the flight, as a precaution. The same year, Pilâtre de Rozier became the first man performing a free balloon flight in a Montgolfier (hot air) balloon. In 1852, a French engineer Henri Giffard designed a steam-powered airship and flew becoming the first man performing an engine powered flight. After that, in July 1900, the successful first free flight of LZ1, the first airship of the Zeppelin program, transported five passengers. During several years, airships gained popularity for passenger transport and military use, such as tactical bombing, reconnaissance, patrolling, and communications. But in May 1937, the Hindenburg, a hydrogen filled rigid airship burst into flames few moments before landing, killing 36 people on-board. The public's confidence in airships was shattered by this disaster and the use of airships for passenger transport came to a halt.

Nowadays, because of the number of potential missions, the technological advances and environmental constraints as well, airships are trying to come back to their historical roles. They are considered as lower cost energy aircraft and they might be in the run for missions handled today by conventional means of transportation like large aircraft, helicopters, ships or trucks. Figure 5-2 shows that airships might be a suitable answer compared to current other solutions if we are taken into account the rapidity of service and the consumption of fuel. They might offer in the very near future applications for both military and civil usage, such as aerial surveillance, and/or reconnaissance platforms, aerial sightseeing and transportation of goods (large and/or oversized payloads) or passengers over mountainous terrains.

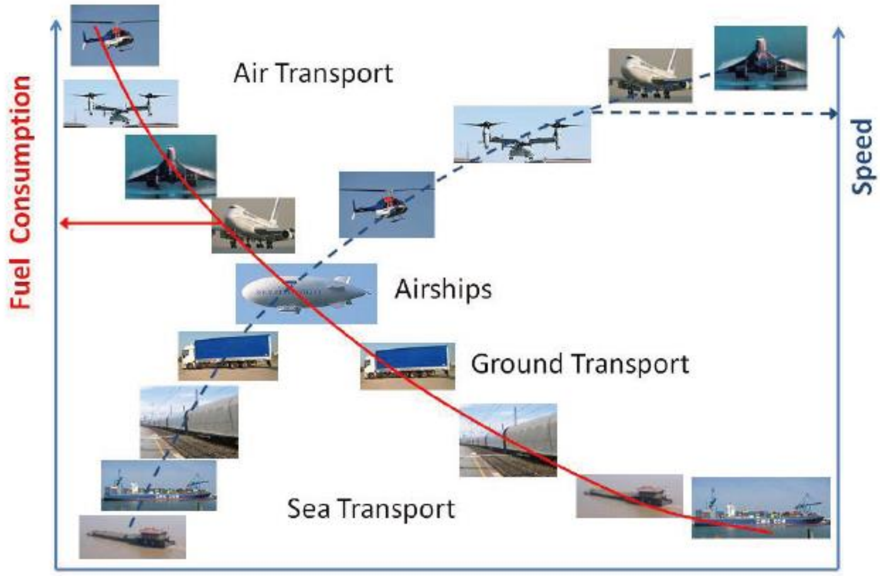

Figure 5 - 2 Airship Efficiency vs. Conventional Transport Systems [164]

Since several decades, several projects were under development, but until now only few succeed and arrive on the market: actually military propositions and aircraft with advertising targets.

C. Basic structure of a Lighter-Than-Air (LTA) aircraft

An airship is usually composed of 6 main parts, which are as following:

- **Envelope or hull -** The envelope is the outer surface, usually surrounding one or more gas-bags or ballonets within it;
- **Lifting gas system -** Lifting gas is contained within the envelope and/or gas bags producing buoyancy forces for airship to stay aloft in the air. Lifting gases are used because of their lower density compared to the atmosphere. Theoretically, many gases could be used as lifting gases. However, considering the performance and safety of gas, only hydrogen, helium and hot air are usually used;
- **Cabin -** A cabin, slung beneath the center or front of the envelope, can be used to contain crew, passenger, engine, landing gear etc;
- **Tail group -** The tail group normally comprises a set of fixed fins fitted with control surfaces from hinged brackets at the trailing edge. They are located at the airship's rear end to contribute the stability in flight by operation of the moveable trailing surfaces similar in principle to the tail planes;
- **Nose structure -** The nose structures are the forward part of the envelope, which can be used to provide an attachment to a mooring mast, to install mass balance weight and to mount a bow thruster;
- **Propulsion system -** Typically, the propulsion structures contain the engines, engine controls, electrical starters and propellers. The engines may be mounted in the cabin or off the envelope, in separate nacelles, called power cars or engine cars.

A balloon is usually composed of only the 3 first mentioned components: an envelope, a lifting gas system and a cabin usually called “gondola”. Unlike a free balloon and a stratospheric balloon, a tethered gas balloon is captive. Its movements are restricted by an anchorage system fixed to a ground surface or a mobile platform. The anchorage system is composed mainly by a cable or a set of cables, a winch and a pulley. The gondola and the envelope are kept aloft by the buoyant force provided thanks to the lighter-than-air gas trapped in the envelope.

The design of an aerostat is traditionally considered simpler compared to an aerodyne. However innovative aerostats may face technical challenges with regards the operational conditions. The aerostat operations are for example strongly dependent on the weather (strong wind, snow, hailstones, etc) and can be sensitive to freezing and lightning.

5.1.2. Certifications requirements for a lighter-than-air aircraft

Chapter 2 provided a comprehensive overview on the airworthiness requirements from a general point of view. In this section, airworthiness requirements are detailed with a particular focus on aerostats. In section 2.1.3, airworthiness codes or Certification Specifications (CS) have been presented. CSs are additional requirements to Part 21 ensuring a sufficient and standard level of safety per type of system. There is an official CS for each already certified type of aircraft, and for several specific parts and appliances as well (see EASA website to get the full list of CSs [50]).

Lighter-Than-Air aircraft (LTA) are considered to be non-conventional mean of air transportation. Only a few are currently certified by EASA. The list of certified balloons is available on the EASA website (around 221 models only [51]). Most of them are free balloons mainly used for commercial leisure trips. The list of certified airships, as well available on EASA Website[52], shows only 25 models: 9 medium-sized airships, 16 small-sized airships and no large airships. Certified airship manufacturers are today exclusively coming from Germany, United Kingdom and the USA. The current aerostat regulation presents a mixed picture with partial availability of the CSs and airship regulation is being written in parallel with airships development. Table 5-1 presents the current aerostat regulations. As shown, whereas some of the CSs are available for balloons (CS31HB, CS31GB, CS31TGB, but no CS for stratospheric balloons), there is no official airworthiness code for airships.

[50] https://www.easa.europa.eu/document-library/certification-specifications/reg/initial-airworthiness
[51] https://www.easa.europa.eu/download/easa-product-lists/EASA-PRODUCT-LIST-Balloons.pdf
[52] https://www.easa.europa.eu/download/easa-product-lists/EASA-PRODUCT-LIST-Airships.pdf

Table 5 - 1 Current Aerostats regulation[53]

AEROSTAT TYPE	AIRWORTHINESS CODE	EASA CATEGORY	EXISTING CERTIFIED AEROSTAT?
BALLOONS			
Free Hot Air Balloon	CS-31HB	Manned Hot Air Balloon	Y
Free Gas Balloon	CS-31GB	Manned Free Gas Balloon	Y
Tethered Balloon	CS-31TGB	Manned Tethered Gas Balloons	Y
Stratospheric Balloon	NA		N
AIRSHIPS			
Hot Air Airship	NA (CS-31HA Draft since 2003)	Hot Air Airship	Y
Normal Gas Airship	NA (CS-30N Draft since 1995)	Normal and Commuter Airship	Y
Large Gas Airship	NA (TAR or CS-30T Draft since 2000)	Large Transport Airships	N

NA: Not Available

All today's certified airships have been certified according rules in place before EASA existed (before 2002). For the 25 certified airships, the origin of the manufacturers and the kind of airships are different, it means that applied regulation was different as well.

Germany and the German Federal Aviation Bureau (Luftfahrt BundesAmt, known or LBA) have been active actors to provide the three regulation texts for the three types of airships (see table 5-1):

1- For **hot air airships**: the Airworthiness Requirements for Hot Air Airships (known as Lufttüchtigkeitsforderungen Für HeißLuft-LuftSchiffe or LFHLLS) was issued first in October 1997 and updated in 2003 by LBA; it is still in a draft version.

2- For **normal gas filled airships**: the German code Airworthiness Requirements for Normal and Commuter Category Airships (known as Lufttüchtigkeitsforderungen Für LuftSchiffe der Kategorie Normal und Zubringer or LFLS), was issued in August 1999 by LBA; it is still in a draft version. Recent Zeppelin Airships (NT program) have been certified according these airworthiness requirements.

3- For **large airships**: the Transport Airship Requirements (TAR) is available and known now as CS30T; it was issued in March 2000 jointly by the German Federal Aviation Bureau and Dutch Aviation Service; it is still in a draft version. Existing airworthiness codes FAR P8110-2 of the Federal Aviation Administration of the United States of America (issued in June 1995) and JAR-25 of the Joint Aviation Authorities of Europe have been selected to form the basis of this Transport Airship Requirements (TAR). No airship has been certified yet according to these requirements.

[53] https://www.easa.europa.eu/regulations

English airships, certified after 2002, beneficiated of the CS31HA code based on the German airworthiness requirements LFHLLS but known as CAP 471: BCAR Section Q - Non Rigid Airships. EASA has not officially validated this CS and the text is not available on the EASA website.

American airships have been certified according to the American airworthiness requirements (FAR Part 23, Amdt. 12, Subpart E) and have benefited of the bi-lateral agreement to get their certification approval. TAR and LFLS are still used as guidance material for FAA[54].

All today's certified airships have restricted conditions of operations and are used either for aerial promotion or commercial leisure trips. No airship has been properly certified by the official European CS from 2002 up until now.

5.1.3. Detailed Certification Lifecycle

Section 2.2.1 showed in detail the Type Certification (TC) lifecycle, divided in the four following phases:

- Phase 1 – Technical Familiarisation
- Phase 2 – Establishment of the TC Basis
- Phase 3 – Agreement of the Certification Programme
- Phase 4 – Compliance Demonstration, Final Report and issue of a TC approval

Before the end of the Phase 4, a design approval (such as DOA or APDOA) and a production approval (such as POA) are required to be issued first. No TC will be issued without these 2 approvals.

The figure 5-3 illustrates the certification lifecycle with the 4 elementary steps from TC application to the issuance of the three approvals: TC, Design Approval and Production Approval.

In a context of large aircraft certification, the time frame is shared with the following rules:

- Familiarization (Phase 1) lasts between 6 months and 9 months;
- Certification Basis (Phase 2) lasts maximum 18 months
- Certification Program (Phase 3) lasts maximum 30 months;
- Compliance Demonstration (Phase 4) usually lasts 25 months.

This usually leads to a TC application timeframe of around 60 months i.e. 5 years.

[54] https://www.faa.gov/aircraft/air_cert/design_approvals/airships/airships_regs/

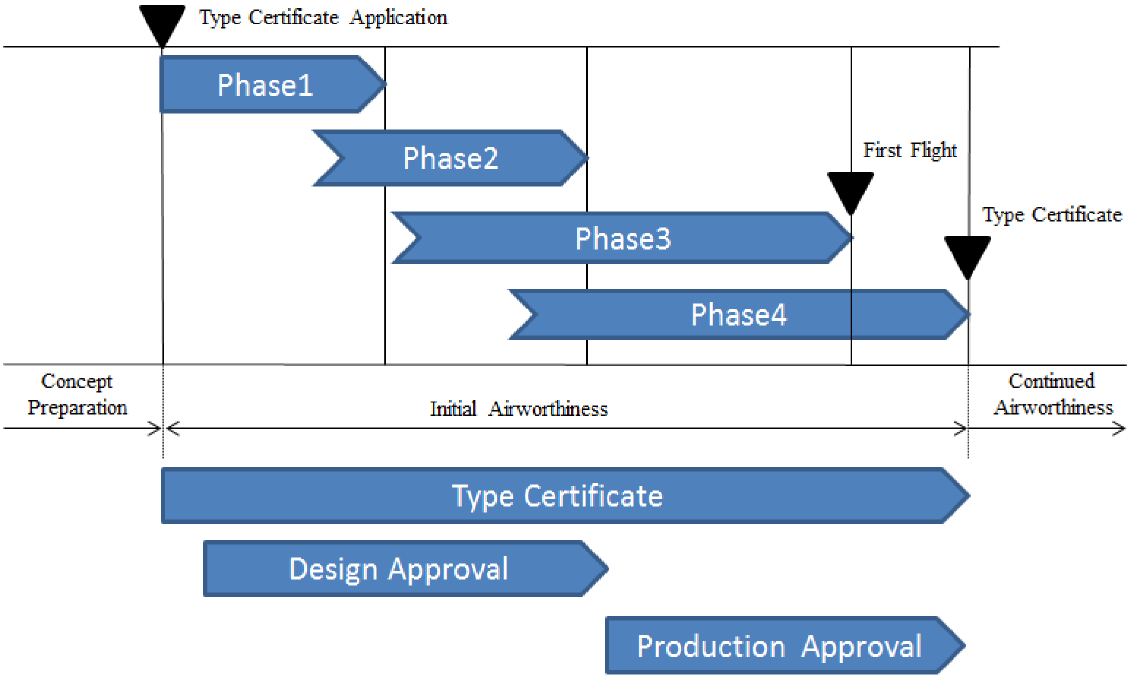

Figure 5 - 3 Full certification lifecycle with TC, Design and Production approvals

In the context of smaller aircraft certification, the time frame is usually reduced by adapting the rules:

- Familiarization lasts between 2 months and 6 months;
- Certification Basis and the Certification Program lasts respectively maximum 6 months, and 10 months;
- Compliance Demonstration usually lasts 10 months.

This usually leads to a TC application timeframe of around 36 months i.e. 3 years.

According to the definitions provided by regulations [15] and [16], a 'complex motor-powered aircraft' is either an aeroplane, a helicopter or a tilt rotor aircraft. Aerostats are defined only through the two designations ELA1 and ELA2 for manned European Light Aircraft (see chapter 2 and Annex B for detailed definitions). It means current regulations do not consider aerostats as 'complex'.

This research highlights the need to create additional groups to differentiate the aerostats. To complete the EASA approach, two groups are proposed in this thesis:

- Complex Aerostats; and
- Non-Complex Aerostats.

The definitions are synthetized in Table 5-2. ELA1 and ELA2 categories are kept as part of non-complex aerostats. Six additional categories are proposed. Volume of envelop, type of sustainable gas and weight of the system are the three main features determining if the aerostat is complex or non-complex.

Table 5 - 2 Proposed classification of Aerostats

Complex Aerostats	**Non-Complex Aerostats**
Airships with helium or hot air volume of over 20,000m^3 (Rigid, Semi-Rigid, Blimp)	ELA1 aerostats
Airships with design lifting gas other than helium or hot air.	ELA2 aerostats
Tethered balloon with design lifting gas other than helium or hot air.	Tethered balloons respecting CS31TGB.
Hybrid Airships	Airships with helium or hot air volume below 20,000m^3 (Rigid, Semi-Rigid, Blimp)

Innovation, or “novelty”, is also a feature that the regulator is taking into account (see chapter 2). Using the definitions of the categories from Table 5-2, and taking into account of the innovation aspects of aerostats, we propose to use complexity and innovation to categorize the aerostats. Four categories are then proposed:

- Complex and Innovative;
- Complex but not Innovative;
- Non-Complex but innovative
- Non-Complex and not Innovative

The four categories are used to propose four references in term of certification durations; TC/DOA/POA durations in particular. Table 5-3 summarizes the three different propositions that could be retained for aerostat certification: 3 years (36 months), 4 years (48 months) and five years (60 months).

Table 5 - 3 Reference Duration for Aerostats

	Reference Duration in months (in years)			
	Complex and Innovative	Complex but not Innovative	Non-Complex but Innovative	Non-Complex and not Innovative
DOA	25 months	18 months	18 months	15 months
POA	25 months	18 months	18 months	15 months
TC	**60 months**	**48 months**	**48 months**	**36 months**

5.2. CASE STUDY : AN AIRSHIP MANUFACTURER

5.2.1. Introduction to the case study

The case study concerns a real running French industrial program, where the EASA regulation is applicable. A new airship manufacturer, a SME, is developing a heavy load aerostat. Figure 5.4 depicts a computer aided design model of the project.

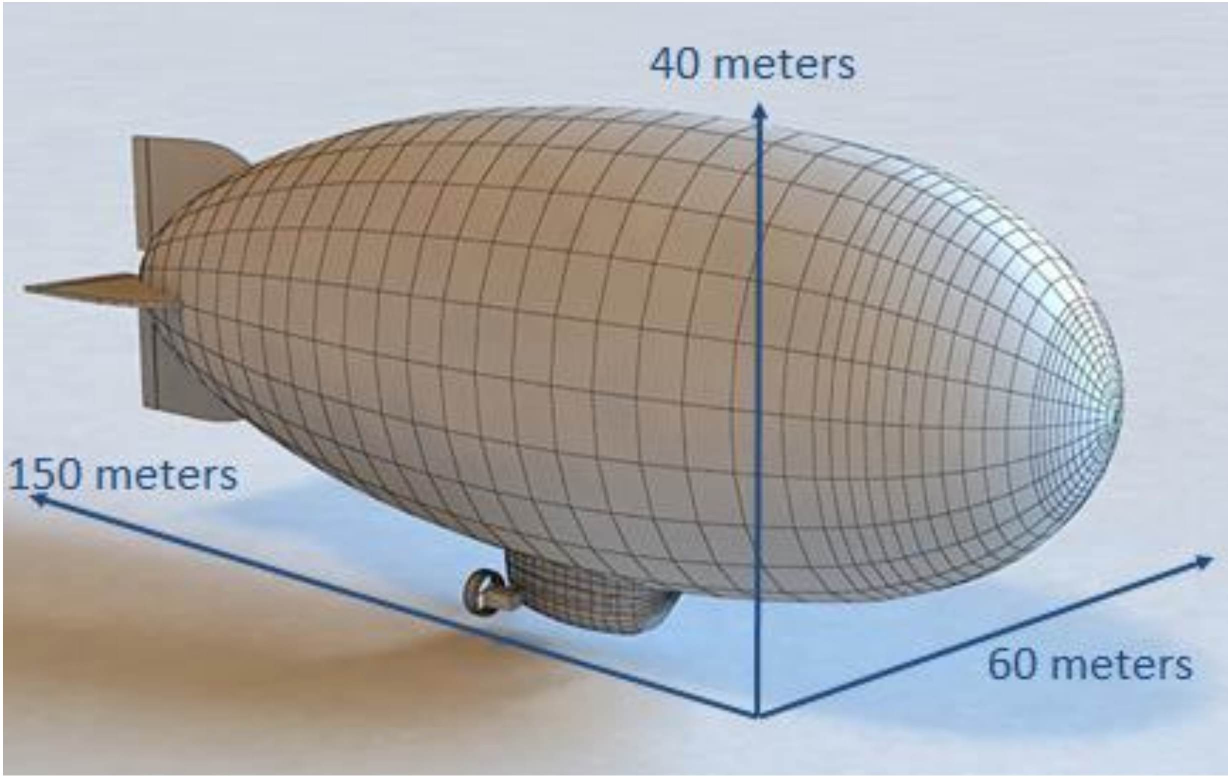

Figure 5 - 4 Case Study Project: aerial segment (with case study's courtesy)

The case study concerns a first certification without any official competition or any institutional reference to support or compare the activities. As explained in section 4.4, the application will follow the three steps of the methodology:

- Step 1: Enterprise Analysis
- Step 2: Certification Requirements Elicitation
- Step 3: Process Definition

The implementation of the methodology requires to know internally the company, the project and to meet people from the organisation. The project is presented with a focus on the technical objectives, on the development organisation and on the certification targets. But for the purpose of confidentiality, the real names, figures and technical details have been changed in this chapter, but the main characteristics of each situation remained unchanged.

5.2.2. Step 1: Enterprise Analysis

In this first phase, the dedicated company value parameters are identified. As described in section 4.4.2, step 1 is composed of three sub-steps:

A. Enterprise Investigation;
B. Risk Assessment; and
C. Level Of Involvement (LOI) Determination

A. Enterprise Investigation

The project is a manned airship with a rigid structure made of lightweight composites. Helium is used to ensure the aerostatic lift. The envelop receives several gas bag cells, a water system used as ballast, and a storage hold with the following size: 80m x 8m x 5m. To reach the target to transport 60T, the size of the airship is planned to be: 150 meters long, 40 meters high and 60 meters span, reaching a volume of largely more than 20,000m^3.

Taking into account the definitions of the Table 5-2, the case study is considered as a complex aerostat (reaching a volume of largely more than 20,000m^3).

Operated by a crew of two people, one pilot and one loadmaster, the airship is designed to transport heavy loads, from point to point, especially where access is difficult. The airship is planned to cruise at the maximum altitude of 3,000m, with an average speed of 100km/h. The operational parts include several kinds of application and several kinds of customers are involved in the project. A production of minimum ten airships per year is planned to be produced.

In common agreement with EASA, CS-30T (see section 5.1.2) is considered as the certification basis. But this regulation text is not sufficient to cover all the functionalities of the aerostat. For the purpose of completeness, other CSs are also partly concerned (CS-23 for Normal, Utility, Aerobatic and Commuter Aeroplanes, CS-25 for Large Aeroplanes, CS-29 Large Rotorcraft). Without proper CS of reference, the case study is considered as an innovative aerostat.

Taking into account the definitions of the Table 5-3, the case study is considered as complex and innovative. A priori certification activities are planned over 5 years. Figure 5-5 illustrates this planning in parallel with the development plan of the program.

Step1-Part A aims to identify a list of ten value parameters as recalled in table 5-4.

Table 5 - 4 Objective of Enterprise Investigation (Step 1-Part A)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
ACF Input Parameters	Values for the following ACF Input Parameters: • Type of organisation: Organisation • Origin of the organisation: OO • Main element to certify: PPA • Sub element to certify: PA • Type of product to certify: Product • Type of aircraft to certify Aircraft • Aircraft complexity level: Complexity • Level of production: Production • Status of service: EIS • Operational conditions: Airworthiness_Provision	Identify the values of the main parameters: main characteristics of the enterprise and the development project

The step 1-Part A enabled to identify that the organisation is an OEM established in a Member State (MS) country. The product to develop is a complex aircraft of more than 2T. The objectives of production are not limited to a few numbers of airships. A regular production is planned in the next decades. On the end of this first sub-step, following input parameters values are identified:

- Organisation = ’OEM’
- OO=’MS’
- PPA=’Pr’
- Product=’Aircraft’
- Aircraft= ‘> 2T’
- Complexity=’Yes’
- Production=’Regular’

At the beginning of the project, no restrictions regarding the operational conditions are made. Sometimes this may change later during the project duration, typically within the framework of the safety assessment of the certification process. The associated input parameter Airworthiness_Provision is for the moment set with default value ’NoRestriction’. As the program is a new one, no airship are under operations at this step of development: EIS is for the moment set with default value ’No’. For the purpose of simplification, we consider that the OEM is only an integrator and do not plan to certify any equipment, part or appliance: PA is for the moment set with default value ’None’. At the end of this first sub-step, we have values for the ten expected input parameters.

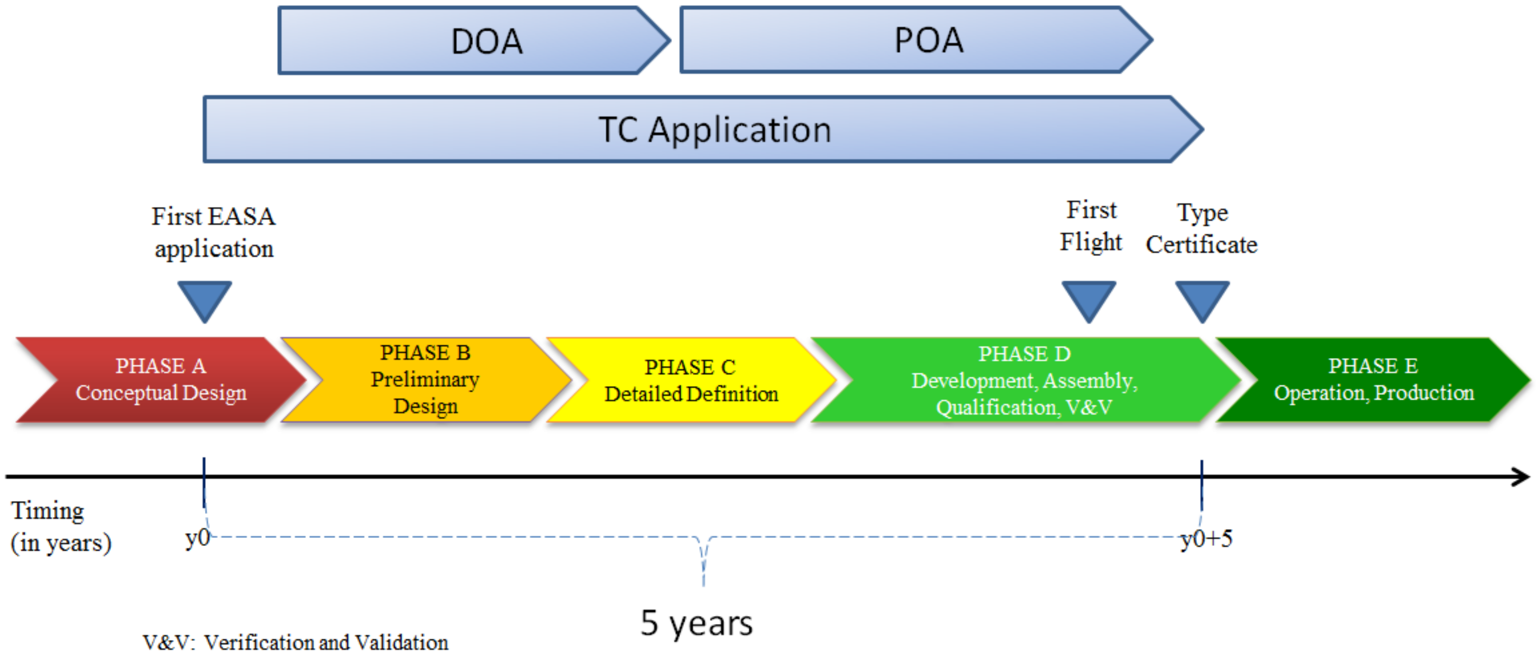

Figure 5 - 5 Case study development plan

B. Risk Assessment

In this project, around 80 people are working in six different departments (see Figure 5-6). The Airworthiness department and the Design Office are two essential departments required by the regulation. They are working jointly for the development of the airship and its certification. For the purpose of the risk assessment, it has been necessary to meet and interview people from these two departments.

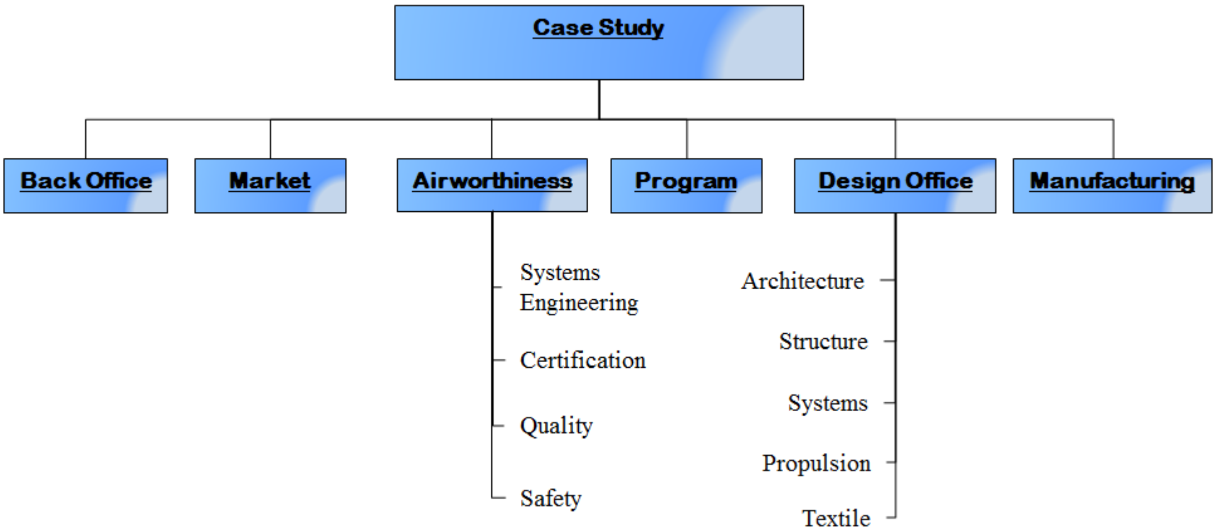

Figure 5 - 6 Internal organisation of the case study

In this organization, the situational awareness and the analysis of the context highlight several risks (identified from R01 to R12) and several opportunities (identified from O01 to O06) to achieve successfully the certification process.

Following the rules presented in section 4.3.4, each risk and opportunity has been rated (see Table 5-5 and 5-6 for the results), identifying variations in the risk and opportunity levels. This rating has been shared and validated internally. As suggested by [151] and [152], these risks and opportunities have been classified in three categories: organizational, technological and market. This classification emphasizes that organizational risks and opportunities are the most numerous and with the strongest impact.

