Rail to Digital automated up to autonomous train operation

D33.2 – Practical Migration Methods Report

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1 EXECUTIVE SUMMARY

Digital and Automated Train Operation (DATO) is central to Europe's ambition to increase rail capacity, improve safety and accelerate the shift toward sustainable mobility. Yet migrating from today's rail systems to higher Grades of Automation (GoA) and digital technologies remains complex, slow and risky. Deliverable D33.2 addresses this challenge by analysing how five various approaches - DevOps, Architecture4evolution, Formal Methods, Theoretical models for People-Oriented Change Management Models and Deployment Strategies and Roadmapping - can support practical migration pathways.

The European rail migration programmes face long asset lifecycles, cross-border interoperability constraints and the need for sustained collaboration among infrastructure managers, operators, suppliers, regulators and end-users. Earlier work of WP33, presented in D33.1, identified extensive gaps in technical integration, organisational alignment, data quality, certification, human readiness and governance. These gaps were derived from interviews with various stakeholders participating in FP2-R2DATO and similar programmes. This deliverable, D33.2, builds on these findings by examining how the five selected methods can help bridge these gaps, address recommendations and strengthen the foundations for fast and effective deployment within FP2-R2DATO.

The objectives of this deliverable are to analyse the applicability of each method to (DATO) migration challenges and to map each approach to specific gaps and recommendations. In addition, this deliverable aims at providing a structured guidance on where methodological support exists and where human-driven action remains essential. Moreover, this deliverable offers insights relevant not only to FP2-R2DATO but also to the System Pillar, future ERJU waves and other projects even outside EU-RAIL.

We first evaluate how each method and its principles can support practical migration. In particular:

- DevOps contributes to continuous integration, shared ownership, version control and rapid feedback loops.
- Architecture4evolution promotes modular, evolvable software architectures that can accommodate change and support long-term interoperability.
- Formal Methods provide precision, traceability, early error detection and a foundation for modular certification and harmonised interface definitions.
- Theoretical models for People-Oriented Change Management explains how acceptance, readiness, leadership behaviour and communication play a role in the success of technological transitions.
- Deployment Strategies and Roadmapping integrates all layers (e.g., technical, human, operational, tactical, regulatory, strategic) and offers a structured, scenario-based migration that integrate SWOT, multi-disciplinary impact assessment, stakeholder engagement and long-term coordination including uncertainties.

The analysis systematically maps these methods to 136 gap-recommendation combinations, which have been initially reported in D33.1 and further organised in this deliverable. We then identify where each method can meaningfully support effective migration.

The results show that most migration challenges are socio-technical, not purely technical. In particular, 36 recommendations require human initiative where many gaps relate to alignment, trust,

communication, role clarity and human readiness. Another set of 47 recommendations depend on human initiative as well, with support by one or more of the investigated methods.

Formal Methods are especially valuable for clarity of requirements, interface definition, certification, and interoperability. The Deployment Strategies and Roadmapping Framework encompass all models as they can be integrated as supportive tools within the framework. This supports multi-stakeholder alignment, scenario planning, and long-term migration coherence. DevOps and Architecture4evolution help modernise development and integration practices. They support continuous integration, modularity, and evolvability, critical for future DATO systems that must update far more frequently than traditional rail assets. Theoretical models for People-Oriented Change Management addresses gaps related to organisational and individual readiness.

Eighteen recommendations are identified to be specific to FP2-R2DATO, such as developing a long-term, system-of-systems DATO integration plan that covers signalling, onboard systems, operational rules, traffic management and safety-case requirements across their full lifecycle. Fifteen recommendations are identified to be directly relevant to the System Pillar. Among them, conducting structured alignment sessions between EU, national and regional authorities to harmonise certification expectations and reduce conflicting interpretations, as well as co-developing synchronised homologation roadmaps to harmonise evidence requirements and reduce divergent interpretations, supported by the Deployment Strategies and Roadmapping Framework.

Overall, D33.2 concludes that no single method can address the full complexity of DATO migration. Instead, a combined approach, integrating technical methodologies with strong human-centred governance, is essential for achieving scalable and cross-border deployment of future train operations. The strategic layer is an overarching framework that can support the determination of where and when the other models and methods can be applied. The integration with other methods directly supports policy, regulation, and stakeholder alignment.

ABBREVIATIONS AND ACRONYMS

ATB	Automatic Train Control (Dutch)
AHP	Analytic Hierarchy Process
ATO	Automatic Train Operation
ERJU	Europe's Rail Joint Undertaking
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
ETCS HL3	ETCS Hybrid Level 3
FP	Flagship Project within the ERJU Programme
FP1	Flagship Project 1, "Motional"
FP2	Flagship Project 2, "R2DATO"
GoA 1–4	Grade of Automation (Levels 1 to 4)
HL3	Hybrid Level 3
HTD	Hybrid Train Detection
HTD L2	HTD Level 2
IM	Infrastructure Manager
IP	Intellectual Property
IRTC	Individual Readiness to Change
MA	Movement Authorities
MCA	Multicriteria Analysis
MBSE	Model-Based Systems Engineering
OEM	Original Equipment Manufacturer
R2DATO	Rail to Digital automated up to autonomous train operation
RU	Railway Undertaking
SWOT	Strengths, Weaknesses, Opportunities and Threats
SysML	Systems Modelling Language
TAM	Technology Acceptance Model
TE	Technical Enabler
TIMS	Train Integrity Monitoring System
UTAUT	Unified Theory of Acceptance and Use of Technology
VSS	Virtual Sub-Sections
WP	Work Package

DEFINITIONS

Architecture 4evolution
Architecture4evolution refers to methods intended to identify software development tools, methods and patterns and unify them into a single software architecture or harmonised architectural patterns that better suit on-train software systems.

Complexity
A condition arising from multiple interdependent and evolving technical, organisational, human, and regulatory elements, generating uncertainty and risk, particularly in early project phases.

Deployment Strategies and Roadmapping Framework
A methodological framework that provides a structured, sequenced approach to long-term implementation that integrates technical, organisational, regulatory, and human factors to guide the staged introduction of new systems or capabilities. It provides a coordinated way to assess migration options, compare alternative pathways, sequence activities over time, and align stakeholders around shared priorities and assumptions. By combining scenario analysis, dependency mapping, risk evaluation, and multi-stakeholder governance, the framework creates a coherent method that adapts as conditions evolve, ensuring that complex transformations, such as DATO migration, progress in a controlled, transparent, and future-proof manner.

