



Deliverable D 6.1

Evaluation report on the technical concepts and operational procedures of the envisaged Pod system

Project acronym:	Pods4Rail
Starting date:	2023-09-01
Duration (in months):	34
Call (part) identifier:	HORIZON-ER-JU-2022-01
Grant agreement no:	101121853
Due date of deliverable:	30.10.2025
Actual submission date:	19.03.2026
Code:	Pods4Rail-WP06-D-UPM-001-4
Responsible/Author:	Jesus Felez / UPM
Dissemination level:	PU
Status:	I

Reviewed: yes

Reviewer: DLR, SMO



This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No 101121853.

Document history		
<i>Revision</i>	<i>Date</i>	<i>Description</i>
1	20-12-2024	Intermediate draft, pending the consolidation of the results of the previous involved deliverables that are at this moment in the review process.
2	10-03-2025	Revision of the technical and operational assessment
3	01-04-2025	Revision of the qualitative and quantitative analysis
4	20-01-2026	Version for general review
5	30-01-2026	Final version sent for approval
6	19.03-2026	Version after review

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1 Executive Summary

According to the Grant Agreement, Task 6.1 (D6.1) of the Pods4Rail project aims to determine whether the Pods4Rail system is technically, operationally and safely feasible, while economic and stakeholder aspects are covered separately in Task 6.2 (D6.2).

Chapter 5 introduces the overall methodology, summarising key results from previous work packages and establishing the definitions and information required for a consistent assessment. Chapter 6 then defines several Operational Application Scenarios (OASs), based on inputs from users, stakeholders and prior economic analyses. These scenarios form the main basis for the feasibility evaluation.

A central aim of the deliverable is to assess whether the system reaches the expected level of Technical Feasibility at this stage of the project. Chapter 7 therefore provides a detailed assessment through two approaches:

- **Qualitative analysis:** Using earlier deliverables, it evaluates technologies and components through hierarchical criteria, bar charts and heat maps to estimate Technology Readiness Levels (TRLs). This helps illustrate system maturity, scenario representativeness and key technological challenges.
- **Quantitative analysis:** This focuses on Integration Readiness Levels (IRLs) and system-level performance, applying Monte Carlo simulation to model uncertainties and dependencies. The result is a robust estimate of the System Readiness Level (SRL).

The qualitative assessment shows that most criteria apply to both passenger and freight use cases, although passenger-related scenarios include slightly more criteria. Efficiency, sustainability and safety are the most influential categories, while aspects such as passenger comfort or specific freight packaging are less critical overall. The most demanding challenges appear in automation, digitalisation and sustainability.

The quantitative results indicate that the system's overall SRL ranges between SRL 1 (Concept Refinement) and SRL 2 (Technology Development), consistent with the early development stage foreseen in the Grant Agreement. Translated to TRL terms, the system lies between levels 2 and 3.

At component level, the Operations and Planning System, Logistics/Ticketing/Booking, Passenger Information and Incident Management, and the Handling System show higher maturity. By contrast, the Transport Unit, Rail Carrier Unit and Coupling System fall below the composite SRL, making them the most technically challenging components to develop.

2 Abbreviations and acronyms

Abbreviation / Acronym	Description
ATO	Automatic Train Operation
BC	Business Case(s)
CBA	Cost-Benefit Analysis
Dx.x	Deliverable x.x
EC	Economic criteria
EU-RAIL MAWP	EU-RAIL Multi Annual Work Plan
FR	Functional Requirement
FRS	Functional Requirement Specification
GA	Grant Agreement
GoA	Grade of Automation
IRL	Integration Readiness Level
OAS	Operational Application Scenarios
OC	Operational criteria(s)
PAS	Practical Application Scenario
PMR	Passenger with Reduced Mobility
RAMS	Reliability, Availability, Maintainability and Safety
ROI	Return of Investment
SC	Safety criteria(s)
SRL	System Readiness Level
SWOT	Strengths, Weaknesses, Opportunities y Threats
TC	Technical criteria(s)
TRL	Technology Readiness Level(s)
Tx.x	Task x.x
UC	Use Case(s)
WP	Work Package
WS	Work Stream

3 Background

The Pods4Rail project is clustered into three Work Streams (WS) (Figure 1). The WS1 contains of five WPs dealing with the “Identification of use Cases, Business Cases/CBA, operating concept.” The WS2 also contains of five WPs dealing with the “Moving Infrastructure vessel and operation System”. Finally, the WS3 comprises three WPs dealing with “Moving infrastructure carrier incl. Locking System and handling System”.

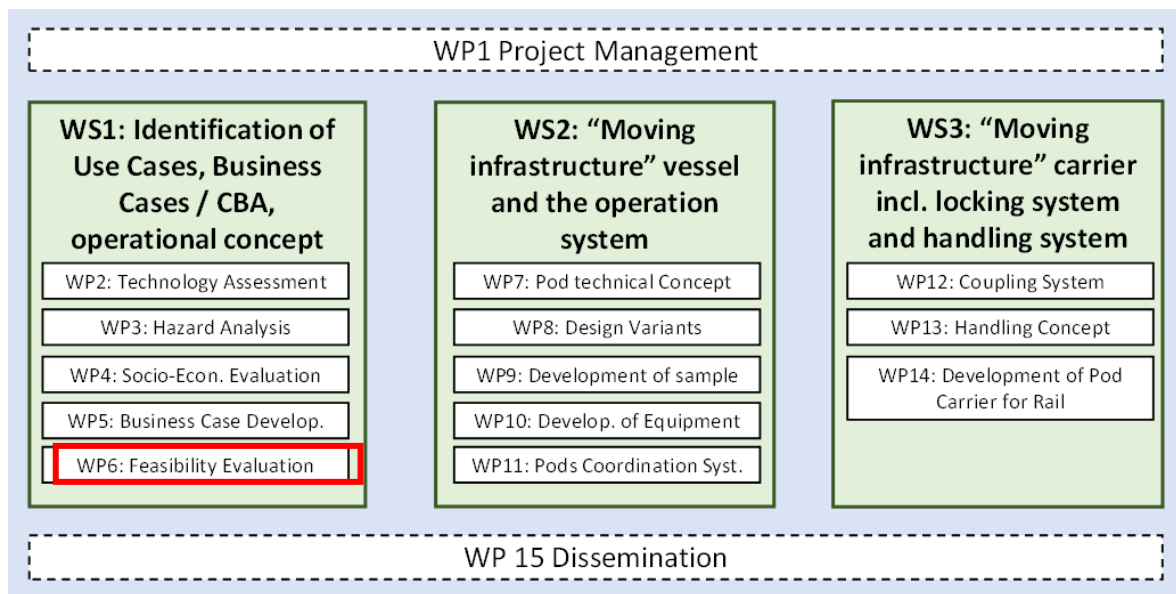


Figure 1: Pods4Rail division into three Work Streams

As highlighted in the Executive Summary, WP6 is divided in two deliverables and tasks: the current D6.1 and a following D6.2 document. The work reported in both deliverables has been performed within WP6 “Feasibility evaluation” as part of WS1 “Identification of use Cases, Business Cases/CBA, operating concept”.

The present document constitutes the Deliverable D6.1 “Technical evaluation of the feasibility of envisaged operational procedures” in the framework of the Flagship Area 7, project Pods4Rail as described in the EU-RAIL MAWP.

4 Objective/Aim

The operational procedures of Pods4Rail will rely on normal railway, mainly, and road principles but need to be adopted with respect to the operational tasks to be fulfilled. The major chance here is to design a specific solution for highly automated, unattended operation. In addition, new operating scenarios shall be considered in which conventional railway operations can be combined with fully automated and autonomous forms of operation. The control and system technology must therefore also be designed for these new forms of operation, and their technical feasibility must be thoroughly evaluated.

Consequently, the Pods4Rail operational framework is not an evolutionary step on top of normal operation but reduced to the needs of e.g., ATO GoA4. This needs to be evaluated with respect to technical feasibility. The economic perspective and stakeholders' analysis are addressed in Deliverable D6.2.

This document aims to provide the core information necessary for a qualified assessment of the Pods4Rail system's feasibility in terms of technical, safety and operational criteria. It consolidates relevant findings from previous Work Packages (WP), establishes key definitions, outlines the methodology to be applied, and identifies the Operational Application Scenarios (OAS) that will be assessed.

The primary objective of this report, beyond providing general context and shared background information, is to determine whether the Pods4Rail system meets the necessary Technical Feasibility level needed at this stage of the project. To achieve this, several secondary objectives have been defined:

- To perform a qualitative analysis of the system and its components according to a hierarchy. As a result, bar charts and heat maps related with the Technology Readiness Level of the subjects is expected as a visual tool to understand where the maturity of whole system can be established in an approximate way and to evaluate if the selected OAS are enough representative for the assessment.
- To estimate the level of maturity (System Readiness Level) of the whole Pods4Rail System and its corresponding components through a statistical approach based on Monte Carlo method (Wachholz & Malzew, 2024) to minimize the inherent uncertainty related to the assignment of TRLs and IRLs (Integration Readiness Level) of the system's components.

5 Methodology for the assessment of the Pods System concept

The following chapter outlines the general methodology to be employed in a comprehensive assessment of the Pods System concept, evaluating its feasibility in terms of technical, operational, and safety criteria.

5.1 Introduction

The evaluation process is divided into two essential criteria, the technical feasibility (developed in the present document), and the economic success of the best operating scenarios (developed in D6.2).

This is evaluated with respect to technical feasibility in this deliverable (D6.1). The economic and stakeholder's perspective is addressed in Task 6.2.

This chapter will firstly discuss the relevant information of the Deliverables of the previous tasks. The goal of this is to give an impression on the wide variety of perspectives that are used to investigate the feasibility of the Pods-concept in multiple contexts. From this, overlaps and synergies from these perspectives are derived, as well as a clear distinction in definitions used throughout the project.

Then, in this Chapter, a summary of the relevant results from the previous Tasks is provided in Section 5.2. These Deliverables, that will be summarized below, provide the building blocks for the evaluation in this Task. After that, some important definitions are going to be stated and explained in Section 5.3. Subsequently, the methodological approach is then presented in Section 5.4.

5.2 Overview of relevant results from previous Tasks

Since WP6 deals with the evaluation of the results of the previous work packages, it is necessary to identify the outputs provided by these WPs and which will serve as the basis for the work that is going to be done in this WP6. To this end, a series of criteria will be extracted from the previous deliverables that will allow a qualified assessment of the feasibility of the Pods4Rail system.

In brief, D4.4 "High-Level functional requirements specification" (Pods4Rail, 2024d) will be the basis for extracting the main technical and operational criteria; some few safety criteria will be extracted from here too. This deliverable D4.4 together with D3.2 "Proposition for an evolution of the existing safety framework and preliminary safety requirements" (Pods4Rail, 2024a) will serve to identify the main safety related criteria. In addition, to add end-users' perspective to the analysis, information will be extracted from the different Use Cases defined in D4.1 "Description of Use Cases" (Pods4Rail, 2024b) and the stakeholders' interests will be obtained from D4.2 "SWOT analysis" (Pods4Rail, 2024c) and from the analysis of the Business Cases in deliverables D5.1 "Report on a generic Business Case elements" (Pods4Rail, 2024e) and D5.2 "Business Case Study for Selected Use Cases" (Pods4Rail, 2024f).

Table 1 provides a more detailed summary of the information provided by each of the deliverables that serve as inputs to this document.

Table 1: Deliverable contents and inputs provided to D6.1

Deliverable	Contents and inputs provided
D3.2 Proposition for an evolution of the existing safety framework and preliminary safety requirements	D3.2 provides a synthesis of the European and national standards, laws, and legal framework that are related to or can be involved in the development of the future Pod systems. The focus of the overview is the safety and security aspects, as well as the system digitalisation and automation. The study includes the standardisation and legislative frameworks related to the different existing modes of transportation (railways, urban guided systems, buses, trucks, automotive, ropeways, etc.) D3.2 is one of the inputs for the selection of safety criteria.
D4.1 Description of use cases	D4.1 identifies and describes potential Use Cases (UC) for Pod systems. The definition of the UCs considers technological feasibility, environmental impact, economic viability as well as user- and society-centred design and operation. In total, 22 UC were subjected to analysis. D4.1 shows that mainly three kinds of transport solutions have to be considered for Pod systems, representing a range of possible and feasible UC: Passengers, Freight, and Combined transport. Passenger transport UCs such as premium and individual transport services are highly relevant, since they can offer new services and better comfort for several user groups. For freight transport and combined (passenger and freight) transport, Pod systems offer new solutions for more effective, flexible freight transport and for specific event-driven UC D4.1 is the main input for the end-users' perspective analysis.
D4.2 SWOT analysis	D4.2 describes the performed qualitative assessment of the socio-economic factors or Pod system applications. The analysis highlights strengths, weaknesses, opportunities, and threats of the autonomous Pods system for passenger and freight transport. D4.2 represents a key input in the analysis of stakeholders' interests.
D4.3 Estimation of economical effort	D4.3 provides an initial overview of the socio-economic parameters that influence the development of a new intermodal transport system (Pods system) and the extent to which these parameters are affected by this new system. This report qualitatively assesses the application of the Pods system in two different scenarios (a freight and a passenger scenario, UC1-4, UC17-20, respectively, as mentioned in D4.1) in terms of their societal impact and a first view of their economic viability. D4.3 is one of the inputs for the selection of the economic assessment.

Deliverable	Contents and inputs provided
D4.4 High-Level functional requirements specification	D4.4 provides the high-level functional requirements for the Pods System, covering the transport units, rail carrier units and related operational system components. In total, approximately 500 high-level functional requirements were identified and specified in 11 system areas. D4.4 is the main input for the technical and operational criteria selection and, also, one of the inputs for the selection of the safety and economic criteria.
D5.1 Report on a generic Business Case element	D5.1 provides the description of the different elements to be used for the specific Business Cases development. This deliverable constitutes the steps 1 and 2 (of the 4 steps of the WP5 as a whole). In this document, generic Business Cases will be developed through and ideation process. Subsequently, the identified BC will be categorised and evaluated in terms of their technical and economic feasibility. Furthermore, a cost-structure framework is determined and analysed for it to be applicable for all the brain-stormed BC.
D5.2 Business Case Study for Selected Use Cases	D5.2 has conducted a comprehensive Business Case study of various transportation and mobility services for Pod Systems. Based on a selection of BC (from the variety of 5.1), this study (Business Model Canvas, Business Analysis using Fact Sheets and other methodologies) covers a wide range of scenarios from manufacturing to service provision, thus covering different business models within the public transport sector. The objective of this deliverable (steps 3 and 4) is to evaluate a variety of specific Pods4Rail Business Cases for target customer markets, in terms of Use Cases, in order to increase efficiency and sustainability in the mobility sector. D5.2 constitutes the main input of the stakeholders' interest's analysis.
D7.1 Concept proposal Pod system ¹	D7.1 provides a first concept proposal for the Pod System, consisting of the TU, the interfaces towards the CU- and towards the surroundings as well as the operation system for the Pods. The document shows different detail levels of the given concept developments.

5.3 Definitions

In order to establish the methodological approach of the analysis conducted, it is first necessary to define the following terms.

¹ Although deliverable D7.1 belongs to WS2 and D6.1 to WS1, due to the general planning of the project, they have been developed in parallel and in coordination, so it is also considered as one of the reference documents for this deliverable

Functional requirement (FR): Functional requirements (from D4.4) are product/service features or functions that developers must implement to enable users to accomplish their tasks. Functional requirements specify what a system should do. They define the actions, tasks, and operations that a system must perform to satisfy user needs and achieve its goals. These requirements are concerned with the functionality of the system and describe the input, behaviour, and output of the system.

Criterion: (Structure Fourth Level) Functional requirement that the experts, in this deliverable, will indicate can be converted into criteria. In that sense, they are previous requirements (FR) that are validated to form part of the criteria. The process of this evaluation will be specified various chapters underneath. They are in the lowest place of the hierarchy. A graph will explain this hierarchy/structure in Chapter 7.

Criteria: Criteria are a set of measurable and clearly defined requirements that a project, product, or service must meet in order to be considered successful. The criteria defined, in this document, are going to be used as a measure that allows the evaluation of the compliance of the Pods System Profitability that WP6 states as the main objective.

Technical criteria (TC): These are criteria that affect the functional, operational and quality aspects of a product or service, as well as the limitations and assumptions that affect its design and development.

Operational criteria (OC): These criteria affect the specific conditions and scenarios under which a product will function, encompassing aspects such as mission profiles, necessary infrastructure, logistics, maintenance, responsible parties, and environmental factors. They are used to assess the effectiveness and efficiency of operations. These criteria focus on the processes, procedures, and performance metrics that ensure the smooth functioning of day-to-day activities.

Safety criteria (SC): Criteria on safety are related to the prevention of damage to the transport system and the environment, the protection and well-being of passengers and cargo, and the safe operation in the environment.

Subcategory: (Structure Third Level) Subcategories are the next level of the hierarchy compared to the defined criteria. They also form the previous level of the hierarchy before what will be called Group of criteria.

Group of criteria: (Structure Second Level) These definitions are the same that were developed in D4.4 as High-Level Functional Requirements. D4.4 define 11 Groups of criteria like “Operation and Planning System”, “Logistics and Storage”, “Ticketing and booking”, etc. These elements have the second highest level of hierarchy and constitute the main elements that conform the project Pods4Rail System (Structure First Level).

Use Case (UC): A Use Case is a written, detailed description of how an end user (i.e., customer) uses a system or product. The purpose of writing a UC is the specifically understanding of the step-by-step interactions between the customer and the system or products (Pods System). The UC describes the system's behaviour under

various conditions as it responds to requests from the stakeholders, called the primary actors.

Business Case (BC): A Business Case is an analysis of the benefits, costs and potential risks associated with a proposed action based on research by business analysts. By studying costs, benefits, risks, etc., a Business Case is a methodology that helps the making-decision process for stakeholders. A Business Case focuses on the potential financial and operational benefits of a product, process, project or initiative.

Practical Application Scenario (PAS): A Practical Application Scenario is a real-life application of the Pods for passenger and/or freight transport, where a benchmark (assessment of the impact compared to conventional transport systems) has been presented and will be used for the basis of the Operational Application Scenario analysis.

Operational Application Scenario (OAS): An Operational Application Scenario (OAS) is defined as a scenario that considers all three dimensions: users, stakeholders and economic aspects. The definition and election of these scenarios is going to be detailed paragraphs below. The OAS are a main concept in this WP because they are going to be the final subjects of evaluation of their performance and feasibility.

Technology Readiness Level (TRL): The Technology Readiness Level (TRL) is a nine-level scale used to assess the maturity and risk of a technology, allowing for comparisons with others. It is a well-known variable used in the Pods4Rail project since its introduction in previous WPs as WP4. However, it focuses solely on individual components or technologies, without considering entire systems. As a result, it does not fully capture the challenges of integrating a technology or subsystem into an operational system, and it doesn't provide guidance on the uncertainty associated with progressing through the different maturity levels. Additionally, it lacks a comparative analysis technique for different TRL levels. The scale for the different TRL is included in Appendix 1.

Integration Readiness Level (IRL): IRL is a variable that allows the description and measurement of how well two components, technologies or subsystems are connected and integrated. IRL is introduced as a metric for systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points. The main concept of IRL is to be used to evaluate integration of two technologies that were evaluated by the TRL process. Its measurement of integration maturity has been developed in a similar scale to TRL with the aim of combining both of these variables for further analysis. In that sense, levels from 1 to 9 have been defined (Tan et al., 2011), (Sandu, 2022), (Jentsch et al., 2023). These levels and their corresponding descriptions are included in Appendix 2.

System Readiness Level (SRL): SRL is a methodological approach that measures the readiness of a system for its deployment and is determined by combining the individual TRLs within a system and their integration with other technologies (IRLs) providing a snapshot of a system's holistic state of maturity during system development. This interaction forms a function that corresponds to a five-level SRL index. Mathematically, SRL is derived from the combination (product) of the TRL and

IRL matrices. It has to be mentioned that SRL is a variable that is still in a development phase; in consequence, not only one scalation can be found for it, because the SRL methodology is new and is currently being validated through a number of program pilots. There are several scales for this variable as ranges like [0,1], [1,5], and even some conversions to a [1,9] scale to allow a further easier comparison with both already mentioned variables. In this document, the scale 1-5 and its equivalence to the normalized 0-1 scale will be considered (Tan et al., 2011), (Sandu, 2022), (Jentsch et al., 2023).

5.4 Methodological approach

The previous work packages identified the main requirements for the new system concept, as described in D4.4 (and other mentioned deliverables), several qualitative analyses were also carried out on the technical and economic aspects, the competitive position and the criteria that a new Pods transport system must have to meet.

However, as the Grant Agreement (GA) states, the whole analysis of this document requires the definition of new operating scenarios in which conventional railway operations can be combined with fully automated and autonomous forms of operation. In this line, before the evaluation of the compliance of the several stated criteria, the first step is to develop an analysis to define which are going to be these new operating scenarios (OAS).

In that line, a synthesis of the previous activities in the referenced previous deliverables is then compiled into a set of comprehensive scenarios. The assessment of the different collected information will be used to evaluate and define what will be known as Operational Application Scenarios (OASs).

After the OAS are defined, they are going to be subject to an evaluation to determine their compliance with the demands of Technical Feasibility that the Pods4Rail project seeks to achieve.

Subsequently, two phases can be clearly distinguished in the main approach and methodology, as shown in Figure 2:

- Phase 1 (Developed in D6.1) – Chapter 6: The development and definition of Operational Application Scenarios with the help of the inputs, from previous deliverables, to match the definition of OAS to what the GA states.
- Phase 2 (Developed in D6.1) – Chapter 7: The assessment of the OAS in terms of technical, operational and safety criteria to validate the Technical Feasibility of the subjects and to estimate the level of maturity of the whole Pods4Rail system and its corresponding components.

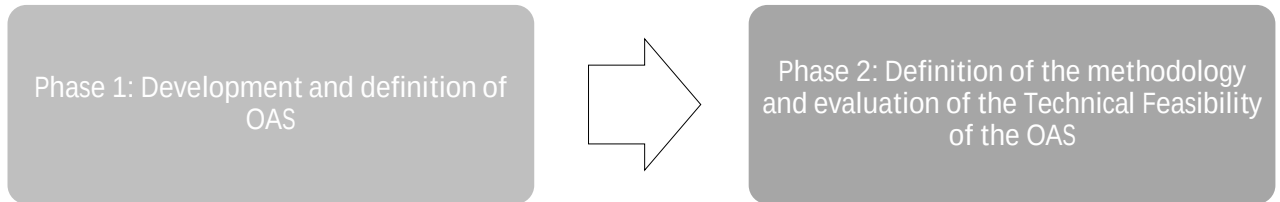


Figure 2: Process to be followed in the WP6 divided in 2 phases

Thereafter, each phase is going to be described in a more focused way. However, the complete explanation of each phase will be done in the corresponding chapter.