First it has been identified that the company has faced a large ramp-up of the internal organisation from the beginning of the conceptual design phase (see Figure 5-5 for the sequence of development phases) to now. The technical team has increased by 70% each year (R01). In addition, the technical team has a significant share of engineers just starting their professional careers (around 30%), and for some without any aeronautical knowledge (R02). It generates a lot of misunderstandings regarding the development objectives and many communication problems as well (R03). These three risks are magnified by the fact that some suppliers, working with the case study, are SMEs with limited aeronautical knowledge (R04). The complexity regarding the supplier management is difficult to comprehend by the internal teams, which generates persistent tensions. There are no common rules for writing the specifications, which would require more homogeneity (R05). The Requirements management process is being written in parallel with the airship definition which induces many changes permanently (R06). The organisation is still not fully aligned with the airship architecture as the design is changing regularly (R07). In general all the processes are being written in parallel with the development. Many indicators are changing permanently, which makes it difficult to establish the status of the overall program, in a context of rapid ramp-up, small team and construction of the company (R08). Airworthiness department and design Office are working jointly to identify the right design for an acceptable level of risk. Unfortunately they may miscommunicate and identify an unsuitable level of safety and negotiate either over-budget or under-safety technologies (R09). Being innovative also means relying on technologies that have not always proven to be worthy when they seem necessary (R10). In parallel, as there is no airship still certified with these specificities (no reference to be compared against), there is a real competition worldwide. Those competitors may do some more efficient choices and could be certified before our case study (R11). Finally, market expectations are not always easy to understand and this can lead to strategic mistakes (R12).

Table 5 - 5 Risks rating for the case study

	Title	Impact	Probability of occurring	Risk Level
Organizational Risks assessment				
R01	Ramp-Up	Very High	Nearly Certain	16
R02	Team Composition: lack of experience	High	Nearly Certain	12
R03	Development Logic	High	Likely	9
R04	Partnership Management	Very High	Likely	12
R05	Documentation / Specification Structure	High	Likely	9
R06	Requirement Management Process deployment	Very High	Possible	8
R07	Internal Project Organization	High	Nearly Certain	12
R08	Missing Indicator to track the health of the Program	Medium	Possible	4
Technological Risks assessment				
R09	Identification of an unsuitable level of safety	High	Likely	9
R10	Availability of the necessary technologies	High	Possible	6
Market Risks assessment				
R11	Achievements from potential competitors	High	Likely	9
R12	Misunderstanding of market expectations	High	Possible	6

In this difficult context, five main opportunities are identified. The first one is regarding the EN 9100 certification which is running in parallel. This process helps the company to structure its processes (O01). Also the EASA certification applications help the company to identify the main objectives and the prioritizations (O02). The composition of the teams can be considered as a great asset. First, the fact that there is a relatively large share of beginners in the technical teams induces high motivation and enthusiasm to participate to this innovative project (O03). On the other hand, the managers are with a strong experience and for some in aeronautics (O04). Regarding the technical point of view, the enterprise has an internal strategy to choose as much as possible the technology with sufficient maturity like the COTS (Commercial Off-The-Shelf). It will create the conditions for an easier integration (O05). Finally, the case study may generate large market shares by developing several new applications in different industries and for different customers (O06).

Table 5 - 6 Opportunities rating for the case study

	Title	Impact	Probability of occurring	Opportunity Level
Organizational Opportunities assessment				
O01	EN 9100 certification in progress	High	Nearly Certain	12
O02	EASA Support	Very High	Nearly Certain	16
O03	Team Composition 20-30% of the resources are beginners: energy and involvement	High	Likely	9
O04	Team of Managers with a strong experience	High	Nearly Certain	12
Technological Opportunities assessment				
O05	Technology solution maturity	High	Possible	9
Market Opportunities assessment				
O06	Many potential applications	High	Likely	6

Step1-Part B aims to identify the maturity of the organisation and defines the value of the “Maturity” parameter as recalled in the table 5-7.

Table 5 - 7 Objective of Risk Assessment (Step 1-Part B)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
• ACF Input Parameters • Risk Assessment tool	Value for the following ACF Input Parameter: • Maturity	Identify the maturity of the organisation.

The case study can benefit from significant opportunities and the program is in line with market and societal demand. But it has to manage an initial certification without any comparison reference and already faces several difficulties that can hinder the achievement of the certification process. Particularly several organisational risks are identified, leading to set the value of the parameter Maturity to‘Low’.

C. Level Of Involvement (LOI) Determination

Step1-Part C aims to identify the level of privilege at which the organization can benefit by estimating the EASA Level Of Involvement (LOI). To determine the expected LOI for this case study, EASA approach was applied (see section 2.2.4). As the detailed certification program for this airship development is still under construction, the list of the CDIs (Compliance Demonstration Items) is not available yet. Even if the necessary inputs for the assessment of EASA LOI are not available, some extrapolations can be done based on the available information of the project. Through the Certification Memorandum published in July 2019[55] and thanks to the official EASA regulation published in December 2019[56], some guidelines are available to perform the LOI determination:

1. the likelihood of an unidentified non-compliance, assessed on the basis of the following criteria:
   - Novelty (a CDI may be either novel or not novel);
   - Complexity (a CDI may be either complex or not complex); and
   - Performance of the design organisation (High, Medium, Low or Unknown).
2. the expected EASA's involvement assessed on the basis of the following criteria:
   - the likelihood of an unidentified non-compliance (result of step 1); and
   - the criticality of the CDI.

According to EASA regulation, "the determination that a CDI is novel may be driven by the use of new technology, new operations, new kind of installations, the use of new requirements or the use of new means of compliance […]. When an applicant utilises a type of technology for the first time, or when that applicant is relatively unfamiliar with the technology, this technology is considered to be 'novel'." Consequently, for this case study, most CDIs would be assessed as "novel" by EASA.

According to EASA regulation, "the compliance demonstration may be considered to be 'complex' for a complex (or highly integrated) system, which typically requires more effort from the applicant." For example, the introduction of complex work-sharing scheme with system or equipment suppliers should be taken into account to assess a CDI as "complex".

According to EASA regulation, "the assessment of the level of performance of the design organisation takes into account the applicant's experience with the applicable certification processes, including their performance on previous projects and their degree of familiarity with the applicable certification requirements…". As in this case study, a first certification takes place, the organization performance will be then assessed as "Low".

Finally, with CDIs assessed as "novel and complex" and the performance of the design organisation assessed as 'Low", step 1 (table 2-4) will lead to a "High" likelihood estimation to generate a non-compliance in the certification process.

Regarding step 2, as we are in a situation of an innovative product where the CS-30T (Airship) is under development and inspired for some points by CS-23 (Normal-Category Aeroplane), CS-25 (Large Aeroplane) or CS-29 (Large Rotorcraft), we can assume that some non-compliance will have a critical impact and some will have non-critical impact.

[55] https://www.easa.europa.eu/sites/default/files/dfu/CM-21A_21.B-001.pdf
[56] https://www.easa.europa.eu/document-library/general-publications/easy-access-rules-initial-airworthiness

Table 2-5 will lead to the result of the "High" likelihood estimation column where the risk classes for the case study will be either class 3 or class 4. It means that, whatever the non-compliance criticality, the involvement of EASA will be quite important to support and investigate the certification demonstration.

At the end of the sub-step the value of the "Privilege" parameter will be defined, as recalled in the table 5-8.

Table 5 - 8 Objective of LOI Determination (Step 1-Part C)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
• ACF Input Parameters • EASA LOI Determination tool	Value for the following ACF Input Parameter: • Privilege	Estimate the EASA Level Of Involvement (LOI).

A high EASA Level Of Involvement (LOI), with class 3 and class 4 CDIs, implies that EASA will review a large amount of compliance data, will require the detailed interpretation of test results, will participate in some compliance activities (witnessing of tests, audits, etc.), As a consequence the organisation will expect to get only few privileges. On the end of this last sub-step, input parameter value of Privilege is set to 'No'.

5.2.3. Step 2: Certification Requirements Elicitation

Step 2 of the methodology aims to extract the requirements suitable to the organisation configuration, following the three sub-steps:

A. Automatic selection of applicable rules;
B. Elicitation of applicable subparts; and
C. Adapted requirements diagram generation.

A. Automatic selection of applicable rules

The parameters identified in step1 will enable to identify the applicable Expert System rules of the certification governance: for example Rule 1, Rule 2, Rule 3, Rule 4, Rule 8, Rule 9, Rule 16 and Rule 17 are selected by the expert system (see table 5-9).

Table 5 - 9 Applicable decision rules for Certification Governance for the case study

ID	Rule content	Rule Meaning	Application to Case Study
Rule 1	**{**|If Organisation='OEM' and Product='Aircraft' and Aircraft='>2T' Then MainStrategy=CoA.|}	An integrator aiming to market an aircraft over 2T shall request for a Certificate of Airworthiness.	Y
Rule 2	**{**|If MainStrategy='CoA' Then MainCertificate='TC'.|}	An organisation applying to a Certificate of Airworthiness shall apply to a Type Certificate.	Y
Rule 3	**{**|If MainCertificate='TC' Then DesignCertificate='Y'.|}	An organisation applying to a Type Certificate shall apply to a design approval.	Y
Rule 4	**{**|If MainCertificate='TC' Then ProductionCertificate='Y'.|}	An organisation applying to a Type Certificate shall apply to a production approval.	Y
Rule 8	**{**|If MainCertificate='TC' and Privilege='No' Then FC='Yes' and PtF='Yes'.|}	An organisation applying to a Type Certificate and having no privileges will have to request for a Permit to Fly and Flight Conditions.	Y
Rule 9	**{**|If MainCertificate='TC' Then NoiseCertificate='Yes'.|}	An organisation applying to a Type Certificate will have to request for a Noise Certificate.	Y
Rule 16	**{**|If Production='Regular' and DesignCertificate='Y' Then DesignApproval='DOA'.|}	If the organisation shall apply to a design approval and if the planned production is sufficient then The Design Approval to get is DOA.	Y
Rule 17	**{**|If Production='Regular' and ProductionCertificate='Y' Then ProductionApproval ='POA'.|}	If the organisation shall apply to a production approval and if the planned production is sufficient then The Design Approval to get is POA.	Y

As expected by the methodology in section 4.4.3, the application of these rules will allow identifying the values associated to a list of output parameters linked to the specific enterprise context (see table 4-12 for the complete list of the Output Parameters).

It enables to identify the certification strategy described with a list of official approvals to apply for, in compliance with Part 21. Following parameters are expected to be filled:

- MainStrategy
- MainCertificate
- DesignCertificate
- ProductionCertificate
- FC
- PtF
- NoiseCertificate
- DesignApproval
- ProductionApproval
- ValidatedCertificate
- ValidatedStrategy

Following the applications of the applicable rules, the values of the Enterprise Output Parameters are now established (see table 5-10).

Table 5 - 10 Output parameters values for the case study

Output Parameter Name	**Output Parameter Values**	**Output Parameter Description and Meaning**
MainStrategy	CoA	Certificate of Airworthiness
MainCertificate	TC	Type Certificate
DesignCertificate	Y	DOA or APDOA still have to be considered
ProductionCertificate	Y	POA or Production without POA still have to be considered
FC	Yes	Flight Conditions approval has to be requested.
PtF	Yes	Permit to Fly has to be requested..
NoiseCertificate	Yes	Noise Certificate has to be requested.
DesignApproval	DOA	DOA is the chosen strategy
ProductionApproval	POA	POA is the chosen strategy
ValidatedCertificate	TC	TC is the chosen strategy
ValidatedStrategy	CoA	CoA is the chosen strategy

Step2-Part A aims to identify a list of parameters values, describing the expected certification strategy of the organisation, as recalled in table 5-11.

Table 5 - 11 Objective of Automatic selection of applicable rules (Step 2-Part A)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
• ACF Input Parameters values • Enterprise Output Parameters • Expert System rules	• Applicable Expert System Rules • Enterprise Output Parameters values	Identify the certification strategy for the enterprise

For the case study, the list of the main expected certificates is now known. This list constitutes the main strategy of the enterprise and is composed of the following certificates

- Certificate of Airworthiness;
- Type Certificate;
- DOA;
- POA;
- Flight Conditions Approval;
- Permit to fly;
- Noise Certificate.

B. Elicitation of applicable subparts

Following the step 2-Part A, it is now possible to elicitate the only subparts concerned by the study case. Based on the list of expected certificates the following subparts are automatically identified:

- Subpart H for Certificate of Airworthiness:
- Subpart B for Type Certificate;
- Subpart D for Changes to Type Certificate;
- Subpart J for DOA;
- Subpart G for POA;
- Subpart P for Flight Conditions Approval and Permit to fly;
- Subpart I for Noise Certificate.

Additionally some subparts are applicable for any context of enterprise. This is the case of the following subparts:

- Subpart A for General Provisions;
- Subpart K for Parts and Appliances;
- Subpart M for Repairs;
- Subpart Q for Identification of Products, Parts and Appliances.

Step2-Part B aims to elicitate the applicable subparts from Part 21 as presented in table 5-12.

Table 5 - 12 Objective of Elicitation of applicable subparts (Step 2-Part B)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
• Enterprise Output Parameters values • List of expected certificates • Default applicable subparts	List of applicable subparts	Elicitate the applicable subparts

At the end of the step 2-Part B, eleven subparts are identified as applicable.

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C. Adapted requirements diagram generation.

Based on the results of Step 2-Part B, a first requirements diagram is automatically generated (Figure 5-7) showing the eleven identified subparts.

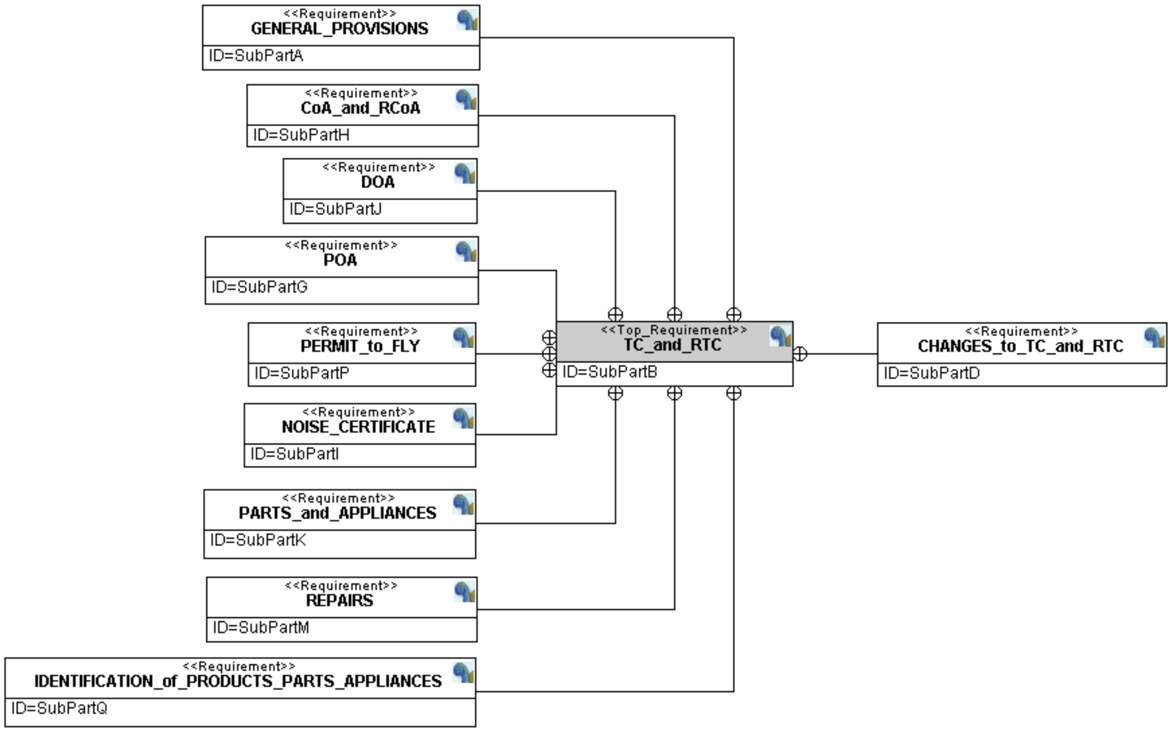

Figure 5 - 7 Requirements diagram for the case study

The ACF methodology defines automatically the requirements list from the eleven following subparts, with some adaptation to reduce the number of requirements in phase with the enterprise context. The requirements are limited to:

- TC (part of Subpart B dedicated to TC; requirements concerned by RTC are excluded);
- Changes to TC (part of Subpart D, dedicated to TC; requirements concerned by RTC are excluded);
- General Provision (Subpart A);
- CoA (part of Subpart H dedicated to CoA; requirements concerned by RCoA are excluded);
- DOA (part of Subpart J dedicated to DOA; requirements concerned by AP DOA are excluded);
- POA (Subpart G);
- Permit to Fly (Subpart P);

- Noise Certificate (Subpart I);
- Repairs (Subpart M);
- Parts and Appliances (Subpart K);
- Identification of Products, Parts and Appliances (Subpart Q).

Step2-Part C aims to elicitate the applicable requirements from the applicable subparts from Part 21. This objective is presented in table 5-13.

Table 5 - 13 Objective of Adapted requirements diagram generation (Step 2-Part C)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
List of applicable subparts	List of applicable requirements	Elicitate the applicable requirements

Step 2 – Part C results are synthetized in Table 5-14.

Table 5 - 14 Requirements Certification Basis for the case study

Subpart	**Requirements**
Subpart A	Full subpart
Subpart B	TC scope only / RTC scope excluded
Subpart D	TC scope only/ RTC scope excluded
Subpart G	Full subpart
Subpart H	CoA scope only / RCoA scope excluded
Subpart I	Full subpart
Subpart J	DOA scope / APDOA scope excluded
Subpart K	Full subpart
Subpart M	Full subpart
Subpart P	Full subpart (with Flight Conditions approval included)
Subpart Q	Full subpart

5.2.4. Step 3: Process Definition

This section illustrates the results of the final step of the methodology which aims to provide the necessary material to support the organisation in its certification process. As presented in section 4.4.4, this section will detail the application of the three following sub-steps:

A. Requirements Refinement
B. Adapted Processes Identification (and associated diagrams generation)
C. Adapted Organisation Identification (and associated diagrams generation)

A. Requirements Refinement

As an example, the methodology to refine the requirements from subpart A will be detailed. A similar review will be made for subpart J and G but with less detail.

Subpart A is applicable for any case of enterprise. All requirements from this subpart are selected until this step. Subpart A has five requirements:

- 21.A.1 Scope
- 21.A.2 Undertaking by another person than the applicant for, or holder of, a certificate
- 21.A.3A Failures, malfunctions and defects
- 21.A.3B Airworthiness directives
- 21.A.4 Coordination between design and production

Requirement 21.A.1 (see Figure 5-8) is not a proper requirement as it enables only to introduce the subpart but provides no specific right and obligation for the potential applicant. It is therefore no longer taken into account to identify specific activity or task.

21.A.1 Scope

Regulation (EU) No 748/2012

This Section establishes general provisions governing the rights and obligations of the applicant for, and holder of, any certificate issued or to be issued in accordance with this Section.

Figure 5 - 8 Content of 21.A.1 Requirement [12]

Requirement 21.A.2 (see Figure 5-9) is dealing with the transferability of the subpart A activities to a third party. For simplicity reasons, it is here assumed that the company will undertake the activities of the subpart A. This requirement is therefore excluded for the case study.

21.A.2 Undertaking by another person than the applicant for, or holder of, a certificate

Regulation (EU) No 748/2012

The actions and obligations required to be undertaken by the holder of, or applicant for, a certificate for a product, part or appliance under this Section may be undertaken on its behalf by any other natural or legal person, provided the holder of, or applicant for, that certificate can show that it has made an agreement with the other person such as to ensure that the holder's obligations are and will be properly discharged.

Figure 5 - 9 Content of 21.A.2 Requirement [12]

Requirement 21.A.3A is composed of three points; all related to a global system of collection, investigation and analysis of data:

- 21.A.3A (a) requires to put in place a system for collecting, investigating and analysing any information related to failures, malfunctions, defects or any other occurrence of the certified product, part or appliance. Any concerned stakeholders (operators, owners, etc) shall be informed about this system.
- 21.A.3A (b) requires to put in place a direct reporting system to inform EASA about any possible unsafe condition.

- 21.A.3A (c) requires to put in place the means to investigate the reasons for the deficiency of the reported occurrences, report to EASA and take the necessary actions to correct them.

The case study is fully concerned by the requirement 21.A.3A.

Requirement 21.A.3B is composed of four points; all related to the Airworthiness directives, EASA accountability document:

- 21.A.3B (a) provides a definition of an Airworthiness directive.
- 21.A.3B (b) provides a management rule for EASA.
- 21.A.3B (c) requires to put in place the means to take the necessary actions, to inform any concerned stakeholders (operators, owners, …) and to report to EASA.
- 21.A.3B (d) provides the expected content of an Airworthiness directive.

The case study is directly concerned only by the requirement 21.A.3B (c).

Requirement 21.A.4 requires a proper coordination between design and production organisations:

- 21.A.4 (a) imposes coordination before EIS.
- 21.A.4 (b) imposes coordination after EIS.

The case study is fully concerned by the requirement 21.A.4.

See Table 5-16 for details regarding the requirements 21.A.3A, 21.A.3B and 21.A.4 as proposed by the regulation. The grey parts of the tables are requirements not retained for the case study.

With the concerned approvals and the list of the related requirements now identified, Step3-Part A aims to refine the list of the applicable requirements as presented in table 5-15.

Table 5 - 15 Objective of Requirements Refinement (step 3-Part A)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
List of applicable requirements	List of refined requirements	Identify the necessary and sufficient requirements for certification process

At the end of the step 3-Part A, only the requirements concerned by the case study are retained. For subpart A, only 21.A.3A, 21.A.3B (c), and 21.A.4 are selected. For subpart J, all not greyed requirements from table 5-17 are selected. For subpart G, all not greyed requirements from table 5-18 are selected.

Table 5 - 16 Relevant Subpart A Requirements for Case Study [12]

Requirements Identification			**Requirement Content**
21.A.3A	(a)		System for Collection, Investigation and Analysis of Data.The holder of a type-certificate, restricted type-certificate, supplemental type-certificate, European Technical Standard Order (ETSO) authorisation, major repair design approval or any other relevant approval deemed to have been issued under this Regulation shall have a system for collecting, investigating and analysing reports of and information related to failures, malfunctions, defects or other occurrences which cause or might cause adverse effects on the continuing airworthiness of the product, part or appliance covered by the type-certificate, restricted type-certificate, supplemental type-certificate, ETSO authorisation, major repair design approval or any other relevant approval deemed to have been issued under this Regulation. Information about this system shall be made available to all known operators of the product, part or appliance and, on request, to any person authorised under other associated implementing Regulations.
	(b)		Reporting to the Agency
		1	The holder of a type-certificate, restricted type-certificate, supplemental type-certificate, ETSO authorisation, major repair design approval or any other relevant approval deemed to have been issued under this Regulation shall report to the Agency any failure, malfunction, defect or other occurrence of which it is aware related to a product, part, or appliance covered by the type-certificate, restricted type-certificate, supplemental type-certificate, ETSO authorisation, major repair design approval or any other relevant approval deemed to have been issued under this Regulation, and which has resulted in or may result in an unsafe condition.
		2	These reports shall be made in a form and manner established by the Agency, as soon as practicable and in any case dispatched not later than 72hours after the identification of the possible unsafe condition, unless exceptional circumstances prevent this
	(c)		Investigation of Reported Occurrences
		1	When an occurrence reported under point (b), or under points21.A.129(f)(2)or 21.A.165(f)(2)results from a deficiency in the design, or a manufacturing deficiency, the holder of the type-certificate, restricted type-certificate, supplemental type-certificate, major repair design approval, ETSO authorisation, or any other relevant approval deemed to have been issued under this Regulation, or the manufacturer as appropriate, shall investigate the reason for the deficiency and report to the Agency the results of its investigation and any action it is taking or proposes to take to correct that deficiency.
		2	If the Agency finds that an action is required to correct the deficiency, the holder of the type-certificate, restricted type-certificate, supplemental type-certificate, major repair design approval, ETSO authorisation, or any other relevant approval deemed to have been issued under this Regulation, or the manufacturer as appropriate, shall submit the relevant data to the Agency.
21.A.3B	(a)		An airworthiness directive means a document issued or adopted by the Agency which mandates actions to be performed on an aircraft to restore an acceptable level of safety, when evidence shows that the safety level of this aircraft may otherwise be compromised.
	(b)		The Agency shall issue an airworthiness directive when:
		1	an unsafe condition has been determined by the Agency to exist in an aircraft, as a result of a deficiency in the aircraft, or an engine, propeller, part or appliance installed on this aircraft; and
		2	that condition is likely to exist or develop in other aircraft
	(c)		When an airworthiness directive has to be issued by the agency to correct the unsafe condition referred to in point (b), or to require the performance of an inspection, the holder of the type-certificate, restricted type-certificate, supplemental type-certificate, major repair design approval, ETSO authorisation or any other relevant approval deemed to have been issued under this Regulation, shall:
		1	propose the appropriate corrective action or required inspections, or both, and submit details of these proposals to the Agency for approval;
		2	following the approval by the Agency of the proposals referred to under point (1), make available to all known operators or owners of the product, part or appliance and, on request, to any person required to comply with the airworthiness directive, appropriate descriptive data and accomplishment instructions.
	(d)		An airworthiness directive shall contain at least the following information: 1.an identification of the unsafe condition; 2.an identification of the affected aircraft; 3.the action(s) required; 4.the compliance time for the required action(s); 5.the date of entry into force.
21.A.4			Each holder of a type-certificate, restricted type-certificate, supplemental type-certificate, ETSO authorisation, approval of a change to type-certificate or approval of a repair design, shall collaborate with the production organisation as necessary to ensure:
	(a)		the satisfactory coordination of design and production required by 21.A.122, 21.A.130(b)(3) and (4), 21.A.133and 21.A.165(c)(2) and (3)as appropriate; and
	(b)		the proper support of the continued airworthiness of the product, part or appliance.

Table 5 - 17 Relevant Subpart J Requirements for Case Study [12]

Requirements Identification	Requirement Content	Retained requirement?
21.A.231	Scope	No
21.A.233	Eligibility	No
21.A.234	Application	Yes
21.A.235	Issue of design organisation approval	Yes
21.A.239	Design assurance system	Yes
21.A.243	Data	Yes
21.A.245	Approval requirements	Yes
21.A.247	Changes in design assurance system	Yes
21.A.249	Transferability	Yes
21.A.251	Terms of approval	Yes
21.A.253	Changes to the terms of approval	Yes
21.A.257	Investigations	Yes
21.A.258	Findings	Yes
21.A.259	Duration and continued validity	Yes
21.A.263	Privileges	No
21.A.265	Obligations of the holder	Yes

Table 5 - 18 Relevant Subpart G Requirements for Case Study [12]

Requirements Identification	Requirement Content	Retained requirement?
21.A.131	Scope	No
21.A.133	Eligibility	No
21.A.134	Application	Yes
21.A.135	Issue of production organisation approval	Yes
21.A.139	Quality system	Yes
21.A.143	Exposition	Yes
21.A.145	Approval requirements	Yes
21.A.147	Changes to the approved production organisation	Yes
21.A.149	Transferability	Yes
21.A.151	Terms of approval	Yes
21.A.153	Changes to the terms of approval	Yes
21.A.157	Investigations	Yes
21.A.158	Findings	Yes
21.A.159	Duration and continued validity	Yes
21.A.163	Privileges	No
21.A.165	Obligations of the holder	Yes

B. Selection of the adapted processes

Now in Step3-Part B, the extraction of the related processes enabling to be compliant with the refined certification requirements will take place, as presented in table 5-19.

Table 5 - 19 Objective of Adapted Processes Identification (Step 3-Part B)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
List of refined requirements	• List of adapted processes • Diagram of processes	Identify the adapted processes and the related elements (objective, activities, tasks, inputs, outputs)

Step3-Part B starts with the extraction of the necessary activities per each refined requirement and the identification of concerned inputs and outputs. From this selection, activities and necessary tasks can be organised. Again as an example, the methodology will be detailed for subpart A, with also a similar review for subpart J and G.

The analysis of the remaining refined requirements of the subpart A enables to identify a list of six main activities:

- Reliability Data Collection
- Reliability Data Analysis
- Failures, Malfunctions and Defects Investigation
- Deficiencies Correction
- Reporting to the Agency and other authorities
- Coordination with other Organisations

The Table 5-20 shows the coverage between the refined requirements and the activities.

Table 5 - 20 Activities and requirements coverage for Subpart A

Requirements	**Activities**
21.A.3A	Reliability Data Collection (Deficiencies, Failures, Malfunctions and Defects) Reliability Data Analysis Failures, Malfunctions and Defects Investigation Reporting to the Agency and other authorities
21.A.3B (c)	Deficiencies Correction Reporting to the Agency and other authorities Coordination with other Organisations
21.A.4	Coordination with other Organisations

It can be observed that the level of description of the activities is not sufficient. For example, the activity “Coordination with other Organisations” will not concern the same organisations if we are considering the requirement 21.A.4 or the requirement 21.A.3B. That is why each activity has been decomposed in different tasks. The activity “Coordination with other organisations” is decomposed in three tasks:

(i) Make available the corrective actions to the Production Organisations;
(ii) Make available the corrective actions to the Maintenance Organisations;
(iii) Make available the corrective actions to the Operators.

Similarly, the other activities can be decomposed into different tasks. The coverage of the requirements by activities and tasks constitutes an important check to ensure that the methodology is answering to all the requirements. Proposed tasks and requirements coverage for Subpart A are summarized in Table 5-21.