DevOps
Term used to signify the merge of software development (Dev) and IT operations (Ops).

Digital and Automated Train Operation (DATO)
Technologies and operational concepts enabling higher Grades of Automation (GoA) in railway systems, including onboard automation, traffic management, communications, and associated organisational and regulatory arrangements.

Digital Map
A Digital Map in the railway domain is a secure, standardised digital representation of the railway infrastructure that includes the exact geometry of the track, the location of physical and virtual balises, and other key reference points required by ETCS on-board systems to validate and interpret train position data.

Digital Transformation (DT)
The process by which railway systems undergo significant technical, organisational, and operational change through the integration of digital technologies.

Formal Methods
Term referring to techniques and tools which are used for the development and analysis of new products.

Grade of Automation (GoA)
Standardised classification of train operation levels from manual operation (GoA1) to fully autonomous operation (GoA4).

Lessons Learned
Structured knowledge derived from experience, used to improve future project performance and prevent recurrence of known problems.

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2 INTRODUCTION

The present document constitutes Deliverable 33.2 (D33.2) “Practical Migration Methods Report” in the framework of the TE20/WP33 of FP2-R2DATO; providing input to TE1 Automating Functions, T9.1 “Analysis of migration and deployment strategies”, from FP2/WP9 “Prototype development of automating functions” and to TE7 Remote Driving, T12.1 “Analysis of migration and deployment strategies” of FP2/WP12 “Prototype development of remote control”. WP33 is part of Cluster 4 ‘Fast and Effective Deployment’ of FP2-R2DATO.

Technology migration in the railway sector on an inter-European scale is a long and risky road. For it to be smooth and successful, sustaining cross-border and cross-company collaboration for a longer period is required. Participants of WP33 recognised that apart from the many technical challenges that you will find along the way, success also depends on long term willingness and a certain level of risk appetite of involved stakeholders, based on the trust that the benefits lie not too far in the future. How to keep all kinds of stakeholders on board in a complex environment while the road ahead is full of uncertainty?

WP33 provides guidelines for migration and deployment strategies for applying DATO technologies from a technical, operational and human-centred perspective. It does so by collecting lessons learned from FP2-R2DATO Demonstrators, State of the Art projects and other technical migration programmes for rail, like ATO and ETCS. Deliverable 33.1 “Migration Strategy Research Report” contains the analysed data that resulted from the research executed by WP33, resulting in an overview of lessons learned, a gap-analysis and recommendations – the guidelines.

These results from D33.1 provide input to a more organised and detailed gap-analysis presented in this Deliverable, in which is shown how models, methods and roadmaps for migration could support bridging the mentioned gaps. This analysis lays the foundation of this Deliverable, D33.2 “Practical Migration Methods Report”. A systematic analysis is presented to show to what extent the models and methods within Cluster 4 ‘Fast and Effective Deployment’ of FP2-R2DATO, bridge the gaps presented in D33.1.

A clarification regarding one particular deviation is warranted. While the Grant Agreement specifies “models for transition to decouple migration from ETCS deployment,” the gap-analysis employs “deployment strategies and roadmapping framework” as a fifth model instead. The models intended to facilitate the transition to decouple migration from ETCS deployment were not developed within the R2DATO project, as the architecture under development for DATO deployment remains fundamentally integrated with ETCS. Furthermore, within Work Package 37, deployment strategies for ETCS HTD (Hybrid Train Detection), formerly HL3, are being formulated. The defined methodological framework and strategies are of significant relevance and therefore merit inclusion and examination in the present study.

The specific objectives of this deliverable (D33.2) are:

- Exploring technologies and methodologies applied already in other domains.
- Exploring Models and methods for transition and migration: DevOps, Formal Methods, Architecture4evolution, People-oriented change management, and Deployment Strategies and Roadmapping Framework.

- Developing a gap-analysis and bridging gaps through the defined methodologies and organising the related recommendations in various combinations.

Chapter 3 provides descriptions of the five theoretical models, which are referenced in the Grant Agreement as foundational elements for the gap-analysis: DevOps, Architecture 4evolution, Formal Methods Deployment Strategies and Roadmapping Framework and models for People Oriented Change Management.

Chapter 4 shows to which recommendations any of the models can be applied and to what extent. Tables are presented to show to which recommendations more than one models can be applied and to which none of the models apply. Subsequently, tables are presented to show which recommendations are specific to FP2-R2DATO, which are especially relevant to the System Pillar and which recommendations require ‘human initiative’.

In Chapter 5 the conclusions drawn from the analysis are presented.

3 DESCRIPTIONS OF METHODS AND MODELS

One of the main goals of the FP2-R2DATO is to investigate how we can speed up and optimise the migration and deployment of DATO. The methods described in this chapter are frameworks that can support faster deployment and improve quality.

3.1 DEVOPS

DevOps is a combination of cultural philosophies, practices, and tools that aim to break down the traditional silos between software development (Dev) and IT operations (Ops) teams. Its goal is to shorten the software development lifecycle and provide continuous delivery with high software quality by emphasising collaboration, automation, and rapid feedback loops. This allows organisations to deliver applications and services faster and more reliably.



Figure 1 Dev Ops Cycle

Key components and practices

- **Collaboration:** encourages communication, cooperation and shared ownership between development, operations, quality assurance and security teams.
- **Automation:** uses tools to automate repetitive, manual tasks, such as building, testing, and deploying software, which accelerates the process and reduces errors.
- **Continuous Integration/Continuous Delivery (CI/CD):** a key practice where code is continuously integrated and tested and then automatically delivered to a production or staging environment. This allows for more frequent and reliable releases.
- **Monitoring and Feedback:** continuously monitors application performance and collects feedback to identify issues early and inform future development cycles.
- **Infrastructure as Code (IaC):** manages and provisions infrastructure through code and automation, making it repeatable, consistent and version controlled.

Benefits of DevOps

- **Faster delivery:** enables faster and more frequent releases of new features and updates.
- **Improved reliability:** reduces service interruptions and improves stability through continuous testing and monitoring.

