Zonal Safety and Particular Risk Analysis for Early Aircraft Design using Parametric Geometric Modelling

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Abstract

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Safety assessment is paramount in aircraft design. For unconventional aircraft or aircraft with novel propulsion or system architectures or technologies, it is critical to investigate safety as early as possible in the design process to eliminate unfeasible aircraft configurations and system architectures. In this context, the Zonal Safety Analysis (ZSA) and the Particular Risk Analysis (PRA) that evaluate the safety aspects from an aircraft configuration and system placement perspective are essential to perform early. These analyses require a three-dimensional (3D) model of the aircraft and systems and substantial manual effort, limiting the ability to perform rapid iterations required to support design space exploration and, eventually, multidisciplinary design optimization. To analyze many aircraft configurations and system architectures, parametric 3D modelling, ZSA, and PRA require automation. This thesis reviews the methodologies for performing the ZSA and PRA from a systems point of view and proposes a novel methodology for semi-automated conceptual-level ZSA and PRA (CZSA and CPRA) implemented using Python and OpenVSP. As part of CZSA, automated aircraft 3D modelling, parametric zone definition, and zone-component interaction analysis methods are developed that are supported by a manually prepared database of safety-driven best practices. The CPRA involves parametric modelling of particular risk threat zones for trajectory-based PRAs and automated detection of system components in these zones. The effectiveness of the proposed approach is demonstrated with case studies for conventional and unconventional aircraft designs and novel system technologies. The presented work is a step towards integrating system safety analysis into multidisciplinary analysis and optimization environments, thus increasing conceptual design maturity and reducing development time.

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As I reflect on the journey, a profound sense of humility and gratitude envelops me. Finding the right words to express the indescribable emotions that accompany this proves to be both a challenge and a privilege. Within the pages of this thesis, I embark on one of the most cherished sections to express my sincere appreciation for all the people who have supported me throughout this journey.

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Nomenclature

Capitals

CI Component interaction risk score

ZR Zone-level risk score

CR Component-level intrinsic risk score

COR Component-level overall risk score

ZOR Zone-level overall risk score

Subscripts

i relating to zone-level risk

j relating to component-level intrinsic risk

m number of component-level intrinsic risk

n number of zone-level intrinsic risk

tot total

WC worst case scenario

Symbols

ρ Bay packing density

List of Acronyms

AC	Advisory Circulars
AEA	All Electric Aircraft
AEB	Aft Equipment Bay
AIR	Aerospace Information Report
AMC	Acceptable Means of Compliance
API	Application Programming Interface
APU	Auxiliary Power Unit
ARP	Aerospace Recommended Practice
AS	Aerospace Specification
ASSESS	Aircraft System Safety Assessment
ATA	Air Transport Association of America
CAD	Computer-Aided Design
CAE	Computer Aided Engineering
CATALIST	CATIA Advanced Design Linking and Iterations Software and Tool
CCA	Common Cause Analysis
CMA	Common Modes Analysis
CPACS	Common Parametric Aircraft Configuration Schema
CPRA	Conceptual-level Particular Risk Analysis
CSFL	Continued Safe Flight and Landing
CZSA	Conceptual-level Zonal Safety Analysis

DMU	Digital Mockup Unit
DS	Degree of Simplification
EWIS	Electrical Wiring and Interconnection System
FAA	Federal Aviation Administration
FHA	Functional Hazard Assessment
FMEA	Failure Mode and Effect Analysis
FOD	Foreign Object Damage
MDAO	Multidisciplinary Analysis and Optimization
MEA	More Electric Aircraft
OML	Outer Mold Line
PRA	Particular Risk Analysis
PSSA	Preliminary System Safety Assessment
RAT	Ram Air Turbine
SSA	System Safety Assessment
UERF	Uncontained Engine Rotor Failure
XML	Extensible Mark-up Language
ZSA	Zonal Safety Analysis

Chapter 1

Introduction

Safe air transport is a driver of social and economic development. The projected doubling of air passenger and freight traffic in the next two decades raises concerns about the aviation industry's environmental impact. To address these concerns, the International Civil Aviation Organization (ICAO) has set strategic objectives for the sustainable growth of an economically-viable global air transport network [7]. Accomplishing these objectives demands proactive enhancement of the current aircraft development process and refining methodologies for seamless integration of advanced technologies that enable sustainable growth. In this context, this chapter elucidates the background and rationale that shape the research in this thesis.

1.1 Background and Motivation

Governments and industries optimistically target to achieve carbon neutrality by 2050 [8]. Thus, calling for extensive research and exploration of innovative technologies and designs to support the transition to sustainable aviation. The most prominent solutions include unconventional aircraft designs, greener propulsion alternatives like hydrogen, electric propulsion, and more electric system[1] architectures.

The system placement for conventional airplanes has been matured over decades, while the

[1] Aircraft systems refer to the equipment responsible for essential functions like flight control, navigation, communication, power, and fuel management to name a few.

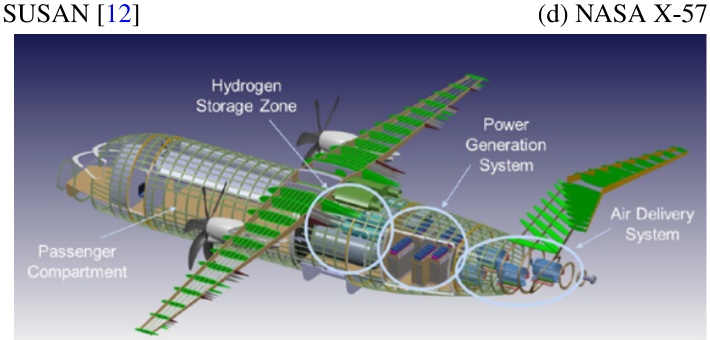
novel configurations and technology implementations (as shown in Figure 1.1) present new challenges. For example, for hydrogen-powered aircraft, considering the safety risks associated with the placement of hydrogen tanks, power generation systems, and cryogenic system paths is important [9].

(a) NASA N3-X [10]

(b) Bombardier EcoJet [11]

(c) NASA SUSAN [12]

(d) NASA X-57 Maxwell [13]



(e) Notional aircraft for hydrogen fuel cell propulsion by GKN Aerospace [9]

Figure 1.1: Examples of unconventional aircraft designs.

Similarly, the location of energy storage systems, routing of wires, thermal risk management, and segregation of redundancies for electrified systems is a concern. The adoption and safe integration of these innovative solutions necessitates a rigorous assessment of their feasibility and safety implications early in design.

Among the three aircraft design stages: conceptual, preliminary, and detail design, the conceptual design stage is crucial for designers to establish the feasibility of innovative design options. The certification and system safety considerations directly affect critical concept design decisions. Therefore, an early and rapid assessment of safety aspects is quintessential for the development and success of these solutions.

The objective of the complete safety assessment process during aircraft development is to ensure that all safety-related requirements are met and demonstrate compliance with Part 25.1309 [14]. The current safety assessment process for commercial aircraft follows the Aerospace Recommended Practice (ARP) 4761 [15], which defines system safety assessment as "A systematic, comprehensive evaluation of the implemented system to show that the relevant requirements are met".

The safety evaluation process includes several methods like Functional Hazard Assessment (FHA), which establishes the safety objective, Preliminary System Safety Assessment (PSSA) to lay down safety requirements, followed by the System Safety Assessment (SSA)- a complete assessment of the system and verification of the safety objective and requirements. In parallel, the Common Cause Analysis (CCA) evaluates the effect of common cause [2] events on the systems architecture using Zonal Safety Analysis (ZSA), Particular Risk Analysis (PRA), and Common Modes Analysis (CMA).

The ZSA assesses the aircraft system installation against the safety-driven placement requirements and evaluates the effect of interference between system components during regular operation and in case of component failure. The analysis involves examining the interaction of the system components with the zone environment, structure, and components from other systems, together with the impact of technology, maintenance, and overall aircraft design requirements (Figure 1.2).

[2] ARP 4761 [15] defines common cause as "Event or failure which bypasses or invalidates redundancy or independence."

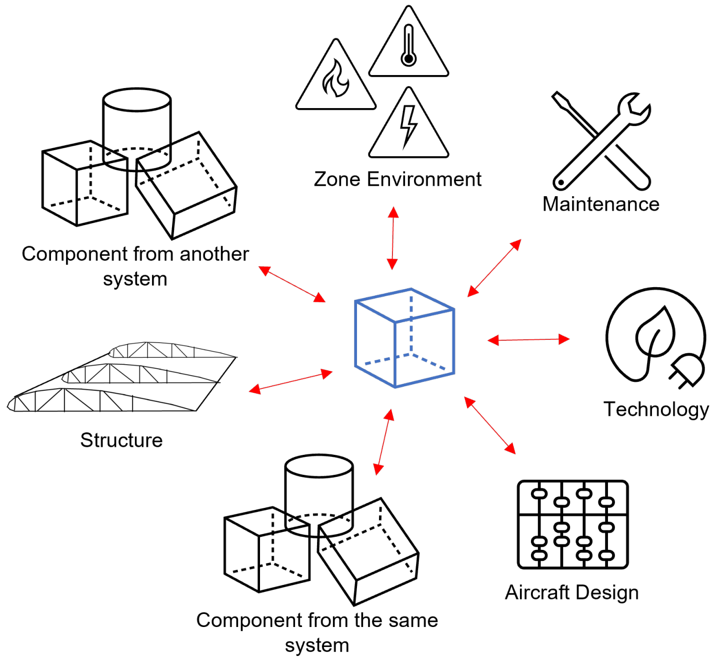


Figure 1.2: Interference studies performed in ZSA.

In the PRA, the effect of specific threats, both due to internal (e.g., Uncontained Engine Rotor Failure) and external (e.g., Bird strike) events, on the continued safe flight and landing is analyzed. It assumes that these risk events have a probability of 1 and evaluates the vulnerability of the system placement to these threats. If any safety requirement is violated, then appropriate steps must be taken to omit or minimize the impact of the particular risk.

It is vital to consider analyses like ZSA and PRA upfront as their outputs directly affect the placement of critical components[3] and the system architecture, which will impact aircraft weight, cost, and, potentially, the viability of the overall aircraft configuration due to the detrimental safety-related consequences.

Performing a ZSA per ARP 4761 requires a systematic review of each aircraft zone, the equipment installed in the zone, and their potential failure modes. Similarly, the PRA is a risk-by-risk analysis of potentially impacted zones and components and a determination of the overall aircraft-level effects. These analyses typically require a substantial manual effort, which limits the ability

[3]A critical component is any component whose failure would contribute to or cause a failure condition which would prevent the continued safe flight and landing of the airplane.

to perform rapid iterations as required to support optimization. Deviation from the conventional aircraft configuration and system architecture further complicates the safety assessment, especially from a system placement perspective. In addition, these unconventional aircraft expose the knowledge gaps in multiple disciplines involved in aircraft design.

Another challenge is to harmonize the highly interdependent requirements arising from different disciplines. Multidisciplinary Analysis and Optimization (MDAO) [16] methods are being excessively explored to address this challenge. However, the current multidisciplinary optimization methods for early design studies focus more on structural and aerodynamic optimization. Aspects like safety assessment are typically not integrated within MDAO because they require a more detailed definition of systems and structure.

Hence, to maximize the conceptual design potential, there is a need to adapt the ZSA and PRA methodologies and make them more generic for early assessment, along with other disciplines.

One example of current research efforts to increase the maturity of MDAO frameworks is the AGILE 4.0 project [4], which attempts to reduce the time to market and development costs for novel aircraft design [18]. In this project, several aspects, like thermal risk, certification, and safety assessment, are considered in the MDAO framework [19, 20].

The Aircraft Systems Lab at Concordia University is developing a safety-focused systems architecting framework called Aircraft System Safety Assessment (ASSESS) [1], in collaboration with Bombardier Aviation as a part of the AGILE 4.0 MDAO-NextGen project to support better integration of system safety analysis into MDAO environments. The ASSESS framework, as shown in Figure 1.3, comprises different methods for design exploration and for conceptual-level formalized safety analyses in line with the ARP 4761 guidelines. The work in this thesis focuses on developing the conceptual-level ZSA and PRA methodologies for system placement and safety validation.

[4] AGILE 4.0 refers to Aircraft 3rd Generation Multi-disciplinary Optimization for Innovative Collaboration of Heterogeneous Teams of Experts. It is a research project funded by the European Union's Horizon 2020 research and innovation framework program. [17]

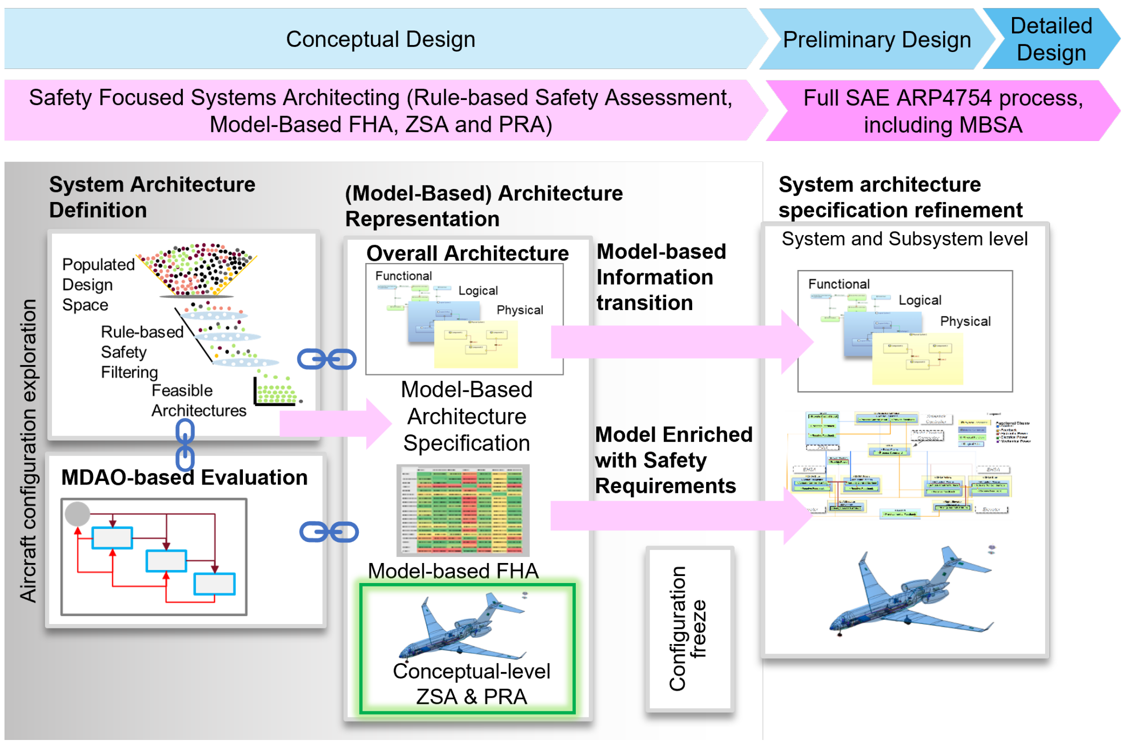


Figure 1.3: ASSESS framework developed by Concordia's Aircraft Systems Lab for safety assessment in early design phases (Adapted from [1]).

1.2 Thesis Scope and Objectives

The objectives of this thesis are the following:

- Development of a methodology for conceptual level Zonal Safety Analysis
- Development of a methodology for conceptual level Particular Risk Analysis.
- Development of the three-dimensional (3D) modelling support for performing the conceptual level Zonal Safety and Particular Risk Analysis.
- Adapt and automate the above-mentioned methods to facilitate their integration into Multidisciplinary Design and Analysis Frameworks.

1.3 Organization of the Thesis

The organization of the presented research work is as follows.

Chapter 2 provides a detailed literature analysis of ZSA and PRA in aircraft conceptual design and explores the use of parametric system definition and 3D modelling for system safety analysis. Chapter 3 addresses the gaps identified in Chapter 2 and develops the methodology to perform the ZSA and PRA at the conceptual design stage. The implementation and validation of the proposed methodology are also presented. Chapter 4 demonstrates the efficacy and usefulness of the developed methods by analyzing different application cases. Finally, Chapter 5 presents the concluding remarks and discusses future work to enhance the capabilities of the method.

Chapter 2

State of the Art

This section provides an overview of the recent studies focused on performing ZSA and PRA early in the design cycle. It also explores the advantages of parametric Computer-Aided Design (CAD) for system modelling during early design stages and discusses the use of CAD systems to support the system safety analysis and integration into the MDAO process. Finally, a summary table highlights the research gaps.

2.1 Systems Architecture Integration

Aircraft systems architecture integration and validation take place from requirements capture until aircraft verification. System integration activities try to identify conflicts, as early as possible, between aircraft or system-level requirements or implementations that are valid and logically consistent when considered separately but cannot be implemented simultaneously. The CMA, ZSA, and PRA (ARP 4761 [15]) are integration activities whose outputs should flow into the formal analyses. Systems integration focuses on the physical and data interfaces between system elements.

Acknowledging the importance of considering system integration and installation at early design stages, Liscouët-Hanke and Huynh [21] have developed a methodology to assess the feasibility of aircraft configuration considering the volumetric and placement requirements of critical system components. Recognizing the trend towards More Electric Aircraft (MEA) and All Electric Aircraft (AEA) systems architecture, Rao [22] underlines the drawback of the application of the current empirical design methods to novel aircraft designs by highlighting the snowball effect over other domains in an interdisciplinary design process resulting in questionable accuracy of the predictions hence made. This effect has also been discussed by Liscouët-Hanke [23, 24], Chakraborty [25], and Lammering [26].

Furthermore, the limited information available at the conceptual phase and the multiple disciplines involved propose significant challenges to the designer. Dean et al. [27] highlight the risk of making critical concept design decisions based on inadequately detailed information at the conceptual design stage.

2.2 Zonal Safety Analysis

ZSA studies the zone-component interactions (Figure 1.2) and helps highlight any safety issues that the inspected installation might present to guide the rectification strategy. Several researchers have investigated how the ZSA process can be improved.

Xiaolei et al. [28] proposed a ZSA approach to analyze the cause of failure events and their risk evaluation. This so-called "improved" ZSA was applied to the undercarriage bay of CRJ200 aircraft to identify the cause of its accident in 2005 in China. They propose to demarcate the hazards assessed in a specified zone by defining a set of zonal hazard factors induced by energy factors, component failures, and a combination of the two. After examining the equipment interaction in a zone, they use a qualitative risk assessment method that provides a risk rank to the hazard based on its severity grade and frequency level. Firstly, a universal set of zonal hazard factors was defined, which set boundaries for analyzing hazard factors and the hazards inside the selected zone. Secondly, they analyzed the hazard sources and finally assessed the risk of zonal hazards to formulate rules for safety design and operation.

Chiesa et al. [29] suggest using parametric digital mockups to perform the ZSA at the conceptual design phase. They propose a quantitative hazard analysis method and discuss its application in their System for Unmanned Aerial Vehicle Advanced Alternative Energy (SAvE) aircraft concept. The preliminary risk level of each bay is estimated using a scoring method based on the mode of operation, working environment, and equipment nature. First, they calculate the risk of each component by considering the duty cycle, the interaction of electric power, inflammable-corrosive fluids, and the risk score based on engineering judgments. Then, they compute the risk of each isolated bay by adding the risk score of each component in the bay and the intrinsic risk of the bay obtained by summing up the environmental working conditions. The effect of neighboring bays on the risk score, which considers the effect of permeability and interface area, is also added. The global risk is finally obtained by summing up the risk of the isolated bay and the risk due to neighboring bays for each bay and is used for comparing alternative designs.

Acknowledging the limited amount of information available during the early design stage when the system architecture is under development and inputs from PSSA are unavailable, Chen and Fielding [3] developed a ZSA methodology more suited to preliminary aircraft design based on the existing method described in ARP 4761 and performed a case study on the NASA N3-X blended-wing-body aircraft.

Liu et al. [30] underscore the problems with the traditional ZSA techniques. They find the substantial number of digital models of systems and design and installation guidelines make manual inspection complicated and time-consuming. To improve the efficiency and quality and automate the ZSA, they suggest a digital approach for onboard inspection based on an intelligent positioning algorithm that processes the information from the digital model using fusion positioning technology, location-based services algorithm (LBS), and time of arrival (TOA). They use the edit distance algorithm and Deep Convolutional Neural Network (DCNN) to perform installation compliance checks.

Recognizing the inadequate information available at the early stages of design, Li et al. [31] underscore the need to consider the concurrent application of ZSA during the aircraft design process. They also identify the excessive reliance on an experience-based approach for ZSA as a problem leading to non-uniform application. As a solution, they propose a Zonal Digital Mockup Unit (ZDMU), which supports the implementation of Virtual and Augmented reality (VR and AR) to create an immersive digital environment integrated with geometric and non-geometric information databases to perform the ZSA.

It is observed that there is an increased focus on early analysis ([29], [3]), the use of digital technology [31], and quantitative [29] and qualitative [28] mapping of zonal safety hazards. The method by Chiesa et al. [29] is the most promising for quantitatively assessing the zone characteristics at the conceptual level and inspires the zone-component interaction matrix discussed in Chapter 3.

2.3 Particular Risk Analysis

The ARP 4761 [15] lists typical risks, such as fire, lightning, bird strike, flailing shafts, high energy devices (including events such as the rotor-burst or sustained engine imbalance), high-pressure duct burst, tire burst, leaking fluids, and more. Each particular risk has a different analysis methodology specified by respective regulations and/or guidance provided by Advisory Circulars (AC) to demonstrate compliance with the safety requirements. Dalton [32] encourages performing the PRA multiple times during the aircraft development to make the design robust by demonstrating acceptable responses to safety-critical events. It makes characterization, modelling, and assessment of particular risks due to external events important.

The AC 20-128A [4] delineates the design considerations to minimize the hazards caused by Uncontained Engine Rotor Failure (UERF). It provides guidance to model the impact area[1] or a rotor burst zone for different types of prescribed rotor fragment models (discussed in detail in Chapter 3). Based on AC 20-128A [4], the Federal Aviation Administration (FAA) developed a software tool called Uncontained Engine Debris Damage Assessment Model (UEDDAM) [33] to perform the fragment trajectory-level UERF analysis. They demonstrated the capability of their tool on a generic twin-engine jet by following a systematic approach starting with a Damage Mode and Effect Analysis (DMEA), followed by the formation of a functional hazard tree, the definition of a geometric model, selection of a fragment model, specification of flight phase, and application of the associated risk factors.

While UEDDAM is helpful for hazard probability calculation, Cid et al. [34] present an open-source Computer Aided Engineering (CAE)-based tool called "DamageCreator" that integrates the

[1] Impact area refers to the airplane area that could be could be affected during a UERF event

statistical data from real accidents to precisely apply the finite element modelling approach to predict the location and size of holes in the wing and fuselage to assess the residual strength of the aircraft damaged due to UERF. They state that the industry adopts a more conservative approach of assuming the loss of the complete structural element when hit by the UERF debris, whereas using their tool could help with precise damage estimation to enable fail-safe optimization.

Kale et al. [35] applied the UERF analysis approach to the propeller burst event for a novel aircraft concept. Highlighting the unsafe aircraft zones in a digital mockup by analyzing the debris trajectory, they proposed structural reinforcements to protect the flight crew and helium tank present in the rotor burst zone from an explosion.

Zhao et al. [36] propose a boundary discretization approach to analyze the UERF risk to help in system layout optimization. They discretize the boundary surface and curves of the target system or structure into points and determine the risk angle where the rotor fragment hits the part. The risk angle value is then used to calculate the probability. They also conduct a parametric analysis to investigate the relationship between the resulting hazard probability, the target part size, and the distance between the rotor and the target part. They conclude that the distance between the target and the rotor is more critical for hazard control than the target size.

Yang [37] presents a methodological approach to performing Sustained Engine Imbalance Particular Risk Analysis based on AC 25-24 [38] for certification purposes.

Tire and wheel failure PRA can be performed based on the threat envelope models presented in Acceptable Means of Compliance (AMC) 25.734 [5] to analyze the threat imposed by tire burst, wheel flange debris, flailing tire strips, and tire pressure jet blast on the aircraft level.

The CATIA Advanced Design Linking and Iterations Software and Tool (CATALIST) tool by Bombardier ([39], [6]) employs a top-bottom CAD-oriented design approach and implements the engine, Auxiliary Power Unit (APU) rotor burst and tire burst.

Similarly, for lightning strike risk, the ARP 5414B [40] describes the method to define lightning zones on the aircraft. Lee and Collins [41, 42] analyze the lightning strike effect on the aircraft from a systems point of view. They model the effect using a standard risk model, which aids in identifying the risk event and impact drivers. They use the probability of these drivers to assess the loss and present some mitigation strategies to prevent this hazard. Austin [43] has developed a computational tool to predict lightning attachment points and lightning strike zone definitions for unconventional aircraft configurations. The author of reference [43] envisions it as useful for conceptual design iterations and early assessment of lightning strike risk.

Recognizing the critical role the Electrical Wiring and Interconnection System (EWIS) can play in aircraft safety, FAA [44] has developed an EWIS risk assessment tool. This tool uses a database containing zone-level, bundle section-level, and component-level data, regulatory requirements, design guidelines, failure rate, and potential damage data to perform an exhaustive quantitative and qualitative analysis. Considering the complexity of the wiring system, AC 25-27A [45] presents an enhanced zonal analysis procedure.

The review of the existing literature for the analysis of different particular risks indicates that each particular risk has its unique examination method. Work done in references [35], [39] and [6] demonstrate PRA application early in design, while others ([33], [34], [41], [44], [37], [36]) focus on applying the methodology from the guidance material during later design stages with a detailed definition of aircraft structure and system components.

2.4 Parametric System Definition and CAD Modelling

According to Camatti et al. [46], a Digital Mockup at Conceptual Level (DMUCL) can be a powerful means to carry out weight estimation, verify assembly procedures, analyze structural performance and operational performance, while assessing the Reliability, Availability, Maintainability, and Safety characteristics (RAMS). Highlighting these advantages, they also shed light on the associated challenges that include: lack of a standard approach and maturity level of the current digital tools.

Ledermann et al. [47] demonstrated how modern CAE systems using a knowledge-based modular architecture could represent complicated assemblies like aircraft structures. They realized the importance of a clearly defined interface and data flow for the highly multidisciplinary problem. Therefore, the authors of ref. [47] set up a digital mockup in CATIA using hierarchical structures based on parametric associativity. However, they found that the bottom-up information flow that supports the digital mockup involves considerable coding, and the sluggish behavior of the scripting language makes it inefficient.

Liscouët-Hanke and Huynh [21] have developed an approach to estimate the so-called equivalent design volume for system placement. Their approach enhances conceptual design maturity by outlining the standardized way of measuring available volume for system installation. They consider critical system components' volumetric and placement requirements using a 3D model developed in Bombardier's in-house parametric tool CATALIST [39].

Based on pre-defined rules in line with Bombardier's design practices, Tfaily et al. [48] have developed a tool for automated parameterized modelling and placement of aircraft systems in CATALIST. The system placement is based on the typical layouts of existing aircraft, and some PRA aspects are considered (as discussed in the Section 2.3)

Attempting the semi-automated wing subsystem sizing and orientation from a volumetric perspective, Rao [22] follows a physics-based and knowledge-based approach for system selection based on aircraft type and architecture selection based on the technology level in Python using Common Parametric Aircraft Configuration Schema (CPACS)[2] [49] for data exchange. The technology levels are allocated based on whether the subsystem architecture utilizes electric, hydraulic, pneumatic power, or a combination. Using the aircraft design parameters, mass, and power requirements as an outline, Rao presents a method for individual subsystem sizing and system component to structure intersection detection for an MEA case study.

Tarkian and Tessier [50] argue that code-based geometry modelling limits fidelity due to the large amount of coding involved. They constructed a parametric reference model of an aircraft in CATIA, which can be changed to represent different configurations based on associative modelling. Representing the reference model as a standalone visualization tool, the authors demonstrated its usefulness by referencing it to develop a parametric mesh model in CATIA and using it to perform aerodynamic analysis using the panel method. They recommend similar integration of the reference model with other disciplines for quick design assessment.

Using an XML schema for storage and communication of design data between the analytical

[2]CPACS is an open-source data definition format developed by the German Aerospace Center - DLR, for the air transportation system that enables engineers to exchange information between their tools using an Extensible Mark-up Language (XML) schema.

tool (Tango) and geometry-oriented 3D design tool (RAPID-Robust aircraft parametric interactive design) was developed at Linkoping University [51]. It utilizes knowledge-based engineering automation within the CAD environment. Recognizing the advantage of including fuel system design in the earlier design stages, López and Munjulury [52] integrated the knowledge-based parametric definition of aircraft fuel systems in the RAPID tool for conceptual design.