Table 5 - 21 Activities, Tasks and Coverage for Subpart A

Requirements	**Activities**	**Tasks**
21.A.3A 21.A.3B(c)	Reliability Data Collection	• Collect adequate data according the channels of collection • Collect Airworthiness Directives from EASA • Record known and planned preventive actions
21.A.3A	Failures, Malfunctions and Defects Investigation	• Check information (origin, date, impact, etc) • Validate information • Analyse the impact • Elaborate the actions plan • Share the actions plan
21.A.3A	Reliability Data Analysis	• Check information (origin, date, impact, etc) • Validate information • Analyse the impact • Elaborate the actions plan • Share the actions plan
21.A.3A 21.A.3B(c)	Reporting to the Agency and other authorities	• Notify the Agency within the adequate period according the type of the occurrence with the right form • Apply the right reporting according the type of the occurrence • Report 'security incidents' to the appropriate local security agency • Report related to air traffic, aerodrome occurrences or bird strikes to the appropriate air navigation, aerodrome or ground agency
21.A.3B(c) 21.A.4	Coordination with other Organisations	• Make available the corrective actions to the Production Organisations; • Make available the corrective actions to the Maintenance Organisations; • Make available the corrective actions to the Operators.
21.A.3B(c)	Deficiencies Correction	• Propose the appropriate corrective action • Validate the actions plan • Apply the validated actions plan • Record the new information for preventive actions

The EASA requirements are detailed enough to identify some inputs and outputs for each activity. Based either on provided AMC and GM by EASA and based on our own analysis, we were able to provide some propositions for appropriate Mean of Compliance as well (see Table 5-22).

Table 5 - 22 Identified activities for the case study: Subpart A Requirements

Activities	**Inputs**	**Outputs**	**MoC**
Reliability Data Collection	Specific tracking for FRM DATA Specific tracking for ETOPS DATA EASA Airworthiness Directives Service experience Analysis Tests	Collected data on Failures, Malfunctions and Defects Collected Reliability data	[GM 21.A.3A(b)] See AMC 20-8 from AMC-20 document to better understand the expectations of the Reporting Occurrence System.
Failures, Malfunctions and Defects Investigation	Collected data on Failures, Malfunctions and Defects EASA Form DO-13 (Occurrence record Form)	Analysis of Reliability Data DO-13 filled	[AMC No 1 to 21.A.3A(a)] Develop service instructions or revise the applicable airship manual.
Reliability Data Analysis	Collected Reliability data	Analysis of Reliability Data Collected data on Failures, Malfunctions and Defects	Develop service instructions with a proper description of the analysis activity An example of an existing analysis shall be provided.
Reporting to the Agency	FRM Data ETOPS Data Collected Reliability Data Identified Failures, Malfunctions and Defects EASA Form 44	EASA report FRM Report Reliability Reports, Malfunction or Defect New AD	See AMC 20-8 from AMC-20 document to get expected contents on reports.
Coordination with other Organisations	Collected data on Failures, Malfunctions and Defects	Analyse from the other organisation to implement the correction	Appropriate reporting should exist for operators, maintenance organisations, design organisations and production organisations. [AMC No 2 to 21.A.3A(a)] Appropriate coordination should exist between engine TC holder, propeller TC holder and APU ETSO authorisation holder with the aircraft TC holder. See AMC 20-8 from AMC-20 document to get a list of examples of reportable occurrences
Deficiencies Correction	FRM Failures, Malfunctions and Defects ETOPS Failures, Malfunctions and Defects Actions table	Reporting on fixed Failures, Malfunctions and Defects ETOPS	Develop service instructions with a proper description of the corrective activity An example of an existing correction shall be provided.

Assuming that the identified tasks and activities are necessary and sufficient to cover the requirements of the subpart A, they were grouped into one new unique process: “Manage the Occurrence Reporting System (ORS)”. The objective of this process is to use the reported information to contribute to the improvement of aviation safety. It was decided to define the objectives of this process as follows: “Collect, analyse, investigate and report to the appropriate organisations and authority the necessary reliability data”.

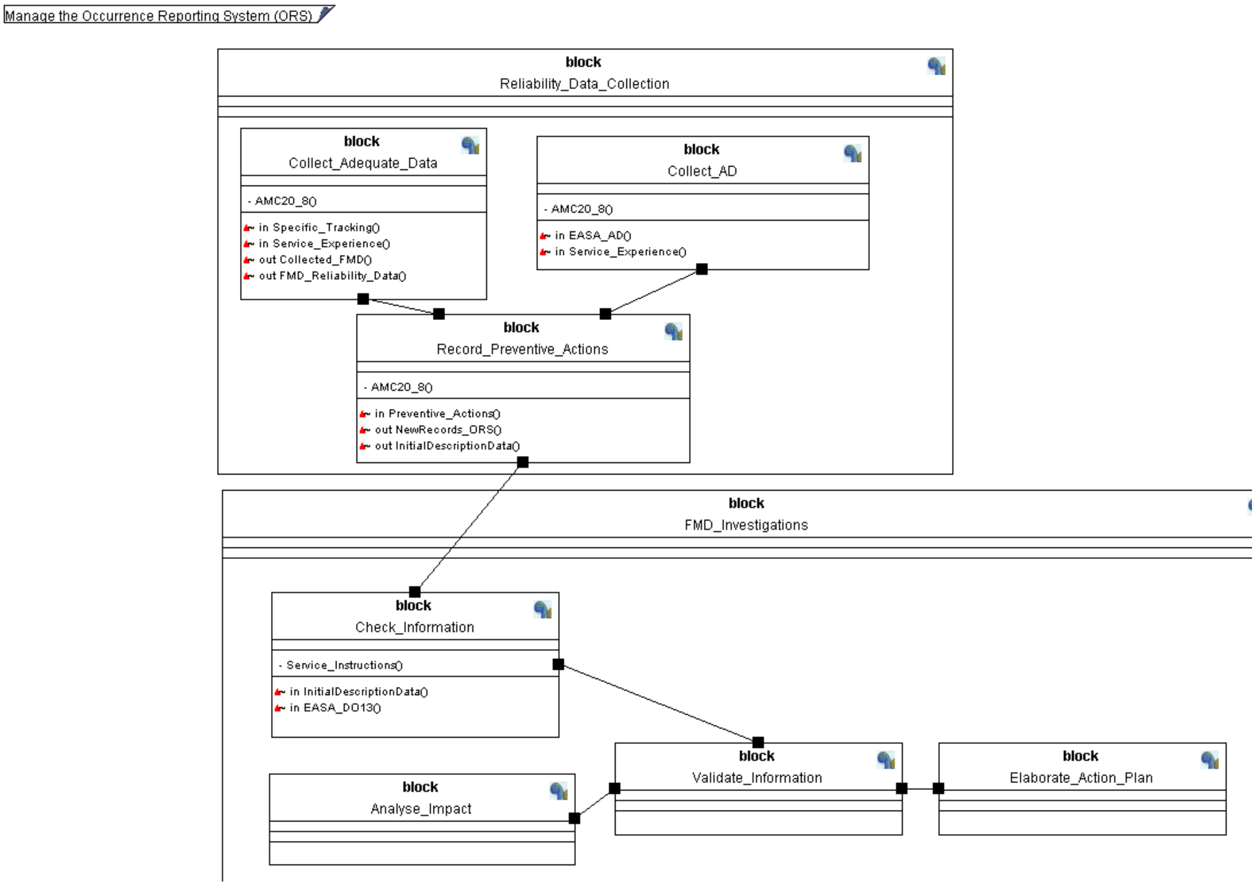

Figure 5 - 10 Diagram for “Manage the Occurrence Reporting System (ORS)” (extract)

Similarly, the subparts J and G have been analysed:

- The constitution of a Design Assurance System (DAS) for the control and supervision of the design and design changes is the critical part from Subpart J.
- The constitution of a Quality Assurance System (QAS) for the control and supervision of the production and production changes is the critical part from Subpart G.

Following the same approach as for subpart A, Tables 5-23, 5-24, 5-25, 5-26 present the different expected activities, their decomposition in tasks and their inputs and outputs regarding subparts J and G.

In subpart J, three activities have been excluded and seven activities have been identified, covering the applicable requirements for the case study (see tables 5-23 and 5-24).

Table 5 - 23 Requirements and Activities for Subpart J

Requirements	**Activities**
21.A.231 Scope	N/A
21.A.233 Eligibility	N/A
21.A.234 Application	• Application to DOA
21.A.235 Issue of design organisation approval	N/A
21.A.239 Design assurance system	• DAS Elaboration and Update • Monitor and Control Suppliers • People Responsibility and Knowledge Management
21.A.243 Data	• DAS Elaboration and Update • People Responsibility and Knowledge Management
21.A.247 Changes in design assurance system	• Renewal and Validity Management of DOA • DAS Elaboration and Update • EASA Approval Management for changes in DAS
21.A.249 Transferability	• Renewal and Validity Management of DOA
21.A.251 Terms of approval	• Application to DOA • Renewal and Validity Management of DOA
21.A.253 Changes to the terms of approval	• Monitor and Control Suppliers • Renewal and Validity Management of DOA
21.A.257 Investigations	• Compliance Demonstration Elaboration
21.A.258 Findings	• Compliance Demonstration Elaboration
21.A.259 Duration and continued validity	• People Responsibility and Knowledge Management
21.A.263 Privileges	• Design Realisation
21.A.265 Obligations of the holder	• Design Realisation

Table 5 - 24 Activities, Tasks and coverage for the case study: Subpart J Requirements

Requirements	**Activities**	**Tasks**	**Inputs**	**Outputs**
21.A.234 Application 21.A.251 Terms of approval	Application to DOA	• Apply to DOA • Apply for a re-approval • Apply for an approval for changes to the design assurance system • Apply for an approval for changes to the design assurance system • Manage validity of DOA	Form EASA 080	Form EASA 080 filled and validated by EASA
21.A.247 Changes in DAS 21.A.249 Transferability 21.A.251 Terms of approval 21.A.253 Changes to the terms of approval	Renewal and Validity Management of DOA EASA Approval Management for changes in DAS	• Communicate changes to DAS • Apply for a re-approval • Apply for an approval for changes to the design assurance system • Apply for an approval for changes to the design assurance system • Manage validity of DOA	Form EASA 082 - Proposed change	Form EASA 082 filled and validated by EASA
21.A.239 Design assurance system 21.A.243 Data 21.A.247 Changes in DAS	DAS Elaboration and Update	• Establish the DAS • Maintain the DAS • Ensure arrangement with Production organisation • Elaborate procedure for corrective action • Define planned and systematic actions • Produce the Design Organisation Handbook (DOH) • Update the DOH • Plan monitoring and audit activities		DOH
21.A.239 Design assurance system	Monitor and Control Suppliers	• Specify the manner in which the design assurance system accounts for the acceptability of the parts or appliances designed or the tasks performed by partners or subcontractors • Monitor Suppliers • Control Suppliers • Perform surveillance of design suppliers		
21.A.257 Investigations 21.A.258 Findings	Compliance Demonstration Elaboration	• Independently monitor the compliance with the DOH • Elaborate procedure for corrective action demonstration • Sign a declaration of compliance • Perform monitoring and audit activities • Enable investigations from EASA • Manage findings from EASA • Manage corrective actions • Manage findings and improvements Ensure corrective actions	Form EASA DO-42	Compliance demonstratio n
21.A.239 21.A.243 Data 21.A.245 Approval requirements	People Responsibility and Knowledge Management	• Nominate a DAS independent checking function • Nominate personnel belonging to the Office of Airworthiness • Provide a statement of the qualifications and experience of the management staff • Nominate DE • Nominate CVE • Nominate HDO • Nominate HOA • Nominate HISM	Form EASA DO-30 Form EASA 4-DOA	
21.A.263 Privileges 21.A.265 Obligations of the holder	Design Realisation	• Determine that the design of products, or changes or repairs thereof, as applicable, comply with applicable requirements and have no unsafe feature Provide to the Agency information or instructions related to required actions • Control and Monitor the Design • Perform planned and systematic actions	CS 30 requirements Form EASA DO-01	

Then activities were reorganised and regrouped into four different processes:

- Manage the Design Assurance System (DAS) process, for proper design activities;
- Manage the Initial Airworthiness (IA) process, for management of activities linked to liaison with Authorities;
- Manage the Continued Airworthiness (CA) and Changes process, for management of the DAS changes;
- Manage Suppliers process, for dedicated management of the suppliers and third parties.

The same approach was followed for subpart G. Seven activities were identified, covering the applicable requirements for the case study (see tables 5-25 and 5-26).

Table 5 - 25 Requirements and Activities for Subpart G

Requirements	**Activities**
21.A.131 Scope	N/A
21.A.133 Eligibility	N/A
21.A.134 Application	• Application to POA
21.A.139 Quality System	• QAS Elaboration and Update • Monitor and Control Suppliers • People Responsibility and Knowledge Management
21.A.143 Exposition	• Compliance Demonstration
21.A.145 Approval requirements	• QAS Elaboration and Update • Compliance Demonstration
21.A.147 Changes to the approved production organisation	• Renewal and Validity Management of POA
21.A.148 Changes of location	• Renewal and Validity Management of POA
21.A.149 Transferability	• Renewal and Validity Management of POA
21.A.151 Terms of approval	• Application to POA • Renewal and Validity Management of POA
21.A.153 Changes to the terms of approval	• Renewal and Validity Management of POA
21.A.157 Investigations	• Compliance Demonstration
21.A.158 Findings	• Compliance Demonstration
21.A.159 Duration and continued validity	• Renewal and Validity Management of POA
21.A.163 Privileges	• Production Realisation
21.A.165 Obligations of the holder	• Production Realisation

Table 5 - 26 Activities, Tasks and coverage for the case study: Subpart G Requirements

Requirements	**Activities**	**Tasks**	**Inputs**	**Outputs**
21.A.134 Application 21.A.151 Terms of approval	Application to POA	• Apply to POA	EASA FORM 50	
21.A.147 Changes to the approved PO 21.A.148 Changes of location 21.A.149 Transferability 21.A.151 Terms of approval 21.A.153 Changes to the terms of approval 21.A.159 Duration and continued validity	Renewal and Validity Management of POA	• Apply for a change	EASA FORM 2 EASA FORM 12 EASA FORM 51 EASA FORM 60	EASA FORM 52 EASA FORM 53 EASA FORM 55
21.A.139 Quality System 21.A.145 Approval requirements	QAS Elaboration and Update	• Establish the QAS • Maintain the QAS • Document the process • Describe the updating process • Elaborate Procedures and Instructions • Distribute the process, prodedures and instructions • Distribute the POE • Elaborate procedure for corrective action demonstration • Independently Monitor the compliance with the POE • Control and Monitor the Production • Ensure arrangement with Design organisation Elaborate a procedure to ensure that airworthiness, noise, fuel venting and exhaust emissions data are correctly incorporated in its production data • Ensure coordination with design Organisation • Manage liaison with TC/ RTC holder • Manage liaison with the Member State of registry • Manage liaison with the Agency	The applicable type-certification basis, the applicable operational suitability data certification basis and environmental protection requirements	Procedures for control, Procedures for traceability, Independent quality assurance function to monitor compliance with, POE issue, letter of approval, stating the acceptance of POE
21.A.139 Quality System	Monitor and Control Suppliers	• Define the control of suppliers • Vendor and sub-contractor assessment, audit and control • Manage OP to perform supplier assessments and surveillance • Perform surveillance of design suppliers	Supplier delivery, Procedures to adequately carry out the assessment and surveillance of suppliers, Procedures required for assessment and surveillance, …	Acceptance delivery

Requirements	**Activities**	**Tasks**	**Inputs**	**Outputs**
21.A.157 Investigations 21.A.158 Findings 21.A.143 Exposition 21.A.145 Approval requirements	Compliance Demonstration	• Perform the POE Manual • Update POE • Allow authorities to do investigations • Provide Assistance to the competent authority • Manage non-compliance requirements • Perform corrective actions Make available airworthiness, noise, fuel venting and exhaust emissions data		Demonstration compliance with the POE, Recording data procedure
21.A.163 Privileges 21.A.165 Obligations of the holder	Production Realisation	• Prepare the Aircraft statement of conformity • Issue the release certificate for each relevant item • Prepare a weight and balance report • Manage Approval Requirements and Manufacturing Data	Cerfa 47, manufacturing processes, POE, Form EASA DO-05	EASA Form 1 EASA DO-06 weight and balance report
21.A.139 Quality System	People Responsibility and Knowledge Management	• Assign the independent quality assurance function • Assign the manager responsibility of QAS= accountable manager • Assign people to check compliance with the airworthiness requirements • Elaborate procedures for Personnel training and qualification • Record evidence for certifying staff • Perform an evaluation of the competence of personnel • Perform facility checks • Nominate liaison with competent authorities	EASA Form 4, Qualifications and experiences of the management staff	Personnel training and qualification procedures

Similarly to the subpart J, it was decided to reorganize the activities in four different processes:

- Manage the Quality Assurance System (QAS) process, for production activities;
- Manage the Initial Airworthiness (IA) process, for management of activities linked to liaison with Authorities;
- Manage the Continued Airworthiness (CA) and Changes process, for management of the QAS changes;
- Manage Suppliers process, for dedicated management of the suppliers and third parties.

The process Manage the Initial Airworthiness (IA) is dealing with major activities of subpart (TC) and H (CoA), taking into account all the applications to EASA and updates of the certificates. The process Manage the Continued Airworthiness (CA) and Changes process is dealing with the major activities of subpart D and all the transverse requirements through the different subparts linked to continued airworthiness. The process Manage the suppliers is regrouping the activities related to suppliers and third parties. These activities, like the continued airworthiness, are spread over all the subparts.

In analogy to subparts A, J and G, the other relevant subparts for the case study have been analysed:

- The elaboration of the Certification Basis and the production of the Compliance Demonstration are the two critical parts from Subpart B.
- The constitution of the change classification is the critical part from Subpart D.
- The production of the Statements of Conformity, the Weight and Balance Report and the Flight Manual is the critical part from Subpart H.
- The release of all parts and appliances is the critical part from Subpart K.
- The production of the Flight Tests Programme is the core part from Subpart P.
- The identification of all the products, parts and appliances is the critical part from Subpart Q.

The identified processes, for the case study, are shown in Table 5-27.

Table 5 - 27 Summary of Processes for the case study

Subpart **Name of Subpart**	**Process**
Subpart A GENERAL PROVISIONS	• Manage the Occurrence Reporting System (ORS)
Subpart B TYPE-CERTIFICATES	• Manage the Initial Airworthiness (IA) • Manage the Continued Airworthiness (CA) and Changes
Subpart D CHANGES TO TYPE-CERTIFICATES	• Manage the Continued Airworthiness (CA) and Changes
Subpart G PRODUCTION ORGANISATION APPROVAL	• Manage the Quality Assurance System (QAS) • Manage the Initial Airworthiness (IA) • Manage the Continued Airworthiness (CA) and Changes • Manage Suppliers
Subpart H CERTIFICATES OF AIRWORTHINESS	• Manage the Initial Airworthiness (IA) • Manage the Continued Airworthiness (CA) and Changes
Subpart I NOISE CERTIFICATES	• Manage the Initial Airworthiness (IA) • Manage the Continued Airworthiness (CA) and Changes
Subpart J DESIGN ORGANISATION APPROVAL	• Manage the Design Assurance System (DAS) • Manage the Initial Airworthiness (IA) • Manage the Continued Airworthiness (CA) and Changes • Manage Suppliers
Subpart K PARTS AND APPLIANCES	• Manage the Initial Airworthiness (IA) • Manage the Continued Airworthiness (CA) and Changes • Manage Suppliers • Manage the Design Assurance System (DAS) • Manage the Quality Assurance System (QAS) • Manage Marking
Subpart P PERMIT TO FLY	• Manage Permit to Fly • Manage the Initial Airworthiness (IA) • Manage the Continued Airworthiness (CA) and Changes
Subpart Q IDENTIFICATION OF PRODUCTS, PARTS AND APPLIANCES	• Manage the Initial Airworthiness (IA) • Manage the Continued Airworthiness (CA) and Changes • Manage Marking

In conformity with the ACF metamodel (see section 4.1.4), each process addresses at least one objective, a list of activities and linked tasks. Some means of compliance, when possible, have been attached to the activities.

As a result, for case study, eight processes were identified (see table 5-28):

1. Manage the Occurrence Reporting System (ORS)
2. Manage the Initial Airworthiness (IA)
3. Manage the Continued Airworthiness (CA) and Changes
4. Manage the Quality Assurance System (QAS)
5. Manage the Design Assurance System (DAS)
6. Manage Suppliers
7. Manage Permit to Fly
8. Manage Marking

Table 5 - 28 Processes and associated objectives for the case study

Process	**Objective**
Manage the Occurrence Reporting System (ORS)	Collect, analyse, investigate and report to the appropriate organisations and authority the necessary reliability data
Manage the Initial Airworthiness (IA)	Establish and maintain the certification programme as expected by Part 21
Manage the Continued Airworthiness (CA) and Changes	Collect, assess, implement all necessary changes during IA and anticipate changes management during CA
Manage the Quality Assurance System (QAS)	Establish and maintain a system for the control and supervision of the production, and of production changes of products, parts and appliances
Manage the Design Assurance System (DAS)	Establish and maintain a system for the control and supervision of the design, and of design changes of products, parts and appliances
Manage Suppliers	Select, assess and monitor the suppliers involved in the development.
Manage Permit to Fly	Provide the necessary conditions to get the authorisations to fly
Manage Marking	Ensure proper identification of eligible products, parts and appliances

Processes, activities and tasks are modelled for each process using block diagrams and state machines to create flows between the block diagrams. An example is provided in Figure 5-11. The diagram is taking into account the imbrication between process, activities and tasks as presented in section 4.2.3 with Figure 4-10.

At the end of the step 3-Part B, the adapted processes and the related objective, activities, tasks, inputs, and outputs are identified for all the requirements. For each process, a process diagrams is proposed.

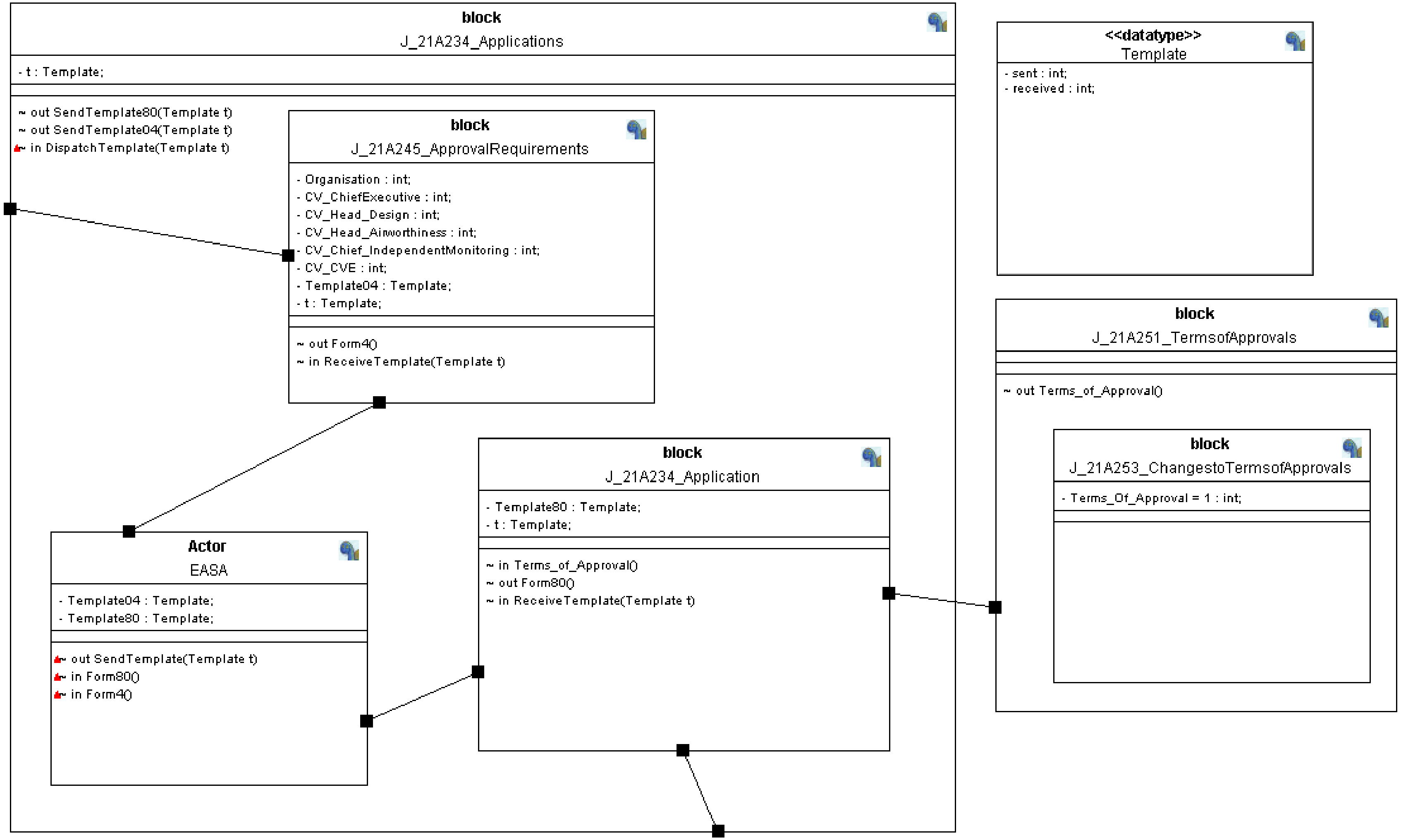

Figure 5 - 11 Process diagram extract for the case study

C. Selection of the adapted organisation

Finally, in Step3-Part C, the adapted organisation to the specific context of the case study is proposed, as presented in table 5-29.

Table 5 - 29 Objective of Requirements refinement (Step 3-Part C)

INPUT	OUTPUT	SUB-STEP OBJECTIVE
Adapted processes with related objective, activities, tasks, inputs, and outputs	• List of necessary roles • Diagram of organisation • Optimized roadmap	Identify the adapted organisation and propose an optimized roadmap

For the case study, the generic functions and roles expected by EASA, as listed in Table 2-3, are all relevant. It has been seen in section 2.2.3.D, that in accordance of the maturity of the organisation, some alternatives may be recommended. The maturity of the case study was assessed as “Low” in Step 1-Part B. We assume here that some alternatives can be applied. Here are the relevant chosen arrangements:

- The Chief Executive and Head of the design organisation is performed by the same person;
- Quality Manager and Head of Independent Monitoring is performed by the same person.

Figure 5-12 shows a proposal for the organisation of the case study in compliance with Part 21. Figure 5-13 associates the use cases to the roles. Additionally Figure 5-14 proposes an optimized roadmap adapted to the case study. As we can see, ten months are gained to achieve the same certification objectives as defined initially in Figure 5-5.

At the end of the ACF Step 3-Part C, the adapted organisation in compliance with regulation is proposed. An optimized roadmap is built with the optimized duration for each phase.