- **Increased efficiency:** automates manual tasks and streamlines the development-to-deployment pipeline.
- **Better collaboration:** breaks down team silos, leading to more effective teamwork and shared goals.
- **Enhanced security:** can be integrated into every phase of the lifecycle.

Software development in the Rail Domain

Rail industry and rail operators face serious challenges that result in conflicting time scales for operations (long, with the need for adaptations and changes over decades) on the one hand, and realisation of new features and fixes (short, shall be brought into the field much faster than today) on the other hand. Therefore, WP29 is investigating what the rail industry can learn from the DevOps methodology for a quicker realisation of new features and fixes.

Software engineering in the rail domain is uniquely challenging because it is tightly integrated into a broader systems engineering environment and governed by strict V-model processes and legal homologation. Rail software must operate reliably for decades, requiring ongoing updates while dealing with hardware obsolescence and rail-specific hardware constraints. The industry is seeing a rise in the number and complexity of IT systems, but development remains a low-volume, multi-project solution business rather than a scalable product business.

Despite the differences between the rail world and the non-rail world, there are many of the same drivers for DevOps to be implemented.

- Improve engineering efficiency.
- Reduce time-to-market for new features and changes.
- Overall increase the evolvability of on-train software systems.

This motivates to investigate IT-DevOps principle and methodologies and how these could be adapted to the rail domain.

3.2 ARCHITECTURE4EVOLUTION

Architecture4evolution intends to identify software development tools, methods and patterns and unify them into a single software architecture or harmonised architectural patterns that better suit on-train software systems. The core interest in performing this exploratory work is to circumvent the inflexibility of long-living legacy systems employed by the railway sector by allowing software architectures to evolve within tightly constrained environments, which are usually governed by safety and security standards and mission-critical software and hardware components.

The design goals for Architecting4Evolution include:

- Design software modules and services as autonomous units.
- Encapsulate uncertainty, risk and change.
- Minimise the need for explicit adaptation.

The resulting software architecture must tolerate change in the long run with features that are characterised by their:

- Ease in integrating new features while discarding old ones.
- Ease of migration among versions, version updates, and during the incorporation of new technologies.
- Ease of supporting new deployment strategies that account for multivariable scenarios.

Change is considered the most harmful agent during software and systems development in the railway industry. To make change more manageable, the initiative intends change to become the cornerstone of the resulting software architecture with the following design goals for it:

- Single Responsibility Principle – a single reason for changing a software component, module, service or interface must remain univocal. The scope or granularity of this 'single reason' should be able to scale with the scope of the unit under consideration for changes.
- Open-closed principle – Software assets and interfaces can be extended but their core must remain unchanged.
- Interface design will follow the Liskov Substitution Principle, such that an entity may be replaced by a functionally extended version of itself.
- Be aware of implicit and explicit coupling and reduce the grade of coupling where possible.
- Encapsulate uncertainty, risk and change. Choosing between A and B loses relevance against the fact that choosing between A and B is possible. In other words, guaranteeing alternatives and options for each decision becomes a dogma.

To conclude, the expected result of Architecture4evolution is software architecture comprised of multiple software development practices, methods, tools and principles that guarantee that change is manageable. The benefits of its implementation include more flexibility, affordability (due to a reduced software development overhead), efficiency, and security that are provided by compatibility layers that modernise legacy software with the most modern execution environments.

3.3 FORMAL METHODS

Formal methods are rigorous techniques and tools which are used for the development and analysis of new products, starting from the specification phase until the implementation. In the railway sector, the application of formal methods is not yet very widespread, but it is becoming more important due to the increasing complexity and safety requirements of modern railway systems.

The core value of formal methods in the railway sector lies in their ability to deliver consistent, repeatable and traceable processes. These tools facilitate the management and tracking of requirements from the earliest stages through to validation and final system verification. In ATO projects, where multiple systems and interfaces must interact reliably across different countries and technical contexts, such precise modelling and traceability are essential for technical harmonisation and interoperability.

Another clear benefit is the ability to catch errors and ambiguities early in the development process, which can save time and resources during later testing and certification phases. Formal methods support the modelling of business rules, data architectures and interfaces, thereby enabling

automated checking, simulation and validation of design choices. This not only streamlines the development of new systems but also aids in the migration and retrofitting of legacy rolling stock and trackside equipment, facilitating the transition to modern, digitalised railway operations.

Formal methods help to make requirements more precise and reduce the risk of misinterpretation, which is important for harmonisation and for ensuring that the developed systems meet the necessary specifications.

A key application in railway is the automated authorisation of systems. Here, formal models are automatically generated from system specifications (e.g., SysML models). These models are then used for automatic verification and validation. This process not only increases confidence in the correctness of the system, but it also supports the development of standardised safety assessments, potentially reducing time, cost and effort in system approval processes.

It is important to highlight that formal methods can be applied at different stages of the system life cycle, from the early specification to the verification and validation phases. Although the use of formal methods requires some investment in training and tools, this cost is often justified by the reduction of errors and the improvement of safety, especially in safety-critical railway applications. The migration from traditional text-based specifications to model-based and formal methods is a key step for the railway sector to improve reusability and safety and reduce time to market.

Demonstrators and practical examples have shown that formal methods can be successfully integrated into railway projects, supporting the development of reliable and safe railway systems. However, it is also necessary to address the mindset and acceptance of formal methods among engineers and stakeholders, as there are still misconceptions that formal methods are only for experts or mathematicians. Therefore, a clear introduction and guidance on how to start with formal methods is essential for a successful migration in the railway domain.

In ATO projects, where multiple systems and interfaces must interact reliably across different countries and technical contexts, such precise modelling and traceability are essential for technical harmonisation and interoperability.

3.4 THEORETICAL MODELS FOR PEOPLE ORIENTED CHANGE MANAGEMENT

This section explores how to successfully implement ATO and other digital tools in skilled professions such as train driving. It integrates theories from organisational change and technology acceptance to explore the factors that help employees effectively embrace and use new automation technologies.