- Phase 1: Development of OAS (Chapter 6)

Operational Application Scenarios (OAS) will be developed in order to be assessed (applied, weighted and evaluated) by the criteria that, up next, will be defined. The criteria will be derived from the extended list of the system requirements of D4.4 and other inputs that are going to be mentioned in Phase 2. The selection of the OAS will be done by first selecting the most likely and applicable combination of Use Cases, Business Cases and Practical Application Scenarios. The study of the relation between these three inputs will allow the selection of the OASs that cover the majority of operational scenarios as the GA states in the description for this Work Package. This process is schematically shown in Figure 3:

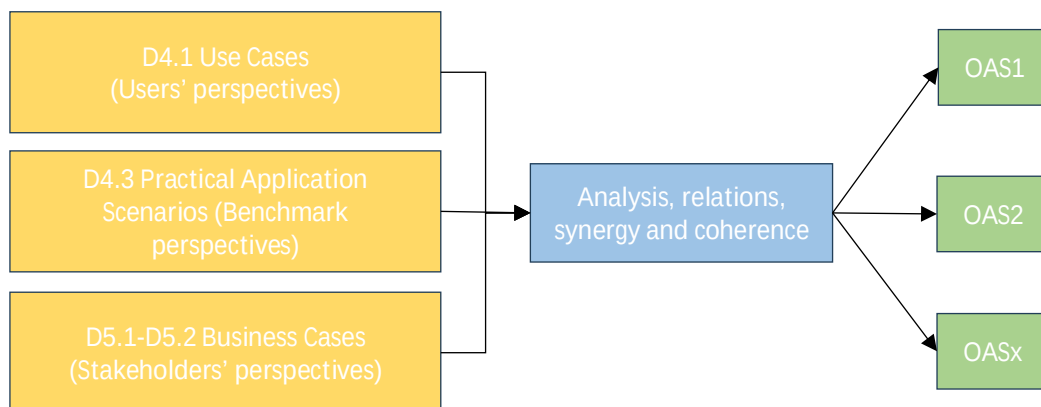


Figure 3: Phase 1 - Definition of Operational Application Scenarios (OAS)

- Phase 2: Definition and assessment of the criteria for the Technical Feasibility evaluation of the subjects (Chapter 7)

The OAS defined in Phase 1 will, in turn, be analysed according to technical, operational and safety criteria. For this analysis, the overview of criteria coming from the requirements elaborated in D4.4 will be categorized and assessed to decide which of them can be

converted into criteria, considering the level of maturity and availability of the criterions' technologies by a preliminary estimation of TRL level. This will be carried out based on a combination of literature and expert judgement and will be checked and reviewed by other experts. This analysis will create a widespread impression of the Technical Feasibility of the Pods System in the previous determined OAS.

The different steps of this phase's methodology are presented in Figure 4:

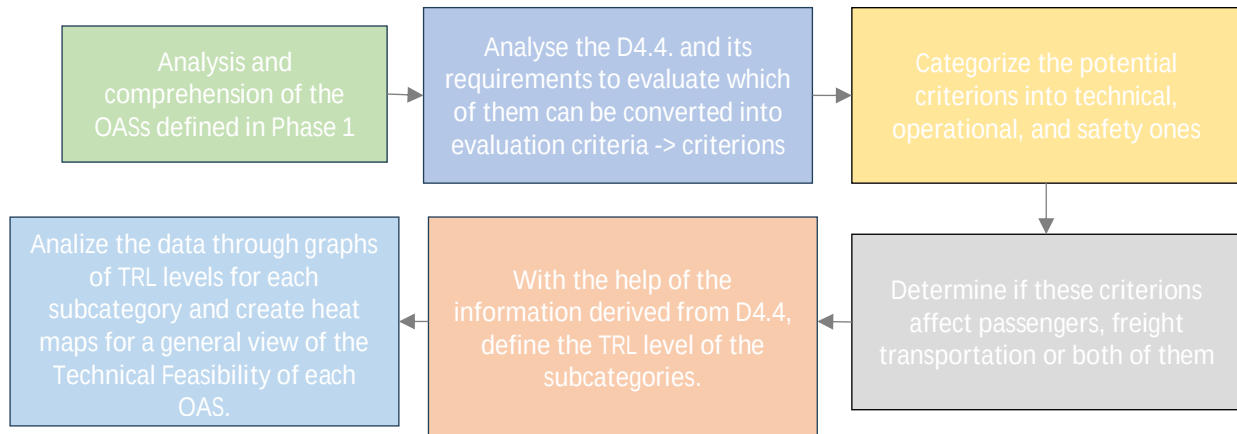


Figure 4: Phase 2 - Methodology for the definition of relevant criteria for the analysis of the Technical Feasibility of OAS

After the qualitative analysis that is going to be done through the evaluation of bar charts and heat maps, a quantitative approach will be followed through operations between TRLs and IRLs to estimate the tendencies of the System Readiness Level of the Pods4Rail system. Further conclusions about the maturity of the individual components, their respective connections and the whole system will be developed.

6 Development of Operational Application Scenarios

Before the process of definition of OAS starts, it is key to specify that these OAS are going to be defined in compliance with what the GA states: OAS will integrate scenarios in which conventional railway operations can be combined with fully automated and autonomous forms of operation. It is also significant to mention that these OAS will be contextualised (e.g. urban/rural, passengers/freight) but not localised (e.g. Hamburg, Montpellier), and that an excessive high-definition level of these Operational Application Scenarios is not sought.

In order to define the OAS that are going to be used in this document for their respectively analysis, first, we have considered the study of the UC defined in D4.1 and the relation between each of them. D4.1 provides a list of 22 UC divided into three main categories (passenger services, freight services and combined services). Each of these categories also has subcategories, e.g. in the case of passenger services: public transport, individual transport and special applications. Deliverable D4.1 in its analysis also includes, for each UC, which UC are related to one another.

With this information, a table has been constructed in which the UC have been mapped to the UC to which they are related, by marking an X in the corresponding box, as shown in Figure 5. Highlighted in blue and orange, the main relationships between the UC can be mainly knit together into two main groups: passengers only transportation (highlighted in blue) and freight only transportation (highlighted in orange). Beforehand, with this analysis, it could be predicted that the work can be done with these two preliminary OAS.

		Use Case	UC1	UC2	UC3	UC4	UC5	UC6	UC7	UC8	UC9	UC10	UC11	UC12	S-UC1	UC13	UC14	UC15	UC16	UC17	UC18	UC19	UC20	UC21
Passenger transport services	Public transport	UC1 Basic public passenger transport		X	X	X		X																
		UC2 Premium public passenger transport	X		X	X	X	X																
		UC3 First class public passenger transport	X	X		X		X	X															
		UC4 Mass public passenger transport	X	X																				
	Individual transport	UC5 Basic individual passenger transport		X					X	X				X					X					
		UC6 Premium individual passenger transport		X	X				X	X				X					X					
		UC7 Luxury individual passenger transport			X		X	X		X				X					X					
		UC8 PRM application	X	X	X	X	X	X	X		X	X	X	X		X			X					
	Special applications	UC9 Ambulance application	X	X	X	X	X	X	X		X	X	X	X		X			X					
		UC10 Tourism application	X	X	X		X	X						X					X					
Combined services	Service-to-people transport	UC11 Transport services		X	X							X		X					X				X	
		UC12 Shopfloor									X		X					X						X
		S-UC1 Transport in rural areas (reactivation of branch lines)	X	X	X	X	X	X	X	X		X	X	X					X	X	X	X		
	Temporary space	UC13 Rescue application								X	X							X					X	
		UC14 Housing application									X	X	X	X		X				X			X	
		UC15 Event application	X	X	X	X	X	X	X	X	X	X	X	X		X								
Freight transport services	Parcel delivery	UC16 Parcel delivery	X									X	X							X	X	X	X	
		UC17 Night logistics	X									X	X						X		X	X	X	
	General cargo transport	UC18 (10'20') container	X									X	X						X	X			X	
		UC19 Temperature-specific application											X						X		X		X	
	Special applications	UC20 Individual Pods dis-patching (e.g. Hazardous application, etc)											X						X	X	X	X		
		UC21 Energy supply application																						

Figure 5: Use Case Analysis and their interrelationships

The boxes that are marked with an 'X' but are not highlighted, neither in blue nor orange, are specific applications as PMR, ambulance, tourism applications, etc. As the GA seeks, the highlighting process has been done with the purpose of covering the most representative operational cases (conventional scenarios).

Next, the UCs considered in D4.1 have been mapped with the BC analysed in D5.2. A similar analysis, as the one that has been done before, can be conducted by matching the BC with the UC through their future and most suitable operation cases. This is shown in Figure 6.

		Use Case	BC1	BC2	BC3	BC4	BC5	BC6	BC7	BC8
Passenger transport services	Public transport	UC1 Basic public passenger transport	X	X		X	X	X		
		UC2 Premium public passenger transport	X	X		X	X	X		X
		UC3 First class public passenger transport	X	X		X	X	X		X
		UC4 Mass public passenger transport	X	X		X	X	X		
	Individual transport	UC5 Basic individual passenger transport	X	X		X	X	X		
		UC6 Premium individual passenger transport	X	X		X	X	X		
		UC7 Luxury individual passenger transport	X	X		X	X	X		X
	Special applications	UC8 PRM application	X	X		X	X	X		X
		UC9 Ambulance application		X		X	X	X		
		UC10 Tourism application	X	X		X	X	X		X
Combined services	Service-to-people transport	UC11 Transport services	X	X	X		X	X		
		UC12 Shopfloor	X	X	X		X	X		
		S-UC1 Transport in rural areas (reactivation of branch lines)		X				X		
	Temporary space	UC13 Rescue application	X	X			X	X	X	
		UC14 Housing application	X	X				X	X	
Freight transport services	Parcel delivery	UC15 Event application	X	X				X	X	X
		UC16 Parcel delivery	X	X	X		X	X		
	General cargo transport	UC17 Night logistics	X	X			X	X		
		UC18 (10'20') container		X			X	X		
	Special applications	UC19 Temperature-specific application		X			X	X		
		UC20 Individual Pods dis-patching (e.g. Hazardous application, etc)		X			X	X	X	
	Other transport Services	UC21 Energy supply application		X			X	X	X	

Figure 6: Use Cases – Business Cases relationships

Observing Figure 6, it can be seen that, with the highlighted boxes selected for the practical operational scenarios, most of the conventional passenger and freight services are covered, although indirectly, and only the Use Cases corresponding to “special services” such as PRM or ambulances for passengers, night logistics for freights or rescue of housing applications for combined services, for which a particularised analysis would be necessary, are left out. This action is similar with the one that has been stated in previous paragraphs for the marked but not highlighted boxes in the Use Cases analysis of their interrelationships.

The conclusion of the analysis is similar to what the first chart's outcomes said. Two preliminary OAS (one for passengers and one for freight transportation) cover the relations and studies that have been done in former deliverables.

Furthermore, to support the conclusions of the beforehand defined OAS, it shall be considered that two practical applications (PAS) were developed in D4.3, where hypothetical transport systems are described in which Pods for, respectively, passenger and freight transport on a regional scale are deployed on existing rail infrastructure (PAS). The initial proposal of OAS can be compared with the results of the PAS "Local passenger transport network around the city of Plzen", considered in D4.3, and “Transport of retail goods and the distribution of mail and parcels on a regional scale and using regional rail and urban rail and

road networks". These previous results back up the decision that has been made through the analysis of the relations between UC/UC and UC/BC.

Thus, the choice of the OAS proposed to be developed in order to be assessed by the criteria is made by selecting the most likely and applicable combination and analysis of UC, BC and PAS.

To sum up, two OAS, one corresponding to passenger regional transportation (OAS1), and the other one corresponding to regional freight transportation (OAS2) are selected as the most representative and the two ones that cover the largest number of UC and BC in conventional operations.

Table 2 shows the defined OAS and their corresponding relations with UC, BC and PAS.

Table 2: Combination of UC, BC and PAS related with the two selected OAS

OASs	OAS 1: Passenger regional transportation	OAS 2: Freight regional transportation
Related UC	UC1: Basic public passenger transport UC2: Premium public passenger transport UC5: Basic individual passenger transport UC6: Premium individual passenger transport UC7: Luxury individual passenger transport	S-UC1: Transport in rural areas (reactivation of branch lines) UC16: Parcel delivery UC17: Night logistics UC18: (10'/20') container UC19: Temperature-specific application UC20: Individual Pods dis-patching (e.g. Hazardous application, etc)
Related BC	BC1: Manufacturing of Transport Units BC2: Pod network capacity service for Transport Service Operators BC4: Ride-Sharing Service for Private Passenger Transport (Franchise) BC5: Data Services Company for Pod Systems BC6: Leasing/Rental Service of Carrier for Public Passenger & Freight Transport BC8: Leasing/Rental Service of Transport Units for Tourism, Events and Leisure	BC1: Manufacturing of Transport Units BC2: Pod Network Capacity Service for Transport Service Operators BC3: Freight Transport Service for Cities BC5: Data Services Company for Pod Systems BC6: Leasing/Rental Service of Carrier for Public Passenger & Freight Transport BC7: Leasing/Rental Service of Transport Units for Emergency Medical Services

OASs	OAS 1: Passenger regional transportation	OAS 2: Freight regional transportation
Related PAS	Local passenger transport network around the city of Plzen	Transport of retail goods and the distribution of mail and parcels on a regional scale and using regional rail and urban rail and road networks.

7 Assessment of the Technical Feasibility analysis

The aim of this section is to determine the overall System Readiness Level (SRL) of the Pods4Rail concept. Since the system represents an entirely new and non-existent technological solution, a direct assessment of its global maturity is not feasible through established methods. Only the Technology Readiness Levels (TRLs) of individual components can be estimated with reasonable confidence. The main challenge therefore lies in evaluating how the interactions and interdependencies among these individually assessed components influence the maturity of the integrated system as a whole. To address this, the TRL of each component is first estimated through a structured qualitative assessment carried out by a dedicated group of experts—namely, those participating in this Work Package of the Pods4Rail project. Based on this expert-derived estimation, a subsequent quantitative analysis is performed, applying statistical methods to derive the System Readiness Level and to characterise the uncertainty associated with the integration of the system components.

The qualitative assessment was carried out using expert judgement, structured checklists, document reviews, and consensus-based discussions. The expert team consisted of Pods4Rail members involved in WP6. Technology readiness levels were assigned using recognised external references, supported by insights gathered during regular expert meetings. Expert judgement is considered suitable for early-stage readiness evaluations, especially when empirical data are limited. This qualitative basis, combined with quantitative modelling, enables a more robust and evidence-informed assessment of system readiness.

For the quantitative stage, this work adopts the methodology described by (Tan et al., 2011), which integrates the component-level TRLs with Integration Readiness Levels (IRLs) to derive an estimate of the overall System Readiness Level. By simultaneously accounting for the maturity of each component and the performance of their interconnections, this method offers a holistic perspective on the evolution of system-level readiness and provides a structured means of capturing the influence of component interactions on the maturity of the integrated Pods4Rail system.

The following sections provide a detailed description of the qualitative and quantitative methods employed, including the procedures, criteria, and analytical tools used to conduct the readiness assessment of the Pods4Rail system.

7.1 Qualitative Analysis

As outlined in the previous section, the Technology Readiness Levels (TRLs) of the Pods4Rail components were determined by combining recognised external references with the collective expertise of the project team. Prior to conducting this assessment, it was essential to define the system architecture and establish a clear breakdown of the Pods4Rail concept into subsystems and components.

To this end, a structured decomposition of the Pods4Rail vehicle was developed, deriving a hierarchical breakdown from the project's Functional Requirements Specification (FRS), as presented in D4.4 (Pods4Rail, 2024d). The FRS sets out the functional and performance

expectations of the system and served as the foundation for the initial identification of system requirements.

For the readiness assessment undertaken in this study, the conceptual Pods4Rail design was divided into ten primary subsystems. Each of these ten subsystems was further disaggregated into its constituent components to enable a detailed evaluation of technological maturity. The complete breakdown structure is shown in . This structure provides the basis for the TRL assessment of the following core subsystems of the Pods4Rail concept.

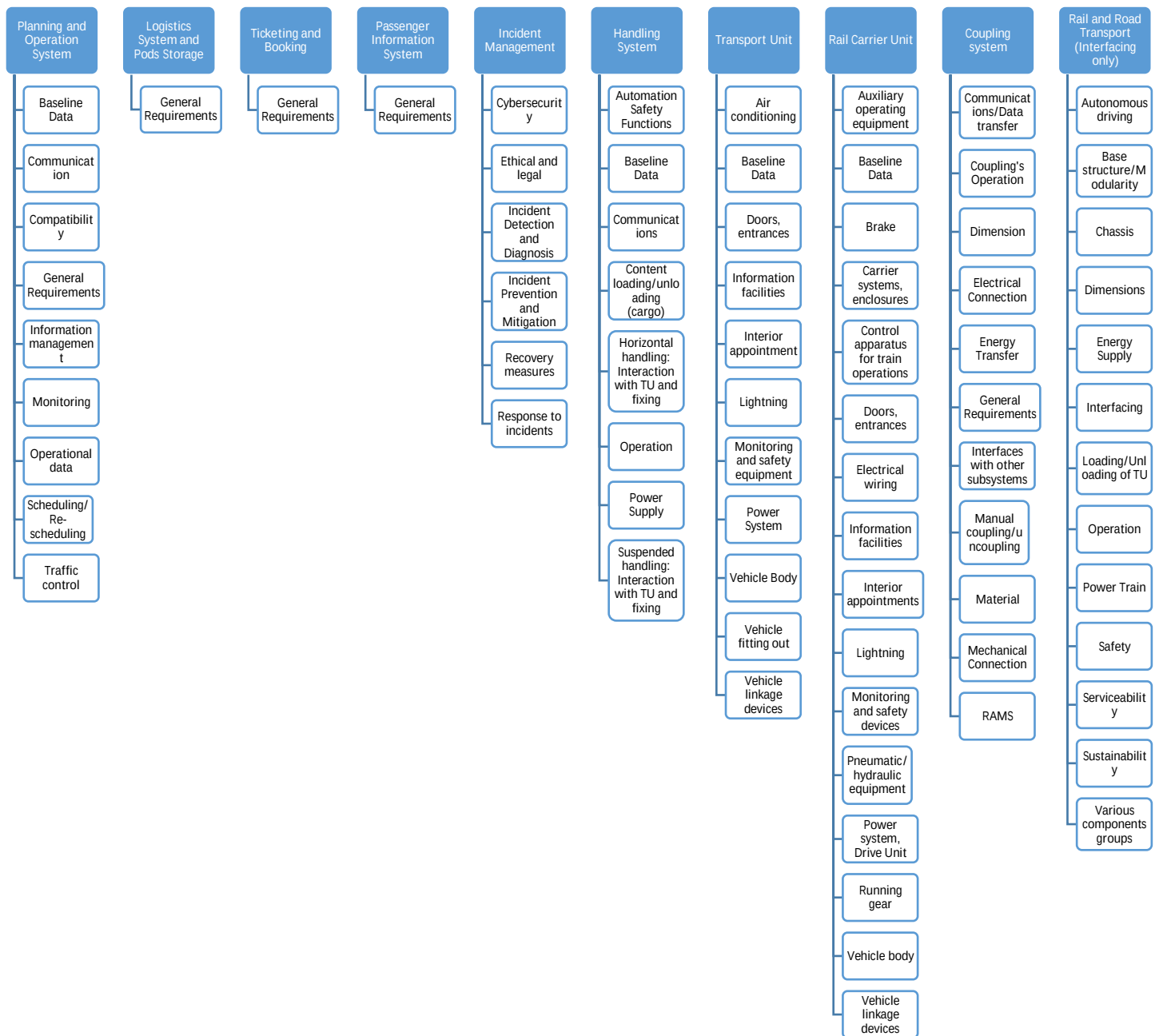


Figure 7: Groups of criteria and their corresponding subcategories extracted from D4.4

To assess the maturity of these subsystems, specific evaluation criteria were defined. These criteria represent measurable aspects derived from the high-level functional requirements contained in the FRS, ensuring a targeted and coherent TRL evaluation. Each criterion is explicitly linked to a functional requirement and is used to judge the maturity of the associated technology at the component level.

For a better understanding of the hierarchy of the groups of criteria, subcategories and criteria, the Figure 8 has been made for the same example that has been explained in the former paragraph (this figure doesn't contain all the subcategories and criteria of the group). Note that the number of criteria for each subcategory doesn't have to be the same for OAS1 and OAS2; this will be graphically seen in the Bar Charts and Heat Maps that will be constructed for each group of criteria.

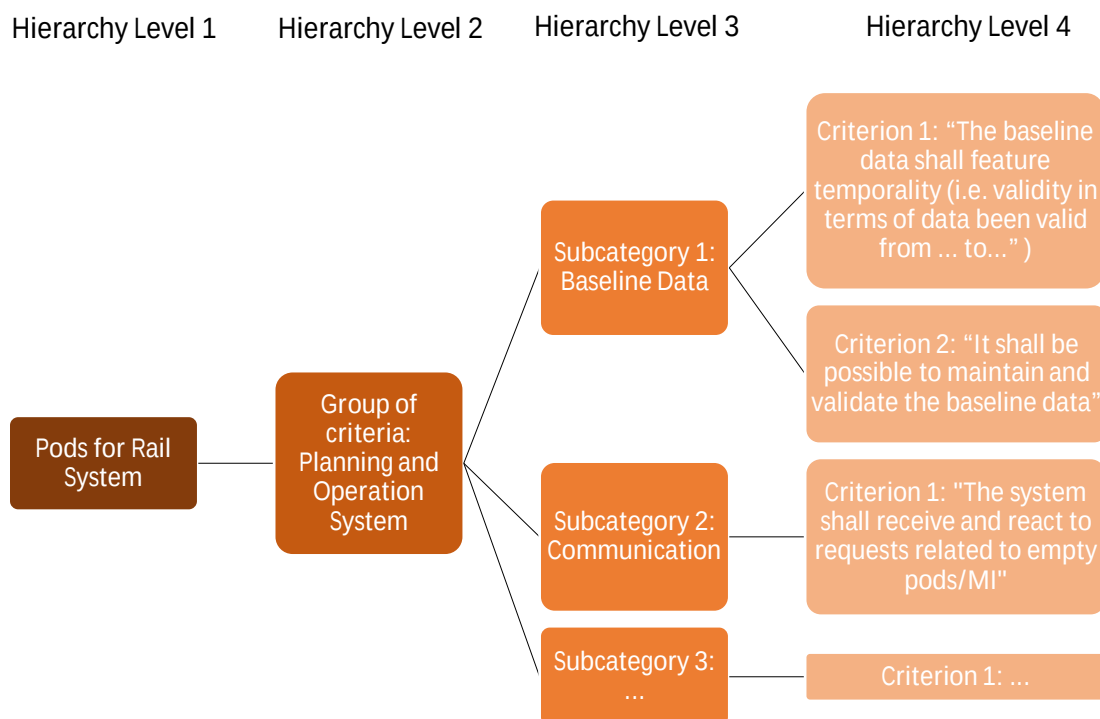


Figure 8: Hierarchy between group of criteria, subcategories and criteria

During the validation of requirements to be converted into criteria, several were excluded when they fell outside the scope of this assessment or proved redundant. Once the relevant requirements were selected, they were classified as technical, operational, or safety-related. Some criteria clearly fit only one category, while others span multiple dimensions. In such cases, if one aspect is evidently predominant, the criterion is assigned to that category. A similar classification was applied to distinguish whether each criterion concerns passenger services (OAS1), freight services (OAS2), or both.