As per Herbst and Staudenmaier [53], XML parsing may not be an efficient communication solution when dealing with comprehensively parametrized geometries. Leveraging the easy integration of open-source software like OpenVSP[3] with other software, they have developed an Application Programming Interface (API) for communication between their MATLAB-based aircraft design environment ADEBO (Aircraft DEsign BOx) and OpenVSP.

Schwinn et al. [55], who have developed structural sizing and preliminary crashworthiness assessment tools that use CPACS files as inputs, also support open-source software, which is advantageous as they reduce the overall license costs and provide a common software framework.

Fuchte et al. [56] introduced a method of creating a preliminary digital mockup of the system architecture. It allows the physical modelling of systems using the design rules based on knowledge patterns from the current aircraft to size and place components with adherence to the local geometric constraints. While a pathfinding algorithm is used to support the system routing.

Royal Netherlands Aerospace Centre (NLR) [57] has developed a tool for installation optimization of an electric system at the conceptual design stage called NEXT: Novel Equipment placement and routing eXploration Tool in MATLAB, that can easily integrate with CAD software like CATIA. Considering the component placement, it automatically routes and optimizes the interconnections in 3D space using graph-based algorithms.

Hence it is evident that there is an enhanced emphasis on employing CAD-based tools to support the system integration process early in design.

[3]OpenVSP or Open Vehicle Sketch Pad [54] is an open-source parametric aircraft geometry tool for creating 3D models of the aircraft.

2.5 Summary and Gap Analysis

Table 2.1 summarizes the literature review by providing an overview of parametric CAD modelling and the application of CAD models for safety assessment.

Table 2.1: Literature overview on the use of parametric modelling for safety analysis ("-" means not considered, "+" is used to indicate the degree of simplification, and "✓" means analysis performed).

Ref.	Systems scope	Parametric System Modelling				Design Stage	System Safety Analysis			Aircraft Configuration Type
		Sizing	Placement	Degree of simplification	Software used		FHA, FTA and PSSA	CCA		
								ZSA	PRA	
(Liscouet-Hanke and Huynh, 2013), (Tfaily et al., 2015), (Sanchez et al., 2021), (Banerjee et al., 2013)	Electrical systems, avionics systems, hydraulic systems, flight-control systems, wiring, and tubing	Model-based integrated prelim. sizing;	Estimation of effective design volume and placement based on design rules	++	CATALIST (CATIA)	Conceptual	-	-	Uncontained engine rotor failure, landing gear tire burst	Conventional, MEA
(Munjulury et al., 2016)	FCS, Fuel System	Based on KBE	Based on CAD templates	++	RAPID (CATIA)	-	-	-	-	Conventional
(Rao, 2017)	Flight control actuators, fuel tank, anti-ice elements	Integrated sizing approach, knowledge-based subsystem sizing	Design rules from the previous aircraft; connections routed using pathfinding algorithm; intersection detection	++	-	Conceptual	-	-	-	Conventional, MEA
(Moebs et al., 2022)	Fuel System	KBE	-	-	-	Conceptual	Perform FHA, FTA, and PSSA	-	-	MEA, hybrid
(Fuchte et al., 2012)	ECS Ducting	-	Using knowledge-based design rules	-	CAD and CPACS		-	-	-	Conventional
(Chen and Fielding, 2018)	Fuel System	-	-	+		Preliminary	Use FHA and FTA as input.	✓		Hybrid, unconventional
(Chiesa et al., 2013)	Intrinsic risks due to zone environment considered	-	-	-	CAD	Conceptual	Use FTA as input	✓	-	MALE UAV using alternative energy
(Li et al., 2021)	Systems in the engine pylon bay zone	-	-	+	CATIA	Suitable for concurrent application	-	✓	Possible to perform as per the authors	Conventional

Note: FCS= Flight control system, KBE= Knowledge-based engineering, ECS= Environment control system, MALE= Medium Altitude and Long Endurance, UAV= Unmanned Aerial Vehicle, FTA= Fault Tree Analysis.

Several researchers have explored parametric system sizing and CAD model representation. However, the use of these models for the safety assessment process is less evident. Some research works [31, 46] propose using a centralized Digital Mockup Unit (DMU) to perform different analyses to support the iterative design process. Most of the studies focus on the utilization of CAD-based models for ZSA [3, 31, 29], whereas for PRA, CAD is used to model rotor burst [33, 35, 6] and tire burst [39] risk events.

The study of the standard methods and related research work helps make important observations about the current ZSA and PRA process:

(1) It is observed that the guidance material (ARPs, ACs, and AMCs) is available to analyze each particular risk and inspect specific systems installation separately. Therefore, there is a lack of a well-defined holistic approach that looks at these placement constraints resulting from both ZSA and PRA in combination.

(2) These dedicated methods are more suitable for detail design assessments and must be adapted for use at the conceptual design stage.

(3) There is a lack of parametric integration of these analyses that enables repeatability, which is quintessential for rapid and iterative conceptual-level assessments.

Some researchers have started to address the early design phases, but more work is required to adapt the methods to unconventional configurations and new technologies and improve automation.

Acknowledging that safety assessment is a crucial design driver and an inherent part of the design process, this work attempts to bridge the gap between safety assessment and conceptual design by proposing a new methodology for ZSA and PRA using a parametric CAD modelling approach and by considering the interactions between both the analyses. It will build on the work done in the context of CATALIST [39, 6], and also draws inspiration from other works like by Chiesa et al. [29] for the ZSA scoring approach, presented in Chapter 3.

Chapter 3

Methodology

This chapter discusses the development of the conceptual level ZSA and PRA methodology to meet the objectives formulated in Chapter 1, Section 1.2, and the gaps identified in Chapter 2. An overview of the early assessment approach is presented first. This is followed by an elaboration and validation of the proposed approach for conceptual-level ZSA and PRA.

3.1 Methodology Overview

ZSA and PRA support the aircraft safety assessment process by verifying the safety, survivability, and functional and physical independence requirements to help generate installation requirements or placement rules for highly integrated complex aircraft systems. They must be performed throughout the development process of a novel aircraft configuration. However, their implementation early in design requires a simple yet robust approach that can address the evolving requirements and level of detail while making optimum use of the available knowledge from current processes and guidance.

In light of the aforementioned requirement and observations made in Chapter 2 (Section 2.5), a novel approach for Conceptual-level Zonal Safety Analysis (CZSA) and Conceptual-level Particular Risk Analysis (CPRA), in line with the standard assessment process [15] is proposed. Figure 3.1 provides an overview of the proposed CZSA and CPRA methods.

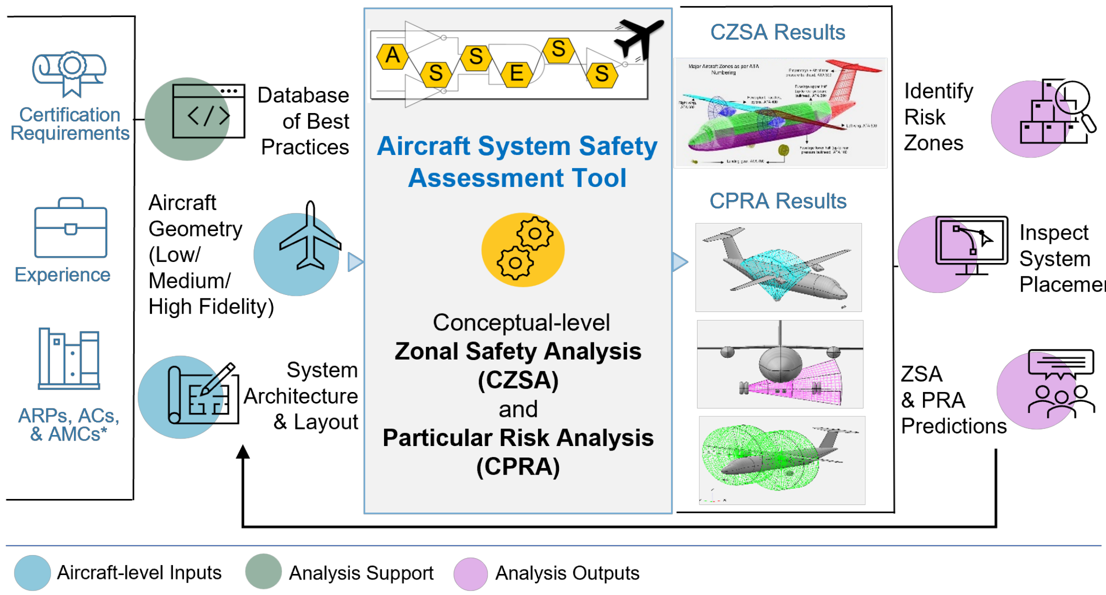


Figure 3.1: CZSA and CPRA methodology overview.

Under the umbrella of the ASSESS framework, the CZSA and CPRA methods use the aircraft geometry and system architecture and layout as an input, together with a database of installation requirements and best practices that supports the safety assessment. The database is prepared by compiling the certification regulations, knowledge from engineering experience, and guidance from the ARPs, ACs, Aerospace Specifications (ASs), Aerospace Information Reports (AIRs), and AMCs.

The CZSA helps to define the aircraft zones and capture the installation requirements and best practices by performing a zone-component interaction study, while the CPRA helps identify risk zones.

The complete CZSA and CPRA methodology (Figure 3.2) will be further expanded and discussed in detail in the following sections.

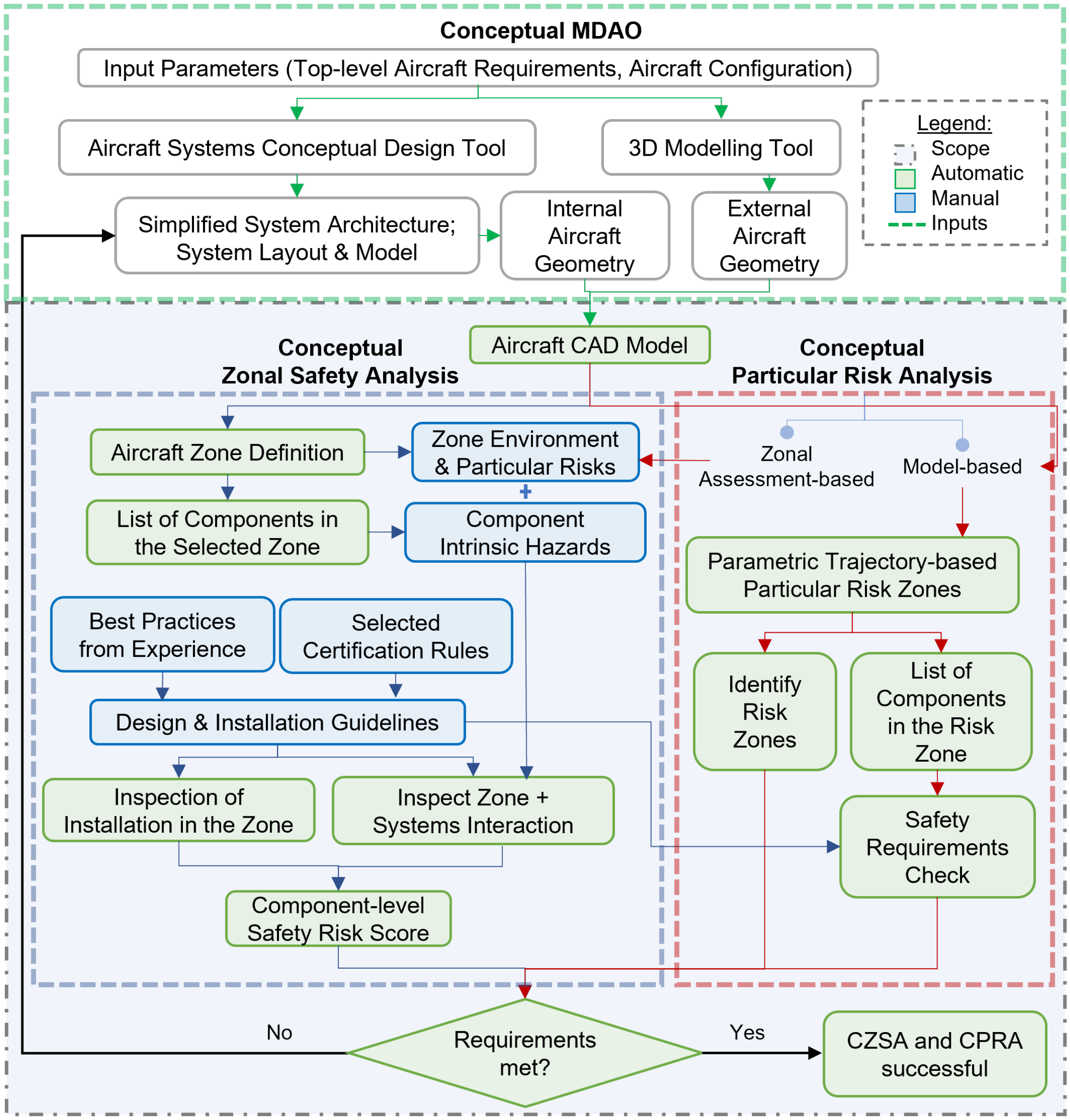


Figure 3.2: Simplified and semi-automated CZSA and CPRA methodology.

Together the outputs of both CZSA and CPRA help assess and guide the component placement. As shown in Figure 3.3, using the aircraft design input, the system placement is evaluated using CZSA and CPRA. If the current placement meets the installation requirements, then no change is required. However, an appropriate risk mitigation strategy must be adopted if specific installation risks are identified in CZSA and CPRA predictions. This step requires the designer or systems integration engineer to interpret the CZSA and CPRA results and accordingly suggest modifications to the current system layout.

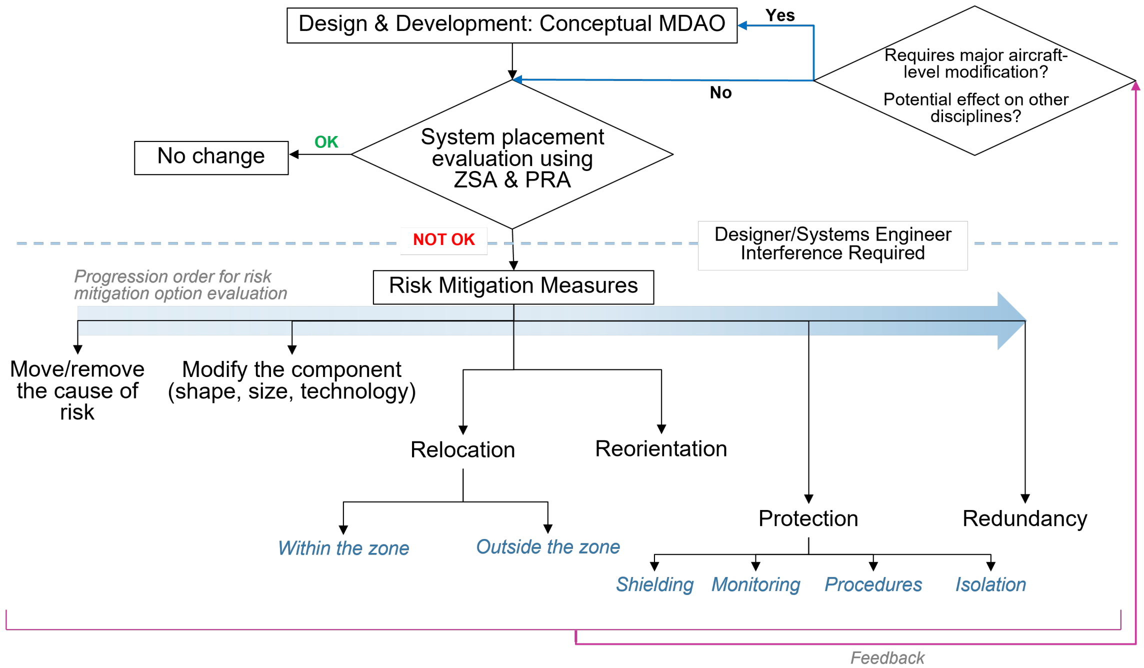


Figure 3.3: CZSA and CPRA risk minimization measures and feedback link to MDAO .

The different risk mitigation options are broadly classified into six main categories: removing the cause of risk, modification of the system component, relocation, reorientation, protection, and addition of redundancy. The progression order for the consideration of risk mitigation options is illustrated in Figure 3.3. It starts from minor adjustments like removing the cause of risk to the more substantial changes like adding redundant systems that might require major aircraft-level modifications and potentially impact other disciplines. In the latter case, the outputs should be fed back to the overall design and development MDAO. If the former case applies, then CZSA and CPRA must be performed again after the minor modification to check the effectiveness of the change.

Some examples of different risk mitigation strategies are as follows:

- Remove the cause of risk: If, for instance, the high-temperature environment in a zone affects the installed components, then the risk of high temperature can be removed by adjusting the ventilation in the zone or adding a cooling system.

- Modify the component (shape, size, or technology): If the rotor burst zone impacts the inboard part of the wing and interferes with the fuel tank, then the boundaries of the feed tanks are modified to keep them out of the risk zone [58].

- Relocation: Critical electrical equipment in the aft equipment bay might need relocation out of the rotor burst zone for aft-fuselage-mounted engines [6].

- Reorientation: The orientation of the APU could be altered to protect specific critical components, like the rudder actuators, from the APU burst zone [6].

- Protection: In cases where it is impossible to respect the minimum required clearance between two systems, like hydraulic tubing and air-conditioning ducts, we must add protective shielding to either of the systems. Protection can also be in the form of monitoring systems or procedures for the flight crew to avert a catastrophic failure resulting from a chain of events triggered by a critical component failure.

- Redundancy: Redundant or backup system components like three different hydraulic rudder actuators are present on certain aircraft to prevent losing control if one of the hydraulic systems powering an actuator fails. This philosophy can be extended to other critical components as well.

3.1.1 Analysis Fidelity based on Level of Geometric Granularity

The evolving detail of aircraft internal geometry (Degree of Simplification (DS): Figure 3.1) is addressed by adopting a variable fidelity multi-level approach. The levels span from early conceptual design to the early preliminary design stage and are consistent with the level definition used by Piperni et al. [16] and Sanchez et al. [6].

Table 3.1: Levels of DS for system and subsystem definition (Adapted from [6]).

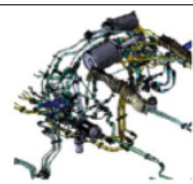
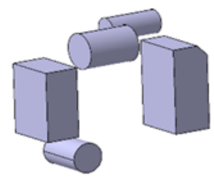
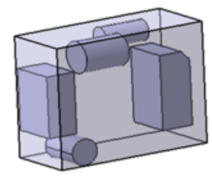
	DS 0-2	**DS 3**	**DS 4**
System architecture descriptor	Complete bill-of-material and connections between elements defined	List of principal components, lumped space reservations, high-level technology	High-level, lumped definition
Geometric description (E.g.: Hydraulic system in the left hydraulic bay)			

Table 3.2 discusses the varying fidelity level of the safety assessment tool based on the 3D modelling granularity. The first level is Level 0 (L0), which involves basic checks; the final level is Level 3 (L3), which allows detailed inspection.

Irrespective of the level, specific inputs are always required. These include information about aircraft configuration, system architecture type, and the aircraft's Outer Mold Line (OML). The detail of the structural definition increases, and the system model granularity refines from a high level to a detailed (or low level) as we go towards a higher fidelity level. The work in this thesis focuses on implementing the CZSA and CPRA for levels 0, 1, and 2 because these levels represent the system-level detail (or DS) available at early design stages.

Table 3.2: Formalization of required granularity in 3D modelling for safety assessment.

Level	Input			CZSA tasks	CPRA tasks	Advantage
	Required inputs	Level of structural definition	System definition			
0	Aircraft Configuration: High, medium, and low wing; landing gear: fixed or retractable; engine: no. and location Architecture Type: Conventional, hybrid or all-electric Basic external geometry: Outer mold line of the aircraft	Forward and aft pressure bulkheads, floor	-	Major zone definition	Pre-placement trajectory-based Ram Air Turbine (RAT) and propeller blade release CPRA	Support/facilitate component placement, helps designer make informed decisions.
1		Forward and aft pressure bulkheads, floor, frames, and keel beam	Critical systems, no wiring (DS 4- High level lumped space reservation)	Level 0 tasks + Fuselage system section or equipment bay definition + Zone-component interaction analysis	Pre and post-placement CPRA: UERF Level 1, RAT blade release, propeller blade release, tire debris threat, and flailing tire strip (extended and retracted)	High-level evaluation of component placement strategy using CZSA and definition of stay out zones based on CPRA.
2		Forward and aft pressure bulkheads, floor, frames, keel beam, ribs, and spars	Critical systems, no wiring (DS 3 - High level lumped, simplified geometry)	Level 1 tasks + Major sub-zone definition	Pre and post-placement CPRA: UERF Level 2, RAT blade release, propeller blade release, tire debris threat, wheel flange debris threat, and flailing tire strip (extended and retracted)	More precise CZSA and CPRA predictions to assess system placement strategy.
3		Forward and aft pressure bulkheads, floor, frames, keel beam, ribs, spars, wing box, and pylon structure	All systems, with wiring (DS 0-2- Real geometry)	Level 2 tasks + placement in space, clearance and minimum separation checks	Post-placement CPRA trajectory level analyses	Increased maturity of early analysis. Detailed checks to assess conformance with installation guidelines. Helps in determining critical system separation

3.1.2 Validation Strategy and Case Study Overview

Overall, the validation of the developed methodology is challenging, as certified designs typically comply with the ZSA and PRA placement requirements, making it difficult to demonstrate that the method properly catches non-compliance. Moreover, the time frame of a master's thesis is insufficient to validate the effectiveness of a real design process. Therefore, multiple case studies are employed to illustrate the capability and efficacy of the developed methodology.

Various case studies are interspersed throughout the upcoming sections (as shown in Table 3.3) to validate the different methods developed as a part of the CZSA and CPRA methodology for different geometric granularity levels.

Table 3.3: Case study overview.

Analysis Type	Case Study	Geometric Granularity Level	Method	Reference Location in the Thesis
CZSA	Major zoning for different aircraft configurations	0	Aircraft zone definition	Chapter 3: Section 3.4, sub-section 3.4.1
	Aft equipment bay with system space reservation	1	Zone-component interaction risk scoring	Chapter 4: Section 4.3
	Example Zone XXX	2	Zone-component interaction risk scoring	Chapter 3: Section 3.4, sub-section 3.4.1
	Main landing gear bay with simplified system geometry		Zone-component interaction risk scoring	Chapter 4: Section 4.1
	Aft equipment bay with simplified system geometry (Conventional Systems and More electric systems)		Zone-component interaction risk scoring	Chapter 4: Section 4.3 & Section 4.4
CPRA	RAT blade release analysis for RAT placement	0	RAT blade release modelling	Chapter 3: Section 3.4, sub-section 3.4.2
	Propeller blade release analysis for Hydrogen tank placement		UERF modelling	Chapter 4: Section 4.2
	Rotor burst analysis for sizing the dry bay	1	UERF CPRA modelling	Chapter 3: Section 3.4, sub-section 3.4.2
	Wheel rim release analysis for system separation consideration in the wing		Wheel rim/flange release modelling	Chapter 3: Section 3.4, sub-section 3.4.2
	Tire burst analysis for S18 aircraft	2	Tire burst modelling and affected component detection	Chapter 4: Section 4.1

3.2 Conceptual-level Zonal Safety Analysis

The CZSA methodology as illustrated in Figure 3.2 (left side in the highlighted scope area) comprises of three main tasks: Aircraft zone definition, inspection of installation in a zone and component-level risk score assignment. The pre-requisite for the analysis are the aircraft 3D CAD model and design and installation guidelines database.

3.2.1 Aircraft Zone Definition

The aircraft needs to be divided into zones to facilitate the CZSA. A zone refers to an easily identifiable and logically arranged area in an aircraft. Zoning helps in the location of components and identification of panels and access doors.

The definition of these aircraft zones should be generic and follow a standard approach to be consistent with the zoning nomenclature used in the industry for operations ranging from component installation to maintenance. For this, a study of the specification standards used in the aerospace field is performed. Most documentation (manuals, pilot training handbooks) follows the Air Transport Association of America (ATA) 100 specification. The ATA 100 specification by the Air Transport Association of America uses the major structural components like bulkheads, floors, partitions, frames, wing spars, and ribs to define zone boundaries. The specification uses a three-digit number to identify the zone. The numbering sequence follows a specific order: bottom to top, left to right (within the fuselage), front to back, and inboard to outboard (in the wing).

In line with the current standardization approach for aircraft zone definition, the CZSA method uses the latest issue of S1000D (Issue 5) [2]: an international specification for procuring and producing technical publications which use ATA 100 as a source document to standardize the documentation with perceived benefits of uniformity, ease, and reduced cost of data exchange while working on collaborative projects.

As per the ATA 100 specification, the aircraft is divided into major zones, as described in Table 3.4, with the standard three-digit number to identify the major zone.

Table 3.4: Aircraft major zone description.

Major Zone	Description
100	The lower half of the fuselage up to the rear pressure bulkhead (radome, side nose avionics compartments, compartments under the lower nose shelf, the area below the flight compartment floor, cabin floor, and cabin seat decks to the aft pressure bulkhead)
200	The upper half of the fuselage up to the rear pressure bulkhead (compartments above the lower nose shelf, the area above the flight compartment floor, cabin floor, and cabin seat decks to the aft pressure bulkhead, including the baggage compartment)
300	Stabilizers/ empennage, including fuselage aft of the rear pressure bulkhead
400	Power plants, nacelles – pylons, engine compartments, spinners, and propellers
500	Left wing
600	Right wing
700	Landing gear compartment, including landing gear, wheel wells, and doors
800	Doors and emergency exits
900	Lavatories and galleys

The major zones divide into major sub-zones by replacing the second digit of the standard number with a non-zero number. For example, the major zone 700 can divide into major sub-zones 710 (nose landing gear), 720 (gear doors and wheel wells), 730 (left main landing gear), and 740 (right main landing gear). The subdivision of major sub-zones uses the third digit of the standard number for identification.

In addition, the S1000D standard prescribes certain principles and requirements for zone allocation to maintain consistency for different aircraft versions. It suggests adding new zone numbers only in case of major changes, assigning individual zone numbers to major structural components (like doors, bulkheads, control surfaces, and landing gear), and clearly defining the zone boundaries without dividing the related structures or compartments into separate zones. The standard also suggests storing the zone information in a dedicated repository using the standard S1000D XML structure, wherein the markup elements store the zone description (name, number, side, boundary, reference zones), as shown in Figure 3.4.

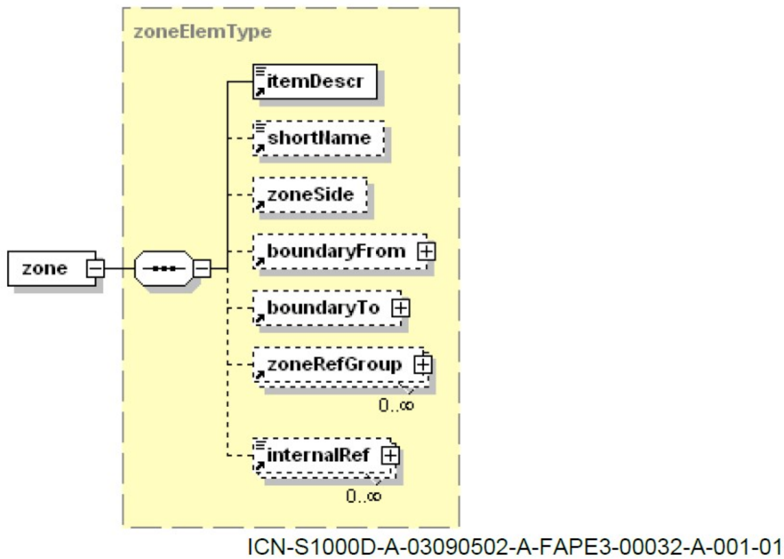


Figure 3.4: S1000D standard XML elements for zone description [2].

For major-sub zone definition a different approach is proposed. As previously stated, for the unconventional configurations, the zoning methodology originally designed for the tube and wing configuration poses difficulties and relies heavily on user perception to demarcate the zone boundaries. Similarly, for aircraft with conventional configuration but novel propulsion technologies like hybrid-electric propulsion, all-electric propulsion, and hydrogen fuel cells, the placement of the energy storage systems and fuel tanks may not fit well with the ATA 100 sub-zone specifications. To account for these exceptions, the user is given the flexibility to define the major zone and major sub-zone boundaries manually following the S1000D standard format and assign the zone number in line with the ATA 100 specification. Chen et al. [3] also use a similar approach for defining the zones for NASA N3-X (Figure 3.5).