Organisational change involves making lasting adjustments to a company's operations to remain competitive and effective amid evolving circumstances. Research indicates that most organisations undergo substantial change every four to five years ([i]Rafferty et al., 2012). Yet, many change efforts fail: between 40 and 70 percent do not meet their objectives ([ii]Freisinger & McCarthy, 2024). Although there is no single best approach to managing change, understanding employees' attitudes and readiness is crucial to improving the chances of success ([iii]Holt & Vardaman, 2013).

Digital transformation poses an even greater challenge, as it requires fundamental changes to business processes and models ([iv]van Dun & Kumar, 2023). Employees play a central role in this transition, since their acceptance and adaptation to new digital tools are essential ([v]Szőts-Kováts & Kiss, 2023). Failures often arise when organisations fail to influence employees' perceptions of

change. Leading consultancy reports highlight the importance of combining technology with human skills to drive growth and efficiency during digital transformations ([vi]PwC, 2017; BCG, 2021).

Technology Acceptance: TAM Model and UTAUT Model

Two key models are commonly used to explain how employees adopt new technology:

- The **Technology Acceptance Model (TAM)**[vii] suggests that employees' decisions to use a technology depend on their perceptions of its usefulness (Perceived Usefulness) and its ease of use (Perceived Ease of Use) ([viii]Davis, 1989). The more beneficial and user-friendly the technology appears, the more inclined employees are to accept and use it.

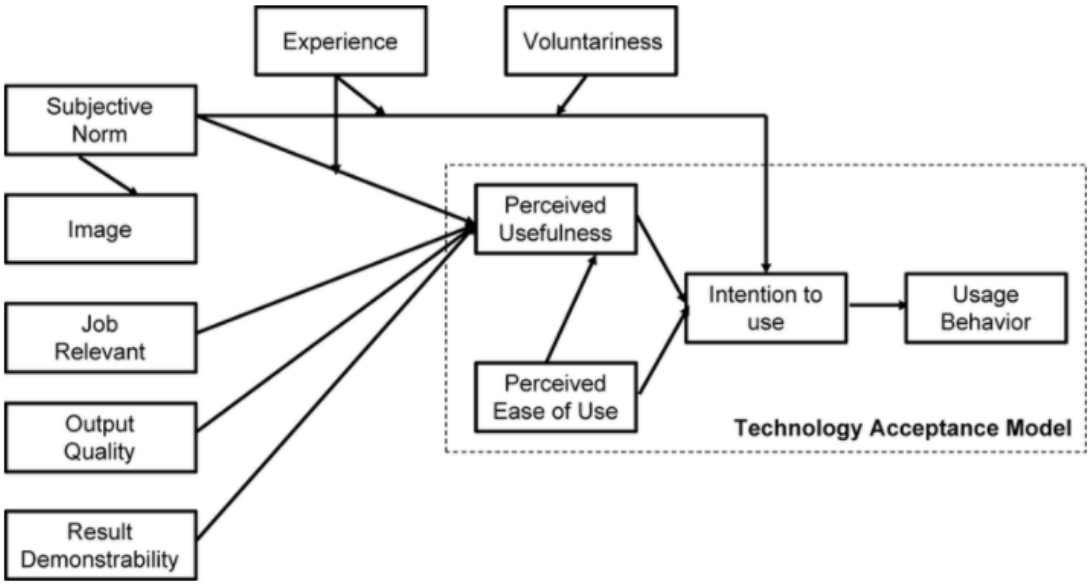


Figure 2 Technology Acceptance Model (TAM)

- The **Unified Theory of Acceptance and Use of Technology (UTAUT)** developed by Venkatesh et al.[ix] (2003) integrated eight prior models, including the Technology Acceptance Model (TAM), to identify four key determinants of technology acceptance:
    1. **Performance Expectancy** refers to the degree to which an individual believes that using the technology will improve their job performance or yield valuable outcomes. It reflects the perceived usefulness of the system.
    2. **Effort Expectancy** captures how easy or difficult the user perceives the technology to be, including the simplicity of use and the mental effort required.
    3. **Social Influence** encompasses the degree to which users perceive that important others (e.g., colleagues, supervisors) think they should use the technology, emphasising social pressure and normative beliefs.
    4. **Facilitating Conditions** describe users' perceptions of the organisational and technical infrastructure available to support the use of the technology, such as resources, knowledge, and compatibility.

UTAUT also incorporates moderating variables such as age, gender, experience, and voluntariness of use. These moderating variables influence how these determinants affect behavioural intention and usage, thus providing a nuanced understanding of technology acceptance across diverse user groups and contexts (Venkatesh et al., 2003;[x] 2012).

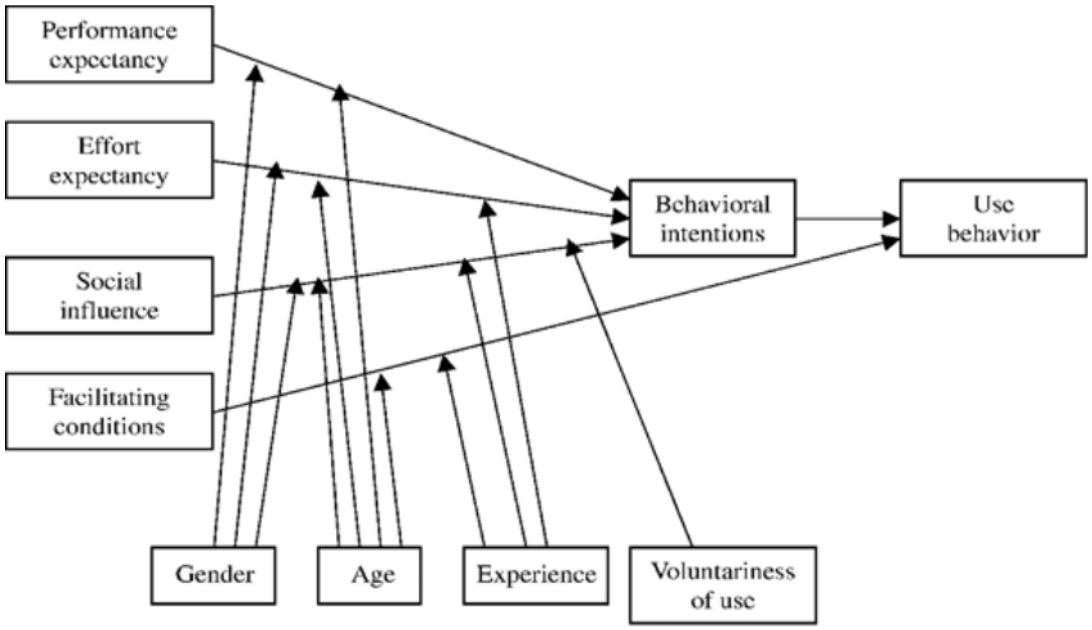


Figure 3 Model of Unified Theory of Acceptance and Use of Technology (UTAUT)

These models show that for effective ATO integration, technology must be both user-friendly and perceived as improving job performance and supported by the organisation and colleagues.