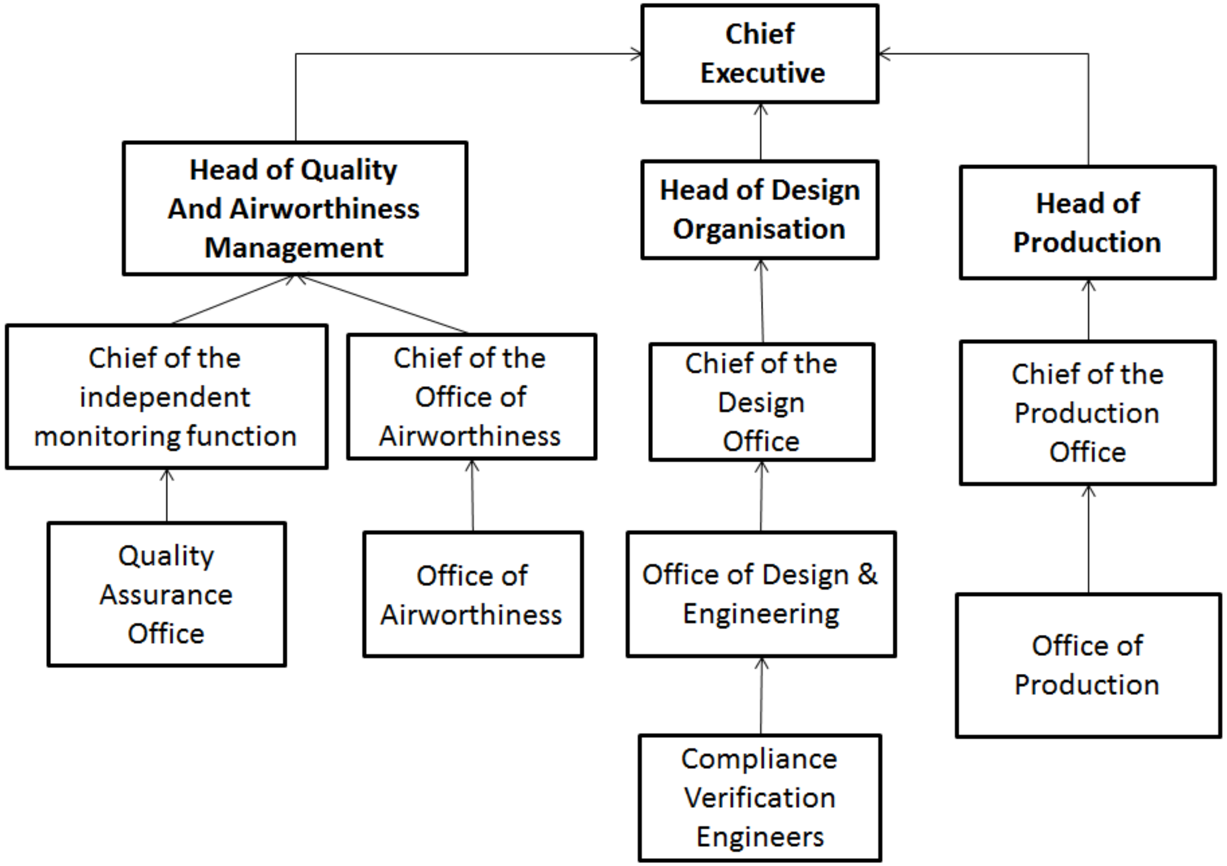

Figure 5 - 12 Proposed organisation for the case study

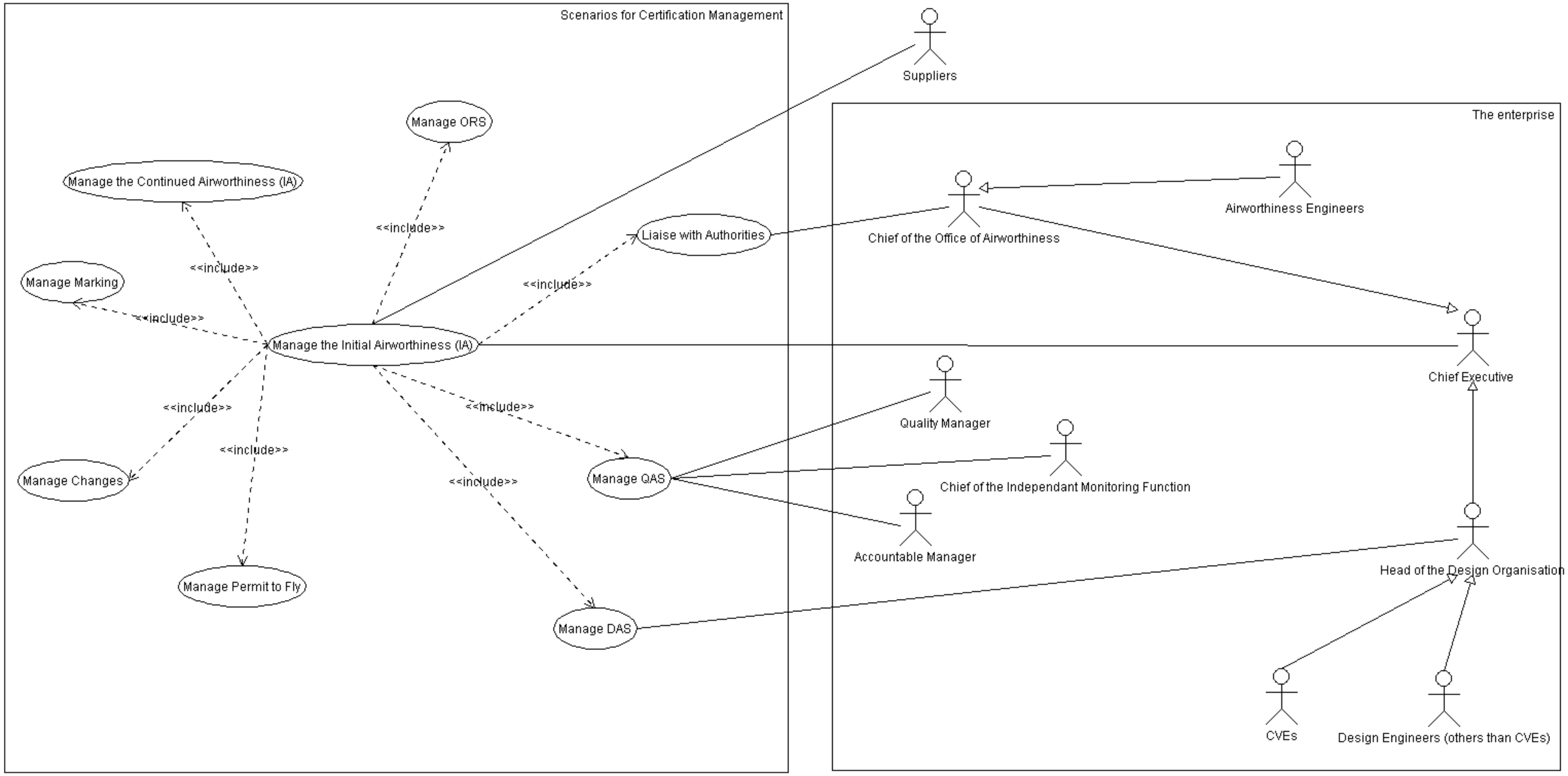

Figure 5 - 13 Main SysML Use Cases for the case study

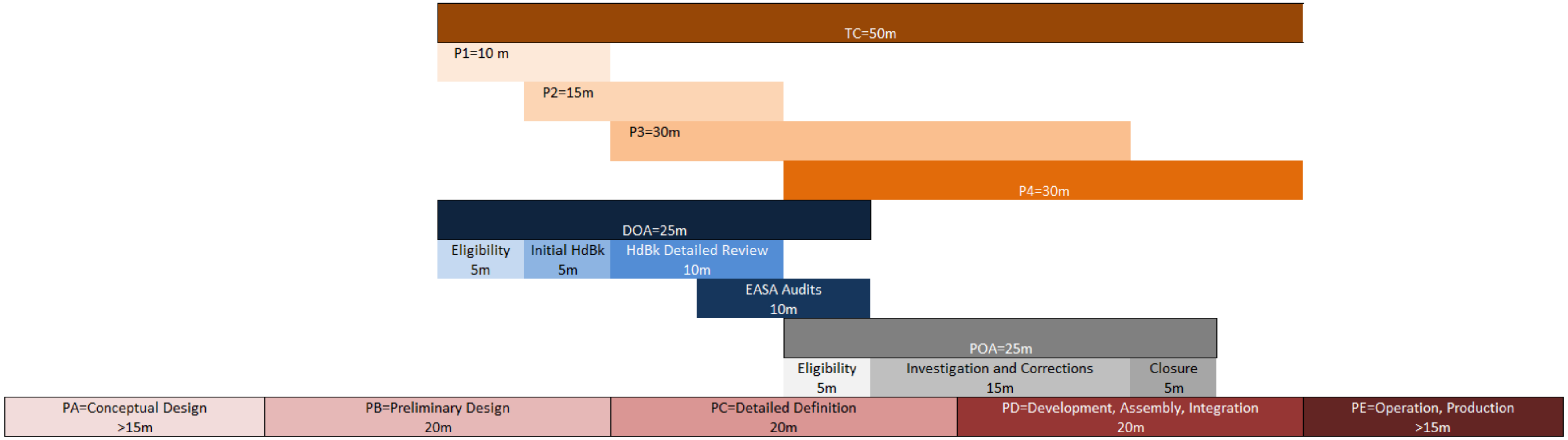

Figure 5 - 14 Optimized roadmap for the case study

5.2.5. Proposed Maturity Model for the case study

To go further, it is identified that the process implementation is a huge investment requiring a lot of resources, especially in case of a first aeronautical certification. We propose to the company to reach the full certification objectives going through several steps as proposed in section 4.3.4. The idea is to break down the objectives of the certification and so share the processes, activities and tasks in different parts.

Maturity Model Level 1 (Figure 5-15): the main objectives are to build the bricks of the EN 9100.

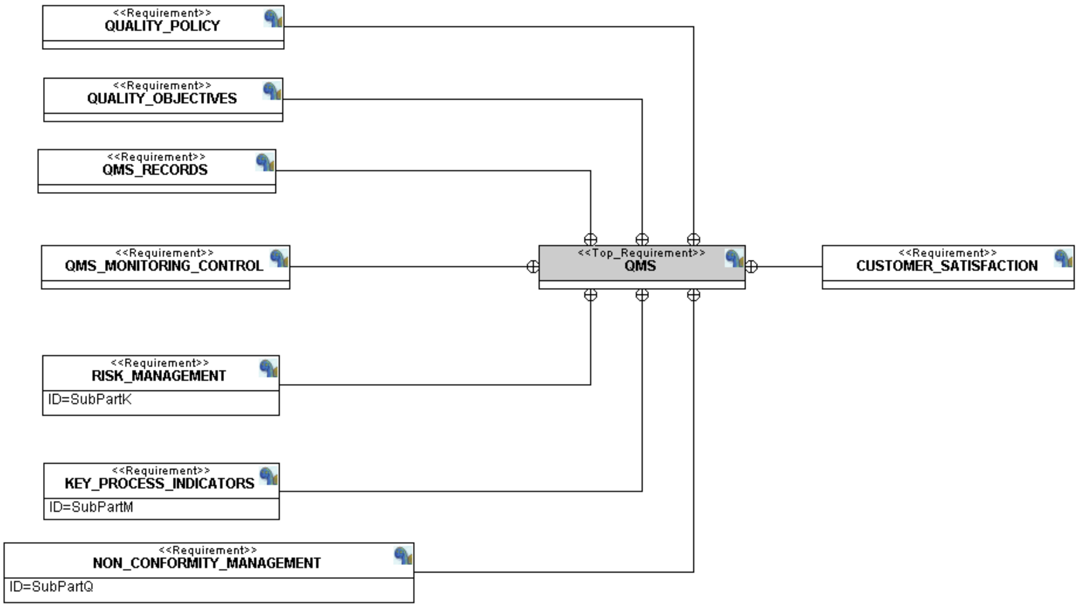

Figure 5 - 15 Requirements diagram – Maturity Model Level 1

Maturity Model Level 2 (Figure 5-16): the main objectives are to build the bricks of the DAS and the supplier management process and the change management process for design part only, and the first brick of the ORS as well.

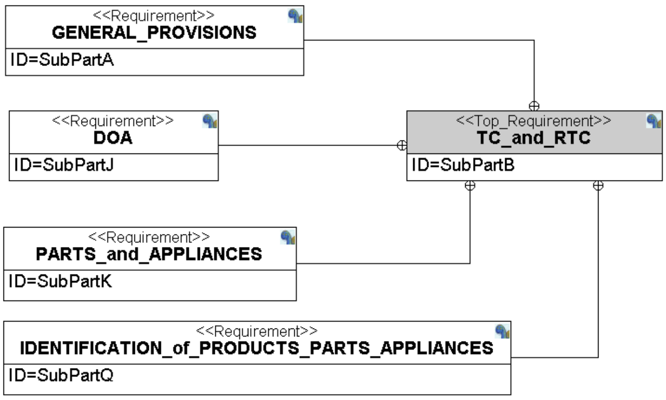

Figure 5 - 16 Requirements diagram – Maturity Model Level 2

Maturity Model Level 3 (Figure 5-17): the main objectives are to build the bricks of the QAS, the change management process for the production part, and to finalize the implementation of the ORS as well.

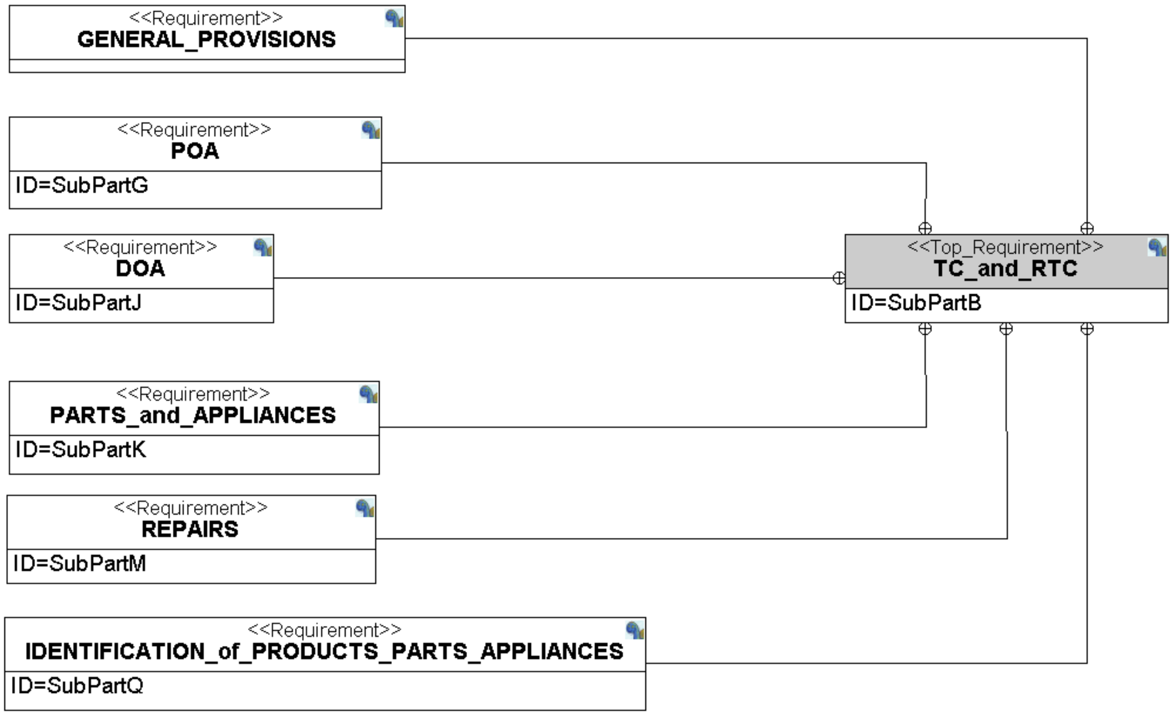

Figure 5 - 17 Requirements diagram – Maturity Model Level 3

An organisation having a Quality system designed to meet a recognised Standard such as ISO9001 (relevant to the scope of approval being requested) should expand it to include at least the following additional topics, as appropriate, in order to demonstrate compliance with the requirements of Part 21 Subpart G:

- Mandatory Occurrence Reporting and continued airworthiness as required by 21.A.165(e)
- Control of work occasionally performed (outside the POA facility by POA personnel)
- Co-ordination with the applicant for, or holder of, an approved design as required by 21.A.133(b) and (c)and 21.A.165(g)
- Issue of certifications within the scope of approval for the privileges of 21.A.163
- Incorporation of airworthiness data in production and inspection data as required in 21.A.133(b) and (c)and 21.A.145(b)
- When applicable, ground test and/or production flight test of products in accordance with procedures defined by the applicant for, or holder of, the design approval

- Procedures for traceability including a definition of clear criteria of which items need such traceability. Traceability is defined as a means of establishing the origin of an article by reference to historical records for the purpose of providing evidence of conformity
- Personnel training and qualification procedures especially for certifying staff as required in 21.A.145(d).

Maturity Model Level 4 (Figure 5-18): the main objectives are to finalize the certification with the Noise Certificate and the Permit to Fly Objectives.

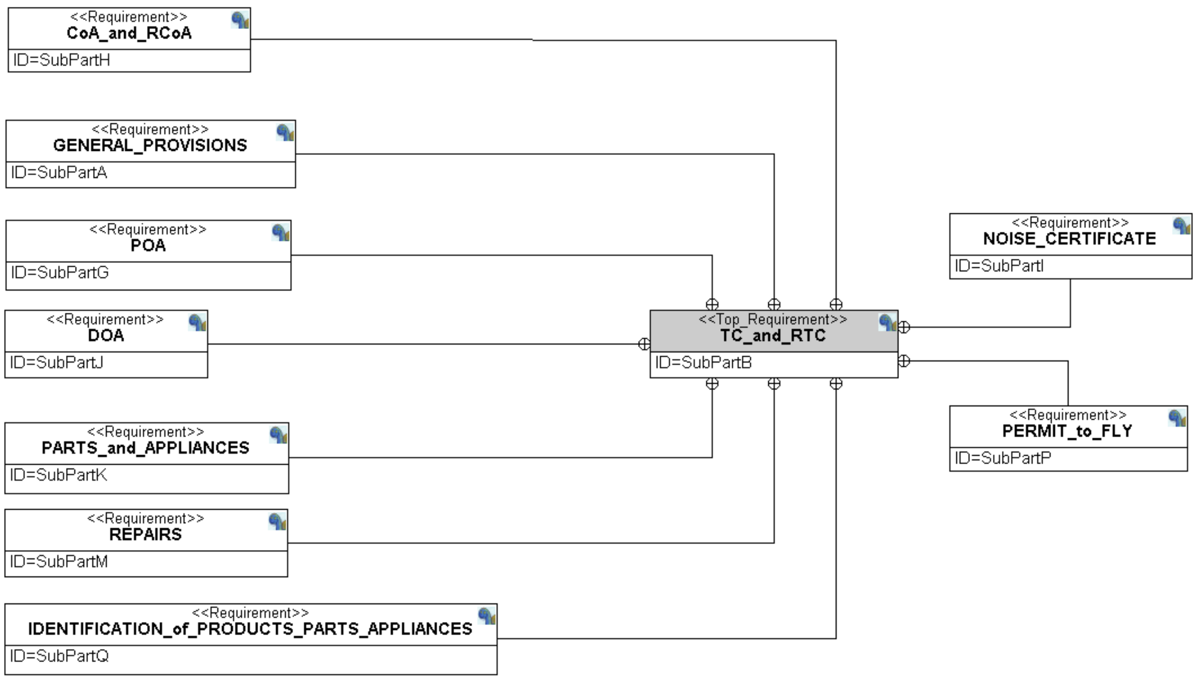

Figure 5 - 18 Requirements diagram – Maturity Model Level 4

5.3. DISCUSSION ON THE FRAMEWORK PROPOSITION

The application presented in the previous section aimed to better understand the scope and challenges of the proposed methodological framework. The application to an innovative and complex project enabled to validate the approach as a whole. Even if they were not presented, two additional study cases were performed to confront the framework with real projects:

- An organisation without previous experience in aircraft development but with a strong aeronautical culture aiming to develop an innovative but not complex aerostat;
- An organisation with a strong maturity in its activities but without experience in the aeronautical sector, aiming to provide equipment for an innovative and complex aerostat integrator.

These two additional cases allowed to test and verify the global approach and to assess the methodology; in particular the parameters and rules of governance, as well as the maturity model.

Strengths and potential improvements have been identified. This section will discuss each of them first per sub-part of the framework and finally for the global approach.

GENERAL MODELLING APPROACH

The choice of SysML to model the regulation objective is validated as it enables to easily make the link between the requirements system and the system modelling views. It constitutes an adequate language to represent the system in a structural and behavioural way.

TTool has been used to build the framework. It shows several strengths compared to other tools but imposed some limitations in the modelling project as well. For instance, even if it was possible to make improve the tool with new functionalities answering to the need of the framework (thanks to the help of its designer L. Apvrille), the implementation of the framework was constrained by the modelling tool.

Many models still need to be developed to answer to the diversity of organisations. The application to other real and representative cases of the sector could be carried out to verify the adaptability of the framework and build a real repository of available models.

METAMODEL

The simplicity of the metamodel makes it possible to focus on the essential elements of certification. As there were no link between the built model and the metamodel, the models have been created with more degrees of freedom than if the models would have been resulted from a design pattern. However, despite particular attention to ensure consistency between the metamodel and the models, inconsistencies may have crept in during manual work. Future research could address the possibilities of generating the models automatically through the metamodel.

REQUIREMENTS DIAGRAMS

The first difficulty of the project was to analyse Part 21 and find an automatic rule to extract atomic, complete, non-ambiguous and non-redundant requirements. The requirements diagrams aim to represent the certification requirements with less ambiguity than text-based requirements, written in natural language (English most of the time). Misunderstandings should be reduced and comprehensive understanding should be increased. Figure 5-19 illustrates the list of functions that model-based requirements can complete: gather the requirements coming from different documents, ensure a global analysis, verify the whole, relate each of them, visualize by selected sets or globally, and share with other stakeholders.

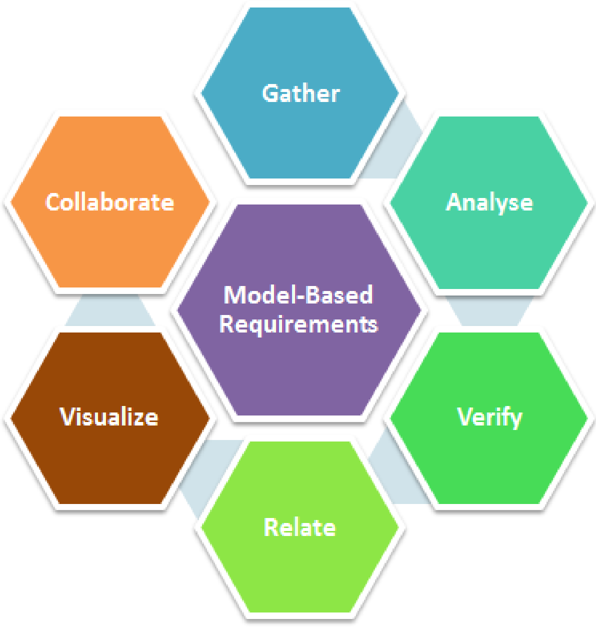

Figure 5 - 19 Model-Based Requirements objective

To go further, it could be interesting to use Natural Language Processing (NLP) techniques to provide automatic analysis of the regulatory texts and automatic diagrams. This approach could be complementary to our work and could provide a way to verify and validate the approach.

STRUCTURAL AND BEHAVIOURAL PROCESS DIAGRAMS

The choice to structure the processes in activities which themselves are composed of tasks enables to have a simplified representation of what it is requested to do. It is not always easy to know what the activity level and task level are and additionally it is not always easy to limit the description to only such two levels.

In TTool, Block Definition Diagrams (BDDs) and Internal Block Diagrams (IBDs) are represented with the same technical element. It may generate confusion for some users accustomed to other modelling tools.

The proposal is using both state machines and activity diagrams. TTool does not support simulation of activity diagrams (only state machines can be simulated). Activity diagrams are more used to illustrate the processes and provide a communication tool. It may be difficult to coordinate any updates between the two kinds of diagrams.

Moreover if the proposal incorporates a dynamic approach, the framework should evolve to allow the company to start its application at specific key points in development without having to study the upstream phases that would not concern it.

GOVERNANCE APPROACH

The applications validate the interest to use a governance approach to identify the right objectives for the right context of enterprise. But in case of change of the regulations, we identify that the impact on the framework might be difficult to analyse. Impact Analysis of what should be taken into account in case of change and maintenance problematics should be anticipated.

Different than a review conducted by an external auditor in compliance with an official procedure, the risk management assessment could be improved and transformed to be closer to a questionnaire grid to determine in a more systematic manner the enterprise maturity. The approach could gain in objectivity.

In case of change of the regulations, an expert system approach was selected offering a suitable solution able to take into account updates. The problematic is more on the modelling approach where models have to be re-examined and re-evaluated for each update of the regulation.

The possibility of providing a progressive solution to implement the necessary processes seems to respond to a strong problem of SMEs who do not know by what or where to start. The maturity model approach has been validated by the case studies. It is noted that in case of change of the regulations, this needs to be re-assessed, such as the modelling approach.

GLOBAL APPROACH FOR AIRCRAFT CERTIFICATION

The proposed approach provides a representation of the operational objectives of the certification in a more formal way than the regulatory texts or the normative texts currently propose. Misunderstandings should be reduced and comprehensive understanding should be increased. The proposed approach should allow the organization to acquire, store and distribute knowledge on the certification requirements more quickly. It should increase modularity and reusability of the different processes for different projects within the same organisation or between different organisations. It should allow companies to know better the certification objectives and earlier. It should enable to identify the necessary investments before incurring significant costs with the risk of having to undo and redo what has been built. The approach should enable to reduce rework.

However, it is identified that the complexity of the ACF implies that the framework will be difficult to be used directly by the enterprise concerned by the innovative development project. Much rather, in its current form, the ACF can be used by external organisations, supporting the applicant to the certification.

The development time of an innovative project in the aeronautics sector is longer than a thesis project. The complete validation of the framework during a project timeframe could not be completed and therefore remains to be finalised in the near future.

Additionally, it is identified that the proposed three-step methodology could be reused for other different sectors where, like in the aeronautics sector, regulation is important. For example, rail or nuclear sector could be new targets for this approach.

The ACF is not yet using the full scope of regulation provided by EASA. This is a first step of a new paradigm and governance rules shall be improved with the adequate additional rules to take into account the full lifecycle of the aircraft.

Finally, EASA has not been directly implicated in the development of the project. It could be interesting to get the point of view of the regulator on the approach and make them participate and validate in future extensions of the framework.

To go further, Figure 5-20 illustrates a potential structure of the framework in future development. In this proposition, three modules are identified:

- Assessment Module: the governance module for the Aircraft Certification Framework;
- Solution Module: the displayed results in adequacy with the context of the assessed enterprise (requirements and processes diagrams, organisation proposition, roadmap);
- Add-on Module: optional material for a progressive implementation of the processes.

Additionally, three repositories are identified:

- Certification knowledge: set of regulations to take into account;
- Requirements and Processes Models: set of models at disposal of the users of the Aircraft Certification Framework;
- Recommendations, Tools and Methods: set of complementary and explanatory materials.

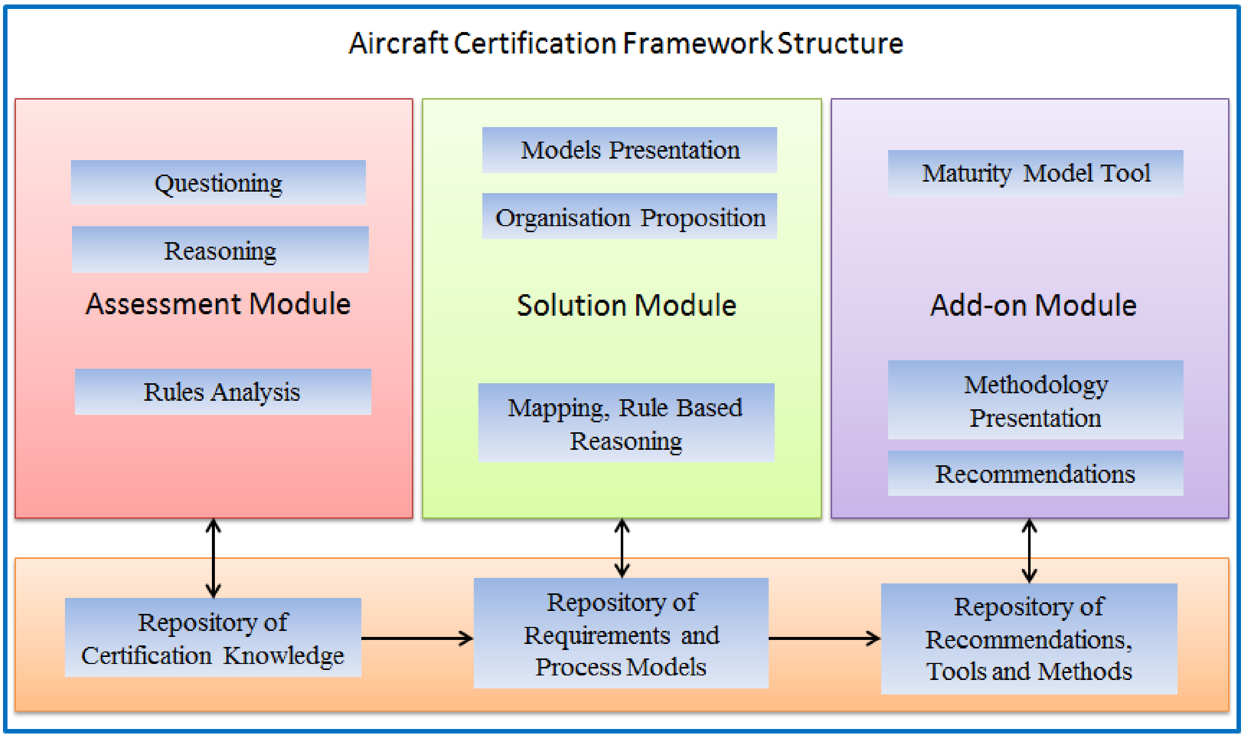

Figure 5 - 20 Potential Extension of the Aircraft Certification Framework

CHAPTER 6

CONCLUSION

CONTENTS

ABSTRACT

This chapter summarizes the work of the research and concludes the end of the thesis. Triggered by a specific need concerning innovative projects in the aviation sector, and particularly for those SMEs with a little certification experience, this research work allowed highlighting a more general problem in this industrial sector. This thesis aimed to provide a new solution to support organisations in their certification process. The goal is to build a solution for SMEs in the same time economically reasonable, technologically practicable without too much knowledge involved and appropriate to the particular organisation. The presented approach is the first step for a new paradigm for certification. Some additional work must be provided to build the three modules (Assessment, Solution and Add-on) in parallel with the three repositories:

- Certification knowledge;
- Requirements and Processes Models;
- Recommendations, Tools and Methods.

At the same time, the provided results enable to distinguish several promising avenues of research.

In section 6.1, the initial objective and the contributions are recalled. The thesis has presented a methodological framework where both requirements and processes are the central elements. The set of contributions enables to answer to the questions raised in section 4.1.1.

In section 6.2, some limitations are highlighted. If the results validate the global approach, it remains to complete the proposal with validation and simulation aspects. In addition the appropriation of the methodology remains complicate for a SME and the role of consulting firms should constitute an important support.

In section 6.3, several perspectives in the short, medium and long term are identified for further research.

6.1. SUMMARY OF THE THESIS

Certification is often seen as an organizational and financial constraint. The main challenge of this work is to guide companies in the aeronautical sector towards more maturity in order to both open up market opportunities towards innovative products while maintaining a sufficient level of security so that the general public can calmly accept the large upheavals awaiting the aeronautical sector. Certification requirements must be known and understood as soon as possible so that companies can integrate them and not be confronted with reorganizations and rework.

