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Model-Based Systems Engineering Approach for a Systematic Design of Aircraft Engine Inlet

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Model-based systems engineering (MBSE) is known to streamline complex system design by providing a unified, model-based approach to capture, analyze, and simulate system requirements, behavior, and structure throughout the development lifecycle. This study applies MBSE to the design of aircraft engine inlets, specifically integrating Systems Modeling Language (SysML) in the process. The study leverages MBSE's systematic approach to enhance collaboration and traceability in the design process. Utilizing a structured Requirements, Functional, Logical, Physical (RFLP) process with MagicDraw and a realistic set of industry-defined requirements from Collins Aerospace, the study incorporates design constraints, regulatory requirements, and stakeholder preferences to ensure safety, reliability, and environmental compliance. The MBSE approach could provide a unified platform for communication and decision-making, mitigate risks, reduce development time and costs, and facilitate the delivery of superior propulsion systems. In a first, this study demonstrates the transformative potential of MBSE in enhancing design efficiency and fostering innovation, particularly for electric and hydrogen-powered propulsion systems.

I. Nomenclature

AR	=	Aerodynamic requirement
ARCADIA	=	Architecture Analysis and Design Integrated Approach
CFR	=	Code of federal regulation
CPU	=	Central processing unit
EBU	=	Engine build up
EMIR	=	Electromagnetic induction requirement
FCR	=	Fire containment requirement
FOD	=	Foreign object damage
GWR	=	Guaranteed weight requirement
ISR	=	Icing system requirement
MBSE	=	Model-based systems engineering
MDAO	=	Multidisciplinary Design Analysis and Optimization
NR	=	Noise requirement
PSTR	=	Protection and surface treatment
P_2T_2	=	Ambient pressure and temperature during flight operation

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RFLP = Requirements engineering, functional design, logical design, and physical design
SysML = Systems modelling language
SDR = Structures and design criteria requirement
U-M = University of Michigan

II. Introduction

The aviation industry continuously explores innovative approaches to enhance the performance, efficiency, and safety of aircraft and their subsystems. The evolution of aircraft design process is a testament to the relentless pursuit of excellence in aeronautics. From the rudimentary piston engines of the past to the sophisticated turbofan engines of today, each iteration represents innovation and engineering prowess. Yet, as aircraft evolve and diversify, the methodologies employed in their design and development must also evolve [1].

In recent years, the rapid evolution of aircraft technology, coupled with stringent regulatory requirements and environmental considerations, has underscored the critical need for robust and efficient design processes. The quest for optimal performance, fuel efficiency, and environmental sustainability has propelled design engineers to explore new methodologies and technologies in the pursuit of next-generation aircraft and propulsion technologies [2]. Model-based systems engineering (MBSE) has emerged as a transformative framework for the systematic design and development of aircraft and their subsystems. MBSE is helpful for designers to gain a comprehensive understanding of the entire system early in the design process. By leveraging advanced computational modeling and simulation techniques, MBSE offers a holistic and integrated approach to address and capture the complex interdependencies among various subsystems and disciplines in aircraft design [1–3].

Aircraft design involves collaboration between diverse engineering teams such as aerodynamics, structures, avionics, and propulsion. Conventional design approaches often involve different disciplines working in isolation, leading to significant challenges in subsystem integration. Traditional methods struggle to accommodate the multidisciplinary nature of modern aircraft subsystem design and integration, resulting in fragmented development efforts, increased costs, and prolonged time-to-market. In contrast, MBSE provides a unified platform that facilitates collaboration among diverse engineering disciplines, enables early-stage validation of design concepts, and supports seamless integration of system components [1,4].

At the core of MBSE lies Systems Modeling Language (SysML), a tool that enables engineers to capture, analyze, and visualize the intricate interdependencies inherent in systems design [4]. SysML provides a standardized framework for expressing system architectures, behaviors, and requirements, empowering engineers to tackle the multifaceted challenges of aircraft systems design with clarity and precision [5]. By integrating SysML with advanced simulation tools, designers can simulate and analyze the performance of aircraft subsystems under various operating conditions, identify design trade-offs, and make informed decisions throughout the design lifecycle [5,6]. For example, engineers can readily understand how changes in one aspect (e.g., wing design) impact other parts of the system (e.g., weight distribution, flight performance, etc.), thereby reducing misunderstandings and miscommunication between respective teams and resulting rework. s

SysML promotes the creation of a single source of truth, a central model encompassing the entire aircraft system's structure, behavior, and requirements. This fosters clear communication and traceability across disciplines [5,7]. MBSE fosters a deeper understanding of complex engineering systems by establishing digital thread that connects requirements, architecture, behavior, and verification/validation activities. Moreover, the iterative nature of MBSE enables engineers to rapidly iterate on designs, assess design trade-offs, and optimize system performance in real-time [1,8,9].

Studies [3,4,7–24] have demonstrated the versatility and effectiveness of the MBSE/SysML approach in various aviation applications. Booth et al. [17] proposed leveraging MBSE for designing the aircraft missions. Pessa et al. [15] applied MBSE to the design of a control maintenance system for an aircraft fuel system, using the IBM Rational Rhapsody® tool and the Harmony® methodology. Wang et al. [14] proposed a step-by-step design method based on MBSE and SysML for the high lift system of a civil aircraft, emphasizing the clarity and reliability of the design process. Fei et al. [23] developed a generic MBSE methodology for aviation system design, addressing the complexity of interactions between components. Kulkarni and Price [16] applied MBSE to the design of a gas turbine tip clearance control system for a Trent XWB engine, focusing on capturing system level requirements and functional aspects, using the Capella software and the Architecture Analysis and Design Integrated Approach (ARCADIA) framework. Similar to the study by Kulkarni and Price [16], the scope of this work is reduced to aircraft powerplants or propulsion systems and there are a limited number of studies which apply MBSE towards design of aircraft powerplants.

The aircraft propulsion systems are marvels of engineering and push the boundaries of power generation while ensuring exceptional safety and reliability. However, the increasing demands for improved fuel efficiency, reduced emissions, and noise pollution without increasing weight and cost of the overall design necessitate a fundamental change in engine design [25]. Traditional document-centric approaches, while successful in the past, struggle to manage the growing complexity of modern engines and their intricate interactions with the overall aircraft system.

Propulsion system design spans over the entire development cycle of an aircraft and is one of the most critical initial decisions made by an airframer. These propulsion systems are designed jointly between three or more separate entities including the airframer, engine manufacturer, and an equipment supplier developing the nacelle, generators, and other critical systems. Traditionally these teams have managed communication about critical aspects of the design via exchanged documentation and a set of agreed upon design and stress models which include the latest set of design iterations between the three groups. While this exchange of models and documents have been sufficient for the design of these complex systems in the past, their use often requires further clarification (version control of documents, difficulties in visualization of the system interfaces, engine, and aircraft settings throughout the design mission) throughout the design process which can slow down development. The clarifications required can often lead to communication gaps, inconsistent data across without robust version control, and difficulty in visualizing the overall system design for system-level trades. All these impacts can and often do result in costly design errors and delays in the development cycle. Additionally, the models themselves benefit designers by allowing traceability from the requirements being addressed to the characteristics of the overall system design. This can be beneficial in later stages of development where significant learning has taken place and designers must trace those changes through their design decisions to understand their impacts. The use of MBSE/SysML can enable a systematic and digital propulsion systems design process.

MBSE, by enabling the exchange of models as opposed to documentation, allows these inter-disciplinary teams to collaborate and evaluate each other's designs in ways that would have been far more difficult in the state-of-the-art methods. The use of models and the single source of truth is meant to eliminate inconsistencies and communication gaps that required strict version control at each of the design entities. By enabling visibility by the suppliers and OEMs to each other's relevant interfaces as well as the compliance to each other's requirements the design discussions can begin at a shared understanding of the design limitations thus reducing the delays due to communication gaps. Additionally, due to the shared single source of truth, changes by one or more of the performing entities can quickly be relayed to the other interested parties resulting in a faster turnaround on design changes as more information is ultimately learned about the system during its design. Ultimately, by embracing MBSE as a fundamental paradigm for aircraft engine design, the aviation industry can pave the way for a new era of innovation, efficiency, and sustainability in aviation propulsion systems design [25].

A structured RFLP (requirements engineering, functional design, logical design, and physical design) is employed in some MBSE applications [26]. The RFLP process is crucial in the early stages of product design. This process is particularly suitable for breaking down requirements into functions that can subsequently be assigned to logical and physical elements [26]. Studies [25,27–32] have applied MBSE/SysML to different types of aircraft propulsion systems – jet engines, and hybrid-/electric- propulsion systems. These studies collectively demonstrate the potential of MBSE and SysML in enhancing the design process for aircraft propulsion systems. However, these studies do not consider a structured and systematic RFLP process towards the design of propulsion systems. Through the synthesis of the comprehensive review of existing literature above, the key principles, methodologies, and best practices associated with the application of MBSE in aircraft propulsion systems design, are elucidated.

The present study is a collaborative research work between researchers at the University of Michigan and Collins Aerospace. A detailed set of real-world aircraft gas turbine engine inlet design requirements are available from Collins Aerospace. This work proposes a transformative approach to aircraft engine inlet design – an MBSE approach leveraging the power of SysML and identifying key challenges and opportunities for further research and development in this rapidly evolving field.

The objective of this work is to employ the RFLP process of MBSE towards formulating a systematic digital design process of the engine inlet using MagicDraw tool [33] based on the engine inlet design requirements from Collins Aerospace. By showcasing the application of MBSE in this specific context, a compelling case for MBSE's transformative impact on the future of aircraft propulsion design is provided, especially electric and/or hydrogen-powered propulsion (qualitatively), due to the flexibility offered by MBSE along with traceability. In this work, the application of MBSE in the context of aircraft engine inlet design is explored, with a focus on its role in enhancing design efficiency, mitigating risks, foster interdisciplinary collaboration, facilitate rapid iteration and optimization, and accelerating the development lifecycle. The use of an MBSE integrated engine design process is of significance to the industry in the long-term within the context of the evolution of the design process. In this work, the authors build an MBSE model with applicability to advanced propulsion systems in mind as future work. Also, in this work, the authors qualitatively showcase how the model could be used for electric/hydrogen propulsion. The ability to explore design alternatives efficiently, conduct virtual tests to assess engine behavior, and maintain regulatory compliance throughout the development cycle paves the way for a new generation of aircraft engines – powerful, efficient, and environmentally responsible – propelling the aviation industry towards a brighter, more sustainable future.

III. Methodology

In this work, the RFLP process of MBSE is employed for formulating a systematic digital design process of the engine inlet using MagicDraw based on the engine inlet design requirements from Collins Aerospace. The core requirements for this work were provided by Collins Aerospace and are listed in Table A.1 in Appendix A which are 54 in number. The requirements are for a general nacelle inlet, with proprietary information removed.

A. MBSE approach

MBSE is the "formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases" [34]. While the concept has existed for more than twenty years, interest in MBSE has intensified significantly in recent years in both academia and in the aerospace industry due to its potential for improved traceability, increased capacity for reuse, and reduction of cost, time, and errors [34].

By embracing a system-centric approach to design, MBSE transcends the limitations of traditional siloed methodologies, allowing engineers to consider the aircraft powerplant as a holistic system comprised of interconnected subsystems and components. Through the lens of MBSE and SysML, engineers can seamlessly integrate aerodynamic, thermodynamic, and structural considerations into the design process, ensuring that every aspect of the aircraft powerplant is optimized for performance, efficiency, and reliability [1–4].

MBSE facilitates the incorporation of design constraints, regulatory requirements, and stakeholder preferences into the design process, ensuring that the resulting aircraft propulsion system meet the highest standards of safety, reliability, and environmental compliance. By providing a unified platform for communication and decision-making, MBSE mitigates risks associated with design uncertainties, reduces development time, and costs, and ultimately leads to the delivery of superior propulsion systems that exceed customer expectations [1–5,8,15].

Additionally, MBSE allows designers and program managers to manage complex systems without the use of fixed design documents which may create an incomplete view of the final system at the end of the program. The resultant models from the MBSE process enable 'living' model which documents the features of a system along with the logic and traceability that designers used to arrive at the system level characteristics. This is beneficial to future programs where engineers can query a model for design logic as opposed to an individual or a design document which may be out of date.

Due to the relative recent development of MBSE, many of the benefits associated with the process have not yet been proven [34], prompting a need for studies such as this one to methodically explore the impact of MBSE processes on a development cycle. This work focuses on the ways that MBSE can be used to support traceability in complex projects, such as those that involve many stakeholders working in a variety of different companies and environments. In these situations, there is a need for improved communication in a common language, and the unified model created through the MBSE process offers an organized way to do so. Similarly, traceability – the process of verifying that requirements are properly flowed down to the system, subsystem, and component levels – can be done in a more formalized manner using MBSE tools, which ensures that the finalized product meets customer needs and avoids costly delays due to design oversights.

B. RFLP process

This work focuses on the use of MBSE through an RFLP approach. RFLP was chosen for its utility in the initial stages of the product design life cycle, as the RFLP process is ideal for decomposing requirements into functions that can then be allocated to logical and physical components [26]. The first step of the RFLP process is requirements design. The functional design emerges from requirements design, and the logical and physical design architecture is based on the functional design (and requirements design) [$R \rightarrow F \rightarrow L$ and P].

The RFLP approach is particularly advantageous for projects involving modifications to existing systems (e.g., the electrification of an existing aircraft), so that efforts can be concentrated on the areas being impacted and redundant work can be avoided. The goal, therefore, of the RFLP approach is to streamline the requirement verification and validation processes and minimize the associated time and costs [26].

It should be noted that this work primarily concentrates on the first three sections of the RFLP approach, that is, the requirements engineering, functional design, and logical design. This study considers physical design at a preliminary level, focusing on high-level requirements rather than detailed hardware specifications. Further research is required to incorporate proprietary information and more advanced physical modeling. While all the given requirements are categorized and included in the requirements interrelation map, and all the functions were decomposed, only the functions related to the logical system were allocated to components in the system.

C. Tools used - MagicDraw

The inlet requirements provided by Collins were organized and decomposed using Dassault Systèmes's MagicDraw software, a highly customizable SysML and unified modelling language (UML) 2.5.1-compatible modeling tool [4,6,35]. It is to be noted that MagicDraw operates on the same software as Cameo and can be considered synonymous. Both SysML and UML are modeling languages intended to provide a standardized way to display a system, though SysML can be considered a retooled version of UML that is better-suited for systems engineering applications, as SysML expands the software-centric UML framework to include hardware, processes, requirements, etc. [4,6,35]. For this reason, SysML diagrams were used within MagicDraw rather than the more general UML diagrams.

While other MBSE software programs, such as Capella or HarmonySE, exist, MagicDraw was selected for this work because MagicDraw works with SysML and supports a wide arrange of systems engineering activities, while Capella is restricted to a unique ARCADIA-based domain modeling language and HarmonySE is more limited in terms of the systems engineering activities it supports [4,6,35,36]. In addition to its capability as tool for creating models, MagicDraw also offers analysis of the system and system interfaces via traceability and dependency matrices, executable requirements, and simulation capabilities [4,6,35,36]. By showcasing the application of MBSE/SysML in this specific context, there could be a transformative impact on the future of aircraft propulsion design, especially electrified and/or hydrogen-powered propulsion, due to the flexibility offered by MBSE/SysML along with traceability. The SysML diagrams in MagicDraw used to capture the various stages of the RFLP process are listed in Table 1.

Table 1. SysML diagrams in MagicDraw used to capture the various stages of the RFLP process

Stage	Purpose	Diagram used
Requirements Engineering	Organizing and categorizing given requirements	Requirements table
	Verifying stakeholder requirements with internally defined requirements	Traceability matrix
	Capturing and displaying interrelations between requirements	Requirements diagrams
	Capturing and displaying interrelations between requirements	Dependency matrix
Functional Design	Decomposing functions into subfunctions	Activity diagrams
Logical and Physical Design	Interfacing the physical components with logical components for enabling set of functions	Internal block diagram

D. Process of requirements formulation

The requirements provided by Collins Aerospace (Collins) required additional transformation and organization prior to use in the MagicDraw model. Initially, the requirements from Collins were grouped by type without any hierarchical structure applied. These requirements were uploaded in the MagicDraw model as 'stakeholder needs.' To begin organization of the requirements, the University of Michigan (U-M) requirement sections were designated to match the sections provided by Collins, as shown in Table 2.

Next, each requirement line from the Collins requirements was allocated to a section in the U-M requirements. The requirements were then read carefully to determine if any could be condensed or otherwise modified to help the modeling process while keeping the intent of requirement intact. Examples of requirements that were changed are included in Table 3. Each section listed in Table 3, will be referred to as a ‘block’ in the RFLP process (example: AR is aerodynamics block, NR is noise block, etc.).

Once the U-M requirements were finalized, the requirement diagram (model) was created in the MagicDraw model. A verification/traceability matrix was then created within MagicDraw where each U-M requirement was traced back to at least one Collins requirement. This ensured that moving forward the U-M requirements captured each of the stakeholder requirements originally defined by Collins. The U-M requirements are 55 in number. These requirements are further classified into 42 product and 13 process requirements. A product requirement is a requirement which conveys an operation or a task to be performed (function-oriented requirement), and a process requirement is a requirement with specific characteristics of a sub-system and/or a pathway to achieve the characteristics. The U-M requirements with their product and process classifications are included in Table A.2 in Appendix A.

Table 2. U-M requirement sections

U-M requirement section code (Block)	Collins requirement section title
ISR	Icing system
AR	Aerodynamic
NR	Noise
FCR	Fire containment – passive fire protection
EMIR	Electromagnetic induction (EMI) and lightning strike protection
PR (P_2T_2)	T_2 or P_2T_2 (Ambient temperature and pressure probe)
SDR	Structures and design criteria
PSTR	Protection and surface treatment
GWR	Guaranteed weight

Table 3. Modified requirements list

Collins requirement	U-M requirement(s)	Reason for change
(SK-4) The inlet lip skin shall be protected against ice accretion to the level necessary to prevent potentially harmful ice accretion on the inner surface of the inlet as defined by the certifying requirements of code of federal regulation (CFR) 25, without the use of special operating procedures. This applies for both maximum continuous and intermittent icing conditions as defined within CFR 25	(ISR 1.2) The anti-icing system shall prevent ice accumulation on critical components of the inlet system	The Collins requirement SK-4 was condensed because it is not guaranteed that future inlet designs will be required to comply under 14 CFR 25. The condensed requirement still captures the nature of the requirement.
(SK-24) All aerodynamically exposed fasteners shall be nominally flush with a maximum step of +X in. and -X in.. Use of dimpled washers shall be minimized as much as possible	(AR 1.3) Aerodynamically exposed fasteners shall be nominally flushed with a maximum step of +/- A2 (AR 1.4) Minimal use of dimpled washer	The Collins requirement was converted into two separate requirements, as they contribute to separate functions of the nacelle inlet.

The U-M requirements were categorized by type, based on definitions from the MagicDraw documentation (Table A.3 in Appendix A). Of the eight possible requirement types, only physical, design constraint, functional, and performance types were used in this model. In the future, interface requirements will be necessary to model interactions between the inlet and other nacelle system components.

The U-M requirements were organized hierarchically, with sub-requirements identified through internal analysis and feedback from Collins. These were nested under their parent requirements within the model. A high-level requirement was also established for each U-M requirement section, with all related sub-requirements grouped accordingly. Outside of the hierarchical structure, interrelations between different requirements within the same section were identified and added onto the MagicDraw model using the general 'allocation' tool. To determine how different requirements were related, shared components, functions, materials, operating conditions, or other similarities were identified. For example, AR 1.1 ('*surfaces shall conform to loft contours provided*') is dependent on ISR 1.2 ('*the anti-icing system shall prevent ice accumulation on critical components of the inlet system*'). In this context, ISR 1.2 (due to ice accumulation on inlet) will affect AR 1.1 (contours of the inlet surface), i.e., ice accumulation would directly cause an increase in drag. After determining intra-block relations, inter-block relations were added to the model to demonstrate how different requirements can interact with requirements outside of their subsection. These inter-block relations enable traceability between requirements.

E. Process of functional decomposition

Following the requirements formulation and the identification of interactions and interrelationships between different requirements in the RFLP process, the next step is functional decomposition.

Table 4. High-level functions for all engine inlet design blocks

Block/Aspect	Req. code	Requirement
Aerodynamics	AR_1	The inlet system shall meet the drag obligations
Anti-icing system	ISR_1	The anti-icing system shall meet all design and performance requirements over the entire flight envelope
Noise	NR_1	The inlet shall meet all acoustic design and performance requirements
Weight	GWR_1	The guaranteed weight of the inlet system shall be W1 for the basic configuration
Fire containment	FCR_1	The inlet system should be segregated from other parts of the nacelle so that it is not a fire zone
Electromagnetic induction	EMIR_1	The inlet system shall be protected from EMI and lightning strikes
P_2T_2 probe	PR_1	The T_2/T_2P_2 probe shall meet all design and performance requirements
Protection and surface treatment	PSTR_1	The inlet structure shall use materials, coatings, and processes that are of high strength that are selected regarding health, safety, corrosion/erosion, and lifecycle requirements.
Structures and Design criteria	SDR_1	The inlet structure shall demonstrate structural capability and maintain airworthiness at the ultimate load condition
	SDR_2	The inlet structure shall withstand and not show permanent deformation at the limit load condition
	SDR_3	The inlet structure shall not have any life-limited components
	SDR_4	Structural components of the inlet shall meet all design requirements.