Individual Readiness to Change (IRTC)

Readiness for change refers to employees' mental and emotional preparedness to embrace a change ([xi]Armenakis et al., 1993). This readiness is influenced by how the change is communicated, the specific nature of the change, and individual differences among employees ([xii]Holt et al., 2007). Through close working relationships, employees often develop shared attitudes that shape their collective readiness ([xiii]Rafferty et al., 2012). A positive level of readiness helps reduce resistance and enables smoother adaptation to new tools, such as ATO systems ([xiv]Vakola, 2013).

The Role of Leadership

Leaders have a vital role in guiding employees through change by clarifying the process and helping them understand what to expect, thereby reducing uncertainty and frustration ([xv]Kraft et al., 2018). The attitudes and behaviours of leaders significantly influence employees' feelings about change. When leaders demonstrate trust, support, and enthusiasm, employees tend to be more open and ready to accept new technologies ([xvi]Hartge et al., 2015).

Two leadership styles are particularly effective in boosting readiness for change:

- **Ethical Leadership**, which builds trust and positive relationships between leaders and employees ([xvii]Metwally et al., 2019).

- **Transformational Leadership**, which inspires and motivates employees, enhancing their confidence and willingness to embrace change ([xviii]Peng et al., 2020).

Leaders who actively promote change and remove barriers facilitate employees' adoption of automation and digital tools ([xix]Adil, 2014).

3.5 Deployment Strategies and Roadmapping Framework

A deployment strategy ensures that what works becomes operationally adopted, business models are viable, risks are mitigated, and organizational change is managed. A roadmap is used as a strategically flexible tool to visualize timelines and priorities of market trends, actions and steps towards the deployment of HTD. The most general and flexible approach to develop roadmaps is a visual time-based, multi-layered chart that enables several functions and perspectives to be aligned. Three key questions must be answered for any coherent strategy: where do we want to go, where are we now, and how to get there.

The first step to design a roadmap is to define objectives and a common vision (i.e. where we want to go). This can correspond to the EU vision in addressing demand and consequently increasing railway capacity, reducing CO_2 emissions and decreasing lifecycle costs. The second step consists of understanding the current situation (i.e. where we are now). The third step in-between is the gap-analysis that fits into the strategic management process, when reviewing how well a current strategy is working with the necessary steps and actions (i.e. how to get there). Proceeding on with the current strategy gives rise to a gap that needs to be covered to reach the desired goal. As a result, a knowledge gap arises between what we know from the current state (i.e. the state-of-the-art, definition, scope, etc.) and what we must know to cope with the future changes and decide which direction/scenario to follow.

Figure 4 displays the deployment strategies and roadmapping framework. Outcomes from a SWOT analysis, a multi-criteria analysis (MCA) and expert judgement are used as input to define the step-changes for the deployment strategies. The SWOT is used as input for strategic planning as it provides a clear overview on what we can do in a current situation by taking the knowledge in the current state into account. The SWOT results are therefore used to develop the strategies and generate ideas on how to close the gaps by identifying step-changes in the operational, technological and business domains to ultimately serve a roadmap. To develop a good strategy, we need to build on the strengths, address or remedy the weaknesses, grasp the opportunities, and avoid or minimise the threats. The MCA provides a structured way to compare options such as different deployment sequences (e.g., freight first vs. passenger first), different technical pathways (e.g., HTD vs. ETCS L2 readiness), different organisational approaches (e.g., centralised vs. decentralised testing), etc. The combination of the identified criteria weights from the MCA and the SWOT results, both based on expert judgement, help to determine which actions unlock the most value early, which dependencies must be resolved before others, which steps carry the highest risk if delayed and where readiness gaps are the largest.

The relations between the four elements in the 'Step-changes' box of Figure 4 are based on three components: the core (middle text in each box), the aim (the upper text in the oval) and an identifier (the bottom text in each box). The connections between those elements are explained as follows:

1) We define the 'Do know' because we aim at understanding the definition and scope of the strategy that we want to build. To do that, we need to investigate what we know in the current state to be able to build what we can do (knowledge strategy link).

2) We define the 'Must know' because we aim at a certain direction by looking at what must be known. To do that, we need to understand why there is a need for new knowledge. This is an identifier to determine the 'Must know' based on what we do know.

3) We define the 'Can do' because we aim at having an overview of the current strategy to be able to build a futuristic one. To do that, we need to understand what can be done in the current state. The “Can do” element can be affected by threats encountering a certain technology as they can engender business risks that hamper the effective development of an application roadmap.

4) We define the 'Must do' because we aim at building an action plan that leads to the desired direction (strategy knowledge link). To do that, we need to look at how we can do what we can do.