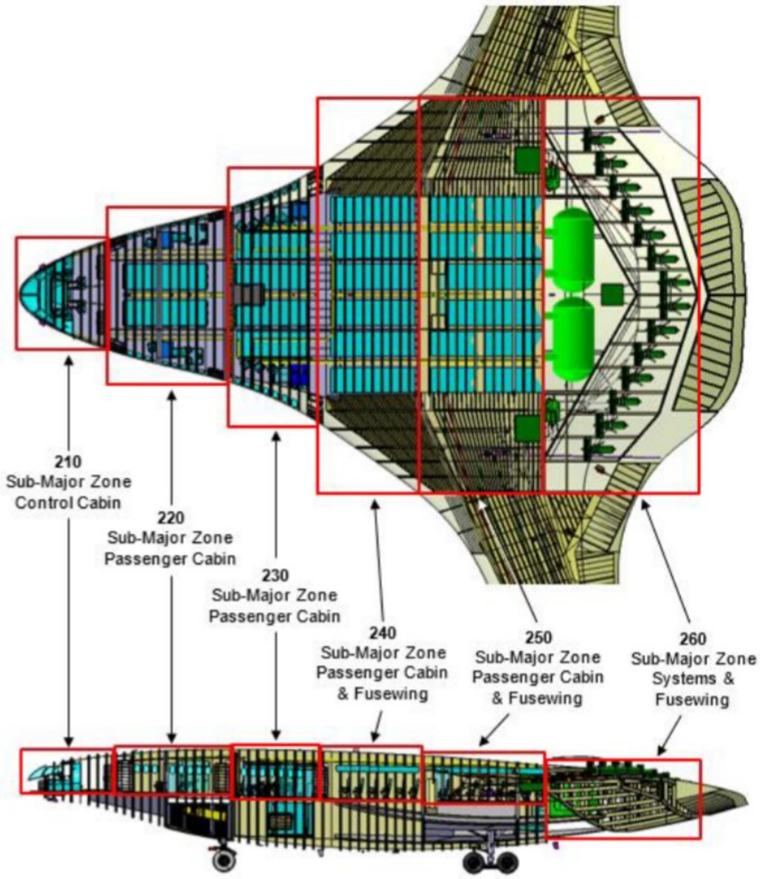


Figure 3.5: Division of major zone 200 (upper fuselage) of NASA N3-X hybrid wing aircraft into major sub-zones [3].

3.2.2 Design and Installation Guidelines

As per ARP 4761 [15], preparing design and installation guidelines is the first step in ZSA. The guidelines are specific for every aircraft program and are usually derived from previous programs. However, for early assessment, the reuse of detailed guidelines from previous aircraft programs may not be effective due to two main reasons:

(1) The level of system detail available at early design stages and the level of detail of the guidelines being reused may not match (too detailed installation guidelines for the less detailed system), making it difficult to apply these guidelines.

(2) For novel designs that deviate from the reference aircraft, the old and detailed guidelines

might overlook the new installation risks arising from the unconventional configuration.

Hence, for efficient early application and reusability, the guidelines must be formulated such that:

- They are generic, that is not specific to any aircraft program, and
- Focus on high-level system components and zone interaction to flag the obvious risks without needing too much detail about the system components.

The purpose of having the installation guidelines is to ensure that system placement and layout abide by the certification requirements for Continued Safe Flight and Landing (CSFL). These guidelines are equally effective and applicable to unconventional designs, the reason being that irrespective of the technology and configuration, the aircraft will have to satisfy the safety objective per the certification regulations and demonstrate compliance. Therefore, to formulate the design and installation guidelines, the certification requirements themselves, along with other regulatory guidance documents like ARPs, ACs, AMCs, ASs and AIRs, and engineering knowledge and experience are used. This consolidation of guidelines and best practices is called a database of best practices for system installation (Table B.1).

The generic nature of the database is a consequence of the documentation used to prepare it, which is the principal reference for demonstrating compliance with the CSFL requirements and certification purposes.

Furthermore, from the methodology's industrialization perspective, this database can be updated and combined with an aircraft manufacturer's internal requirements and checklists based on experience and best practices.

Table 3.5 summarises the systems covered and associated reference regulatory and guidance documents for CZSA and CPRA system placement considerations in the database.

Table 3.5: Aircraft systems and reference documents for placement considerations in CZSA and CPRA.

S. No.	Aircraft System	Reference documents for placement considerations
1	Fuel system	Part 25.993 Fuel system lines and fittings, Aircraft Fuel System Design Guideline AIR 7975, Part 25.1185 Flammable fluids, AC 20-128A, AMC 25.734, AC 25.905-1
2	Hydraulic system	Design of Tubing Installation for Aerospace Hydraulic Systems ARP 994B, Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP 4752B, AC 25.584, AC 25.583, AC 20-128A, AMC 25.734
3	Flight control system	AC 25.905-1, AC 20-128A, AMC 25.734
4	Environmental control system	AC 25.905-1, AC 20-128A, AMC 25.734
5	Auxiliary power system	AC 25.905-1, AC 20-128A, AMC 25.734
6	Electrical power system	Aircraft Electrical Installations ARP 4404C, Part 25.1707 System separation: EWIS, AC 20-128A, AMC 25.734
7	Oxygen system	Part 25.1707 System separation: EWIS, ARP 5021 B Oxygen Cylinder Installation Guide, Oxygen System Integration and Performance Precautions AIR 825_12A, AC 20-128A, AMC 25.734
8	Landing gear system	AMC 25.734
9	Hydrogen fuel cell system	Considerations for Hydrogen Fuel Cells in Airborne Applications AIR 7765, Installation of Fuel Cell Systems in Large Civil Aircraft AS 6858
10	Miscellaneous	Part 25.1457 Cockpit voice recorders, Part 25.1459 Flight data recorders.

The requirements and considerations in the database (Table B.1) are categorized by aircraft system, hazard, applicability to conceptual design, applicable geometry granularity level (elaborated in sub-section 3.1.1), and evaluation means (discussed in the following sections). These guidelines and practices can be reused and serve as a first compliance check for the system installation in a zone and also as a reference for guiding the component placement early in design. Furthermore, the database also covers the placement guidelines for new technologies like Hydrogen fuel cells [59].

For example, the ARP 4752B [60] advises that no hydraulic reservoirs should be placed in a designated fire zone (as defined by [61]; like engine power section, APU compartment). For aircraft electrical installations, ARP 4404C [62] recommends adequate ventilation in the zones where there is a risk of passenger compartment contamination or the formation of an explosive mixture by the emission of gases and battery fumes. As per AIR 825-12A [63], Oxygen system component placement close to EWIS and components with moving parts must be evaluated. Similarly, other requirements must be satisfied to prevent failure due to the interaction between the component and the zone environmental conditions like high ambient temperature or humidity. Therefore, a qualitative approach that enables a quick evaluation of such intrinsic risks must be adopted. An approach to assess the component installation against the risks posed by the zone environment and other component operational risks is developed in the following section (Section 3.2.3).

Some guidelines are more suggestive and focus on mitigating or minimizing the possible risk events arising from the placement (not highlighted as very high risk from the zone-component interaction study (upcoming in Section 3.2.3) For example, Part 25.1707(l) [64] for EWIS separation, according to which the installation of EWIS must ensure adequate physical separation from the aircraft structure and other components to minimize the chances of damage and abrasion due to the presence of sharp edges, vibration. As per Part 25.1453 [65], oxygen tanks and lines in unsafe/high-temperature environments must be protected.

The guidelines in the database that prescribe a clearance value or positioning with respect to other components can be translated into a logical check for the specified zone in the aircraft's three-dimensional CAD model.

For example, as per Part 25.795(c)(2) [66], the redundant flight control systems required for CSFL must be segregated by a minimum physical distance (Equation (1)) equal to a sphere of diameter D,

$$D = 2\sqrt{H_0/\pi}, \tag{1}$$

where H_0 is the maximum opening size in square feet in any pressurized compartment [67] as calculated in Equation (2),

$$\begin{aligned} H_0 &= P.A_S, \\ P &= A_S/6240 + 0.024, \end{aligned} \tag{2}$$

where A_S is the maximum cross-sectional area of the pressurized shell normal to the longitudinal axis in square feet.

The whole sphere of diameter D only applies in pressurized compartments. In non-pressurized zones, only a half-sphere placed on the pressurization boundary applies. There are also zones of “lesser separation”, where the external geometry constrains available space (e.g., tapering in the aft fuselage or flight deck). To prevent the risk of fire in the presence of flammable fluids, Part 25.1185 [68] requires a minimum airspace clearance of one-half inch between each firewall or shroud and flammable fluid tank or reservoir.

The associated guidance documents also suggest specific placement considerations. For example, as per AIR 7975 [69], the fuel line installations should maintain a 0.25-inch separation from the surrounding subsystem and structural components. AIR 825-12A [63] for oxygen system integration and performance precautions states that the oxygen system components must not be installed below fuel, hydraulic, or oil fittings to prevent combustion hazards in case of combustible fluid leakage on oxygen lines.

Table 3.6 shows an example of how the installation guidelines for the hydraulic system components in the main landing gear bay from the ARP 4761 example can be translated into a logical check.

Table 3.6: Examples of zone-level risk score attribution based on the zone environment.

Requirement ID	**Description (from ARP 4761)**	**Requirement Type**	**Applicable Zone**	**Component(s) involved**	**Mathematical representation (Logic)** ***(All dimensions are in SI units)***	**Output**
29-160-1	The air conditioning (A.C.) piping should normally be routed above the hydraulics	Location	160	A.C. piping and hydraulic lines	(Z_AirCond - (Diameter_AirCond/2)) $>$ $\alpha*$(Z_Hydr_blue + (Diameter_Hydr_blue/2))	if(logic=TRUE): print("Requirement met") & (check ReqID2) else: print ("Replacement required")
29-160-2	Protective shielding is necessary when the proximity of hydraulic and air conditioning systems is unavoidable.	Segregation	160	AC piping and hydraulic lines	(Z_AirCond - (Diameter_AirCond/2)) - (Z_Hydr_blue + (Diameter_Hydr_blue/2))$<$ β (Repeat for X and Y coordinates)	if(logic=TRUE): print("Increase separation") or ("Segregation required") else: print("Requirement met")

Note: Here, α is a parameter for the location of A.C. piping with respect to the hydraulic piping, and β is the minimum separation required between the A.C. and hydraulic systems. The systems engineer or safety engineer may prescribe these values.

However, to perform logical checks, a low level of geometric detail (falls under level 3 of geometric granularity (Table 3.2)) is required, which is out of scope of this thesis.

Therefore the focus is on the important high-level early checks that involve considering zone environment characteristics, component intrinsic risks, and the interaction between the two. Such considerations and interactions from the database are mapped and evaluated using the methodology developed in the next section.

3.2.3 Component-Zone Interaction

As highlighted in the previous section, it is important to evaluate the component installation from the perspective of zone and component characteristics and the interaction between different components and the zone.

Analysis results like Failure Mode and Effect Analysis (FMEA) are required to inspect the influence of the failure of one system component on the neighboring components. However, system designers typically perform FMEA in later design stages when a detailed system definition is available and the placement of components is near finalization. Hence, checking the component-to-zone and component-to-component interaction while determining the appropriate placement within a zone necessitates a different approach.

The Guide for Evaluating Combustion Hazards in Aircraft Oxygen Systems: AIR 825-13 [70] presents an oxygen hazard analysis chart to evaluate the risk of combustion due to different functional components within the oxygen system. The analysis considers the component material (flammable or inflammable), the presence and probability of ignition hazards (like mechanical impact, electric arc, frictional heating, and chemical reaction), and accounts for the secondary and reaction effects.

AC 25-27A [71] uses an Enhanced Zonal Analysis Procedure (EZAP) for EWIS maintenance and inspection activities of transport category airplanes. EZAP follows a step-by-step evaluation procedure starting with the collection of zone information (zone number, description, and list of components), zone characteristics (size and density), and considers the likelihood of accidental damage and zone environment hostility to plan the inspection and maintenance activities for the particular zone.

As discussed in Chapter 2, section 2.2, Chiesa et al. [29] consider the duty cycle, the interaction of electric power and inflammable-corrosive fluids, motion between parts, static and dynamic mechanical failures (in terms of temperature, rotating speed, exchanged forces between components, etc.) of the equipment and the environmental working conditions (temperature, explosions, vibration, impacts, and mechanical stresses) of the zone.

The approaches reviewed above evaluate the hazards at different levels: system level (Oxygen system), zone level with a focus on one system (EWIS installations in an aircraft), and zone level with a focus on all the constituent components (SaVE aircraft concept). However, all the approaches evaluate the interactions between the characteristics of the entities (component part, component, or zone) to analyze the hazard. Moreover, these analysis approaches rely on knowledge about the zone and systems characteristics from experience and engineering judgment, which makes them suitable to adapt to the level of detail available during conceptual design.

To fulfill the requirement of a component and zone intrinsic hazard interaction assessment, a novel component-level risk-scoring method is developed that builds upon the concepts from the aforementioned approaches. A component-zone interaction matrix (Figure 3.6) is used to quantify the overall risk of placing a component in a specific zone.

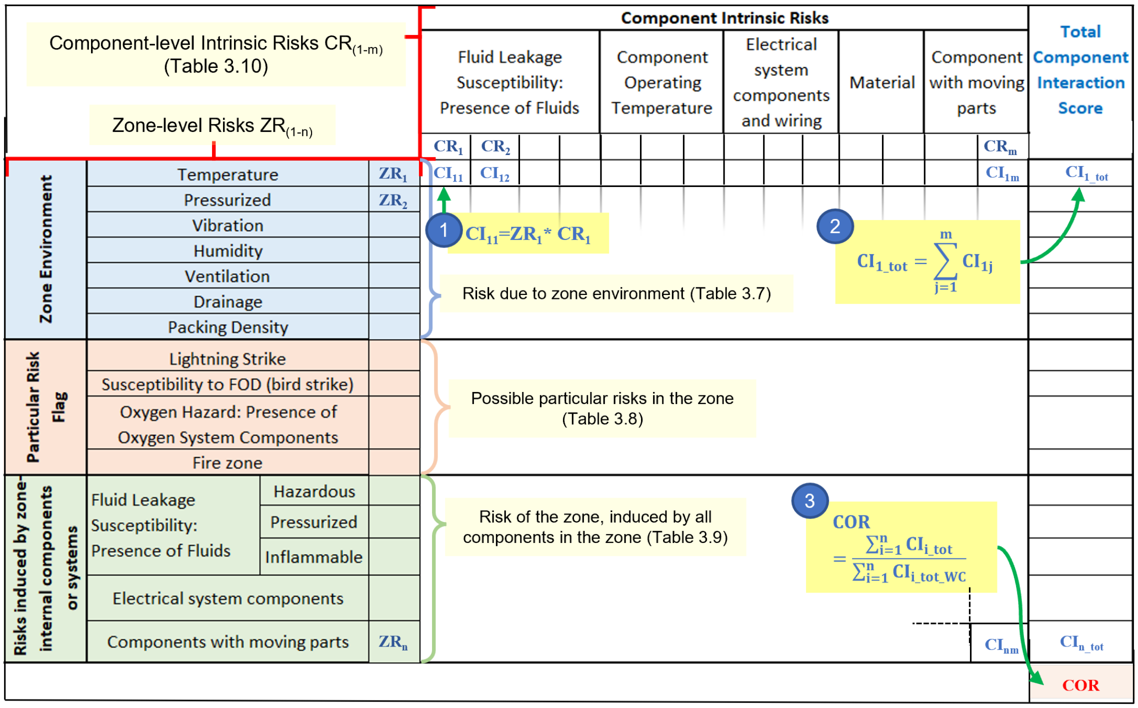


Figure 3.6: Component-Zone interaction matrix for component-level overall risk scoring.

Unlike the scoring method by Chiesa et al.[29] that calculates the risk score for the zone, the proposed scoring method computes the component overall risk score that helps evaluate the installation and suggest risk minimization measures (e.g., component relocation or protection) accordingly.

The guidelines and best practices database is synthesized with the engineering experience from experts on Reliability, Maintainability, and Safety and Advanced design from the industry to quantify the safety risk associated with the components in a zone in the CZSA, thus, capturing the complex zone-component and component-component interactions by performing first-hand and high-level placement checks at the conceptual phase.

Each zone has a fixed risk score based on Table 3.7 and Table 3.8. In addition, Table 3.9 accounts for the risk induced by zone-internal components.

To characterize the risk due to the zone environment, Table 3.7 uses humidity, temperature, level of vibrations, ventilation, drainage, pressurization, and bay packing density (sum of the volume of all the bay components divided by the bay's volume).

Table 3.7: Zone-level risk score attribution based on the zone environment.

Zone Environment	**Description**	**Risk Score**
Temperature	Controlled	0
	Not Controlled	1
Pressurized	Yes	0
	No	1
Vibration	No	0
	Low	1
	High	2
Humidity	Standard Humidity Environment (environmentally controlled zone)	0
	Severe Humidity Environment (not environmentally controlled zone)	1
Ventilation	Present	0
	Not Present	1
Drainage	Present	0
	Not Present	1
Packing Density (ρ)	$0.00 < \rho < 0.10$	0
	$0.10 \leq \rho < 0.30$	1
	$0.30 \leq \rho < 1.00$	2

In addition, a score is assigned to each zone based on the susceptibility to possible risk events like lightning strikes, oxygen hazards, fire, and bird strikes, as detailed in Table 3.8.

Table 3.8: Zone-level risk score attribution based on particular risks.

Particular Risk Flag	Description	Risk Score
Lightning Strike	Zone 1A: First return stroke zone	1
	Zone 1B: First return stroke zone with long hang on	2
	Zone 1C: Transition zone for the first return stroke	1
	Zone 2A: Swept stroke zone	1
	Zone 2B: Swept stroke zone with long hang-on	2
	Zone 3: Attachment of lightning channel is unlikely	0
Susceptibility to FOD (bird strike)	No	0
	Low	1
	High	2
Oxygen Hazard: Presence of Oxygen System Components	No	0
	Yes (lines)	1
	Yes (tanks)	2
Fire zone	Non-hazard zone/Low hazard zone	0
	Ignition zone	1
	Flammable zone	2
	Flammable fluid leakage zone	1
	Designated fire zone	2

Some are scored higher than others based on the system placement constraint they might impose. For example, the flammable zone has a higher score than a flammable fluid leakage zone because the flammable zone has a normal presence of flammable fluids (e.g., fuel tank) and is considered a higher risk, imposing more constraints on system installation versus flammable fluid leakage zones.

The oxygen hazard is considered explicitly in the zone-level PRA list instead of grouping it in other fluid categories because it is not flammable. However, it is an excellent oxidizing agent, and its increased concentration can increase the flammability of other materials. Here an interaction between PRA and ZSA is considered. It is important, as particular risks impact the ZSA, and this interaction is of particular interest in early design phases. However, while performing ZSA, the focus is on one zone at a time, whereas PRA focuses on one particular risk that might impact multiple zones.

Finally, as shown in Table 3.9, the risk induced by other components in the zone on a particular component considers the presence of electrical system components, moving parts, and hazardous, pressurized, and flammable fluids.

Table 3.9: Zone-level risk score attribution based on risks induced by zone-internal components or systems.

Zone risks induced by components or systems	**Description**	**Risk score**
Fluid Leakage Susceptibility: Presence of Fluids	Non-hazardous	0
	Hazardous	1
	Non-pressurized	0
	Pressurized	1
	Non-flammable	0
	Flammable	1
Electrical system components	No	0
	Wires	1
	Machines	2
Components with moving parts	No	0
	Yes	1

Similarly, for each component, a score is provided for the component operating temperature, flammability of the material, presence of electrical devices, moving parts, flammable fluids, corrosive fluids, fluids under pressure, and operating temperature to quantify the component level intrinsic risk, as shown in Table 3.10.

Table 3.10: Component-level intrinsic risk score attribution.

Component Risks	**Description**	**Risk Score**
Fluid Leakage Susceptibility: Presence of Fluids	Non-hazardous	0
	Hazardous (Line, tank)	1,2
	Non-pressurized	0
	Pressurized (Line, tank)	1,2
	Non-flammable	0
	Flammable (Line, tank)	1,2
	No Oxygen present	0
	Oxygen present (Line, tank)	1,2
Component Operating Temperature	$T_{comp\_Op(min)}$ & $T_{comp\_Fail}/T_{zone\_Av} \leq 1$	0
	$T_{comp\_Op(min)}/T_{zone\_Av} > 1$ OR $T_{comp\_Op(max)}/T_{zone\_Av} < 1$	1
	$T_{comp\_Fail}/T_{zone\_Av} > 1$	2
Electrical system components and wiring	No	0
	Wires	1
	Machines	2
	Power$< 200W$	1
	Power$> 200W$	2
Material	Non-flammable	0
	Flammable	1
Components with moving parts	No	0
	Yes	1

Associating a high risk with a high temperature can be misleading as sometimes very low temperatures can lead to hazards. An example is low temperature, causing fluids to freeze and cause leakage. Hence, the component level temperature score depends on the installation zone's temperature. Therefore, the component-level intrinsic risk needs to be re-calculated for each proposed installation. The proposed scoring for component temperature compares minimum and maximum operating temperatures with average zone temperature. In addition, it is essential to consider the thermal risk in ZSA that accounts for the component failures, as some components might operate at low temperatures in normal operation but can induce high temperatures in case of failure.

The boundaries and scores for different risk categories have been defined after discussion with industry experts. However, they might be adapted according to the case study or future use of the method.

The risk quantification for each component in a specified zone employs an interaction matrix (Figure 3.6) to determine the overall score for each component, as installed in a zone and follows three steps. In step one of Figure 3.6, a component interaction risk score (CI_{ij}) is assigned by multiplying each component-level intrinsic risk score (CR) with the zone-level risk score (ZR) in consideration, as shown in Equation (3).

$$CI_{ij} = ZR_i * CR_j, \tag{3}$$

where i refers to the zone-level risk (ranging from 1 to n (number of zone-level risks)), and j refers to the component-level intrinsic risk (ranging from 1 to m (number of component-level intrinsic risks)).

Step two involves summing up the interaction scores for different component-level intrinsic risks to get the total component interaction score for one zone-level risk, CI_{i_tot}, as in Equation (4):

$$CI_{i\_tot} = \sum_{j=1}^{m} CI_{ij} \tag{4}$$

To enable comparison of component-level intrinsic risk scores for different components, CI_{i_tot} is normalized with the worst case CI_{i_tot} that is denoted by $CI_{i\_tot\_max}$, to calculate the component-level overall risk score (*COR*) (Equation (5)), out of 1. $CI_{i\_tot\_max}$ is calculated assuming that all the zone-level risk and component-level risk values are at the maximum (worst case scenario).

$$COR = \sum_{i=1}^{n} CI_{i\_tot}/CI_{i\_tot\_max} \tag{5}$$

Based on the value of COR, it can be categorized into low, medium, high, or very high, as shown in Table 3.11.

Table 3.11: Classification of *COR* score.

COR Range	Risk Category	Color
0.00 - 0.25	Low	
0.25 - 0.50	Medium	
0.50 - 0.75	High	
0.75 - 1.00	Very High	

The next step in the analysis is to verify the installation of the concerned component in a specific zone if the overall score is high. For example, if a component with inflammable fluids is present in a bay with many electrical lines, a high packing density, and a high-temperature and high-vibration environment, the installation would require a review to evaluate the risk of fire. Therefore, such combinations receive a high-risk score to draw the designer's attention.

To illustrate the concept and how the scoring matrix works, a test zone, called Zone XXX is analyzed (see Figure 3.7).

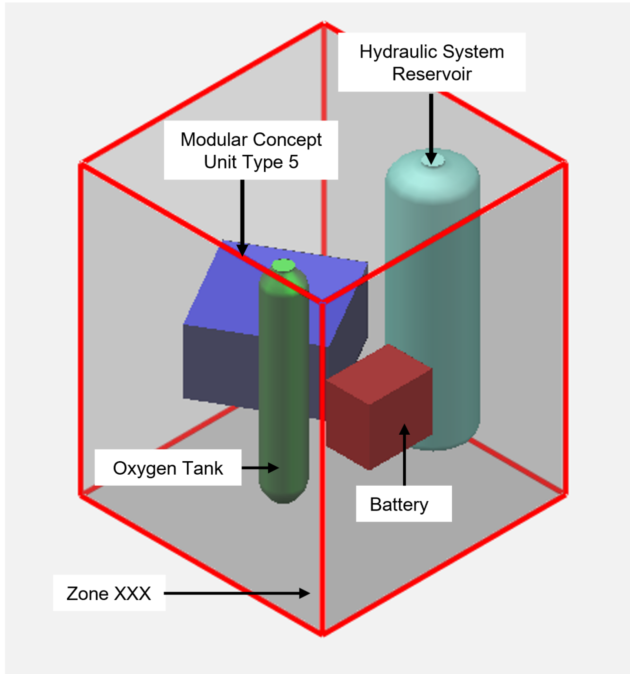


Figure 3.7: Example Zone XXX with four components.

It is assumed that Zone XXX has a pressurized, temperature-controlled, no vibration and standard humidity environment with no drainage, low susceptibility to Foreign Object Damage (FOD), unlikely attachment of lightning, and no moving parts. The zone houses an oxygen cylinder, a battery, an avionics system component (Modular Concept Unit Type 5 (600 W)), and a hydraulic system reservoir. The packing density is very high 53%.

Based on the zone description and its components, the zone-level risk scores and component-level intrinsic risk scores are assigned. This is followed by calculating the component-level overall risk score for each component as per the above-discussed approach that we call “Approach 1”, as summarized in Table 3.12

Table 3.12: Comparison of different scoring approaches for example Zone XXX in Figure 3.7.

S.No.	Component	COR			
		Approach 1	**Approach 2**	**Approach 3**	**Approach 4**
1	Hydraulic System Reservoir	0.21	0.09	0.21	0.37
2	Oxygen Tank	0.12	0.09	0.26	0.45
3	Modular Concept Unit	0.15	0.07	0.15	0.26
4	Battery	0.28	0.13	0.30	0.52

However, as per the placement considerations in the guidelines database (Table B.1), some zone-component interactions are more critical and must be avoided as much as possible. For example, in Zone XXX, from engineering judgment, the placement of an Oxygen cylinder (supporter of combustion) with high electrical power components (ignition source) and a hydraulic reservoir (containing flammable hydraulic fluid) should result in a high score for Oxygen cylinder due to inter-component interactions. On the contrary, this is not reflected in the COR calculated using "Approach 1". Therefore, when looking at all the interactions with equal importance (as per "Approach 1"), the absence of less critical interactions may shadow the presence of more critical ones. To avoid this, the critical interactions are penalized by multiplying with a user-defined value to highlight their presence for a given component in the zone.

The critical interactions are classified into three main categories:

- **High Risk**: The unacceptable interactions where no risk minimization strategy would be deemed acceptable for compliance are called high-risk interactions. For example, oxygen system components must not be placed in a designated fire zone. Therefore, whenever such an interaction is encountered, it must be heavily penalized to draw the safety assessor's attention.

- **Medium Risk**: The interactions that are not unacceptable but have a considerable impact on zonal safety. Therefore, the safety assessor must be made aware of their presence. Such interactions are termed as medium-risk interactions. For example, the placement of flammable fluid components in a zone that has equipment with high operating temperatures is a risk that can potentially become a high risk based on the physical placement and distance between the two components and thus needs further evaluation.

- **Low Risk**: The interactions where risk minimization is possible but must be highlighted for attention are low-risk interactions. For example, the presence of electrical system wiring in a low-risk lightning strike zone (Zone 2A: Swept stoke zone).

The penalization strategy for the different interactions as per the zone-component interaction matrix (Figure 3.6) is illustrated in Table C.1 in Appendix C. This revised scoring approach or "Approach 2" is applied to the example Zone XXX by multiplying the component interaction risk score (CI_{ij}) by 1.3 (30% penalty) for high-risk interactions, 1.2 (20% penalty) for medium risk interactions, and 1.1 (10% penalty) for low-risk interactions. As observed in Table 3.12, the COR score for all the components decreases as compared to "Approach 1". Penalization of both the component and worst case score is responsible for this behavior. When the worst-case scenario is penalized, it results in a very high COR because all the critical interactions are present and are penalized, thus increasing the worst-case COR. The effect of using the penalty assignment is almost nullified when the penalized worst-case scenario is used for normalization of CI_{i_tot}. Despite the overall decrease in COR, a relative change in score is observed. The oxygen cylinder has a COR equal to that of the hydraulic reservoir, which was not the case earlier. This shows that the penalty application does help in increasing the score of certain components as compared to others because of the relative criticality and number of zone-component interactions present.

To fully benefit from the interaction penalization concept, the approach is revised, and the worst-case scenario is not penalized. Hence, as per this new approach ("Approach 3"), the effect of interaction penalization is clearly reflected in the COR score for each component (as shown in Table 3.12).