Table 5. Examples of identifying function from requirement and its decomposition

ID	Requirement	Type	Basic function	Functional decomposition
AR_1.1	Surfaces shall conform to loft contours provided	Product	Meet targeted drag and manufacturability	Identify aerodynamic surfaces; Create a contour profile; Ensure that aerodynamic surfaces conform during lofting within the contour profile
NR_1.2	The acoustic liner shall be designed to provide a drainage solution among other and minimize impact on acoustic performance	Process	Reduce noise and prevent fluid accumulation	Does acoustic liner provide a drainage solution? If no, redesign and loop, if yes, check if the impact on acoustic performance can be reduced. If yes, redesign and loop; if not, then done.

For each U-M requirement, a high-level function is identified, and that function is executed in multiple steps or using a flowchart (depending on the type of requirement). Table 4 lists all high-level functions for different engine inlet design blocks. In Table 5 two examples are included, one each of product (AR 1.1) and process (NR 1.2) requirement type, where a basic function is identified from the requirement followed by decomposition of this function into multiple steps (function execution). The full list of the 55 U-M requirements and their corresponding functions, is included in Table A.4 in Appendix A. These functional decompositions are input to the MagicDraw model and results will be in form of 'activity diagram' as discussed earlier.

F. Process of logical and physical design

The next step in the RFLP process after functional design (decomposition) is logical design. Typically, the logical and physical design are conducted together. The 'logical' part of this process is an interaction between different physical hardware to execute function(s) based on requirement(s). As noted earlier, the scope of this work is limited primarily to RFL but a preliminary level physical design is considered. Given the need for physical hardware elements to conduct logical decomposition, only the physical hardware (of the inlet) that are required for a given set of requirements and functions are considered.

Table 6. Physical elements and logical elements identified for the logical and physical design

i. Operations/performance based design	
List of physical elements	List of logical elements
a. Icing system	
Icing system sensor	Signal
Engine anti-ice bleed valve	Damage
Swirl nozzle	Pilot controls
Inlet structure	
Inlet barrel	
Aircraft central processing unit (CPU)	
Engine	
Pilot	
Visual ice indicator	
Display	
b. Fire, lightning strike and bird impact based structural damage design requirements	
Fire detection sensor	Damage
Deformation damage	
Bird/Hail/Foreign object damage (FOD)	
Lightning strike	
Aerodynamic surfaces	
Acoustic surfaces/areas	
ii. Inspection and maintenance based design (due to damage)	
Aspects	Physical element/properties
Structure	Corrosion, functional mechanical joints, structural integrity, positioning of cowl without error, airworthiness, and permanent deformation
Noise	Acoustic liner drainage, acoustic liner area, acoustic panel is one-piece panel
Protection and surface treatment	Sealants, primer, and paint for aerodynamics, noise; prevention of corrosion, static charge accumulation, and contamination; impact/scratch resistant for noise and aerodynamics
Aerodynamics	Fastener flushing, steps and gaps, surface profile, component mean deviation, and inlet aerodynamics
Fire containment	Firewalls

The logical and physical design architecture is created based on these requirements and functions. Given the type of the requirement and its structure, the logical and physical design process are divided into two categories: 'operations/performance' and 'inspection and maintenance' based design. The 'operations/performance' design primarily addresses requirements related to ISR (icing system requirements), as well as structural damage from fire, lightning strikes, and bird impacts. The remaining requirements fall under the 'inspection and maintenance' category. Table 6 lists the physical elements and logical elements identified for this design, which serve as inputs to MagicDraw and the overall architecture. It should be noted that in Table 6, the physical and logical elements in sections i.a. and i.b. are listed separately, and the connections between them have not yet been established.

IV. Results

The results comprise of diagrams from Requirements design, Functional design, and Logical and Physical design based on methodology discussed in section III.D, section III.E, and section III.F, respectively. All Figures/diagrams are available to be viewed in higher resolution using resource [37]. Additionally, the traceability and adaptability aspects of the present model to alternative propulsion systems are discussed.

A. Requirements design

The MagicDraw representation of requirements table and traceability matrix, discussed in Table 1, are in Figure B.1 (U-M requirements) and Figure B.2 (tracing U-M requirements with Collins requirements), respectively, in Appendix B. Additionally, Figure B.3 in Appendix B (should be viewed in higher resolution using resource [37]) shows a full requirements diagram. It demonstrates the interactions between different blocks and inter-relations between different requirements. It is used for exemplary purposes to show that there is a strong inter-relationship between different sets of requirements and blocks. Each of the blocks in Figure B.3 (i.e., the high-level requirement of each block) is represented with separate Figures, where each Figure shows the connection between different blocks and requirements. These will be discussed next.

Figure 1 illustrates the aerodynamic requirements diagram, showing the interactions between different blocks and interrelations between various requirements. One-directional arrows indicate that one requirement depends on another. For example, in Figure 1, a one-way arrow from ISR 1.2 to AR 1.1 signifies that AR 1.1 depends on ISR 1.2. In this case, ice accumulation on the inlet (ISR 1.2) affects the contours of the inlet surface (AR 1.1), leading to an increase in drag. Bidirectional arrows indicate interdependent requirements. For example, in Figure 1, AR 1.6 (allowable tolerance limits of steps and gaps) and AR 1.1 (contours of the inlet surface) are interdependent. This is because the inlet surface contours define the steps and gaps, and if the steps and gaps exceed the prescribed limit, it would alter the loft contour profiling. The overall objective of the AR block is to meet drag obligations, making AR 1.1 and AR 1.6 interdependent. Additionally, the yellow boxes on the right-hand side represent design constraints, linked to the specific requirements from which they originate. For example, in AR 1.5, the mean deviation for each manufactured unit at reference hot condition is defined as “constraint A1”. All constraints are labeled with variable names. Within the context of Multidisciplinary Design Analysis and Optimization (MDAO), these constraints are critical, as their values are input from the design environment, ensuring that the optimization of the engine inlet (or any other system) remains within the boundaries of these constraints.

Referring to Figure 1, there are dependencies and interdependencies among the sub-requirements of the AR block, which in turn depends on and/or affects other blocks. The AR block interacts with the ISR, PSTR, NR, and GWR blocks. Icing on the engine inlet and the operation of the anti-icing system affect the profile of the engine inlet, impacting drag obligations. Similarly, protection and surface treatments, such as paints and primers, directly impact surface drag. Within the MDAO framework, optimization of the engine inlet surface profile (aerodynamics) affects the acoustic area (NR) and the inlet weight (GWR).

Figure 2 illustrates the icing system requirements diagram showing the interactions between different blocks and interrelations among various requirements. The ISR block interacts with PR, AR, FCR, and GWR. The pressure temperature probe requirement (PR 1.2) and ISR (1.1) are interdependent, as PR 1.2 defines the thermal conditions associated with deicing system failure. As previously discussed, AR and ISR are directly associated, with the anti-icing system operation being essential for meeting the AR drag obligation. The functioning and design of the anti-icing system drive the engine inlet weight estimation, which subsequently drives other factors of the inlet design, further affecting the anti-icing system. Thus, this establishes an interdependency between ISR 1 and GWR 1. Lastly, FCR 1.2 specifies that the anti-icing system should be constructed with fireproof materials, which affects the design and operations of the anti-icing system, thereby creating an interdependency between FCR 1.2 and ISR 1.

Figure 3 illustrates the structural requirements (design criteria) diagram, showing the interactions between different blocks and interrelations among various requirements. The SDR 4 block interacts with the PSTR, EMIR, FCR, and GWR blocks. SDR 4.1 and 4.3 describe structural characteristics for preventing erosion. SDR 4.4 specifies that the structures requiring mechanical joints must be sealed. PSTR 1 describes the necessity of high-strength materials to ensure health, safety, resistance to corrosion and erosion, and overall lifecycle requirements. Therefore, SDR 4.1, 4.3 and 4.4 are essential for meeting the requirement defined in PSTR 1.

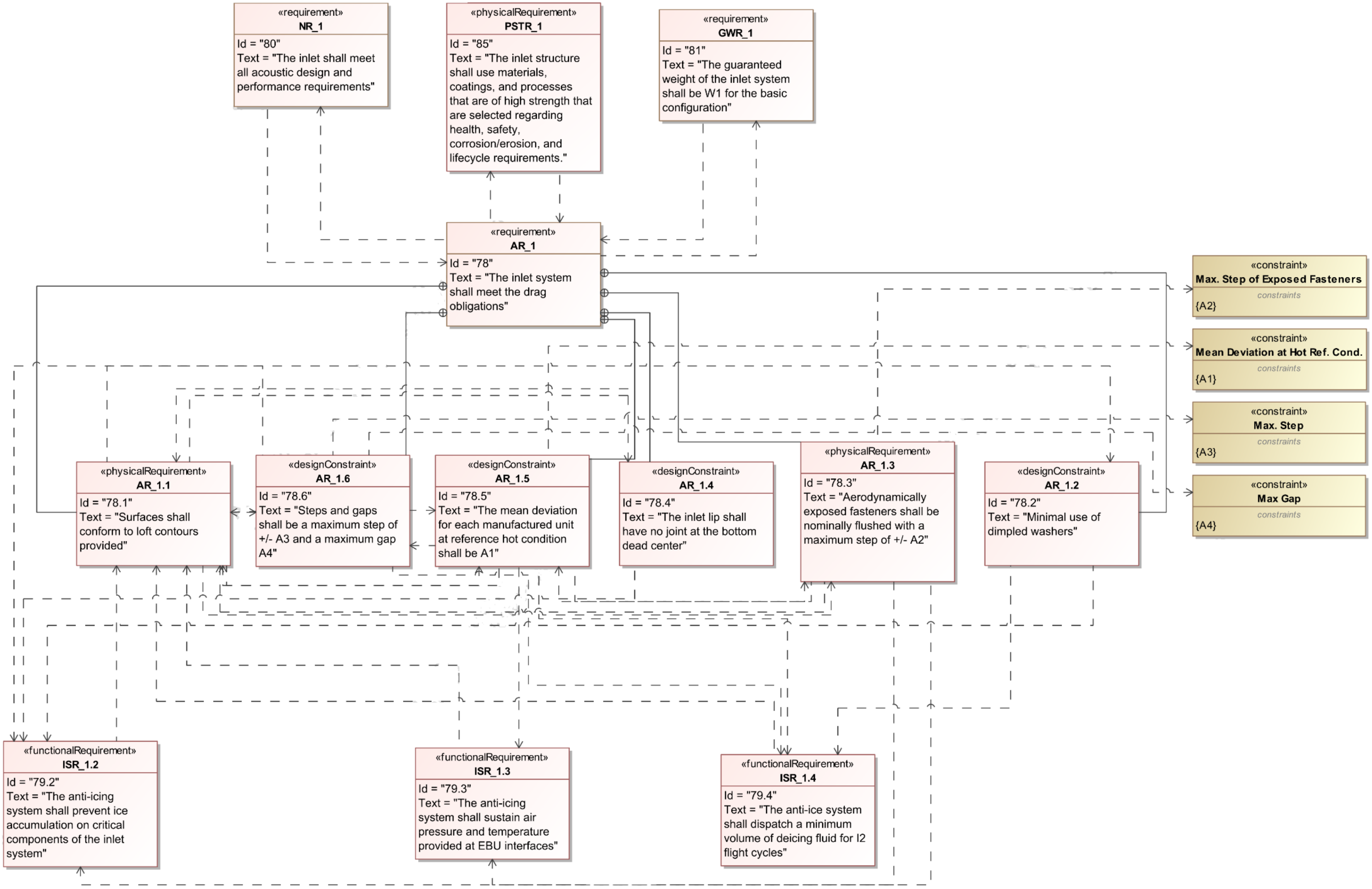
The need for resilience against lightning strikes and electromagnetic induction requires appropriate materials and structural strength to ensure safe operations. During the structural design and testing/simulation, the structure (CAD or mathematical model) will be is tested over a series of simulations, and the engine inlet structural design evolves based on multiple EMI tests. Therefore, in the context of MDAO, there is an interdependency between SDR 4 and EMIR 1. Requirements FCR 1.1 to 1.3 mandate that the subsystems must be made of fireproof construction, and these drive SDR 4.2 which details the construction of fire barriers using suitable materials to form a fireproof construction, establishing a one-directional relationship from FCR 1.1 and 1.3 to SDR 4.2. Lastly, the structural weight directly affects the gross weight, and gross weight targets affect the structural strength, especially considering the MDAO environment. Thus, GWR 1 and SDR 4 are interdependent.

Figure B.4, Figure B.5, Figure B.6, Figure B.7, Figure B.8, Figure B.9, Figure B.10, Figure B.11, and Figure B.12 in Appendix B show requirements diagram for EMI, FCR, GWR, NR, PR (P_2T_2), PSTR, structural requirements (at ultimate load condition, SDR 1), structural requirements (at limit load condition, SDR 2), and structural requirements (component life, SDR 3), respectively. As observed from Figure B.4, EMIR interacts with SDR (4 and 4.5) and PSTR (1), as they are directly related to the materials/structural strength for withstanding EMI and lightning strikes. Additionally, certain materials that are part of PSTR would prevent the electrostatic charge accumulation on the engine inlet surface. Referring to Figure B.5, FCR is directly related to ISR (1) and SDR (4.2) in terms of the requirement of a fireproof construction/structure. As observed from Figure B.6, the weight (GWR) of the engine inlet depends on and drives AR, NR, ISR, PSTR, and SDR. PSTR (1, materials for structure) and NR (1, acoustic surfaces) directly affect the weight of the engine inlet. The relation/ dependency of AR, ISR, and SDR with/on GWR has been discussed above. Figure B.7 illustrates that NR (acoustic liner/surface area) interacts with AR (1, discussed above), GWR (1, discussed above), and PSTR (1). PSTR (1) describes coating materials for structural surfaces in terms of health, safety, corrosion/erosion, and lifecycle considerations, but the coating material could have acoustic (and aerodynamic) implications, and hence are interdependent. It can be seen from Figure B.8, PR depends on SDR (1.1) and ISR (1.1, discussed previously). SDR (1.1) describes the structural strength for bird impact and interacts with PR (1.1, structural attachment strength in case of bird impact). Referring to Figure B.9, PSTR relates with AR (1), NR (1), GWR (1), EMIR (1), and SDR (4.1, 4.3, and 4.4), and these have been discussed above.

As observed from Figure B.10, SDR 1 (structural requirement at ultimate load condition and airworthiness) is related to PR 1.1 (as discussed above), GWR 1 (structural weight implications), and SDR 4.5. SDR 4.5 describes the structural resilience to lightning strikes, which directly affects the airworthiness aspect of the engine inlet. Referring to Figure B.11, SDR 2 (structural requirements at limit load condition) interacts with SDR 3.1 and GWR 1 (structural weight implications). SDR 3.1 describes the design life for a user-defined number of cycles under normal operating conditions, and this directly affects SDR 2, which requires the structure to withstand and avoid any deformation at the limit load condition. Lastly, as shown in Figure B.12, SDR 3 (structural requirements related to component life) is related to GWR 1, SDR 2, and SDR 4. As discussed previously, Figure B.3. in Appendix B presents a full requirements diagram that includes the interactions between different blocks and the interrelations among various requirements (discussed for Figure 1 to Figure 3, and Figure B.4 to Figure B.12). The information in Figure B.3 can be represented in a matrix form referred to as 'dependency matrix' (described in Table 1), which is included as Figure B.13. in Appendix B. These requirements are next considered for functional design.

B. Functional diagram

The results comprise of activity diagrams for each of the 55 high-level functions identified. Each activity diagram depicts the steps involved in achieving a function or the flow path used to achieve it. Two examples of functions are discussed for each of product and process requirements (as defined in Section III.D.). Figure 4 shows examples of functional decomposition for product requirements (AR 1.1 and ISR 1.2). The functional decomposition for product requirements type is typically a simple multistep process to execute a function. AR 1.1 states that '*surface shall conform to loft contours provided*' and this can be achieved by identifying the key elements of the function. The first step is to identify aerodynamic surface, followed by the creation of a contour profile. The process is finalized by ensuring that the aerodynamic surfaces conform to lofting within the contour profile created. Similarly, ISR 1.2 states that *'the anti-icing system shall prevent the ice accumulation on critical components of inlet system*.' The first step is to define the metrics for icing condition, followed by the identification of critical components of the inlet system. The next step is to identify or sense the icing on the inlet and activate the anti-icing system. The final step is to ensure that sufficient amount of anti-icing fluid is provided to enable anti-icing to prevent ice accumulation on critical components of the inlet system.



«requirement»
NR_1
Id = "80"
Text = "The inlet shall meet all acoustic design and performance requirements"

«physicalRequirement»
PSTR_1
Id = "85"
Text = "The inlet structure shall use materials, coatings, and processes that are of high strength that are selected regarding health, safety, corrosion/erosion, and lifecycle requirements."

«requirement»
GWR_1
Id = "81"
Text = "The guaranteed weight of the inlet system shall be W1 for the basic configuration"

«requirement»
AR_1
Id = "78"
Text = "The inlet system shall meet the drag obligations"

«physicalRequirement»
AR_1.1
Id = "78.1"
Text = "Surfaces shall conform to loft contours provided"

«designConstraint»
AR_1.6
Id = "78.6"
Text = "Steps and gaps shall be a maximum step of +/- A3 and a maximum gap A4"

«designConstraint»
AR_1.5
Id = "78.5"
Text = "The mean deviation for each manufactured unit at reference hot condition shall be A1"

«designConstraint»
AR_1.4
Id = "78.4"
Text = "The inlet lip shall have no joint at the bottom dead center"

«physicalRequirement»
AR_1.3
Id = "78.3"
Text = "Aerodynamically exposed fasteners shall be nominally flushed with a maximum step of +/- A2"

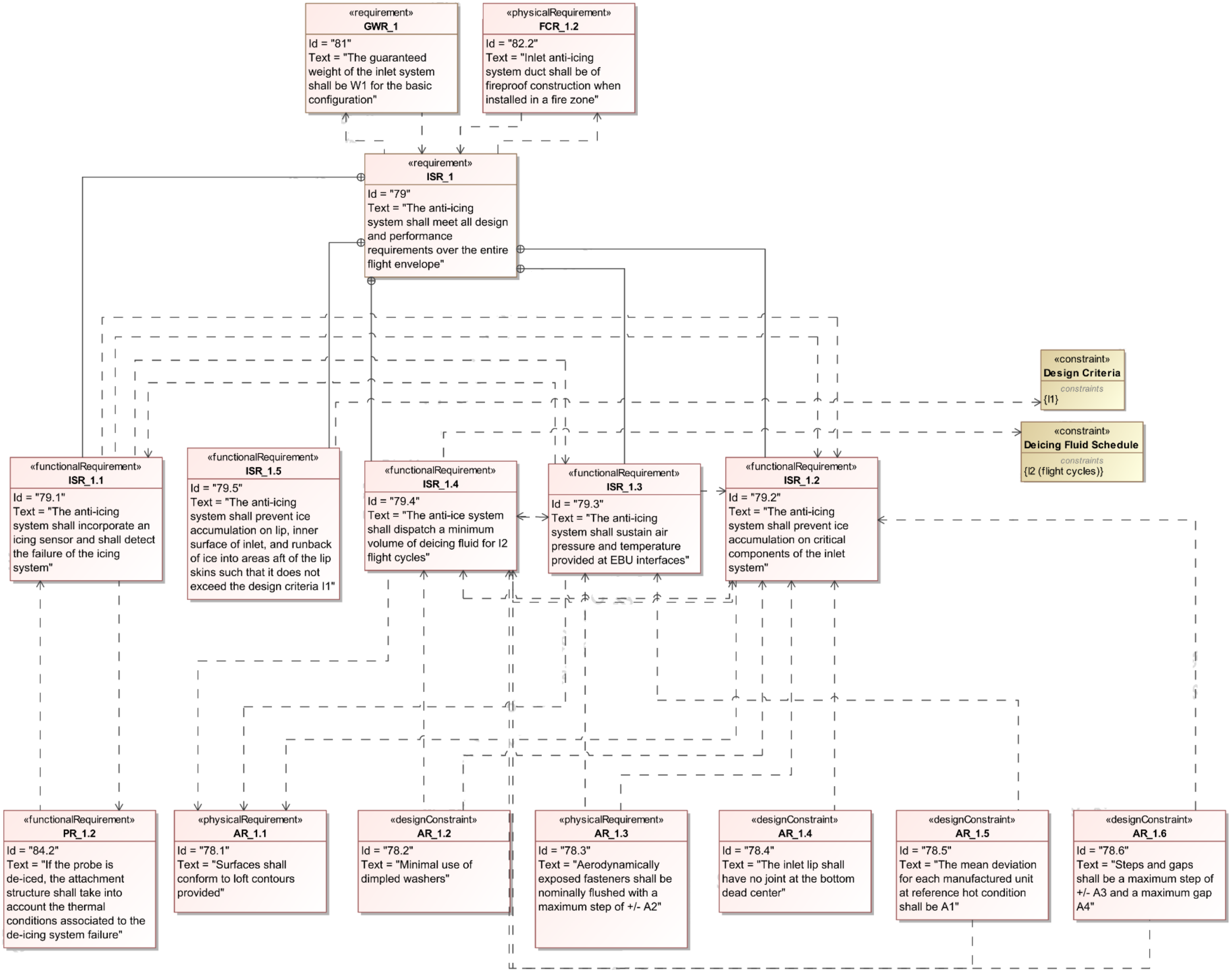
«designConstraint»
AR_1.2
Id = "78.2"
Text = "Minimal use of dimpled washers"