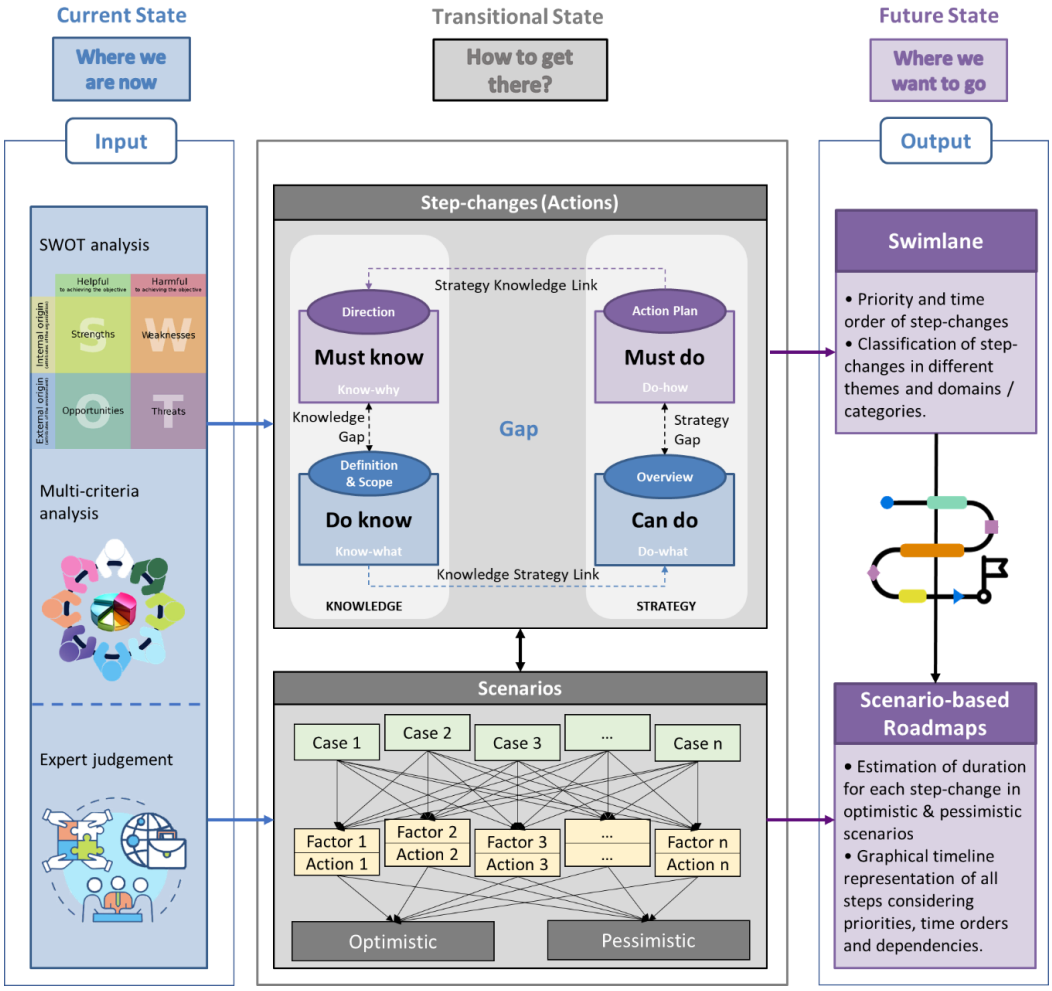


Figure 4 Deployment Strategies and Roadmapping Framework

A strategy gap is the gap between what we must do in the future state and what we can do in the current state. It arises between the current performance and the desired performance towards a common vision and well-defined objectives. The strategy for achieving them stems from what must be done and what we could actually do, given the facts and limitations of the current circumstances. The action plan provides a strategic link to the future knowledge that interacts with the current knowledge state. The scenarios are a collection of plausible future events to assess their impacts over a long-term strategy. The optimistic and pessimistic scenarios in the developed scenario-based

roadmaps vary for each market segment (case) in terms of *(i)* durations for each step-change (action) based on expert judgement, and *(ii)* prediction uncertainties represented by factors related to the market pulls.

The size of the gaps (i.e. how big/important the problem is) is assessed by means of priorities and time order for a set of steps and actions in the operational, technological and business domains. The Swimlane is used as a domain/theme-oriented visualization of roadmap items on dynamic grids where fields can be moved, ordered and prioritized based on stakeholders' feedback. The identification of gaps that stem from the SWOT are addressed by means of the Swimlane through a list of step-changes that are categorized based on defined domains and themes.

Scenarios must be used to design a robust roadmap. Using scenarios in an early stage of roadmapping ensures that risks and uncertainties are considered, and that the roadmap is more robust. A roadmapping process should accommodate those uncertainties associated with forecasts by means of scenario planning or other methods such as a sensitivity analysis.

This framework is flexible and can be applicable to any technology as the proposed approach helps in effectively visualizing a future action plan according to plausible future scenarios. This is particularly important when companies attempt to manage market and technology activities for both strategic planning and technology management. Scenario-based roadmaps can be used as an efficient tool for stakeholders to identify and solve potential criticalities/risks to the deployment of a system, product or technology, as well as to setup investment and development plans. In practice, companies can use the developed deployment strategies or roadmapping methodology at a corporate level for the management of toolkits to foster business growth and organizational changes. The integration of SWOT, MCA, expert judgement, gap-analysis and scenarios in the framework also provides a means for addressing corporate challenges and exploring new opportunities. Moreover, the developed roadmap framework provides a coherent and holistic architecture within the development and evolution of other dynamic businesses or systems where step-changes can be explored, mapped and interpreted based on distinct scenarios. Various methodologies can be integrated within this framework and integrated in modules. For instance, the DevOps method can be used to emphasize collaboration, automation, and rapid feedback loops among various stakeholders. Moreover, embedding theoretical models for people-oriented change-management would make scenario-based roadmaps more robust from a technical/strategic point-of-view and more actionable. Formal methods are beneficial in the assessment of the multi-criteria analysis, allowing for more reliable and reproducible results. Therefore, the methodology developed in this section is generic and can be adapted to different systems and business processes and integrated to other management frameworks and disruptive technological game changers.

An example of the application of the Deployment Strategies and Roadmapping Framework within ERJU can be found in WP37 "ETCS HTD Deployment strategies" [xx][D37.1].

ETCS HL3 or HTD (Hybrid Train Detection) is a railway signalling concept aimed at increasing railway capacity and efficiency while maintaining safety. HTD combines the ETCS L2 functionalities to enable gradual migration and compatibility with different train types. HTD uses virtual sub-sections (VSSs) to divide track segments into smaller blocks, allowing for the release of the VSSs more precise train tracking for trains with TIMS (Train Integrity Monitoring System) and supporting movement authorities (MAs) for all trains (i.e., with or with various equipment types, e.g., TIMS, ERTMS without TIMS), and non-ERTMS trains. Train location is determined through a combination of onboard systems and trackside detection. Train integrity is verified either onboard (via TIMS) for

trains equipped with TIMS or by the trackside systems for all trains. The main challenge of this approach is ensuring safe and reliable detection for all types of trains.