The objective of this work was to provide a new methodological support for organisations in their certification process. The approach was oriented towards a solution to transform the implicit knowledge of the regulation and associated standards into more explicit knowledge, in order to:

- provide a more comprehensive understanding of the regulation;
- provide formalized information through requirements and process modelling;
- provide just necessary information adapted to the specific business context.

Chapters 1 to 3 provided the contextual and theoretical background of this thesis. The related works have been reviewed and summarized to establish the basis of the approach. Systems Engineering assets have been first explored, to make emerge a specific interest on Model-Based Systems Engineering (MBSE) and Knowledge Engineering. The Process and Process Modelling area enabled to identify the core of the approach and the language to use. Knowledge modelling brought the necessary means to classify and organize the knowledge, mainly coming from experts in the certification domain. Finally, Capability and Maturity Modelling provided guidance to propose a progressive solution for organisations with little experience in certification.

Chapter 4 presented the framework with its different parts. In addition to the traditional documentary support, a new reference was been built with the following foundations:

- the texts of the initial European airworthiness;
- recommendations from experts in certification domain and in systems engineering;
- general expectations of the aeronautical sector; and
- the specific needs of SMEs.

This new reference framework called Aircraft Certification Framework (ACF) is composed of three main parts (see Table 6-1 for the list of contributions):

- a modelling approach;
- a governance approach; and
- a methodological approach broken down into three stages.

Table 6 - 1 Summary of proposals and contributions

	PROPOSALS	CONTRIBUTIONS PROVIDED BY THE ACF PROPOSAL
P1	**A modelling approach**	**Provide the elements of the framework**
a	a metamodel	Provide the concepts of the framework
b	functional requirements diagrams	Formalize the requirements
c	structural process diagrams	Describe the expected processes in a structural way
d	behavioural process diagrams	Describe the expected processes in a behavioural way
P2	**A governance approach**	**Provide the rules to structure and administrate the framework**
a	a risk-based solution	Provide a means for a risk-based analysis
b	an expert system	Determine the appropriate certification strategy
c	a maturity model	Provide a means to break down the objective in a progressive solution
P3	**A methodological approach**	**Provide a support for organisations to settle the framework**
a	Step 1 : Enterprise Analysis	Provide a methodology to assess the enterprise
b	Step 2 : Certification Requirements Elicitation	Provide a means to select the necessary and sufficient requirements from regulation
c	Step 3 : Process Definition	Provide a methodology to present the static structure of the processes and the dynamic relation between the processes and their inherent elements.

The set of contributions enables to answer to the questions raised in section 4.1.1. Proposal P1 enable to answer to question Q1. Both proposals P2 and P3 enable to answer to question Q2. P1 and in particular P1-b, P1-c and P1-d enable to answer to question Q3. P1 and in particular P1-c and P1-d enable to answer to question Q4. Recommendations as required by Q5 are planned to be a part of the framework but could not be implemented fully at the end of the thesis. Q6 and Q7 need additional research.

Finally, chapter 5 presents the results of an application of the ACF proposition. A real case study, a French innovative manufacturer, enables to assess the proposed certification framework. This case study validates the general approach and identifies some potential for improvement to the proposition.

6.2. LIMITATIONS

If even if the obtained results validate the global approach, it remains to complete the proposal, in particular on the aspects of validation and simulation.

Validation

The development time of an innovative project in the aeronautics sector is longer than a thesis project. The complete validation of the framework during a project timeframe could not be completed and therefore remains to be finalised in the near future.

Simulation

Even if the proposal incorporates a dynamic approach, the proposal should evolve to allow to simulate the behaviour of the processes and to allow the company to start its application at specific key points in development without having to study the upstream phases that would not concern it.

Performance

The methodology should better prove a substantial improvement in time, cost and quality to support the company to reach the EASA certification.

Scope

Finally, the ACF is not yet using the full scope of certification specifications (CSs) as provided by EASA. CSs are an important stake to support companies. The proposal is a first step of a new paradigm and governance rules could be improved with the adequate additional rules.

The timeframe of the thesis does not allow for providing a complete proposition ready to use for any kind of enterprise aiming to develop a new airborne system. Additional work must be provided to build the three expected modules presented in the section 5.3:

- Assessment Module: rules list must be validated and probably completed with other case studies;
- Solution Module: the proposed prototype could be transformed to become a web-based solution;
- Add-on module: the maturity stages could be proposed as an option to the global framework.

Moreover additional work must be provided to complete the three repositories presented in the section 5.3:

- Certification knowledge: CSs requirements could complete the global knowledge of the framework. Other regulations could be integrated such as environmental requirements as well;
- Requirements and Processes Models: models must be validated and probably completed with other case studies;
- Recommendations, Tools and Methods: additional material should be provided within the framework to support its usage.

Even in its complete stage, the ACF framework remains an important investment for SMEs to understand and implement. An appropriate and close support is still required to help them in their certification process. The proposition is probably more acceptable for consultancy companies which would be aware of the intricacies of the regulations and would be able to maintain and update the framework with more insight.

6.3. PERSPECTIVES FOR FUTURE RESEARCH

This research work presented in this thesis will contribute to a global proposition to support the enterprises in their tasks of certification in the aeronautics sector. It is a first step for a new paradigm, providing a rigorous framework and a new methodology for aircraft certification, opening up numerous perspectives in the short, medium and long term.

Short term perspectives

In the short term, the proposed approach has to be consolidated and enriched with other real cases. The rules of the governance part could be improved with additional parameters. The repositories of Certification knowledge and Requirements and Processes Models have to be completed.

Also, the three modules (Assessment, Solution Module, and Add-on) could be consolidated in an integrated tool as we begin to build during the research an adapted to become a web-based solution.

Medium term and long term perspectives

It could be interesting to think about the construction of the metamodel under a supported tool. At the end of the research, a project has begun in order to build the metamodel thanks to a dedicated profile developed under a tool called Eclipse Papyrus. The objective behind was to facilitate the construction of the models and their validation by automatic routines. The project succeeded to validate the global approach but additional time was required to consolidate the proposition.

The approach could be extended to all regulatory texts without being limited to initial airworthiness, but taking into account all the texts of continuous airworthiness and all the particularities of the different stakeholders involved in these phases (airlines, air traffic controllers, maintenance, repair and overhaul companies, etc.).

Key indicators should be integrated to the approach to demonstrate the performance of this new certification approach. The actual improvement in terms of time, costs and quality to support the company in achieving certification should be better assessed and proven.

To go further, it could be interesting to use Natural Language Processing (NLP) techniques to provide automatic analysis of the regulatory texts and automatic diagrams. This approach could be complementary to our work and could provide a way to verify and validate the approach.

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[171] S. Lemoussu, J.-C. Chaudemar, P. H. G. van Langen, F. M. T. Brazier, and R. A. Vingerhoeds, ‘Methodological Approach to Certification Processes for New Forms of Air Transportation’, under review processing.

LIST OF DEFINITIONS

LIST OF PUBLICATIONS

This section provides the list of conferences and publications released during this thesis. We presented the motivations behind the research work in a first international conference in Valenciennes (France) [167]. Then a first paper has been published attending an international conference in Amsterdam [168]. Conference paper [169] introduced specifically the metamodel whereas [170] introduced the governance part.

International Conference with Proceedings

[168] S. Lemoussu, J.-C. Chaudemar, and R. A. Vingerhoeds, 'Systems Engineering and Project Management Process Modeling in the Aeronautics Context: Case Study of SMEs', presented during 20th International Conference on Mechanical and Systems Engineering (ICMSE 2018) in Amsterdam, February 2018, Int. J. Mech. Mechatron. Eng., vol. 12, pp. 88–96, 2018.

[169] S. Lemoussu, J.-C. Chaudemar, and R. A. Vingerhoeds, 'Proposition pour une Démarche de Modélisation des Processus', presented at the 12ème Conférence Internationale de MOdélisation, Optimisation et SIMulation - MOSIM'18, Toulouse, France, June 2018.

French Conference with Proceedings

[170] S. Lemoussu, J.-C. Chaudemar, and R. A. Vingerhoeds, 'Modélisation des processus de développement pour les petites et moyennes entreprises du secteur aéronautique', presented at the Congrès Lambda Mu 21 « Maîtrise des risques et transformation numérique : opportunités et menaces », Reims, France, October 2018

International Conference without Proceedings

[167] S. Lemoussu, 6th International Conference on System Modeling and Optimization, Valenciennes, February 2018.

International Journal

[171] S. Lemoussu, J.-C. Chaudemar, P.H.G van Langen, F.M.T Brazier and R. A. Vingerhoeds, Methodological Approach to Certification Processes for New Forms of Air Transportation, in progress after a first reviewing process

APPENDIX A – Synthesis in French

Chapitre A 1. **Introduction**

Le processus de certification est une garantie pour l'industrie aéronautique de gérer un haut niveau de sécurité et un faible taux d'accidents; c'est une contrainte importante pour les entreprises du secteur. L'enjeu est commercial car le certificat de navigabilité est le seul moyen de commercialiser un aéronef. C'est également un enjeu de société car les constructeurs s'engagent à assurer la sécurité des passagers à bord, des personnes au sol et des infrastructures. Sous l'impulsion des recommandations de l'Organisation de l'Aviation Civile Internationale (ICAO ou International Civil Aviation Organisation en Anglais), de nombreux pays ont créé leurs propres institutions pour gérer localement le processus de certification et les exigences de sécurité, en prenant la responsabilité de délivrer les certificats de navigabilité des aéronefs. En Europe, l'Agence Européenne de la Sécurité Aérienne (EASA ou European Aviation Safety Agency en Anglais) est en charge de la sécurité des voyages en avion. L'exploitation de tout aéronef en Europe nécessite une autorisation de cette administration. Cela signifie que les entreprises doivent démontrer qu'elles ont mis en place un suivi et un contrôle de leurs développements. Pour les concepts nouveaux et innovants, la certification aérienne est un défi particulier car la règlementation associée n'est pas toujours disponible.

Dans l'aéronautique, les Petites et Moyennes Entreprises (PMEs) jouent traditionnellement le rôle de fournisseurs et dépendent fortement de leurs relations avec les intégrateurs, les équipementiers ou d'autres partenaires dits de niveau 1-2-3. Avec l'arrivée de nouveaux concepts d'avions, certaines PMEs s'engagent à prendre désormais le rôle d'intégrateur et doivent gérer à leur tour les différents échanges avec leurs propres fournisseurs. Il s'agit d'un changement de paradigme important.

Une contrainte majeure est que l'industrie aéronautique est régie par de nombreuses règles, législations et autres directives. Les PMEs, quel que soit leur rôle dans la chaîne d'approvisionnement, doivent également faire face à ces contraintes. Si elles ont le rôle d'intégrateur, elles devront assumer les mêmes rôles que les grandes entreprises, entretenant des liens avec les fournisseurs de la chaîne d'approvisionnement, soutenant et supervisant leur travail de chef de projet, tout en étant capable de communiquer avec les autorités de certification. Elles devront démontrer leur capacité à concevoir, produire et exploiter leurs systèmes avec le niveau de sécurité et de fiabilité attendu, comme le prévoit la réglementation. Comme toute organisation commerciale, les PMEs doivent faire face aux contraintes habituelles de sécurité, de coût, de temps et de performance. La principale différence, et contrainte, est qu'elles doivent effectuer toutes ces activités avec beaucoup moins de ressources que les grandes entreprises.

Dans cette thèse, des voies alternatives sont étudiées, réduisant la complexité et facilitant les PMEs innovantes notamment, pour comprendre et intégrer les règles de certification à leurs processus internes. Nous identifions deux besoins majeurs:

- Un soutien méthodologique est requis pour les PMEs; et
- Les exigences de certification pourraient être plus facilement disponibles et adaptables pour chaque situation d'entreprise.

Chapitre A 2. **Réglementation et Standards du Secteur Aéronautique**

L'industrie aéronautique est contrainte par une règlementation stricte. Le principe de navigabilité est le concept central de la règlementation aérienne. La navigabilité doit être établie et doit être maintenue tout au long de la vie de l'aéronef. La recherche dans cette thèse s'intéresse aux entreprises européennes, l'analyse s'est naturellement concentrée sur la réglementation européenne régie conjointement par l'Union Européenne (European Union ou EU en Anglais) et par l'Agence Européenne de la Sécurité Aérienne (European Aviation Safety Agency ou EASA en Anglais). Par ailleurs, des guides existent pour accompagner les entreprises dans leur développement et les soutenir dans le processus de certification. Cette section s'attache à explorer ce paysage particulier.

A 2.1 La réglementation européenne

La réglementation européenne est structurée en quatre niveaux principaux (Cf. Fig.A2-1):

- Le règlement de base. Sur la base des recommandations de l'ICAO, des exigences communes sont établies pour la réglementation de la sécurité et de la durabilité environnementale dans l'aviation civile européenne. Ces textes, sous la responsabilité de l'Union Européenne, sont regroupés aujourd'hui sous la règlementation (EU) 2018/1139.
- Les règles de mise en œuvre (IR ou Implementing Rules en Anglais). Ils sont composés de plusieurs textes ayant chacun un sujet différent et comprenant principalement la navigabilité initiale, (EU) No 748/2012, et le maintien de la navigabilité, (EU) No 1321/2014, mais aussi les opérations aériennes, les licences du personnel, les aérodromes, la gestion du trafic aérien et les services de navigation aérienne. Ces textes sont sous la responsabilité de l'Union Européenne.
- Les annexes des IRs. Elles constituent des règles plus pratiques mais sont considérées comme des «lois strictes» (appelées « Hard Law » en Anglais), en ce sens que tous les candidats doivent se conformer à ces annexes. Par exemple, l'IR du texte (EU) n°748/2012, qui concerne la navigabilité initiale, est liée à l'annexe I qui est également appelée Partie 21 (Part 21 en Anglais). Autre exemple, l'IR du texte (EU) n°1321/2014, qui concerne la navigabilité continue, connait cinq annexes : Partie M (Part M en Anglais), Partie 145 (Part 145 en Anglais), Partie 66 (Part 66 en Anglais), Partie 147 (Part 147 en Anglais) et Partie T (Part T en Anglais).
- La «Soft Law». Le nom de ces textes, en opposition avec la « Hard Law », vient du fait que les candidats à la certification peuvent négocier leur contenu sous certaines conditions. Ces textes sont sous la responsabilité de l'EASA et se composent principalement de trois types de documents: les AMCs, les GMs et les CSs. Ces documents sont détaillés plus bas.

Les AMCs ou Acceptable Means of Compliance en Anglais

Moyens de conformité acceptables, ce sont des recommandations fortes fournies par l'EASA pour permettre aux candidats de se conformer à la loi stricte.

Les GMs ou Guidance Material en Anglais

Guides de référence, ce sont des informations supplémentaires pour aider les entreprises à trouver le bon moyen de conformité en fonction de leur contexte d'organisation.

Les CSs ou Certification Specifications en Anglais

Spécifications de certification, il s'agit des règles spécifiques relatives au type d'aéronef à certifier.

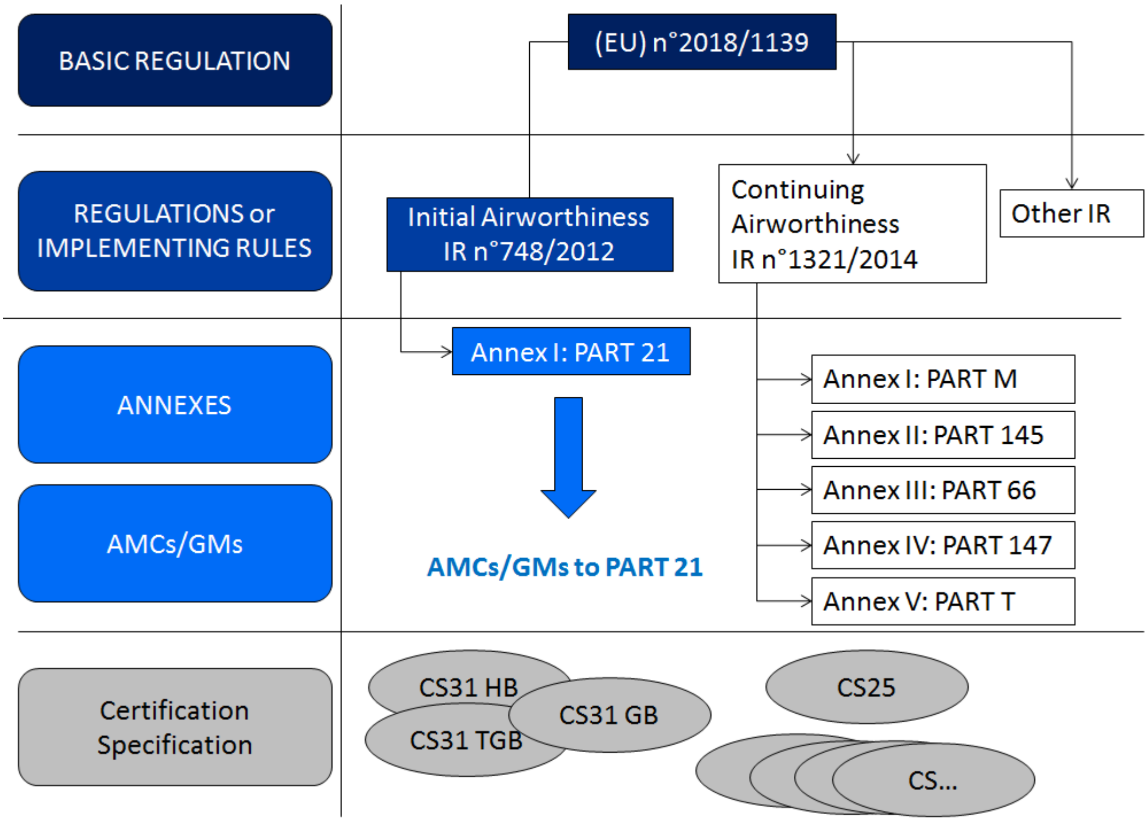

Figure A2 - 1 Structure de la réglementation Européenne

D'autres publications de l'EASA

L'EASA publie également des guides de bonnes pratiques à des fins d'information. Ils ne doivent pas être considérés comme officiellement adoptés par l'EASA. Les bonnes pratiques n'introduisent pas de règles nouvelles ou modifiées et ne constituent aucune obligation légale ni aucun droit pour l'Agence ou les organisations.

De plus, l'EASA est responsable de la distribution des directives de navigabilité (ADs ou Airworthiness Directives en Anglais). Une AD est une communication formelle qui impose certaines actions correctives que les concepteurs et fabricants se doivent de prendre en compte.

Annexe I ou Partie 21

Traditionnellement dénommée Partie 21 (Part 21 en Anglais), l'annexe I du règlement IR n° 748/2012 constitue le véritable cœur de la certification des aéronefs. Elle décrit uniquement les conditions attendues de la navigabilité initiale et est composée de 2 sections principales:

- La section A décrit les exigences techniques adressées aux candidats à la certification. Cette section est composée de 14 sous-parties (de A à Q);
- La section B décrit les procédures adressées aux autorités compétentes, essentiellement l'EASA ou toute autre autorité nationale (National Aviation Authority ou NAA en Anglais) comme par exemple la DGAC (Direction Générale de l'Aviation Civile en France). Cette section est aussi composée de 14 sous-parties (de A à Q).

La plupart des 14 sous-parties font référence à une approbation particulière ou à un certificat, mais pas systématiquement. Par exemple, la conformité aux sous-parties A, F et Q ne nécessite pas d’effectuer une demande associée à l’EASA et n’entraîne pas non plus l’émission d’une approbation ou d’un certificat.

Un autre concept majeur de la Partie 21 est que différents contextes coexistent dans la Partie 21. Les exigences inhérentes peuvent concerner différents types d'entreprises ayant des objectifs différents. Selon la situation, l'organisation devra traiter différents types de sous-ensembles d'exigences de la Partie 21. Une organisation particulière n'est ainsi généralement pas concernée par les exigences complètes.

La liste des certificats et approbations est fournie ici:

- La Sous-Partie B constitue les exigences des Certificats de Type (Type Certificates and Restricted Type Certificates, ou TC et RTC en Anglais) ;
- La Sous-Partie D constitue les exigences en cas de modification des TC ou RTC (Changes to Type Certificates and Restricted Type Certificates en Anglais) ;
- La Sous-Partie E constitue les exigences pour les Certificats de Type additionnels (Supplemental Type Certificates ou STC en Anglais) ;
- La Sous-Partie G constitue les exigences pour l'agrément d'organisme de production (Production Organisation Approval ou POA en Anglais) ;
- La Sous-Partie H constitue les exigences des certificats de navigabilité (Certificates of Airworthiness and Restricted Certificates of Airworthines, soit CoA ou RCoA en Anglais);
- La Sous-Partie I constitue les exigences pour les certificats relatifs au bruit généré par les aéronefs (Noise Certificates en Anglais) ;
- La Sous-Partie J constitue les exigences pour l'agrément d'organisme de conception (Design Organisation Approval ou DOA en Anglais) ;
- La Sous-Partie K constitue les exigences pour l’approbation des constituants de l’aéronef (Parts and Appliances en Anglais) ;
- La Sous-Partie M constitue les exigences en cas de réparation (Repairs en Anglais) ;

- La Sous-Partie O constitue les exigences pour la certification particulière des constituants de l'aéronef (European Technical Standard Order Authorisations ou ETSO en Anglais) ;
- La Sous-Partie P constitue les exigences pour les autorisations de vol (Permit to fly en Anglais) ;

Il est important de noter que la Partie-21 s'intéresse à trois catégories d'élément potentiellement certifiable (Cf. Fig.A2-2):

- les produits, qui peuvent être l'avion ou la motorisation (Products en Anglais);
- les équipements et instruments (Appliances en Anglais); et
- les petits éléments (Parts en Anglais).

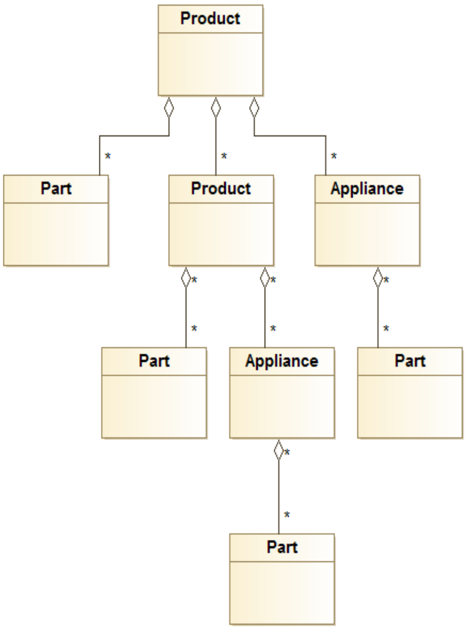

Figure A2 - 2 Structure Produit d'un aéronef selon la Partie 21 (en notation SysML)

Enfin trois concepts importants permettent de comprendre la règlementation européenne :

- Les Privilèges accordés aux organisations si elles peuvent démontrer une certaine autonomie et une certaine maturité par rapport aux exigences de certification ;
- La volonté affichée de l'EASA de fournir de l'accompagnement adapté pour les plus petites entreprises qui ont moins de ressources pour être en conformité avec la règlementation (Proportionnality en Anglais) ; et
- Le niveau d'implication de l'EASA (Level of Agreement ou LOI en Anglais).

A 2.2 Les standards aéronautiques

Traditionnellement, dans le secteur aéronautique, un objectif de certification est atteint en se conformant à une liste de guides bien connus dont les cinq plus importants sont les suivants:

- ARP4754A / ED-79A [17]: Considérations relatives à la certification des systèmes d'aéronef hautement intégrés ou complexes ;
- SAE AIR6110 [18]: Exemple de processus de développement d'aéronefs / systèmes contigus ;
- SAE ARP4761 [19]: Lignes directrices et méthodes pour la conduite du processus d'évaluation de la sécurité des systèmes et équipements aéroportés civils ;
- RTCA DO-178C / ED-12C [20]: Guide d'assurance de la conception pour le matériel électronique aéroporté ;
- RTCA DO-254 / ED-80 [21]: Guide d'assurance de la conception pour le matériel électronique aéroporté.

Ces guides représentent tous un consensus pour la communauté aéronautique et peuvent être considérés comme les meilleures pratiques dans cette industrie. De plus, ils sont reconnus par les deux plus grandes institutions de l'aviation civile, l'EASA et la FAA (Federal Aviation Agency en Anglais, administration fédérale de l'aviation aux Etats-Unis). Ils sont applicables à différents niveaux du développement de l'avion et sont interdépendants. Les directives et méthodes fournies dans les 4 documents sont destinées à être utilisées conjointement avec le matériel fourni par l'administrateur de certification (EASA, etc…). Leur contenu est clairement orienté processus. Une liste de processus à mettre en place dans l'entreprise est décrit sans pour autant expliquer comment les mettre en place.

A 2.3 L'Ingénierie Système

L'Ingénierie Systèmes (Systems Engineering ou SE en Anglais) est une approche interdisciplinaire, itérative et collaborative visant à aider à la réalisation de systèmes dits complexes. En aéronautique, cette approche est largement utilisée et constitue un guide méthodologique pour mener à bien les projets avec la performance, la fiabilité et la maintenabilité attendues.

Sur le secteur aéronautique, deux normes sont le plus souvent citées :

- ISO/IEC/IEEE 15288:2015 Ingénierie des systèmes et du logiciel — Processus du cycle de vie du système [34];
- ANSI/EIA 632:1998, Processus d'ingénierie système [32];

Ces normes décrivent les processus à mettre en place pour maximiser les chances de réussite dans la réalisation de systèmes complexes. Mais elles ne décrivent pas les méthodes et encore moins les outils à utiliser.

Pour répondre aux besoins spécifiques des PMEs, une nouvelle norme a émergé récemment : ISO/IEC 29110:2016 [6]. Plus simple mais aussi plus restrictive, elle s'adresse à des entreprises qui ne sont pas familières avec les concepts de l'Ingénierie Système et qui ont de fait moins de maturité pour déployer tous les processus attendus par les deux autres normes. De plus elle est plus orientée méthode car elle fournit des guides, des modèles et des exemples pour soutenir les entreprises dans leur déploiement.

Malgré un grand potentiel, l'ISO/IEC 29110 présente trois faiblesses concernant notre problématique :

- L'ISO/IEC 29110 s'applique aux projets de développement de systèmes non critiques. Les exigences de sûreté et de sécurité ne sont en effet pas traitées comme des exigences spécifiques.
- Les profils «Intermédiaire» et «Avancé» ne sont pas encore complètement disponibles.
- Étant donné que la norme ne traite pas de la question de la réglementation ni même de l'évaluation de la sécurité, cette norme ne permet pas de soutenir les nouvelles PME sur le marché de l'aéronautique.

A 2.4 Conclusions pour les nouvelles entreprises du secteur aéronautique

La situation actuelle en matière de législation, de normes réglementaires et de guides dans l'industrie aéronautique se révèle complexe à comprendre, en particulier pour les PMEs, qui arrivent sur le marché.

Les nombreux guides recommandés sont tous basés sur une liste de processus à mettre en œuvre dans l'entreprise. L'application de tous les documents disponibles, objectif ambitieux pour les PMEs, pourrait constituer une approche nécessaire mais elle demeure non suffisante. La Partie 21, document central du règlement européen, est effectivement plus que l'agrégation de ces lignes directrices. Une approche différente devrait être proposée.

Ainsi, l'objectif de ce travail de recherche est de fournir une compréhension plus complète des exigences de navigabilité en complément du support documentaire traditionnel. Une solution est nécessaire pour transformer la connaissance implicite de la réglementation en connaissance explicite. Les PME ont, par ailleurs, besoin de solutions plus progressives pour maîtriser le risque inhérent au processus de certification des systèmes critiques.

Chapitre A 3. Travaux connexes

A 3.1 Retours d'expérience en Ingénierie Système

La promotion de l'Ingénierie Système (IS) au sein des PMEs est très importante pour les groupes de travail issus d'industriels et d'universitaires. C'est le principal objectif d'associations telle que l'INCOSE (International Council on Systems Engineering en Anglais). Les représentants de l'INCOSE en France, l'AFIS (Association Française d'Ingénierie Système), et en Allemagne, GfSE (Gesellschaft für Systems Engineering), travaillent tous deux activement à l'expansion de l'IS dans les PMEs européennes.

i. Retours d'expérience de l'AFIS

Récemment, un guide en français a été publié pour fournir les concepts clés de l'Ingénierie Système (SE ou Systems Engineering en Anglais) aux PMEs [62]. Basé sur la norme ISO/IEC 29110, l'ouvrage propose une approche didactique à destination des PMEs qui visent à mettre en œuvre l'approche SE dans leur organisation. En particulier, une approche de déploiement des deux processus principaux: la réalisation du système et la gestion de projet associée est expliquée. En parallèle, AFIS a soutenu l'expérience PISOC (initiative PIlot pour le déploiement de l'ingénierie des systèmes au sein des PME en OCcitanie) dont l'objectif était d'accompagner six PMEs à déployer la SE dans leur organisation, à se conformer à la norme ISO/IEC 29110 et à expérimenter les recommandations du guide. Les résultats du projet montrent que les PMEs sont motivées à découvrir de nouvelles approches et à changer leur pratique actuelle si elles ont le potentiel de mieux gérer leurs risques [59] et [60]. Par ailleurs, le retour d'expérience montre que les implémentations SE permettent:

- un effet structurel sur l'organisation;
- une meilleure intégration des changements de produits;
- une capacité de réactivité accrue;
- un meilleur contrôle de la gestion de la configuration, de la gestion des exigences, de la gestion des risques et de la gestion des défauts.