«functionalRequirement»
ISR_1.2
Id = "79.2"
Text = "The anti-icing system shall prevent ice accumulation on critical components of the inlet system"

«functionalRequirement»
ISR_1.3
Id = "79.3"
Text = "The anti-icing system shall sustain air pressure and temperature provided at EBU interfaces"

«functionalRequirement»
ISR_1.4
Id = "79.4"
Text = "The anti-ice system shall dispatch a minimum volume of deicing fluid for I2 flight cycles"

Figure 1. Aerodynamic requirements diagram showing interactions between different blocks and inter-relations between different requirements



GWR_1: Id = "81"; Text = "The guaranteed weight of the inlet system shall be W1 for the basic configuration"

FCR_1.2: Id = "82.2"; Text = "Inlet anti-icing system duct shall be of fireproof construction when installed in a fire zone"

ISR_1: Id = "79"; Text = "The anti-icing system shall meet all design and performance requirements over the entire flight envelope"

ISR_1.1: Id = "79.1"; Text = "The anti-icing system shall incorporate an icing sensor and shall detect the failure of the icing system"

ISR_1.5: Id = "79.5"; Text = "The anti-icing system shall prevent ice accumulation on lip, inner surface of inlet, and runback of ice into areas aft of the lip skins such that it does not exceed the design criteria I1"

ISR_1.4: Id = "79.4"; Text = "The anti-ice system shall dispatch a minimum volume of deicing fluid for I2 flight cycles"

ISR_1.3: Id = "79.3"; Text = "The anti-icing system shall sustain air pressure and temperature provided at EBU interfaces"

ISR_1.2: Id = "79.2"; Text = "The anti-icing system shall prevent ice accumulation on critical components of the inlet system"

PR_1.2: Id = "84.2"; Text = "If the probe is de-iced, the attachment structure shall take into account the thermal conditions associated to the de-icing system failure"

AR_1.1: Id = "78.1"; Text = "Surfaces shall conform to loft contours provided"

AR_1.2: Id = "78.2"; Text = "Minimal use of dimpled washers"

AR_1.3: Id = "78.3"; Text = "Aerodynamically exposed fasteners shall be nominally flushed with a maximum step of +/- A2"

AR_1.4: Id = "78.4"; Text = "The inlet lip shall have no joint at the bottom dead center"

AR_1.5: Id = "78.5"; Text = "The mean deviation for each manufactured unit at reference hot condition shall be A1"

AR_1.6: Id = "78.6"; Text = "Steps and gaps shall be a maximum step of +/- A3 and a maximum gap A4"

Figure 2. Icing system requirements diagram showing interactions between different blocks and inter-relations between different requirements

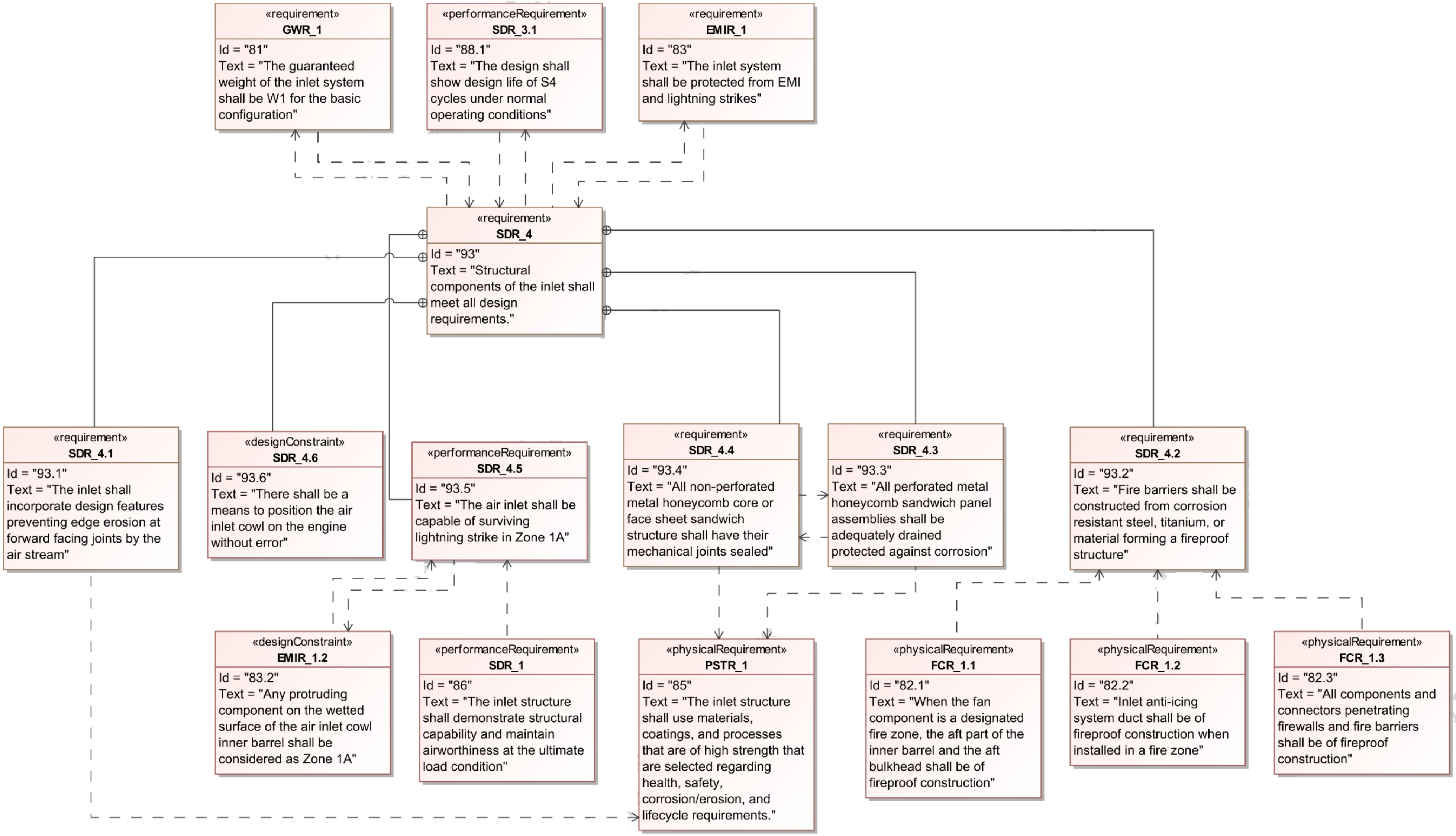


Figure 3. Structural requirements (design criteria) diagram showing interactions between different blocks and inter-relations between different requirements

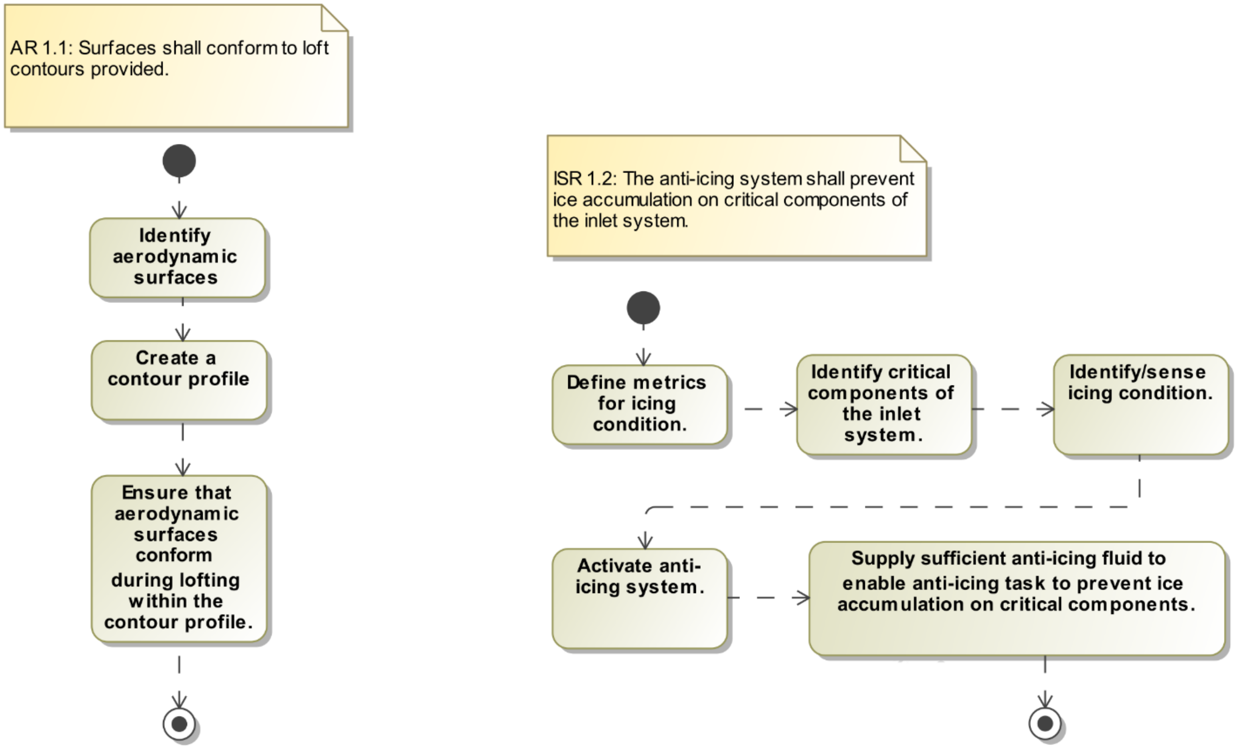


Figure 4. Functional decomposition examples of product requirement type

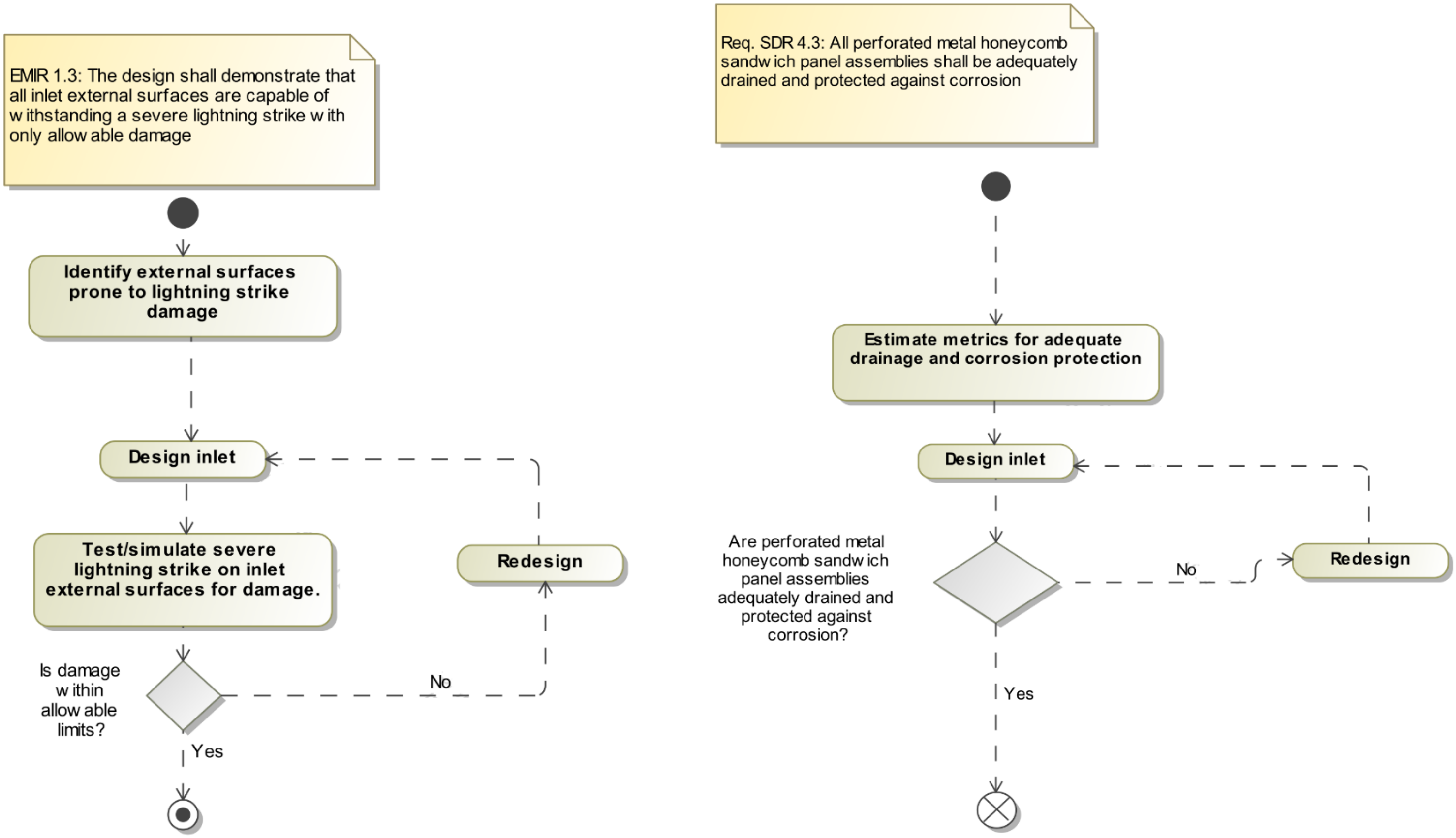


Figure 5. Functional decomposition of examples of process requirement type

Figure 5 presents the functional decomposition examples of process requirements (EMIR 1.3 and SDR 4.3). The functional decomposition for process requirement type is in form of an iterative flowchart in contrast to a simple multistep process for a product requirement type. This is because the requirements are structured with a narrowed-down boundary with the specific features of the system under consideration. For example, EMIR 1.3 states that '*the design shall demonstrate that all inlet external surfaces are capable of withstanding a severe lightning strike with only allowable damage*.' This can be achieved by identifying the external surfaces prone to lightning strikes damage and designing the inlet accordingly. The process continues with testing or simulating a severe lightning strike on inlet external surfaces, then verifying if the damage remains within allowable limit. If the design meets this criterion, it is finalized; otherwise, the inlet is redesigned.

Similarly, SDR 4.3 states that '*all perforated metal honeycomb sandwich panel assemblies shall be adequately drained and protected against corrosion*.' This can be achieved by first estimating the metrics for adequate drainage and corrosion protection, then designing the inlet to meet this and other requirements. Thereafter, within the design space, the design is evaluated to ensure that all perforated metal honeycomb sandwich panel assemblies are adequately drained and protected against corrosion. If the design satisfies this criterion, it is finalized; otherwise, the inlet is redesigned.

All 55 functional diagrams are available and can be viewed in higher resolution using Resource [37]. These 55 functions for the respective requirements are next considered for logical and physical design architecture.

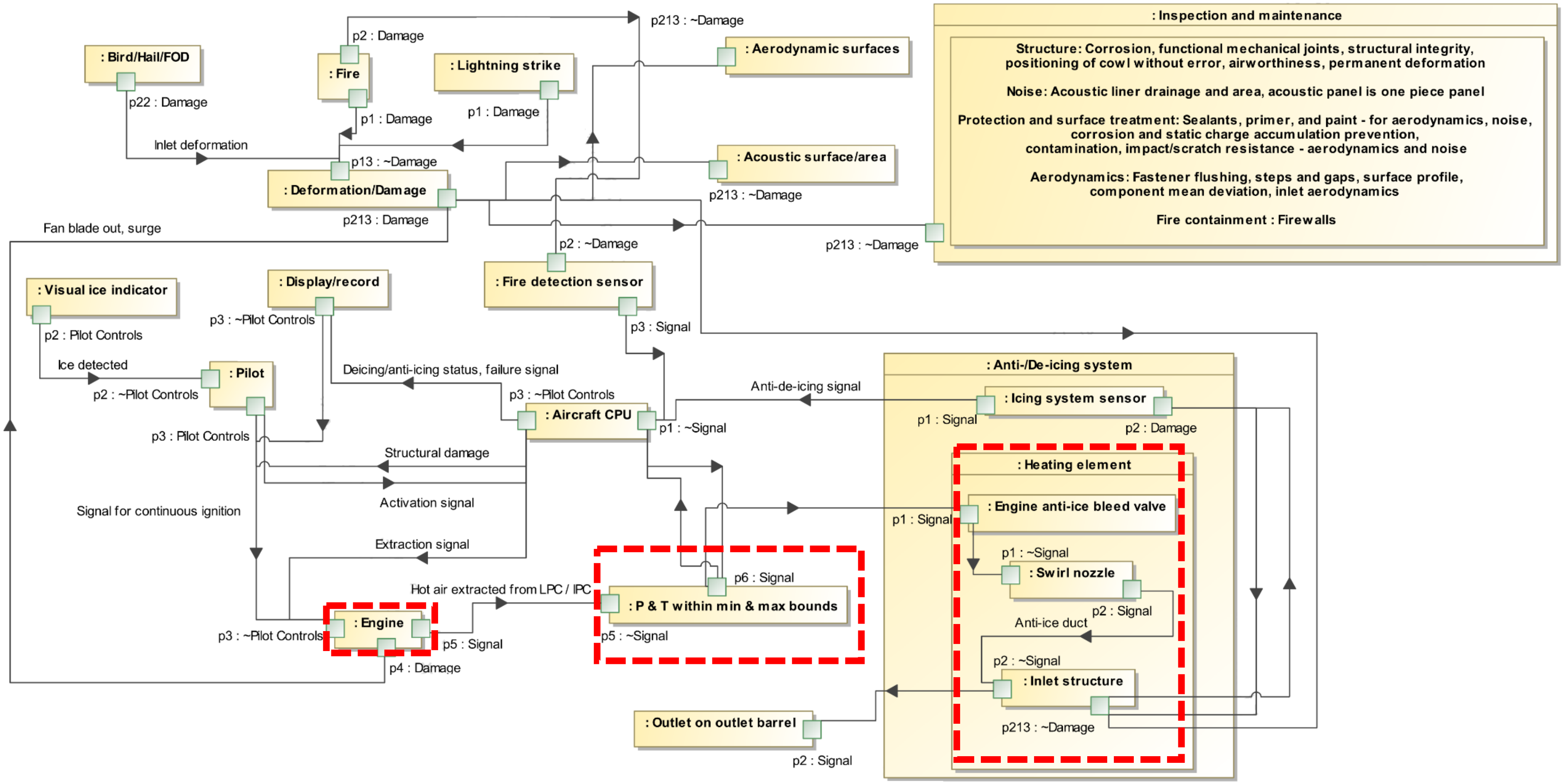
C. Logical and physical design

The results include an internal block diagram that enables different functions in the form of a logical and physical design architecture layout connecting different physical hardware. The physical elements and logical elements are identified for this design and are included in Table 6 (as discussed in Section III.F).

Figure 6 shows the logical and physical design architecture of the engine inlet. Due to the nature and structure of the requirements, the design process is split into two categories: 'operations/performance'-based design and 'inspection and maintenance'-based design. Specifically, the 'operations/performance' design category includes requirements related to ISR, as well as those addressing structural damage from fire, lightning strikes, and bird impacts, are included. All other requirements are categorized under the 'inspection and maintenance'-based design.

Referring to Figure 6, the anti-icing system functioning is as follows: The pilot detects ice from the visual ice indicator and/or the icing system sensor identifies the icing condition, and a signal is sent to the aircraft CPU to activate the anti-icing system. The CPU sends a signal to the engine to extract hot air (de-/anti-icing fluid) from the low pressure and/or intermediate pressure compressor. The pressure and temperature of this hot air are regulated by the CPU within the predefined limits based on the design specifications. Once the required pressure and temperature of the hot air are achieved, the hot air is supplied to the inlet structure via an anti-icing system duct. This flow is regulated by a swirl nozzle, activated after the engine anti-ice bleed valve opens. After de-/anti-icing, the temperature and pressure of the hot air drop, and the air exits into the atmosphere through an outlet on the outer barrel. Additionally, during icing conditions, the pilot activates continuous ignition of the engine to melt ice particles ingested into the engine core/combustor. This process continues as long as the icing condition persists and the engine requires deicing. Once deicing is complete, the icing system sensor sends signal to the CPU, which displays the status to the pilot and/or records it in the aircraft systems. Overall, the anti-/de-icing system comprises of the icing system sensor and heating elements, and the latter includes engine anti-ice bleed valve, swirl nozzle, and inlet structure.

Additionally, Figure 6 shows that sources of damage or deformation to the structure can be bird strikes, hail, FOD, fire, and lightning strikes. This icing system sensor detects deformation/damage of the inlet structure and sends a signal to the CPU, which then communicates this information to the pilot. Also, fire is detected by a fire sensor, which sends a signal to the pilot via the CPU to prevent further damage. These functionalities fall under the 'operations/performance'-based design category. The significance of the red boxes in Figure 6 is described in the next sub-section (III.D).