When taking a closer look at the COR score calculation for the worst-case scenario, it assumes the maximum risk score value for all the zone-level risks and all the component-level intrinsic risks. Therefore, in terms of components, the worst case refers to a component with power $>$ 200 W, an operating temperature exceeding the zone ambient temperature, and hazardous, pressurized, flammable fluids, all present in it at the same time. In reality, such a component will not exist, and normalizing the CI_{i_tot} score with this worst case will again reduce the CI_{i_tot}.

To overcome this shortcoming, a realistic worst-case component is investigated. Based on the discussions with Reliability, Maintenance, and Safety (RM&S) specialists from the industry, the electrical fuel pump is selected to represent the worst-case component as it requires more than 200 W of power, has rotating mechanical parts, and is in contact with flammable fluids. Though they are built such that power electronics and fuel are separated, yet, it all resides in a single component. There is a risk of high-pressure fluid leakage or burst, component or fluid overheating, and high-energy debris. Therefore, they could be considered as a very high intrinsic risk component. The COR for the Zone XXX example is recalculated using the new worst-case component, and the scores are listed in Table 3.12 in the "Approach 4" column.

"Approach 4" helps in clearly identifying the risks associated with each component placed in Zone XXX. It shows a medium risk for the hydraulic system reservoir because it is placed in a zone with Oxygen system components (Oxygen cylinder), electrical components (battery and modular concept unit), and no drainage. Similarly, the modular concept unit also has medium risk as it is a high-power component which, in case of failure, can act as an ignition source in the high-density zone with an Oxygen cylinder, hydraulic system reservoir, and battery (sensitive to high-temperature environments). The oxygen cylinder has the second highest COR (0.45), which is closer to the high-risk lower limit, thus reflecting the expected behavior that was missing in "Approach 1". Battery, on the other hand, has a risk of overheating and thermal runaway, and in a densely packed zone with Oxygen, hydraulic, and other electrical components can be problematic. Therefore, a high COR helps in flagging the battery placement in Zone XXX.

Henceforth, "Approach 4" is adopted for quantifying the component-zone interactions in CZSA.

Moreover, the need to quantify the overall zone risk arises to facilitate the comparison of different zones based on the risk level of its components. Unlike the approach proposed by Chiesa et al., which considers all the components present, an approach based on COR and captures the risk due to critical interactions is proposed. A zone overall risk "*ZOR*" metric calculated using Equation (6) is proposed to quantify the zone risk.

$$ZOR = \sum_{e} COR/N_e, \tag{6}$$

where e corresponds to the components in the maximum risk category. *ZOR* is the average of the *COR* of the components that lie in the maximum risk category of that specific zone. For example, if a zone contains five components and performing the zone-component interaction analysis results in two components with low-risk scores, one with medium, and the remaining two with high-risk scores, then the *ZOR* is calculated by taking the average of the *COR* scores of the high-risk components. Alternatively, if there were two low-risk and three medium-risk components, then the *ZOR* is equal to the average of the *COR* scores of medium-risk components.

3.3 Conceptual-level Particular Risk Analysis

The right side of Figure 3.2 presents the process for the CPRA. The parametric CAD model is also used to perform CPRA. As stated earlier, particular risks may affect multiple systems and zones; therefore, analyzing their impact at the aircraft level is essential. It is important to note that the analysis approach to particular risks varies depending on how they impact the aircraft. Table 3.13 provides an overview of the categorization of different particular risks and how they are proposed to be addressed at the conceptual level.

Effective use of the limited information available and wise application of engineering judgment and experience can give valuable safety insights from a system placement perspective. As discussed in Section 3.2 some particular risks are addressed as part of CZSA and therefore are not discussed in this section.

For some particular risks posed by the aircraft components themselves (internal hazards), a 3D risk zone modelling approach is adopted (Figure 3.8). This is because multiple reasons can cause them, thus making them difficult to capture and predict using other failure analysis methods. For example, uncontained engine rotor failure (or rotor burst) is caused by structural failure of the rotor that can, in turn, be caused by overspeeding, weakness of the rotor, or a combination of both. Therefore, the ACs propose risk zone models (also referred to as impact or threat zone models) for these particular risks. A risk zone encompasses all possible trajectories of the failed component debris.

Table 3.13: Classification of particular risks.

Risk type	**Particular risk**	**Reference**	**CPRA**
Trajectory based (Internal hazard)	Uncontained Engine Rotor Failure	AC 20-128A [4]	Three-dimensional model of the risk zone
	APU rotor failure	AC 20-128A [4]	Three-dimensional model of the risk zone
	Pressure vessel/duct rupture	Part 25.1435 [72]	Not addressed
	Propeller/RAT release	Part 25.905 [73]	Three-dimensional model of the risk zone
	Wheel and tire burst	AMC 25.734 [5]	three-dimensional model of the risk zone
External hazards:involves testing or simulation; addressed by qualification.	Bird strike	Part 25.631 [74]	Addressed in CZSA
	Hail, ice, snow	AC 20-73A [75]	Not addressed
	Lightning strike	ARP 5414B [40]	Addressed in CZSA
Partly addressed by equipment qualification + Other constraints specific to the requirement.	Fire and explosion	Part 25.1181 [61], 25.1207 [76], 25.863 [77], AC 25.869-1A [78], AC 25.981-1C [79]	Addressed in CZSA
Addressed by qualification	Fluid leakage	Part 25.863 [77]	Addressed in CZSA
Addressed by qualification	Sustained engine imbalance	AC 25-24 [80]	Not addressed
Addressed by equipment qualification	High-Intensity Radiated Fields	Part 25.1317 [81], AC 20-158A [82]	Not addressed

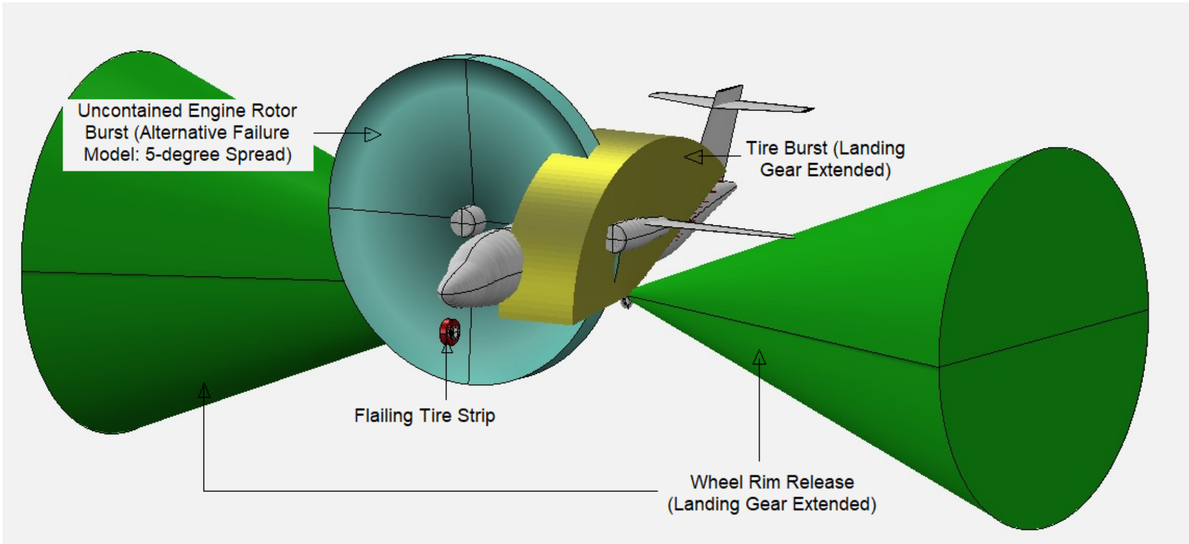


Figure 3.8: Trajectory-based PRA threat envelope modelling in OpenVSP.

A standard definition of these risk zones or threat envelopes is provided by the ACs based on tests and statistical data from past failures and incidents. Since the focus is on mapping the debris trajectories, the assessment of such particular risks is called trajectory-based PRAs. In practice, the analysis of trajectory-based particular risks involves 3D plotting each trajectory based on debris fragment characteristics and assessing the impact on overall aircraft safety due to the presumed loss of system components that it strikes.

This rigorous assessment requires a detailed system and routing definition in the aircraft 3D model that is not available in the early design stages. Therefore, plotting each trajectory is not as useful and feasible at the conceptual design stage. Instead, modelling of 3D risk zones that give an overview of the debris spread is suggested.

Sub-section 3.3.1 summarises the definition of the threat zone envelopes for different particular risk zones based on the guidance from ACs and AMCs. As a part of the implementation of CPRA, the parametric 3D modelling of risk zones and detection of system components present in that zone is elaborated in Section 3.4.

It is suggested to perform the CPRA twice: pre- and post-placement of the systems. A pre-placement CPRA includes modelling risk zones like rotor burst and tire burst zone and feeding to aid the designer in deciding the initial placement of critical systems with respect to these zones. A system component is considered to be "critical" [4] if the loss of single or multiple system components (redundant or non-redundant) can result in the loss of an essential aircraft function and prevent continued safe flight and landing.

In a post-placement CPRA, the risk zones are modelled and the list of components in these zones is output. Using this information and knowledge about the criticality of the component (based on FHA, FMEA, and Damage Mode Effect Analysis (DMEA)- if available), the designer can decide whether to relocate, reorient, duplicate, or shield the component from the damage.

Particular risks like sustained engine imbalance involve cross-functional assessments and can only be addressed by component qualification. Therefore, it is assumed that the equipment will be qualified to minimize the associated risk and hence are not addressed in CPRA.

3.3.1 Trajectory-based PRA Models

Uncontained Engine Rotor Failure

UERF refers to the failure that could result in a hazard due to rotor (rotating components like blades, disks, impellers) fragments with sufficient energy released from the engine or APU. The risk posed by uncontained rotor burst[1] events in the past has been well studied and documented. The analysis of this particular risk is essential owing to the critical safety events that may follow if the infinite energy debris pierces through critical aircraft systems. The AC 20-128A [4] outlines the steps to model UERF threat zones to assess specific risks imposed by this event. It specifies different fragment models based on fragment size (Table 3.14) and defines the respective spread angle (angle initiating at the centerline of the engine or APU shaft measured fore and aft from the center of the rotor's plane of rotation) for modelling the risk zone (Figure A.1), also known as rotor burst cones for different rotor stages or groups of rotor stages (using the diameter of the largest rotor stage). The fragment models also specify the maximum dimension of the fragment, the distance of the fragment sector centroid from the rotor axis (Figure A.2), and fragment mass for trajectory-level analysis (Figure A.3) that is typically performed at later design stages. The AC 20-128A also establishes an acceptable risk level for each fragment model, which refers to the

[1] Rotor burst zone, risk zone, and threat zone are the terms used interchangeably to refer to the impact area for UERF.

probability of catastrophic damage resulting due to fragment release and is used while performing the trajectory-level analysis.

Table 3.14: UERF fragment models [4].

Fragment Model	**Maximum Dimension**	**Distance to C.G.**	**Spread Angle**	**Mass**	**Acceptable Risk Level**
Single One-Third Disc Fragment (Figure A.4)	$2 * \sin 120 * (R + b/3)$	(R+b/3)/2	±3°	$1/3*$Bladed disc mass	1/20
Intermediate Fragment (Figure A.5)	$1/3*(R+b)$	R	±5°	$1/30*$Bladed disc mass	1/40
Alternative Engine Failure Model (Figure A.4)	$2 * \sin 120 * (R + b/3)$	$(R + b/3)/2$	±5°	$1/3*$Disc mass	1/20
Small Fragments	$1/2*$Blade tip length	$3/4*$Blade tip length	±15°	$1/2*$Blade mass	-
Fan Blade Fragments (Figure A.6)	$1/3*$Fan blade airfoil height		±15°	$1/3*$Fan blade mass	-
Note: R= Disc radius, b=Blade length					

Tire and Wheel Failure

Part 25.729 (f) (1 & 2) [83] requires protecting equipment essential for safe flight in the wheel wells and landing gear from tire and wheel failure threats. ARP 4752B [60] and ARP 994B [84] recommend considering the effect of tire burst, flailing tire strip, and wheel rim release for hydraulic system components and tubing installation. Hence, it is essential to define the impact area for different tire and wheel failures.

The European Aviation Safety Agency prescribes AMC 25.734 [5] to define the threat models for protection against wheel and tire failures in extended and retracted landing gear positions. In addition, these threat models also ensure damage protection from foreign objects projected from the runway. Table 3.15 summarizes the threat models for the failure scenarios defined in AMC 25.734 [5].

Table 3.15: Tire and wheel failure threat models extracted from reference [5].

Model	**Threat model name**	**Landing gear position**	**Debris size**	**Zone of vulnerability**
Model 1	Tire Debris Threat	Extended	Large: $W_{SG} * W_{SG}$	±15° spread projected in the wheel plane: 45° to 180° from ground horizontal plane (rearward direction). Assume that both tires installed on the same axle (companion tires) fail simultaneously.
			Small: $0.5W_{SG}$ $*$ $0.5W_{SG}$ or 1.5% of the total tread area	±30° spread projected in the wheel plane: 45° to 180° from ground horizontal plane (rearward direction)
Model 2	Wheel Flange Debris Threat	Extended	60° arc segment of the wheel flange	Release: lateral to the flange segment + 20° spread at the edges; Model 1 covers the vertically released debris
Model 3E	Flailing Tire Strip Threat Model	Extended	Flailing tire strip (Length: 2.5* W_{SG}, Width= $W_{SG}/2$, Thickness= thickness of tire tread and carcass)	30°
Model 3R	Flailing Tire Strip Threat Model	Retracting or retracted	Flailing tire strip (Length: 2.5 *W_{SG}, Width= $W_{SG}/2$, Thickness= thickness of tire tread and carcass)	30°
Model 4	Tire Burst Pressure Effect Threat	Retracting or retracted	No debris: Gas jet ('blast effect')	18° cone axis rotated over the tread surface of the tire ±100°
				30° wedge axis rotated over the tread surface of the tire ±90°
Note: W_{SG}= Tire and Rim Association Maximum Growth Shoulder Width				

Propeller and Ram Air Turbine Blade Release

For propeller blade release, the impact zone definition is provided by the AC 25.905-1 [85] as the "the region between the surfaces created by lines passing through the center of the propeller hub, making angles of ±5 degrees forward and aft of the plane of rotation of each propeller.".

It also advises that the impact zone definition could vary for novel propeller designs (like unducted fans), and the manufacturer must be consulted for defining the risk zone.

Release of the RAT blade should also be considered as per Part [86]. The impact zone definition for RAT blade release is the same as for propeller blade release.

3.3.2 Parameters for Threat Zone Modelling

The threat zone envelopes for different trajectory-based particular risks discussed in sub-section 3.3.1 can be used to define the parameters for modelling these zones and perform quick and repeatable analysis to guide the placement of components with respect to the risk zone and check if the components are in the threat zone for a given system placement. Table 3.16 enlists the parameters required for modelling different particular risk zone models covered in CPRA.

Table 3.16: Parameters for CPRA risk zone modelling.

S. No.	CPRA Risk Zone Model	Level	Parameter(s)
1	Propeller blade release	0	Propeller location
2	RAT blade release	0	RAT location
3	UERF	1	Engine location, first and last turbine stage location
4	UERF	2	Engine location, stage location, disc radius, and blade length
5	Tire burst (Model 1)	1	Wheel radius and location
6	Wheel Rim Release (Model 2)	2	Wheel rim diameter and wheel location
7	Flailing Tire Strip (Model 3E & 3R)	1	Wheel radius, location and width

The models are classified into different levels in line with the geometric granularity levels formalized in 3.1.1 based on available structural and system-level information.

3.4 Implementation and Validation

The CZSA and CPRA methods in the ASSESS framework are embodied as a Python-based tool that interfaces with OpenVSP [54], an open-source aircraft modelling software, and CPACS [49] interface format for storing aircraft geometry, system architecture, and system placement information. In principle, the methodology developed in the preceding sections can be implemented using any CAD software and interfacing means. However, in this thesis, OpenVSP is used as it is open-source and has a Python API, which facilitates automation. CPACS is used because this work is a part of the AGILE 4.0 NextGen-MDAO project, which uses CPACS to interface between tools from different disciplines and organizations. Figure 3.9 illustrates the implementation approach for CZSA and CPRA.

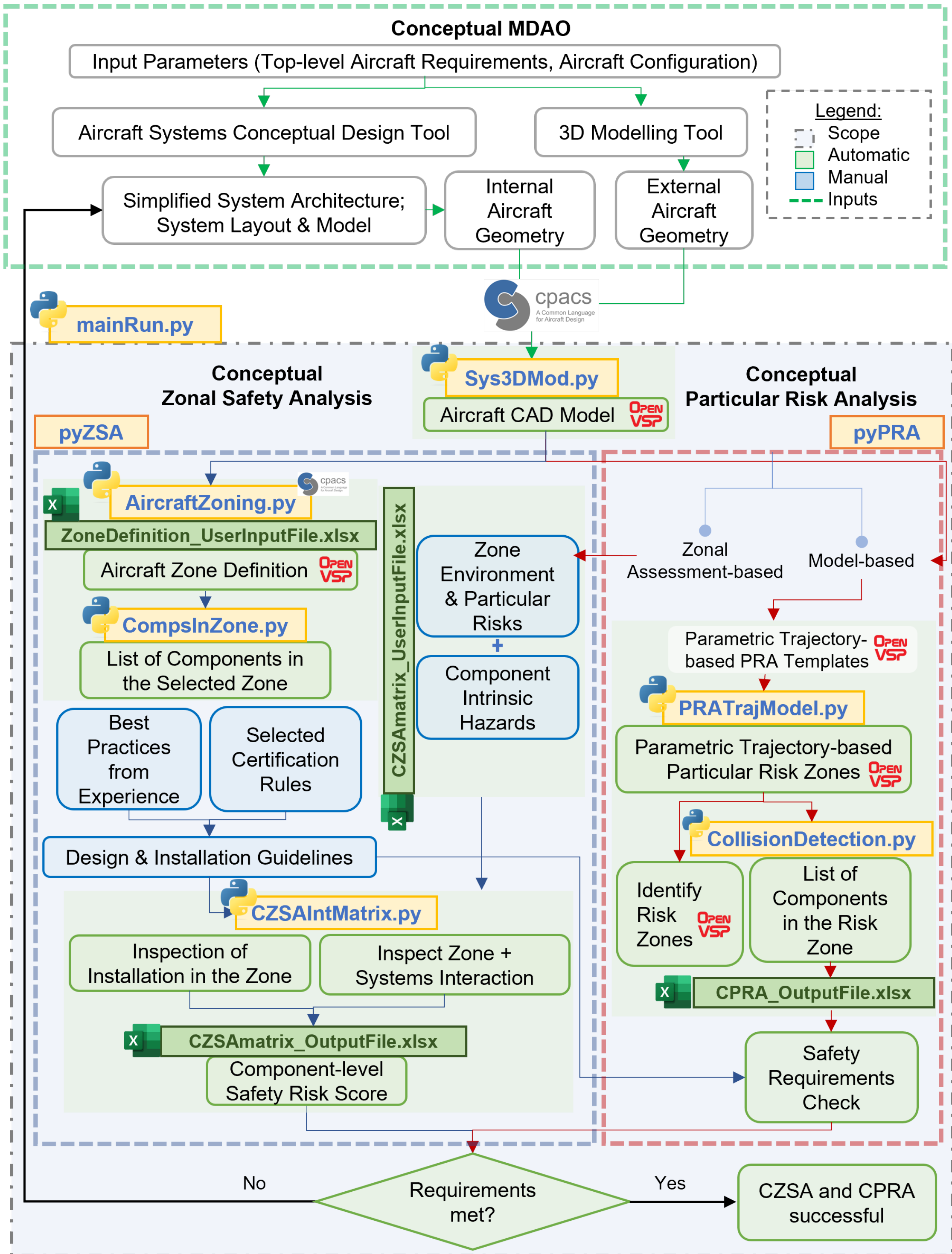


Figure 3.9: CZSA and CPRA methodology implementation using Python, OpenVSP, and interaction with CPACS and Excel.

As shown in Figure 3.9, the aircraft 3D model is an input to perform CZSA and CPRA. If the 3D model is not available, then the tool can automatically generate it in OpenVSP by reading the aircraft geometry and system parameters from the input CPACS file using "`Sys3DMod.py`" script.

3.4.1 Conceptual-level Zonal Safety Analysis

To execute CZSA, the following Python scripts are packaged into a module called ***pyZSA***:

- `Sys3DMod.py`: It has functions for reading the aircraft information from the CPACS file and modelling the aircraft in OpenVSP.
- `AircraftZoning.py`: It contains the functions to divide the aircraft three-dimensional model obtained either using `Sys3DMod.py` or an OpenVSP model (`.vsp3` file) into major zones as per ATA 100 specification and divide major zones into major sub-zones based on user input in the `ZoneDefinition_UserInputFile.xlsx`. It also writes the zone information to CPACS under <pySysZone> XML element.
- `CZSAIntMatrix.py`: For the automatic computation of COR, based on user input zone-level risk and component-level intrinsic risk scores. It reads the user inputs from the `CZSAMatrix_UserInputFile.xlsx` and writes the analysis results to `CZSAMatrix_OutputFile.xlsx`. The zone component interactions captured in the `CZSAIntMatrix.py` are informed by the best practices database, engineering knowledge, and experience.
- Other supporting scripts: `GetLength.py` and `CompsInZone.py`.

Similarly, the Python scripts for execution of CPRA are packaged into a module called ***pyPRA*** as follows:

- `PRATrajModel.py`: It has different functions to model different trajectory-based particular risks parametrically.
- `CollisionDetection.py`: It is used to detect the components in the risk zone using the Delaunay triangulation algorithm.

A run file, `mainRun.py`, acts as a user interface and performs the CZSA and CPRA based on user selection.

If the user selects the option to perform CZSA, it follows a step-by-step approach as per the CZSA methodology (Figure 3.2) and calls the respective functions from the ***pyZSA*** module. The CZSA uses a python script `AircraftZoning.py` to divide the aircraft three-dimensional model into major zones and major sub-zones. For major zones definition as per Table 3.4, the Python script first reads the information about the location of major structural delimiters such as the aft pressure bulkhead, skin, and floor for the lower fuselage, and then accordingly divides the aircraft volume into major zones as shown in Figure 3.10. The major zone information is then written to the CPACS file within the <pySysZone> element using the standard XML elements prescribed by S1000D standard (Figure 3.4).

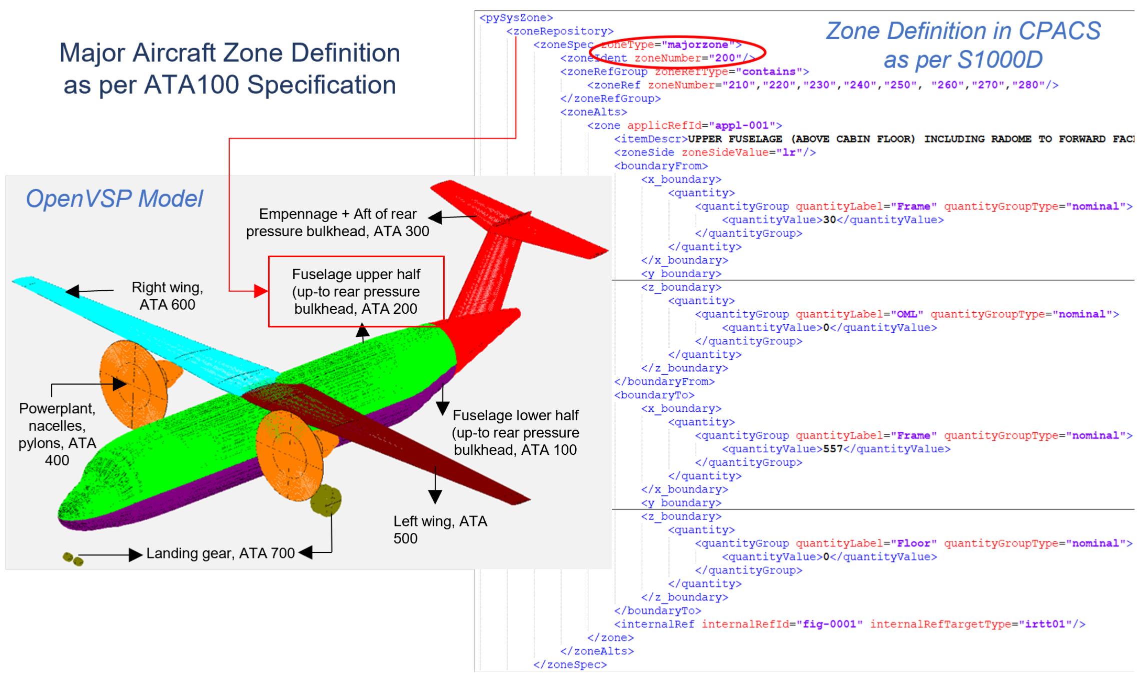


Figure 3.10: Aircraft major zone definition in OpenVSP and zone description in CPACS using ASSESS-L1-M2.

Alternatively, the information about the location of major zone boundaries can also be taken as user input using the Python script if a CPACS file for the aircraft under consideration is not available. As illustrated in Figure 3.11, the aircraft zone definition code used the zone boundary information in the CPACS file available for AGILE 4.0 application case 3 aircraft and Dornier 228 and used user input (aft pressure bulkhead and floor location) for Boeing 777 and Falcon 5X to define major zones. Also, the major zones for an unconventional aircraft- a fictitious blended wing body concept are defined using the same approach, assuming that such designs would also have major structural partitions like the aft pressure bulkhead and floor for fuselage zoning and that aircraft parts such as the wing (or major lift producing surface protrusion), landing gear, power plant, and stabilizers would be easily distinguishable.

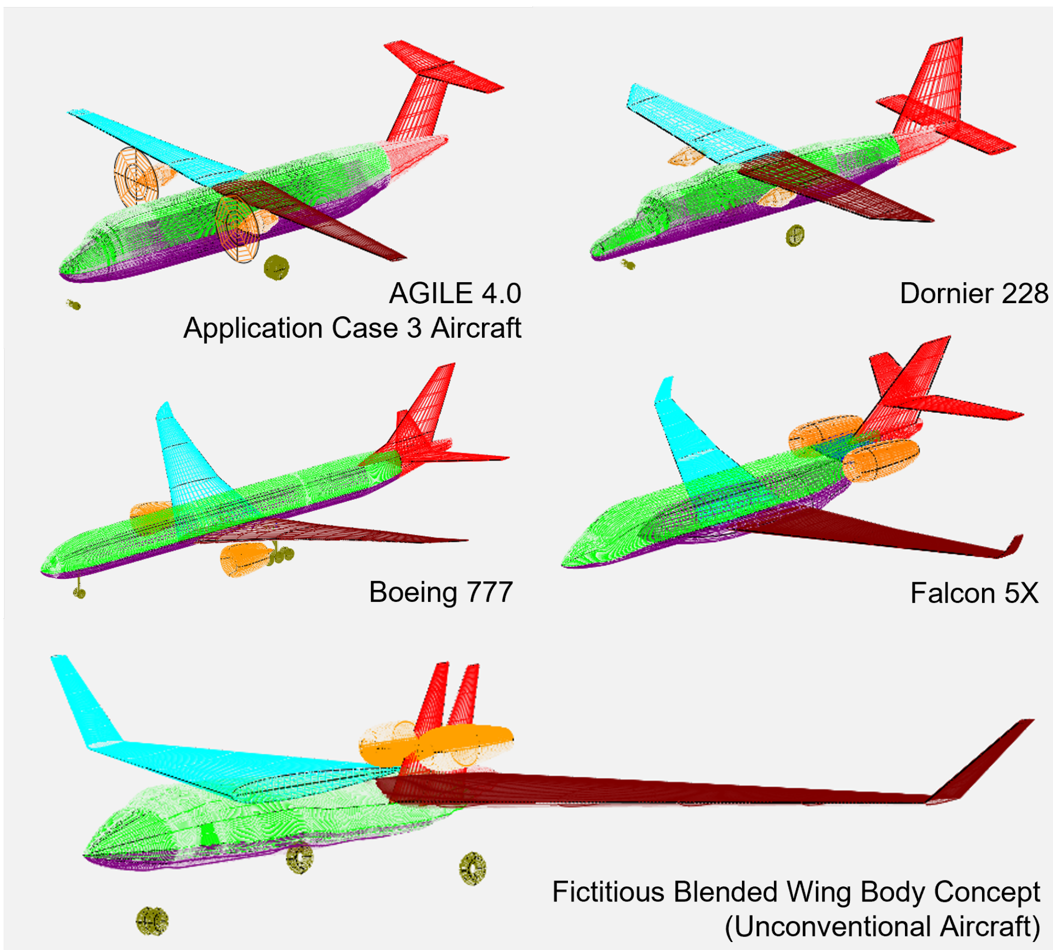
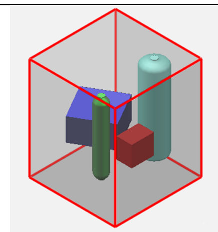
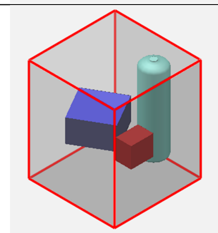
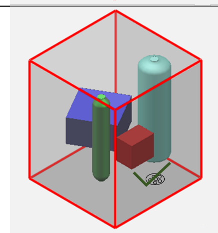
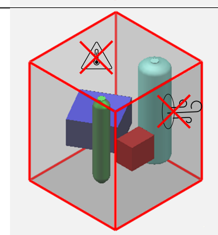
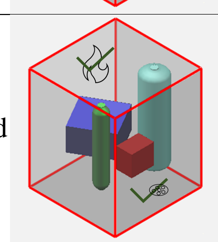
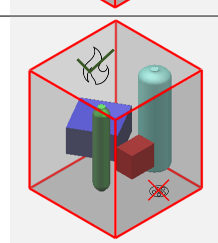
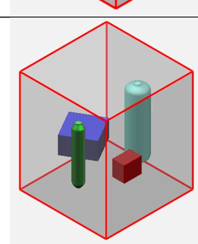


Figure 3.11: Aircraft major zone definition for different aircraft in OpenVSP.