Mais le chemin n'est pas facile et les PMEs sont confrontées à de nombreux obstacles pour appliquer pleinement tous les principes. L'expérience PISOC identifie un certain nombre de bonnes pratiques dont la nécessité de sensibiliser les PMEs à travers une formation courte et adéquate, d'adapter les recommandations aux objectifs commerciaux de l'organisation et de promouvoir des perspectives concrètes de gain à court terme.

ii. Retours d'expérience du GfSE

L'étude menée par GfSE [65] a signalé plusieurs obstacles à l'utilisation de l'Ingénierie Système. Ordonnés par ordre d'importance, les principaux obstacles retenus sont les suivants:

- Les avantages de l'application du SE sont non quantifiables, notamment le retour sur investissement ; ce qui est très dommageable pour les PMEs;
- Les méthodes introductives sont insuffisantes et le coût d'investissement initial est souvent identifié être un frein;
- L'expertise disponible est insuffisante ; notamment des ingénieurs systèmes qualifiés sont encore rares;
- L'intérêt du SE n'est pas toujours bien reconnu ; les méthodes et les bonnes pratiques issues des expériences d'autres entreprises ne sont pas systématiquement bien reconnues et valorisées, prétextant un contexte différent.

L'étude met en évidence différents domaines d'intérêt dans lesquels les organisations devraient fournir des efforts importants. Pour chaque domaine, les experts de l'étude font état des barrières actuelles à l'application des principes SE dans les organisations et notamment dans les PME. Les cinq domaines suivants sont retenus pour les objectifs de cette thèse :

1. La gestion des exigences est un domaine particulièrement difficile à gérer pour les PMEs, qui utilisent généralement des outils tels que MS Office pour la documentation des exigences.

2. L'architecture de système couvrant plusieurs domaines, créant le modèle de système, est toujours considérée comme trop coûteuse et impossible à gérer.

3. L'ingénierie des systèmes basée sur les modèles (MBSE ou Model-Based Systems Engineering en Anglais) est entravée par le manque de chaînes d'outils continues et de normes établies pour permettre la cohérence des modèles.

4. La vérification et la validation virtuelles reposent encore, pour les PME, sur de vrais prototypes. L'aspect du développement de produits virtuels est reconnu comme un précurseur, mais pas encore comme un équivalent.

5. L'adaptation des processus ne convainc pas les PME qui pensent que la diversité des méthodes est trop étendue et les processus trop rigides ou trop formels. Ils pensent que l'adaptation des processus n'est finalement pas transposable aux petites entreprises.

A 3.2 Concept de processus et la modélisation associée

Tout langage peut être caractérisé selon deux attributs: la syntaxe et la sémantique. La syntaxe définit les objets manipulables et la sémantique est le sens apporté par les objets. La syntaxe des différentes langages peut être textuels ou graphiques et naturels (informels) ou formels. On peut en ce sens distinguer quatre groupes:

- les langages dits naturels qui sont informels et textuels (les langues maternelles par exemple);
- les langages informels et graphiques (sous forme d'organigrammes par exemple) ;
- les langages formels et graphiques (les notations musicales par exemple);
- les langages formels et textuels (langages machine ou langages informatiques par exemple).

Quel que soit le choix concernant le type de syntaxe, au sein d'une organisation, un modèle de processus doit suivre une notation commune pour pouvoir être partagé et compris par tous. Plusieurs notations ou langages existent pour modéliser les processus. Dans cette thèse, seuls les langages suivants sont considérés : BPMN, OPM, UML et SysML.

i. BPMN

Le BPMN (Business Process Model and Notation en Anglais) est un langage graphique et informel orienté vers l'activité. Il est souvent considéré dans la littérature et dans l'industrie comme la norme de facto pour la modélisation des processus [116] et [117].

La version actuelle de la spécification BPMN 2.0.2 [118] fournit quatre types de diagrammes différents:

1. Diagramme de processus, décrivant les façons dont les opérations sont effectuées pour atteindre les objectifs prévus pour une organisation;

2. Diagramme de collaboration, présentant les interactions entre les différents processus;

3. Diagramme de conversation, qui spécifie la relation logique des échanges de messages;

4. Diagramme de chorégraphie, définissant le comportement attendu entre deux ou plusieurs participants commerciaux en interaction dans le processus.

ii. OPM

Le langage OPM (Object Process Methodology en Anglais) intègre les aspects structurels, fonctionnels et comportementaux d'un système dans un seul type de diagramme, appelé diagramme de processus objet (OPD ou Object Process Diagram en Anglais). L'ontologie de ce langage comprend trois types d'entités différents:

• Objets;
• Processus; et
• États.

Un modèle OPM consiste en un ensemble de différents OPD avec un niveau d'abstraction différent. Basé sur les fondements mathématiques formels des grammaires graphiques et d'un sous-ensemble du langage naturel, OPM permet de représenter graphiquement un système et génère automatiquement du texte en langage naturel spécifiant les exigences inhérentes [119].

iii. UML

Avec le développement de l'informatique, des approches d'ingénierie basée sur les modèles ont émergé pour le développement des logiciels. Le langage de modélisation UML (Unified Modeling Language en Anglais) [120] est un langage qui s'est alors très répandu et est souvent considéré comme un standard de facto [121]. Comme BPMN, l'UML orienté objet est un langage standardisé OMG[57] (Object Management Group en Anglais). UML est historiquement utilisé pour analyser, modéliser et concevoir des systèmes logiciels orientés objet. Cependant, il peut également être utilisé pour la modélisation de processus comme proposé dans le méta-modèle d'ingénierie des processus logiciels et systèmes (SPEM ou Software & Systems Process Engineering Metamodel en Anglais) [94] qui vise à fournir des éléments indicatifs pour la modélisation de méta-processus.

iv. SysML

Le SysML, profil basé sur le langage UML et couramment utilisé en ingénierie des systèmes [123], est l'un des piliers de l'ingénierie des systèmes basés sur les modèles (MBSE ou Model-Based Systems Engineering en Anglais) [123]. Il est utilisé pour soutenir le développement du système de manière interdisciplinaire [124]. SysML a certainement facilité la connaissance et l'adoption de MBSE mais même s'il a évolué pour mieux répondre aux besoins des utilisateurs, il a encore besoin d'améliorations fonctionnelles substantielles (essentiellement pour améliorer l'intégration), d'un meilleur affichage dans les outils avec des types de visualisation différenciés (texte, diagramme, tableaux, affichage interactif, différenciation des modèles,…) et d'un mécanisme adapté pour l'interopérabilité entre outils [125]. A l'instar de l'UML, le SysML est structuré autour de différents types de diagrammes, décrivant les différents aspects d'un système, permettant plusieurs vues d'un système. Tout comme pour l'UML et le BPMN, il n'y a pas de méthode standard associée au SysML. Des méthodes doivent être définies pour rendre explicite l'utilisation des diagrammes et exprimer une méthodologie dédiée conforme à l'approche déployée. Parmi les neuf diagrammes SysML disponibles pour représenter un système, cinq théoriquement peuvent être utilisés pour décrire l'aspect structurel et quatre peuvent être utilisés pour décrire l'aspect comportemental. Il est recommandé par l'OMG d'utiliser ces deux aspects pour décrire un système. Le principal inconvénient de ce langage, en plus de ne pas fournir de méthode spécifique, est que la cohérence entre les diagrammes doit être démontrée pour gagner la confiance dans le système modélisé [115] car les différents diagrammes et objets des diagrammes ne sont pas systématiquement liés.

[57] https://www.omg.org/

A 3.3 Concept de connaissance et la modélisation associée

Les connaissances constituent une ressource importante dans les organisations et la gestion des connaissances établit un avantage concurrentiel pour toutes les entreprises et en particulier pour les entreprises innovantes [127] et [128]. Malgré un intérêt grandissant, il n'y a pas de définition commune et acceptée de la connaissance et de la gestion des connaissances. Selon [115] et [116], la gestion des connaissances est définie comme un ensemble de quatre types d'activités:

- L'acquisition de connaissances, processus de création et développement de connaissances;
- La conversion des connaissances, comment les connaissances sont stockées et distribuées ou mises à la disposition des personnes dans l'organisation;
- L'application des connaissances, utilisation des connaissances;
- La protection des connaissances.

Au sein des organisations, la connaissance collective peut dépendre beaucoup des connaissances individuelles. Si la gestion des connaissances n'est pas prise en compte dans l'organisation et promue comme réalité stratégique, l'organisation prend le risque de perdre ses connaissances lors du départ de ses salariés [130]. Les connaissances communes et capitalisées ont une importance stratégique.

La gestion des connaissances peut également être utilisée pour les méthodes de résolution de problèmes ou comme aide à la décision. En particulier, la modélisation des connaissances est devenue une discipline cognitive pour aider formellement à prendre la bonne décision dans un environnement très complexe. Plusieurs approches existent. Dans cette thèse, ont été explorées deux approches principales de construction de connaissances par des méthodes inductives: les classificateurs d'arbre de décision et les systèmes experts.

i. Arbres de décision

Les arbres de décision sont l'une des techniques de base pour la classification des données et la prise de décision en plusieurs étapes [131], [132]. Leur construction est simple et facile à comprendre. Ils sont généralement puissants en termes de précision. Ils sont utilisés à la fois pour découvrir les facteurs appropriés influençant une situation particulière et pour trouver une solution à une question particulière. Ils sont bien adaptés pour classer les problèmes en fonction d'attributs ou de fonctionnalités [133]. Dans une approche en plusieurs étapes, la décision finale et complexe est divisée en un ensemble de décisions plus simples, simplifiant la prise de décision. Cependant, les classificateurs d'arbre de décision peuvent devenir volumineux, subir une complexité excessive et peuvent donc devenir incompréhensibles ou inutilisables [134].

Les classificateurs d'arbre de décision sont utilisés dans de nombreux domaines divers tels que le diagnostic médical, la classification des signaux radar [131], [135]. En particulier, ils sont largement utilisés dans l'évaluation de la sécurité aérospatiale et le diagnostic des pannes.

Dans cette thèse, l'accent est mis sur les arbres acycliques dirigés (DAT ou Directed Acyclic Tree en Anglais), satisfaisant aux propriétés suivantes :

1. Un DAT est un arbre sans cycle et dans lequel on peut trouver les quatre types de composants suivants :
    - une racine unique
    - des nœuds internes
    - des bords
    - des nœuds foliaires
2. Un DAT est traditionnellement composé de plusieurs chemins, chacun défini de la racine au nœud feuille. Chaque chemin est une séquence unique de nœuds et d'arêtes, menant à un nœud feuille particulier. Chaque chemin constitue une décision de règle telle que la règle «SI-ALORS».
3. Les nœuds internes sont étiquetés par des attributs ou des caractéristiques, déterminant les étapes de décision intermédiaires et décrivant les critères de fractionnement. Chaque critère de fractionnement crée un nouveau «ET» logique dans la «partie SI» et le nœud feuille constitue la «partie ALORS» [132].
4. Les nœuds internes présentent une paire d'arêtes: les arêtes d'entrée et de sortie. La racine est le seul nœud sans bord d'entrée. Les nœuds feuilles n'ont pas de bords de sortie.
5. La profondeur d'un chemin dans un DAT est la longueur du chemin du nœud racine au nœud feuille. Chaque chemin peut avoir une profondeur différente.

ii. Systèmes Expert

Le concept des systèmes experts a été introduit avec la construction d'ordinateurs intelligents en parallèle avec le développement de l'ingénierie des connaissances [137]–[139]. Le terme «expert» fait référence à l'objectif de développer des programmes capables de résoudre des problèmes avec le même niveau de compétence ou d'expertise que les spécialistes ou experts dans leur domaine.

Un système expert est traditionnellement composé de deux parties (Cf. Fig.A3-1):

- la base de connaissances, constituée à la fois de connaissances factuelles et heuristiques;
- le moteur de raisonnement ou d'inférence, conduisant à la solution du problème en s'appuyant sur la base de connaissances.

Cela signifie que deux étapes sont nécessaires pour construire un système expert. Il faut choisir:

1. la technique adaptée pour organiser et formaliser les connaissances disponibles;
2. le mécanisme d'inférence adapté pour raisonner les connaissances.

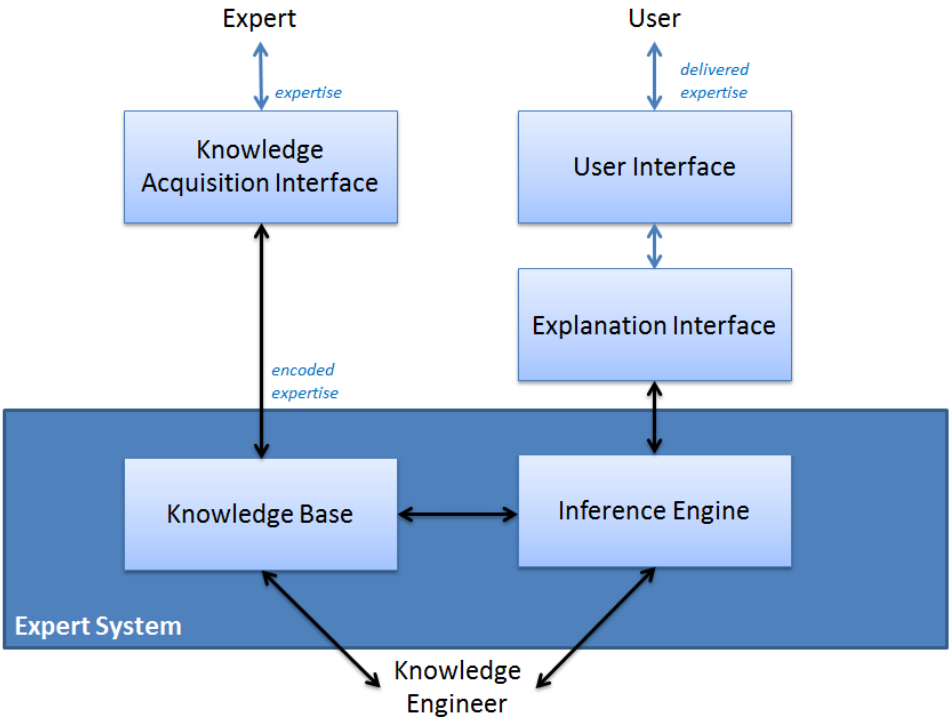

Figure A3 - 1 Structure d'un système expert (selon [137])

A 3.4 Concept de maturité et la modélisation associée

Une source majeure pour le concept des étapes de maturité est la grille de maturité du processus de gestion de la qualité [142]. Dans ce texte, les meilleures pratiques selon des stades de maturité et des catégories de mesure sont proposées pour mieux gérer les processus internes de l'entreprise. Dans les années 1990, lorsque les concepts d'amélioration de la qualité et des processus se développaient, de nombreux modèles de maturité sont apparus [143], mais le Capability Maturity Model Integration (CMMI) demeure le modèle le plus appliqué aujourd'hui dans l'industrie [144]. Cette section propose une courte description du CMMI et d'autres modèles de maturité utilisés dans l'industrie et présents dans la littérature.

i. Le CMMI, le SECM et le modèle SPICE

Cette section présente les spécificités de trois modèles majeurs : le CMMI-DEV, le SECM (pour Systems Engineering Capability Model en Anglais) et le modèle SPICE (pour Software Process Improvement and Capability dEtermination en Anglais).

Le CMMI-DEV V2.0 [145] propose deux types de représentation des processus: la représentation continue et la représentation par étapes. La représentation continue des processus se réfère généralement à un modèle de capacité tandis qu'une représentation par étapes des processus se réfère généralement à un modèle de maturité. Les modèles de capacité et les niveaux de maturité ne sont généralement pas utilisés en parallèle. Les modèles de capacité fournissent des niveaux de capacité de processus qui sont un moyen d'améliorer progressivement les processus un par un et permettent de classer leurs performances dans le contexte de l'organisation. Les modèles de maturité fournissent des niveaux de maturité de l'entreprise qui permettent de classer les organisations en fonction de leur capacité à contrôler une liste de processus identifiés. L'organisation est évaluée dans son ensemble et peut atteindre chaque niveau de maturité selon différents objectifs.

Le CMMI-DEV V2.0 propose pour les deux représentations (modèles de capacité et niveaux de maturité), cinq niveaux comme suit:

- Niveau 1 - Initial: les travaux sont terminés mais ils sont souvent retardés et dépassent le budget;
- Niveau 2 - Géré: les projets sont planifiés, exécutés, mesurés et contrôlés;
- Niveau 3 - Défini: l'organisation fournit des conseils sur les projets;
- Niveau 4 – Géré quantitativement: l'organisation est basée sur les données;
- Niveau 5 – En optimisation: l'organisation se concentre sur l'amélioration continue.

L'EIA 731 SECM [146] est un autre modèle reconnu dans le domaine de l'ingénierie système. Ce modèle constitue un modèle de capacité pour soutenir le développement et l'amélioration de la capacité d'ingénierie des systèmes. Il s'utilise en complément de l'EIA 632, norme d'ingénierie système [31], dont il a pour visée de fournir une couverture complète. L'EIA 731 SECM est un outil que les organisations peuvent utiliser pour évaluer la performance de processus d'ingénierie système déjà implémentés. Il peut être utilisé comme guide pour développer ou améliorer un processus d'ingénierie des systèmes [147].

L'EIA 731 SECM fournit un outil pour évaluer la capacité de 19 processus ou FA selon six niveaux de capacité:

- Niveau 0 – Pas effectué. Il s'agit du niveau par défaut.
- Niveau 1 – Effectué de manière informelle. Les pratiques spécifiques du domaine d'intervention sont effectuées de manière informelle et les performances ne sont pas planifiées et suivies de manière rigoureuse.
- Niveau 2 – Planifié et tracé. Les activités de la zone d'intérêt sont planifiées et suivies.
- Niveau 3 – Bien défini. Un processus standard est rigoureusement documenté et utilisé au sein de l'organisation.
- Niveau 4 - Contrôlé quantitativement. Des objectifs de qualité mesurables sont établis.
- Niveau 5 – En amélioration continue. Les objectifs d'efficacité des processus sont établis en fonction des objectifs commerciaux de l'organisation.

Le modèle SPICE (aujourd'hui connu sous la norme ISO/IEC 15504 [148]) propose un modèle de gestion des processus ainsi qu'une liste d'exigences pour évaluer et améliorer les processus. Chaque processus peut être évalué selon six niveaux de maturité :

- Level 0 – Incomplet.

- Niveau 1 – Effectué.
- Niveau 2 – Géré.
- Niveau 3 – Etabli.
- Niveau 4 – Prévisible.
- Niveau 5 – Optimisé.

La norme ISO/IEC 15504 est actuellement en révision et devrait être remplacée à terme par la famille de standard ISO/IEC 330xx family [149].

ii. Modèles alternatifs

La recherche sur les modèles de maturité propose de nombreuses publications, par exemple [143], [144], [150]–[154]. La plupart des modèles sont basés sur des modèles de maturité traditionnels, tels que CMMI ou ISO/IEC 15504-5 (ancien modèle SPICE). En particulier, [151] compare 16 modèles de maturité différents et identifie les principales caractéristiques permettant de sélectionner un modèle de maturité ou d'en concevoir un nouveau. Comme autre exemple, [154] compare 15 modèles de capacité / maturité qui suivent le cadre de mesure, le modèle de référence de processus, le support d'utilisation et comment ils ont été développés et validés. En outre, [139] propose un outil pour sélectionner le bon modèle de maturité des processus métier parmi 69 modèles à travers un questionnaire de 14 questions.

Dans [155], une grille de critères est proposée pour évaluer le niveau de maturité d'une entreprise concernant la mise en œuvre des processus SE. Il pourrait être un outil efficace pour promouvoir et appliquer les principes SE, mais en réalité, il ne fournit pas de méthode de déploiement claire. [155]–[159] proposent de nouveaux modèles de maturité. Tous ces modèles de maturité dans la littérature sont basés sur des niveaux de maturité qui représentent différents états par lesquels une organisation est transformée. Ses processus sont améliorés, passant de pratiques mal définies et incohérentes (généralement de niveau 0 ou 1) à des pratiques répétables et des processus prévisibles jusqu'à l'innovation et l'optimisation des processus (généralement de niveau 5 ou 6).

[160] souligne que les modèles de maturité peuvent être utiles pour gérer la complexité de la gestion de projet et peuvent être utilisés comme aide à la décision. Les auteurs présentent le modèle de maturité de la complexité de gestion qui évalue la maturité de l'organisation en matière de gestion de la complexité. Ce modèle présente quatre niveaux de maturité:

- Niveau 1: manque de gestion active de la complexité;
- Niveau 2: gestion de la complexité opportuniste;
- Niveau 3: gestion continue de la complexité;
- Niveau 4: gestion systématique de la complexité.

Chapitre A 4. Cadre méthodologique pour la certification des aéronefs

A 4.1 Les objectifs et l'approche générale du cadre proposé

En s'appuyant sur les concepts abordés dans le chapitre A3, l'ingénierie des systèmes basés sur les modèles (MBSE ou Model-Base Systems Engineering en Anglais) et la modélisation des processus sont combinés dans une seule et unique approche pour représenter graphiquement les exigences, les processus et les rôles de l'entreprise. L'approche vise à créer un nouveau cadre, appelé Aircraft Certification Framework (ACF pour Aircraft Certification Framework) qui incorpore les deux parties principales suivantes (Cf. Fig.A4-1):

- Design Engineering qui traite de l'ingénierie de conception des modèles ;
- Tooling, qui traite de la mise à disposition d'outils au sein du cadre.

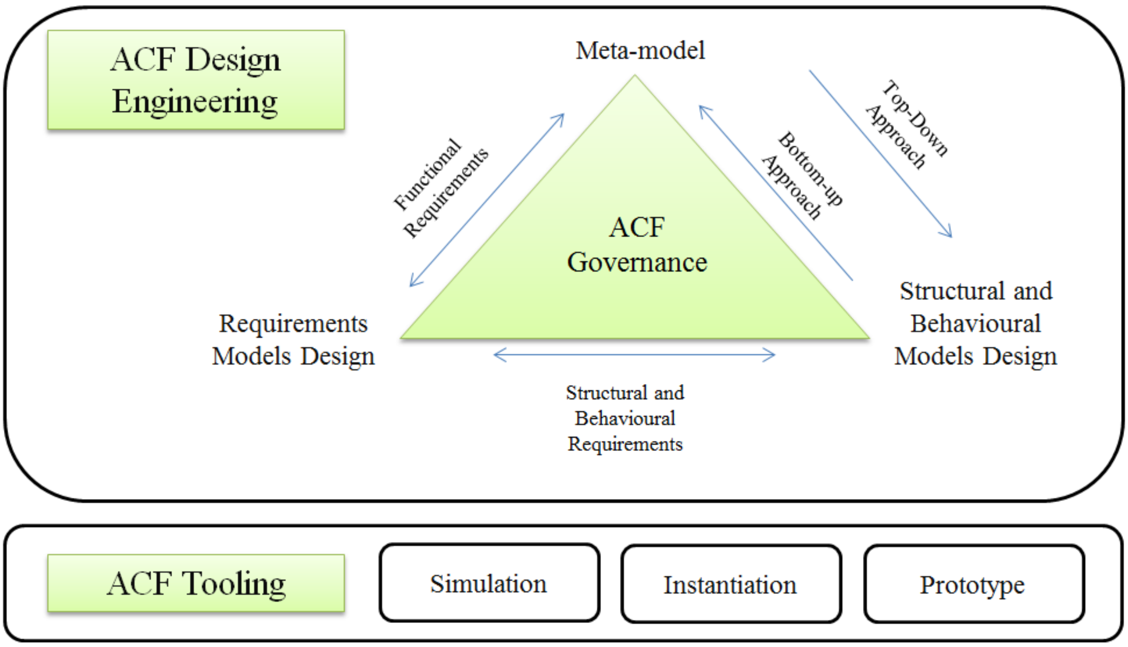

Figure A4 - 1 Vue générale du cadre proposé ACF

La partie Design Engineering est le cœur de l'ACF et constitue l'environnement de modélisation intégré. Cette partie est elle-même constituée de quatre composantes principales:

- Un méta-modèle décrit les définitions du concept de l'approche méthodologique ;
- Un ensemble de modèles fonctionnels ou d'exigences, représentant graphiquement les exigences de certification;
- Un ensemble de modèles structurels et comportementaux, décrivant les exigences structurelles et comportementales ;
- Un ensemble d'outils pour gérer la gouvernance globale du cadre.

Le cadre ACF de certification des aéronefs s'inspire de la hiérarchie des modèles à quatre couches proposée par l'OMG et propose une architecture à trois couches (Cf. Fig.A4-2):

- Une couche avec un méta-modèle (M2);
- Une couche avec un ensemble de modèles (M1);
- Une couche avec des données réelles provenant des PME (M0).

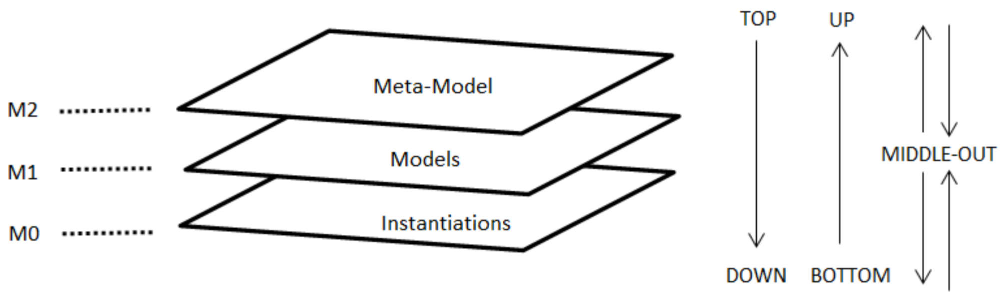

Figure A4 - 2 Approches Top-Down, Bottom-Up and Middle-Out utilisées pour l'ACF

L'idée est de parvenir à une cohérence entre les modèles. Il est possible de tracer un concept depuis sa définition (niveau M2), en passant par la modélisation (niveau M1) et enfin jusqu'à son utilisation réelle (niveau M0). Cette architecture à trois couches est un mécanisme structurant qui permet de raisonner sur nos modèles et classifications.

Dans cette approche, les trois couches se doivent d'être cohérentes, construisant une représentation fiable de l'organisation. De plus, l'approche de modélisation a été conçue en trois étapes, travaillant ensemble simultanément:

- Une approche descendante (ou «Top-Down» en Anglais),
- Une approche ascendante (ou «Bottom-Up» en Anglais),
- Une approche hybride mixant les deux autres approches (ou «Middle-Out» en Anglais).

A 4.2 Le méta-modèle

Les exigences sont considérées comme un concept important du méta-modèle (Cf. Fig.A4-3). Des moyens de conformité acceptables (AMCs, voir la section A2.1) sont proposés pour démontrer que les exigences sont mises en œuvre. Les AMCs sont fournis par l'EASA et font partie de la réglementation. Les moyens de conformité (MOCs ou Means Of Compliance en Anglais) sont les moyens choisis pour démontrer que l'activité a été effectuée. Les preuves de conformité (POCs ou Proofs Of Compliance) prouvent que les exigences ont été mises en œuvre par le biais des processus. Les justifications font partie de l'analyse des exigences et de la construction des moyens de conformité acceptables (AMC). Les hypothèses et potentiels arguments ne sont pas pris en compte dans ce méta-modèle.

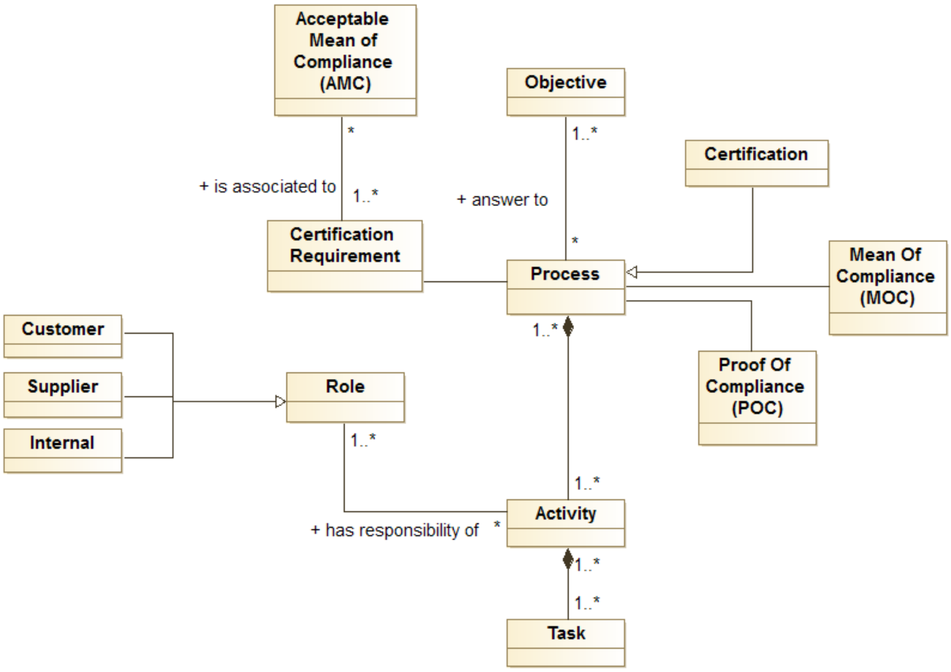

Figure A4 - 3 Métamodèle proposé pour l'ACF

Chaque processus, par sa structure et sa conception comportementale, se concentre sur au moins un objectif et est conforme aux exigences de certification pertinentes. Certaines exigences de certification peuvent être associées aux AMCs. La promulgation de chaque processus donne lieu à au moins une preuve de conformité aux exigences de certification, comme indiqué dans la section A2.1. Chaque processus est composé d'au moins une activité. Chaque activité, avec au moins une tâche, est liée à un rôle interne ou externe à l'entreprise via un rôle client ou fournisseur.