Structure: Corrosion, functional mechanical joints, structural integrity, positioning of cowl without error, airworthiness, permanent deformation

Noise: Acoustic liner drainage and area, acoustic panel is one piece panel

Protection and surface treatment: Sealants, primer, and paint - for aerodynamics, noise, corrosion and static charge accumulation prevention, contamination, impact/scratch resistance - aerodynamics and noise

Aerodynamics: Fastener flushing, steps and gaps, surface profile, component mean deviation, inlet aerodynamics

Fire containment : Firewalls

Figure 6. Logical and Physical design architecture of the engine inlet

Furthermore, as shown in Figure 6, the deformation or damage discussed above affects the aerodynamic and acoustic performance. These aspects are part of ‘inspection and maintenance’-based design category. In this design type, the blocks and design aspects (from the U-M requirements) that are directly affected are as follows:

- *Aerodynamics*: Fastener flushing, steps and gaps, surface profile, component mean deviation, and inlet aerodynamics
- *Noise*: Acoustic liner drainage, acoustic liner area, and acoustic panel is a one-piece panel
- *Fire containment*: Firewalls
- *Protection and surface treatment*: Sealants, primer, and paint for aerodynamics, noise; prevention of corrosion, static charge accumulation, and contamination; and impact/scratch resistant for noise and aerodynamics
- *Structure*: Corrosion, functional mechanical joints, structural integrity, positioning of cowl without error, airworthiness, and permanent deformation

This completes the RFLP design process. The discussion now turns to an important aspect of MBSE – traceability and adaptability to alternative propulsion systems.

D. Traceability and adaptability to alternative propulsion systems

In this work, the system-level design of a conventional engine inlet was explored, and a corresponding SysML model was developed. This section examines benefits of using MBSE/SysML, specifically in terms of design traceability and adaptability. This analysis highlights the versatility and effectiveness of MBSE in adapting to future innovations in propulsion.

Alternative propulsion systems or alternative fuels include sustainable aviation fuels (SAF) (or synthetic paraffin kerosene), hydrogen (combustion-based), and electrified propulsion (which could include the use of batteries, hydrogen fuel cells, turbogenerators, etc.). SAF have similar fuel properties to conventional jet fuel, meaning aircraft and propulsion systems using SAF are expected to resemble conventional systems [38–41]. In contrast, combustion-based hydrogen aircraft and/engines are expected to be significantly different to the conventional systems [42–44]. Hydrogen engines are expected to be smaller and shorter than conventional engines [45–47]. For an electrical powerplant, the propulsion system will be drastically different than gas turbine engines [48], resulting in modifications to the aircraft sub-systems. Based on the existing set of engine inlet requirements, the following high-level modifications for alternative propulsion are identified. These include modifications to:

- The anti-/de-icing system. This is expected to be smaller for hydrogen engine and drastically different for electric propulsion in terms of the need for electrical heating elements.
- The lofting lines and geometry (diameter, length, and thickness).
- The electromagnetic induction (lightning strike) requirements. These would be more stringent for electric propulsion and hydrogen (electrostatic charge accumulation leading to safety concerns).
- The fire containment requirements. These will be more rigorous for hydrogen and electric propulsion, especially for hydrogen due to its highly flammable nature.
- Other propulsion systems. These include fuel lines (diameter size for hydrogen due to its flame characteristics and quenching), and additional pneumatic (alternative) systems and electrical lines (for electric propulsion).

The effects of the above aspects are explored via the RFLP process.

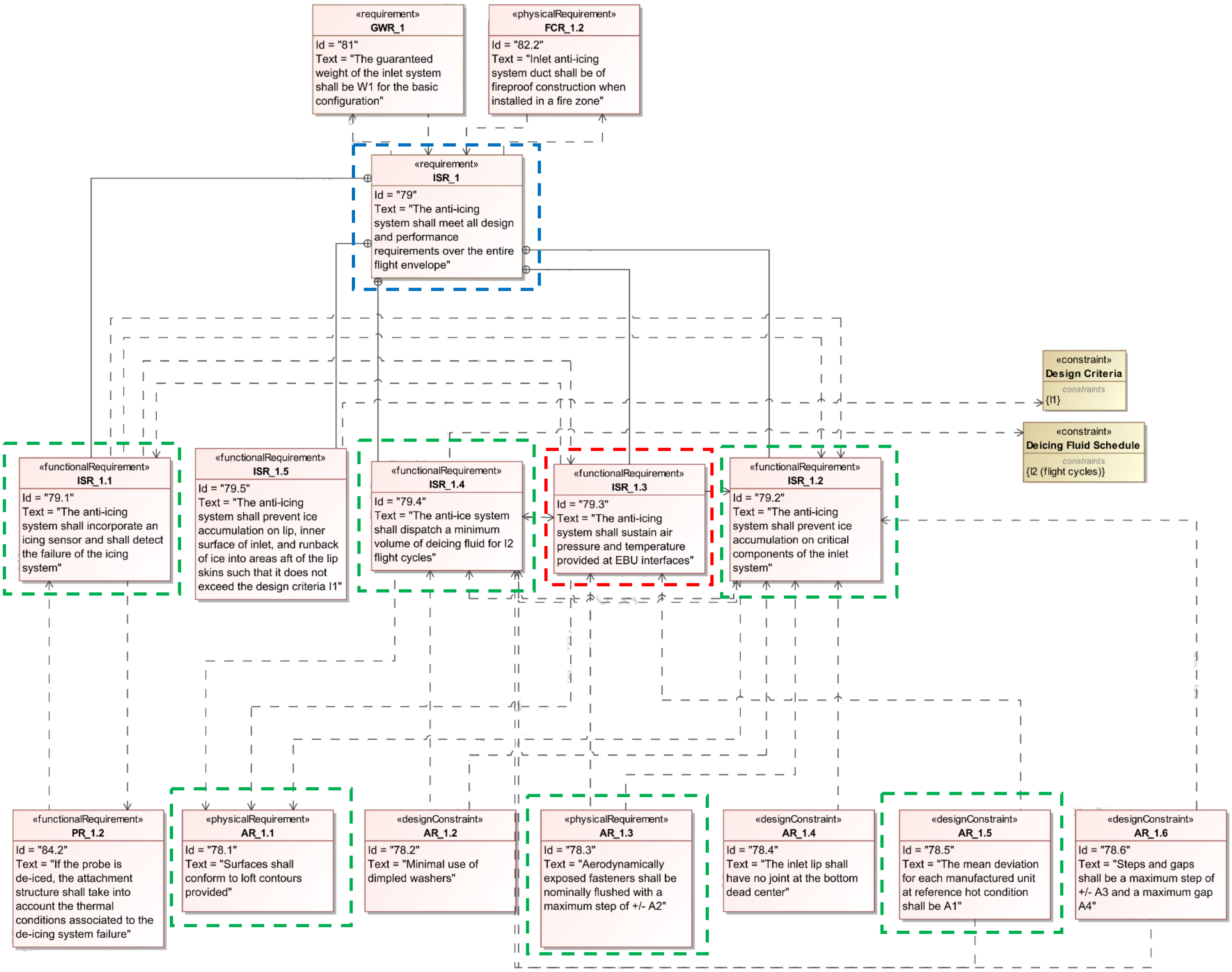
i. Requirements design

Based on the above discussion, he requirements that would be directly impacted due to alternative propulsion technologies are identified. Table 7 lists Collins requirements and the corresponding U-M requirements directly affected by alternative propulsion technologies. This is the first benefit of traceability, which enables tracking the requirements that would be impacted. From Table 7, one example requirement ISR 1.3 (#2 from Table 7) is considered for further signifying traceability benefits to alternative propulsion systems design.

Table 7. List of Collins and U-M requirements directly affected by alternative propulsion technologies

Requirements	Collins requirements	U-M requirements
1	Dispatch with the lowest pressure threshold valve in locked-open position shall be considered for X flights during the aircraft life (SK-11)	The anti-ice system shall dispatch a minimum volume of anti/deicing fluid for I2 flight cycles (ISR 1.4)
2	Nacelle Anti-Ice system shall be designed to sustain the air pressure and temperature provided at Engine Build-Up interfaces for all flight conditions (SK-13)	The anti-icing system shall sustain air pressure and temperature provided at EBU interfaces (ISR 1.3)
3	For the basic configuration, the guaranteed weight of the operational Inlet is X lbs. (SK-16)	The guaranteed weight of the inlet system shall be W1 for the basic configuration (GWR 1)
4	Propulsion system structure shall be designed to ensure electrical continuity between components and protection against lightning strikes, electrostatic charge accumulation, and EMI (SK-63)	Propulsion system structure shall be designed to ensure electrical continuity between components and protection against lightning strikes, electrostatic charge accumulation, and EMI (EMIR 1.1)
5	All aerodynamic surfaces shall conform to loft contours provided (SK-19)	Surfaces shall conform to loft contours provided (AR 1.1)
	–	The inlet system shall meet the drag obligations (AR 1)
6	Firewalls, fire seals, and fire barriers shall be incorporated as necessary to isolate fire zones from each other and to isolate fire in the designated fire zone from the aircraft primary structure (SK-67)	Firewalls, fire seals, and fire barriers shall be incorporated as necessary to isolate fire zones from each other and to isolate fire in the designated fire zone from the aircraft primary structure (FCR 1.4)

ISR 1.3 is directly impacted due to alternative propulsion systems. ISR 1.3 states 'the anti-icing system shall sustain air pressure and temperature provided at engine build up (EBU) interfaces.' The EBU interfaces are significantly different for hydrogen and/or electric propulsion, compared to conventional engine. The pressure and temperature at EBU interface are different for hydrogen engines particularly. Considering the above, the effect of ISR 1.3 on other requirements can be traced using Figure 2 which has already been discussed. Figure 7 shows the icing system requirements diagram (based on Figure 2) and it demonstrates interactions between different blocks and interrelations between different requirements, and relation of ISR 1.3 with other requirements for alternative propulsion systems. The other requirements that will be directly impacted due to ISR 1.3 based on Figure 2 are highlighted/marked, and this is shown in Figure 7. ISR 1.3 is marked with a red box, and other requirements that will be directly impacted are marked with a green box. ISR 1 is marked with a blue box, since it is the parent requirement for ISR 1.3. The Functional design of ISR 1.3 is explored next.



«requirement»
GWR_1
Id = "81"
Text = "The guaranteed weight of the inlet system shall be W1 for the basic configuration"

«physicalRequirement»
FCR_1.2
Id = "82.2"
Text = "Inlet anti-icing system duct shall be of fireproof construction when installed in a fire zone"

«requirement»
ISR_1
Id = "79"
Text = "The anti-icing system shall meet all design and performance requirements over the entire flight envelope"

«constraint»
Design Criteria
constraints
{I1}

«constraint»
Deicing Fluid Schedule
constraints
{I2 (flight cycles)}

«functionalRequirement»
ISR_1.1
Id = "79.1"
Text = "The anti-icing system shall incorporate an icing sensor and shall detect the failure of the icing system"

«functionalRequirement»
ISR_1.5
Id = "79.5"
Text = "The anti-icing system shall prevent ice accumulation on lip, inner surface of inlet, and runback of ice into areas aft of the lip skins such that it does not exceed the design criteria I1"

«functionalRequirement»
ISR_1.4
Id = "79.4"
Text = "The anti-ice system shall dispatch a minimum volume of deicing fluid for I2 flight cycles"

«functionalRequirement»
ISR_1.3
Id = "79.3"
Text = "The anti-icing system shall sustain air pressure and temperature provided at EBU interfaces"

«functionalRequirement»
ISR_1.2
Id = "79.2"
Text = "The anti-icing system shall prevent ice accumulation on critical components of the inlet system"

«functionalRequirement»
PR_1.2
Id = "84.2"
Text = "If the probe is de-iced, the attachment structure shall take into account the thermal conditions associated to the de-icing system failure"

«physicalRequirement»
AR_1.1
Id = "78.1"
Text = "Surfaces shall conform to loft contours provided"

«designConstraint»
AR_1.2
Id = "78.2"
Text = "Minimal use of dimpled washers"

«physicalRequirement»
AR_1.3
Id = "78.3"
Text = "Aerodynamically exposed fasteners shall be nominally flushed with a maximum step of +/- A2"

«designConstraint»
AR_1.4
Id = "78.4"
Text = "The inlet lip shall have no joint at the bottom dead center"

«designConstraint»
AR_1.5
Id = "78.5"
Text = "The mean deviation for each manufactured unit at reference hot condition shall be A1"

«designConstraint»
AR_1.6
Id = "78.6"
Text = "Steps and gaps shall be a maximum step of +/- A3 and a maximum gap A4"

Figure 7. Icing system requirements diagram showing interactions between different blocks and inter-relations between different requirements, and relation of ISR 1.3 with other requirements for alternative propulsion systems

ii. Functional design

The functional decomposition by itself might not change for ISR 1.3 but the absolute values of the design aspects and/or the criterion for selection of design will change. Figure 8 shows the functional decomposition for ISR 1.3 and the steps impacted due to alternative propulsion system. These are marked with red boxes. The EBU interfaces will be significantly different for both hydrogen and/or electric propulsion, compared to conventional engine. The pressure and temperature at EBU interface will be different for hydrogen engines. The criterion 'are pressure and temperature greater than allowable values' is dependent on the absolute values of pressure and temperature for a given engine inlet design (size, geometry, materials, etc.), and therefore will be different for alternative propulsion systems.

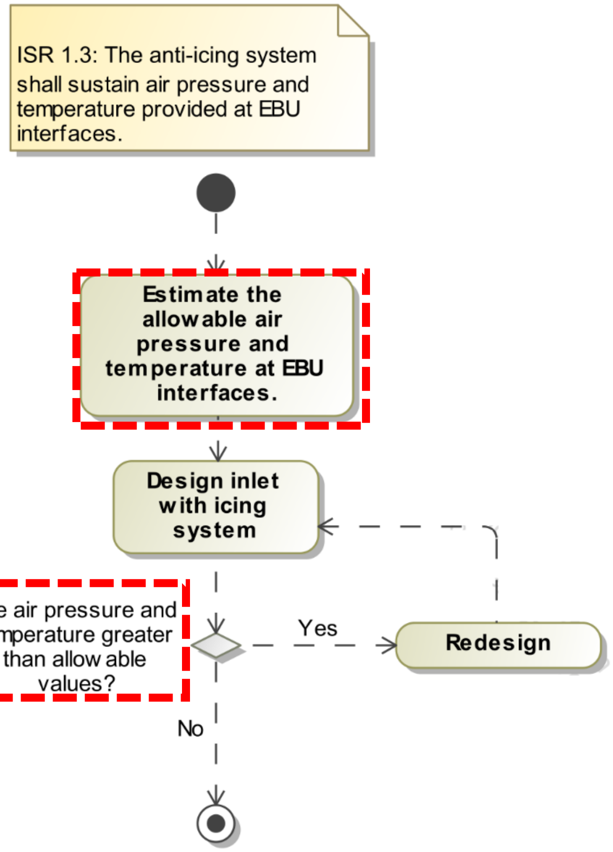


Figure 8. Functional decomposition for ISR 1.3 and the steps impacted due to alternative propulsion system

iii. Logical and Physical design

In terms of Logical and Physical design, the traceability aspect for alternative propulsion system is shown in Figure 6. The red boxes indicate the physical elements that will be directly affected due to an alternative propulsion system for ISR 1.3. These are 'heating element,' 'engine,' and 'P & T within minimum and maximum bound.' For electric propulsion, the heating element could be electrical heating systems and the 'engine' that provides hot air for icing system will be missing from the logical architecture. For hydrogen propulsion, as discussed previously, the absolute values of 'P & T within minimum and maximum bound' will be different than the conventional engine.

E. Comments

In this work, the benefits of MBSE/SysML for the design of engine inlet are evident thanks to its systematic approach within a unified platform. This approach is highly communicative and interactive, which can enhance decision-making and mitigates risks. The digitized environment it provides enables and greatly improves collaboration. MBSE/SysML is observed to be a powerful tool for the MDAO design space, especially due to its strengths in traceability and adaptability. This work demonstrates the transformative potential of MBSE in enhancing design efficiency and fostering innovation, particularly for conventional and advanced propulsion systems. An MBSE-based MDAO approach will inevitably reduce development time and costs, facilitating the delivery of advanced propulsion systems.

V. Future work

In this work, the physical design was at a preliminary level, and a more detailed physical design should be pursued in the future, which will require proprietary information on physical hardware. Additionally, the study has demonstrated the transformative impact of MBSE/SysML on the future of aircraft propulsion systems design, especially electrified and hydrogen-powered propulsion. However, this work was limited to the qualitative design of an engine inlet and the impacts of alternative propulsion systems to the present model.

The same approach can be extended to other subsystems with potential scaling to engine-level, aircraft-level, and beyond. Further understanding of the traceability and adaptability benefits of MBSE/SysML can be achieved through the development of a quantitative model of an engine inlet or other systems. For example, if the engine diameter reduces from 3.5 m for a conventional engine to 3 m for a hydrogen engine, the quantified effects on AR, ISR, NR, GWR, FCR, EMIR, PR, PSTR, and SDR could be analyzed.

With the design of these models comes the opportunity for system level optimization using the design logic inherent in the RFLP breakdown of the system. Typically, optimization is limited within a design to several discrete features, with the opportunity space potentially encompassing designs which would not entirely meet the full set of requirements. The MBSE model creates a graph of the design which can then be used for optimization with a check on compliance to all requirements.

VI. Conclusion

MBSE has emerged as a powerful approach to simplify the design of complex systems by providing a unified, model-driven framework. This methodology effectively captures, analyzes, and simulates system requirements, behaviors, and structures across the entire development lifecycle. In this research, the application of MBSE to the design of aircraft engine inlets, specifically focusing on the integration of the SysML has been explored.

Utilizing a structured RFLP framework with the MagicDraw tool, a comprehensive set of industry-standard requirements sourced from Collins Aerospace was incorporated – a solid foundation for the design process. This study emphasizes the importance of balancing design constraints, regulatory obligations, and stakeholder needs, all while prioritizing critical factors such as safety, reliability, and environmental sustainability.

A cohesive set of 55 unique requirements (denoted as U-M requirements) was formulated, and this was derived from the original 54 requirements provided by Collins Aerospace. To illustrate the interdependencies among these design requirements, a complete requirements diagram was developed alongside individual diagrams for each design block. This representation highlights the intricate relationships inherent in the SysML design model.

This analysis proceeded with a detailed functional decomposition of each of the 55 U-M requirements, leading to the creation of functional diagrams for every function identified. This step allowed the authors to clarify the specific operations needed to fulfill each requirement. Building on this foundation, both logical and physical design architecture was established, which illustrate how physical elements interact to perform designated functions and operations.

Through the RFLP approach, this study showed the inter-relations between different requirements (e.g. inter- and intra-block relations), within the design process. These affect the functions and resultantly the logical and physical architecture. All of these inter-relations are observed within the digital space. This has implications in terms of how change in one requirement of one sub-component can affect the whole design process in terms of requirements, functions, and logical and physical framework. Furthermore, these benefits can be interpreted in terms of adaptability and versatility of MBSE and SysML in enhancing design efficiency and fostering innovation i.e. adapting the present model to advanced propulsion technologies. This is the first study to explore the adaptability of MBSE for emerging technologies (qualitatively), such as electrified and hydrogen-powered propulsion systems, by outlining key modifications to the existing framework. The insights gained from this study can be applied to other complex aerospace systems. Along with the above benefits, MBSE could potentially mitigate risks, shorten development timelines, and reduce costs associated with R&D on future propulsion sub-systems.

Appendix A – List of Collins and U-M requirements

Appendix A includes list of requirements, type of requirements and list of functional decomposition. Table A.1, Table A.2, Table A.3, and Table A.4 provide Collins requirements list, U-M requirements list, type of requirements, and functional decomposition, respectively.