For each validated and categorised criterion, a Technology Readiness Level (TRL) was assigned to reflect the maturity of the associated technology. These TRLs were derived from external references and expert input from the team involved in developing the FRS.

Subcategory TRLs were defined as the minimum and maximum TRLs among their constituent criteria.

As previously mentioned, the TRL assessment itself was carried out by a panel of experts from the Pods4Rail consortium, including specialists in vehicle engineering, control systems, operations, safety, and multimodal integration. The evaluation process was conducted through three structured meetings during which experts first proposed TRL ranges independently and subsequently reached a shared consensus through moderated discussion. All criteria and the reasoning supporting each TRL assignment were documented in the project's internal records to ensure traceability and reproducibility.

The resulting TRL ranges were used to establish probabilistic TRL distributions, capturing epistemic uncertainty inherent in early-stage conceptual assessments. These probabilistic inputs form the basis for the later quantitative estimation of the System Readiness Level (SRL), ensuring that the system-level evaluation remains grounded in expert judgement while maintaining full transparency.

Each component could be evaluated against multiple criteria. Because TRL values were assigned during periodic expert meetings, some degree of uncertainty was inevitable. To capture this variability, the minimum and maximum TRL values for each component were identified, providing a concise representation of its maturity. This hierarchical approach—from system to subsystem, component, and associated technologies—offers a clear and structured view of the overall technological readiness (Figure 8).

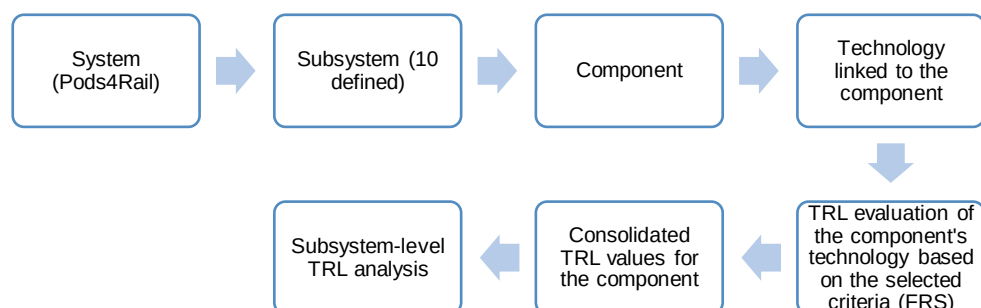


Figure 9: Steps for TRL evaluation through the selected hierarchy for Pods4Rail project.

To facilitate interpretation, heat maps were created for each subsystem to display TRL assignments and related analyses. These visualizations highlight components with the highest and lowest technological readiness and link the number of evaluation criteria to their TRL values. This approach enables the calculation of absolute and relative frequencies, providing a clear overview of maturity levels across the Pods4Rail system.

For clarity and simplicity, this section illustrates the methodology and the resulting assessment for one of the most representative subsystems, while the full set of subsystem analyses is provided in Appendix 4.

Therefore, the Rail Carrier Unit subsystem was selected, as it represents one of the core subsystems of the Pods4Rail concept, given that the system is designed to operate through the coupling of pods with an autonomous underframe.

Table 3 shows the results of the TRL assignment process for the Rail Carrier Unit subsystem components. As an example, the Vehicle Linkage Devices component was evaluated against five requirements derived from the FRS (“Number of criteria” column). According to the table below, the five associated technologies or functionalities fall within a TRL range of 3 to 4, indicating that further development is required, as the component remains at the Observation of Basic Principles stage. TRL 8–9 components were intentionally excluded from this analysis. These elements correspond to fully mature technologies whose functionality is already well established in conventional railway systems. In this case, the only excluded element was the Vehicle body. Since it does not contribute to the technological feasibility or the innovative aspects of the Pods4Rail concept, its inclusion would provide no meaningful insight into system-level readiness. Moreover, incorporating such legacy technology would artificially inflate subsystem-level TRL distributions and mask the actual maturity gaps associated with the novel architectural and operational elements under development.

A broader interpretation of these findings can also be drawn from the corresponding heat map. This evaluation process was applied to all subsystems and their respective components.

Table 3: Rail Carrier Unit TRL evaluation

Rail Carrier Unit			
Components	Min TRL	Max TRL	Number of Criteria
Auxiliary operating equipment	6	6	1
Baseline data	2	7	20
Brake	7	7	3
Carrier systems, enclosures	4	4	1
Control apparatus for train operations	2	6	8
Doors, entrances	7	7	4
Electrical wiring	7	7	6
Information facilities	7	7	5
Interior appointments	7	7	2
Lightning	7	7	3
Monitoring and safety device	4	7	9
Pneumatic/hydraulic equipment	7	7	1
Power system, drive unit	3	7	11
Running gear	7	7	2
Vehicle linkage devices	3	4	5

Figure 10 presents the heat map for the Rail Carrier Unit, showing the distribution of TRL levels (1–9) across its components and the number of criteria used for each evaluation. Absolute and relative frequencies are also included, which are essential for the subsequent quantitative analysis. In Figure 10, the blue intensity of each cell reflects its absolute frequency: zero appears as light blue, seven as the darkest shade, and all other frequencies are shown with proportional color levels, forming a heat map.

RAIL CARRIER UNIT										
Number of subcategories: 16	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criteria per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Auxiliary operating equipment	0	0	0	0	0	1	0	0	0	1
Baseline Data	0	1	7	5	1	0	6	0	0	20
Brake	0	0	0	0	0	0	3	0	0	3
Carrier systems, enclosures	0	0	0	1	0	0	0	0	0	1
Control apparatus for train operations	0	3	4	0	0	1	0	0	0	8
Doors, entrances	0	0	0	0	0	0	4	0	0	4
Electrical wiring	0	0	0	0	0	0	6	0	0	6
Information facilities	0	0	0	0	0	0	5	0	0	5
Interior appointments	0	0	0	0	0	0	2	0	0	2
Lightning	0	0	0	0	0	0	3	0	0	3
Monitoring and safety device	0	0	0	3	0	2	4	0	0	9
Pneumatic/hydraulic equipment	0	0	0	0	0	0	1	0	0	1
Power system, drive unit	0	0	1	8	0	0	2	0	0	11
Running Gear	0	0	0	0	0	0	2	0	0	2
Vehicle Body	0	0	0	0	0	0	0	0	0	0
Vehicle linkage devices	0	0	2	3	0	0	0	0	0	5
Absolute frequency	0	4	14	20	1	4	38	0	0	81
Relative frequency	0.000	0.049	0.173	0.247	0.012	0.049	0.469	0.000	0.000	1.000

Figure 10: Rail Carrier Unit heat map.

By combining hierarchical evaluation with visual representations, the methodology delivers a comprehensive view of the Pods4Rail concept's technological maturity. It enables the detailed assessment of individual subsystems, components, and associated technologies, while supporting a robust evaluation of the system's overall technical feasibility.

7.2 Quantitative technical analysis: SRL of Pods4Rail System

This section presents the complete methodological framework used to estimate the system-level maturity of the Pods4Rail System. The approach relies on Monte Carlo simulation to translate the qualitative engineering assessments previously described in Section 7.1 into a probabilistic model of technological and integration readiness. The expanded description provided here offers a deeper theoretical justification of the method, clarifies the relationship between statistical sampling and practical project work, and provides the conceptual and operational detail necessary for full reproducibility.

In this section, some of the concepts introduced in the 5.3 section are going to be applied in order to evaluate an approximate level of preparation and maturity of the whole Pods4Rail project.

IRL (Integration Readiness Level), as described before, is a variable that helps to understand the level of connectivity between two components or technologies. Its main objectives are to assess the maturity of integration between two or more components or subsystems, and to reduce the uncertainty associated with technology integration within a system.

Next, SRL (System Readiness Levels) constitutes a combination of the TRL (Technology Readiness Levels) of each component and the IRL (Integration Readiness Levels) of each interaction between a pair of components. As can be supposed, SRL considers different factors to measure the readiness of a system such as the state of individual technologies and the state of their corresponding connections. In this task, a scale with values from [0,1] for SRL are going to be used according to (Tan et al., 2011). The mentioned scale can be found in Appendix 3.

As described, the goal is to find a range of approximate values where the SRL (System Readiness Levels) of the project lies. To achieve this, first, information from some sections before has to be recalled. A WBS (Work Breakdown Structure) has been defined, in 7.1 section, for the decomposition of the system initiating from the information developed in D4.4 “High-Level Functional Requirements Specification”.

To calculate the level of preparation of the whole system Pods4Rail, the same hierarchy (WBS) is going to be relied on. For the calculation that is going to be done, some elements with hierarchy 2 are going to be merged and changed. As a reminder, the currently developed WBS between level 1 and level 2 is the following Table 4:

Table 4: Current WBS Hierarchy 1-2

Hierarchy level 1	Hierarchy level 2 – Group of criteria
Pods4Rail System	1. Planning and Operation System
	2. Logistics System and Pods Storage
	3. Ticketing and booking
	4. Passenger Information System (PIS)
	5. Incident Management
	6. Handling System
	7. Transport Unit (TU)
	8. Rail Carrier Unit (RCU)
	9. Coupling System
	10. Road Transport

To unify the number of requirements (hierarchy level 4) that each group of criteria has, since there are groups with a difference of tens, some groups will be merged. For this action, the similarity and integration between groups have been considered. In addition, the group of criteria 10 (Road Transport) is going to be neglected for this calculation because, at this state, the project’s focus is mainly on railway transport mode. From this point, also, the groups of criteria are going to be called “components” for simplifying the explanation of the procedure. Applying these changes, the new components in hierarchy level 2 are included in Table 5 and Figure 11:

Table 5: New Hierarchy 1-2

Hierarchy level 1	Hierarchy level 2 – Group of criteria - Components
Pods4Rail System	1. Planning and Operation System
	2. Logistics, Storage, Ticketing and Booking
	3. PIS and Incident Management
	4. Handling System
	5. Transport Unit (TU)
	6. Rail Carrier Unit (RCU)
	7. Coupling System

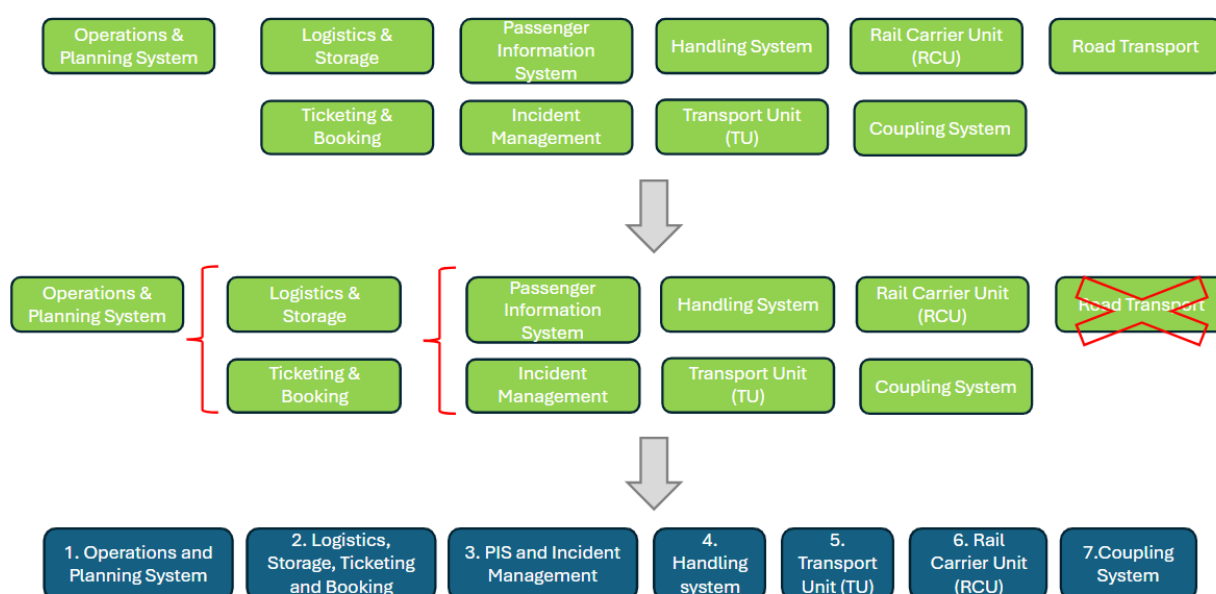


Figure 11: Transformation to 7 main components for the quantitative analysis

Now that the main components for the calculation have been determined, the two variables mentioned (TRL, IRL) are generally assigned through the knowledge and criteria of experts; other methods are used to combine different opinions, such as the Delphi method, but although these procedures aim to minimise the inherent uncertainty of human opinion, the results showed that this is not enough and that there is always a spread of uncertainties. For reflecting the reality of the subjective estimations and assignment of the parameters, a statistical approach must be used. (Tan et al., 2011) proposes a Monte Carlo method to find a range of SRL values with its respective statistical parameters that will allow a more representative analysis of the maturity of the whole system: *“It is necessary to identify and mitigate the risk resulting from subjectivity when prescriptive metrics are used for project evaluation. In general, if more information is given in advance, there will be less subjectivity, and vice versa”* (Tan et al., 2011).

The Monte Carlo statistical method is based on a random sampling that is repeated a given number of times (*num samples* = *N*) to analyse problems with uncertainty propagation. It

is important to consider that probabilities are necessary to apply this method. In this sense, for the calculation of the SRL of the Pods4Rail system the following steps are going to be followed:

- Determine the TRL corresponding to each of the 7 main components. This step will rely on the sections above where heat maps showed the number of requirements for each component, their respective TRL and frequencies.
- Determine IRLs between the connections of the subjects. For this step is necessary to establish how the relationships between the seven components are going to be. For this task, it is considered that every component has interactions with the other ones, since the whole system needs all the components to function with synergy and in a correctly manner. Figure 12 represents the estimated relationship between all the seven main components:

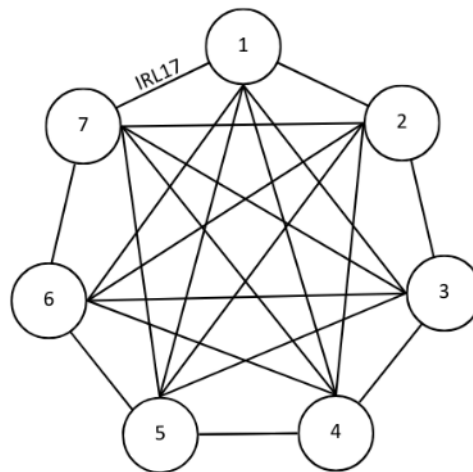


Figure 12: Relationships between the 7 main components

- Determine SRLs through matrix operations. As a result, according to (Tan et al., 2011), 7 main SRLs are going to be estimated (one for each component); these individual SRL describe which of these components are in a lower or higher level of the maturity progress from the whole system's life cycle and development. Furthermore, one variable named as "COMPOSITE SRL" is going to be found; in a simplified way, COMPOSITE SRL is the arithmetic mean of the individual SRL of each component. In that sense, COMPOSITE SRL constitutes the variable of importance to analyse the state of maturity of the whole Pods4Rail system.

7.2.1 Methodological Framework for the System Readiness Assessment

First, for obtaining the TRL matrix, it has to be considered that, in the standard process, obtained frequencies of TRL for each component are considered as relative frequencies for the calculation but these, in turn, can be interpreted as probabilities.

These probabilities were assigned based on the tendencies of relative frequencies showed in the former heat maps. A compilation of the mentioned probabilities for the corresponding TRLs and components is showed in Table 6:

Table 6: TRL and their corresponding probabilities

Component	TRL									Probabilities TRL							
1. Operations and Planning System	1	2	3	4	5	6	7	8	9	0.000	0.190	0.143	0.587	0.063	0.016	0.000	0.000
2. Logistics, Storage, Ticketing and Booking	1	2	3	4	5	6	7	8	9	0.000	0.429	0.048	0.190	0.238	0.095	0.000	0.000
3. PSI and Incident Management	1	2	3	4	5	6	7	8	9	0.000	0.173	0.250	0.250	0.231	0.096	0.000	0.000
4. Handling System	1	2	3	4	5	6	7	8	9	0.000	0.833	0.056	0.111	0.000	0.000	0.000	0.000
5. Transport Unit (TU)	1	2	3	4	5	6	7	8	9	0.000	0.111	0.000	0.125	0.056	0.000	0.708	0.000
6. Rail Carrier Unit (RCU)	1	2	3	4	5	6	7	8	9	0.000	0.049	0.173	0.247	0.012	0.049	0.469	0.000
7. Coupling System	1	2	3	4	5	6	7	8	9	0.000	0.278	0.167	0.167	0.028	0.000	0.361	0.000

For the run of a determined N samples and the execution of the Monte Carlo statistical method, MatLab is going to be used as the main software. In the code, first, the TRLs for the 7 main components were defined. A function of random sampling is used including 9 numbers [1,9] and, also including, the corresponding probability distribution of the TRLs. Note that is important that the sum of probabilities equals to 1 and it is a condition that is achieved for every component.

Since the values for TRL are going to be obtained in the range of [1,9], the factor of normalization is going to be $(TRL-1)/8$ to normalise the values between the range of [0,1]. An example of the code for the first component is given in Equation 1; this function guarantees that N random numbers from 0 to 1 are generated according to the introduced probabilities. The same procedure is followed for the 6 remaining components.

$$TRL1 = (randsample([1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9], num_samples, true, [0\ 0.19\ 0.143\ 0.587\ 0.063\ 0.016\ 0\ 0\ 0]) - 1)/8$$

Equation 1: TRL construction

After this procedure, as explained above, N random samples are run. As a result, the TRL matrix dimension is going to be as shown in Equation 2 and Equation 3:

$TRL = 7 \text{ rows} \times N \text{ (num samples) columns}$

Equation 2: TRL matrix's dimension

$$\begin{bmatrix} TRLcomponent1_{run1} & TRLcomponent1_{run2} & \dots & TRLcomponent1_{runN} \\ TRLcomponent2_{run1} & TRLcomponent2_{run2} & \dots & TRLcomponent2_{runN} \\ TRLcomponent3_{run1} & TRLcomponent3_{run2} & \dots & TRLcomponent3_{runN} \\ TRLcomponent4_{run1} & TRLcomponent4_{run2} & \dots & TRLcomponent4_{runN} \\ TRLcomponent5_{run1} & TRLcomponent5_{run2} & \dots & TRLcomponent5_{runN} \\ TRLcomponent6_{run1} & TRLcomponent6_{run2} & \dots & TRLcomponent6_{runN} \\ TRLcomponent7_{run1} & TRLcomponent7_{run2} & \dots & TRLcomponent7_{runN} \end{bmatrix}$$

Equation 3: TRL bi-dimensional matrix's configuration

Subsequently, the values for IRL are generated. IRL is a parameter that allows the description of the connection between each component. Following the same procedure for the construction of the TRL matrix, the probabilities for the IRL matrix must be determined.

Since the IRL levels between each component, in this state of the project, are unknown, it has been estimated that the values of IRL of the interactions between components lie in the range of 4 to 6. In their definition, levels 4 to 6 of IRL indicate the transition from a theoretical and conceptual understanding of integration (4) to a practical implementation (6), where components are tested in controlled and relevant environments. At this stage, the focus shifts from analysing potential integration challenges to actively addressing them through real-world testing, so these IRL are coherent with the project development status. The goal is to ensure that all system components work together as intended before moving on to more advanced phases of deployment.

This decision has been made on the basis that IRL4 requires quality and assurance of the integration between the technologies, and that they can be related to each other in an effective manner. For IRL5, there must exist sufficient control to establish the integration, and some testing must have been done in environments similar to the real ones (this point can be justified since the whole system, and its components are derived from a conventional railway transport system). Finally, for IRL6, the integration must have been proved in an environment that reflects operational conventional conditions (same justification as the given one for IRL5).

After the justification of the IRL values that are going to be applied, it must be highlighted that the probabilities of IRL constitute a matrix (PROB_IRL) with a $7 \times 7 \times 3$ dimension. The third dimension, known as depth, saves the information for the probabilities of IRL=4, IRL=5 and IRL=6, respectively, for each layer.

The assignment of probabilities for the connection between each pair of components and the connection with themselves has followed the next general approach showed in Table 7.

Table 7: Assignment of probabilities of IRL

Assignment of probabilities for IRLs					
Integration of system 'i' with system 'j'			Integration of the 'i' system with itself		
Probabilities of IRL =			Probabilities of IRL =		
4	5	6	4	5	6
0.25	0.5	0.25	0.1	0.1	0.8

The values considered for the probabilities were configured in a way that the highest value of probability (0.8 for IRL=6) is assigned in the interaction of one component with itself. In a practical way, the interaction of one component with itself is always equal to IRL=9, but this will be programmed in the construction of the final IRL matrix.

For the other values of the three layers, regarding the interaction between different components, a pragmatic approach has been applied since 0.5 was assigned as probability to the average considered value for IRL (IRL=5). In, the same line, a probability value of 0.25 has been assigned both for IRL=4 and IRL=6 for the remaining connections.

Note that the sum of probabilities between the three layers for the same pair of components equals to 1.

The final structure of the three-dimensional matrix of Probabilities for IRL matrix is shown in Figure 13:

ProbIRL = 6 ₁₁	ProbIRL = 6 ₁₂	ProbIRL = 6 ₁₃	ProbIRL = 6 ₁₄	ProbIRL = 6 ₁₅	ProbIRL = 6 ₁₆	ProbIRL = 6 ₁₇	
ProbIRL = 6 ₂₁	ProbIRL = 6 ₂₂	ProbIRL = 6 ₂₃	ProbIRL = 6 ₂₄	ProbIRL = 6 ₂₅	ProbIRL = 6 ₂₆	ProbIRL = 6 ₂₇	
ProbIRL = 5 ₁₁	ProbIRL = 5 ₁₂	ProbIRL = 5 ₁₃	ProbIRL = 5 ₁₄	ProbIRL = 5 ₁₅	ProbIRL = 5 ₁₆	ProbIRL = 5 ₁₇	6 ₃₇
ProbIRL = 5 ₂₁	ProbIRL = 5 ₂₂	ProbIRL = 5 ₂₃	ProbIRL = 5 ₂₄	ProbIRL = 5 ₂₅	ProbIRL = 5 ₂₆	ProbIRL = 5 ₂₇	6 ₄₇
ProbIRL = 4 ₁₁	ProbIRL = 4 ₁₂	ProbIRL = 4 ₁₃	ProbIRL = 4 ₁₄	ProbIRL = 4 ₁₅	ProbIRL = 4 ₁₆	ProbIRL = 4 ₁₇	6 ₅₇
ProbIRL = 4 ₂₁	ProbIRL = 4 ₂₂	ProbIRL = 4 ₂₃	ProbIRL = 4 ₂₄	ProbIRL = 4 ₂₅	ProbIRL = 4 ₂₆	ProbIRL = 4 ₂₇	6 ₆₇
ProbIRL = 4 ₃₁	ProbIRL = 4 ₃₂	ProbIRL = 4 ₃₃	ProbIRL = 4 ₃₄	ProbIRL = 4 ₃₅	ProbIRL = 4 ₃₆	ProbIRL = 4 ₃₇	5 ₅₇
ProbIRL = 4 ₄₁	ProbIRL = 4 ₄₂	ProbIRL = 4 ₄₃	ProbIRL = 4 ₄₄	ProbIRL = 4 ₄₅	ProbIRL = 4 ₄₆	ProbIRL = 4 ₄₇	5 ₆₇
ProbIRL = 4 ₅₁	ProbIRL = 4 ₅₂	ProbIRL = 4 ₅₃	ProbIRL = 4 ₅₄	ProbIRL = 4 ₅₅	ProbIRL = 4 ₅₆	ProbIRL = 4 ₅₇	5 ₇₇
ProbIRL = 4 ₆₁	ProbIRL = 4 ₆₂	ProbIRL = 4 ₆₃	ProbIRL = 4 ₆₄	ProbIRL = 4 ₆₅	ProbIRL = 4 ₆₆	ProbIRL = 4 ₆₇	
ProbIRL = 4 ₇₁	ProbIRL = 4 ₇₂	ProbIRL = 4 ₇₃	ProbIRL = 4 ₇₄	ProbIRL = 4 ₇₅	ProbIRL = 4 ₇₆	ProbIRL = 4 ₇₇	

Figure 13: Configuration of PROB_IRL three-dimensional matrix

Now, that the three-dimensional matrix of Probabilities of IRL has been defined both in the explanation of this document and in the code, the following step is the construction of the IRL sample matrix. For this, the following statements must be accomplished (Tan et al., 2011).