After the major zone and major sub-zone definition, the `mainRun.py` script prompts the user to select a zone for zone-component interaction analysis (using `CZSAIntMatrix.py`). The advantage of this semi-automated approach is that the user can try different component placement options and adjust the zone properties to perform an early high-level check of the requirements from the guidelines database and identify high-risk combinations. For example, consider Zone XXX with the characteristics and components as assumed earlier (Sub-section 3.2.3). Table 3.17 shows how the CZSA tool provides an overview of the component placement risks for different zone-component combinations.

Another interesting aspect of the zone component interaction analysis based on the best practices database is reflected in case 5, where drainage is added to Zone XXX, but instead of being an ignition zone, it is assumed to be a designated fire zone. In this case, the requirements from Part 25.581 [87] and ARP 5021B [88] are violated, as per which the hydraulic system reservoir and the oxygen cylinder must not be in a designated fire zone. Therefore, to highlight this noncompliance, the tool assigns the highest risk score (=1) to the hydraulic system reservoir and the oxygen cylinder. The user is also made aware of the problem with such a placement by printing the requirement not met in the Python console. Similarly, in case 6, when drainage is also removed from the designated fire zone, then the zone fails to satisfy the Part 25.1187 [89] requirement that emphasizes complete drainage to prevent the accumulation of flammable fluids in a designated fire zone. Hence, to disqualify such a placement, all the components are assigned a score of 1. Case 7 shows an example of the effect of low packing density on the components, which receive a low *COR* compared to the baseline.

Table 3.17: COR score sensitivity case study for Zone XXX.

S. No.	Description	Component	COR	ZOR
1	Zone XXX: Baseline 	Hydraulic system reservoir	0.37	0.52
		Oxygen cylinder	0.45	
		Modular concept unit	0.26	
		Battery	0.52	
2	Zone XXX: No Oxygen Tank 	Hydraulic system reservoir	0.30	0.36
		Oxygen cylinder	-	
		Modular concept unit	0.22	
		Battery	0.42	
3	Zone XXX: Drainage present 	Hydraulic system reservoir	0.33	0.44
		Oxygen cylinder	0.41	
		Modular concept unit	0.24	
		Battery	0.47	
4	Zone XXX: No ventilation and temperature not controlled 	Hydraulic system reservoir	0.43	0.62
		Oxygen cylinder	0.64	
		Modular concept unit	0.30	
		Battery	0.60	
5	Zone XXX: Drainage present but designated fire zone 	Hydraulic system reservoir	1.00	1.00
		Oxygen cylinder	1.00	
		Modular concept unit	0.26	
		Battery	0.50	
6	Zone XXX: No Drainage present and designated fire zone 	Hydraulic system reservoir	1.00	1.00
		Oxygen cylinder	1.00	
		Modular concept unit	1.00	
		Battery	1.00	
7	Zone XXX: Low packing density 	Hydraulic system reservoir	0.30	0.36
		Oxygen cylinder	0.37	
		Modular concept unit	0.22	
		Battery	0.40	

3.4.2 Conceptual-level Particular Risk Analysis

When the option to perform CPRA is selected, the run file, `mainRun.py`, asks the user to select the trajectory-based particular risk and fragment model. It then calls the respective functions from the ***pyPRA*** module to perform the CPRA.

For conceptual level and early design studies, the UERF analysis is restricted to rotor burst zone modelling only. The rotor burst cone models have been implemented in OpenVSP for ±3°, ±5°, and ±15° fragment spread angles (Figure 3.12). To perform the UERF analysis, the user can import each model using the associated Python function and must specify the plane location and orientation of the rotor stage.

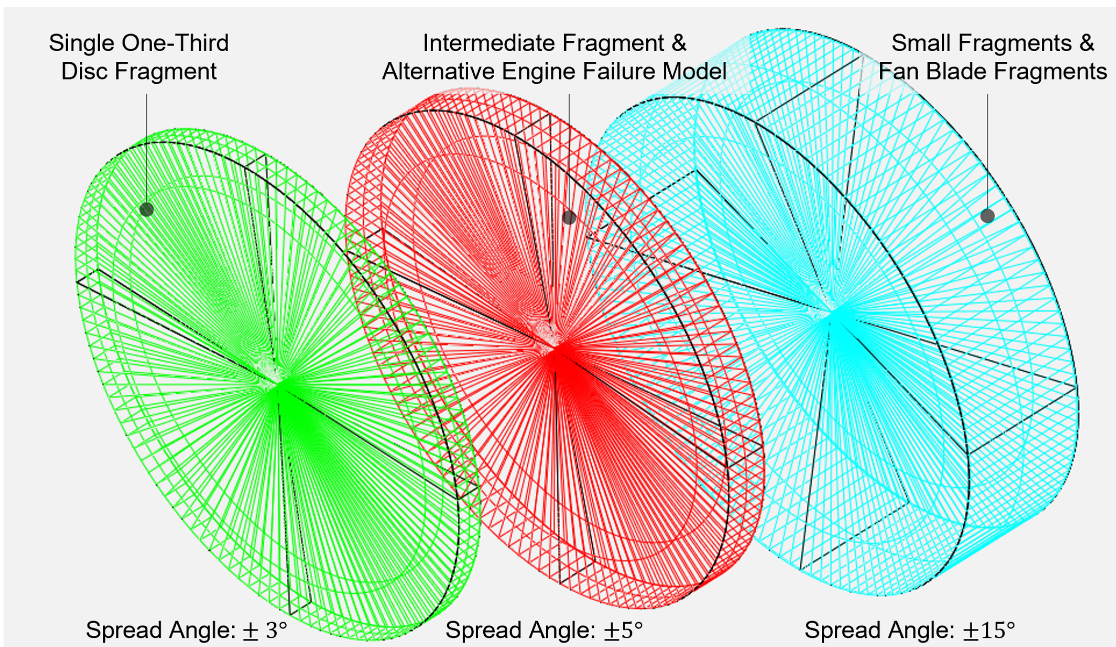


Figure 3.12: UERF parametric models for different fragment spread angles in OpenVSP.

Figure 3.13, shows the difference between UERF level 1 and level 2 parametric modelling in OpenVSP. Level 1 model just requires the engine and rotor stage location as input, while level 2 modelling, in addition, takes disc radius and blade length as input for the specified stage. Using the blade length and disc radius, the *UERF_L2* function in `PRATrajModel.py` calculates the diameter of the fragment centroid locus circle for the specified fragment model (Table 3.14 and models the rotor burst zone as shown in Figure 3.13). The risk zone region changes as instead of modelling the spread from the rotor center, the fragment centroid locus is used.

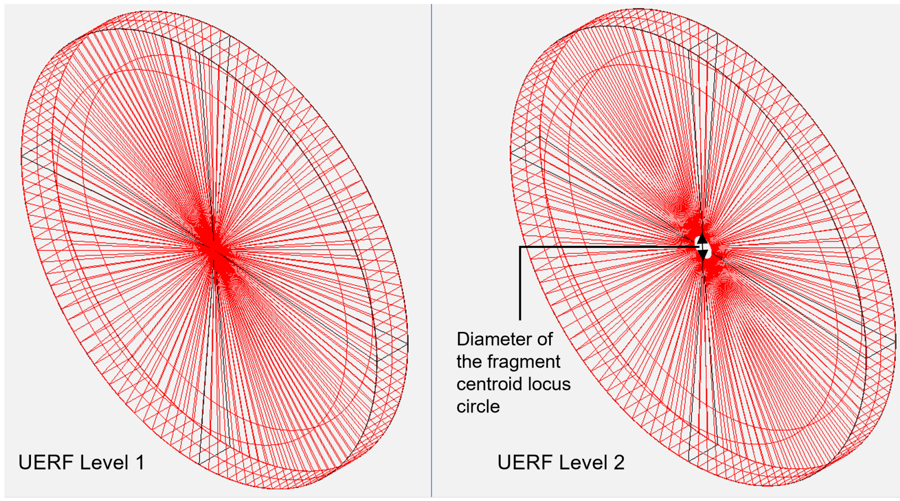


Figure 3.13: Difference between UERF level 1 and 2 parametric models.

An example where UERF level 1 modelling can be useful is fuel tank boundary demarcation and dry bay sizing. Fuel tanks must be sized and located to prevent leakage due to damage from high energy rotor debris [4]. Hence, as shown in Figure 3.14, an early modelling of the rotor burst zone helps to locate and size the dry bay and fuel tanks. Alternatively, it could also be used to decide upon the placement of the engines to minimize the wing impact area.

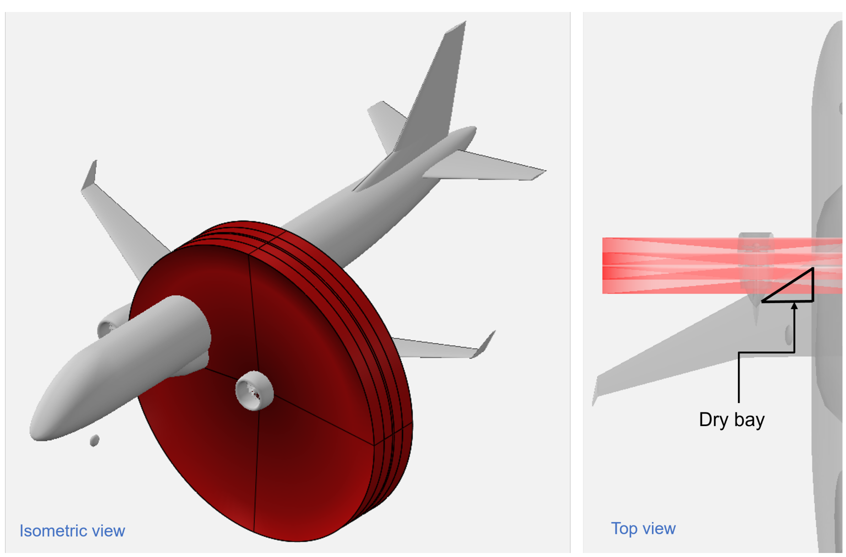


Figure 3.14: UERF level 1 risk zone modelling for sizing of dry bays.

For propeller and RAT blade release, the parametric ±5° spread rotor burst cone can be used.

Similarly, RAT blade release modelling as shown in Figure 3.15, aids in deciding the RAT placement, such that the blade release impact region does not encompass the front pressure bulkhead, or affect the flight deck aft of the bulkhead. From this perspective, placement options 1 and 2 (Figure 3.15) are disqualified because in case 1, the pressure bulkhead is impacted, and in case 2, the pressurized fuselage will be affected. Case 3 seems to be an acceptable placement, however due to the possible impact on the avionics equipment, shielding or duplication of critical components may be required.

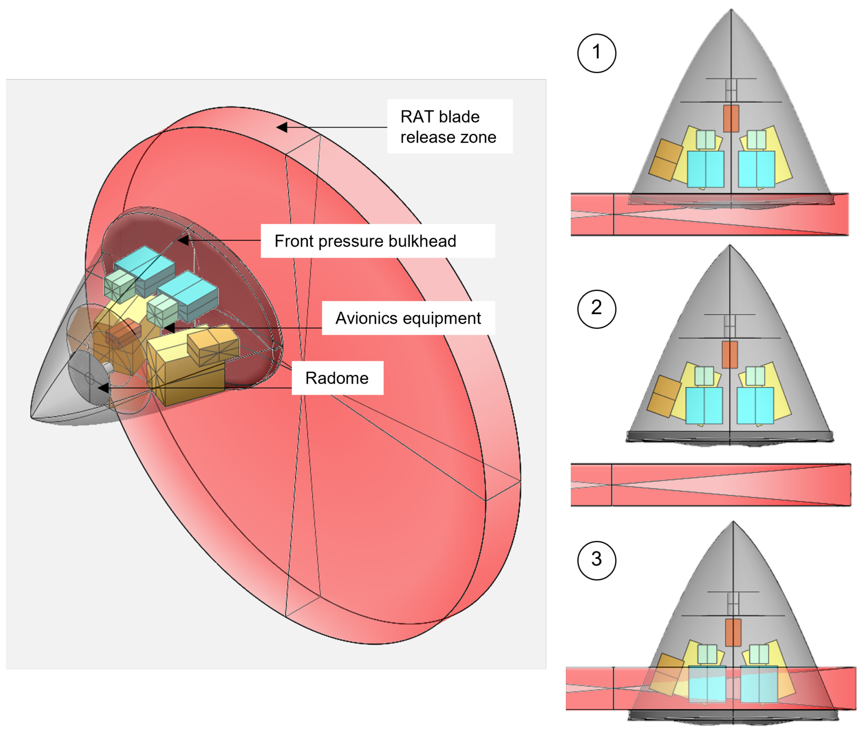


Figure 3.15: Ram air turbine blade release placement consideration.

Modelling of RAT blade release can be performed at any level starting from 1. However, modelling the risk zone with a more refined system definition helps in assessing if it impacts critical avionics components in the nose cone.

Performing the RAT blade release CPRA is only one aspect to be considered for RAT placement. In addition, constraints from other disciplines, like aerodynamics and structures, must also be considered.

To perform the tire burst (Figure 3.16), wheel rim/flange release (Figure 3.17), and flailing tire strip analysis, the user can import the required model using the associated Python function in `PRATrajModel.py`, which uses the tire location, grown tire diameter (D), maximum growth shoulder width (W_{SG}), and rim diameter (d).

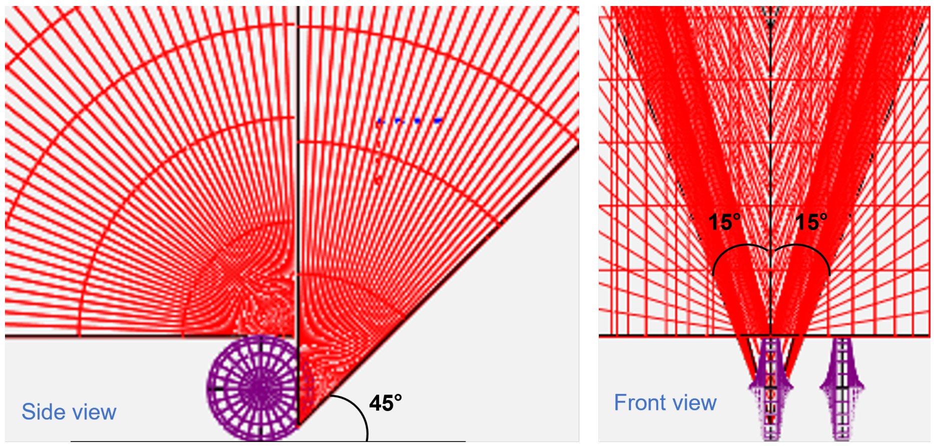


Figure 3.16: Model 1: Tire debris threat for extended landing gear (Large debris size).

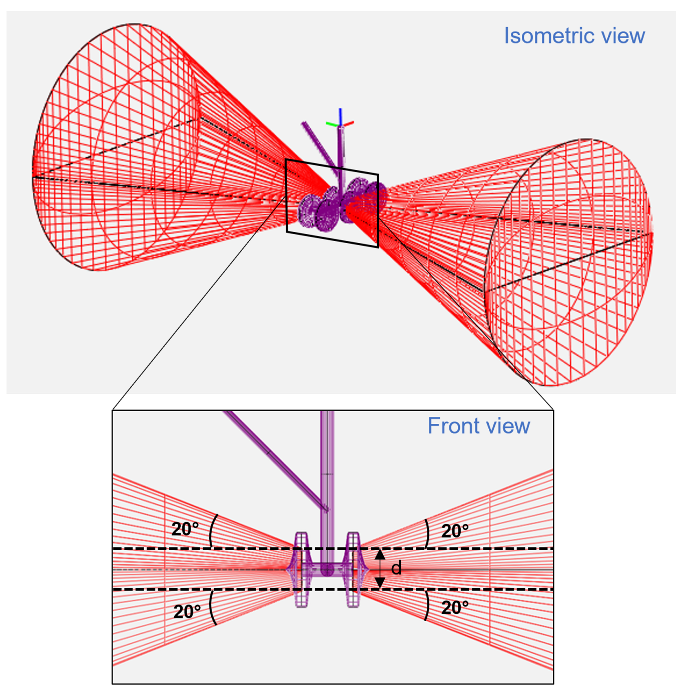


Figure 3.17: Model 2: Wheel flange debris threat.

Performing tire and wheel failure CPRAs early in design helps preclude major design revisions that may arise later. For instance, quick visualization of the main landing gear wheel rim release (debris assumed to have infinite energy) threat zone, as shown in Figure 3.18, helps check if there is a risk of the rim fragments puncturing the pressurized fuselage cabin.

Figure 3.18: Modelling of wheel flange debris threat for landing gear extended (Model 2) for the left wheel of a generic business aircraft.

Figure 3.19 shows the wheel rim release threat zones for both the right and left main landing gear wheels of a generic business aircraft.

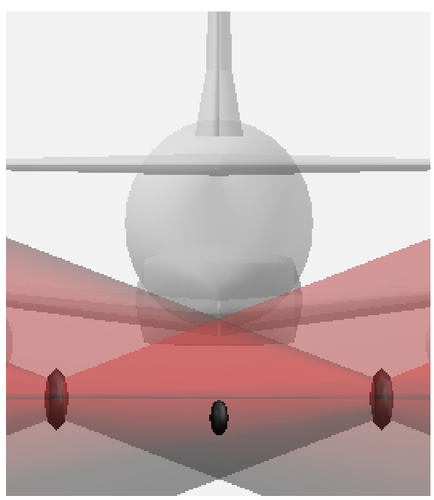


Figure 3.19: Assessing the effect of left and right wheel rim release on the fuselage.

The pressurized cabin is clear of the risk zone. However, if early analysis shows the opposite for a configuration, the gear position, height, and ground clearance might need to be reevaluated. It will impact other design disciplines, but the correction will be very difficult if such a problem is identified late.

In addition, considering the impact on the wing (Figure 3.20) for fuel tank positioning, control requirements due to affected control surfaces, hydraulic system routing, and wing anti-ice ducting separation are other valuable insights given by threat zone modelling.

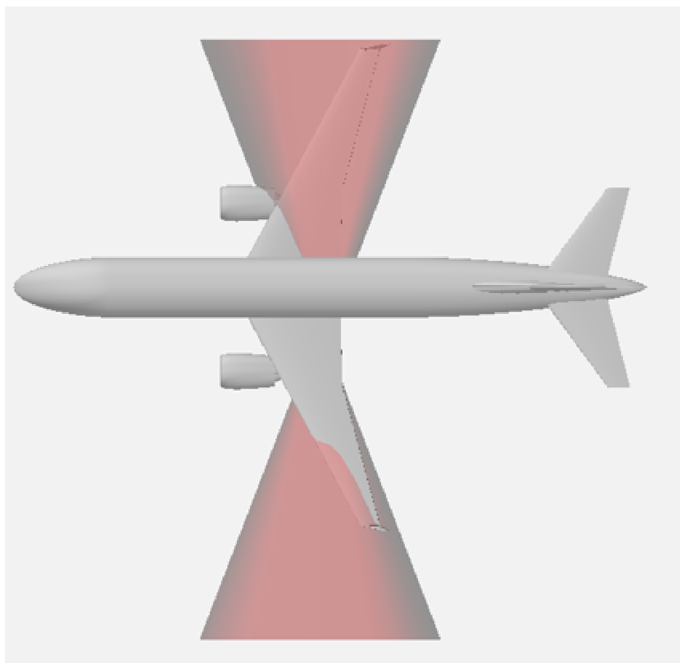


Figure 3.20: Assessing the effect of left wheel rim release on the onside and opposite wing.

Chapter 4

Analysis and Application

The methodology for CZSA and CPRA established in Chapter 3 enables semi-automated, early analysis of aircraft designs with different configurations and system technologies. It facilitates the conceptual design process by adding a dimension of safety from a system placement perspective and supporting the following applications:

- Rapid comparison of different system component layouts
- Early recognition of risks associated with unconventional aircraft configurations
- CZSA and CPRA adaption with evolving detail of aircraft and system geometry
- Assessment of novel system technologies (MEA and AEA) adoption impact on zonal safety

This chapter demonstrates the tool's capability by presenting four application cases. Firstly, the recreation of ZSA and PRA examples from the ARP 4761 at the conceptual level are performed. Secondly, the rapid comparison of different system installation options is demonstrated by analyzing the impact of propeller blade release on hydrogen tank placement. It is followed by a case study to illustrate the handling of different levels of system detail. Finally, a case that compares the safety characteristics of conventional and more electric systems for the same zone is presented.

4.1 Holistic Mapping of CZSA and CPRA Risks

To illustrate the capability of the proposed method, the main landing gear bay CZSA and tire burst CPRA case studies adapted from the ARP 4761 [15] S18 aircraft example are performed. The S18 is a fictitious two-engine conventional aircraft concept that can carry 300 to 350 passengers up to 5000 nautical miles at 0.84 Mach and has an average flight duration of 5 hours [15]. The specifications of the S18 aircraft closely match the Boeing 777; therefore, this case uses the Boeing 777 model from the OpenVSP hangar [54] for the case study. It is important to note that the tool can automatically generate the 3D model of the aircraft in OpenVSP from the data stored in the input CPACS file, but for this case, a CPACS file was not available.

4.1.1 Zone-component Interaction Study for Main Landing Gear Bay

The main landing gear bay is a complex unpressurized zone that hosts the green hydraulic system components, main landing gear, and other systems that can affect the wheel braking and thrust reversers. Therefore, the designer must take the necessary design precautions to prevent catastrophic failure conditions and minimize the risk associated with the design and installation.

This section presents the CZSA study performed on the main landing gear bay to help the designer verify the system placement with minimal available inputs. The main landing gear bay is a subzone (Major sub-zone 160: Figure 4.1) in the lower fuselage (Major zone 100).

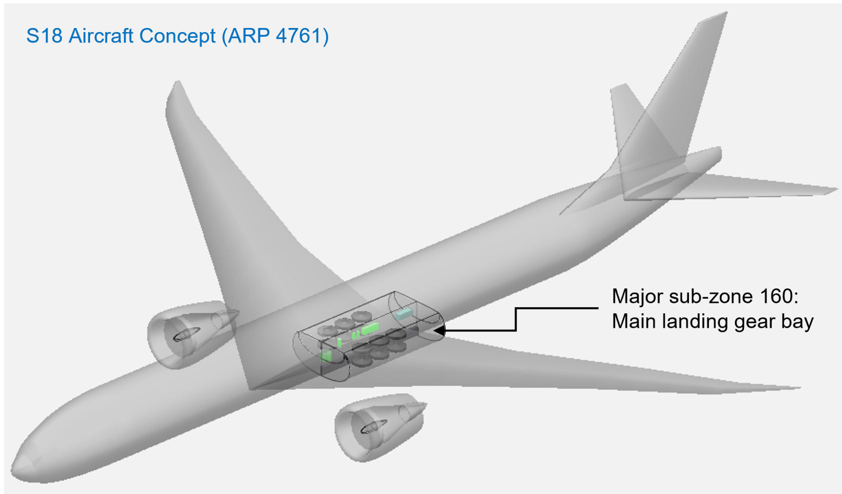


Figure 4.1: S18 aircraft model with the main landing gear bay (Major sub-zone 160) in OpenVSP.

As per the ARP 4761 description, the zone boundaries (Table 4.1) encapsulate the blue, yellow, and green hydraulic pipes, reservoir, and manifold of the green system, power transfer unit, slat and flap drive power control unit, slat gearbox, flap drive transmission shafts, main landing gear, brake system components, constant speed motor generator, APU bleed duct and APU fuel line.

Table 4.1: Main landing gear bay boundaries (Zone limits).

Direction	**Boundary-from**	**Boundary-to**
X	Frame 42	Frame 47
Y	Fuselage structure of the belly fairing (Fuselage OML left)	Fuselage structure of the belly fairing (fuselage OML left)
Z	Ceiling (floor beam)	Lower part (keel beam, landing gear doors, and belly fairing)

The zone and the system components are manually modelled with DS-3 level of detail referring the “Figure 4.2.1.2.2-2 - (CCA - ZSA) Green Hydraulic System Components” in the ARP 4761, as shown in Figure 4.2. The representation is simplistic (Level 2) and does not illustrate all the components situated in the zone.

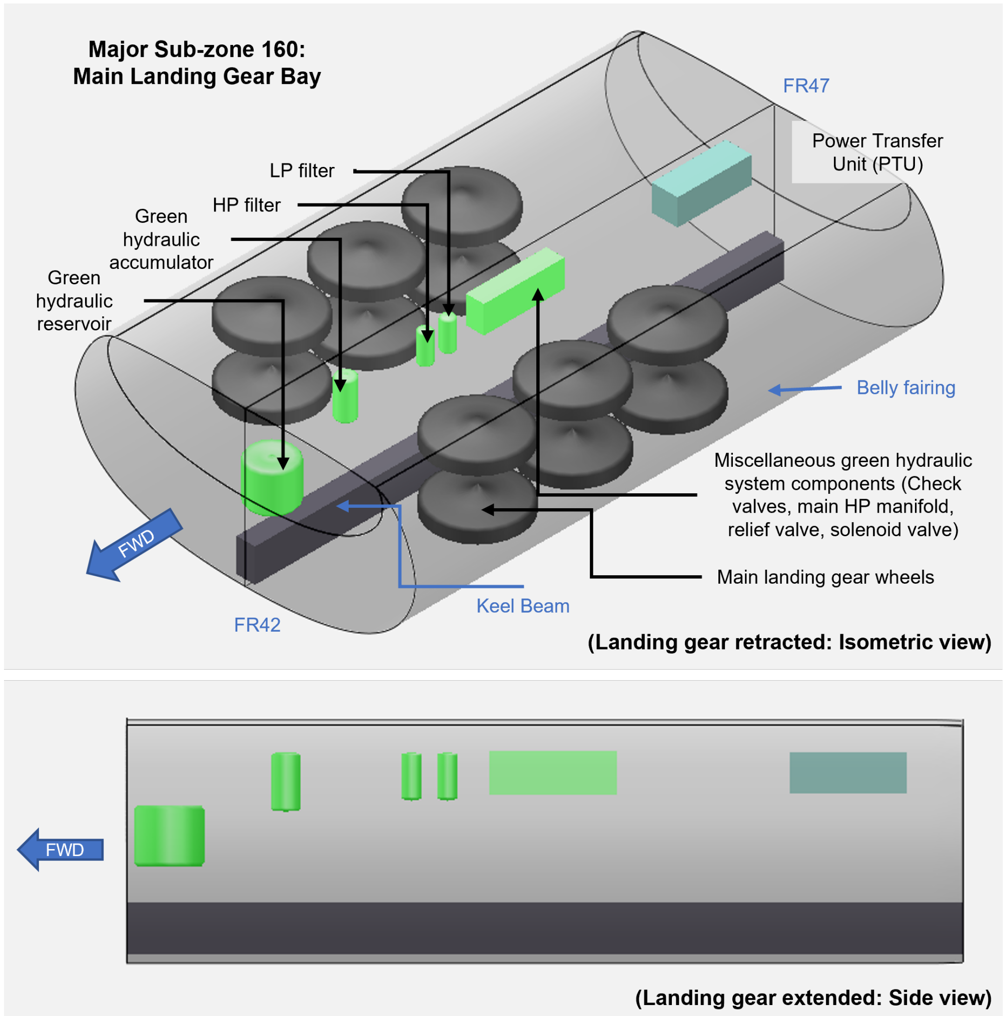


Figure 4.2: Main landing gear bay (Major sub-zone 160) model in OpenVSP.