Table A.1. Collins requirements list

ID	Description
SK-1	INLET
SK-2	ICING SYSTEM
SK-3	ICING SYSTEM GENERAL
SK-4	The inlet lip skin shall be protected against ice accretion to the level necessary to prevent potentially harmful ice accretion on the inner surface of the inlet as defined by the certifying requirements of CFR 25, without the use of special operating procedures. This applies for both maximum continuous and intermittent icing conditions as defined within CFR 25 (Appendix C of Collins internal documentation)
SK-5	Ice protection shall be ensured over the complete aircraft flight envelope
SK-6	The nacelle anti-ice system shall be designed such that, the residual ice on the lip skin or the runback of ice into areas aft of the lip skins shall not exceed the design criteria
SK-7	The nacelle shall be designed for unrestricted flight through continuous maximum icing and intermittent maximum icing
SK-8	Ice accumulation on unprotected areas under icing conditions shall be minimized to ensure Engine and Aircraft operations are not affected
SK-9	A failure in the anti-ice system shall be detected
SK-10	DISPATCH REQUIREMENT
SK-11	Dispatch with the lowest pressure threshold valve in locked-open position shall be considered for X flights during the aircraft life
SK-12	BLEED AIR-FLOW FOR THE INLET SYSTEM
SK-13	Nacelle Anti-Ice system shall be designed to sustain the air pressure and temperature provided at Engine Build-Up interfaces for all flight conditions
SK-14	Means shall be provided to avoid damage to the nacelle structure due to an air leak from high temperature/pressure air ducts
SK-15	GUARANTEED WEIGHT
SK-16	For the basic configuration, the guaranteed weight of the operational Inlet is X lbs.
SK-17	AERODYNAMIC
SK-18	SURFACES
SK-19	All aerodynamic surfaces shall conform to loft contours provided
SK-20	The inlet lip shall have no joint at the bottom dead center.
SK-21	DEVIATION FROM CONTOUR
SK-22	For all zones, target value for mean deviation for each manufactured unit at reference hot condition shall be X mm.
SK-23	FLUSHNESS OF FASTENERS
SK-24	All aerodynamically exposed fasteners shall be nominally flush with a maximum step of +X in. and -X in.. Use of dimpled washers shall be minimized as much as possible
SK-25	STEPS AND GAPS
SK-26	Steps and Gaps shall be a maximum step of +X in. and -X in. and a maximum gap of +X in.
SK-27	STRUCTURES
SK-28	GENERAL STRUCTURAL CRITERIA
SK-29	The Propulsion System shall be able to withstand the limit load condition with a safety factor equal to X
SK-30	The Nacelle shall not have life limited parts or components.
SK-31	The structure shall be generally of high strength material
SK-32	Fire barriers shall be constructed from corrosion resistant steel, titanium or material forming a fireproof structure
SK-33	Aluminum alloy sheet stock shall be corrosion protected and scratch/impact resistant
SK-34	Selection of materials, coatings, processes, shall take into account the health and safety requirements, and long-term provisioning

SK-35	All non-perforated metal honeycomb core or face sheet sandwich structure shall have their mechanical joints sealed
SK-36	All perforated metal honeycomb sandwich panel assemblies shall be adequately drained protected against corrosion
SK-37	The inlet shall incorporate design features preventing edge erosion at forward facing joints by the air stream
SK-38	DESIGN CRITERIA
SK-39	The design shall not show permanent deformation at limit load conditions
SK-40	The design shall show no failure at ultimate load conditions
SK-41	Damaged composite structures with damages not detectable during a walk around shall sustain limit loads
SK-42	The design shall show design life of X cycles under normal operational conditions
SK-43	The structural integrity of the air inlet shall be demonstrated via simulation and test for an X lb. bird strike for non-penetration in the fan zone
SK-44	The design shall demonstrate structural capability at ultimate load level and maintain airworthiness without repair after an X diameter hail stone impact
SK-45	The air inlet shall be capable of surviving lightning strike in Zone 1A
SK-46	The air inlet attach flange shall sustain any load case considering two adjacent attachment bolts missing
SK-47	There shall be a means to position the air inlet cowl on the Engine without error
SK-48	PROTECTION AND SURFACE TREATMENT
SK-49	Metallic parts shall be suitably treated for corrosion protection
SK-50	Areas subject to contamination by hydraulic fluids shall be protected by a hydraulic fluid resistant paint scheme or made of fluid resistant materials
SK-51	All sealant and paint of the nacelle shall be compatible with Propulsion System environmental conditions
SK-52	Fasteners used in permanent joint assemblies shall have a suitable corrosion protection surface treatment or be manufactured from a corrosion-resistant material
SK-53	A sealant or primer filler shall be applied to all edges where fluids might collect
SK-54	NOISE
SK-55	Design shall minimize acoustically treated surface
SK-56	The acoustic treatment shall comply to acoustic definition
SK-57	Liner design shall ensure that a minimum of one entire open hole per cell is achieved after bonding
SK-58	The backing skin shall be rigid and impervious
SK-59	The acoustic liner shall be designed to incorporate drainage features.
SK-60	Drainage solutions shall minimize impact on liner acoustic performance
SK-61	The air intake cowl acoustic panel shall be a one-piece panel
SK-62	EMI AND LIGHTNING STRIKE PROTECTION
SK-63	Propulsion system structure shall be designed to ensure electrical continuity between components and protection against lightning strikes, electrostatic charge accumulation, and EMI
SK-64	Any protruding component on the wetted surface of the air inlet cowl inner barrel shall be considered as Zone 1A
SK-65	The design shall demonstrate that all nacelle external surfaces are capable of withstanding a severe lightning strike with only allowable damage
SK-66	FIRE CONTAINMENT - PASSIVE FIRE PROTECTION
SK-67	Firewalls, fire seals, and fire barriers shall be incorporated as necessary to isolate fire zones from each other and to isolate fire in the designated fire zone from the aircraft primary structure.
SK-68	All components and connectors penetrating firewalls and fire barriers shall be of fireproof construction
SK-69	Nacelle anti-icing system duct shall be of fireproof construction when installed in a fire zone
SK-70	When the fan compartment is a designated fire zone, the aft part of the inner barrel and the aft bulkhead shall be of fireproof construction
SK-71	T_2 or P_2T_2
SK-72	The probe attachment shall avoid probe departure in case of bird impact
SK-73	If the probe is de-iced, the attachment structure shall take into account the thermal conditions associated to the de-icing system failure

Table A.2. U-M requirements list

ID	Description	Type
AERODYNAMIC REQUIREMENTS		
AR_1	The inlet system shall meet the drag obligations	Product
AR_1.1	Surfaces shall conform to loft contours provided	Product
AR_1.2	Minimal use of dimpled washers	Process
AR_1.3	Aerodynamically exposed fasteners shall be nominally flushed with a maximum step of +/- A2	Product
AR_1.4	The inlet lip shall have no joint at the bottom dead center	Product
AR_1.5	The mean deviation for each manufactured unit at reference hot condition shall be A1	Product
AR_1.6	Steps and gaps shall be a maximum step of +/- A3 and a maximum gap A4	Product
ICING SYSTEM REQUIREMENTS		
ISR_1	The anti-icing system shall meet all design and performance requirements over the entire flight envelope	Product
ISR_1.1	The anti-icing system shall incorporate an icing sensor and shall detect the failure of the icing system	Product
ISR_1.2	The anti-icing system shall prevent ice accumulation on critical components of the inlet system	Product
ISR_1.3	The anti-icing system shall sustain air pressure and temperature provided at EBU interfaces	Product
ISR_1.4	The anti-ice system shall dispatch a minimum volume of deicing fluid for I2 flight cycles	Product
ISR_1.5	The anti-icing system shall prevent ice accumulation on lip, inner surface of inlet, and runback of ice into areas aft of the lip skins such that it does not exceed the design criteria I1	Product
NOISE REQUIREMENTS		
NR_1	The inlet shall meet all acoustic design and performance requirements	Product
NR_1.1	The acoustic treatment shall comply to acoustic definition	Process
NR_1.2	The acoustic liner shall be designed to provide a drainage solution among other and minimize impact on acoustic performance	Process
NR_1.3	The acoustic liner design shall ensure that a minimum of one entire open hole per cell is achieved after bonding	Process
NR_1.4	The backing skin shall be rigid and impervious	Product
NR_1.5	The design shall minimize use of acoustically treated surfaces	Process
NR_1.6	The air intake cowl acoustic panel shall be a one-piece panel	Product
GUARANTEED WEIGHT REQUIREMENT		
GWR_1	The guaranteed weight of the inlet system shall be W1 for the basic configuration	Product
FIRE CONTAINMENT REQUIREMENTS		
FCR_1	The inlet system should be segregated from other parts of the nacelle so that it is not a fire zone	Product
FCR_1.1	When the fan component is a designated fire zone, the aft part of the inner barrel and the aft bulkhead shall be of fireproof construction	Product
FCR_1.2	Inlet anti-icing system duct shall be of fireproof construction when installed in a fire zone	Product
FCR_1.3	All components and connectors penetrating firewalls and fire barriers shall be of fireproof construction	Product
FCR_1.4	Firewalls, fire seals, and fire barriers shall be incorporated as necessary to isolate fire zones from each other and to isolate fire in the designated fire zone from the aircraft primary structure	Product
EMI AND LIGHTNING STRIKE REQUIREMENTS		
EMIR_1	The inlet system shall be protected from EMI and lightning strikes	Product
EMIR_1.1	Propulsion system structure shall be designed to ensure electrical continuity between components and protection against lightning strikes, electrostatic charge accumulation, and EMI	Process
EMIR_1.2	Any protruding component on the wetted surface of the air inlet cowl inner barrel shall be considered as Zone 1A	Product
EMIR_1.3	The design shall demonstrate that all inlet external surfaces are capable of withstanding a severe lightning strike with only allowable damage	Process
P_2T_2 PROBE REQUIREMENTS		
PR_1	The T_2/T_2P_2 probe shall meet all design and performance requirements	Product
PR_1.1	The probe attachment shall avoid probe departure in case of bird impact	Product
PR_1.2	If the probe is de-iced, the attachment structure shall take into account the thermal conditions associated to the de-icing system failure	Product
PROTECTION AND SURFACE TREATMENT REQUIREMENTS		
PSTR_1	The inlet structure shall use materials, coatings, and processes that are of high strength that are selected regarding health, safety, corrosion/erosion, and lifecycle requirements.	Process

PSTR_1.1	Metallic parts shall be suitably treated for corrosion protection	Product
PSTR_1.1.1	Aluminum alloy sheet stock shall be corrosion protected and scratch/impact resistant	Product
PSTR_1.2	Fasteners used in joint assemblies shall have a suitable corrosion protection surface treatment or be manufactured from a corrosion-resistant material	Product
PSTR_1.3	Areas subject to contamination by hydraulic fluids shall be protected by a hydraulic fluid resistant paint scheme or made of fluid resistant materials	Product
PSTR_1.4	All sealant and paint of the inlet shall be compatible with Propulsion System environmental conditions	Product
PSTR_1.4.1	A sealant or primer filler shall be applied to all edges where fluids might collect	Process
	STRUCTURAL (AND DESIGN CRITERIA) REQUIREMENTS	
SDR_1	The inlet structure shall demonstrate structural capability and maintain airworthiness at the ultimate load condition	Product
SDR_1.1	The structural integrity of the air inlet shall be demonstrated via simulation and test for an S3 lb. bird strike for non-penetration in the fan zone	Product
SDR_2	The inlet structure shall withstand and not show permanent deformation at the limit load condition	Product
SDR_2.1	The design shall maintain airworthiness without repair after an S1 diameter hail stone impact	Product
SDR_2.2	The inlet structure shall withstand the limit load with a safety factor of S2	Product
SDR_2.3	The air inlet attach flange shall sustain any load case considering two adjacent attachment bolts missing	Product
SDR_3	The inlet structure shall not have any life-limited components	Product
SDR_3.1	The design shall show design life of S4 cycles under normal operating conditions	Process
SDR_4	Structural components of the inlet shall meet all design requirements.	Product
SDR_4.1	The inlet shall incorporate design features preventing edge erosion at forward facing joints by the air stream	Product
SDR_4.2	Fire barriers shall be constructed from corrosion resistant steel, titanium, or material forming a fireproof structure	Product
SDR_4.3	All perforated metal honeycomb sandwich panel assemblies shall be adequately drained protected against corrosion	Process
SDR_4.4	All non-perforated metal honeycomb core or face sheet sandwich structure shall have their mechanical joints sealed	Process
SDR_4.5	The air inlet shall be capable of surviving lightning strike in Zone 1A	Product
SDR_4.6	There shall be a means to position the air inlet cowl on the engine without error	Process

Table A.3. List of requirements type

Requirement Type	Definition (source [49])
Business	A business requirement is a requirement that specifies characteristics of the business process that must be satisfied by the system
Design Constraint	A design constraint is a requirement that specifies a constraint on the implementation of a system or on a part of it
Extended	An extended requirement is a standard requirement subtype, which adds some properties to a requirement element. These properties such as a source, risk, and verify method are important for requirement management. Specific projects should add their own properties. All these properties are now available in the standard requirement specification window and requirements table. If any of these property values is specified, a requirement is automatically converted to extended requirement
Functional	A functional requirement is a requirement that specifies the behavior that a system or a part of a system must perform
Interface	An interface requirement is a requirement that specifies the ports for connecting systems and parts of a system. Optionally, it may include the items that flow across the connector and/or the Interface constraints
Performance	A performance requirement refers to a requirement that quantitatively measures the extent to which a system or a system part satisfies a required capability or condition
Physical	A physical requirement specifies the physical characteristics and/or physical constraints of a system or a system part
Usability	A usability requirement specifies the fitness for use of a system for its users and other actors

Table A.4. List of functional decomposition

ID	Requirement	Type	Basic function	Functional decomposition
AR_1	The inlet system shall meet the drag obligations	Product	Meet targeted aerodynamic performance	Calculate the overall drag. Is the drag target achieved? Y - done, N - loop
AR_1.1	Surfaces shall conform to loft contours provided	Product	Meet targeted drag and manufacturability	Identify aerodynamic surfaces; Create a contour profile; Ensure that aerodynamic surfaces conform during lofting within the contour profile
AR_1.2	Minimal use of dimpled washers	Process	Minimize drag	Estimate number of dimpled washers and their weight. Is the drag minimized and target weight achieved? Y - done, N - loop
AR_1.3	Aerodynamically exposed fasteners shall be nominally flushed with a maximum step of +/- A2	Product	Meet manufacturing tolerances and allowable drag	Flush the aerodynamically exposed fasteners nominally; Estimate the step of such fasteners; Does the step exceed +A2 and -A2; LOOP (Y/N; N then design confirmed, Y-redesign) ….....
AR_1.4	The inlet lip shall have no joint at the bottom dead center	Product	Reduce drag and enable maintenance activities	Identify elements/components on the bottom dead center. Is there a joint at the bottom dead center; Y/N (N, good design, Y-redesign)
AR_1.5	The mean deviation for each manufactured unit at reference hot condition shall be A1	Product	Meet targeted aerodynamic performance at reference condition	Estimate the mean deviation value of each manufactured unit at reference hot condition; Is this value A1? LOOP (Y/N; Y then design confirmed, N - redesign/loop) ….....
AR_1.6	Steps and gaps shall be a maximum step of +/- A3 and a maximum gap A4	Product	Meet manufacturing tolerances and allowable drag	Estimate the step; Does the step exceed +A3 and -A3; LOOP (Y/N; N then design confirmed, Y-redesign) ….....
				Estimate the gap; Does the gap exceed +A4; LOOP (Y/N; N then design confirmed, Y-redesign) ….....
ISR_1	The anti-icing system shall meet all design and performance requirements over the entire flight envelope	Product	The anti-icing system should operate at different points in a flight mission	Define the design and performance metrics for the anti-icing system over the flight envelope. Is this met? Y/N, Y-good design, N-loop

ISR_1.1	The anti-icing system shall incorporate an icing sensor and shall detect the failure of the icing system	Product	The anti-icing system would detect operational failure	Define the metrics for icing condition and for the failure of the anti-icing system. The sensor/probe senses the operational conditions and anti-icing system performs the tasks. If the anti-icing system is not operational during icing conditions, then flag failure of the anti-icing system.
ISR_1.2	The anti-icing system shall prevent ice accumulation on critical components of the inlet system	Product	The anti-icing system prevents ice accumulation	Define the metrics for icing condition. Identify critical component of the inlet system. Identify/sense icing condition. Activate anti-icing system. Supply sufficient anti-icing fluid to enable anti-icing task to prevent ice accumulation on critical component
ISR_1.3	The anti-icing system shall sustain air pressure and temperature provided at EBU interfaces	Product	The anti-icing system shall be robust to withstand typical pressure and temperature at EBU interfaces	Estimate the allowable air pressure and temperature at EBU interfaces. Are air pressure and temperature greater than allowable values? Y-redesign, N-accepted
ISR_1.4	The anti-ice system shall dispatch a minimum volume of anti/deicing fluid for I2 flight cycles	Product	The anti-ice system should be functional over L2 flight cycles with low deicing fluid	Estimate the minimum volume of anti-deicing fluid over I2 flight cycles. Does the anti-ice system dispatch this volume? Y/N, Y-accept, N-loop
ISR_1.5	The anti-icing system shall prevent ice accumulation on lip, inner surface of inlet, and runback of ice into areas aft of the lip skins such that it does not exceed the design criteria I1	Product	The anti-icing system prevents ice accumulation	Define anti-icing design criteria L1. Identify/sense icing condition. Activate anti-icing system. Supply sufficient anti-icing fluid to enable anti-icing and prevent ice accumulation such that run back of ice aft of lip is less than design criteria L1.
NR_1	The inlet shall meet all acoustic design and performance requirements	Product	Reduce noise and meet certification requirements	Identify the acoustic design and performance requirements. Does the inlet meet all acoustic design requirements? If no, redesign and loop. If yes check if inlet meets all acoustic performance requirements. If no, redesign and loop. If yes, then done.
NR_1.1	The acoustic treatment shall comply to acoustic definition	Process	Reduce noise by minimizing acoustic area	Provide the acoustic definition. Does acoustic treatment comply to acoustic definition? If no, redesign acoustic treatment and loop. If yes, then done.
NR_1.2	The acoustic liner shall be designed to provide a drainage solution among other and minimize impact on acoustic performance	Process	Reduce noise and prevent fluid accumulation	Does acoustic liner provide a drainage solution? If no, redesign and loop, if yes, check if the impact on acoustic performance can be reduced. If yes, redesign and loop; if not, then done.

NR_1.3	The acoustic liner design shall ensure that a minimum of one entire open hole per cell is achieved after bonding	Process	Reduce noise while maintaining structural integrity and manufacturability	After bonding, identify # of entirely open holes per cell. If # is less than 1, redesign and loop. If # is a minimum of 1, then done.
NR_1.4	The backing skin shall be rigid and impervious	Product	Prevent structural damage and ingress of fluids or other corrosive elements	Define the metric for rigidity and porosity. Does the backing skin meet both metrics? If no, redesign and loop. If yes, done.
NR_1.5	The design shall minimize use of acoustically treated surfaces	Process	Reduce weight and manufacturing cost	Identify surfaces where acoustic treatment is required. Are there areas where acoustically treated surface usage could be reduced/replaced? If so, redesign and loop. If no, then done.
NR_1.6	The air intake cowl acoustic panel shall be a one-piece panel	Product	Manufacturability ease	Is the air intake cowl acoustic panel a one-piece panel? If no, redesign and loop. If yes, then done.
GWR_1	The guaranteed weight of the inlet system shall be W1 for the basic configuration	Product	The target weight of inlet system is achieved	Does the weight of all components of the inlet system sum to W1 for the basic configuration? If no, redesign and loop. Otherwise, done.
FCR_1	The inlet system should be segregated from other parts of the nacelle so that it is not a fire zone	Product	Prevent spread of fire through design separation	Define metrics for a fire zone. Are these metrics met for the segregation of the inlet system from the other parts of nacelle? Y-accept, N- redesign/loop
FCR_1.1	When the fan component is a designated fire zone, the aft part of the inner barrel and the aft bulkhead shall be of fireproof construction	Product	Meet fire resilience requirements through material selection for designated fire zone condition	Define the metric for parts to be of fireproof construction. Does the aft part of the inner barrel and the aft bulkhead meet the metrics when the fan component is a designated fire zone? Y-accept, N-redesign/loop

FCR_1.2	Inlet anti-icing system duct shall be of fireproof construction when installed in a fire zone	Product	To ensure resilience for the anti-icing system duct	Define the metric for parts to be of fireproof construction. Does the anti-icing duct meet the metrics when installed in a fire zone? Y-accept, N-redesign/loop
FCR_1.3	All components and connectors penetrating firewalls and fire barriers shall be of fireproof construction	Product	Meet fire resilience requirements through material selection	Define the metrics for parts to be of fireproof construction. Are the metrics met for components and connectors that penetrate the firewalls and fire barriers? Y- accept, N-redesign/loop
FCR_1.4	Firewalls, fire seals, and fire barriers shall be incorporated as necessary to isolate fire zones from each other and to isolate fire in the designated fire zone from the aircraft primary structure	Product	Prevent spread of fire and protect from fire through design separation and material selection for safe operation	Are firewalls, fire seals and fire barriers incorporated? N-redesign, Y- Do they isolate fire zones from each other and fire in the designated fire zone from the aircraft primary structure? Y-accept, N-redesign
EMIR_1	The inlet system shall be protected from EMI and lightning strikes	Product	Prevent damage from EMI and lightning strikes	Estimate the metrics of damage to airplane due to EMI/lightning strikes. Is the inlet system able to withstand the damage (metric)?
EMIR_1.1	Propulsion system structure shall be designed to ensure electrical continuity between components and protection against lightning strikes, electrostatic charge accumulation, and EMI	Process	Prevent damage to structure from lightning strikes electrostatic charge accumulation, and EMI, while ensuring safety and performance of electrical components	Estimate the structural resistance to lightning strikes, electrostatic charge accumulation, and EMI while providing electrical continuity between components and protection. For the propulsion system structure design, is there structural resistance to ensure electrical continuity between components? If no, redesign and loop. If yes, is there structural resistance to ensure protection against lightning strikes, electrostatic charge accumulation, and EMI? If no, redesign and loop. If yes, then done.
EMIR_1.2	Any protruding component on the wetted surface of the air inlet cowl inner barrel shall be considered as Zone 1A	Product	Determine component with added lightning protection requirements	Identify all protruding components on the wetted surface of the air inlet cowl inner barrel -> consider them Zone 1A
EMIR_1.3	The design shall demonstrate that all inlet external surfaces are capable of withstanding a severe lightning strike with only allowable damage	Process	Prevent damage outside of allowable tolerance from lightning strikes for safe operation	Identify external surfaces prone to lightning strike damage. Test/simulate severe lightning strike on inlet external surfaces for damage. Is damage within allowable limits? If no, redesign and loop. If yes, then done.