- Probabilities that are going to be used for the construction of the IRL matrix are saved up in the PROB_IRL already explained matrix.

- b) IRL is a symmetric matrix since $IRL_{ij} = IRL_{ji}$
- c) $IRL_{ii} = 9$ (= 1 in a normalized matrix) since the interaction of one component with itself has the highest value in the scale. Although $IRL=9$ was not considered in the matrix of Probabilities of IRL, through the code, this condition will be set up and the assigned probabilities for this case will not affect this condition.
- d) As the TRL matrix, the IRL matrix has to be normalized to take values in a range from [0,1]. The same factor of normalization will be used $(IRL-1)/8$.

Considering this, a IRL three-dimensional matrix is constructed with a dimension of $7 \times 7 \times N$ with the algorithm shown in Equation 4:

```
for k = 1:num_samples
    for i = 1:7
        for j = i:7
            IRL(i,j,k) = (randsample([4 5 6],1,true,squeeze(PROB_IRL(i,j,:))) - 1)/8; Condition a) and d)
            IRL(j,i,k) = IRL(i,j,k); Condition b)
            IRL(i,i,k) = 1; Condition c)
        end
    end
end
```

Equation 4: Construction of IRL $7 \times 7 \times N$ three-dimensional matrix

The code creates IRL bi-dimensional matrices 7×7 from 1 to ($num\ samples = N$) layers of depth, with random numbers in the [0,1] range. Also, each layer of the matrix is symmetrical, and the diagonal values equals 1 according to the mentioned conditions.

Note: $squeeze(PROB_IRL(i,j,:)) \rightarrow$ Convert $PROB_IRL$ to a 1×3 vector (3 related to the layers of depth) which is at position (i, j) of three-dimensional array, in order to match the dimensions for the correct operations of matrices.

The final IRL three-dimensional matrix has axes X and Y related to the interaction of components and axe Z depending on the layer samples ($num\ samples = N$). The following Figure 14 shows an estimation of the configuration of the IRL matrix.

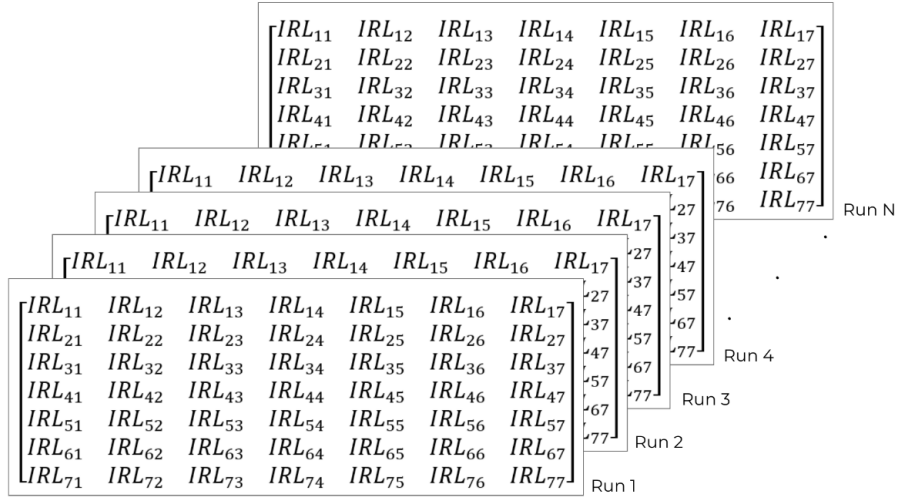


Figure 14: Configuration of the three-dimensional IRL matrix

Finally, according to (Tan et al., 2011), the calculation of the SRL normalized matrix is done by the following operations:

$$\begin{aligned}
 [SRL]_{n \times 1} &= [Norm]_{n \times n} \times [IRL]_{n \times n} \times [TRL]_{n \times 1} \\
 \begin{bmatrix} SRL_1 \\ SRL_2 \\ \dots \\ SRL_n \end{bmatrix} &= \begin{bmatrix} 1/m_1 & 0 & \dots & 0 \\ 0 & 1/m_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & 1/m_n \end{bmatrix} \times \\
 &\quad \begin{bmatrix} IRL_{11} & IRL_{12} & \dots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \dots & IRL_{2n} \\ \dots & \dots & \dots & \dots \\ IRL_{n1} & IRL_{n2} & \dots & IRL_{nn} \end{bmatrix} \times \begin{bmatrix} TRL_1 \\ TRL_2 \\ \dots \\ TRL_n \end{bmatrix} \\
 &= \begin{bmatrix} (IRL_{11}TRL_1 + IRL_{12}TRL_2 + \dots + IRL_{1n}TRL_n)/m_1 \\ (IRL_{21}TRL_1 + IRL_{22}TRL_2 + \dots + IRL_{2n}TRL_n)/m_2 \\ \dots \\ (IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \dots + IRL_{nn}TRL_n)/m_n \end{bmatrix}
 \end{aligned}$$

Figure 15: Operations between matrices to obtain SRL

It should be noted that this operation is only shown for a single sample run out of the total random samples (*num samples* = N). Also, the subscript n makes a reference to the total number of components that, in this case, equals to 7. The final dimension of the SRL matrix will be 7 rows $\times$ N (*num samples*) columns. In a single calculation that is not part of the Monte Carlo method, in other words that doesn't need to run N samples, the SRL will be a vector of 7 rows $\times$ 1 column with a resulting SRL corresponding to each one of the seven components considered.

Now, according to Figure 15 formula, a new normalization matrix is introduced where m_i is the number of integrations of technology i with itself and the other components. The

objective of this matrix is to normalise the results of SRL from $[0, m_i]$ to $[0,1]$ to be in accordance with the scales used for the matrices obtained above. For this case and according to the estimated relationship between the seven components, $m_i = 7$ is a constant since all the components relate to each other (6 connections) plus the connection with themselves. In that sense, the construction of this matrix requires the creation of a diagonal matrix with a 7×7 dimension with a diagonal constant value of $1/m_i = 1/7$. This normalization matrix will be named as (matrix_norm_SRL).

At this point, the Monte Carlo method led to N (*num samples*) operations between bi-dimensional (TRL matrix and matrix_norm_SRL) and three-dimensional matrices (IRL matrix).

As an outcome, SRL is the product of multiplying the normalization matrix (bi-dimensional) by the IRL (7×7) bi-dimensional matrix in position g /layer g (going through all N (*num samples*) layers), by the TRL vector (7×1) in its column g going through all N (*num samples*) columns. The described process is showed in the next code's extract where g is an auxiliary variable that goes over 1 to N (Equation 5).

```
for g = 1:num_samples
    SRL(:,g) = matrix_norm_SRL * IRL(:,g) * TRL(:,g);
end
```

Equation 5: Construction of SRL matrix

The result of SRL is a matrix of 7 rows $\times$ N (*num samples*) columns. Each row corresponds to one of the seven components. The configuration is similar to the following graph:

$$\begin{bmatrix} SRLcomponent1_{run1} & SRLcomponent1_{run2} & \dots & SRLcomponent1_{runN} \\ SRLcomponent2_{run1} & SRLcomponent2_{run2} & \dots & SRLcomponent2_{runN} \\ SRLcomponent3_{run1} & SRLcomponent3_{run2} & \dots & SRLcomponent3_{runN} \\ SRLcomponent4_{run1} & SRLcomponent4_{run2} & \dots & SRLcomponent4_{runN} \\ SRLcomponent5_{run1} & SRLcomponent5_{run2} & \dots & SRLcomponent5_{runN} \\ SRLcomponent6_{run1} & SRLcomponent6_{run2} & \dots & SRLcomponent6_{runN} \\ SRLcomponent7_{run1} & SRLcomponent7_{run2} & \dots & SRLcomponent7_{runN} \end{bmatrix}$$

Equation 6: SRL bi-dimensional matrix's configuration

Note that each column has information about SRL for each of the seven elements. At this point, the variable COMPOSITE SRL is introduced as the arithmetic mean of all the individual SRLs.

$$Composite\ SRL = \frac{SRL_1 + SRL_2 + \dots + SRL_n}{n} = \frac{\sum_{i=1}^n SRL_i}{n}$$

Figure 16: Calculation of COMPOSITE SRL

In that line, according to the Monte Carlo procedure, N (*num samples*) different results for COMPOSITE SRL will be obtained. This empirical distribution will allow the statistical analysis of the resulting range and the study of the statistical related variables arising from the application of the Monte Carlo method and, in turn, arising from the subjectivity of the parameters' assignment (TRL and IRL).

7.2.2 Quantitative analysis results

This section presents the results of the quantitative analysis conducted to estimate the System Readiness Level (SRL) of the Pods4Rail concept. Building on the probabilistic TRL ranges defined in the qualitative assessment, and on the Integration Readiness Levels (IRLs) associated with the interfaces between subsystems, the methodology described in Section 7.2.1 has been applied to derive a system-level readiness indicator and to quantify the associated uncertainty.

The TRL intervals elicited from experts for each criterion–component–subsystem chain were first converted into probability distributions, reflecting the epistemic uncertainty inherent in early-stage conceptual assessments. These distributions were then combined with the IRL values defined for the relevant interfaces, following the approach proposed by Tan et al. (2011), to obtain a probabilistic estimate of the SRL of each subsystem and the Composite SRL for the whole Pods4Rail system. The analysis was implemented through a Monte Carlo simulation framework, in which multiple realisations of component-level TRLs and IRLs were sampled and propagated through the system readiness model.

At the global level, the Pods4Rail concept attains an estimated SRL in the lower range of the scale. The central estimate of the SRL lies between the SRL1 (Concept Refinement) and SRL2 (Technology Development) phases (see Appendix 3) that, translated to a 1–9 scale, results in an average of 2.8, with a 5th–95th percentile interval approximately spanning 2.2 to 3.3. This reflects a system that is conceptually well-defined and supported by technologies that are, in many cases, already demonstrated in relevant environments, but which still requires significant integration, validation, and demonstration activities before it can be considered ready for large-scale deployment. The width of the uncertainty interval indicates that the maturity of certain subsystems, as well as the robustness of some integration links, remains subject to non-negligible expert uncertainty, which is expected at this stage of development.

When examining the contribution of individual subsystems to the overall readiness, the results reveal a heterogeneous picture (Table 19 In Appendix 5)). Subsystems that build predominantly on well-established railway technologies, such as the Rail Carrier Unit and the Coupling System, generally exhibit higher SRLs that represent higher maturity levels. In contrast, subsystems associated with novel operational concepts and digital functionalities—such as the Planning and Operation System, Logistics and Storage, or certain elements of the Incident Management and Handling System—show lower effective maturity. This imbalance is consistent with the innovative nature of Pods4Rail, in which the disruptive aspects are concentrated in the operational and system-integration dimensions rather than in the underlying hardware alone.

The quantitative analysis also highlights the decisive role of integration in determining system-level readiness. Even where individual components display relatively high TRLs, the associated IRLs for some critical interfaces remain modest. For example, several interfaces between the Operations and Planning System and the Logistics, Storage, Ticketing and Booking subsystem, or between the Operations and Planning System and the PIS and Incident Management, are characterised by lower IRL values, indicating that integration concepts have been defined and partially analysed but not yet validated through representative prototyping or large-scale pilots. As a consequence, the effective readiness of these integrated capability chains is significantly lower than the TRL of the most advanced component within them. Conversely, in more conventional areas—such as certain interactions within the Rail Carrier Unit or between the Transport Unit and the Coupling System—IRLs tend to be higher, helping to stabilise the overall SRL.

A scenario-based view of the results, distinguishing between passenger-oriented (OAS1) and freight-oriented (OAS2) applications, shows broadly comparable system readiness levels, with only minor differences. In several subsystems, such as Logistics, Storage, Ticketing and Booking and Incident Management, OAS1-specific functionalities tend to be slightly more mature due to the wider availability of reference solutions from existing passenger transport systems. By contrast, in logistics-related functionalities and Handling System operations, the freight-oriented (OAS2) functions sometimes benefit from more mature reference technologies. Overall, however, the estimated SRL for both OAS1 and OAS2 remains within a similar band around the global value, confirming that the conceptual development of the Pods4Rail system has progressed in a balanced way for both use cases.

Beyond the headline SRL value, the probabilistic framework allows the identification of the main drivers of uncertainty and the most influential subsystems and interfaces. Sensitivity analyses conducted within the quantitative model indicate that uncertainties in the TRLs of certain digital and control-related components and in the IRLs of their associated interfaces account for a significant proportion of the variance observed in the SRL distribution. This suggests that targeted development and validation activities in these areas—such as early integration pilots, digital twin-based verification, or dedicated safety validation studies—would yield the greatest impact in terms of increasing system readiness and reducing uncertainty.

In conclusion, the quantitative analysis confirms that the Pods4Rail concept is at a lower stage of maturity: its innovative system architecture and key enabling technologies are already identified and, in several cases, demonstrated in relevant environments, yet substantial efforts remain necessary to consolidate integration, validate performance, and address residual technical and operational risks.

For clarity and conciseness, this section has focused on summarising the main outcomes at system and subsystem level. The complete set of quantitative results, including the detailed TRL and IRL input distributions, the system readiness matrices, the full Monte Carlo output statistics, and the subsystem- and interface-level contribution analyses, is provided in Appendix 5. That appendix ensures full methodological traceability and contains all numerical values underpinning the SRL estimates presented in this chapter.

8 Conclusions for the assessment of the Technical Feasibility analysis

According to the Grant Agreement, the primary objective of WP6 is to assess whether the Pods4Rail system is technically, operationally and safely feasible, based on the consolidated results of previous Work Packages. This deliverable (D6.1) has addressed this objective by establishing a rigorous assessment framework, defining relevant Operational Application Scenarios (OASs), and performing both qualitative and quantitative evaluations of the system's readiness

8.1 Methodological approach

The deliverable has established a structured and transparent methodology for assessing the Pods4Rail concept. First, it synthesised essential outputs from previous WPs to ensure a consistent foundation, particularly regarding functional requirements, use cases, business cases, user needs and safety principles. Building on this, the document defined two Operational Application Scenarios (OAS1 – regional passenger transport, and OAS2 – regional freight transport) as representative contexts for feasibility assessment.

The methodology combined two complementary perspectives. The qualitative stage applied a hierarchical analysis of functional requirements, deriving evaluation criteria and examining subsystem-level maturity through TRL-based bar charts and heat maps. The quantitative stage then extended this analysis by integrating TRLs with estimated Integration Readiness Levels (IRLs), applying a probabilistic System Readiness Level (SRL) model based on Monte Carlo simulation. This dual approach ensured both conceptual completeness and statistical robustness.

8.2 Technical Feasibility analysis

The second objective of this report has been to assess whether the Pods4Rail system achieves the required level of Technical Feasibility at this stage of the project. Therefore, a detailed assessment of the Technical Feasibility of the Pods System based on the developed OAS has been carried out using two complementary approaches. The main conclusions are as follows:

8.2.1 Qualitative analysis

The qualitative analysis provides a structured and detailed picture of the technological, operational and safety maturity of the Pods4Rail system at subsystem and component level. By transforming the Functional Requirements Specification (FRS) into a coherent set of criteria, and assigning TRLs through expert-based evaluation, the analysis highlights both the technological foundations on which the concept is built and the key areas where innovation is still emerging.

A first important observation concerns the distribution of criteria across the two Operational Application Scenarios (OAS1 for passenger services and OAS2 for freight). The

majority of criteria are common to both scenarios, confirming that Pods4Rail is conceived as a largely interoperable concept in which the core functionalities—vehicle movement, system control, safety, communication and operational management—are shared. Only a relatively small number of criteria are specific to one scenario, primarily in areas such as passenger comfort (OAS1) or packaging and logistics features (OAS2). This supports the conclusion that the Pods4Rail system, even at the conceptual stage, possesses a high degree of cross-scenario compatibility and functional consistency.

The analysis also reveals that the relative importance of criteria varies significantly across subsystems. Domains associated with system-level performance—such as efficiency, operational robustness, sustainability and safety—carry substantial weight in the feasibility assessment. By contrast, criteria related to non-critical functionalities (e.g., auxiliary comfort features or application-specific logistic options) have a more limited influence on the overall feasibility of the system. This differentiation helps identify which aspects should be prioritised in subsequent stages of development and which can be addressed at later phases without jeopardising project goals.

In terms of technological maturity, the qualitative analysis shows a two-tiered structure within the Pods4Rail system. On the one hand, subsystems grounded in established railway engineering principles exhibit high levels of maturity. Components such as braking systems, axle-related equipment, mechanical interfaces, basic wiring, lighting, and foundational control mechanisms typically fall within TRL 6–7. These areas benefit from decades of railway technological development and existing deployment in relevant environments, meaning that their adaptation to Pods4Rail is feasible and supported by strong technological precedents.

On the other hand, subsystems linked to automation, digitalisation, data management and multimodal system intelligence display considerably lower maturity levels. Technologies related to advanced operational planning, predictive analytics, decentralised communication architectures, autonomous incident response, digital passenger information, and the orchestration of multimodal flows generally exhibit TRL values between 2 and 4. These reflect early-stage development, prototype-level validation, or proof-of-concept experimentation. The disparity between these mature and emergent areas is not unexpected: Pods4Rail is conceived as an innovative smart mobility system, and its transformative value lies precisely in the integration of these emerging digital functionalities with a robust railway foundation.

Another conclusion of the qualitative assessment is the identification of technical domains where complexity and maturity interrelate non-linearly. In subsystems such as Planning and Operation, Ticketing and Booking, Logistics and Storage, and Incident Management, many criteria are interconnected rather than independent. As a result, low TRLs in one element (e.g., real-time optimisation algorithms) can influence related functionalities (e.g., automated re-routing or multimodal synchronisation). This interconnectedness underscores the need for coordinated development strategies rather than isolated technological refinement.

The heat maps and bar charts developed during the analysis further illuminate the internal structure of subsystem maturity. Subsystems with broader functional scopes—particularly

those with digital and operational roles—tend to exhibit wider TRL distributions, reflecting heterogeneity in component readiness. Conversely, hardware-focused subsystems show narrower banded maturity levels, indicating more uniform technological readiness. These visual tools help to highlight where development is uneven and where risk mitigation strategies will be needed in future phases.

Finally, the qualitative analysis confirms that technical feasibility is not compromised, but rather conditioned by the evolution of several key innovative technologies. The system is structurally coherent, its requirements are compatible across subsystems, and its functional logic is technically sound. However, the areas of low maturity—primarily associated with digital automation, intelligent orchestration and advanced operational algorithms—constitute the main bottlenecks and therefore represent the strategic priorities to ensure progress toward higher readiness levels.

Overall, the findings provide a clear roadmap for development, highlighting mature areas that can support early prototyping and identifying emerging technologies requiring focused research, targeted integration efforts and progressive validation. The qualitative analysis thus lays the conceptual groundwork for the subsequent quantitative SRL assessment and for the future technical planning of the Pods4Rail system.

8.2.2 Quantitative analysis

The quantitative analysis complements the qualitative findings by providing a structured, numerical estimate of the overall System Readiness Level (SRL) of the Pods4Rail concept and of the relative maturity of its constituent subsystems. By combining expert-derived TRL ranges with integration maturity (IRL) information in a probabilistic framework, the analysis not only yields a central readiness estimate but also quantifies the uncertainty around it, thereby offering a more complete picture of the state of development.

At system level, the results indicate that Pods4Rail currently lies between the SRL1 (Concept Refinement) and SRL2 (Technology Development) stages. The composite SRL index, normalised on a 0–1 scale, exhibits a distribution where approximately 90% of the simulated values fall between 0.15 and 0.29, with a mean of around 0.22. When mapped back into TRL-equivalent terms via the inverse normalisation, this corresponds to an average system maturity between TRL 2 and TRL 3. This confirms that Pods4Rail is still in an early phase of technological development: the concept is clearly defined and supported by identified technologies, but extensive integration, validation and demonstration work remains ahead before higher readiness levels can be claimed.

The shape and spread of the SRL distribution are particularly informative. The absence of values approaching the upper part of the scale indicates that, under the assumptions and expert judgements used, there are no plausible scenarios in which the system could already be considered highly mature. Conversely, the lower tail does not extend to zero, reflecting the fact that none of the key technologies are purely speculative or at the basic research stage. This supports the view that Pods4Rail is a realistically grounded but still emergent system, consistent with the expectations and time frame of the Grant Agreement.

A more detailed examination of the subsystem-level results reveals a differentiated maturity profile across the system architecture. Subsystems 5 (Transport Unit), 6 (Rail Carrier Unit) and 7 (Coupling System) display above-average readiness, with their mean SRL contributions higher than the composite system value. This is aligned with the qualitative observation that these subsystems rely heavily on existing railway technologies and engineering principles, for which high TRLs (typically 6–7) are well documented. Their relatively advanced state provides a robust physical and functional backbone on which more innovative elements can later be integrated.

In contrast, subsystems 1 (Planning and Operation System), 2 (Logistics, Storage, Ticketing and Booking), 3 (Passenger Information System and Incident Management) and 4 (Handling System) exhibit lower SRL values, systematically below the composite mean. These subsystems are characterised by a strong dependence on digital technologies, advanced control algorithms, data-driven decision support tools and novel operational concepts. The underlying component TRLs are typically in the range 2–4, and the integration of these components within the Pods4Rail architecture is still at a conceptual or early prototyping stage. As a result, these subsystems emerge as the main bottlenecks limiting the overall system readiness.