Within R2DATO, Work Package 37 aims to develop strategies that accelerate the deployment of HTD, helping to avoid costly infrastructure upgrade investments. Using ETCS and existing trackside detection systems, the objective is to define optimal implementation strategies, with a focus on the 2025–2030 period. These strategies will serve as tools to help infrastructure managers increase line capacity while reducing development time and operational costs.

WP37 focuses on standardisation and deployment of HTD, in close alignment with the System Pillar. It also involves the optimal line signalling engineering modelling through simulations in collaboration with FP1 WP8/9 and on evaluating the HTD application from both the product and project development lifecycle perspectives, including the generic and specific applications, and the cost analysis.

The deployment strategies methodology developed in FP2 WP37 is built on various components and methods. Figure 4 illustrates the framework developed to design deployment strategies based on a SWOT, a multi-criteria analysis (using the hybrid Delphi-AHP (Analytic Hierarchy Process) method) and expert judgement. The gap-analysis consists of determining the step-changes to be taken to migrate from a current state to a desired future state.

4 GUIDELINES FOR PRACTICAL IMPROVEMENT OF MIGRATION METHODOLOGIES

In this Chapter gaps and recommendations are listed that were taken from D33.1 and which are based on the lessons learned taken from the research data. The List of Tables (p.10-11) can be used to jump to any of the tables.

Paragraph 4.1 presents the main take away reflections and insights resulting from the interviews with Work Package Leads of WPs 29, 30, 31 and 37, the WP's within FP2-R2DATO that have (further) developed the studied methods for the rail sector. Reflections on Theoretical models of People Oriented Change Management have been added to this document specifically.

Paragraph 4.2 summarises all gaps and recommendations, in separate tables: one per category/topic. Each gap-recommendation combination is numbered. Some numbers are reoccurring, since one gap can be resolved by more than one recommendation. Therefore, a letter is added to the number to be able to easily distinguish between them. In paragraph 4.3 the next steps in the analysis are taken: the methods are plotted on the gap-recommendation combinations, giving insight into which method could help address which gap by supporting the recommendation, and to what extent.

4.1 REFLECTIONS ON THE METHODOLOGIES

Reflections on DevOps

Implementing a DevOps-based methodology in a railway environment faces several challenges, like:

- Strict regulations and homologation procedures limit flexibility.
- Inter-organisational collaboration is difficult due to credentialing, IP concerns and siloed processes.
- Legacy systems pose barriers to integration and adaptation.
- Lack of risk assessment and unclear goals regarding legacy infrastructure adaptation.

DevOps as a methodology is flexible, automation-driven and experimentation-friendly. Railways, however, are characterised by e.g. heavy regulation and long asset lifecycles. These conditions restrict the input DevOps normally relies on (e.g., rapid changes, modern interfaces, modularity, cross-team autonomy). Mentioned limitations are therefore contextual, not methodological.

Reflections on Architecture 4evolution

A software architecture should mitigate risks of "losing money", facing problems towards migration to updates or new versions that need an intensive effort/cost.

Another big risk is losing balance between excessive modularity and performance, that makes it not achieve requirements. Over-granularity is a linked risk to performance.

The need to agree on specific technology, or at least on protocols is a challenge because each party involved has its own wishes.

The use of different protocol versions, even when standardised and open source, can create incompatibilities. Since there are interfaces and adapters between different communication protocols, that is one of the main problems.

The most significant risk identified in WP29 is the challenge of achieving certification for safety-critical systems. Certification is done in the latest phase of the life cycle.

A practical mitigation strategy: instead of certifying entire architectures (whole projects) that can be done at the end, it is proposed, in the beginning when a specific technology is selected, to stack and test it and certified through small, representative examples. This approach helps assess feasibility and reduce effort.

Reflections on Formal Methods

The most critical lessons learned are that successful migration and deployment of ATO technology depend on adopting Formal Methods early to reduce ambiguity, manage risks and ensure system safety. Organisational openness to model-based approaches and proactive change management are vital for overcoming resistance and achieving consistent implementation. Technically, standardising tools and specifications, along with bridging diverse modelling environments, is essential for interoperability. Clear and comprehensive requirements alongside rigorous risk analysis and early demonstrators support smoother transitions and foster stakeholder acceptance.

For future migration projects, it is recommended to adopt model-based and formal specification methods from the outset, foster early and close stakeholder collaboration, invest in training and organisational change management, and prioritise interoperability through standards, executable models, and common guidelines. Demonstrators and case studies should be used to build practical confidence in Formal Methods, while harmonised processes should support scalable, future-proof solutions across borders and domains.

Applying tools based on Formal Methods can help to establish:

- Clear and testable specifications (which are essential to avoid misunderstandings and ambiguities that can derail technical harmonisation efforts)
- Early detection of errors (which will reduce the risk of costly late-stage fixes)
- Modular and scalable solutions with well-defined and testable interfaces (which will help managing complexity and costs of migrating ATO systems)

Essential for successful application of Formal Methods based tools:

- Complementary organisational roles from the start: involving roles such as safety managers early in projects is important to ensure that formal method processes align with safety requirements and regulatory demands.
- Transparency and trust among suppliers: to be able to develop interoperable subsystems, there is a need for trust and openness between suppliers, which is a political and commercial challenge.
- Open and formalised - but non-binding - specifications: having an open, formalised framework on the table gives suppliers and operators a reference point to plan development and mitigate risks, acting as a fallback option.

Reflections on Theoretical models for People Oriented Change Management

The models explained in Chapter 3.4 focus on acceptance of new technologies, the readiness for technological change. These models shed light on the various factors (technological, organisational,

psychological and social) involved in the development of readiness. Even though the described models and concepts help to better understand what kind of obstacles for readiness could prohibit smooth migration, they do not offer practical guidelines as such.

What has become clear from the lessons learned gathered by WP33, is that engagement of end-users – mainly train drivers, in case of ATO migration – is beneficial to migration efforts for many reasons. Next to providing valuable input for technical development, engagement early in the change process builds trust and can help to create a sense of ownership among end-users. If ownership grows, this will help create acceptance of the new technology across the board.

Clear and honest communication about the road ahead, fed by continuous conversation between stakeholders (especially train drivers), also helps building trust among end-users.