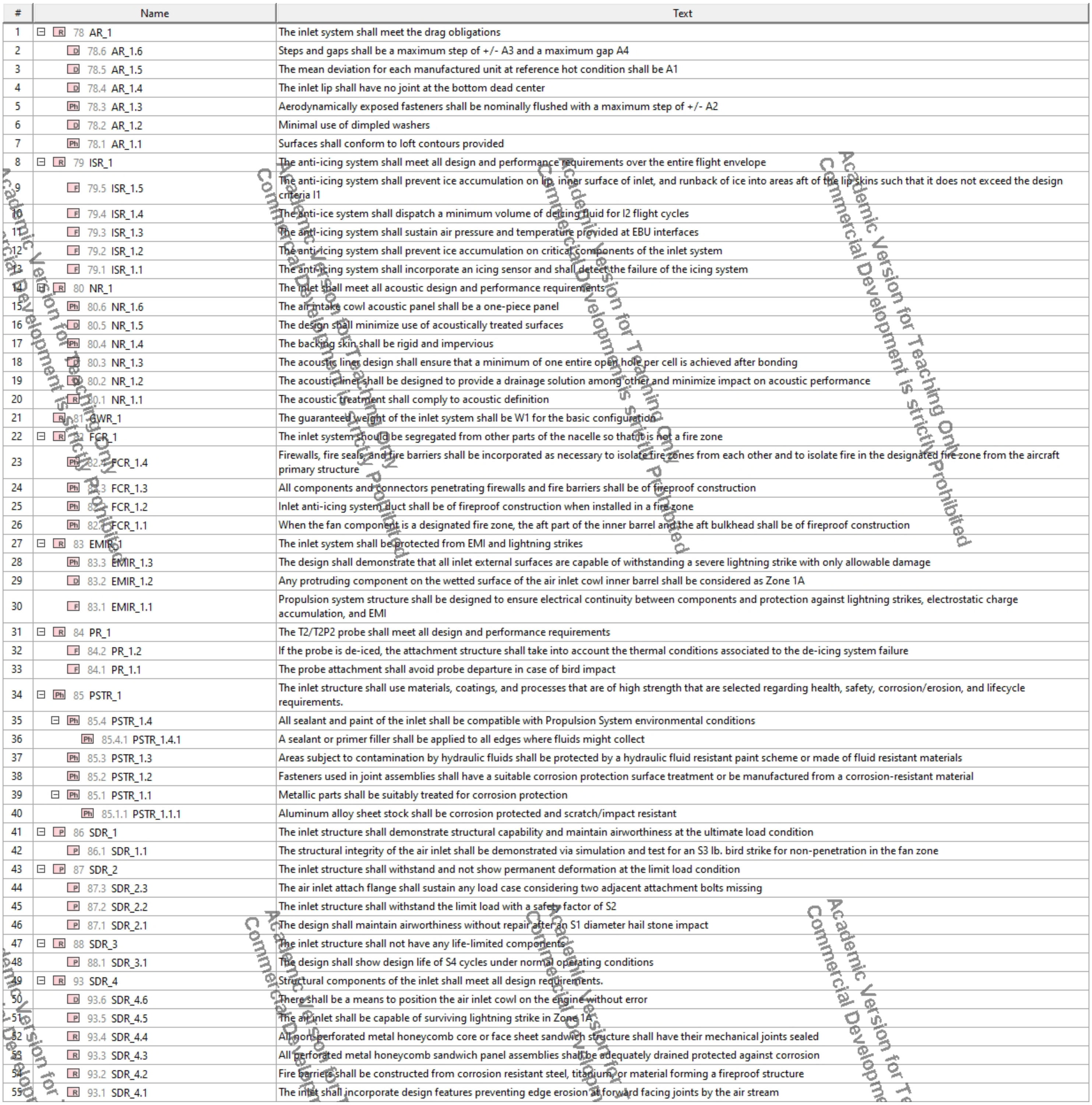
PR_1	The T2/T2P2 probe shall meet all design and performance requirements	Product	To perform tasks at all operating conditions while being structurally resilient	Define the design and performance requirements of the T2/T2P2 probe. Does the T2/T2P2 probe meet all design requirements? If no, redesign and loop. If yes check if T2/T2P2 probe meets all performance requirements. If no, redesign and loop. If yes, then done.
PR_1.1	The probe attachment shall avoid probe departure in case of bird impact	Product	The probe attachment structure is resilient to damage	Calculate the force/momentum of a bird impact (extreme situation). Can the probe attachment withhold probe departure due to this impact? Y-accept, N-redesign
PR_1.2	If the probe is de-iced, the attachment structure shall take into account the thermal conditions associated to the de-icing system failure	Product	To perform tasks at icing conditions	Monitor probe icing status. If probe is de-iced, consider thermal conditions associated to de-icing system
PSTR_1	The inlet structure shall use materials, coatings, and processes and are of high strength that are selected regarding health, safety, corrosion/erosion, and lifecycle requirements.	Process	Meet certification requirements for safe operation, structural integrity, and target lifespan	Determine metrics for high strength. Determine metrics for health, safety, corrosion/erosion, and life cycle requirements. Does the inlet structure use materials, coatings, and processes that are of high strength? (Y/N) N: Iterate design -> Loop. Y: Are materials, coatings, and processes selected due to health, safety, corrosion/erosion, and lifecycle requirements? (Y/N) Y: Complete N: Iterate design -> Loop.
PSTR_1.1	Metallic parts shall be suitably treated for corrosion protection	Product	Prevent damage and ingress of fluids or other corrosive elements and increase the lifespan	Identify sections with metallic parts. Determine metrics for suitable metallic corrosion protection. Is metallic part suitably treated for corrosion protection? (Y/N) Y: Complete N: Iterate design -> Loop
PSTR_1.1.1	Aluminum alloy sheet stock shall be corrosion protected and scratch/impact resistant	Product	Prevent damage and ingress of fluids or other corrosive elements, and meet structural performance requirements	Identify sections with aluminum alloy stock sheet. Determine metrics for aluminum alloy stock sheet corrosion protection and scratch/impact resistance. Is aluminum alloy sheet stock corrosion protected AND scratch/impact resistant? (Y/N) Y: Complete N: Iterate design -> Loop.
PSTR_1.2	Fasteners used in joint assemblies shall have a suitable corrosion protection surface treatment or be manufactured from a corrosion-resistant material	Product	Prevent damage and ingress of fluids or other corrosive elements	Identify joint assemblies. Determine metrics for suitability of fastener corrosion protection surface treatment. Y: Does the fastener have suitable corrosion protection surface treatment OR is it manufactured from a corrosion resistant material? (Y/N) Y: Complete N: Iterate design -> Loop.
PSTR_1.3	Areas subject to contamination by hydraulic fluids shall be protected by a	Product	Prevent damage and ingress of hydraulic fluids	Determine areas that are subject to contamination by hydraulic fluids. Is area protected by hydraulic fluid resistant paint scheme OR made of fluid resistant materials? (Y/N) Y: Complete N: Iterate design -> Loop.

	hydraulic fluid resistant paint scheme or made of fluid resistant materials			
PSTR_1.4	All sealant and paint of the inlet shall be compatible with Propulsion System environmental conditions	Product	Protect the propulsion system at all environmental conditions	Determine propulsion system environmental conditions. Determine compatibility metrics. Are all sealants and paints of the inlet compatible with the propulsion system environmental conditions? (Y/N) Y: Complete N: Iterate design -> Loop.
PSTR_1.4.1	A sealant or primer filler shall be applied to all edges where fluids might collect	Process	Prevent damage and ingress of fluids or other corrosive elements	Determine the edges where fluid might collect. Is sealant or primer filler applied? (Y/N) Y: Complete N: Iterate design -> Loop.
SDR_1	The inlet structure shall demonstrate structural capability and maintain airworthiness at the ultimate load condition	Product	To ensure airworthiness and structural integrity for safe operation.	1. Estimate the metrics for the structural capability for the inlet structure at the ultimate load condition. 2. Estimate the airworthiness metrics for the inlet structure at the ultimate load condition. Is the inlet structure demonstrating structural capability at ultimate load condition? (Y/N) N: Iterate design -> Loop. Yes - Is the inlet structure maintaining airworthiness at ultimate condition? (Y/N) Y: Complete N: Iterate design -> Loop
SDR_1.1	The structural integrity of the air inlet shall be demonstrated via simulation and test for an S3 lb. bird strike for non-penetration in the fan zone	Product	Meet certification requirements for safe operation during bird strike	1. Estimate metrics for structural integrity of air inlet for non-penetration in the fan zone. Is air inlet in a test or a simulation of S3 lb. bird strike? (TEST/SIMULATION) TEST: Is air inlet demonstrating structural integrity for non-penetration in the fan zone? (Y/N) Y: Complete N: Iterate design -> Loop. SIMULATION: Is air inlet demonstrating structural integrity for non-penetration in the fan zone? (Y/N) Y: Complete N: Iterate design -> Loop.
SDR_2	The inlet structure shall withstand and not show permanent deformation at the limit load condition	Product	Meet certification requirements for safe operation and structural integrity	Estimate the ultimate load condition for the inlet structure. Is inlet withstanding the ultimate load (Y/N) N: Iterate design -> Loop. Y: Is inlet showing permanent deformation? (Y/N) Y: Iterate design -> Loop N: Complete
SDR_2.1	The design shall maintain airworthiness without repair after an S1 diameter hail stone impact	Product	To ensure a resilient structure to damage for safe operation	Estimate metrics for airworthiness without repair of inlet structure. Is the design maintaining airworthiness without repair after an S1 diameter hail stone impact? (Y/N) Y: Complete N: Iterate design -> Loop. N: Loop
SDR_2.2	The inlet structure shall withstand the limit load with a safety factor of S2	Product	To ensure robustness of the structural design	Estimate limit load condition with a safety factor S2. Is the inlet structure able to withstand limit load with a safety factor S2? (Y/N) Y: Complete N: Iterate design -> Loop.
SDR_2.3	The air inlet attach flange shall sustain any load case considering two adjacent attachment bolts missing	Product	To ensure structural integrity for safe operation	Identify section of inlet containing flanges. Estimate metrics for inlet flange sustaining load cases. Is inlet flange sustaining load case where two adjacent attachment bolts are missing? (Y/N) Y: Complete N: Iterate design -> Loop.

SDR_3	The inlet structure shall not have any life-limited components	Product	Reduce need for maintenance and improve inlet life cycle	Define a metric for life-limiting aspect for components. Does the inlet structure have any life-limited components? (Y/N) Y: Iterate design -> Loop N: Iterate design -> Complete
SDR_3.1	The design shall show design life of S4 cycles under normal operating conditions	Process	Meet certification requirements for safe operation and target lifespan	Define normal operating conditions. Does the design show design life of S4 cycles? (Y/N) Y: Complete N: Iterate design -> Loop.
SDR_4	Structural components of the inlet shall meet all design requirements.	Product	Meet certification requirements for safe operation	1. List all structural components. 2. List all design requirements for structural components. 3. Do structural components of inlet meet all design requirements? (Y/N) Y: Complete N: Determine which requirements are not met -> Iterate design -> Loop
SDR_4.1	The inlet shall incorporate design features preventing edge erosion at forward facing joints by the air stream	Product	Prevent edge erosion	Identify joints that are facing forward into the air stream. Determine the design features that could prevent edge corrosion. Does the inlet incorporate design features that prevent edge erosion at those joints? (Y/N) Y: Complete N: Iterate Design -> Loop
SDR_4.2	Fire barriers shall be constructed from corrosion resistant steel, titanium, or material forming a fireproof structure	Product	Prevent fire from spreading	Identify components that are fire barriers. Are fire barriers constructed from corrosion resistant steel, titanium, or material forming a fireproof structure? (Y/N) Y: Complete N: Iterate Design -> Loop
SDR_4.3	All perforated metal honeycomb sandwich panel assemblies shall be adequately drained and protected against corrosion	Process	Prevent fluid accumulation and corrosion	Estimate metrics for adequate drainage and corrosion protection. Are perforated metal honeycomb sandwich panel assemblies adequately drained and protected against corrosion? (Y/N) Y: Complete. N: Iterate design -> Loop.
SDR_4.4	All non-perforated metal honeycomb core or face sheet sandwich structure shall have their mechanical joints sealed	Process	Prevent fluids and other corrosive elements from penetrating through mechanical joints	Identify all non-perforated metal honeycomb core or face sheet sandwich structures with mechanical joints. Are all mechanical joints on the non-perforated metal honeycomb core or face sheet sandwich structures sealed? (Y/N) Y: Complete. N: Iterate design -> Loop.
SDR_4.5	The air inlet shall be capable of surviving lightning strike in Zone 1A	Product	Prevent damage from lightning strikes	List components of air inlet in Zone 1A. Define the lightning strike survival metrics for the inlet system. Does the air inlet survive lightning strike in Zone 1A? (Y/N) Y: Complete N: Iterate design -> Loop
SDR_4.6	There shall be a means to position the air inlet cowl on the engine without error	Process	Ease of maintenance and manufacturing	1. Identify means [physical/software component] of positioning air inlet cowl on the engine. 2. Is there indication if positioned erroneously? (Y/N) Y: Iterate design -> Loop N: Complete

Appendix B – Results of the RFLP process in MagicDraw

Appendix B includes the additional set of figures from the results section of this work. The MagicDraw representation of requirements table and traceability matrix are in Figure B.1 (U-M requirements) and **Figure B.2** (tracing U-M requirements with Collins requirements), respectively. Figure B.3 shows a full requirements diagram. Figure B.4, Figure B.5, Figure B.6, Figure B.7, Figure B.8, Figure B.9, Figure B.10, Figure B.11, and Figure B.12 show requirements diagram for EMI, FCR, GWR, NR, PR (P_2T_2), PSTR, structural requirements (at ultimate load condition, SDR 1), structural requirements (at limit load condition, SDR 2), and structural requirements (component life, SDR 3), respectively. Figure B.13 shows the dependency matrix for requirements.



#	Name	Text
1	⊟ R 78 AR_1	The inlet system shall meet the drag obligations
2	D 78.6 AR_1.6	Steps and gaps shall be a maximum step of +/- A3 and a maximum gap A4
3	D 78.5 AR_1.5	The mean deviation for each manufactured unit at reference hot condition shall be A1
4	D 78.4 AR_1.4	The inlet lip shall have no joint at the bottom dead center
5	Ph 78.3 AR_1.3	Aerodynamically exposed fasteners shall be nominally flushed with a maximum step of +/- A2
6	D 78.2 AR_1.2	Minimal use of dimpled washers
7	Ph 78.1 AR_1.1	Surfaces shall conform to loft contours provided
8	⊟ R 79 ISR_1	The anti-icing system shall meet all design and performance requirements over the entire flight envelope
9	F 79.5 ISR_1.5	The anti-icing system shall prevent ice accumulation on lip, inner surface of inlet, and runback of ice into areas aft of the lip skins such that it does not exceed the design criteria I1
10	F 79.4 ISR_1.4	The anti-ice system shall dispatch a minimum volume of deicing fluid for I2 flight cycles
11	F 79.3 ISR_1.3	The anti-icing system shall sustain air pressure and temperature provided at EBU interfaces
12	F 79.2 ISR_1.2	The anti-icing system shall prevent ice accumulation on critical components of the inlet system
13	F 79.1 ISR_1.1	The anti-icing system shall incorporate an icing sensor and shall detect the failure of the icing system
14	⊟ R 80 NR_1	The inlet shall meet all acoustic design and performance requirements
15	Ph 80.6 NR_1.6	The air intake cowl acoustic panel shall be a one-piece panel
16	D 80.5 NR_1.5	The design shall minimize use of acoustically treated surfaces
17	Ph 80.4 NR_1.4	The backing skin shall be rigid and impervious
18	D 80.3 NR_1.3	The acoustic liner design shall ensure that a minimum of one entire open hole per cell is achieved after bonding
19	D 80.2 NR_1.2	The acoustic liner shall be designed to provide a drainage solution among other and minimize impact on acoustic performance
20	R 80.1 NR_1.1	The acoustic treatment shall comply to acoustic definition
21	R 81 GWR_1	The guaranteed weight of the inlet system shall be W1 for the basic configuration
22	⊟ R 82 FCR_1	The inlet system should be segregated from other parts of the nacelle so that it is not a fire zone
23	Ph 82.4 FCR_1.4	Firewalls, fire seals, and fire barriers shall be incorporated as necessary to isolate fire zones from each other and to isolate fire in the designated fire zone from the aircraft primary structure
24	Ph 82.3 FCR_1.3	All components and connectors penetrating firewalls and fire barriers shall be of fireproof construction
25	Ph 82.2 FCR_1.2	Inlet anti-icing system duct shall be of fireproof construction when installed in a fire zone
26	Ph 82.1 FCR_1.1	When the fan component is a designated fire zone, the aft part of the inner barrel and the aft bulkhead shall be of fireproof construction
27	⊟ R 83 EMIR_1	The inlet system shall be protected from EMI and lightning strikes
28	Ph 83.3 EMIR_1.3	The design shall demonstrate that all inlet external surfaces are capable of withstanding a severe lightning strike with only allowable damage
29	D 83.2 EMIR_1.2	Any protruding component on the wetted surface of the air inlet cowl inner barrel shall be considered as Zone 1A
30	F 83.1 EMIR_1.1	Propulsion system structure shall be designed to ensure electrical continuity between components and protection against lightning strikes, electrostatic charge accumulation, and EMI
31	⊟ R 84 PR_1	The T2/T2P2 probe shall meet all design and performance requirements
32	F 84.2 PR_1.2	If the probe is de-iced, the attachment structure shall take into account the thermal conditions associated to the de-icing system failure
33	F 84.1 PR_1.1	The probe attachment shall avoid probe departure in case of bird impact
34	⊟ Ph 85 PSTR_1	The inlet structure shall use materials, coatings, and processes that are of high strength that are selected regarding health, safety, corrosion/erosion, and lifecycle requirements.
35	⊟ Ph 85.4 PSTR_1.4	All sealant and paint of the inlet shall be compatible with Propulsion System environmental conditions
36	Ph 85.4.1 PSTR_1.4.1	A sealant or primer filler shall be applied to all edges where fluids might collect
37	Ph 85.3 PSTR_1.3	Areas subject to contamination by hydraulic fluids shall be protected by a hydraulic fluid resistant paint scheme or made of fluid resistant materials
38	Ph 85.2 PSTR_1.2	Fasteners used in joint assemblies shall have a suitable corrosion protection surface treatment or be manufactured from a corrosion-resistant material
39	⊟ Ph 85.1 PSTR_1.1	Metallic parts shall be suitably treated for corrosion protection
40	Ph 85.1.1 PSTR_1.1.1	Aluminum alloy sheet stock shall be corrosion protected and scratch/impact resistant
41	⊟ P 86 SDR_1	The inlet structure shall demonstrate structural capability and maintain airworthiness at the ultimate load condition
42	P 86.1 SDR_1.1	The structural integrity of the air inlet shall be demonstrated via simulation and test for an S3 lb. bird strike for non-penetration in the fan zone
43	⊟ P 87 SDR_2	The inlet structure shall withstand and not show permanent deformation at the limit load condition
44	P 87.3 SDR_2.3	The air inlet attach flange shall sustain any load case considering two adjacent attachment bolts missing
45	P 87.2 SDR_2.2	The inlet structure shall withstand the limit load with a safety factor of S2
46	P 87.1 SDR_2.1	The design shall maintain airworthiness without repair after an S1 diameter hail stone impact
47	⊟ R 88 SDR_3	The inlet structure shall not have any life-limited components
48	P 88.1 SDR_3.1	The design shall show design life of S4 cycles under normal operating conditions
49	⊟ R 93 SDR_4	Structural components of the inlet shall meet all design requirements.
50	D 93.6 SDR_4.6	There shall be a means to position the air inlet cowl on the engine without error
51	P 93.5 SDR_4.5	The air inlet shall be capable of surviving lightning strike in Zone 1A
52	R 93.4 SDR_4.4	All non-perforated metal honeycomb core or face sheet sandwich structure shall have their mechanical joints sealed
53	R 93.3 SDR_4.3	All perforated metal honeycomb sandwich panel assemblies shall be adequately drained protected against corrosion
54	R 93.2 SDR_4.2	Fire barriers shall be constructed from corrosion resistant steel, titanium, or material forming a fireproof structure
55	R 93.1 SDR_4.1	The inlet shall incorporate design features preventing edge erosion at forward facing joints by the air stream