The analysis of confidence intervals further reinforces this differentiation. The 90% confidence intervals of the SRL means for the subsystems do not overlap with that of the composite system for several components, which indicates that the differences in maturity are not artefacts of statistical noise but rather robust features of the model. In particular, the higher-maturity subsystems 5, 6 and 7 consistently show SRL means that lie above the upper bound of the composite SRL interval, while the lower-maturity subsystems 1–4 have SRL means below its lower bound. This statistically supports the interpretation that the system is anchored by a set of relatively mature hardware-oriented subsystems, while its readiness is constrained by the less mature, innovation-driven digital and operational subsystems.

An important insight of the quantitative work is the role of integration, as captured by IRLs, in shaping the system-level outcome. Even when individual components reach relatively high TRLs, the associated IRLs for certain critical interfaces remain modest. Interfaces involving the Planning and Operation System, often exhibit lower IRL values, indicating that the integration concepts are defined and partially explored but not yet validated in representative environments. This leads to a situation where the effective readiness of the end-to-end capability chains (e.g., planning–ticketing–information–response) is significantly lower than the maturity of the best-performing individual component within them. The quantitative model thus makes explicit that integration gaps, rather than isolated low-TRL components, are key drivers limiting the SRL.

The probabilistic formulation of the model enables a sensitivity analysis, which identifies which inputs (TRLs and IRLs) contribute most to the variability of the SRL estimate. The results show that uncertainties in the TRLs of digital and control-related technologies—particularly within the Planning and Operation System and Incident Management—as well as the IRLs of their critical interfaces, account for a substantial fraction of the variance in the SRL distribution. By contrast, uncertainties in the TRLs of conventional hardware (e.g.,

braking or basic vehicle equipment) have a comparatively minor effect on the composite SRL. This suggests that investments in reducing uncertainty—through targeted prototyping, pilot integration tests, or simulation-based validation—should prioritise the digital, control and integration domains if the objective is to increase confidence in the Pods4Rail readiness assessment.

Furthermore, scenario and robustness analyses were conducted to examine the effect of different assumptions about subsystem interdependencies (e.g., stronger or weaker coupling, alternative IRL structures). These variations produced only modest changes in the composite SRL values and did not alter the ranking of subsystems by maturity. This indicates that the main conclusions of the quantitative analysis are robust to reasonable modelling variations, and that the identification of high-priority subsystems for further development is not overly sensitive to the specific details of the interrelationship model.

Taken together, the quantitative results lead to several overarching conclusions:

- The Pods4Rail system is at an early but well-defined stage of development, consistent with TRL 2–3 and SRL1–2, where the concept is clear and aligned with existing technological trends but still far from deployment-ready status.
- The physical railway-based subsystems (Transport Unit, Rail Carrier Unit, Coupling System) provide a relatively mature technological foundation.
- The digital, automated and operational subsystems (Planning and Operation, Logistics and Storage, Ticketing and Booking, PIS, Incident Management, Handling System) are the main contributors to low system-level readiness, and thus represent the critical focus areas for future R&D and integration efforts.
- Integration maturity (IRLs) is a decisive factor: system readiness is constrained not only by individual component TRLs but also by the limited maturity of key interfaces, especially those involving advanced operational coordination and digital services.
- The SRL estimate is statistically and structurally robust, with results remaining stable under plausible modelling variations, providing a solid basis for decision-making and roadmap planning.

In summary, the quantitative analysis confirms and sharpens the insights from the qualitative assessment: Pods4Rail is technically feasible and conceptually coherent, but its deployment will depend on the progressive maturation and integration of a set of critical digital and operational technologies. The numerical results provide a transparent, evidence-based foundation for prioritising future research, development and demonstration activities, and they are further detailed in the dedicated statistical Appendix 5.

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10 Appendices

Appendix 1: Technology Readiness Level (TRL)

(Jentsch et al., 2023; Sandu, 2022)

Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operation

Appendix 2: Integration Readiness Level (IRL)

(Jentsch et al., 2023; Sandu, 2022)

Level	IRL	Description
1	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship	This is the lowest level of integration readiness and describes the selection of a medium for integration.
2	There is some level of specificity to characterize the interaction between technologies through their interface	Once a medium has been defined, a “signalling” method must be selected such that two integrating technologies are able to influence each other over that medium. Since IRL 2 represents the ability of two technologies to influence each other over a given medium, this represents integration proof-of-concept.
3	There is compatibility between technologies to orderly and efficiently integrate and interact	IRL 3 represents the minimum required level to provide successful integration. This means that the two technologies are able to not only influence each other but also communicate interpretable data. IRL 3 represents the first tangible step in the maturity process
4	There is sufficient detail in the quality and assurance of the integration between technologies	Many technology integration failures never progress past IRL 3, due to the assumption that if two technologies can exchange information successfully, then they are fully integrated. IRL 4 goes beyond simple data exchange and requires that the data sent is the data received and there exists a mechanism for checking it.
5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration	IRL 5 simply denotes the ability of one or more of the integrating technologies to control the integration itself; this includes establishing, maintaining, and terminating
6	The integrating technologies can accept, translate, and structure information for its intended application	IRL 6 is the highest technical level to be achieved, it includes the ability to not only control integration, but specify what information to exchange, unit labels to specify what the information is, and the ability to translate from a foreign data structure to a local one.

Level	IRL	Description
7	The integration of technologies has been verified and validated with sufficient detail to be actionable	IRL 7 represents a significant step beyond IRL 6; the integration has to work from a technical perspective, but also from a requirements perspective. IRL 7 represents the integration meeting requirements such as performance, throughput, and reliability.
8	Actual integration completed and mission-qualified through test and demonstration in the system environment	IRL 8 represents not only the integration meeting requirements, but also a system-level demonstration in the relevant environment. This will reveal any unknown bugs/defect that could not be discovered until the interaction of the two integrating technologies was observed in the system environment.
9	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle	IRL 9 represents the integrated technologies being used in the system environment successfully. In order for a technology to move to TRL 9 it must first be integrated into the system, and then proven in the relevant environment, so attempting to move to IRL 9 also implies maturing the component technology to TRL 9.

Appendix 3: System Readiness Level (SRL):

(Jentsch et al., 2023; Sandu, 2022)

Level	0-1 scale	Name	Definition
1	0.1 to 0.2	Concept refinement	Refine the initial concept. Develop system / technology development strategy.
2	0.2 to 0.5	Technology Development	Reduce technology risks and determine and appropriate set of technologies to integrate into a full system.
3	0.5 to 0.8	System Development and Demonstration	Develop a system or increment of capability; reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for productibility; ensure affordability and protection of critical program information; demonstrate system integration, interoperability, safety and utility.
4	0.8 to 0.9	Production and Development	Achieve operational capability that satisfies mission needs.
5	0.9 to 1.0	Operations and Support	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle.

Appendix 4: Detailed TRL qualitative analysis for each subsystem and its components

This appendix provides the complete qualitative assessment of Technology Readiness Levels (TRLs) for each subsystem of the Pods4Rail concept, together with the detailed evaluation of their constituent components. Whereas Chapter 7 presented the methodological framework and illustrated the assessment using a representative subsystem, this appendix consolidates the full set of results obtained during the expert-driven TRL evaluation process. For each subsystem, the corresponding subcategories, criteria and associated technologies are examined, and their TRL ranges are presented alongside the bar charts and heat maps generated during the analysis. This comprehensive breakdown offers a transparent view of the maturity of all technical, operational and safety-related aspects of the Pods4Rail system and forms the basis for the subsequent quantitative estimation of the System Readiness Level (SRL).

A4.1 Planning and Operation System

To achieve the appropriate management of the Pods System, and their demands and availabilities, a coordination intelligence is required. Its goal is to know at any time the status of the vehicles and TUs, of course, including their current assignment to booked journeys. An overall Pod management system provides the basis for the required intelligence and includes the following components: Pod Coordination System (PCS), Disaster Management, Closed Circuit Television (CCTV) System, Communication systems, Pods trip planning and allocation system. This group of criteria will allow the evaluation of if the OAS1, and OAS2 have the sufficient independence and technology level to fulfil the demands to manage the movement of the vehicles and their itineraries among other functionalities.

Table 8 includes the different subcategories considered in this group, where the minimum and maximum TRL for the set of criteria included in each subcategory are indicated.

Table 8: TRLs for each subcategory for the Planning and Operation group of criteria

Subcategory	Min TRL	Max TRL
Baseline Data	4	4
Communication	4	4
Compatibility	2	2
General requirements	2	6
Information management	4	4
Monitoring	5	5
Operational data	2	5
Scheduling and re-scheduling	2	4
Traffic control	2	4

Table 8 includes the distribution of TRL for each criterion type (operational / technical / safety) in each subcategory for the different scenarios (passengers-(OAS1) / freight-(OAS2) / both).

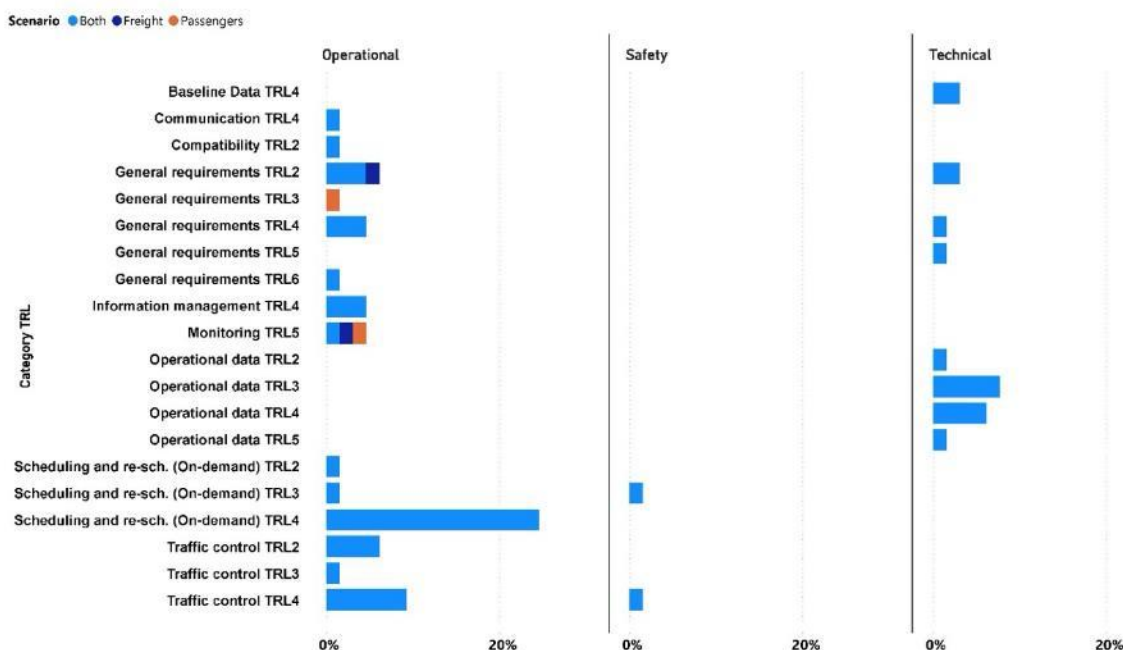


Figure 17: TRL distribution for each criterion type for the different scenarios for Planning and Operation System group of criteria

In general terms, most of the criteria are of an operational nature, and in many cases, there is a moderate level of technological maturity (max TRL6). The majority of the criteria correspond to Technology development stage, mainly associated with scheduling and re-scheduling, operational data and general requirements. Some operational criteria are found in the Observation of basic principles stage, particularly compatibility, general requirements, operational data, scheduling and re-scheduling, and traffic control. Regarding technical or safety criteria, they are significantly less represented compared to operational criteria.

Figure 18 includes the heat maps for the “Planning and Operation System” group. These heat maps have been developed, for each OAS, considering the level of TRL of each criterion of the corresponding subcategory. For example, in the group “Planning and Operation System”, the subcategory “General requirements” has, in OAS1, five criteria with TRL 2, one with TRL 3, four with TRL 4, one with TRL 5 and one criterion with TRL 6. The conclusion of the analysis of this subcategory, in OAS1, is that this subcategory is mainly between the Operation of basic principles and the Technological development stages.

Similarly, for the same group and the same subcategory, in OAS2, it has 6 requirements with TRL 2, four with TRL 4, one with TRL 5, and one criterion with TRL 6. The conclusion is the same as the stated before for the subcategory of “General requirements” in OAS1.

OPERATIONS AND PLANNING SYSTEM OAS1										
Number of subcategories: 9	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Baseline Data	0	0	0	2	0	0	0	0	0	2
Communication	0	0	0	1	0	0	0	0	0	1
Compatibility	0	1	0	0	0	0	0	0	0	1
General requirements	0	5	1	4	1	1	0	0	0	12
Information management	0	0	0	3	0	0	0	0	0	3
Monitoring	0	0	0	0	2	0	0	0	0	2
Operational data	0	1	5	4	1	0	0	0	0	11
Scheduling and re-scheduling (On-demand)	0	1	2	16	0	0	0	0	0	19
Traffic control	0	4	1	7	0	0	0	0	0	12
Absolute frequency	0	12	9	37	4	1	0	0	0	63
Relative frequency	0.000	0.190	0.143	0.587	0.063	0.016	0.000	0.000	0.000	1.000

OPERATIONS AND PLANNING SYSTEM OAS2										
Number of subcategories: 9	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Baseline Data	0	0	0	2	0	0	0	0	0	2
Communication	0	0	0	1	0	0	0	0	0	1
Compatibility	0	1	0	0	0	0	0	0	0	1
General requirements	0	6	0	4	1	1	0	0	0	12
Information management	0	0	0	3	0	0	0	0	0	3
Monitoring	0	0	0	0	2	0	0	0	0	2
Operational data	0	1	5	4	1	0	0	0	0	11
Scheduling and re-scheduling (On-demand)	0	1	2	16	0	0	0	0	0	19
Traffic control	0	4	1	7	0	0	0	0	0	12
Absolute frequency	0	13	8	37	4	1	0	0	0	63
Relative frequency	0.000	0.206	0.127	0.587	0.063	0.016	0.000	0.000	0.000	1.000

Figure 18: Heat maps for Planning and Operation System group

It shall also be seen that the number of criteria is not the same for OAS1 and OAS2, there may be some similarities due to the majority of criteria are present for both forms of transportation, but the changes in the numbers are generated by the specific presence of criteria only for OAS1 or only for OAS2.

A4.2 Logistics System and Pods Storage

This group of criteria contains the capacity of planning and executing the efficient transportation and storage of the vehicles from the point of origin to the point of consumption. The scope of the logistics system embraces the MaaS (Mobility as a Service) applications as well as dispatching the vehicles to the current demand. On the other hand, the storage system must guarantee that the vehicles are protected from external and environmental influences and that can also be used for service check-ups while they are not in active functioning outside the storage for a certain period.

Table 9: TRLs for each subcategory for the Logistics System and Pods Storage group

Subcategories	Min TRL	Max TRL
General requirements	2	5

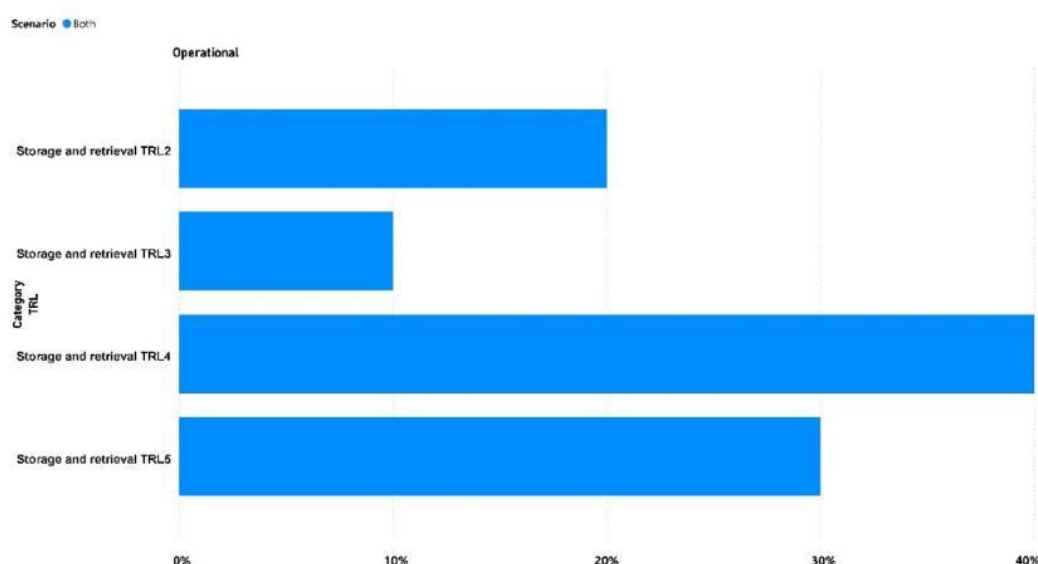


Figure 19: TRL distribution for each criteria type for the different scenarios for Logistics System and Pods Storage group

All requirements are operational and most of them have a medium level of technological maturity, with the majority of requirements corresponding to the Technological development stage, with less requirements being in the Proof-of-concept or Observation of basic principles stage (TRL2 / TRL3), as seen in Figure 19.

LOGISTICS & STORAGE OAS1 & OAS2										
Number of subcategories: 1	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
General requirements	0	2	1	4	3	0	0	0	0	10
Absolute frequency	0	2	1	4	3	0	0	0	0	10
Relative frequency	0.000	0.200	0.100	0.400	0.300	0.000	0.000	0.000	0.000	1.000

Figure 20: Heat map for Logistics System and Pods Storage group

The reason of there is only one heat map for OAS1 and OAS2 is that the number of criteria for both scenarios is the same; there are not specific criteria for only OAS1 or for only OAS2 (Figure 20). The conclusion for both scenarios is that the only subcategory for this group “Logistics System and Pods Storage” is, in general (70% of the total criteria), in Technological development stage, with a 30% of the criteria in the Observation of basic principles stage.

A4.3 Ticketing and Booking

This group of criteria ensures that a web-based service is present and is offering the planning and requests of trips by end users with and integrated booking capability. The system also must include the provision of digital tickets after a successful booking of a trip.

Table 10: TRLs for each subcategory for the Ticketing and Booking group of criteria

Subcategories	Min TRL	Max TRL
General requirements	2	6

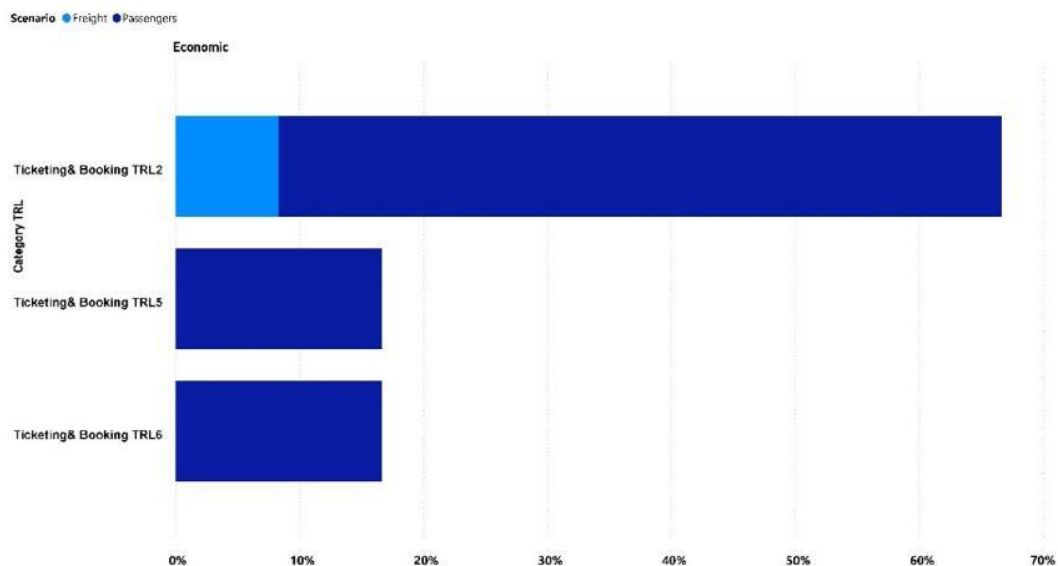


Figure 21: TRL distribution for each criteria type for the different scenarios for Ticketing and Booking group of criteria

TICKETING & BOOKING OAS1										
Number of subcategories: 1	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
General requirements	0	7	0	0	2	2	0	0	0	11
Absolute frequency	0	7	0	0	2	2	0	0	0	11
Relative frequency	0.000	0.636	0.000	0.000	0.182	0.182	0.000	0.000	0.000	1.000

TICKETING & BOOKING OAS2										
Number of subcategories: 1	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
General requirements	0	1	0	0	0	0	0	0	0	1
Absolute frequency	0	1	0	0	0	0	0	0	0	1
Relative frequency	0.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000

Figure 22: Heat maps for “Ticketing and Booking” group

It can be seen that the only subcategory of “Ticketing and Booking” group of criteria is between the Observation of basic principles and Technological development stage for OAS1;

for OAS2, it still is in the Observation of basic principles classification. It is important to emphasize that the change in the number of criteria between the two OASs is evident: there are more specific criteria for the OAS1 scenario.

A4.4 Passenger Information System (PIS)

This group of criteria certifies that there is a PIS system that includes platform and on-board screens/speakers, as well as mobile apps for informing the passengers with relevant information about the current trip. In emergency situations, this system must act as a medium for communication between passengers and the Disaster Management of the Operation System.

Table 11: TRLs for each subcategory for the Passenger Information System group of criteria

Subcategories	Min TRL	Max TRL
General requirements	2	5

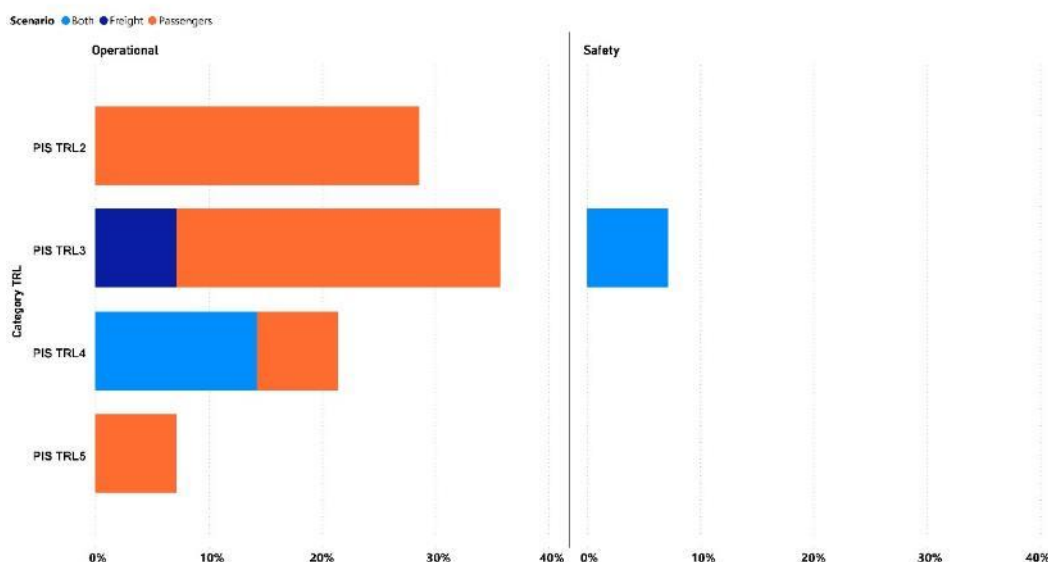


Figure 23: TRL distribution for each subcategory for the different scenarios for Passenger Information System group of criteria

All the requirements, mainly operational oriented towards passenger transport, have a low level of technological maturity as they are at the Proof-of-concept and Observation of basic principles stage, existing a very small percentage of them being safety-related.