A 4.3 Les modèles

i. Diagrammes d'exigences

Les diagrammes d'exigences dans SysML (RDs pour Requirement Diagrams en Anglais) permettent de représenter graphiquement les exigences, en se concentrant sur les relations entre elles et avec d'autres éléments provenant d'autres diagrammes SysML. Ici, ces diagrammes peuvent illustrer par exemple les exigences de haut niveau de la partie 21, en utilisant uniquement des relations d'imbrication. Les différentes sous-parties de la partie 21 sont présentées de manière plus complète et les liens entre les différentes sous-parties de la partie 21 sont mis en évidence. La figure A4-4 fournit un exemple de diagramme d'exigences pour le cas spécifique d'un fabricant d'aéronef.

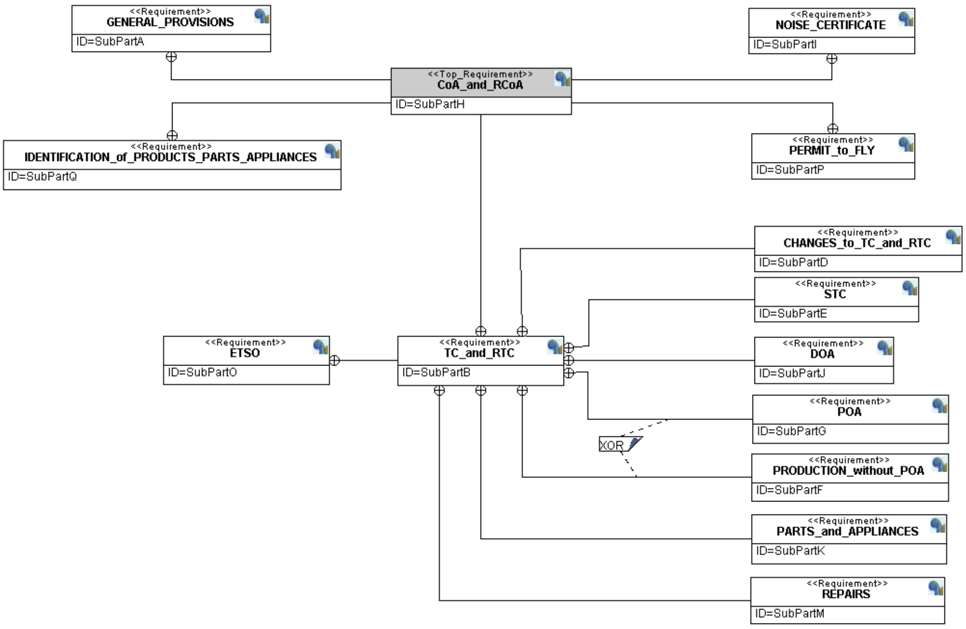

Figure A4 - 4 Diagramme d'exigences de certification pour un fabricant d'aéronef

Les exigences critiques de la sous-partie J sont définies principalement dans la partie 21, article 21.A.239 avec la constitution d'un système d'assurance de la conception (Design Assurance System ou DAS en Anglais) pour le contrôle et la supervision de la conception et des modifications de conception. Le DAS comprendra les activités suivantes:

- Contrôler la conception
- Montrer la conformité à toutes les exigences applicables
- Vérifier indépendamment la conformité
- Assurer la liaison avec l'Agence
- Évaluer en continu l'organisation de conception
- Gérer les sous-traitants

Les exigences critiques de la sous-partie G sont définies principalement dans la partie 21, article 21.A.139 avec la constitution d'un système d'assurance qualité (Quality Assurance System ou QAS en Anglais) pour le contrôle et la supervision de la production et des changements de production. Le QAS comprendra les activités suivantes:

- Contrôler la production
- Montrer la conformité avec la conception
- Vérifier et contrôler indépendamment la conformité
- Assurer la liaison avec l'Agence
- Évaluer en continu l'organisation de production
- Gérer les sous-traitants

La modélisation des exigences des 14 sous-parties doit être effectuée afin d'avoir une meilleure vue d'ensemble des exigences à traiter.

ii. Diagrammes structurels

Pour aller plus en détail sur le contenu des exigences, pour l'organisation (le système d'intérêt), on utilise les Diagrammes de Définition de Blocs (Block Definition Diagram ou BDD en Anglais) de SysML, afin de représenter la structure du système d'un point de vue externe. Diagrammes de Blocs Internes (Internal Definition Diagram ou IBD en Anglais), afin de représenter la structure interne des blocs du système. Les BDDs et les IBDs décrivent la hiérarchie du système en fournissant une description statique du système, une représentation structurelle des processus nécessaires. Les diagrammes structurels obtenus dans cette recherche décrivent les processus nécessaires et suffisants pour se conformer à la Partie 21.

L'outil TTool (environnement de SysML utilisé dans cette recherche) ne fait pas de distinction entre les BDDs et les IBDs, seuls les BDDs existent. Quatre types d'éléments différents sont créés pour décrire la composition de l'organisation (Cf. Fig.A4-5):

- Le niveau **Package** pour décrire les groupes de processus;
- Le niveau **Processus** pour décrire les processus élémentaires;
- Le niveau **Activité** pour décrire les processus éléments élémentaires;
- Le niveau **Tâche** pour décrire la composition des activités.

Dans cette approche, au plus haut niveau, chaque groupe de processus est composé d'un ensemble de processus qui peuvent être décrits en interne avec certaines parties intrinsèques, appelées activités qui à leur tour sont composées de différentes tâches. Les tâches sont le niveau de description le plus bas de l'organisation.

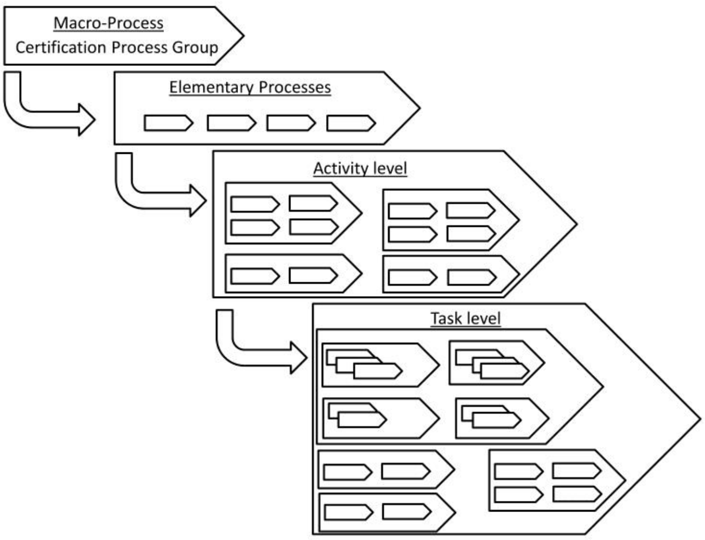

Figure A4 - 5 Structure des processus de certification avec quatre niveaux de paquet

Les BDDs et les IBDs de SysML permettent d'analyser la couverture des exigences du système et d'assurer la traçabilité entre les éléments du système permettant une partie des activités de vérification sur la conception du système.

iii. Diagrammes comportementaux

Les modèles comportementaux fournissent une description dynamique des activités de l'organisation, de leur ordre et de leurs dépendances. Les diagrammes d'activité SysML et les diagrammes de machine d'état SysML sont utilisés pour modéliser le comportement du système. Les figures A4-6 et A4-7 fournissent deux exemples de diagramme d’activité créés pour le cadre ACF.

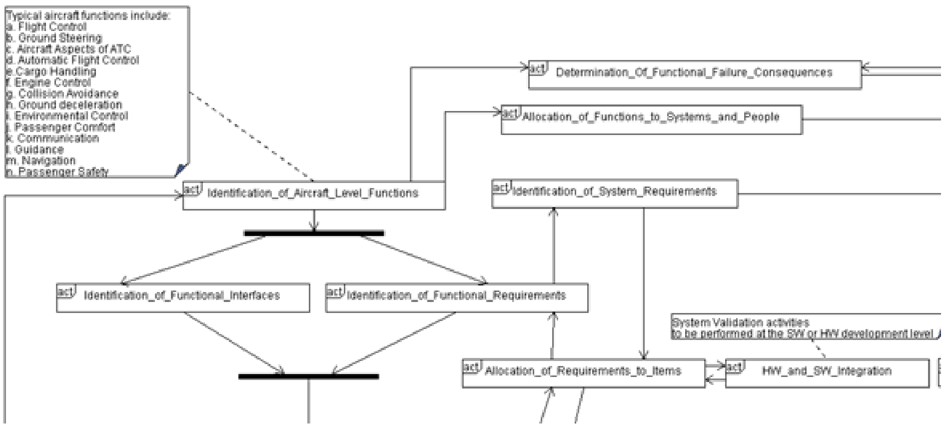

Figure A4 - 6 Diagramme d’activité pour le processus de développement générique (TTool)

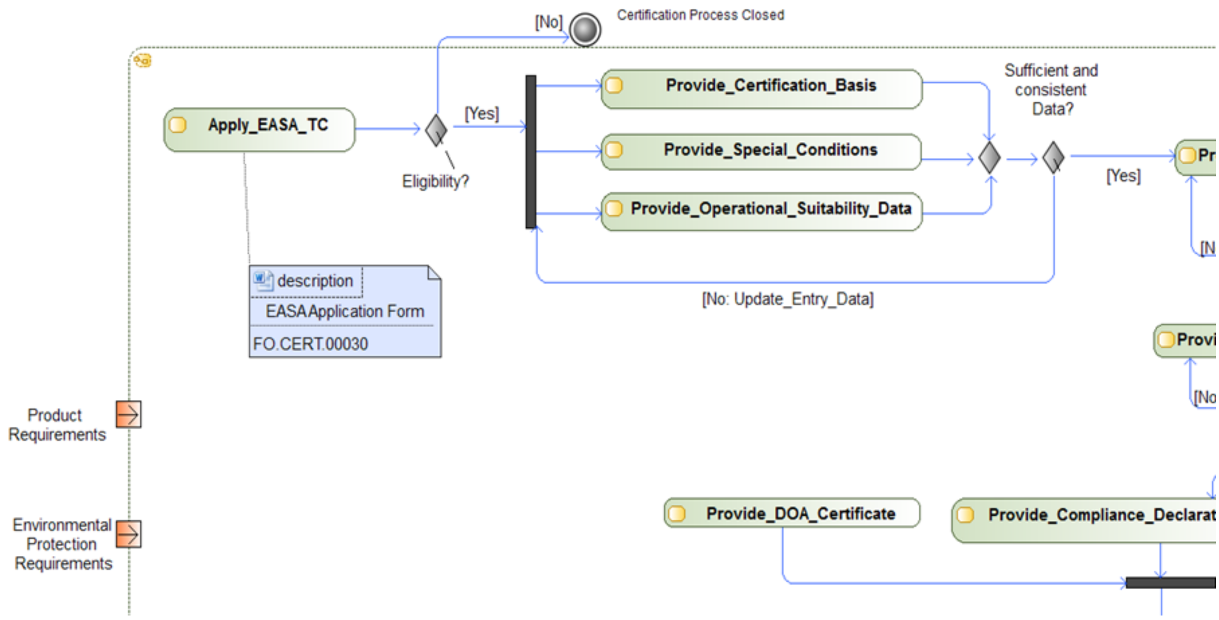

Figure A4 - 7 Diagramme d’activité pour le processus d’obtention du certificat de type

A 4.4 La gouvernance du cadre proposé

Dans la Partie 21, certains certificats sont liés les uns aux autres ou au contraire s'excluent mutuellement. Dans ce dernier cas, la demande d'un certificat peut exclure la demande d'un autre. Ainsi, une organisation visant à se conformer à la Partie 21 n'aura pas à se conformer au texte intégral.

La Partie 21 permet différents objectifs de certification. Selon la conception du projet, la stratégie de certification et l'effort pour l'organisation seront différents.

Dans cette thèse, la gouvernance de la certification est introduite (Cf. Fig.A4-8). Elle est définie comme un processus de prise de décision à partir de l'analyse du contexte de l'entreprise, qui constitue un ensemble de connaissances nécessaires pour générer une décision qui est composée d'une stratégie de certification dédiée, des exigences de certification adaptées ainsi que des objectifs spécifiques pour la mise en œuvre des processus dédiés.

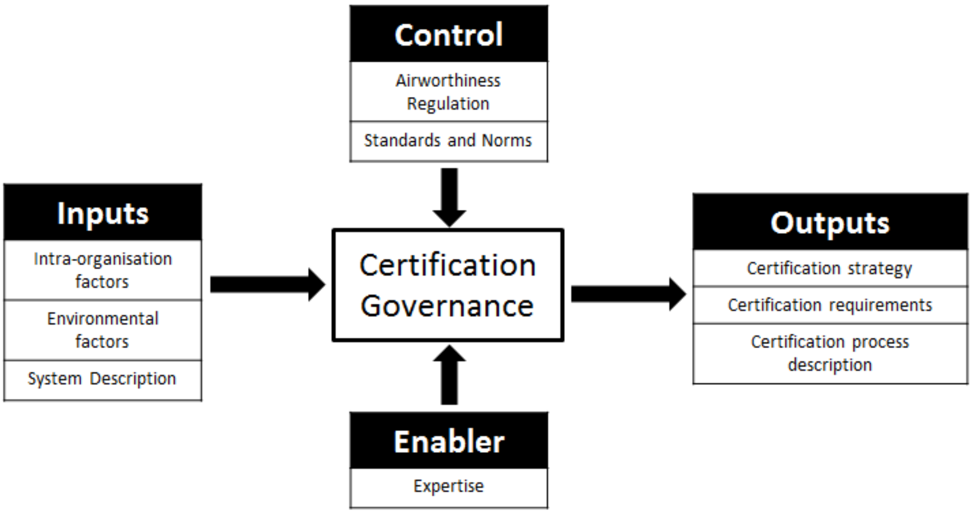

Figure A4 - 8 Principes de gouvernance pour la certification

Les connaissances nécessaires pour développer un nouveau système de transport aérien sont comptabilisées comme des «entrées». La gouvernance de la certification nécessite de connaître en tant que « entrées »:

- Les facteurs intra-organisationnels, caractéristiques de l'organisation elle-même comme la taille de l'entreprise (nombre total d'employés), les types d'activités de l'entreprise, sa stratégie de marché;
- Les facteurs environnementaux, les caractéristiques du système à développer, telles que le type d'aéronef, sa masse ou ses conditions d'exploitation;
- La description du système.

La gouvernance de la certification génère d'abord la stratégie de certification: une liste de certificats adaptés à la situation et au contexte de l'entreprise. Ensuite, le choix de la stratégie se traduira par les exigences de certification nécessaires et une description des processus de certification avec des objectifs de certificats adéquats. Des diagrammes structurels et comportementaux sont fournis. L'expertise est identifiée comme le principal catalyseur de notre contexte (expérience, règles de base…).

Un système basé sur des règles permet de prendre en compte la dimension temporelle, les conflits potentiels entre les solutions à gérer, ainsi que les informations partiellement disponibles. Une règle de décision constitue une correspondance entre un ensemble de conditions et un résultat. La gouvernance de la certification peut être considérée comme un moteur d'inférence gérant une base de connaissances et un ensemble de faits pour générer une stratégie de certification. Le comportement du moteur d'inférence du système expert permet alors un processus de raisonnement conduisant à une recommandation sur la stratégie à adopter. La table A4-1 présente une liste restreinte des règles de décision identifiée pour la gouvernance du cadre ACF.

Table A4 - 1 Règles de décision pour la gouvernance (extrait)

ID	Rule content	Rule Meaning
Rule 1	**{**|If Aircraft='>2T' and Organisation='OEM' Then MainStrategy='CoA'.|}	An integrator aiming to market an aircraft over 2T shall request for a Certificate of Airworthiness.
Rule 2	**{**|If MainStrategy='CoA' Then MainCertificate='TC'.|}	An organisation applying to a Certificate of Airworthiness shall apply to a Type Certificate.
Rule 3	**{**|If MainCertificate='TC' Then DesignCertificate='Y'.|}	An organisation applying to a Type Certificate shall apply to a design approval.
Rule 4	**{**|If MainCertificate='TC' Then ProductionCertificate='Y'.|}	An organisation applying to a Type Certificate shall apply to a production approval.
Rule 5	**{**|If MainCertificate='TC' and AirworthinessProvision='Yes' Then ValidatedCertificate='TC'.|}	An organisation applying to a Type Certificate and demonstrating enough Airworthiness provision can validate its request for a Type Certificate.
Rule 6	**{**|If MainCertificate='TC' and AirworthinessProvision='No' Then ValidatedCertificate='RTC'.|}	An organisation applying to a Type Certificate and failing to demonstrate enough Airworthiness provision shall request for a Restricted Type Certificate instead of a Type Certificate.
Rule 7	**{**|If MainCertificate='TC' and Privilege='Yes' Then FC='No' and PtF='No'.|}	An organisation applying to a Type Certificate and having privileges will not have to request for a Permit to Fly or Flight Conditions.
Rule 8	**{**|If MainCertificate='TC' and Privilege='No' Then FC='Yes' and PtF='Yes'.|}	An organisation applying to a Type Certificate and having no privileges will have to request for a Permit to Fly and Flight Conditions.
Rule 9	**{**|If MainCertificate='TC' Then NoiseCertificate='Yes'.|}	An organisation applying to a Type Certificate will have to request for a Noise Certificate.
Rule 10	**{**|If Aircraft='>2T' and Organisation=Subcontractor and Part<>'propeller' and Part<>'engine' Then MainStrategy='ETSO'.|}	An integrator aiming to market an equipment for an aircraft over 2T shall request for an ETSO if the part is neither an APU, a propeller nor an engine.

A 4.5 Le modèle de maturité

La nécessité d'un modèle de maturité dédié aux objectifs de certification a été établie. Un tel modèle aura un impact sur les règles du système expert. Dans cette thèse, un modèle avec différents niveaux de maturité a été développé. Ce modèle permettra d'accompagner les PMEs dans leur évolution, dès la création de l'entreprise, et d'adapter leur stratégie de certification avec une maturité accrue. Pour chaque «niveau», certains objectifs spécifiques sont associés:

- Niveau 1 : mettre en place les processus nécessaires à la préparation du certificat EN 9100. Un système de gestion de la qualité (Quality Management System ou QMS en Anglais) et ses processus associés sont nécessaires.
- Niveau 2 : mettre en place les processus nécessaires pour obtenir l'agrément d'organisme de conception. Un système d'assurance de la conception (Design Assurance System ou DAS en Anglais) et ses processus associés sont requis par l'EASA.
- Niveau 3 : mettre en place les processus nécessaires pour obtenir l'agrément d'organisme de production. Un système d'assurance qualité (Quality Assurance System ou QAS en Anglais) et ses processus associés sont requis par l'EASA.
- Niveau 4 : mettre en place les processus nécessaires pour obtenir le certificat de type et le certificat de navigabilité. Un système de gestion de la sécurité complet (Safety Management System ou SMS en Anglais) et ses processus associés sont requis par l'EASA
- Niveau 5 : mettre en place les processus nécessaires pour couvrir le maintien de la navigabilité (SMS +) ici au sens de la navigabilité initiale. Pour rappel, le maintien de la navigabilité et les parties concernées telles que ¨Part-M, Part-145, Part-66, etc. ne sont pas l'objet de ce rapport.

A 4.6 Outil de gestion des risques et des opportunités

Une approche pour l'évaluation des risques a été mise au point pour évaluer le niveau de chaque risque par rapport aux objectifs du projet pour atteindre avec succès les objectifs de certification:

- Les risques faibles sont acceptables, gérables facilement au sein de l'équipe de développement et ne nécessitent aucune escalade spécifique;
- Les risques moyens sont partageables au sein d'une équipe ou peuvent être transférables à une autre équipe si nécessaire;
- Les risques élevés nécessitent une surveillance et un contrôle élevés grâce à un plan de prévention et d'atténuation.
- Les risques très élevés nécessitent des mesures de prévention et d'atténuation précises pour les contrôler.

Une approche similaire a été développée pour évaluer les opportunités des organisations, selon quatre niveaux d'impact positif. Chaque impact positif des opportunités est évalué en fonction d'un gain de temps, d'un gain financier ou d'un avantage technologique.

A 4.7 La méthodologie associée au cadre

Un cadre de référence pour gérer la certification des aéronefs, appelé ACF (Aircraft Certification Framework en Anglais) a été construit avec les éléments présentés dans cette section. Une méthodologie en trois étapes successives a été élaborée pour expliquer la genèse du cadre ACF. Les trois étapes sont les suivantes (Cf. Fig.A4-9):

1- Analyse d'entreprise: elle permet à travers l'enquête de l'entreprise d'évaluer l'organisation et le processus internes actuels et de déterminer le niveau d'investissement et d'implication de l'EASA. Cette étape conduit à identifier les paramètres de valeurs de la méthodologie comme prévu par les règles de gouvernance d'ACF;

2- Elicitation des exigences de certification: Connaissant les valeurs des paramètres, les règles applicables sont automatiquement déclenchées et permettent de susciter les exigences de certification adaptées. Les diagrammes d'exigences SysML associés sont générés pour proposer une représentation graphique des exigences suscitées;

3- Définition du processus et de l'organisation: L'élicitation d'exigences de certification adaptées permet de générer les processus et l'organisation conformes aux attendues de la règlementation. Les diagrammes SysML associés pour les processus et l'organisation sont fournis (étape 3).

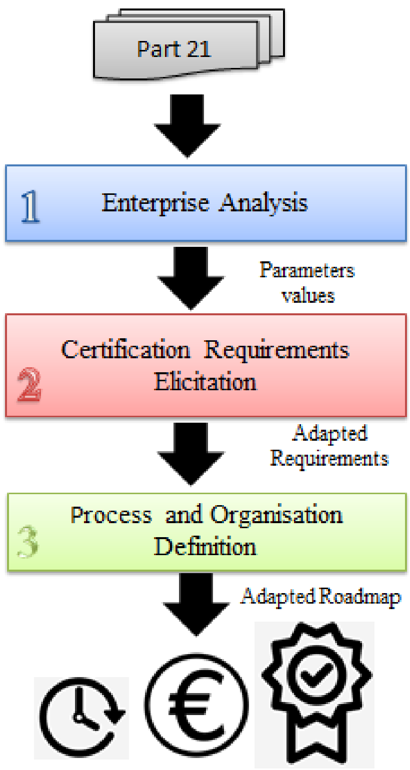

Figure A4 - 9 Description de la méthodologie ACF en trois étapes

À la fin de l'étape 3, une feuille de route dédiée est fournie. Compte tenu des principales caractéristiques de l'entreprise, cette feuille de route décrit le délai acceptable pour DOA, POA et TC.

Chapitre A 5. **Application de la méthodologie à un cas réel d’entreprise**

A 5.1 Introduction à l’étude de cas

L'étude de cas concerne un programme industriel français en cours et avec le règlement de l’EASA applicable. Un nouveau fabricant de dirigeables développe un aérostat à grande capacité. Il s’agit d’une PME confrontée à la fois à des barrières technologiques, économiques et sociétales en plus des contraintes de certification à gérer. L'étude de cas concerne une première certification sans référence institutionnelle pour soutenir ou comparer les activités. L'application suivra les trois étapes de la méthodologie:

Le projet est étudié en mettant l'accent sur les objectifs techniques, sur l'organisation de développement et sur les objectifs de certification. A des fins de confidentialité, les vrais noms, chiffres et détails techniques ont été modifiés dans ce chapitre, maintenant toutefois les principales caractéristiques de chaque situation.

A 5.2 Application de la méthodologie

L'étape 1 a permis d'identifier que l'organisation est un intégrateur établi dans un pays d'un État membre de la communauté Européenne. Le produit à développer est un aéronef complexe de plus de 2 tonnes. Les objectifs de production ne se limitent pas à quelques nombres de dirigeables. Une production régulière est prévue dans les prochaines décennies

Au début du projet, aucune restriction concernant les conditions d'exploitation n'est faite. Parfois, cela peut changer plus tard pendant la durée du projet, généralement dans le cadre de l'évaluation de la sécurité du processus de certification. Le paramètre d'entrée associé Airworthiness_Provision est pour l'instant défini avec la valeur par défaut ‘NoRestriction’.

Le programme étant nouveau, aucun dirigeable n'est en exploitation à ce stade de développement: l'EIS (pour Enter Into Service en Anglais) est pour l'instant réglé avec la valeur par défaut «Non».

À des fins de simplification, il est considéré que l’entreprise ne certifiera aucun équipement, pièce ou sous système: le paramètre PA (pour Part and Appliance en Anglais) est donc pour le moment réglé avec la valeur par défaut.

A l'issue de cette première étape, nous avons des valeurs pour les dix paramètres d'entrée attendus.

L'étude de cas peut bénéficier d'opportunités importantes et le programme est conforme à la demande du marché et de la société. Mais il doit gérer une certification initiale sans référence de comparaison et fait déjà face à plusieurs difficultés qui peuvent entraver la réalisation du processus de certification. En particulier, plusieurs risques organisationnels sont identifiés, ce qui conduit à fixer la valeur du paramètre Maturité à «Faible».

Un niveau élevé de participation de l'EASA, avec les CDIs de classe 3 et de classe 4, implique que l'EASA examinera une grande quantité de données de conformité, exigera l'interprétation détaillée des résultats des tests et participera à certaines activités de conformité (témoin des tests, audits, etc.). Par conséquent, l'organisation ne s'attend à obtenir que peu de privilèges. À la fin de cette dernière sous-étape, la valeur du paramètre d'entrée Privilège est définie sur «Non».

Pour l'étude de cas, la liste des principaux certificats attendus est désormais connue. Cette liste constitue la stratégie principale de l'entreprise et se compose des certificats suivants

- Certificat de navigabilité;
- Certificat de type;
- Agrément de conception (DOA);
- Agrément de production (POA);
- Approbation des conditions de vol;
- Permis de voler;
- Certificat de bruit.

L'étape 2 permet d'identifier onze sous-parties comme applicables (Cf. Fig.A5-1) :

- Sous-partie A pour les dispositions générales;
- Sous-partie B pour le certificat de type;
- Sous-partie D pour les modifications du certificat de type;
- Sous-partie G pour POA;
- Sous-partie H pour le certificat de navigabilité:
- Sous-partie I pour le certificat de bruit.
- Sous-partie J pour DOA;
- Sous-partie K pour les pièces et appareils;
- Sous-partie M pour les réparations;
- Sous-partie P pour l'approbation des conditions de vol et l'autorisation de voler;
- Sous-partie Q pour l'identification des produits, pièces et appareils.

L'étape 3 permet d'identifier les processus adaptés et l'objectif, les activités, les tâches, les intrants et les extrants associés pour toutes les exigences. Pour chaque processus, un schéma de processus est proposé.

De plus, une organisation adaptée en conformité avec la réglementation est proposée (Cf. Fig.A5-2).

Enfin, une feuille de route optimisée est construite avec la durée optimisée pour chaque phase.