Table 4.2 shows the *COR* score for primary components (shown in Figure 4.2) in the main landing gear bay.

Table 4.2: Component-level overall risk scores for the main landing gear bay components.

S. No.	Component Name	COR
1	Hydraulic Reservoir	0.72
2	Accumulator	0.53
3	HP Filter	0.30
4	LP Filter	0.30
5	Main Landing Gear	0.25
6	Power Transfer Unit (PTU)	0.59
7	Manifold green system equipped	0.36

The *ZOR* is 0.61, indicating the high-risk nature of the zone. The presented results are as expected because of the nature of the main landing gear zone environment and the constituent components. Performing the CZSA helps highlight the high-risk components: hydraulic reservoir, accumulator, and power transfer unit. These components have a higher risk because of the intrinsic hazards they pose and the nature of the zone (unpressurized, ventilated, low packing density, and flammable zone susceptible to bird strike and lightning strike (Zone 2A swept strike zone)). The hydraulic reservoir has a risk of fluid overheating and hazardous and flammable fluid leakage (risk of corrosion and fire). The accumulator has a risk of bursting and high-pressure, flammable, and hazardous fluid leakage. The power transfer unit that comprises a hydraulic motor and a pump connected via a shaft poses a risk of electrical sparking, fluid overheating, corrosion, and fire. The risk-scoring methodology helps capture these intrinsic risks and their interaction with the zone environment while assigning the overall zone and component risk scores.

4.1.2 Tire Burst Model 1 and Automatic Affected Component Reporting

The landing gear extended tire burst threat failure model 1 is used to perform the post-placement CPRA case study on the S18 aircraft. This analysis aims to check whether a tire burst particular risk results in a catastrophic failure condition and analyze the effect on fuel tank access panels (Part 25.963(e)) [90], landing gear legs, and wheel well (Part 25.729(f)) [83] and other systems outside the wheel bay (Part 25.1309) [14].

Some assumptions (applicable to large debris only) made in the analysis include the following: failure of the first tire provokes the bursting and tread shed of a second tire due to overloading, and the tire debris penetrates and opens the fuel tank or fuel system structure leading to fuel leakage.

As discussed in Table 3.15, the vulnerability zone is in the wheel plane between 45° and 180° from the horizontal ground plane in an anticlockwise direction. For large particles (considered in this case study), the spread angle is ±15° about the wheel plane. The grown tire diameter and tire center location are the parameters for failure Model 1.

The flight control and fuel subsystem definition is added manually to the OpenVSP model. The `PRATrajModel.py` script models the tire burst threat model by calling the respective function (as shown in Figure 4.3), and automatically outputs the list of system components in the risk/burst zone.

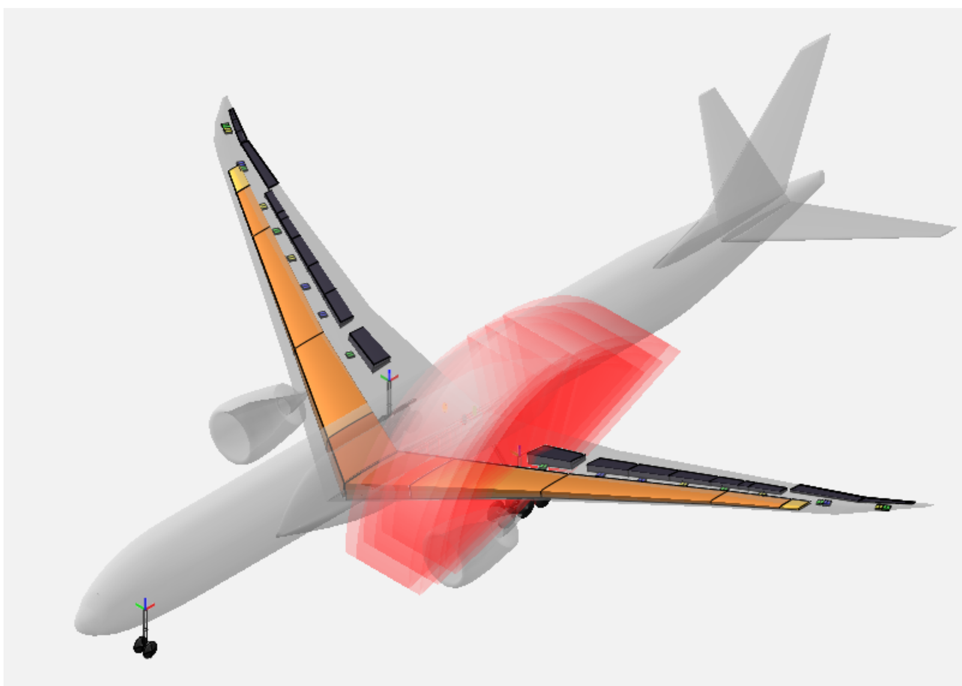


Figure 4.3: S18 aircraft tire burst threat model 1 (Large debris size) modelling in OpenVSP.

The designer can either reposition the listed components out of the risk zone or take other suitable measures if the component necessarily needs to be placed in that zone, like adding redundancy or protective shielding. Figure 4.5 and 4.4 show the regions and components affected by the tire burst threat model 1: slat 1, spoiler actuator 1, spoiler 1, inboard flap, inner rear spar, main landing gear leg, belly fairing, and lower wing skin.

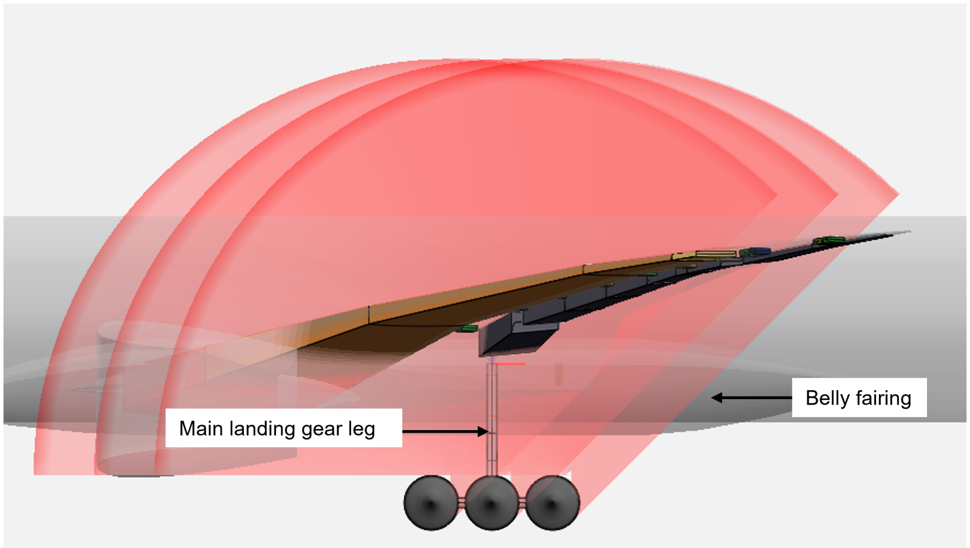


Figure 4.4: Components affected by tire burst model 1: Left side view.

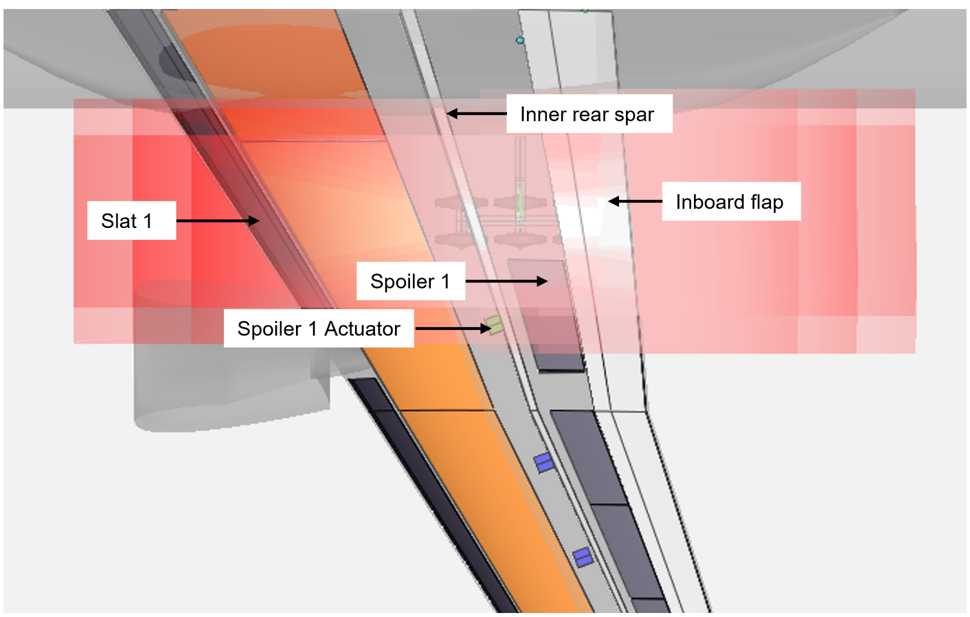


Figure 4.5: Components affected by tire burst model 1: Top view.

Table 4.3 compares the affected components list generated by performing the CPRA on the aircraft 3D model (with level 2 geometric granularity) with that of S18 tire burst example in the ARP 4761 [15] (performed at the detailed design stage).

Table 4.3: Comparison of the list of main landing gear tire burst affected components as per S18 example in ARP 4761 versus CPRA results.

Affected Component List	
ARP 4761 PRA Example [15]	**CPRA**
Main landing gear leg fairing doors	Belly fairing
Main landing gear hinged doors	-
Main landing gear leg and dressings	Main landing gear leg
Lower wing skin	Wing
Access panels 541/641 AB, BB, CB, DB	Fuselage
Access panels 573/673 DB	Fuselage
Fixed underwing panel	Wing
Shroud box	-
Overwing panel	Wing
Inner rear spar	Inner rear spar
Inboard flap	Inboard flap
No. 2 flap track fairing	-
No. 1 slat	No. 1 slat
No. 1 spoiler panel	No. 1 spoiler panel
No. 1 spoiler actuator	No. 1 spoiler actuator
Fuselage (belly fairing, upper lateral shell below window line (Section 13, 14, 16))	Fuselage, belly fairing

It is observed that the tool can detect most of the affected components. However, for the remaining components like main landing hinged doors, fairing doors, access panels, flap track fairing, and wing skin and fuselage shell location, the 3D model needs to contain the definition of these geometric entities to facilitate precise detection, else it simply prints belly fairing, wing and fuselage (super set of these entities) for such entities. Therefore, this example demonstrates that the tool can parametrically model and automatically detect the components in the threat zone (based on the geometric definition), giving the conceptual designer an overview of the threat impact.

4.2 Comparison of System Placement using CPRA

Active research is going on to study the potential of hydrogen as an environment-friendly fuel option to replace kerosene. Many researchers are exploring its integration into conventional aircraft configurations along these lines [91, 9]. Regional turboprop and jet aircraft have been the focus of such retrofitting concepts. It is crucial to consider the effect of CZSA and CPRA to assess the feasibility of such concepts.

Consider three hydrogen tank placement options on a regional turboprop aircraft (Figure 4.6).

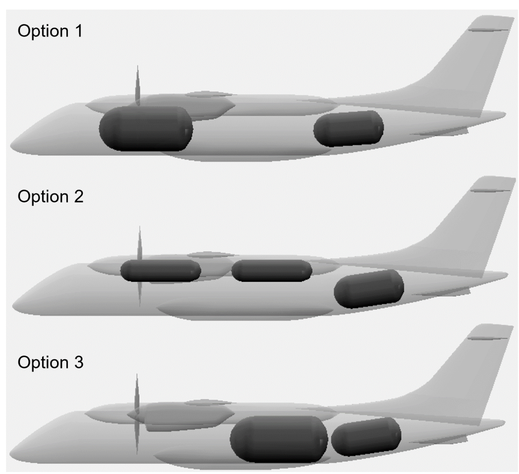


Figure 4.6: Hydrogen tank placement options for a regional turboprop aircraft.

In Option 1, two hydrogen tanks are placed in the forward and aft regions of the fuselage, respectively. Option 2 has two smaller tanks in the upper cabin region, and one larger tank is in the aft fuselage, while in option 3, two large tanks are placed in the aft fuselage region.

AS 6858 [59] states that the components of pressurized oxygen and hydrogen systems must not be installed in any trajectory-based PRA impact area. The placement of tanks must consider several trade-offs between disciplines like aircraft loads, structures, and systems. However, performing a level 1 propeller blade release CPRA analysis helps filter out the placement options feasible from a system safety point of view, thus leaving a reduced set of candidates to investigate further and save the multi-disciplinary analysis effort.

Figure 4.7 shows that the forward tank for option 1 lies in the propeller blade release zone.

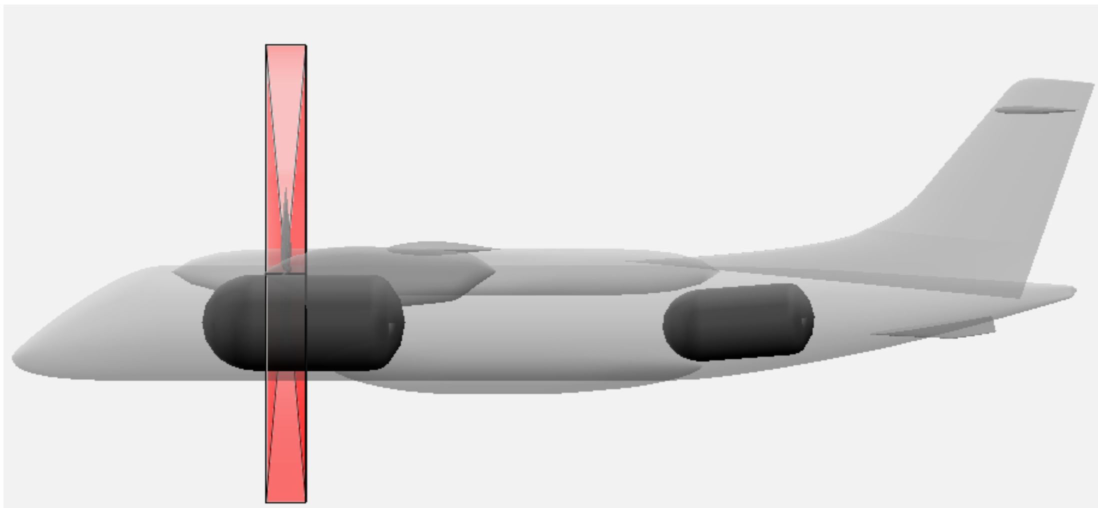


Figure 4.7: UERF consideration for hydrogen tank placement: Configuration 1.

Similarly, in option 2 (Figure 4.8), the forward-most small tank in the upper region of the fuselage is in the high-risk propeller blade release threat zone.

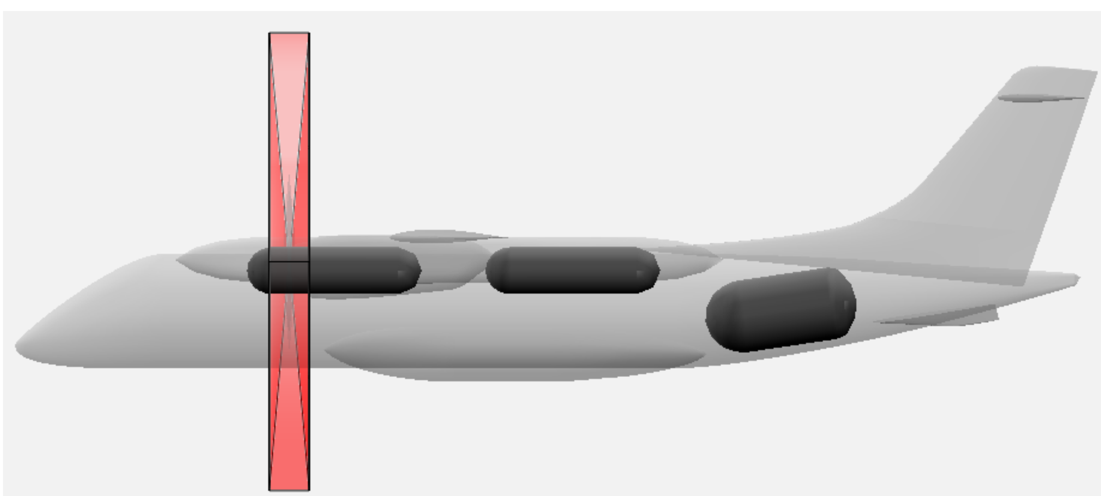


Figure 4.8: UERF consideration for hydrogen tank placement: Configuration 2.

Option 3 (Figure 4.9), however, passes the blade release threat analysis as both the tanks are away from the threat zone.

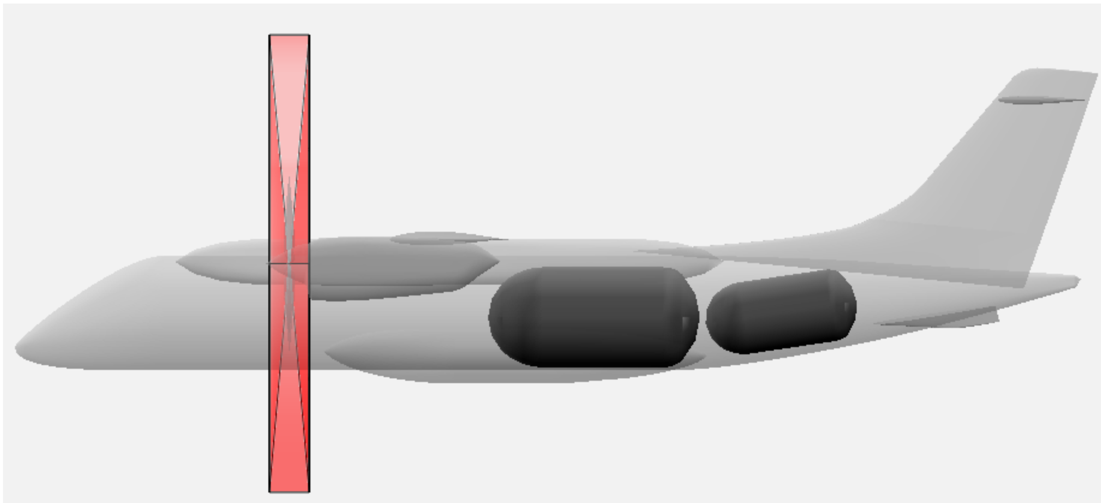


Figure 4.9: UERF consideration for hydrogen tank placement: Configuration 3.

This early check helps reduce the design space to more practical system placement strategies instead of wasting the design exploration time on non-compliant options. The application of CPRA enables the quick performance of these checks early in design,

4.3 CZSA for Evolving Geometric Granularity

The aircraft Aft Equipment Bay (AEB) is a complex zone that houses many components of various systems like fuel, hydraulic, electrical, anti-icing, avionics, and environmental control systems. Thus, it makes it an interesting case to examine if the proposed CZSA methodology can highlight the right high-risk components (known from expert experience). Moreover, comparing the analysis results for two AEB models with increasing levels of system definition detail helps demonstrate the tool's flexibility.

For a generic business aircraft, the AEB is unpressurized with an uncontrolled temperature environment subject to low vibrations due to the aft fuselage-mounted engines. It lies in swept stroke lightning zone (Zone 2A), does not contain oxygen system components, is not susceptible to bird strike events, and has a risk of flammable fluid leakage. It houses components with flammable, hazardous, and pressurized fluids (Fuel tank, air conditioning unit packs, hydraulic reservoirs, manifolds, and pipes) and electrical components with power > 200 W (like, Full Authority Digital Engine Control and AC motor pump).

Figure 4.10 shows an AEB with DS 4-level system definition.

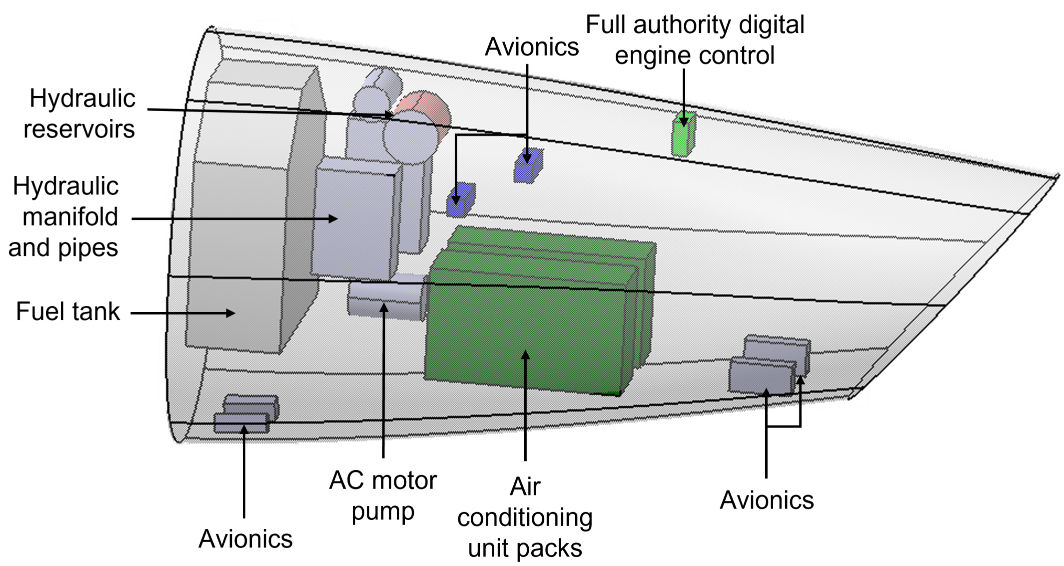


Figure 4.10: Aft equipment bay for a generic business aircraft with DS-4 level system definition.

The CZSA is performed using `ZSAIntMatrix.py` on the CATIA model of the simplified AEB model. Using a CATIA model instead of OpenVSP shows the tool's flexibility and modularity, wherein specific analysis can be performed in isolation on any 3D model file type as required.

The *COR* scores are summarized in Table 4.4, highlighting the fuel tank, hydraulic reservoir, AC motor pump, and Full Authority Digital Engine Control as medium-risk components. The results are as expected because fuel tanks contain flammable fluid (risk of leakage), the hydraulic system reservoir contains hazardous and flammable fluids (risk of leakage), AC motor pump has moving parts and is a high-power electrical component like Full Authority Digital Engine Control (risk of overheating), and the CZSA zone-component interaction study captures the interaction between, flammable and hazardous fluid containing components present in a zone with electrical components. No high-risk components are observed because the critical interactions have been accounted for in the initial system placement used for the analysis. Hence, the *ZOR* is 0.35, indicating that the zone has medium risk.

Table 4.4: CZSA results for AEB with DS 4-level system definition.

S. No.	**Component Name**	**COR**
1	Hydraulic Manifold and Pipes	0.21
2	Hydraulic Reservoirs	0.37
3	Avionics	0.12
4	AC Motor Pump	0.30
5	Full Authority Digital Engine Control	0.30
6	Fuel Tank	0.41
7	Air conditioning unit packs	0.07

Using the AEB with DS3-level of system definition (Figure 4.11) helps capture the components missed by the simplified AEB systems representation.

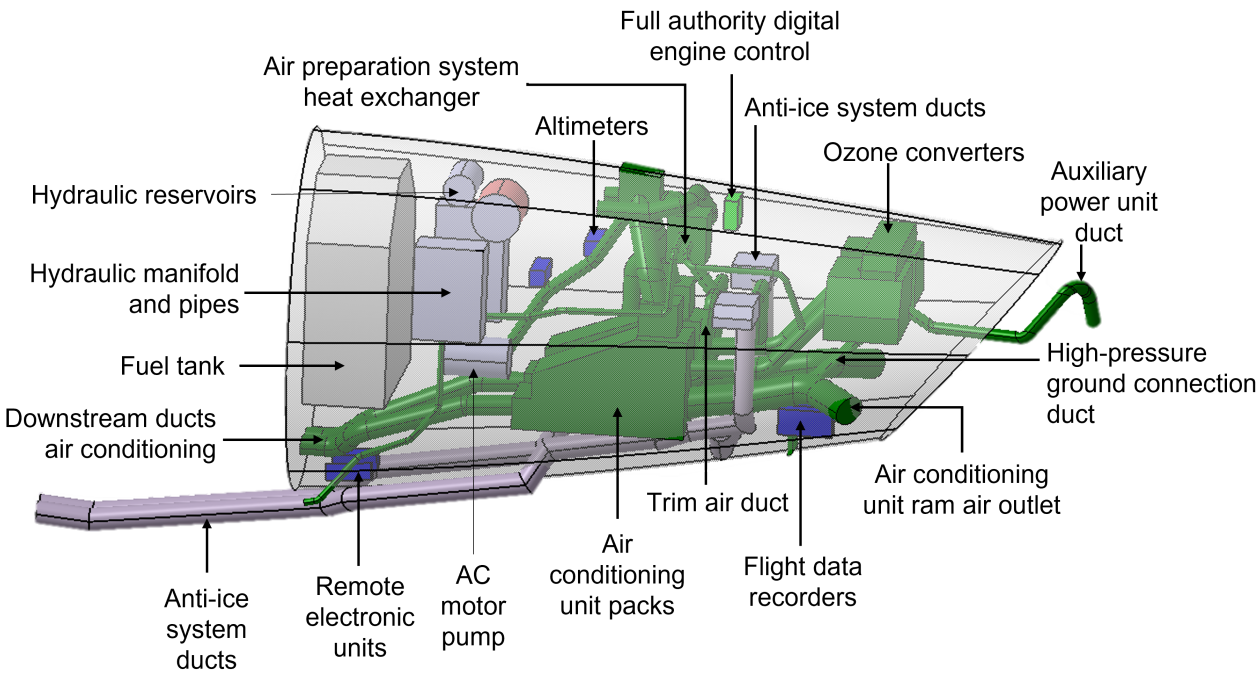


Figure 4.11: Aft equipment bay for a generic business aircraft with DS-3 level system definition.

Table 4.5 shows the *COR* scores for the system components and ducts in the relatively detailed AEB model.

Table 4.5: CZSA results for conventional AEB with DS 3-level system definition.

S. No.	Component Name	COR
1	Hydraulic Manifold and Pipes	0.21
2	Hydraulic Reservoirs	0.37
3	Altimeters	0.12
4	Air Preparation System Heat Exchanger	0.07
5	Full Authority Digital Engine Control	0.30
6	Anti-Ice System Ducts	0.49
7	Ozone Converters	0.15
8	Auxiliary Power Unit Duct	0.00
9	High Pressure Ground Connection Duct	0.09
10	Air Conditioning Unit Ram Air Outlet	0.06
11	Flight Data Recorders	0.12
12	Trim Air Duct	0.16
13	Air conditioning unit packs	0.07
14	AC Motor Pump	0.30
15	Remote Electronic Units	0.18
16	Anti-Ice System Ducts	0.13
17	Downstream Ducts Air Conditioning	0.21
18	Fuel Tank	0.41

The bay retains the medium risk flag with a *ZOR* of 0.38, and in addition to the previously identified medium risk components, it also highlights the anti-ice system ducts, which contain pressurized hazardous fluid, and their failure can increase the zone temperature above the nominal zone temperature. Hence, this illustrates how the scoring technique captures the intrinsic risks of the components.

The presented case study helps demonstrate the tool usage with varying levels of geometric granularity and the ability to use stand-alone tool elements (only `ZSAIntMatrix.py` was used in this case) for specific analysis.

4.4 Assessment of Impact of More Electric Aircraft Systems

This section analyzes the impact of adopting a more electric system architecture, with an electrified hydraulic power and environment control system, on the zonal safety of the AEB. Figure 4.12 shows the AEB with more electric architecture and DS 3-level system definition.