PASSENGER INFORMATION SYSTEM OAS1										
Number of subcategories: 1	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
General requirements	0	4	5	3	1	0	0	0	0	13
Absolute frequency	0	4	5	3	1	0	0	0	0	13
Relative frequency	0.000	0.308	0.385	0.231	0.077	0.000	0.000	0.000	0.000	1.000

PASSENGER INFORMATION SYSTEM OAS2										
Number of subcategories: 1	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
General requirements	0	0	2	2	0	0	0	0	0	4
Absolute frequency	0	0	2	2	0	0	0	0	0	4
Relative frequency	0.000	0.000	0.500	0.500	0.000	0.000	0.000	0.000	0.000	1.000

Figure 24: Heat maps for Passenger Information System group of criteria

In the “PIS” group of criteria, for both OAS1 and OAS2, and their only subcategory “General requirements”, the criteria are in between the Observation of basic principles and the Technological development stages. Similar to the previous group of criteria, the change in the number of requirements between the two OASs is evident: there are more specific requirements for the OAS1 scenario.

A4.5 Incident Management

This group of criteria evaluates if the system counts with an Incident/Disaster Management that focuses on the users (health problems, fire, information problems, etc), the technical system (e.g. drive system failure), problems with the surrounding environment (e.g. obstacle on the route, etc), among others. This system must be able to solve the mentioned problems and other disturbed operational circumstances in to protect the passenger, the freight forwarded, the system provider, and the vehicle rental companies' interests.

Table 12: TRLs for each subcategory for Incident Management group of criteria

Subcategories	Min TRL	Max TRL
Cybersecurity	4	4
Ethical and legal	3	3
Incident Detection and Diagnosis	4	4
Incident Information Management	2	2

Subcategories	Min TRL	Max TRL
Incident Prevention and Mitigation	2	5
Recovery measures	3	6
Response to incidents	5	6

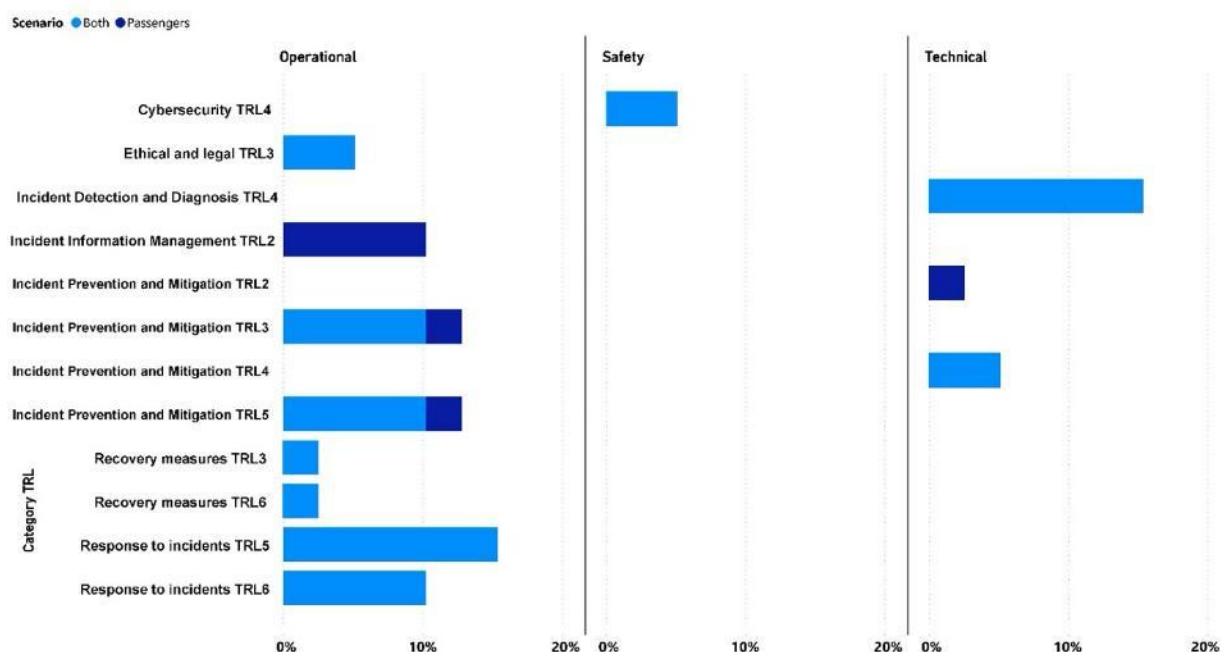


Figure 25: TRL distribution for each subcategory for the different scenarios for Incident Management group of criteria

The distribution of technological maturity levels (TRL) across the different subcategories shows a varied landscape. Most requirements fall within intermediate maturity levels, with a strong presence of TRL2 to TRL5 in Incident prevention and mitigation, reflecting their diverse applications across both freight and passenger-focused scenarios. Incident response measures, particularly at TRL6, are the most technologically advanced in this group of criteria. Safety-related aspects are limited, with only two criteria represented. Incident detection and diagnosis subcategory exhibits a higher concentration at TRL4, indicating a moderate level of technological validation as its state is in the Technological development stage mostly.

INCIDENT MANAGEMENT OAS1										
Number of subcategories: 7	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Cybersecurity	0	0	0	2	0	0	0	0	0	2
Ethical and legal	0	0	2	0	0	0	0	0	0	2
Incident Detection and Diagnosis	0	0	0	6	0	0	0	0	0	6
Incident Information Management	0	4	0	0	0	0	0	0	0	4
Incident Prevention and Mitigation	0	1	5	2	5	0	0	0	0	13
Recovery measures	0	0	1	0	0	1	0	0	0	2
Response to incidents	0	0	0	0	6	4	0	0	0	10
Absolute frequency	0	5	8	10	11	5	0	0	0	39
Relative frequency	0.000	0.128	0.205	0.256	0.282	0.128	0.000	0.000	0.000	1.000

INCIDENT MANAGEMENT OAS2										
Number of subcategories: 7	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Cybersecurity	0	0	0	2	0	0	0	0	0	2
Ethical and legal	0	0	2	0	0	0	0	0	0	2
Incident Detection and Diagnosis	0	0	0	6	0	0	0	0	0	6
Incident Information Management	0	0	0	0	0	0	0	0	0	0
Incident Prevention and Mitigation	0	0	4	2	4	0	0	0	0	10
Recovery measures	0	0	1	0	0	1	0	0	0	2
Response to incidents	0	0	0	0	6	4	0	0	0	10
Absolute frequency	0	0	7	10	10	5	0	0	0	32
Relative frequency	0.000	0.000	0.219	0.313	0.313	0.156	0.000	0.000	0.000	1.000

Figure 26: Heat maps for Incident Management group of criteria

A4.6 Handling System

The criteria related to the handling system group ensure that the automated loading and unloading functions in an unhindered way and allow the transfer of the TUs to different carrier unit, from storages or for a change in the transportation mode (e.g., rail to road). These criteria ensure that the system follows the multi-modality that the Pods System concept promises.

Table 13: TRL for each subcategory for the Handling System group of criteria

Subcategories	Min TRL	Max TRL
Automation Safety Functions	2	3
Baseline Data	2	4
Communications	2	2
Content loading/unloading (cargo)	3	4
Horizontal handling: Interaction with TU and fixing	2	4
Operation	2	4
Power Supply	2	2
Suspended handling: Interaction with TU and fixing	4	4

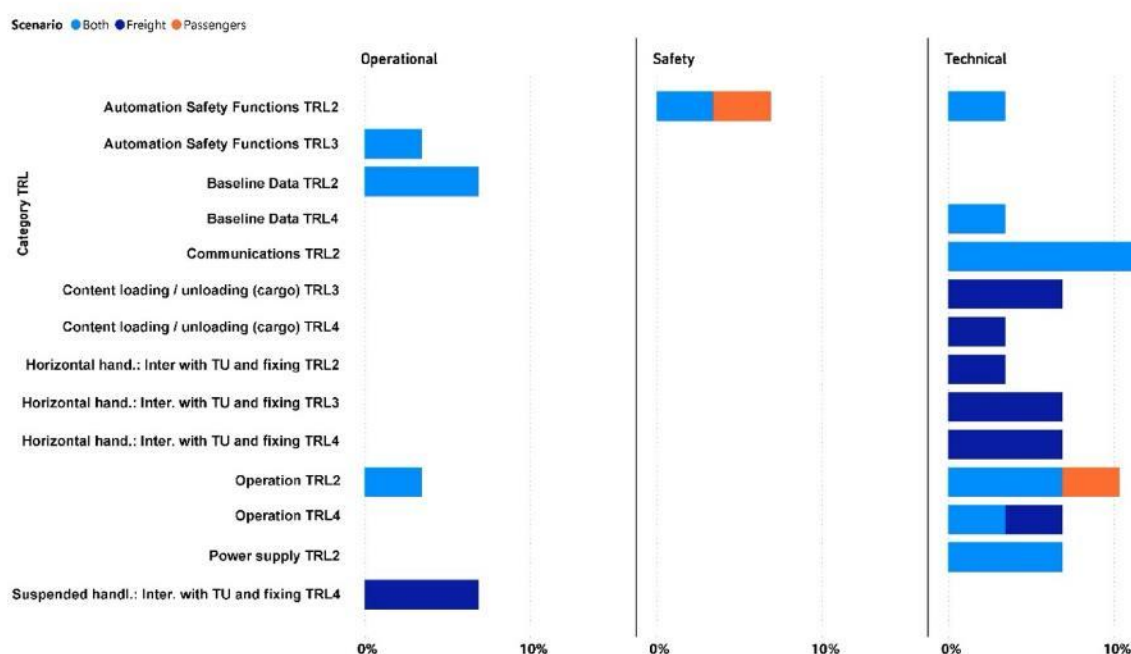


Figure 27: TRL distribution for each subcategory for the different scenarios for Handling System group of criteria

Most of the requirements are of a technical nature, and a large percentage of these are exclusively for freight transport. In general terms, technological maturity is between the Observation of basic principles and the Technological development stages. Nevertheless, in general terms, the level of technology is still very low, for example, in terms of safety, especially in passenger transport.

HANDLING SYSTEM OAS1										
Number of subcategories: 8	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Automation Safety Functions	0	3	1	0	0	0	0	0	0	4
Baseline Data	0	2	0	1	0	0	0	0	0	3
Communications	0	4	0	0	0	0	0	0	0	4
Content loading/unloading (cargo)	0	0	0	0	0	0	0	0	0	0
Horizontal handling: Interaction with TU and fixing	0	0	0	0	0	0	0	0	0	0
Operation	0	4	0	1	0	0	0	0	0	5
Power Supply	0	2	0	0	0	0	0	0	0	2
Suspended handling: Interaction with TU and fixing	0	0	0	0	0	0	0	0	0	0
Absolute frequency	0	15	1	2	0	0	0	0	0	18
Relative frequency	0.000	0.833	0.056	0.111	0.000	0.000	0.000	0.000	0.000	1.000

HANDLING SYSTEM OAS2										
Number of subcategories: 8	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Automation Safety Functions	0	2	1	0	0	0	0	0	0	3
Baseline Data	0	2	0	1	0	0	0	0	0	3
Communications	0	4	0	0	0	0	0	0	0	4
Content loading/unloading (cargo)	0	0	2	1	0	0	0	0	0	3
Horizontal handling: Interaction with TU and fixing	0	1	2	1	0	0	0	0	0	4
Operation	0	3	0	2	0	0	0	0	0	5
Power Supply	0	2	0	0	0	0	0	0	0	2
Suspended handling: Interaction with TU and fixing	0	0	0	2	0	0	0	0	0	2
Absolute frequency	0	14	5	7	0	0	0	0	0	26
Relative frequency	0.000	0.538	0.192	0.269	0.000	0.000	0.000	0.000	0.000	1.000

Figure 28: Heat maps for Handling System group of criteria

A4.7 Transport Unit

These criteria evaluate the integrity, robustness and the correct functioning of one of the most important elements in the Pods System: Transport Unit (group of criteria). This evaluation must ensure the correct loading, coupling, and the appropriate functioning of the interior elements of the component for the security of passengers and freight (depending on the analysed OAS).

Table 14: TRL for each subcategory for the Transport Unit group of criteria

Subcategories	Min TRL	Max TRL
Air Conditioning	7	7
Baseline Data	4	7
Doors, entrances	7	7
Information facilities	7	7
Interior appointment	5	7
Lighting	7	7
Monitoring and safety equipment	5	7
Power System	2	4
Vehicle Body	4	5
Vehicle fitting out	4	7
Vehicle linkage devices	2	7

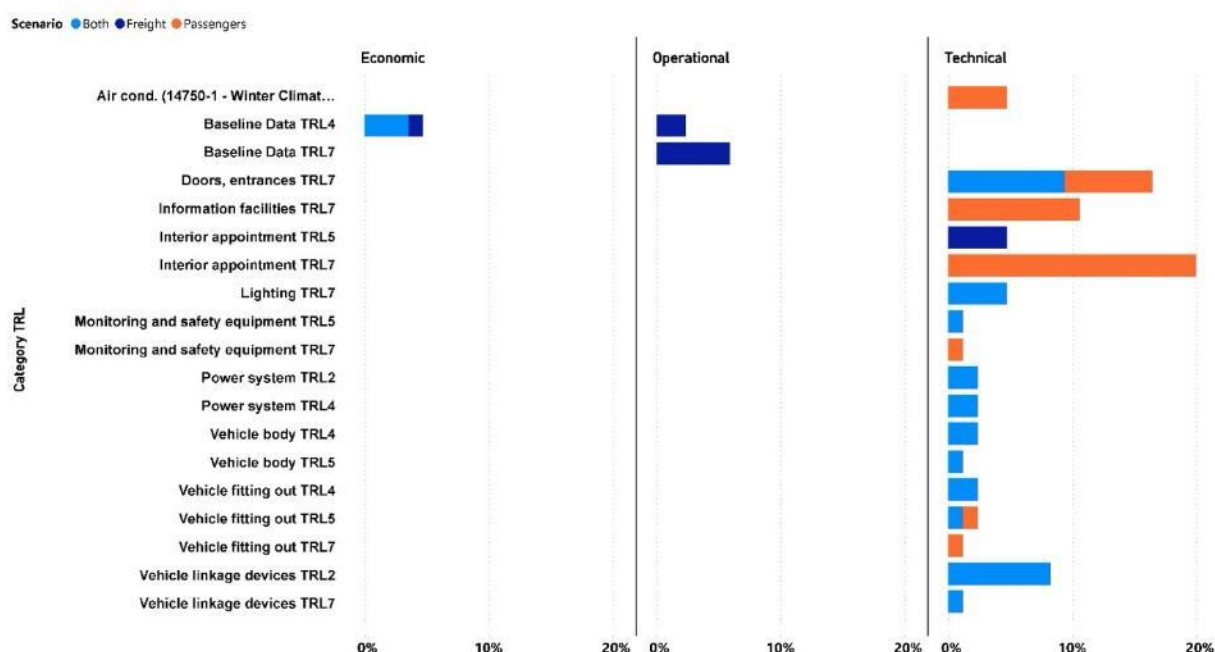


Figure 29: TRL distribution for each subcategory for the different scenarios for Transport Unit group of criteria

As can be seen, most of the requirements are of a technical nature, many of them being applicable only to passenger transport and many others to both passenger and freight transport. In general, the level of technological maturity is high, with technologies in a Maturity and commercialization stage, although the existence of the cases like power system and vehicle linkage devices subcategories with a very low level of TRL (2).

TRANSPORT UNIT OAS1										
Number of subcategories: 11	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Air Conditioning	0	0	0	0	0	0	4	0	0	4
Baseline Data	0	0	0	3	0	0	0	0	0	3
Doors, entrances	0	0	0	0	0	0	14	0	0	14
Information facilities	0	0	0	0	0	0	9	0	0	9
Interior appointment	0	0	0	0	0	0	17	0	0	17
Lightning	0	0	0	0	0	0	4	0	0	4
Monitoring and safety equipment	0	0	0	0	1	0	1	0	0	2
Power System	0	2	0	2	0	0	0	0	0	4
Vehicle Body	0	0	0	2	1	0	0	0	0	3
Vehicle fitting out	0	0	0	2	2	0	1	0	0	5
Vehicle linkage devices	0	6	0	0	0	0	1	0	0	7
Absolute frequency	0	8	0	9	4	0	51	0	0	72
Relative frequency	0.000	0.111	0.000	0.125	0.056	0.000	0.708	0.000	0.000	1.000

TRANSPORT UNIT OAS2										
Number of subcategories: 11	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Air Conditioning	0	0	0	0	0	0	0	0	0	0
Baseline Data	0	0	0	6	0	0	5	0	0	11
Doors, entrances	0	0	0	0	0	0	8	0	0	8
Information facilities	0	0	0	0	0	0	0	0	0	0
Interior appointment	0	0	0	0	4	0	0	0	0	4
Lightning	0	0	0	0	0	0	4	0	0	4
Monitoring and safety equipment	0	0	0	0	1	0	0	0	0	1
Power System	0	2	0	2	0	0	0	0	0	4
Vehicle Body	0	0	0	2	1	0	0	0	0	3
Vehicle fitting out	0	0	0	2	1	0	0	0	0	3
Vehicle linkage devices	0	6	0	0	0	0	1	0	0	7
Absolute frequency	0	8	0	12	7	0	18	0	0	45
Relative frequency	0.000	0.178	0.000	0.267	0.156	0.000	0.400	0.000	0.000	1.000

Figure 30: Heat maps for Transport Unit group of criteria

A4.8 Rail Carrier Unit

These criteria ensure the presence of a mobile drive unit for the railway domain, independent of the TU, so that there is vehicle underframe construction that must guarantee the safety of operation, its structural robustness, effective power transmission, efficient coupling system, correct driving mechanism, brake system integration among other characteristics.

Table 15: TRL for each subcategory for the Rail Carrier Unit group of criteria

Subcategories	Min TRL	Max TRL
Auxiliary operating equipment	6	6
Baseline Data	2	7
Brake	7	7
Carrier systems, enclosures	4	4
Control apparatus for train operations	2	6
Doors, entrances	7	7
Electrical wiring	7	7
Information facilities	7	7
Interior appointments	7	7
Lighting	7	7
Monitoring and safety device	4	7
Pneumatic/hydraulic equipment	7	7
Power system, drive unit	3	7
Running Gear	7	7
Vehicle Body	2	2
Vehicle linkage devices	3	4

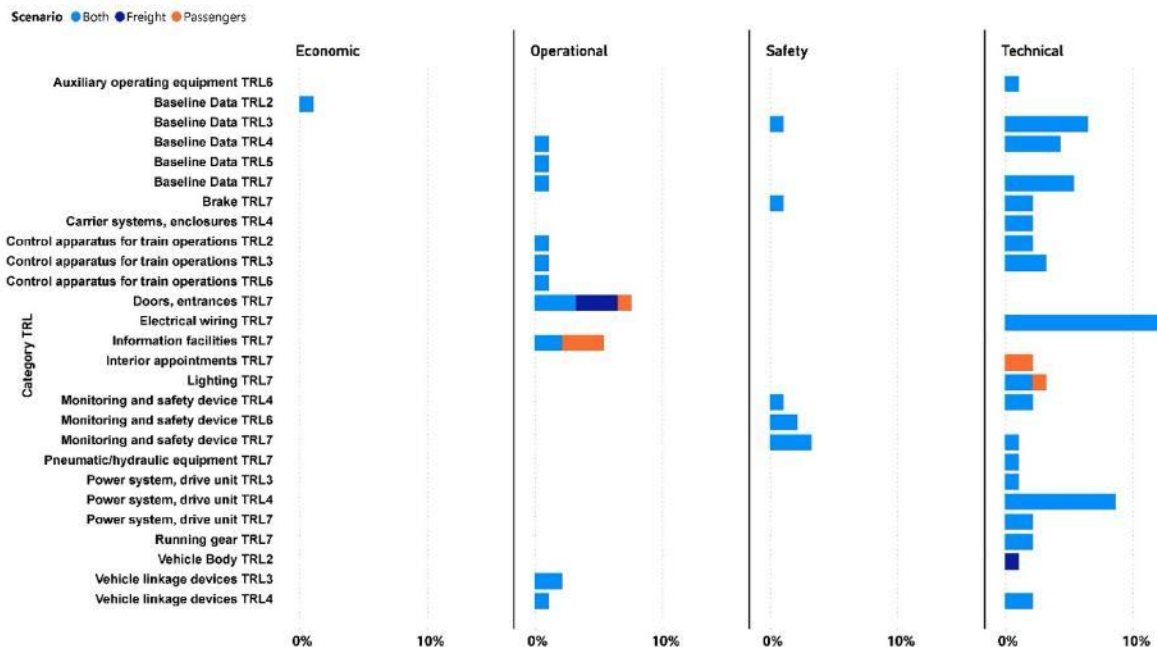


Figure 31: TRL distribution for each subcategory for the different scenarios for Rail Carrier Unit group of criteria

Most of the requirements are technical and applicable to both types of transport, with a generally high level of technological maturity (TRL 7) since there are components with an already high level of development, e.g. in railway vehicles, as lightning, doors, electrical wiring, information facilities and interior appointments. Nevertheless, work is still needed in subcategories as baseline data, control apparatus for train operations and vehicle linkage devices because they are still, mostly, in Observation of basic principles stage with TRLs between 2 and 4.