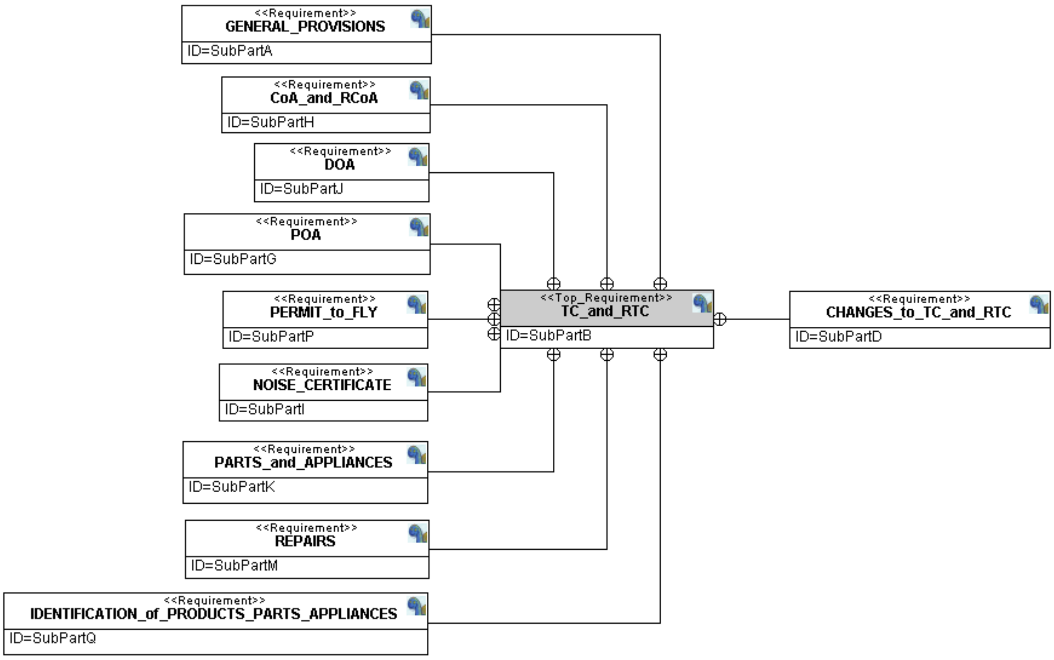

Figure A5 - 1 Diagramme d'exigences pour l'étude de cas

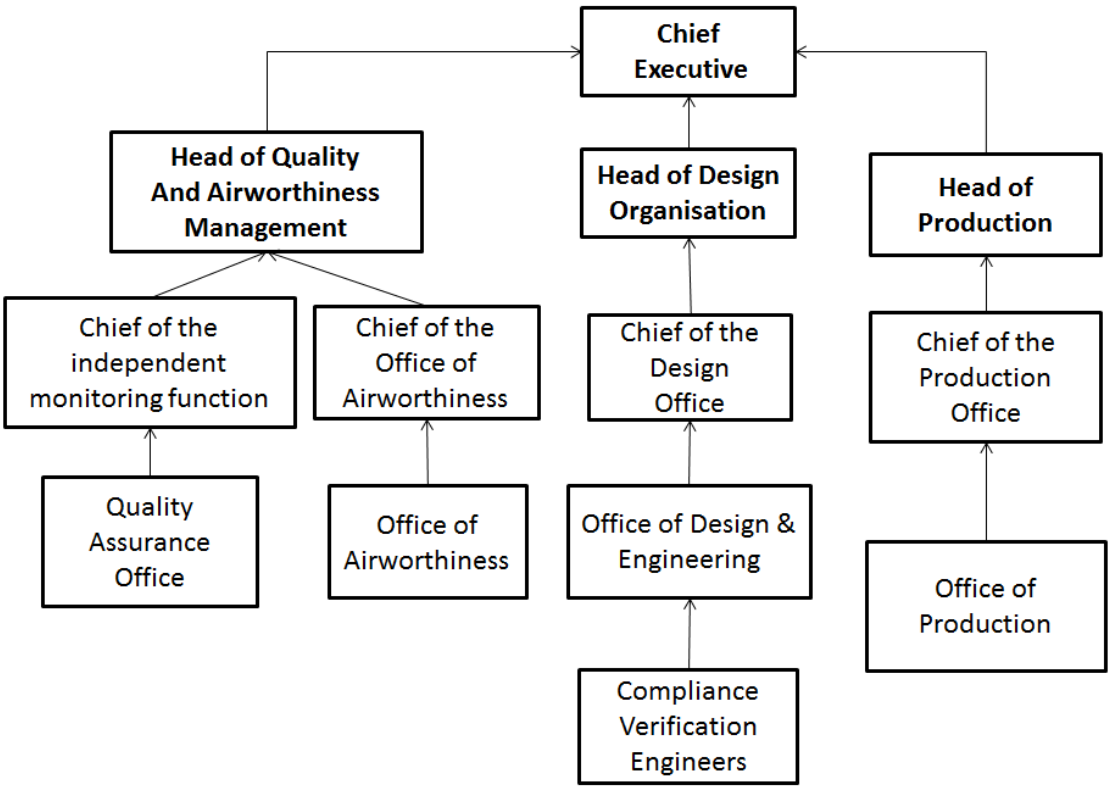

Figure A5 - 2 Proposition d'organisation pour l'étude de cas

A 5.3 Modèle de maturité proposé pour l'étude de cas

Pour aller plus loin, il est identifié que la mise en œuvre du procédé est un investissement énorme nécessitant beaucoup de ressources, notamment en cas de première certification aéronautique. Il est proposé à l'entreprise d'atteindre les objectifs de certification complets en passant par plusieurs étapes. L'idée est de décomposer les objectifs de la certification et ainsi de partager les processus, activités et tâches en différentes parties.

Modèle de maturité niveau 1 (Cf. Fig.A5-3): les principaux objectifs sont de construire les briques de l'EN 9100.

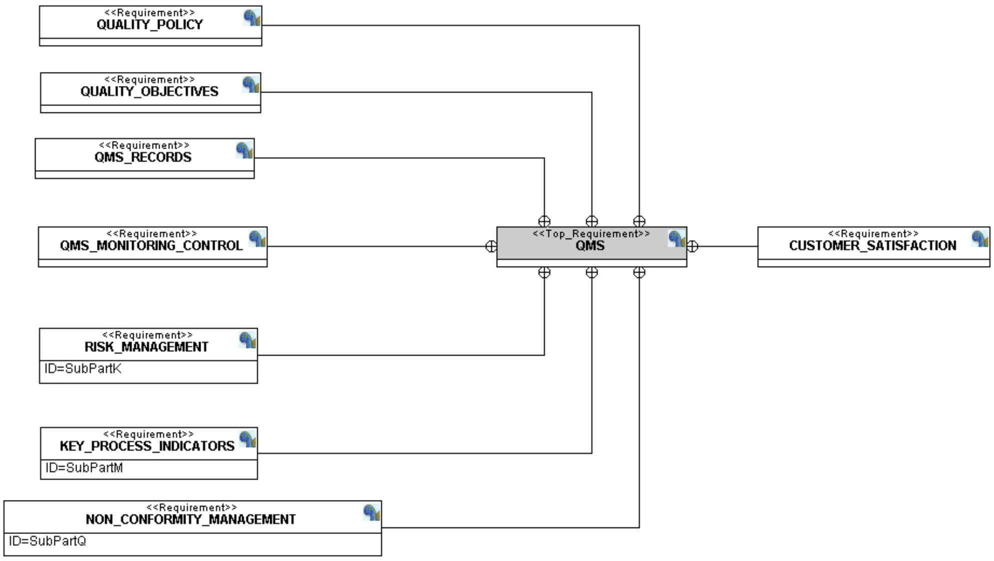

Figure A5 - 3 Diagramme d'exigences – Niveau 1 du modèle de maturité

Modèle de maturité niveau 2 (Cf. Fig.A5-4).: les principaux objectifs sont de construire les briques du système d'assurance pour la conception (DAS), du processus de gestion des fournisseurs et du processus de gestion du changement pour la partie conception uniquement, ainsi que la première brique du système d'enregistrement des occurrences (ORS).

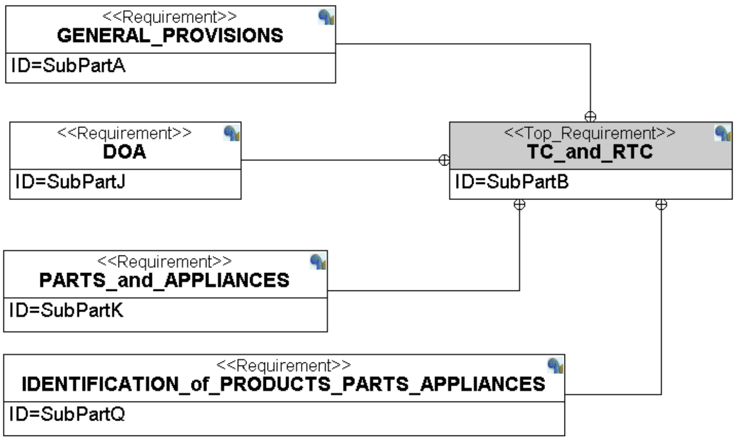

Figure A5 - 4 Diagramme d'exigences – Niveau 2 du modèle de maturité

Modèle de maturité niveau 3 (Cf. Fig.A5-5): les principaux objectifs sont de construire les briques du QAS, le processus de gestion du changement pour la partie production, et de finaliser également la mise en œuvre de l'ORS.

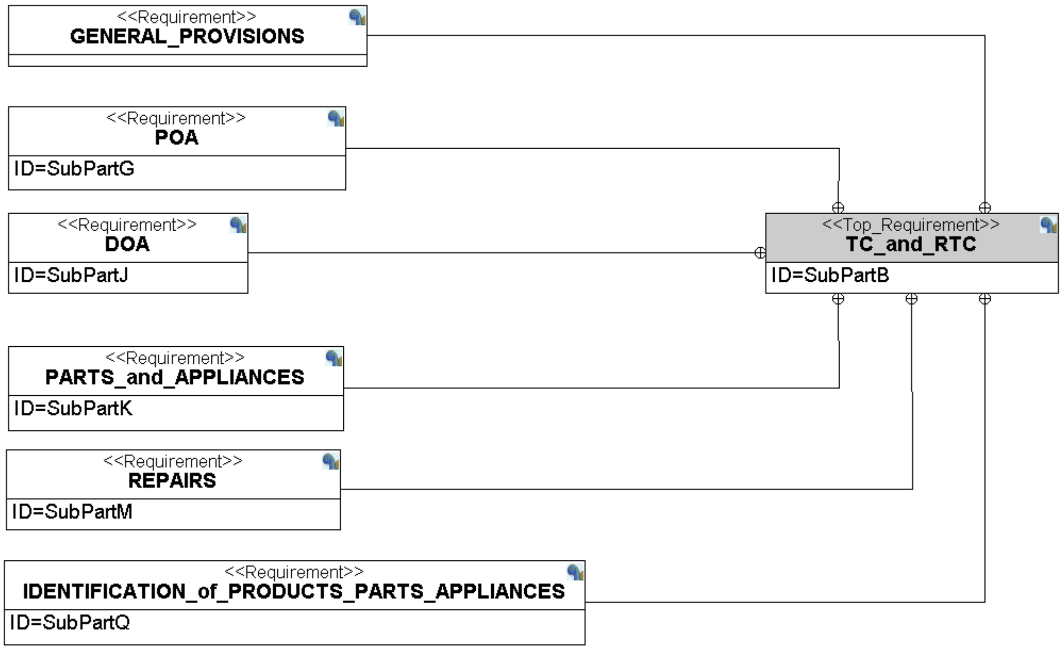

Figure A5 - 5 Diagramme d'exigences – Niveau 3 du modèle de maturité

Modèle de maturité niveau 4 (Cf. Fig.A5-6): les principaux objectifs sont de finaliser la certification avec le certificat de bruit et le permis de vol.

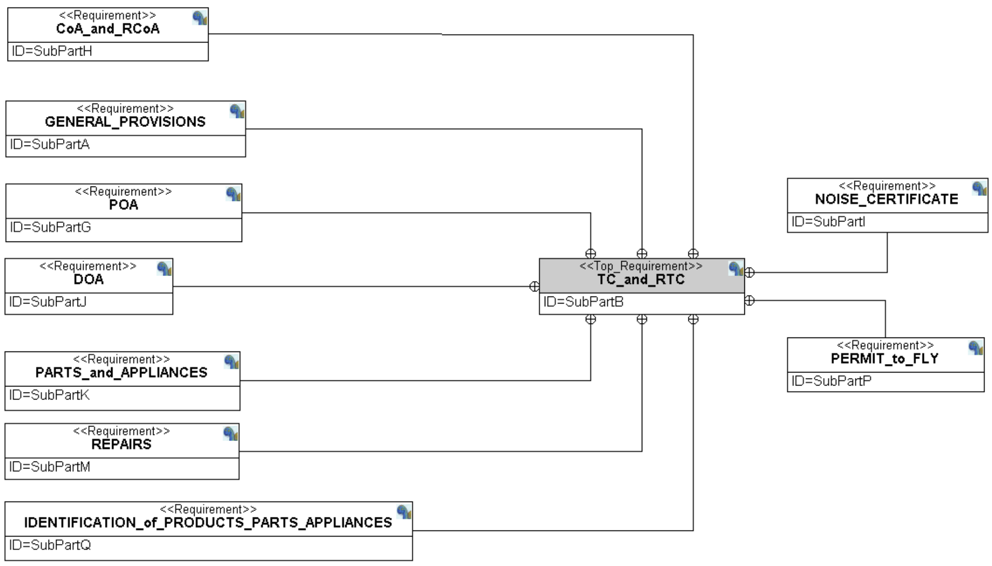

Figure A5 - 6 Diagramme d'exigences – Niveau 4 du modèle de maturité

A 5.4 Discussion autour des résultats de l'application

L'application présentée a permis de mieux appréhender la portée et les enjeux du cadre méthodologique proposé en étudiant un vrai cas industriel. Des points forts ont été identifiés. L'approche proposée permet de formaliser les objectifs opérationnels de la certification de manière plus formelle que les textes règlementaires ou les textes normatifs le proposent actuellement.

L'approche permet aux entreprises de se projeter au plus tôt sur ses ambitions et identifier les investissements nécessaires avant d'engager des coûts importants avec le risque de devoir défaire et refaire ce qui a été construit. Le cadre proposé permet assez rapidement d'avoir une vision sur les exigences règlementaires, les processus et l'organisation interne à mettre en place. A l'issue même un plan de développement est proposé.

La simplicité du méta-modèle permet de se focaliser sur les éléments essentiels de la certification. Une expérience a été menée afin de construire un profile dédié grâce à l'outil Eclipse Papyrus. La démarche s'est avérée plus contraignante et n'a pu fournir immédiatement tous les résultats escomptés. Le projet devra être prolongé dans le futur car il reste néanmoins valide.

L'application à un cas d'entreprise avec un projet innovant et complexe a permis de valider la démarche dans sa globalité. De plus, d'autres cas industriels ont été étudiés en parallèle pour vérifier la capacité d'adaptation du cadre. Notamment il a été choisi une entreprise avec un projet d'aérostat innovant mais non complexe, sans expérience préalable dans le développement d'aéronef mais avec une forte culture aéronautique. Ensuite une entreprise responsable de la production d'équipements pour un projet d'aérostat innovant et complexe, avec une forte maturité sur ses activités mais sans expérience sur le secteur aéronautique a aussi permis de tester l'approche globale. Ces deux cas réels ont servis à évaluer la méthodologie en trois étapes et en particulier les paramètres et les règles de la gouvernance, ainsi que le modèle de maturité. L'application d'autres cas sera nécessaire pour construire à terme une véritable bibliothèque de modèles disponibles.

Si les résultats permettent de valider l'approche, il reste néanmoins à compléter la proposition, en particulier sur les aspects suivants :

- Validation : Le temps de développement d'un projet innovant et le temps de la certification associée sont plus long qu'un travail de thèse. La validation complète du cadre ne pouvait pas être menée à son terme et reste donc à être conduit lors de travaux ultérieurs ;
- Simulation : Même si la proposition intègre une démarche dynamique, les travaux menés sont restés dans des développements plutôt statiques. La proposition doit évoluer pour permettre à la fois de visualiser le comportements des processus et permettre à l'entreprise de démarrer son application à des points clés précis du développement sans avoir à étudier les phases amont qui ne la concerneraient pas.

Chapitre A 6. **Conclusions et Perspectives**

Déclenchée par un besoin spécifique qui concerne les projets innovants du secteur aérien, cette thèse a permis de mettre en exergue une problématique plus générale sur ce secteur industriel. L'objectif de ce travail a été de fournir une compréhension plus complète des exigences de navigabilité en complément du support documentaire traditionnel. Par ailleurs, certains acteurs, comme les PMEs ont besoin de solutions progressives pour intégrer étape après étape les différentes exigences du processus de certification.

L'approche présentée se dirige vers une solution pour transformer la connaissance implicite de la réglementation en connaissance explicite, afin de:

- formaliser le contenu de la règlementation ;
- extraire les exigences adaptées au cas de l'entreprise ;
- proposer une solution globale ou progressive.

Cette thèse propose un ensemble de supports utile dans le contexte de la certification aéronautique. Un nouveau cadre de référence a été construit sur la base de quatre piliers principaux :

- les textes de la navigabilité initiale Européenne;
- les recommandations des experts en ingénierie des systèmes;
- les attentes générales du secteur aéronautique; et
- les besoins particuliers des PME.

Ce cadre de référence appelé ACF (Aircraft Certification Framework en Anglais) est composé de plusieurs éléments:

- une approche de modélisation avec:
    - o un méta-modèle établissant les différents concepts modélisés;
    - o diagrammes d'exigences fonctionnelles;
    - o diagrammes de processus structurels;
    - o diagrammes de processus comportementaux;
- une approche de gouvernance avec:
    - o une solution basée sur les risques;
    - o un système expert pour déterminer la stratégie de certification adaptée;
    - o un modèle de maturité;
- une approche méthodologique décomposée en trois étapes.

Différentes pistes peuvent être envisagées pour poursuivre cette recherche. L'intérêt du cadre méthodologique n'est plus à démontrer. En revanche, à court terme, il pourra être consolidé et enrichi par d'autres cas d'études. L'approche proposée ouvre aussi des perspectives pour formaliser différemment les exigences de la règlementation.

Après validation auprès de suffisamment de cas représentatifs de toutes les situations de certification, il pourra à moyen terme, faire l'objet d'une application intégrée qui servira de support méthodologique soit pour les entreprises candidates à la certification, soit pour des entreprises en charge de les accompagner dans leur développement.

La démarche pour construire des profils dédiés avec des outils adaptés pourrait être une autre piste de recherche pour automatiser la construction des modèles et leur validation.

L'analyse de la Partie 21 a permis de recréer du lien entre les exigences initiales de la règlementation et les standards normatifs en vigueur. Ce travail ouvre des perspectives pour remettre à plat les standards et proposer une nouvelle approche plus adaptée pour les nouveaux entrants sur le secteur.

Enfin, à long terme, l'approche pourrait s'étendre à tous les textes règlementaires sans se limiter à la navigabilité initiale, mais en prenant en compte tous les textes de la navigabilité continue et toutes les particularités des différentes parties prenantes qui interviennent sur ces phases (compagnies aériennes, contrôleurs aériens, entreprises de maintenance, de réparation et de révision, …).

La certification est souvent jugée comme une contrainte organisationnelle et financière. L'enjeu primordial de ces travaux est de changer le paradigme pour guider les entreprises du secteur aéronautique vers plus de maturité pour à la fois ouvrir des opportunités de marché vers des produits innovants tout en conservant un niveau de sécurité suffisant pour que la société puisse accepter l'arrivée de nouveaux aéronefs dans le paysage aérien. Les exigences de certification doivent être connues et appréhendées le plus tôt possible pour que les entreprises les intègrent et ne soient pas confrontées à des réorganisations multiples.

Au-delà des perspectives de consolidation du cadre proposé, d'autres pistes restent aussi à explorer pour proposer un accompagnement à sa compréhension et favoriser son usage : un guide explicatif, des règles de bonnes pratiques, une interface logicielle pourraient compléter la proposition.

APPENDIX B – ELA1 & ELA 2 definitions from EASA Regulation

ELA1 definition

ELA1 aircraft' means the following manned European Light Aircraft:

- an aeroplane with a Maximum Take-off Mass (MTOM) of 1200kg or less that is not classified as complex motor-powered aircraft;
- a sailplane or powered sailplane of 1200kg MTOM or less;
- a balloon with a maximum design lifting gas or hot air volume of not more than 3400m3for hot air balloons, 1050m3for gas balloons, 300m3for tethered gas balloons;
- an airship designed for not more than 4 occupants and a maximum design lifting gas or hot air volume of not more than 3400 m3for hot air airships and 1000 m3for gas airships;

ELA2 definition

'ELA2 aircraft' means the following manned European Light Aircraft:

- an aeroplane with a Maximum Take-off Mass (MTOM) of 2000kg or less that is not classified as complex motor-powered aircraft;
- a sailplane or powered sailplane of 2000kg MTOM or less;
- a balloon;
- a hot air airship;
- a gas airship complying with all of the following characteristics:
  - 3% maximum static heaviness,
  - Non-vectored thrust (except reverse thrust),
  - Conventional and simple design of: structure, control system and ballonet system,
  - Non-power assisted controls;
- a Very Light Rotorcraft

APPENDIX C – List of Office of Airworthiness Objectives in Part 21

- Liaison between the design organisation and the Agency with respect to all aspects of the certification programme.
- Ensuring that a handbook is prepared and updated as required in 21.A.243.
- Co-operation with the Agency in developing procedures to be used for the type certification process.
- Issuing of guidelines for documenting compliance.
- Co-operation in issuing guidelines for the preparation of the manuals required by the applicable implementing rules, Service Bulletins, drawings, specifications, and standards.
- Ensuring procurement and distribution of applicable CS and environmental protection requirements and other specifications.
- Co-operating with the Agency in proposing the type-certification basis
- Interpretation of CS and environmental protection requirements and requesting decisions of the Agency in case of doubt.
- Advising of all departments of the design organisation in all questions regarding airworthiness, environmental protection approvals and certification.
- Preparation of the certification programme and co-ordination of all tasks related to Type Investigation in concurrence with the Agency.
- Regular reporting to the Agency about Type Investigation progress and announcement of scheduled tests in due time.
- Ensuring co-operation in preparing inspection and test programmes needed for demonstration of compliance.
- Establishing the compliance checklist and updating for changes.
- Checking that all compliance documents are prepared as necessary to demonstrate compliance with all CS and environmental protection requirements, as well as for completeness, and signing for release of the documents.
- Checking the required type design definition documents described in 21.A.31 and ensuring that they are provided to the Agency for approval when required.
- Preparation, if necessary, of a draft for a type-certificate data sheet and/or type-certificate data sheet modification.
- Providing verification to the head of the design organisation that all activities required for Type Investigation have been properly completed.
- Approving the classification of changes in accordance with 21.A.91 and granting the approval for minor changes in accordance with 21.A.95(b).
- Monitoring the significant events on other aeronautical products as far as relevant to determine their effect on airworthiness of products being designed by the design organisation.
- Ensuring co-operation in preparing Service Bulletins and the Structural Repair Manual, and subsequent revisions, with special attention being given to the manner in which the contents affect airworthiness and environmental protection and granting the approval on behalf of the Agency.
- Ensuring the initiation of activities as a response to a failure (accident/incident/in-service occurrence) evaluation and complaints from the operation and providing of information to the Agency in case of airworthiness impairment (continuing airworthiness).
- Advising the Agency with regard to the issue of airworthiness directives in general based on Service Bulletins.
- Ensuring that the manuals approved by the Agency, including any subsequent revisions (the Aircraft Flight Manual, MMEL, the Airworthiness Limitations section of the Instructions for Continued Airworthiness and the Certification Maintenance Requirements (CMR) document, where applicable) are checked

APPENDIX D – ISO/IEC 29110 Standard Guidelines Material Status Summary

ISO ID	TITLE/ PROFILE	DATE	STATUS	ACCESS
Part 1	Overview	Definition of the common terms for the ISO/IEC 29110 series		
29110-1	Overview	2016	published	Free
Part 2	Framework for profile preparation	Introduction of the concepts for the framework and taxonomy		
29110-2-1	Framework and Taxonomy	2015	published	Paywall
29110-2-2	Guide for domain-specific profiles	2016	published	Paywall
Part 3	Certification and Assessment guidance	Definition of the process assessment guidelines and compliance requirements		
29110-3-1	Assessment Guide	2015	published	Free
29110-3-2	Conformity Certification Scheme	2018	published	Paywall
29110-3-3	Certification requirements	2016	published	Paywall
29110-3-4	Autonomy-based Improvement Method	2015	published	Paywall
Part 4	Domain Profile Specifications	Definition of the specification for all the profiles of the Generic Profile.		
29110-4-1	Software EP	2018	published	Paywall
29110-4-2	Organizational MP		under development	Unavailable
29110-4-3	Service Delivery	2018	published	Paywall
29110-4-4	Agile Software Development		under development	Unavailable
29110-4-5	DevOps Profile		under development	Unavailable
Part 5	Domain Profile Implementation Guidelines	Management and Engineering guide for the different profiles		
	Software Engineering Profile (EP)			
29110-5-1-1	Software EP (Entry)	2012	published	Free
29110-5-1-2	Software EP (Basic)	2011	published	Free
29110-5-1-3	Software EP (Intermediate)	2017	published	Paywall
29110-5-1-4	Software EP (Advanced)	2018	published	Paywall
	Organizational Management Profile (MP)			
29110-5-2-1	Organizational MG (Entry)	2016	published	Paywall
	Service Delivery			
29110-5-3	Service Delivery Guidelines	2018	published	Paywall
	Agile Software			
29110-5-4	Agile Software DG		under development	Unavailable
	DevOps			
29110-5-5	DevOps Guidelines		under development	Unavailable
	Systems Engineering Profile (EP)			
29110-5-6-1	Systems EP (Entry)	2015	published	Free
29110-5-6-2	Systems EP (Basic)	2014	published	Free
29110-5-6-3	Systems EP (Intermediate)	2019	published	Paywall
29110-5-6-4	Systems EP (Advanced)		under development	Unavailable
Part 6	Management and Engineering guides (not tied to a specific profil)			
29110-6-1	Software EP – Specific profile specifications		under development	Unavailable

Legend: EP= Engineering Profile; MP=Management Profile; MG=Management Guidelines; DG=Development Guidelines

APPENDIX E – CMMI V2.0, List of Processes per Category and Area

CATEGORY	CAPABILITY AREA	PRACTICE AREA
Doing	**Delivering & Managing Service**	Service Delivery Management Strategic Service Management
	Engineering & Developing Product	Product Integration Technical Solution
	Ensuring Quality	Peer Reviews Process Quality Assurance Requirements Development and Management Verification and Validation
	Selecting & Managing Suppliers	Supplier Agreement Management Supplier Source Selection
Managing	**Managing Business Resilience**	Continuity Incident Resolution & Prevention Risk & Opportunity Management
	Managing the Workforce	Organizational Training
	Planning & Managing Work	Estimating Monitor and Control Planning
Enabling	**Supporting Implementation**	Causal Analysis and Resolution Configuration Management Decision Analysis and Resolution
Improving	**Improving Performance**	Managing Performance and Measurement Process Asset Development Process Management
	Sustaining Habit & Persistence	Governance Implementation Infrastructure

APPENDIX F – EIA 731 SECM, List of Processes per Category

TECHNICAL CATEGORY	MANAGEMENT CATEGORY	ENVIRONMENT CATEGORY
1. Define Stakeholder and System Level Requirements	8. Plan and Organize	16.Define and Improve the Systems Engineering Process
2. Define Technical problem	9. Monitor and Control	17.Manage Competency
3. Define Solution	10. Integrate Disciplines	18. Manage Technology
4. Assess and Select	11. Coordinate with Suppliers	19. Manage Support Environment
5. Integrate System	12. Manage Risk	
6. Verify System	13. Manage Data	
7. Validate System	14. Manage Configurations	
	15. Ensure Quality	

APPENDIX G - ACF Prototype

In the frame of this thesis, a prototype has been elaborated to validate the feasibility of a centralized tool.

The project has been managed with the help of students from INSA-Toulouse who developed the tool.

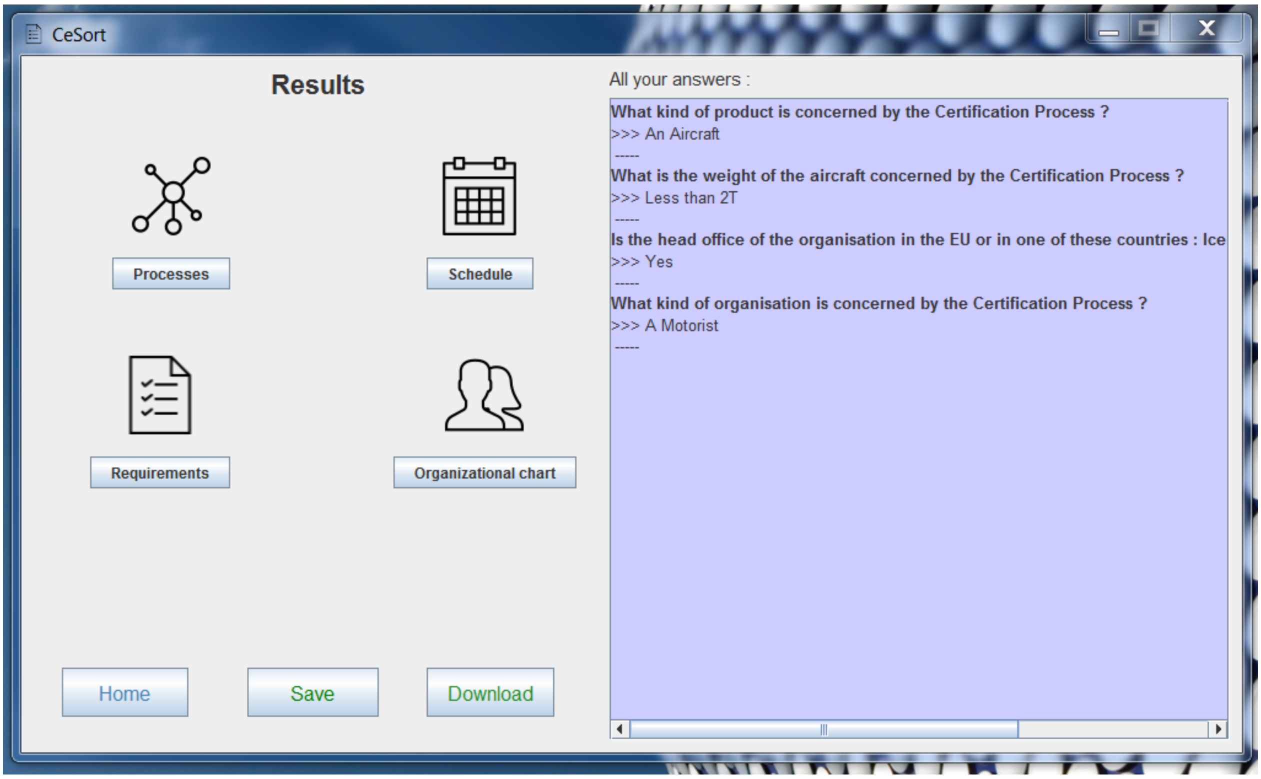

Figure G - 1 CeSort screen result

The tool embeds the governance part. Through a questionnaire, the expert system is analysing the rules and identifying the best strategy for certification and the adequate maturity model phase. Fig 4-19 presents the screen of results following the questionnaire. The results are categorized in 4 menus:

- Requirements
- Processes
- Schedule
- Organizational chart

The tool embeds the requirements diagrams and the processes diagrams of ACF and proposes two additional features with a schedule proposition and an organisational chart compliant with the information provided through the initial questionnaire