Figure B.1. Requirements table

Figure B.2. Traceability matrix

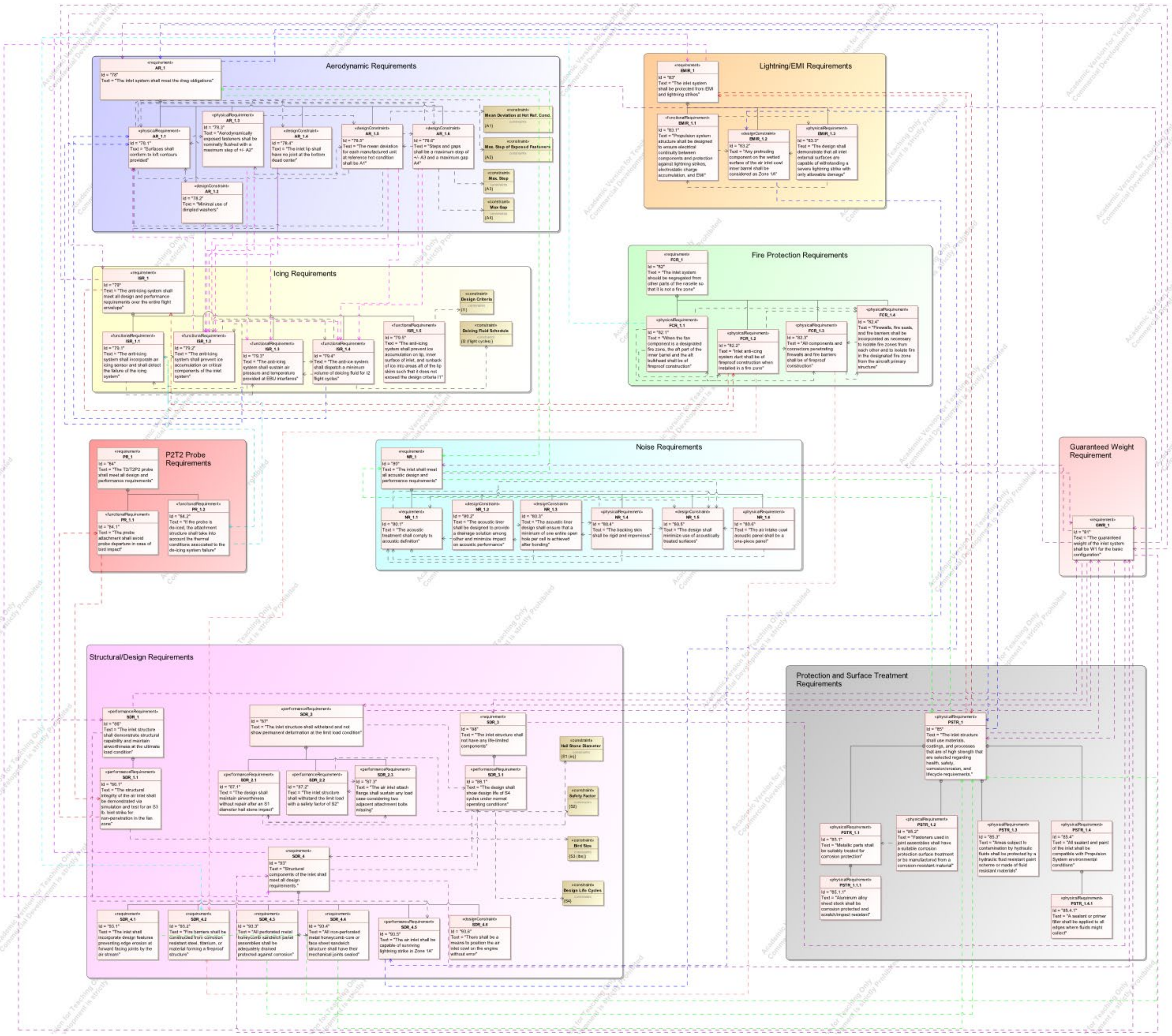


Figure B.3. Full requirements diagram showing interactions between different blocks and inter-relations between different requirements

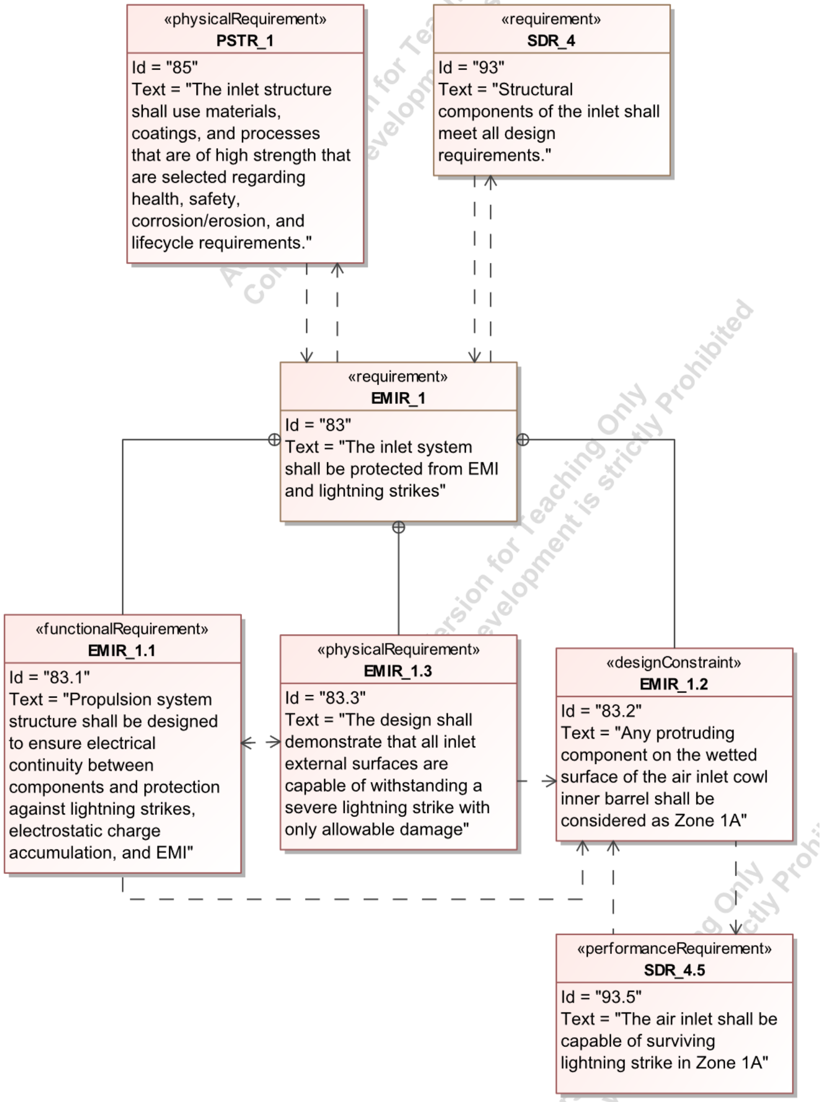


Figure B.4. Electromagnetic induction requirements diagram showing interactions between different blocks and inter-relations between different requirements

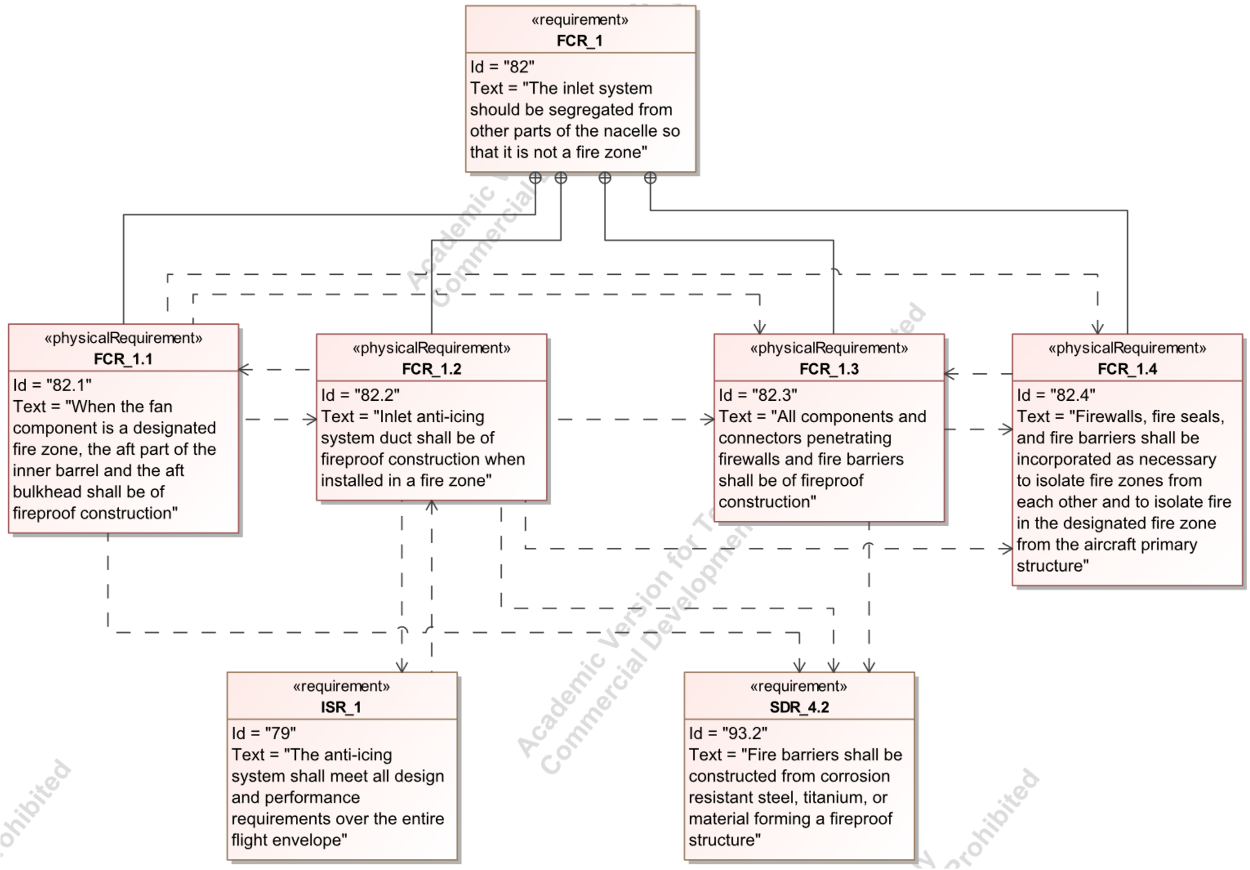
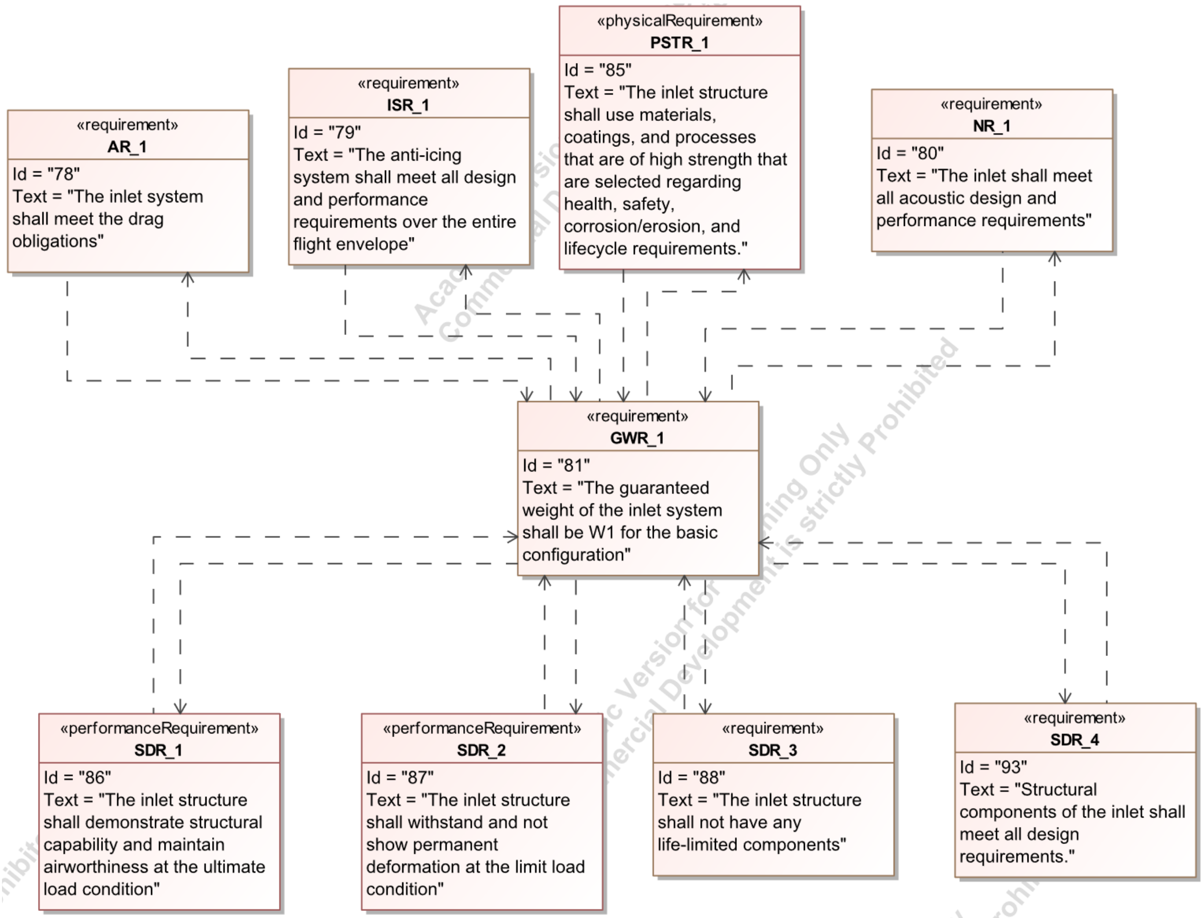


Figure B.5. Fire containment requirements diagram showing interactions between different blocks and inter-relations between different requirements



«requirement»
AR_1
Id = "78"
Text = "The inlet system shall meet the drag obligations"

«requirement»
ISR_1
Id = "79"
Text = "The anti-icing system shall meet all design and performance requirements over the entire flight envelope"

«physicalRequirement»
PSTR_1
Id = "85"
Text = "The inlet structure shall use materials, coatings, and processes that are of high strength that are selected regarding health, safety, corrosion/erosion, and lifecycle requirements."

«requirement»
NR_1
Id = "80"
Text = "The inlet shall meet all acoustic design and performance requirements"

«requirement»
GWR_1
Id = "81"
Text = "The guaranteed weight of the inlet system shall be W1 for the basic configuration"

«performanceRequirement»
SDR_1
Id = "86"
Text = "The inlet structure shall demonstrate structural capability and maintain airworthiness at the ultimate load condition"

«performanceRequirement»
SDR_2
Id = "87"
Text = "The inlet structure shall withstand and not show permanent deformation at the limit load condition"

«requirement»
SDR_3
Id = "88"
Text = "The inlet structure shall not have any life-limited components"

«requirement»
SDR_4
Id = "93"
Text = "Structural components of the inlet shall meet all design requirements."

Figure B.6. Guaranteed weight requirement diagram showing interactions between different blocks and inter-relations between different requirements

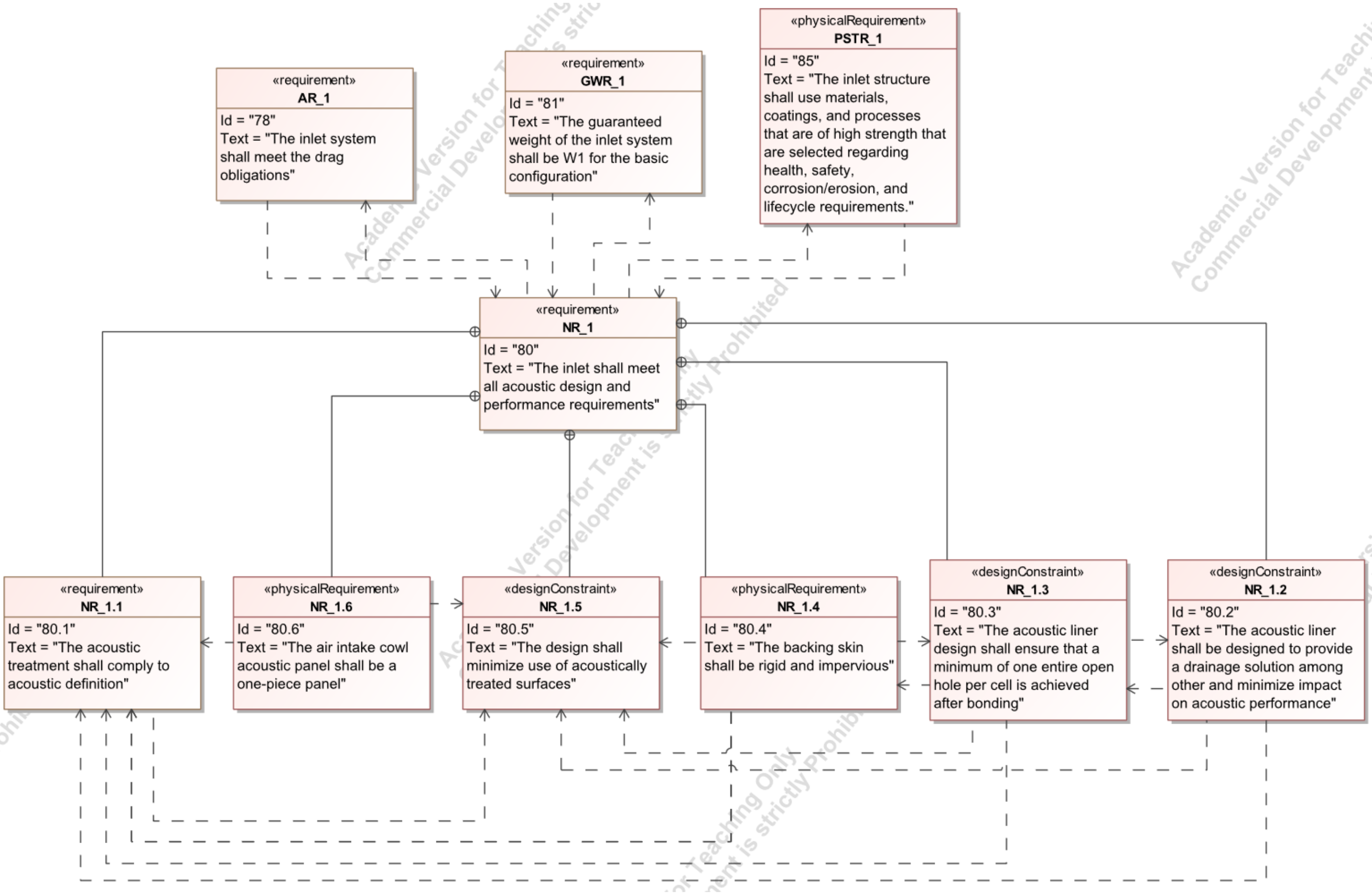


Figure B.7. Noise requirements diagram showing interactions between different blocks and inter-relations between different requirements