RAIL CARRIER UNIT OAS1										
Number of subcategories: 16	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criteria per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Auxiliary operating equipment	0	0	0	0	0	1	0	0	0	1
Baseline Data	0	1	7	5	1	0	6	0	0	20
Brake	0	0	0	0	0	0	3	0	0	3
Carrier systems, enclosures	0	0	0	1	0	0	0	0	0	1
Control apparatus for train operations	0	3	4	0	0	1	0	0	0	8
Doors, entrances	0	0	0	0	0	0	4	0	0	4
Electrical wiring	0	0	0	0	0	0	6	0	0	6
Information facilities	0	0	0	0	0	0	5	0	0	5
Interior appointments	0	0	0	0	0	0	2	0	0	2
Lightning	0	0	0	0	0	0	3	0	0	3
Monitoring and safety device	0	0	0	3	0	2	4	0	0	9
Pneumatic/hydraulic equipment	0	0	0	0	0	0	1	0	0	1
Power system, drive unit	0	0	1	8	0	0	2	0	0	11
Running Gear	0	0	0	0	0	0	2	0	0	2
Vehicle Body	0	0	0	0	0	0	0	0	0	0
Vehicle linkage devices	0	0	2	3	0	0	0	0	0	5
Absolute frequency	0	4	14	20	1	4	38	0	0	81
Relative frequency	0.000	0.049	0.173	0.247	0.012	0.049	0.469	0.000	0.000	1.000

RAIL CARRIER UNIT OAS2										
Number of subcategories: 16	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Auxiliary operating equipment	0	0	0	0	0	1	0	0	0	1
Baseline Data	0	1	7	5	1	0	6	0	0	20
Brake	0	0	0	0	0	0	3	0	0	3
Carrier systems, enclosures	0	0	0	1	0	0	0	0	0	1
Control apparatus for train operations	0	3	4	0	0	1	0	0	0	8
Doors, entrances	0	0	0	0	0	0	6	0	0	6
Electrical wiring	0	0	0	0	0	0	6	0	0	6
Information facilities	0	0	0	0	0	0	2	0	0	2
Interior appointments	0	0	0	0	0	0	0	0	0	0
Lightning	0	0	0	0	0	0	2	0	0	2
Monitoring and safety device	0	0	0	3	0	2	4	0	0	9
Pneumatic/hydraulic equipment	0	0	0	0	0	0	1	0	0	1
Power system, drive unit	0	0	1	8	0	0	2	0	0	11
Running Gear	0	0	0	0	0	0	2	0	0	2
Vehicle Body	0	1	0	0	0	0	0	0	0	1
Vehicle linkage devices	0	0	2	3	0	0	0	0	0	5
Absolute frequency	0	5	14	20	1	4	34	0	0	78
Relative frequency	0.000	0.064	0.179	0.256	0.013	0.051	0.436	0.000	0.000	1.000

Figure 32: Heat maps for Rail Carrier Unit group of criteria

A4.9 Coupling System

These criteria involve the concept of coupling system between the Transport Unit and the Rail Carrier Unit, as well as, if necessary, the coupling of other systems, such as power supply and communication systems. These criteria must ensure the correct connection and coupling between the mentioned elements to guarantee the safety of the operation and the technical feasibility of the group.

Table 16: TRLs for each subcategory for the Coupling System group of criteria

Subcategories	Min TRL	Max TRL
Communications/Data Transfer	2	2
Coupling's Operation	2	2
Dimension	7	7
Electrical Connection	3	7
Energy Transfer	3	3
General requirements	2	5
Interfaces with other subsystems	2	2
Manual Coupling/Uncoupling – Redundant System	2	2
Material	7	7
Mechanical Connection	4	4
RAMS	7	7

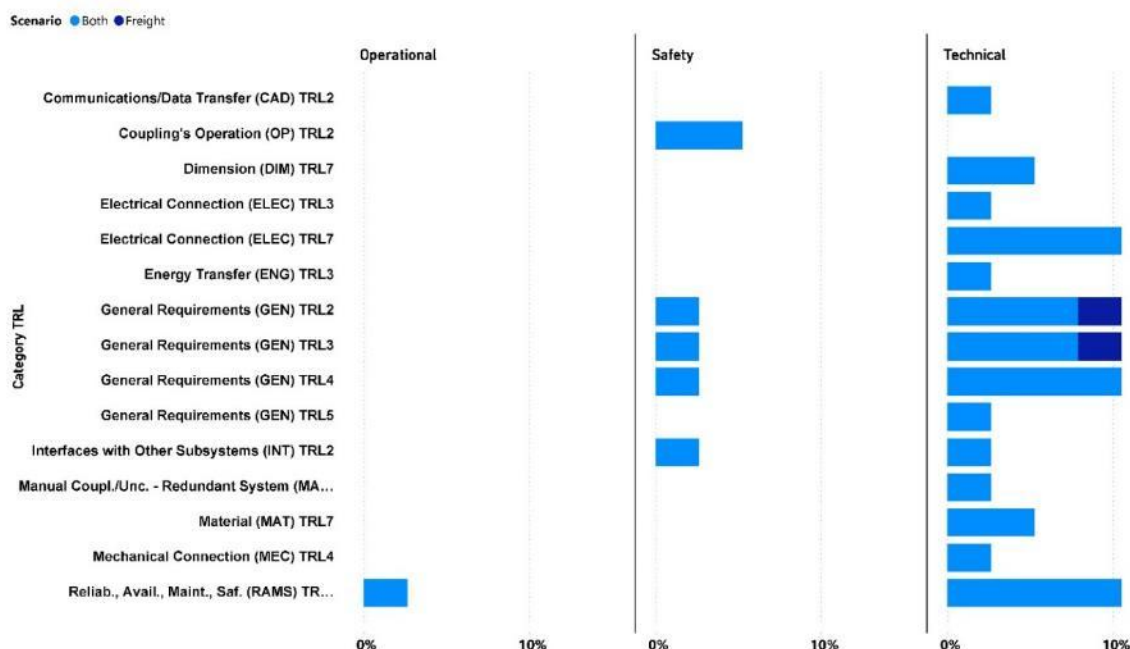


Figure 33: TRL distribution for each subcategory for the different scenarios for Coupling System group of criteria

COUPLING SYSTEM OAS1										
Number of subcategories: 11	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Communications/Data Transfer	0	1	0	0	0	0	0	0	0	1
Coupling's Operation	0	2	0	0	0	0	0	0	0	2
Dimension	0	0	0	0	0	0	2	0	0	2
Electrical Connection	0	0	1	0	0	0	4	0	0	5
Energy Transfer	0	0	1	0	0	0	0	0	0	1
General requirements	0	4	4	5	1	0	0	0	0	14
Interfaces with other subsystems	0	2	0	0	0	0	0	0	0	2
Manual Coupling/Uncoupling – Redundant System	0	1	0	0	0	0	0	0	0	1
Material	0	0	0	0	0	0	2	0	0	2
Mechanical Connection	0	0	0	1	0	0	0	0	0	1
RAMS	0	0	0	0	0	0	5	0	0	5
Absolute frequency	0	10	6	6	1	0	13	0	0	36
Relative frequency	0.000	0.278	0.167	0.167	0.028	0.000	0.361	0.000	0.000	1.000

COUPLING SYSTEM OAS2										
Number of subcategories: 11	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Communications/Data Transfer	0	1	0	0	0	0	0	0	0	1
Coupling's Operation	0	2	0	0	0	0	0	0	0	2
Dimension	0	0	0	0	0	0	2	0	0	2
Electrical Connection	0	0	1	0	0	0	4	0	0	5
Energy Transfer	0	0	1	0	0	0	0	0	0	1
General requirements	0	5	5	5	1	0	0	0	0	16
Interfaces with other subsystems	0	2	0	0	0	0	0	0	0	2
Manual Coupling/Uncoupling – Redundant System	0	1	0	0	0	0	0	0	0	1
Material	0	0	0	0	0	0	2	0	0	2
Mechanical Connection	0	0	0	1	0	0	0	0	0	1
RAMS	0	0	0	0	0	0	5	0	0	5
Absolute frequency	0	11	7	6	1	0	13	0	0	38
Relative frequency	0.000	0.289	0.184	0.158	0.026	0.000	0.342	0.000	0.000	1.000

Figure 34: Heat maps for Coupling System group of criteria

A4.10 Rail Transport and Road Transport Interfacing

These criteria ensure the presence of the interfaces and necessary demands for all road bound vehicles. This includes only the related topics with the interface between the Pods System (originally designed for railway transport) and the road transport/road carrier like the safety in the loading and unloading of the TU on the road carrier.

Table 17: TRL for each subcategory for the Rail Transport and Road Transport Interfacing group of criteria

Subcategories	Min TRL	Max TRL
Autonomous driving	3	7
Base structure/Modularity	7	7
Chassis	7	7
Dimensions	7	7
Energy Supply	4	7
Interfacing	4	7
Loading/Unloading of TU	3	7
Operation	3	7
Power Train	7	7
Safety	4	7
Serviceability	7	7
Sustainability	7	7
Various components groups	7	7

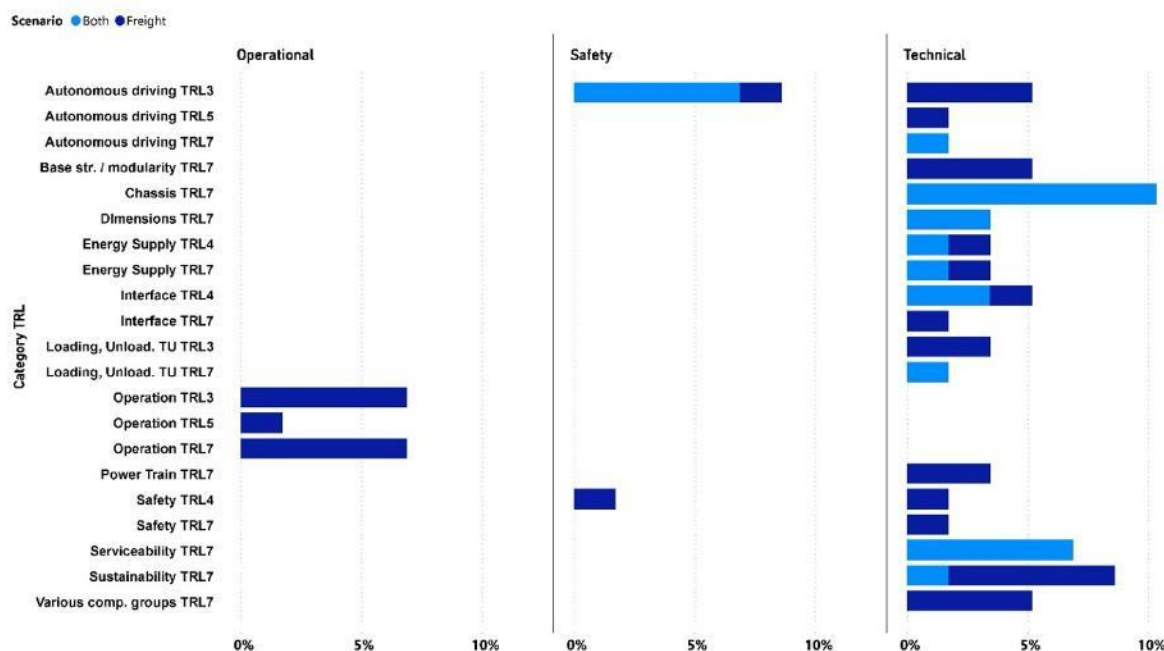


Figure 35: TRL distribution for each subcategory for the different scenarios for Rail Transport and Road Transport Interfacing group of criteria

Such as can be seen, most of the requirements are of a technical nature and half of them are applied exclusively to freight transport, being the technological maturity high in general terms. In the other hand, all the operational requirements are only associated with freight transport, existing different levels of technological maturity in the same category (operations). By last and in a similar way to the requirements discussed above, the maturity is still very low (TRL3 / TRL4) in terms of safety, existing some categories which are necessary to improve.

ROAD TRANSPORT OAS1										
Number of subcategories: 13	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Autonomous driving	0	0	4	0	0	0	1	0	0	5
Base structure/Modularity	0	0	0	0	0	0	0	0	0	0
Chassis	0	0	0	0	0	0	6	0	0	6
Dimensions	0	0	0	0	0	0	2	0	0	2
Energy Supply	0	0	0	1	0	0	1	0	0	2
Interfacing	0	0	0	2	0	0	0	0	0	2
Loading/Unloading of TU	0	0	0	0	0	0	1	0	0	1
Operation	0	0	0	0	0	0	0	0	0	0
Power Train	0	0	0	0	0	0	0	0	0	0
Safety	0	0	0	0	0	0	0	0	0	0
Serviceability	0	0	0	0	0	0	4	0	0	4
Sustainability	0	0	0	0	0	0	1	0	0	1
Various components groups	0	0	0	0	0	0	0	0	0	0
Absolute frequency	0	0	4	3	0	0	16	0	0	23
Relative frequency	0.000	0.000	0.174	0.130	0.000	0.000	0.696	0.000	0.000	1.000

ROAD TRANSPORT OAS2										
Number of subcategories: 13	Observation of basic principles			Technological development stage			Maturity and commercialization stage			Total criterions per subcategory
	TRLs									
	1	2	3	4	5	6	7	8	9	
Autonomous driving	0	0	8	0	1	0	1	0	0	10
Base structure/Modularity	0	0	0	0	0	0	3	0	0	3
Chassis	0	0	0	0	0	0	6	0	0	6
Dimensions	0	0	0	0	0	0	2	0	0	2
Energy Supply	0	0	0	2	0	0	2	0	0	4
Interfacing	0	0	0	3	0	0	1	0	0	4
Loading/Unloading of TU	0	0	2	0	0	0	1	0	0	3
Operation	0	0	4	0	1	0	4	0	0	9
Power Train	0	0	0	0	0	0	2	0	0	2
Safety	0	0	0	2	0	0	1	0	0	3
Serviceability	0	0	0	0	0	0	4	0	0	4
Sustainability	0	0	0	0	0	0	5	0	0	5
Various components groups	0	0	0	0	0	0	3	0	0	3
Absolute frequency	0	0	14	7	2	0	35	0	0	58
Relative frequency	0.000	0.000	0.241	0.121	0.034	0.000	0.603	0.000	0.000	1.000

Figure 36: Heat maps for Rail Transport and Road Transport Interfacing group of criteria

Appendix 5: Detailed Quantitative SRL Analysis and Statistical Modelling Results

This appendix presents the detailed quantitative results supporting the System Readiness Level (SRL) assessment described in Section 7.2.4. While the main chapter provides a consolidated overview of the SRL estimates and the key findings at system and subsystem level, the material compiled here offers full numerical traceability of the statistical models used in the analysis

The system parameters used in the quantitative analysis are summarized in Table 6.

Table 18: System parameters for Monte Carlo method

System parameters		
n	N (num samples)	m_i
7	50000	7

- Results for the $7 \times N$ random sample of TRL two-dimensional matrix (first column as an example):

First column of TRL matrix

$$\begin{bmatrix} 0.3750 \\ 0.5000 \\ 0.3750 \\ 0.1250 \\ 0.7500 \\ 0.6250 \\ 0.2500 \end{bmatrix}$$

Equation 7: Result of the first column of TRL matrix

An example in Equation 7 is given of the first column of the TRL matrix where the values are in a scale $[0,1]$ according to the assigned probabilities in the code. Each row corresponds to the first component until the component number seven, and this configuration continues until the N column.

- Results for the $7 \times 7 \times N$ random sample of IRL three-dimensional matrix (first layer as an example):

First layer of IRL matrix

—	Comp1	Comp2	Comp3	Comp4	Comp5	Comp6	Comp7
Comp1	1.0000	0.3750	0.5000	0.6250	0.5000	0.5000	0.3750
Comp2	0.3750	1.0000	0.3750	0.3750	0.3750	0.6250	0.5000
Comp3	0.5000	0.3750	1.0000	0.5000	0.5000	0.3750	0.6250
Comp4	0.6250	0.3750	0.5000	1.0000	0.3750	0.3750	0.5000
Comp5	0.5000	0.3750	0.5000	0.3750	1.0000	0.5000	0.5000
Comp6	0.5000	0.6250	0.3750	0.3750	0.5000	1.0000	0.6250
Comp7	0.3750	0.5000	0.6250	0.5000	0.5000	0.6250	1.0000

Equation 8: Result of the first layer of the IRL three-dimensional matrix

An example is given of the first layer of the IRL matrix (Equation 8); consider that this three-dimensional array has N layers. Each layer of IRL is a symmetrical matrix and is constituted by a diagonal with value=1 since the integration of one component with itself has the highest value in the scale (9 in normal scale before the normalization to 1 through $(IRL-1)/8$ factor).

- Result of the random sample of SRL two-dimensional matrix (first column as an example):

First column of SRL matrix

0.2299
0.2321
0.2254
0.1964
0.2567
0.2634
0.2433

Equation 9: Result of the first column of the SRL matrix

An example is given of the first column of the SRL matrix where the values are in a scale [0,1] (Equation 9) after the normalization of values through the introduction of *matrix_norm_SRL*. Each row corresponds to the SRL of the first component until the component number seven, and this configuration continues until the N column.

To analyse these results, it is necessary to calculate statistical variables, such as the mean, since the large volume of generated data $N = 50000$ does not allow for a discrete or individual approach.

- Statistical results for individual SRL and COMPOSITE SRL

As results from the first run, we have the following tables containing information about the individual SRL for the seven components and for the COMPOSITE SRL (SRL of the Pods4Rail system).

Table 19: SRLs individual statistical results and COMPOSITE SRL statistical results

Statistical Results from Montecarlo method							
Variables	Means	Medians	Standard Deviations	Minimum	Maximum	Percentile 5%	Percentile 95%
SRL1	0.217434	0.216518	0.040726	0.073661	0.377232	0.149554	0.285714
SRL2	0.216872	0.216518	0.044349	0.075893	0.379464	0.145089	0.290179
SRL3	0.219790	0.218750	0.042565	0.073661	0.388393	0.149554	0.290179
SRL4	0.205989	0.205357	0.039748	0.075893	0.383929	0.142857	0.272321
SRL5	0.238691	0.243304	0.046145	0.071429	0.390625	0.154018	0.308036
SRL6	0.232428	0.234375	0.046847	0.078125	0.395089	0.154018	0.308036
SRL7	0.224718	0.223214	0.049876	0.073661	0.388393	0.145089	0.308036
COMPOSITE SRL	0.222275	0.222895	0.040916	0.079082	0.373724	0.154337	0.288903

A scale of colours has been used in Table 18 in each column as a tool to identify the highest value (darker colour) from the lowest one. Now, a brief analysis of some of these statistical variable's results will be carried out:

o Means

The mean values from 0.238691 (SRL5), 0.232428 (SRL6) and 0.224718 (SRL7) show higher values than the COMPOSITE SRL mean (0.222275). On a first instance, it can be concluded that components 5 (Transport Unit (TU)), 6 (Rail Carrier Unit (RCU)) and 7 (Coupling System) are ahead in the progress of maturity and development of the whole Pods4Rail system.

Following the same analysis, components 1 (Planning and Operation System), 2 (Logistics, Storage, Ticketing and Booking), 3 (PIS and Incident Management) and 4 (Handling System) with means with a lower value than COMPOSITE SRL mean are the components that have a lower level of development and are behind the whole system life cycle's phase.

o Medians

The COMPOSITE SRL median (0.222895) is slightly above its mean, suggesting the presence of a negative bias/asymmetry. In other words, as the median is the value that divides the data at its half, there are several lower values that are affecting the mean, so its tendency goes at the left of the median value.

As this case, a similar conclusion can be drawn for the individual SRL where small negative or positive bias are present according to each chase. Nevertheless, since the difference between these two variables is small, a relatively symmetrical distribution of data can be defined for all SRL.

o Standard Deviations

Standard deviation is a measure of dispersion that indicates how much data vary around the mean. As all of the standard deviations are low values near to zero, it can be said that the overall SRLs' and COMPOSITE SRL' variabilities are controlled, and

the data is not too scattered. The highest standard deviation belongs to SRL7 (0.049876), meaning this variable has the most variation. The lowest standard deviation is SRL4 (0.039748), indicating more consistent values. The COMPOSITE SRL standard deviation (0.040916) suggests that, overall, the variability is moderate. SRL7 is the most volatile, while SRL4 is the most stable.

- o Percentile 5% and percentile 95%

Percentile X% is a concept where the X% of the data is lower or equal than its value, intuitively, with both percentile 5% and percentile 95% for each variable (SRL and COMPOSITE SRL), a 90% probability interval can be set for each one; nevertheless, they give a range of the data, not a confidence interval for the mean (variable of interest). The 95% and 5% percentiles of the data reflect the overall dispersion of the sample, not the precision of the estimated mean. In that sense, the next step is to calculate the 90% confidence interval of all the means.

- o Confidence Interval of 90% for the mean of individual SRLs and COMPOSITE SRL

To calculate the 90% Confidence Interval (CI) of the mean for all the variables some steps must be taken according to theory (Šimundić, 2008). Four inputs are needed: means, standard deviations, number of samples and Z value, assuming gaussianity. In this case, the standard deviations are “sample standard deviations” since the analysis is in a limited number of samples and not in a whole population. The number of samples $N = 50000$ is known and the Z value is a coefficient that depends on the chosen confidence level. For a 90% level, $Z = 1.65$; defined this, an estimated error is calculated as:

$$EE = \frac{std}{\sqrt{N}}$$

Equation 10: Estimated Error for CI

As a final step, the limits for the confidence interval of 90% are calculated as:

$$Limits\ of\ CI = mean \pm (Z \times EE)$$

Equation 11: Calculation of CI limits

Now, Table 20 with the calculation results will be showed followed with Figure 37 of the current CI analysis.

Table 20: 90% CI Results and limits for variables' means

90% CI of variables' means					
Variables	Means	Sample STD	EE	Lower Limit	Upper Limit
SRL1	0.217434	0.040726	0.000182	0.217133	0.217735
SRL2	0.216872	0.044349	0.000198	0.216545	0.217199
SRL3	0.219790	0.042565	0.000190	0.219476	0.220104
SRL4	0.205989	0.039748	0.000178	0.205696	0.206282
SRL5	0.238691	0.046145	0.000206	0.238350	0.239032
SRL6	0.232428	0.046847	0.000210	0.232082	0.232774
SRL7	0.224718	0.049876	0.000223	0.224350	0.225086
COMPOSITE SRL	0.222275	0.040916	0.000183	0.221973	0.222577
N	50000				
CI	90%				
Z	1.65				

These results will allow a more refined analysis of which components are above or below the whole Pods4Rail system' development than what has been stated with the comparison of only the means. *“While COMPOSITE SRL is important, it is also critical to understand the interdependencies of the component SRL to the COMPOSITE SRL”* (Tan et al., 2011). This approach can be done with a comparison not only of the variables' means but also and better with the 90% confidence interval of the means of each variable; in that line, all the means' values in a 90% range of CI, are going to be compared for a more appropriate and realistic conclusions. This approach allows inferences about a population with uncertainty from a determined number of samples.