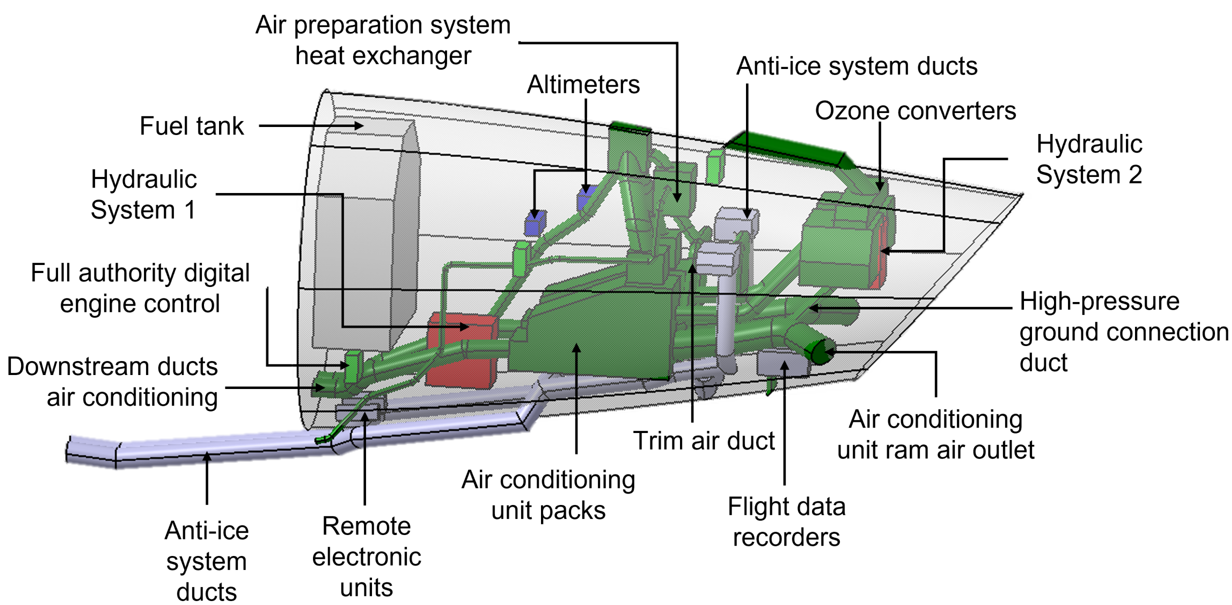


Figure 4.12: Aft equipment bay with more electric systems for a generic business aircraft with DS-3 level system definition.

Electrified air conditioning unit packs and hydraulic power packs may help reduce thrust-specific fuel consumption; however, their impact on the other disciplines must not be neglected. Therefore, to analyze their impact on the overall zone risk, the CZSA zone-component interaction study is performed. Table 4.6 compares the CZSA results for DS 4-level conventional, DS 3-level conventional and DS 3-level more electric AEB.

Table 4.6: Comparison of CZSA results for DS 4-level conventional, DS 3-level system definition conventional, and more electric AEB.

S.No.	Component Name	COR		
		DS 4-level: Conventional AEB	**DS 3-level: Conventional AEB**	**DS 3-level: More Electric AEB**
1	Hydraulic Manifold and Pipes (Conventional) or Electrified Hydraulic System 1 (MEA)	0.21	0.21	0.87
2	Hydraulic Reservoirs (Conventional) or Electrified Hydraulic System 2 (MEA)	0.37	0.37	0.87
3	Altimeters or Avionics(Level 1 Aft Equipment Bay System Definition)	0.12	0.12	0.12
4	Air Preparation System Heat Exchanger	-	0.07	0.07
5	Full Authority Digital Engine Control	0.30	0.30	0.30
6	Anti-Ice System Ducts	-	0.49	0.49
7	Ozone Converters	-	0.15	0.15
8	Auxiliary Power Unit Duct	-	0.00	0.00
9	High Pressure Ground Connection Duct	-	0.09	0.09
10	Air Conditioning Unit Ram Air Outlet	-	0.06	0.06
11	Flight Data Recorders	-	0.12	0.12
12	Trim Air Duct	-	0.16	0.16
13	Air conditioning unit packs	0.07	0.07	0.47
14	AC Motor Pump	0.30	0.30	-
15	Remote Electronic Units	-	0.18	0.18
16	Anti-Ice System Ducts	-	0.13	0.13
17	Downstream Ducts Air Conditioning	-	0.21	0.21
18	Fuel Tank	0.41	0.41	0.41
ZOR		0.35	0.38	0.87

The *ZOR* score for the electrified bay is 0.87 (very high risk), compared to 0.38 for the AEB with conventional systems. The increased system electrical power and heat dissipation increases the *COR* for air conditioning unit packs and hydraulic systems 1 and 2. Hence, a quick CZSA zone-component interaction study helps identify which bay/zone has a potentially higher safety risk and isolates the components responsible for it by assigning a high *COR*.

Chapter 5

Conclusion

The work presented in this thesis proposes a methodology to perform a semi-automated analysis of zonal safety and particular risks associated with an aircraft configuration using a parametric geometric model early in aircraft design to support system safety integration into multidisciplinary design and analysis.

Today ZSA and PRA are cumbersome and lengthy studies, not adapted to the fast pace of rapid concept evaluation in conceptual design, i.e., in the context of rapidly expanding MDAO deployment. The usage of the CAD modelling approach is also limited to aerodynamic and structural analyses. Moreover, the available regulations and guidance material for system installation and safety are not exploited to steer the early placement strategy and for initial configuration feasibility assessments. Overall, there is a lack of efficient use of the available aircraft design information to evaluate the safety aspects.

Hence, the presented research work develops a generic, parametric, and repeatable methodology for a fluid configuration and system technology description with evolving detail that enables the conceptual designer to do some of the work of the safety engineer to avoid later rework and unnecessary/time-consuming/costly iterations. An assessment approach that analyzes the given configuration based on the safety-driven best practices and parametric modelling of threat zones is presented to accomplish this.

5.1 Major Contributions

The major contributions of this thesis include:

- A combined ZSA and PRA analysis methodology for the conceptual design stage with varying fidelity for different levels of aircraft geometric details and degree of simplification of the systems is formalized.
- A comprehensive synthesis of system installation guidelines and best practices are consolidated in a database to perform early high-level placement checks and guide initial placement.
- A metric to compare different zones based on the overall risk posed by the system components present is also developed.
- The application of the analysis approaches implemented in Python is validated using simple and complex test cases with varying levels of geometrical granularity in the early design phase. The cases studied cover both conventional and unconventional aircraft configurations and system technologies.

The major test cases presented in Chapter 4 help illustrate the main features of the developed methodology. Firstly, the S18 aircraft main landing gear bay CZSA and tire burst CPRA studies adapted from the ARP 4761 represent how it could be helpful to perform ZSA and PRA early in a semi-automated way to identify high-risk systems quickly. The second case shows how a level 0 propeller blade release CPRA for a retrofitted regional turboprop aircraft could help sieve out the feasible hydrogen tank placement option from a safety viewpoint. A comparison of CZSA results for a complex zone with closely packed components from different systems for the conventional aft equipment bay for a business jet with varying system DS levels follows this. Finally, the CZSA results for an aft equipment bay concept with more electric architecture are compared with the conventional case, thus showing how the proposed tool can provide a quick insight into the possible placement challenges for novel technologies. Thus, it allows for early deliberation about risk minimization strategies and their impact on aircraft-level requirements.

Nevertheless, the proposed methodology has the potential for improvement on the following shortcomings:

- The component-level intrinsic risks do not represent an exhaustive consideration of all the physical characteristics and potential risks of a component. For example, pressurized components like accumulators have an explosive failure mode and can damage the components in their vicinity.

- The zone-level risks do not consider the number of hazardous fluid-containing or electrical components while assigning the zone risk score based on the components present. Hence, even if a zone contains only one high-power avionics component or several batteries and an AC motor pump, it will assign a score of 1 to the zone risk for the presence of an electrical component.

- The component and zone interaction penalization does not take into account the relative distance or physical location of the components. For example, the method will penalize the presence of oxygen and hydraulic lines together, whereas, in reality, it is acceptable if the oxygen lines are positioned above the hydraulic lines and a minimum clearance as recommended by the guidelines is respected.

- The CZSA risk scoring method has also not been designed to consider the relative criticality of the system component. For example, a component with high criticality might inherently have low risk, but its placement adjacent to a high-risk component increases the chances of affecting the critical component, which will be a more significant hazard on the aircraft level. Hence, for such components, it is important to consider the relative criticality and location with respect to other high-risk components. Further improvement needs to be done to enable the tool to highlight such risks.

- Due to incomplete system and structure modelling in the aircraft CAD model, the list of systems affected by the trajectory-based particular risks modelled in CPRA ignores the shielding that would be provided by the presence of a structural element (not modelled at the conceptual design phase) in the way of the debris source and the component.

5.2 Future Work

The challenges to the proposed methodology presented above pave the way for future enhancements. Therefore, as part of future work, the following improvements are suggested:

- Increase the granularity of the zone-component interaction matrix by capturing other possible particular risks, component failure modes, and physical characteristics.
- Account for system components' criticality, number, and relative placement while calculating the overall risk scores for the component and the bay.
- Automate the check of positional, distance, and clearance type requirements from the guidelines database for DS 3 and DS 0-2 level of geometry detail.
- Develop the CPRA methodology to incorporate the assumptions like the structures shielding effect while studying the impact of certain particular risks like a tire burst on the system components.
- Discretize the aircraft volume based on the overlap of all the different particular risk zones like lightning strike zones, bird strike zones, tire burst zone, and rotor burst zone into high, medium, and low-risk stay-out zones to guide the component placement.
- Integrate the developed methodology into MDAO framework.

Overall, the presented work enhances the conceptual design maturity from a system integration and safety standpoint. Applying the presented methods will prevent possible rework and later design changes, like repositioning or reorientating critical components, thus reducing the downstream development time. Also, the proposed automation will facilitate the integration of safety analyses into MDAO environments and allow the exploration of more configurations in less time, potentially improving the effectiveness of the design process for future aircraft.

List of Publications

Conference

- P. Bamrah, S. Liscouet-Hanke, A. Tfaily, and A. Tamayo,
  Zonal Safety and Particular Risk Analysis for Aircraft Conceptual Design,
  American Institute of Aeronautics and Astronautics (AIAA) Aviation Forum,
  12-16 June 2023, San Diego, California, USA and Online,
  doi: 10.2514/6.2023-4197.

Journal

The above-listed conference paper is under submission to the Journal of Aircraft (the conference committee recommended submitting it in their journal).

- In progress: P. Bamrah, S. Liscouet-Hanke, A. Tfaily, and A. Tamayo,
  Zonal Safety and Particular Risk Analysis for Aircraft Conceptual Design

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Appendix A

Particular Risk Threat Envelopes

This section illustrates the threat envelopes and fragment definitions for trajectory-based PRAs.

A.1 Uncontained Engine Rotor Failure

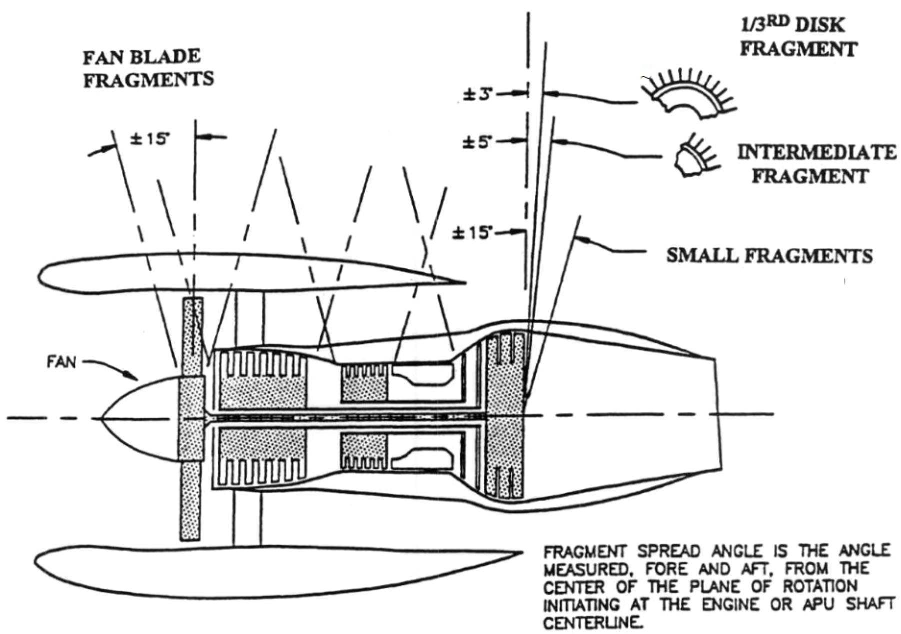

Figure A.1: Estimated rotor fragment paths [4].

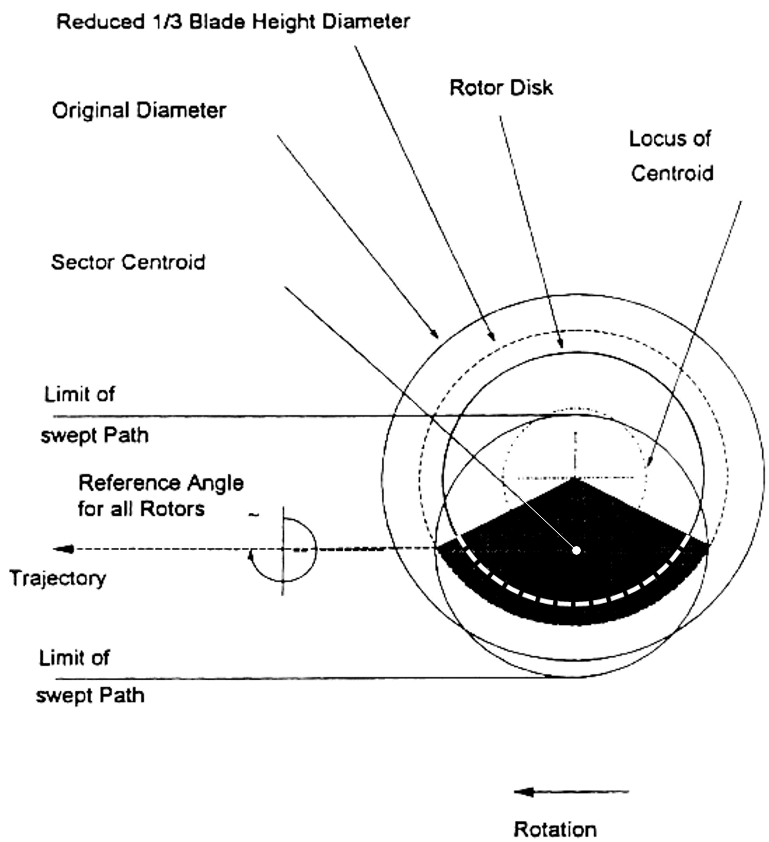

Figure A.2: Rotor burst fragment sector dimensions [4].

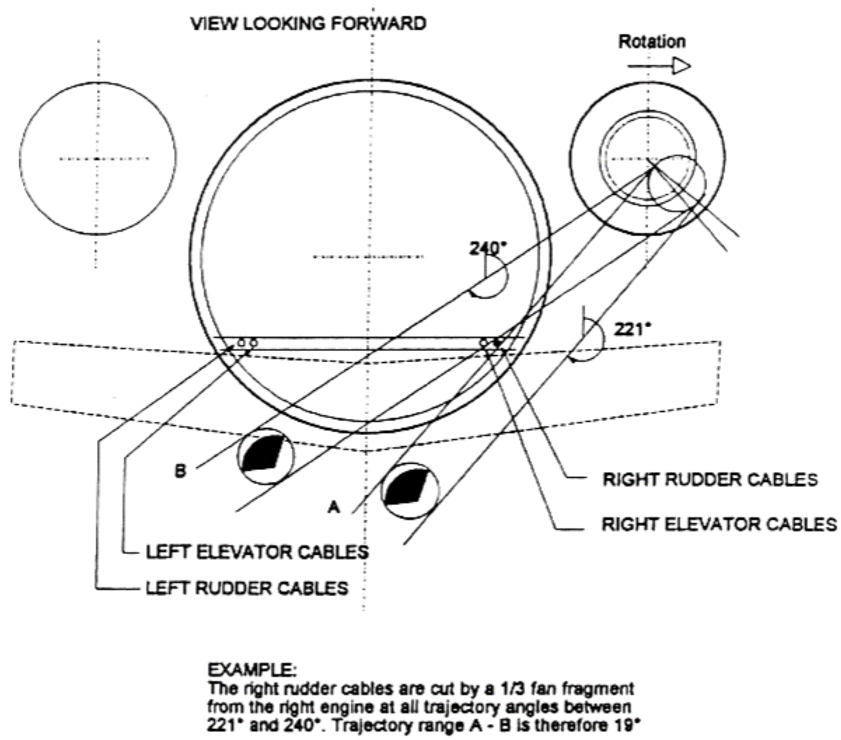

Figure A.3: Rotor burst trajectory range plotting [4].

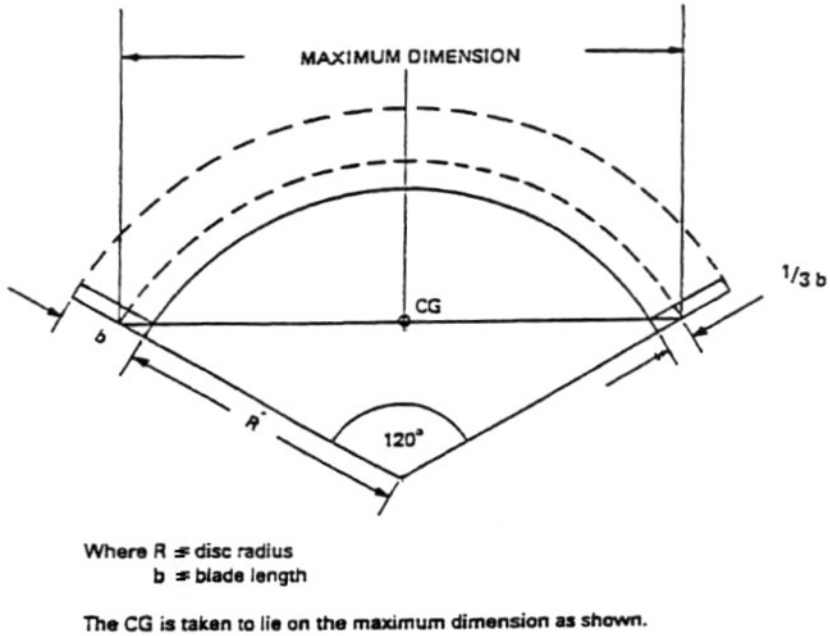

Figure A.4: Single one-third rotor fragment [4].

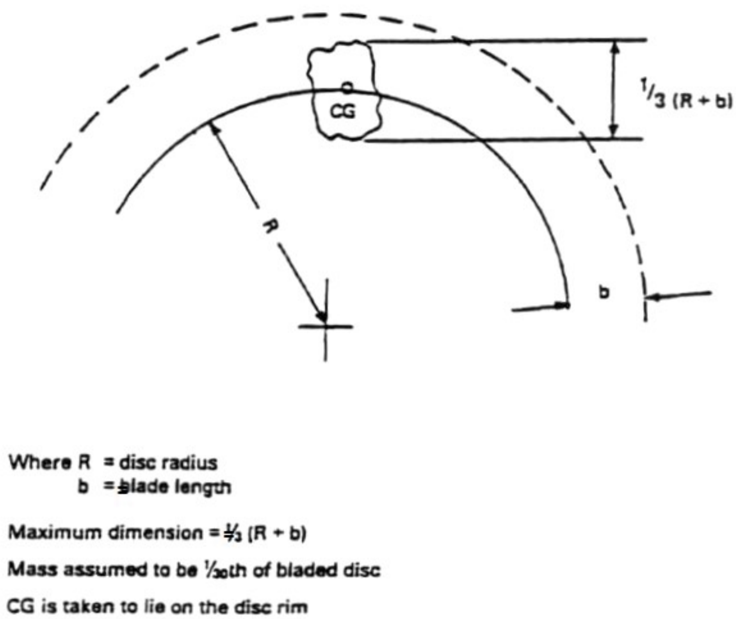

Figure A.5: Intermediate rotor fragment [4].

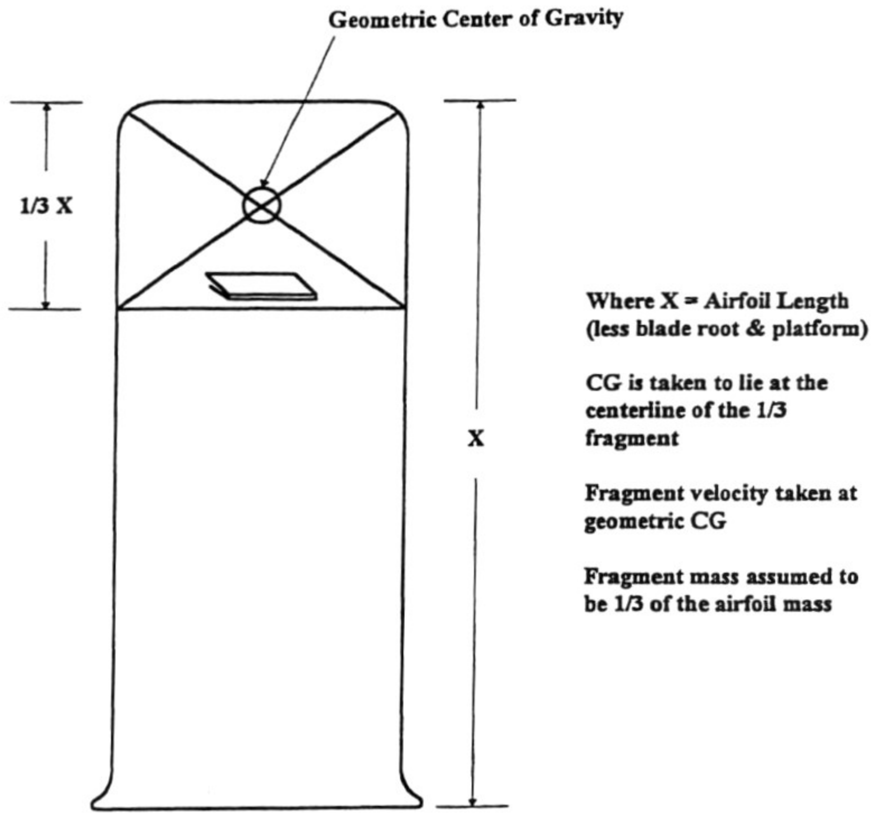

Figure A.6: Fan blade fragment definition [4].

A.2 Tire and Wheel Failure

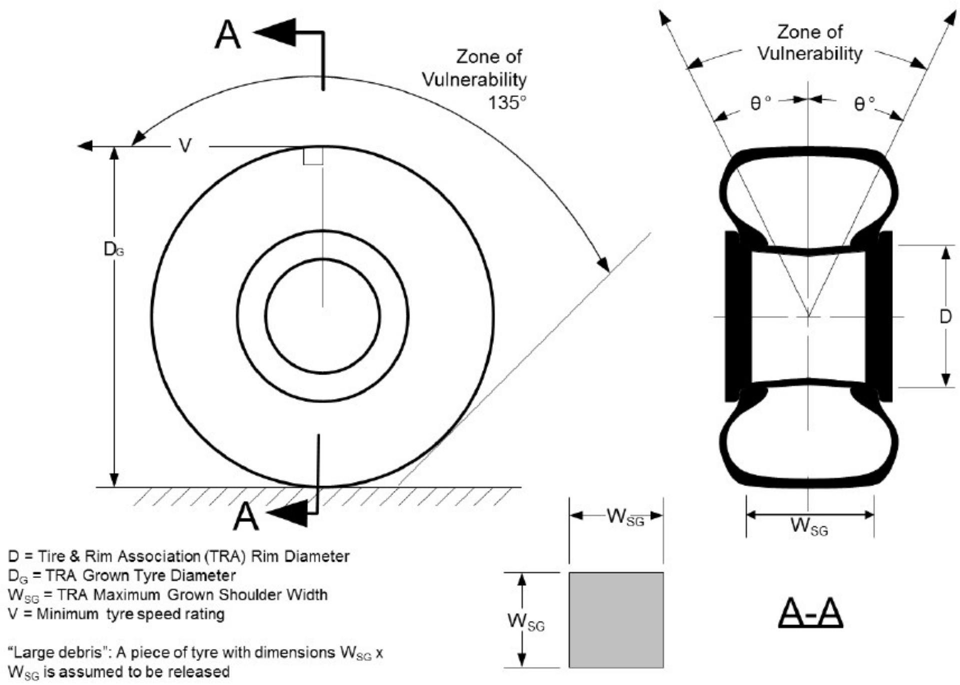

Figure A.7: Model 1: Tire burst threat envelope [5].

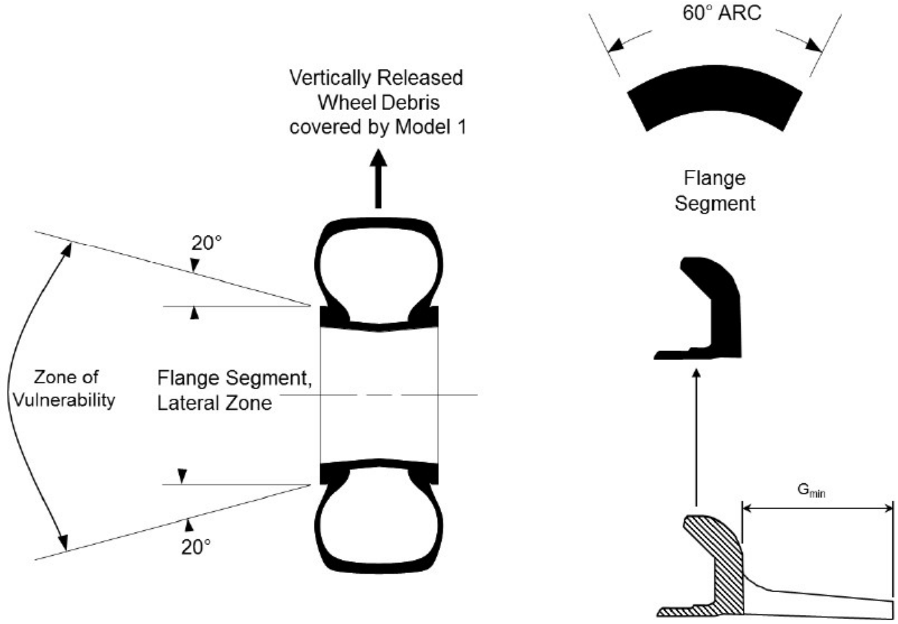

Figure A.8: Model 2: Wheel flange/rim release threat envelope [5].

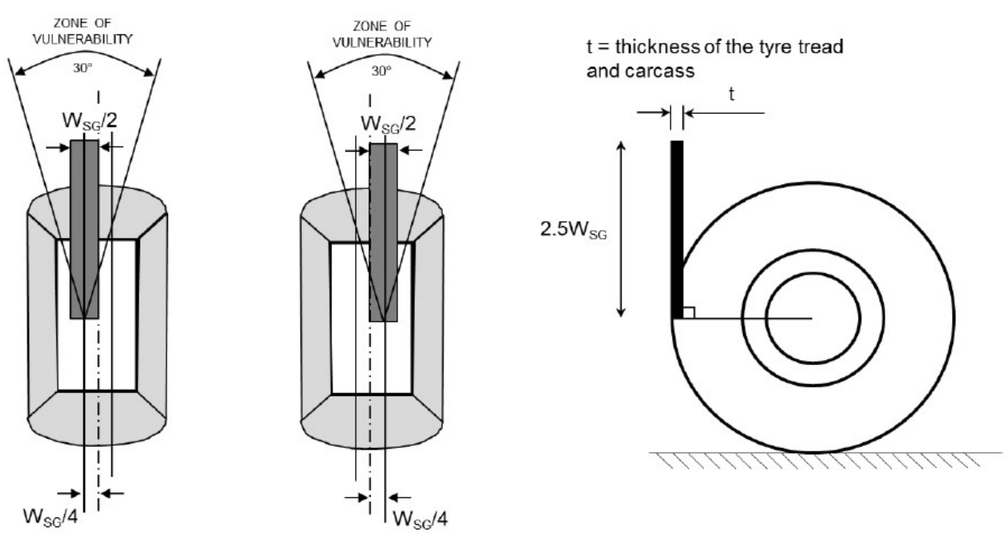

Figure A.9: Model 3: Flailing tire strip threat envelope [5].

Appendix B

Installation Guidelines

Table B.1: Compilation of installation guidelines and considerations.