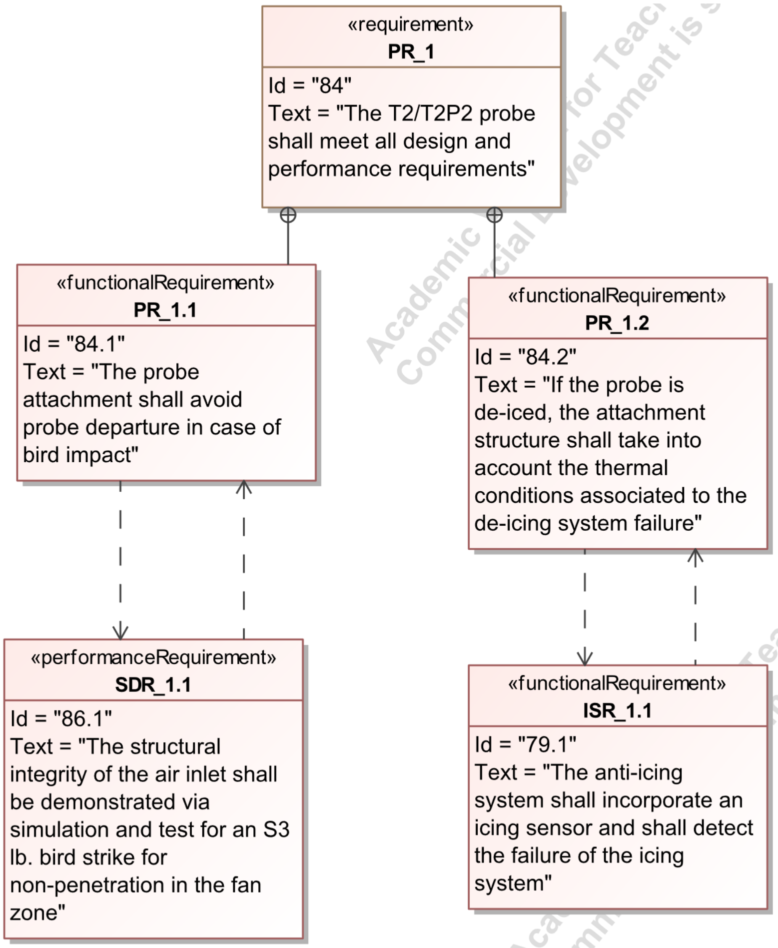
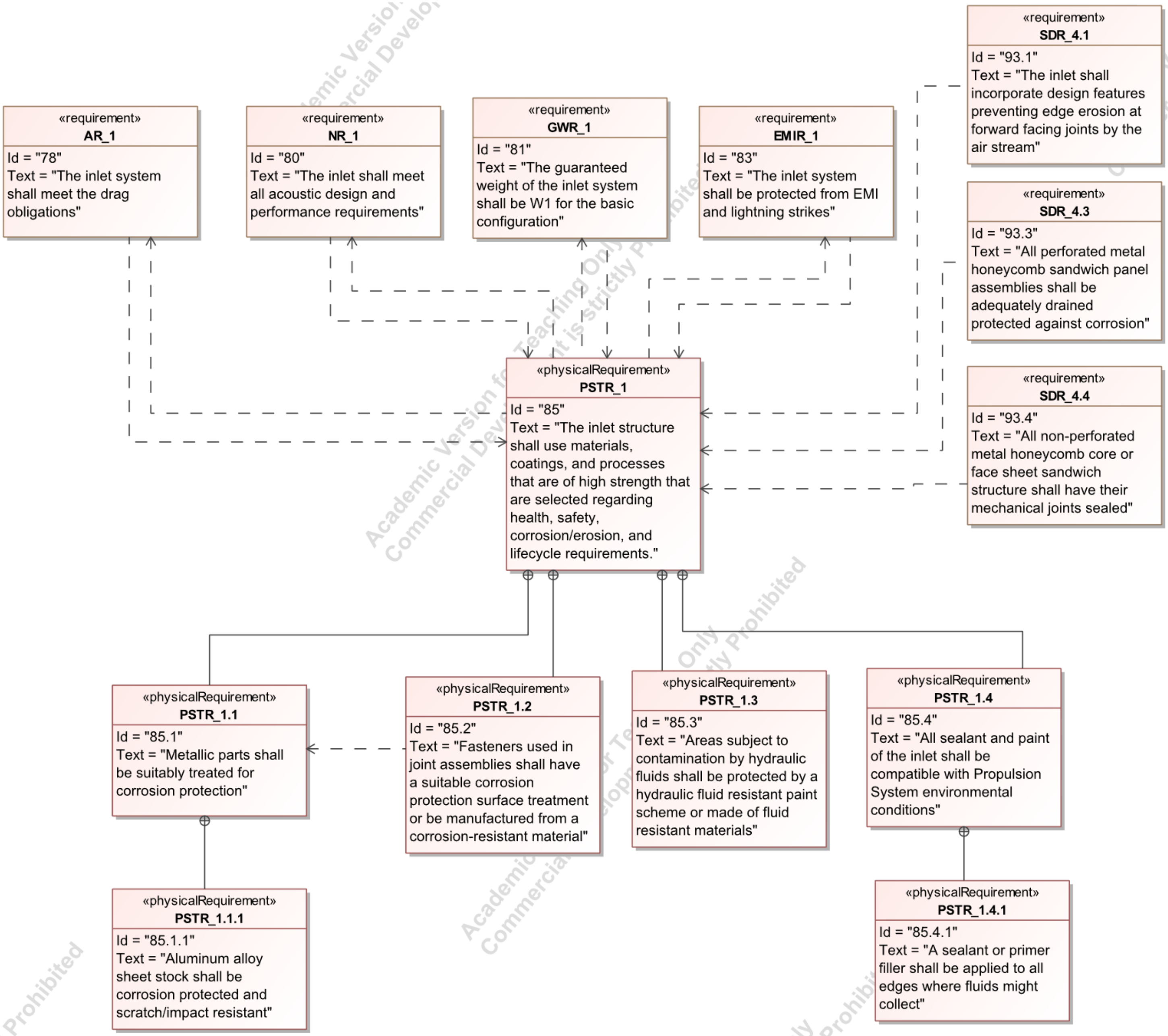


Figure B.8. P_2T_2 probe requirements diagram showing interactions between different blocks and inter-relations between different requirements



«requirement»
AR_1
Id = "78"
Text = "The inlet system shall meet the drag obligations"

«requirement»
NR_1
Id = "80"
Text = "The inlet shall meet all acoustic design and performance requirements"

«requirement»
GWR_1
Id = "81"
Text = "The guaranteed weight of the inlet system shall be W1 for the basic configuration"

«requirement»
EMIR_1
Id = "83"
Text = "The inlet system shall be protected from EMI and lightning strikes"

«requirement»
SDR_4.1
Id = "93.1"
Text = "The inlet shall incorporate design features preventing edge erosion at forward facing joints by the air stream"

«requirement»
SDR_4.3
Id = "93.3"
Text = "All perforated metal honeycomb sandwich panel assemblies shall be adequately drained protected against corrosion"

«requirement»
SDR_4.4
Id = "93.4"
Text = "All non-perforated metal honeycomb core or face sheet sandwich structure shall have their mechanical joints sealed"

«physicalRequirement»
PSTR_1
Id = "85"
Text = "The inlet structure shall use materials, coatings, and processes that are of high strength that are selected regarding health, safety, corrosion/erosion, and lifecycle requirements."

«physicalRequirement»
PSTR_1.1
Id = "85.1"
Text = "Metallic parts shall be suitably treated for corrosion protection"

«physicalRequirement»
PSTR_1.2
Id = "85.2"
Text = "Fasteners used in joint assemblies shall have a suitable corrosion protection surface treatment or be manufactured from a corrosion-resistant material"

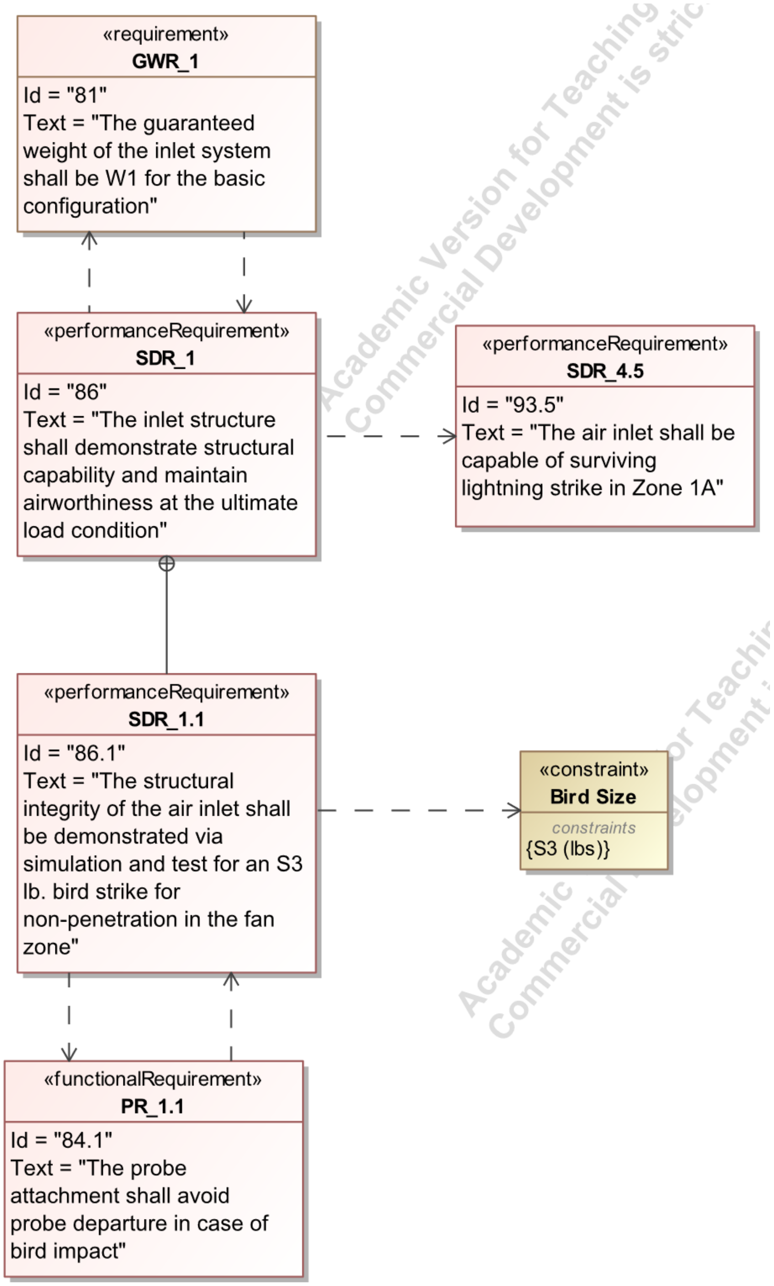
«physicalRequirement»
PSTR_1.3
Id = "85.3"
Text = "Areas subject to contamination by hydraulic fluids shall be protected by a hydraulic fluid resistant paint scheme or made of fluid resistant materials"

«physicalRequirement»
PSTR_1.4
Id = "85.4"
Text = "All sealant and paint of the inlet shall be compatible with Propulsion System environmental conditions"

«physicalRequirement»
PSTR_1.1.1
Id = "85.1.1"
Text = "Aluminum alloy sheet stock shall be corrosion protected and scratch/impact resistant"

«physicalRequirement»
PSTR_1.4.1
Id = "85.4.1"
Text = "A sealant or primer filler shall be applied to all edges where fluids might collect"

Figure B.9. Protection surface treatment requirements diagram showing interactions between different blocks and inter-relations between different requirements



GWR_1
Id = "81"
Text = "The guaranteed weight of the inlet system shall be W1 for the basic configuration"

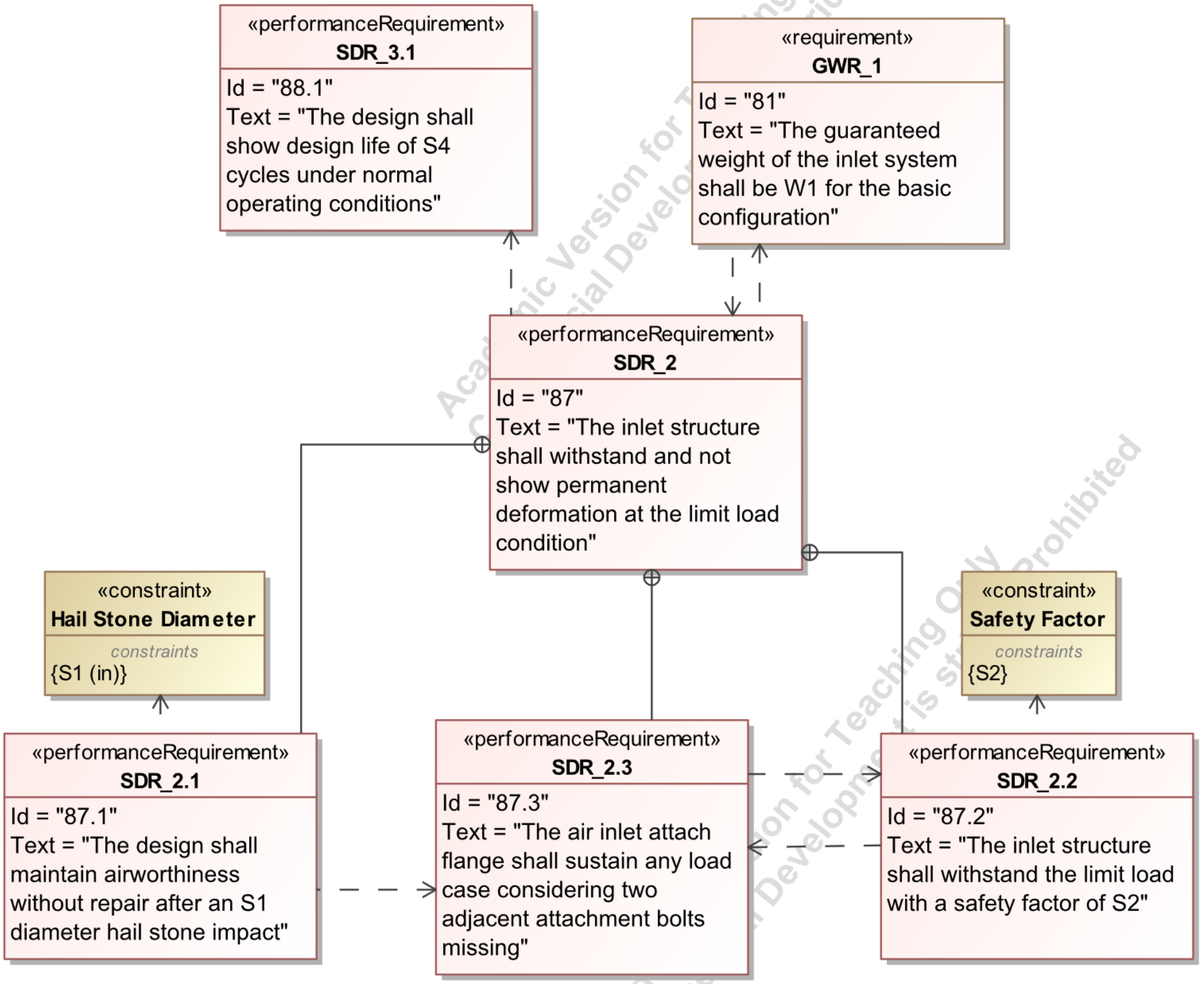
SDR_1
Id = "86"
Text = "The inlet structure shall demonstrate structural capability and maintain airworthiness at the ultimate load condition"

SDR_4.5
Id = "93.5"
Text = "The air inlet shall be capable of surviving lightning strike in Zone 1A"

SDR_1.1
Id = "86.1"
Text = "The structural integrity of the air inlet shall be demonstrated via simulation and test for an S3 lb. bird strike for non-penetration in the fan zone"

PR_1.1
Id = "84.1"
Text = "The probe attachment shall avoid probe departure in case of bird impact"

Figure B.10. Structural requirements (at ultimate load condition) diagram showing interactions between different blocks and inter-relations between different requirements



Id = "88.1"
Text = "The design shall show design life of S4 cycles under normal operating conditions"

Id = "81"
Text = "The guaranteed weight of the inlet system shall be W1 for the basic configuration"

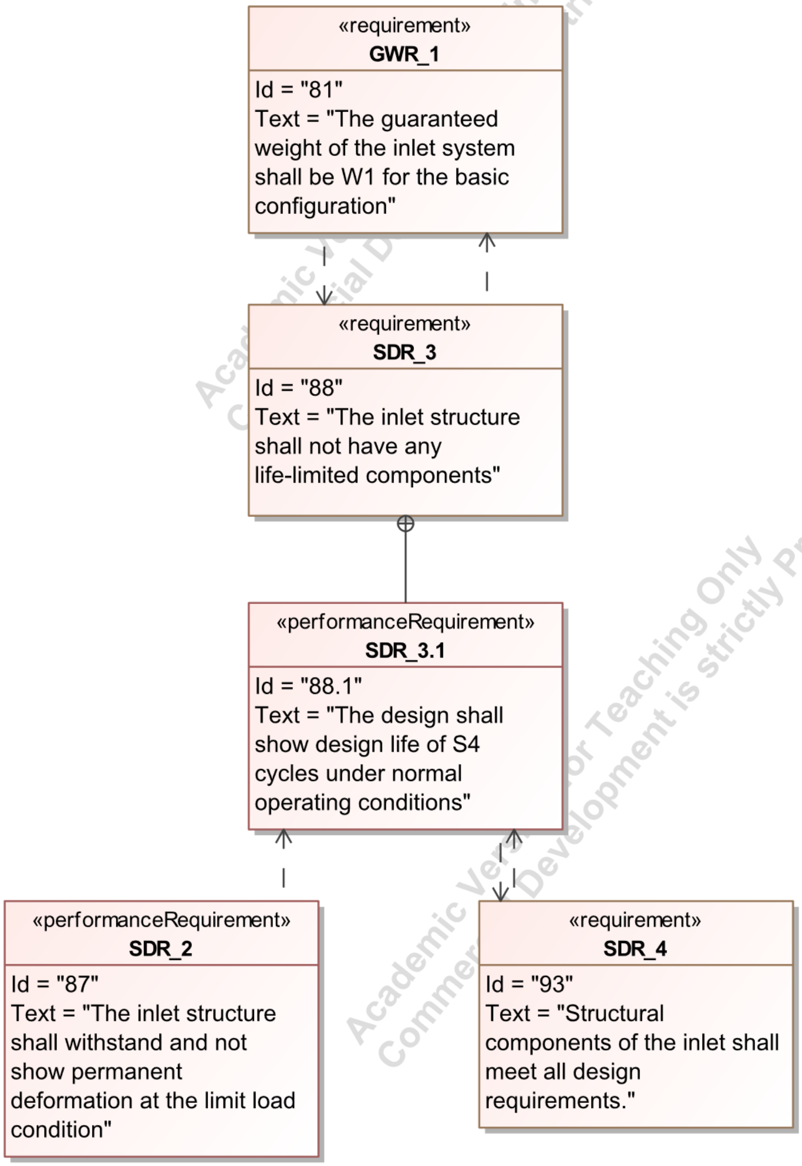
Id = "87"
Text = "The inlet structure shall withstand and not show permanent deformation at the limit load condition"

Id = "87.1"
Text = "The design shall maintain airworthiness without repair after an S1 diameter hail stone impact"

Id = "87.3"
Text = "The air inlet attach flange shall sustain any load case considering two adjacent attachment bolts missing"

Id = "87.2"
Text = "The inlet structure shall withstand the limit load with a safety factor of S2"

Figure B.11. Structural requirements (at limit load condition) diagram showing interactions between different blocks and inter-relations between different requirements



Id = "81"
Text = "The guaranteed weight of the inlet system shall be W1 for the basic configuration"

Id = "88"
Text = "The inlet structure shall not have any life-limited components"

Id = "88.1"
Text = "The design shall show design life of S4 cycles under normal operating conditions"

Id = "87"
Text = "The inlet structure shall withstand and not show permanent deformation at the limit load condition"

Id = "93"
Text = "Structural components of the inlet shall meet all design requirements."

Figure B.12. Structural requirements (component life) diagram showing interactions between different blocks and inter-relations between different requirements

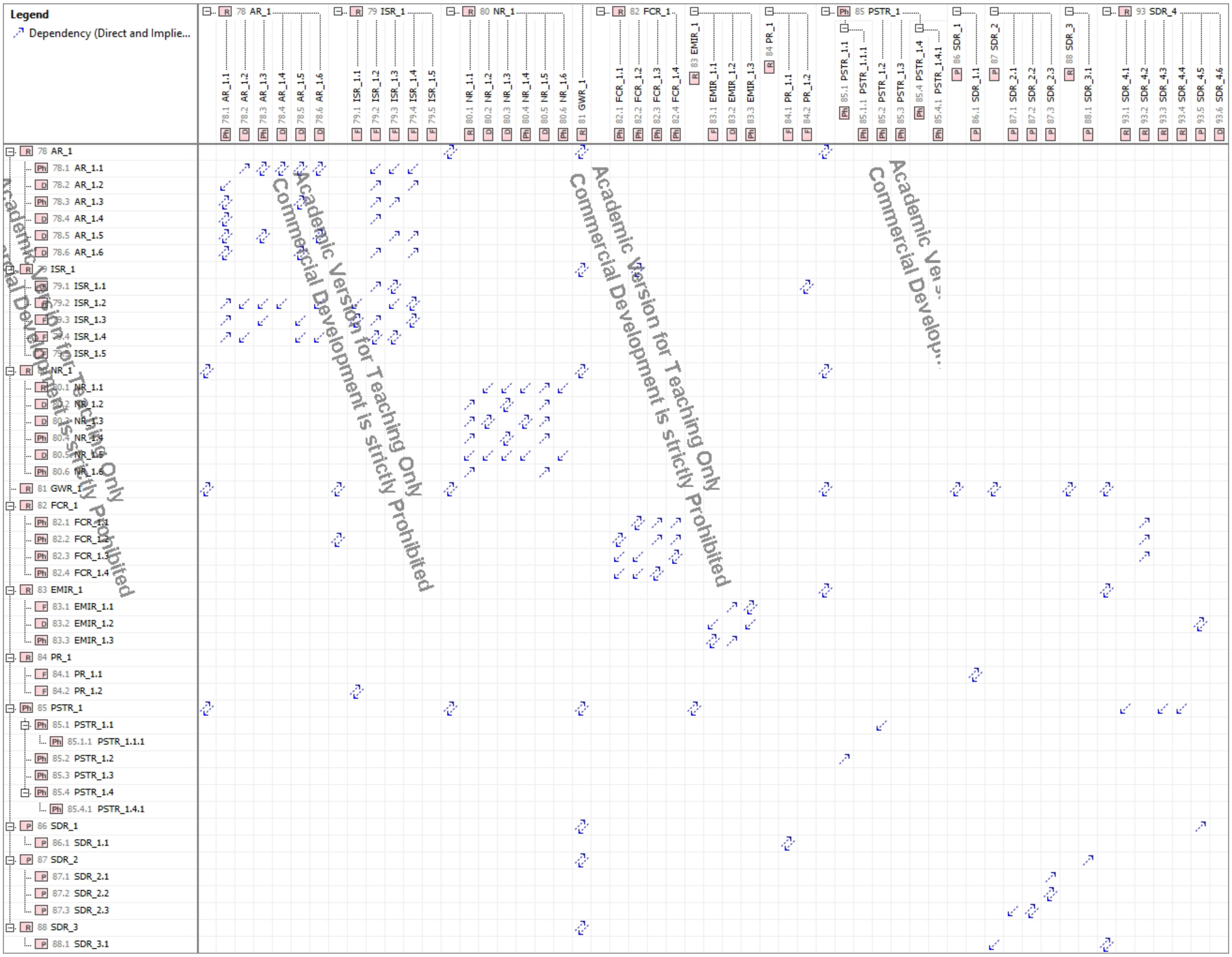


Figure B.13. Dependency matrix

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