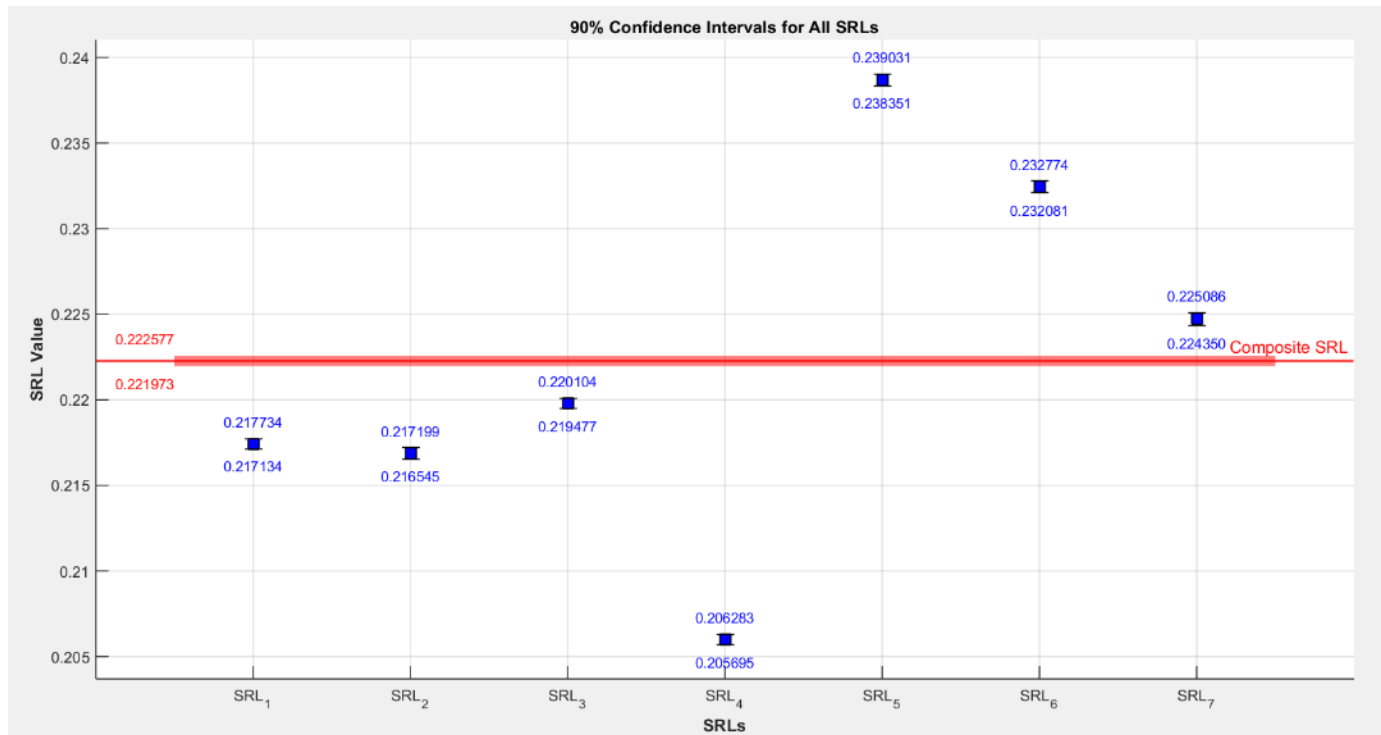


Figure 37: 90% Confidence Intervals of variables' means graphic

In Figure 37, all individuals SRLs are represented with their corresponding 90% CI for their respective means. They can be seen as the represented blue ranges including the information of both the lower and upper limit of their CI. For the “principal” variable COMPOSITE SRL, the representation has been done as a full line with a visible range of its 90% CI limits to allow an easier comparison with the other 7 CI.

Note that there are no overlaps between any of the 90%CI-SRL-mean of the seven components with the COMPOSITE SRL one. This confirms the statements that the comparison of only the means (made some paragraphs before) produced. With a consistent opinion, that can be extended to a population since the use of 90% CI of the means, it can be said that components 5, 6, and 7 are above the whole state of development of the Pods4Rail system. On the other hand, components 1, 2, 3 and 4 are behind the maturity of the whole system with component 4 been the one that needs more work to develop individually and achieve a level of development appropriate for the system. The lower level of development of the component 4 (PIS and Incident Management) can be explained by the presence of disturbed operational modes and the unavailability of specific requirements for the appropriate handling of these modes.

- Histogram for COMPOSITE SRL

A histogram has been obtained as it is a bar chart that shows the distribution of numerical data, in this study, COMPOSITE SRL data. The X axis shows the values that COMPOSITE SRL have taken in the run of the code that, as a reminder, included $N = 50000$ samples. These

50000 values are included in a general range that the X axis shows with some values below 0.1 and other few values above 0.35. It is important to highlight that these values are divided into intervals. For this calculation, intervals of 0.005 have been assigned between the edge values of 0 and 0.4.

The Y axis shows the frequency of the values that belong to a certain interval in the X axis; note that the highest value of frequency belonging to a certain interval does not reach 2500.

The histogram also includes two vertical red lines indicating both percentile 5% and percentile 95%. Percentile 5% equals to 0.15 and percentile 95% equals to 0.29. In consequence, it can be stated that 90% of the COMPOSITE SRL values belong to the range between 0.15 and 0.29.

In consequence, according to the theory, COMPOSITE SRL or, in other words, the System Readiness Level of the Pods4Rail system is between SRL1 (Concept refinement) and SRL2 (Technology Development) stages according to Appendix 3.

It is important to highlight that the individual analysis of this histogram does not include a confidence interval (CI) since it focuses on a single parameter. This parameter, in turn, represents the arithmetic mean of the other seven variables (COMPOSITE SRL). The histogram provides more detailed information about this parameter and its behaviour within the sample not an extension to a population.

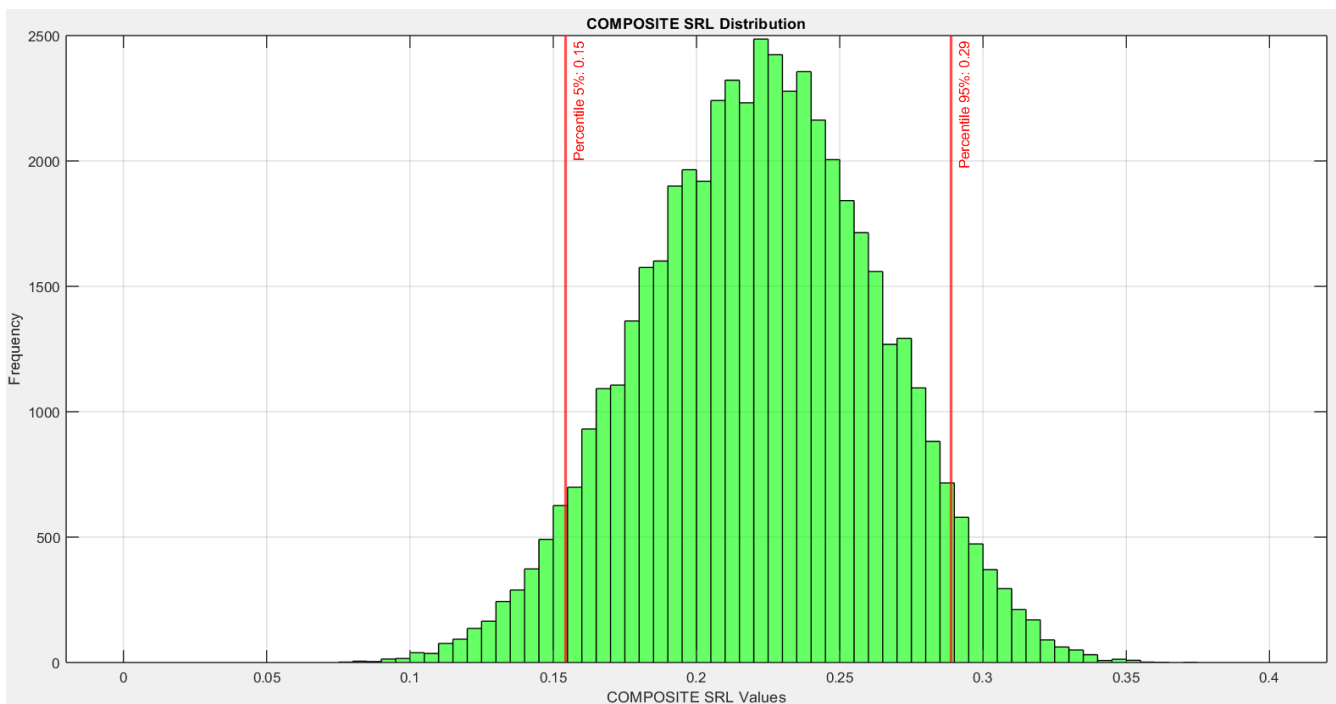


Figure 38: COMPOSITE SRL Histogram

With the presented results and graphics, the question arises of how the analysis of COMPOSITE SRL differs when using a 90% Confidence Interval (CI) versus a histogram.

When analysing a single variable, data interpretation can vary depending on the type of visualization used.

A histogram allows us to observe the distribution of values within the sample. Additionally, it provides insight into data dispersion and concentration without making statistical assumptions, making it a fundamental tool for exploratory analysis, as it focuses on the sample itself.

On the other hand, a confidence interval (CI) for the mean provides an estimate of the variable's average value in the population. In this case, the objective is not to describe the variability of individual data points but rather to determine how precisely we can estimate the population mean based on our sample. However, this approach (CI) does not provide information about the entire data distribution, only the mean and its margin of error. In that sense, the CI has been used solely for a realistic comparison of the range of means across the seven component SRLs and the COMPOSITE SRL. Nevertheless, it is important to note that the width of the confidence interval is also influenced by the variability within the sample, with higher variability leading to wider intervals and lower variability resulting in narrower ones.

Nevertheless, although CI analysis has its advantages, given that the Monte Carlo method is being applied, the large number of samples already captures the variability of COMPOSITE SRL across different scenarios. Therefore, the conclusions regarding the System Readiness Level of Pods4Rail will be primarily based on the histogram analysis.

- Correlation matrix for the seven individual SRLs

“Correlation, also called as correlation analysis, is a term used to denote the association or relationship between two (or more) quantitative variables” (Gogtay & Thatte, 2017). This analysis is based on the assumption of a linear relationship between variables; this approach matches the Pearson's coefficient theory where a linear relation is expected, and a normal distribution behaviour of each variable is also assumed. It helps to understand how the change in the behaviour of one variable affects the behaviour of the other one. The correlation can take positive, negative or null values.

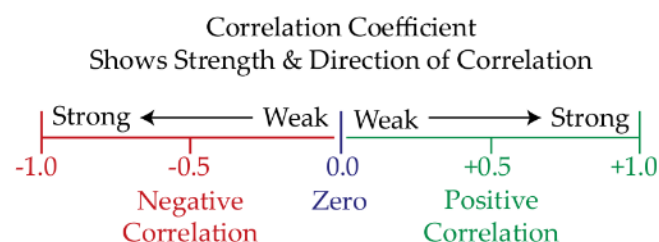


Figure 39: Correlation coefficient's values (Gogtay & Thatte, 2017)

A positive coefficient indicates that two variables have a linear relationship as one variable grows the other one does too. A negative coefficient, on the other hand, indicates a linear with negative slope relationship where one variable grows while the other decreases.

The following array (Equation 12) shows the correlation coefficient between the seven individual components' SRLs. As expected, this matrix is symmetrical since the correlation coefficient between component i and component j must be the same as the one between component j and component i independently of the order of analysis. The diagonal shows a value=1 because the relationship of one variable with itself must have the highest value of Pearson's coefficient since it is perfectly related to itself.

Correlation matrix

—	SRL1	SRL2	SRL3	SRL4	SRL5	SRL6	SRL7
SRL1	1.0000	0.8311	0.8358	0.8387	0.8430	0.8368	0.8307
SRL2	0.8311	1.0000	0.8228	0.8306	0.8242	0.8174	0.8087
SRL3	0.8358	0.8228	1.0000	0.8340	0.8353	0.8270	0.8191
SRL4	0.8387	0.8306	0.8340	1.0000	0.8387	0.8350	0.8299
SRL5	0.8430	0.8242	0.8353	0.8387	1.0000	0.8307	0.8138
SRL6	0.8368	0.8174	0.8270	0.8350	0.8307	1.0000	0.8080
SRL7	0.8307	0.8087	0.8191	0.8299	0.8138	0.8080	1.0000

Equation 12: 7x7 matrix for correlation between individual SRLs

Figure 38 presents the same information as the previous array but in graphical form. In the scatter plot matrix, the relationships between all pairs of variables are positively linear, with a correlation coefficient close to 0.8, indicating a strong interdependence between them.

The diagonal shows histograms representing the relationship of each variable with itself. The histograms suggest that the variables approximately follow a normal distribution. This characteristic supports the validity of using Pearson's correlation coefficient, which assumes a linear relationship between normally distributed variables. However, the justification for using Pearson's correlation coefficient lies in the assumption that the joint distribution of the two variables is normal, not just the individual distributions. This can be visualized as a 3D plot of the two variables, where the normality of their joint distribution is evident. The normality of the data also reinforces the appropriateness of parametric statistical methods for further analyses, providing a more reliable foundation for drawing conclusions.

The cells outside the diagonal display scatter plots of variable pairs. The correlation coefficients in the range of [0.81, 0.84] indicate that all the variables are strongly related. Although the correlation is strong, the components are not fully dependent on each other. This suggests that there is a significant relationship between the variables, but other factors contribute to additional variability that is not captured by the correlation.

Despite the strong correlation observed among the variables, it is important to interpret these results with caution. A high correlation coefficient indicates a strong association, but it does not imply a direct causal relationship between the variables. External factors or underlying dependencies may influence these correlations, meaning that changes in one

variable might coincide with changes in another without necessarily being the cause of those variations.

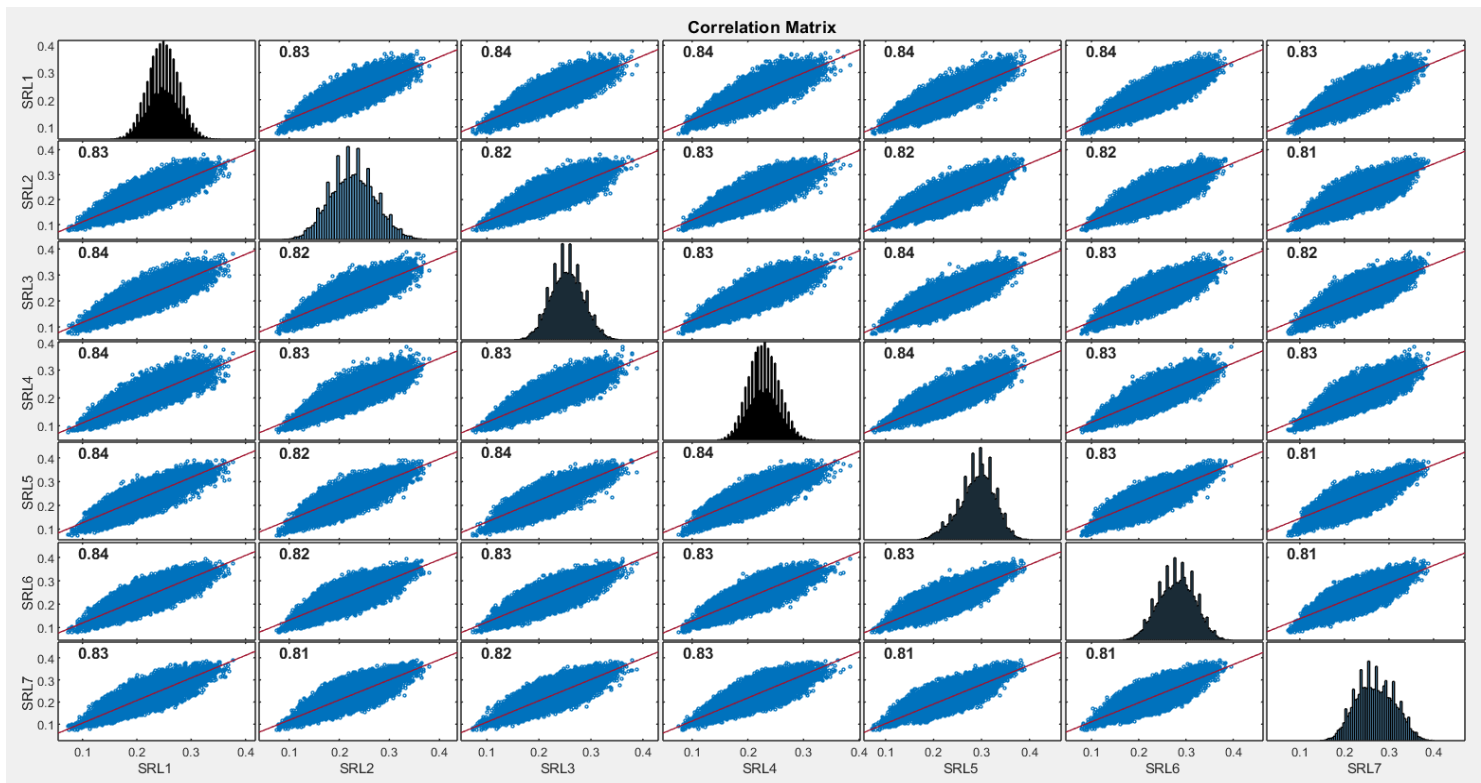
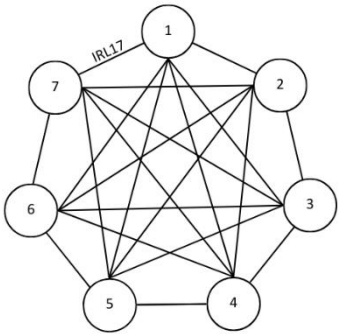
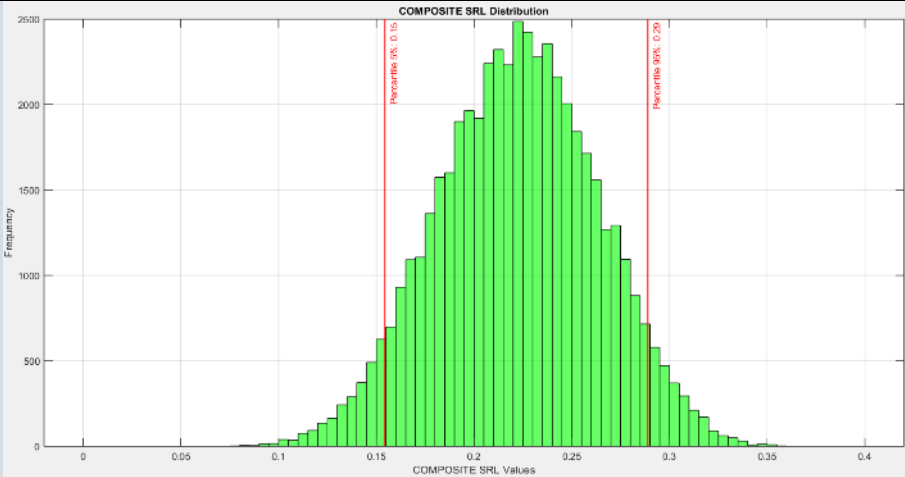
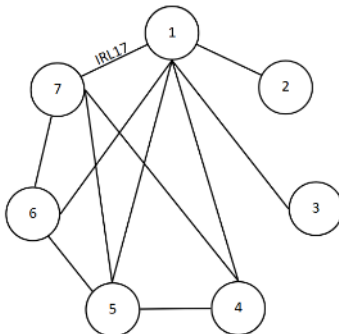
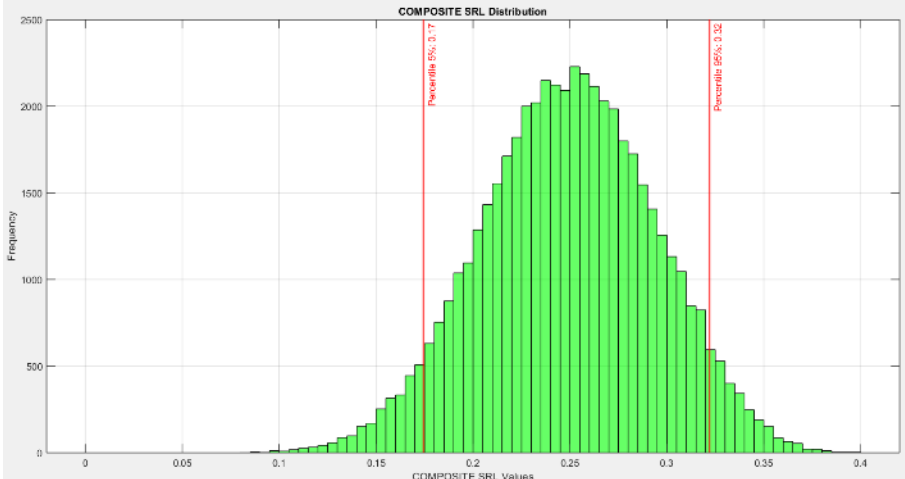
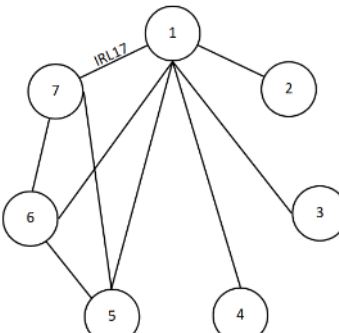
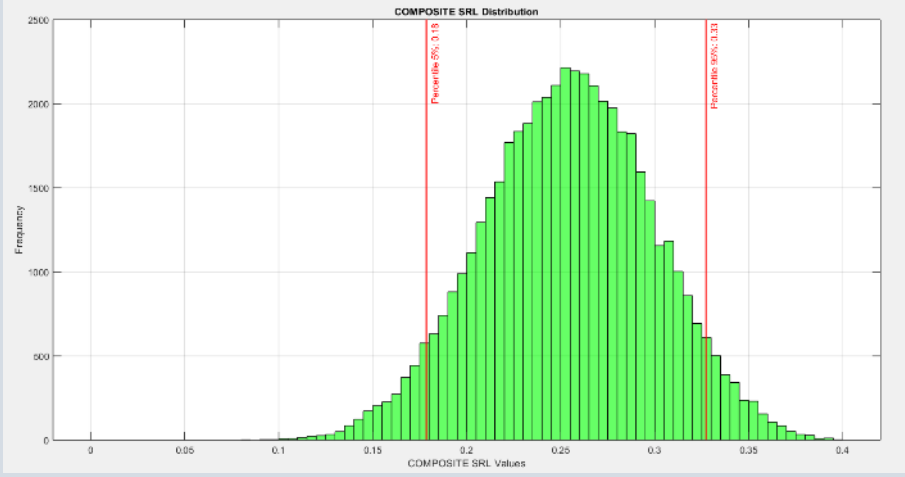


Figure 40: Graphics of correlation between individual SRLs

- Influence of the initial assumption of the interrelationship between the components in the COMPOSITE SRL's results

Three different interrelationships' configurations (including the initial one of Figure 12) have been tested to determine its influence in the percentiles 5% and 95% of the COMPOSITE SRL (whole Pods4Rail's System Readiness Level). In the following Table 21 the comparison can be carried out:

Table 21: Influence of initial assumed interrelationships in the COMPOSITE SRL's results

Assumed interrelationship and percentiles	Composite SRL's Histogram
 - Percentile 5%: 0.15 - Percentile 95%: 0.29	
 - Percentile 5%: 0.17 - Percentile 95%: 0.32	
 - Percentile 5%: 0.18 - Percentile 95%: 0.33	

As observed, the tendency indicates that when fewer connections between components are considered, both percentiles of the COMPOSITE SRL tend to take higher values. In this sense, the initial assumption of interrelationship remains the most conservative and appropriate approach for evaluating the system's overall System Readiness Level.

Despite the observed trend in response to changes in component relationships, at the current stage of the project, the overall SRL of the Pods4Rail system remains primarily near to level 2. At this phase, the system is in a stage of its lifecycle where efforts are focused on reducing technological risks and identifying the most suitable set of technologies to integrate into a fully functional system.

It is important to emphasize that this evaluation is being conducted before the final system proposal is completed. While modifications to the connections between components have been considered, they do not result in significant changes to the system's SRL. As seen in previous analyses, the Pods4Rail's SRL considered percentiles range from 0.15 to 0.29, reinforcing the stability of the system's readiness level despite variations in interconnections.