S. No.	Requirement	Hazard	System	Reference	Applicability to Conceptual design	DS Level	Evaluation Means	Comments
1	The recorder container must be located and mounted to minimize the probability of rupture of	Crash landing	Cockpit voice recorders	§25.1457 Cockpit voice recorders. [92]	No (Too early)	DS 0-2	-	
2	The recorder container must be located as far aft as practicable but need not be outside of the pressurized compartment, and may not be located where aft-mounted engines may crush the container during impact.	Crash landing	Cockpit voice recorders	§25.1457 Cockpit voice recorders. [92]	No (Too early)	DS 0-3	ZSA Level 3	The first part can be considered for initial placement

3	All electric equipment should be so installed that a minimum of exposure to outside influences, such as moisture and mechanical shock, will result. Where such protection cannot be afforded consistent with inspection and maintenance requirements, the equipment should be of such design that it is self-protecting. Wherever feasible, equipment should be so installed that moisture due to condensation or any other source will drain out. Consideration should be given to the possibility of water freezing inside of equipment and, thus, preventing operation of moving parts. Hermetically-sealed units are exceptions	Mechanical Shock Prevention and Moisture Proofing	Electrical Systems	Aircraft Electrical Installations ARP 4404C [62]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix (High level check)	
4	Equipment should not be located in a flammable vapor area unless it is suitably tested for	Flammable Vapor Area	Electrical Systems	Aircraft Electrical Installations ARP 4404C [62]	Yes	DS 0-4	CZSA Interaction Matrix	
5	Battery fumes and gases emitted by normal or abnormal operation, which may form an explosive mixture or contaminate crew or passenger compartments should be dispersed by adequate	Battery Fumes	Electrical Systems	Aircraft Electrical Installations ARP 4404C [62]	Yes (Partially)	DS 0-4	CZSA Interaction Matrix (High level check)	

6	No definite recommendations as to proper drainage for each unit or piece of electric equipment can be made. The type of equipment, the mounting method, the location in the aircraft, the duty cycle, etc. all should be considered when determining the drainage requirements. In general, a 1/8 in diameter or preferably larger hole located at each low point in conduit and non-environment resistant connectors is considered adequate where drainage is required. Junction boxes that are located in wheel wells or other areas where they may be subject to splash may require a 3/8 in diameter drain hole. Drain holes of less than 1/4 in in diameter in junction boxes in such areas should be avoided because of their tendency to clog with dirt, etc.	Drain Hole Size	Electrical Systems	Aircraft Electrical Installations ARP 4404C [62]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	
7	Surfaces within 12 in of aircraft batteries and surfaces further removed, which are subject to electrolyte spillage, spray, or fumes should be provided with corrosion protection to ensure against damage	Battery fumes	Electrical Systems	Aircraft Electrical Installations ARP 4404C [62]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	

8	Each EWIS must be designed and installed so that any electrical interference likely to be present in the airplane will not result in hazardous effects upon the airplane or its systems. Wires and cables carrying heavy current, and their associated EWIS components, must be designed and installed to ensure adequate physical separation and electrical isolation so that damage to circuits associated with essential functions will be minimized under fault conditions.	Electrical interference	EWIS	§25.1707 System separation: EWIS. [64]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	Only partially applicable for conceptual design. The first part can be checked with the interaction matrix, but the separation and installation check can only be done when a more detailed installation and system definition is available.
9	EWIS must be designed and installed with adequate physical separation between the EWIS components and heated equipment, hot air ducts, and lines, so that: (1) An EWIS component failure will not create a hazardous condition. (2) Any hot air leakage or heat generated onto EWIS components will not create a hazardous condition.	Hot air	EWIS	§25.1707 System separation: EWIS. [64]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	Partially applicable to conceptual design, but the risk of not meeting this requirement is captured in the CZSA interaction matrix
10	There must be at least one-half inch of clear airspace between each tank or reservoir and	Fire	Flammable fluids	§25.1185 Flammable fluids [68]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	Can be implemented in tank or firewall conceptual design models

11	Each nonejectable record container must be located and mounted so as to minimize the probability of container rupture resulting from crash impact and subsequent damage to the record from fire. In meeting this requirement, the record container must be located as far aft as practicable but need not be aft of the pressurized compartment and may not be where aft-mounted engines may crush the	Crash landing	Flight Data Recorders	§25.1459 Flight data recorders. [93]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	The ”most far aft” installation could be considered.
12	All fuel lines within the fuselage should be routed so that they pass through the floor beams		Fuel system	§25.993 Fuel system lines and fittings. [94]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	Could be considered for the initial routing
13	A good fuel system installation will have a minimum of low points in the fuel lines.		Fuel system	§25.993 Fuel system lines and fittings. [94]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	Could be considered for the initial routing
14	Fuel lines which run through pressurized zones must be adequately shrouded, with a shroud		Fuel system	Aircraft Fuel System Design Guideline AIR7975 [69]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	Could be added to a simple fuel line model
15	Pump Location : Takes into account negative g effects, collector tank and depends on the		Fuel system	Aircraft Fuel System Design Guideline AIR7975 [69]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	Could be added to a simple fuel system model

16	Good design practice dictates that fuel line installation and retention should maintain 0.25 inch of separation from all surrounding structure and subsystems (i.e., electrical wiring, hydraulic lines, equipment). AS18802 provides guidance for separation and fuel line support and clamping. Less than 0.25 inch may be acceptable, but positive separation via clamping should be demonstrated by analysis and	Clearance from structure	Fuel system	Aircraft Fuel System Design Guideline AIR7975 [69]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	The clearance value can be integrated into a fuel routing model (0.25 in clearance)
17	Equipment containing high energy rotors must be located where rotor failure will neither	UERF	High Energy Rotor	§25.1461 Equipment containing high energy rotors. [86]	Yes (Partially)	DS 0-4	CPRA	
18	Hydraulic System Tubing Installation: The criticality of system function loss due to tire failure or wheel rim release should be considered. The shielding protection offered by primary structure should be	Tire burts and Wheel Rim Release	Hydraulic System	Design of Tubing Installation for Aerospace Hydraulic Systems ARP994B [84]	Yes	DS 0-4	CPRA	
19	Hydraulic System Tubing Installation: Any essential hydraulic system supply that is routed within an UERF impact area should have means to isolate the hydraulic supply required to maintain control of the airplane. The single one-third disc should not result in loss of all essential hydraulic systems or loss of	UERF	Hydraulic System	Design of Tubing Installation for Aerospace Hydraulic Systems ARP994B [84]	Yes (Partially)	DS 0-3	CPRA	Layout of tubing installation requires trajectory-level analysis. Therefore, only a first high-level check is performed in CPRA.

20	Separation of Hydraulic Systems: Where more than one hydraulic system is installed, separate the hydraulic lines of each system with respect to the other by routing on opposite sides of structural elements or by the use of protective shrouding. Separate the normal and emergency lines as far as possible from each other, so that events causing total loss of one system will not affect the other	Separation	Hydraulic System	Design of Tubing Installation for Aerospace Hydraulic Systems ARP994B [84]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	Could be considered for the initial routing
21	Analyze all normal and potential environmental exposures for the tube, fitting, and clamp	Environmental Considerations	Hydraulic System	Design of Tubing Installation for Aerospace Hydraulic Systems ARP994B [84]	Yes	DS 0-4	CZSA Interaction Matrix	Not all possible environmental exposures are captures. E.g.: Presence of toxic gases

22	No single failure should cause the loss of more than one hydraulic system. Where it is unavoidable that two hydraulic systems come together in one housing (such as brake units and switching valves), special precautions must be taken such that housing failures causing loss of both systems is remote. The routing of the hydraulic systems should be such that the primary systems are not within close proximity of each other, regardless of the precautions taken. Consideration shall be given to the effects of engine debris, flailing tires or tire debris, flailing shafts, and damage to the aircraft structure.	Segregation Requirements	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60]	Yes	DS 0-4	CPRA	

23	Ensure that the tubing of each independent system and their respective components are sufficiently physically separated such that a non-contained engine failure could not damage the lines of all systems. It must be possible to retain hydraulic power to those services that are considered essential for safe flight and landing, for example, some primary or secondary flying controls, landing gear deployment and brakes. If necessary, in order to meet this requirement, tubing for one system may be required to be installed in the fuel tank areas in the wing with the other systems installed on the wing front and rear spars. In addition, if the hydraulic bays are all located within the engine burst zones then the bays should be as far apart from each other as practically possible. It may be necessary to route the plumbing from all the hydraulic systems in a single area to achieve the necessary degree of redundancy. Under these conditions, it could be possible that damage to all of the systems in this area would prevent the aircraft from being controlled. Therefore, consideration should be given to providing means to isolate this section of each system so that the operability of the remainder of the system is maintained or that the system redundancy is not reduced.	UERF	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60]	Yes	DS 0-3	CPRA	Requires trajectory level analysis. For conceptual level we just show stay out zones and install with caution zones.

24	Consideration must be given to the effect of flailing tires or tire debris on tubing installed in the wheel well, as required by 14 CFR Part 25/CS 25.729(f). It is required that the design of the tubing installation on landing gears, in landing gear and/or hydraulic bays, etc., is such that only a limited amount of damage is possible, for example, the loss of not more than one system when a redundant system remains functional. The choice of tubing material in this area should consider the risk of exposure of the tubing to the tire failure. The design and installation of components and the tubing in each wheel well area must also take into account the possibility of a tire burst when the landing gear is retracted or deployed. If necessary, some components and tubing may be required to be protected from a tire burst that would otherwise cause a failure of more than one hydraulic system.	Flailing Tire and Tire Burst	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60]	Yes	DS 0-3	CPRA	Requires trajectory level analysis. For conceptual level we just show stay out zones and install with caution zones.
25	The hydraulic system layout must also take into consideration the effect of other situations,	Rapid depressurization	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60]	No	DS 0-2	-	-

26	In addition, in the event of a hard landing such that the floor collapses or there is other substantial structural damage, the hydraulic supply to the braking system must be protected so that it is	Crash landing	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60]	No	DS 0-3	-	Potential to be covered by CZSA by adding crash landing as a particular risk.
27	Consideration should also be given to a birdstrike penetrating the aircraft structure. It should	Bird strike	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	
28	Lightning Protection: Ensure the bonding and grounding of the components to the aircraft structure in order to protect the aircraft against catastrophic effects from lightning. In order to comply with this requirement, the aircraft hydraulic system components and lines should be bonded and grounded to the aircraft in accordance with ARP1870 or the equivalent OEM's requirements.	Lightning	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60] , AC25.581 [87]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix (High level check to highlight at risk components)	

29	There should be no hydraulic reservoirs located in a designated fire zone.	Designated Fire Zone	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60], AC25.581 [87]	Yes	DS 0-3	CZSA Interaction Matrix	The CZSA matrix flags this as the highest risk (requirement not met)
30	Reservoir: The length of suction line to the pump(s) is the minimum possible		Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60], AC25.581 [87]	No	DS 0-2		Requires a detailed model, could be implemented in the future
31	Reservoir: Protection is provided from engine burst or tire debris damage	UERF & Tire Burst	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60], AC25.581 [87]	Yes	DS 0-3	CPRA	Risk minimization suggestion if reservoir is in threat zone

32	Accumulators should be installed with the utmost consideration given to the protection of the flight and ground crew, passengers and critical parts of the aircraft in the case of structural failure or loss of	Accumulator Burst	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60], AC25.581 [87]	No	DS 0-3		Potentail to be covered by CPRA if accumulator burst threat zone definiton is available
33	Care should be taken in the routing of the hydraulic tubing with respect to being placed above electrical assemblies in order to minimize the risk of contamination of electrical plugs, components and wiring in the event of any hydraulic fluid leakage from the tubing. Hydraulic tubes should be routed below wire bundles, connectors, etc.	Leakage	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60], AC25.581 [87]	Yes	DS 0-3	ZSA Interaction Matrix (High-level)	

34	The installation of the hydraulic and ECS systems should be such that they do not run close to each other, particularly where ECS ducting is subjected to high bleed air temperatures, etc. This is in order to prevent: a. Local heating of the hydraulic system b. Parts of the ECS system from being contaminated by hydraulic fluid, particularly on ducting that contains high temperature air. If it is not possible to avoid the two systems from being adjacent to each other, then the hydraulic tube lines should be routed below the ECS ducting. Protection should be specified if some of the air conditioning system elements are subjected to temperatures greater than 450 °F (232 °C), either normally or following a failure.	Heating and contamination	Hydraulic System	Aerospace - Design and Installation of Commercial Transport Aircraft Hydraulic Systems ARP4752B [60], AC25.581 [87]	Yes	DS 0-3	CZSA Interaction Matrix (High-level)	
35	Where hydraulic tubing is located less than 3 inches (76.2 mm) from the centerline of the clamp block, clamp, or port interface, provide a minimum clearance of 0.125 inch (3.2 mm) from adjacent structure. Where relative motion may exist between adjoining members, provide a minimum clearance of	Clearance at Supported Locations	Hydraulic System	Design of Tubing Installations for Aerospace Hydraulic Systems ARP994B	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	This could be implemented into routing model

36	Where hydraulic tubing is located greater than or equal to 3 inches (76.2 mm) from the centerline of the clamp block, clamp, or port interface, provide a minimum clearance of 0.25 inch (6.4 mm) from adjacent structure. Where relative motion may exist between adjoining members, allow a minimum	Clearance at Unsupported Locations	Hydraulic System	Design of Tubing Installations for Aerospace Hydraulic Systems ARP994B [84]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	This could be integrated into a simplified routing model (at least the clearance requirement)
37	Hydraulic tubes crossing each other should be adequately clamped to maintain a minimum clearance of 0.25 inch (6.4 mm). Where this clearance is not possible, back to back (butterfly) clamping	Clearance at Tube Crossings	Hydraulic System	Design of Tubing Installations for Aerospace Hydraulic Systems ARP994B	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	This could be integrated into a simplified routing model (at least the clearance requirement)
38	Hydraulic tubes should clear all control cables and linkages by a minimum of 1.0 inch (25.4 mm). A minimum of 0.5 inch (12.7 mm) clearance is acceptable adjacent to cable pulleys. Cable system deflection should be analyzed under all loading conditions including conditions where the cable might slack	Clearance from Control Cables	Hydraulic System	Design of Tubing Installations for Aerospace Hydraulic Systems ARP994B [84]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	This could be integrated into a simplified routing model (at least the clearance requirement)
39	Provide a minimum clearance of 2.0 inches (50.8 mm) between hydraulic fluid carrying components and electrical wires. It should not be possible for electrical wires to contact hydraulic tubes, hoses, fittings, or manifolds. Routing of hydraulic fluid carrying components should be below electrical wires	Clearance from Electrical Wires	Hydraulic System	Design of Tubing Installations for Aerospace Hydraulic Systems ARP994B [84]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	This cab be implemented with a detailed system defintion

40	Provide a minimum clearance of 6.0 inches (152.4 mm) between hydraulic and oxygen lines.	Clearance from Oxygen Lines	Hydraulic System	Design of Tubing Installations for Aerospace Hydraulic Systems ARP994B [84]	No	DS 0-2	ZSA Level 3 (Out of CZSA scope)	This cab be implemented with a detailed system defintion
41	Leaking hydrogen must be vented overboard unless it can be shown that no hazard exists by its discharge within the compartment in which it is installed. The hazards associated with the potential loss	Leakage	Hydrogen Fuel Cell System	Considerations for Hydrogen Fuel Cells in Airborne Applications AIR7765 [95]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	Only ventilation considered
42	Pressure vessels shall not be installed in any impact area of a trajectory-based PRA. All hazardous or catastrophic failure conditions of the FCS shall be segregated in order to ensure system functionality after the particular risk event. Redundancies shall not be installed on the same trajectory. No permanently pressurized O2 and H2 lines should be installed in the trajectory-based PRA impact areas. If this cannot be avoided, additional precautions shall be taken in order to ensure an adequate level of safety.	Trajectory based PRAs	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]	Yes	DS 0-3	CPRA	Only ventilation considered

43	Pressure vessel installation shall ensure that a bottle burst will not result in a hazardous or	Pressure Vessel Burst	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]; ARP5021 B Oxygen Cylinder Installation Guide [88]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	Taken into account in the component intrinsic risk (pressurized, hazardous or oxygen fluid leakage)
44	The installation and design shall ensure that the Fuel Cell System stays operative under sustained engine imbalance vibrations. A sustained engine imbalance induces significant vibrations at a given frequency into the aircraft. This requirement ensures the integrity and functioning of the Fuel Cell System in case of loss of an engine as the Fuel Cell System is intended to work under those conditions.	Sustained Engine Imbalance	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]	No	-	-	To be shown by qualification
45	The installation and design shall ensure that the Fuel Cell System stays operative under nose	Nose Wheel Imbalance	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]	No	-	-	To be shown by qualification
46	A hot air leakage that could result in hazardous or catastrophic effects shall be detectable. In	Bleed Air Duct Rupture	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]	Yes	DS 0-3	CZSA Interaction Matrix (High-level)	Covered partially by checking if bleed air ducts and fuel cells are present in the same zone.

47	In case of a rupture of the AFT pressure bulkhead proper system segregation shall ensure that there is no case where flammable fluid and an ignition source (e.g., electrical wiring) can be damaged at the same time leading to a fire. System segregation has to be provided. NOTE: This PRA is limited to parts of the Fuel Cell System that are routed through the aft pressure bulkhead.	Aft Pressure Bulkhead Rupture	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]	Yes	DS 0-3	ZSA Interaction Matrix	Covered at a high-level as otherwise more detail is required
48	The lower fuselage could receive damage during a wheels up landing. It shall be ensured that neither pressure vessels nor hydrogen/oxygen/fuel lines will be installed in the given deformation area. The Fuel Cell System installation shall be out of the tail strike area of the specific aircraft considered.	Wheel-up landing	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]	No	DS 0-3	-	Potential to be covered by CZSA by adding crash landing as a particular risk.
49	Redundant Fuel Cell System functions that are essential for continued safe flight and landing	Survivability of Systems	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]	No		ZSA (Out of CZSA scope)	

50	The fuel cell system and components shall comply with the equivalent of ED-14 and DO-160 (Environmental Conditions and Test Procedures for Airborne Equipment). The following intrinsic risks shall be considered for fuel cell module design: •Electric hazards - overcurrent/ short circuit, ionization and electrical shock. •Thermodynamic and fluid hazards - temperature (hot surfaces). Failures of the fuel cell stack module resulting in surface temperatures exceeding the operational range of the stack shall not pose a risk to the zone where the stack is installed. •Chemical Hazards - H2 embrittlement, flammability toxicity (hydrogen-fluoride emissions), Asphyxiation (by H2/ODA), leakage (cooling fluid). •Fuel cell reversal – negative voltage as a result of fuel starvation, over temperature, dehydration etc., which may cause internal or external leaks. •Biological Hazards - fungus or mold. •Protect FCS Components from mechanical damage. •Protect FCS from unauthorized access. •Protect FCS from external environmental effects, e.g., Heat, Dust, external fluids, etc	Environmental Considerations	Hydrogen Fuel Cell System	Installation of Fuel Cell Systems in Large Civil Aircraft AS6858 [59]	Yes (Partially)		CZSA Interaction Matrix	

51	Hydrogen may be stored in the liquid phase at -253 °C (-423 °F) at atmospheric pressure. The associated hazards can be mitigated through: • Choice of specific materials compatible with cryogenic temperature and manufacturing processes. • Avoiding trapping liquid or very cold gaseous hydrogen in transfer pipe and valve assemblies and use of pressure relief devices. • Complete thermal insulation and contact protection from cold parts.	Overpressure and potential burst in case of boil-off or vapor expansion of liquid hydrogen	Hydrogen Fuel Cell System	Considerations for Hydrogen Fuel Cells in Airborne Applications AIR7765 [95]	No	-	-	Potential to be implemented, at least partially
52	Oxygen pressure tanks, and lines between tanks and the shutoff means, must be protected	Unsafe temperature	Oxygen	§25.1453 Protection of oxygen equipment from rupture. [65]	Yes	DS 0-3	CZSA Interaction Matrix	CZSA highlights the risk of high temperature
53	Oxygen pressure tanks, and lines between tanks and the shutoff means, must be located	Crash landing	Oxygen	§25.1453 Protection of oxygen equipment from rupture [65]; ARP5021B [88]; AIR825_12A [63]	No	DS 0-3	-	Potential to be covered by CZSA by adding crash landing as a particular risk.
54	Prior to system design the oxygen cylinder installation should be evaluated by a hazard,	UERF	Oxygen	ARP5021 B Oxygen Cylinder Installation Guide [88]	Yes	DS 0-3	CPRA	

55	Prior to system design the oxygen cylinder installation should be evaluated by a hazard, particular risk, and/or zonal analysis, covering repercussions of: Compatibility with surrounding systems	Oxygen hazard	Oxygen	ARP5021 B Oxygen Cylinder Installation Guide [88]	Yes	DS 0-3	CZSA Interaction Matrix	
56	Prior to system design the oxygen cylinder installation should be evaluated by a hazard, particular risk, and/or zonal analysis, covering repercussions of: Cylinder burst should not lead to a	High-Pressure Vessel Burst	Oxygen	ARP5021 B Oxygen Cylinder Installation Guide [88]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	Taken into account in the component intrinsic risk (pressurized, hazardous or oxygen fluid leakage)
57	Prior to system design the oxygen cylinder installation should be evaluated by a hazard, particular risk, and/or zonal analysis, covering repercussions of: Consequences of oxygen leakage, in particular that the installation area, is sufficiently ventilated to ensure the oxygen concentration will not	Oxygen leakage	Oxygen	ARP5021 B Oxygen Cylinder Installation Guide [88]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	Taken into account in the component intrinsic risk (pressurized, hazardous or oxygen fluid leakage)
58	Prior to system design the oxygen cylinder installation should be evaluated by a hazard,	Vibration and Accelaration	Oxygen	ARP5021 B Oxygen Cylinder Installation Guide [88]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	Taken into account in the zone risk for vibration and component intrinsic risk (pressurized, hazardous or oxygen fluid leakage)

59	Oxygen cylinder(s), associated lines, and equipment shall be protected against high	Fire	Oxygen	ARP5021 B Oxygen Cylinder Installation Guide [88]	Yes	DS 0-3	CZSA Interaction Matrix	If in a designated fire zone, the CZSA matrix flags this as the highest risk (requirement not met)
60	Oxygen lines and supply components shall not be mounted below other lines or tanks that contain combustible fluids that could leak onto the oxygen tubing. In particular, no fuel, oil or hydraulic fitting	Proximity to Combustibles	Oxygen	Oxygen System Integration and Performance Precautions AIR825_12A [63]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix (High-level)	Physical location assessment requires ZSA level 3
61	Proximity to moving parts, electrical wiring and components should be checked.		Oxygen	Oxygen System Integration and Performance Precautions AIR825_12A [63]	Yes	DS 0-4	CZSA Interaction Matrix	
62	Reducing valve(s) should be installed as close as practicable to high pressure oxygen cylinder		Oxygen	Oxygen System Integration and Performance Precautions AIR825_12A [63]	No	DS 0-2	-	Coul be implemented but detailed model required

63	Oxygen cylinder(s) and lines shall be protected against high temperatures and shall not be	Designated Fire Zone	Oxygen	Oxygen System Integration and Performance Precautions AIR825_12A [63]	Yes	DS 0-3	CZSA Interaction Matrix	This requirement has two parts, the first can be evaluated in the CZSA matrix, and the second one should be flagged as the highest risk (requirement not met) in the CZSA
64	Parts of an oxygen system should be above and at least 150 mm (6 in) away from fuel, oil and hydraulic systems or areas where leakage of combustibles can collect. If, for design reasons, it is not possible to maintain the above-mentioned minimum clearance, then the oxygen line shall be covered by a protective sleeve. Deflector plates should also be used to keep liquids (including high pressure spray) away	Proximity to Combustibles	Oxygen	Oxygen System Integration and Performance Precautions AIR825_12A [63]	No	DS 0-3	ZSA Level 3(Out of CZSA scope)	The first part could be implemented and the second is addressed as a risk minimization measure.

65	There should be at least a 50 mm (2 in) clearance at maximum point of movement or deflection between oxygen plumbing and equipment components and any moving aircraft parts. If this minimum clearance is not achievable, the oxygen line must be shielded against mechanical damage by assuming the worst load factors for the shield. Particular attention should be paid to clearance to primary flight and engine controls where the distance should not be less than 12 in.	Proximity to Moving Aircraft Parts	Oxygen	Oxygen System Integration and Performance Precautions AIR825_12A [63]	No	DS 0-3	ZSA Level 3(Out of CZSA scope)	The first and third parts could be implemented, and the second is addressed as a risk minimization measure.

66	When possible a 150 mm (6 in) clearance should exist. When this is not possible or practical a 50 mm (2 in) minimum is acceptable provided that the electrical wiring or wire bundles are rigidly supported by conduit and/or closely spaced clamps or clips. When less than 50 mm (2 in) separation is necessary wires or wire bundles and electrical components must have additional insulation and be so supported that they cannot deflect closer than 13 mm (1/2 in) from the oxygen components. As an additional protection the appropriate area of the oxygen line may be isolated by a retractable hose guard of non-corrosive material. Further, oxygen tubes and tube fittings shall not be closer than 50 mm (2 in) without insulation to any electrical components such as relays that may be a fire source.	Proximity of Plumbing to Electrical Wiring	Oxygen	Oxygen System Integration and Performance Precautions AIR825_12A [63]	No	DS 0-3	ZSA Level 3(Out of CZSA scope)	
67	There must be complete drainage of each part of each designated fire zone to minimize the	Designated Fire Zone		§25.1187 Drainage and ventilation of fire zones. [89]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	If not met, it is flagged in the CZSA matrix as high risk (requirement not met)
68	Each designated fire zone must be ventilated to prevent the accumulation of flammable	Designated Fire Zone		§25.1187 Drainage and ventilation of fire zones. [89]	Yes	DS 0-3	CZSA Interaction Matrix	If not met, it is flagged in the CZSA matrix as high risk (requirement not met)

69	No ventilation opening may be where it would allow the entry of flammable fluids, vapors, or flame from other zones. Each ventilation means must be arranged so that no discharged vapors will cause an additional fire hazard.	Designated Fire Zone		§25.1187 Drainage and ventilation of fire zones. [89]	Yes (Partially)	DS 0-3	CZSA Interaction Matrix	If not met, it is flagged in the CZSA matrix as high risk (requirement not met)
70	Minimum separation between redundant systems, §25.795(c)(2)(i) defines the following formula, which is derived from §25.365(e), governing hole size for consideration of rapid decompression: $D = 2\sqrt{H_0/\pi} = 2\sqrt{(PA_S)/\pi}$ Where: $H_0 = PA_s$ = the hole size from §25.365(e); D = the diameter of a sphere that represents minimum separation distance between redundant systems in feet; As = maximum cross-sectional area of pressurized shell normal to the longitudinal axis in square feet; and $P = A_S/6240 + 0.024$ The separation distance, D, need not exceed 5.05 feet. The designer should use this formula anywhere within the pressurized fuselage.	Survivability of Systems	All	Survivability of Systems AC 25.795-7 [66]	No	DS 0-2	ZSA Level 3 (Out of CZSA Level 0, 1 and 2 scope)	

Appendix C

Penalization of Critical Interactions

Table C.1: Penalty distribution for zone-component interactions.

				Component Intrinsic Risks											
				Fluid Leakage Susceptibility: Presence of Fluids				Component Operating Temperature			Electrical system components and wiring			Material	Component with moving parts
Description			Risk Score	Hazardous	Pressurized	Oxygen	Flammable	$T_{comp\_Op(max)}$ & $T_{comp\_Fail}/T_{zone\_Av} \leq 1$	$T_{comp\_Op(min)}/T_{zone\_Av}>1$ OR $T_{comp\_Op(max)}/T_{zone\_Av}>1$	$T_{comp\_Fail}/T_{zone\_Av}>1$	No	Wires OR Machines	Power <200W OR >200W	Flammable	No/Yes
				1/2	1/2	1/2	1/2	0	0/1	2	0	1/2	1/2	0/1	0/1
Zone Environment	Temperature	Controlled	0												
		Not Controlled	1												
	Pressurized	Yes	0												
		No	1												
	Vibration	No	0												
		Low	1												
		High	2												
	Humidity	Standard Humidity Environment (environmentally controlled zone)	0												
		Severe Humidity Environment (not environmentally controlled zone)	1												
	Ventilation	Present	0												
		Not Present	1												
	Drainage	Present	0												
		Not Present	1												
	Packing Density	0%-33%	0												
		33%-66%	1												
		66%-100%	2												
Particular Risk Flag	Lightning Strike	Zone 1A: First return stroke zone	1												
		Zone 1B: First return stroke zone with long hang on	2												
		Zone 1C: Transition zone for first return stroke	1												
		Zone 2A: Swept stroke zone	1												
		Zone 2B: Swept stroke zone with long hang-on	2												
		Zone 3: Attachment of lightning channel is unlikely	0												
	Susceptibility to FOD (bird strike)	No	0												
		Low	1												
		High	2												
	Oxygen Hazard: Presence of Oxygen System Components	No	0												
		Yes (lines)	1												
		Yes (tanks)	2												
	Fire zone	Non-hazard zone/Low hazard zone	0												
		Ignition zone	1												
		Flammable Zone	1												
		Flammable Fluid Leakage Zone	2												
		Designated Fire Zone	2												
Zone Component Risks	Fluid Leakage Susceptibility: Presence of Fluids	Non-hazardous	0												
		Hazardous	1												
		Non-pressurized	0												
		Pressurized	1												
		Non-flammable	0												
		Flammable	1												
	Electrical system components	No	0												
		Wires	1												
		Machines	2												
	Components with moving parts	No	0												
		Yes	1												

Legend: High Risk- Unacceptable interaction; Medium Risk- Considerable impact; Low Risk- Minimization possible