Communicating transparently and engaging end-users fully are not to be seen as tricks to be used to achieve smooth migration. A culture of trust and pro-transparency mindset within and between organisations are required. Involving Change Management expertise in migration programmes can help to outline an acceptance supporting approach and to guide teams and managers to adopt behaviour that is in line with this culture and mindset. Change management interventions alone will not suffice to ensure such behaviour if it is not institutionalised in governance and management.

Reflections on Deployment Strategies and Roadmapping Framework

The implementation of HTD implies migrating from current signalling systems and various baselines/benchmark systems. Therefore, the migration and deployment strategy must adapt to different baselines (e.g., ATB, Class B, ETCS L1, greenfield) and market segments (high-speed, mainline, urban, regional, freight, etc.).

Early and continuous engagement of diverse stakeholders, including infrastructure managers, railway undertakings, suppliers, manufacturers, the ERA and the System Pilar ensures relevance, credibility and unbiased results.

The cost-benefit distribution of the HTD technology is uneven between Infrastructure Managers (IMs) and Railway Undertakings (RUs). When benefits mainly favour the IMs, RUs often bear most of the costs. A multi-criteria analysis can support a more balanced stakeholder alignment.

Given that the capacity simulations required for WP37 are being developed within FP1 WP8/9, delays in the delivery of WP8/9 are considered a critical path risk that will directly impact subsequent work packages and the overall project timeline. Therefore, effective anticipatory planning and proactive schedule management are essential for mitigating (future) projects interdependency risks.

The core methodology developed in WP37 is highly versatile and applicable to any other technology or system. HTD may be an intermediate step, given the rapid evolution of technologies that may shift priorities away from HTD, e.g., migration to moving block. In such cases, alternative solutions must be clearly defined and contextualised based on their specific objectives and operational purposes.

Interoperability challenges arising from diverse national regulations and jurisdictional incompatibilities pose a significant risk to cross-border implementation. To address this problem, centralised coordination (e.g., the European Commission) and standardised documents are needed to avoid regulatory cross-border barriers and ensuring systemic harmonisation across different countries.

4.2 SUMMARY OF GAPS AND RECOMMENDATIONS

Table 1 Strategic Capability & Alignment

nr	Gap	Recommendation
1	Strategic plans were not consistently updated as conditions shifted.	Institute a structured annual roadmap review that integrates regulatory interpretation updates, operational feedback from test corridors, and assessed system maturity, ensuring the plan remains aligned with evolving conditions.
2	While implementation progressed, partners continued to rely on assumptions set earlier, leading to divergence between planned automation levels and actual readiness.	Define capability targets in incremental stages rather than fixed end-states to accommodate changes in signalling dependencies, operational readiness, and technology development.
3	When revisions did not occur, coordination slowed and corrective work increased, revealing that static roadmaps are incompatible with the continuous evolution characterising DATO environments.	Use scenario-based migration assessments to evaluate alternative progression paths, enabling timely adjustment when underlying assumptions shift.

Table 2 Data-Informed Decision

nr	Gap	Recommendation
4	Validation practices differed across partners and datasets lacked consistent traceability and version control.	Maintain a single validated reference dataset for all integration and performance assessments.
5	Test comparisons were occasionally drawn between fundamentally different operational conditions—for example, scheduled services versus inserted test trains—leading to misleading performance interpretations.	Restrict comparative testing to equivalent operational contexts to prevent inaccurately inferred performance differences.
6	The digital map was not always current and missing or outdated data elements directly influenced DATO responses, complicating fault attribution.	Update the digital map and associated register on a continuous cycle, ensuring alignment between trackside configuration, TMS logic and ATO data inputs.

Table 3 Integration-Interdependencies

nr	Gap	Recommendation
7A	Critical interdependencies—especially those involving signalling transitions, braking curves, operational procedures and supplier-specific behaviours—were underestimated.	Develop a long-term, system-of-systems DATO integration plan that covers signalling, onboard systems, operational rules, traffic management and safety-case requirements across their full lifecycle.
7B	Critical interdependencies—especially those involving signalling transitions, braking curves, operational procedures and supplier-specific behaviours—were underestimated.	Introduce early dependency-mapping and interface-control processes, ensuring that all partners identify and review.
8	Several technical decisions were driven by immediate constraints rather than long-term migration logic, leading to incompatible interfaces, duplicated effort and delays in achieving stable ATO–ETCS interaction.	Anchor all major technology decisions to a modular migration roadmap to avoid short-term optimisations that undermine long-term compatibility.

Table 4 Organisational Learning & Performance Maturity

nr	Gap	Recommendation
9A	The absence of a unified learning mechanism contributed to repeated deviations, loss of continuity during staff transitions and delays in refining operational and technical standards.	Establish mandatory learning reviews after every major test, deviation, or integration issue, with clearly assigned ownership and follow-up actions.
9B	The absence of a unified learning mechanism contributed to repeated deviations, loss of continuity during staff transitions and delays in refining operational and technical standards.	Require that lessons directly inform updates to procedures, standards, operational logic and migration planning.
10A	Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams.	Integrate short, facilitated storytelling exchanges after major tests to capture tacit insights before they dissipate.
10B	Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams.	Introduce structured knowledge-transfer mechanisms—such as cross-team briefings and retrospectives—to reduce dependence on individual memory.
10C	Post-test insights were unevenly documented, reflection routines varied	Create an interactive shared cross-partner lessons-learned repository with traceability,

	widely, and several lessons remained siloed within individual teams.	accessibility and consistent documentation requirements.
10D	Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams.	Implement a learning-maturity metric to monitor whether lessons are being captured, interpreted and institutionalised across the DATO ecosystem.

Table 5 Integrated Change & Risk Governance

nr	**Gap**	**Recommendation**
11	Risk escalation and ownership did not consistently align with change decisions.	Define clear escalation paths and decision authorities to ensure accountability when risks evolve across subsystems.
12	Some risks remained embedded in project layers, delaying visibility for operational stakeholders.	Conduct regular cross-partner governance reviews to verify that change and risk remain integrated as the system matures.
13	While structured mechanisms existed, engagement was uneven, and several late adjustments required substantial rework due to absent early synchronisation between change proposals, safety implications, and operational constraints.	Conduct regular cross-partner governance reviews to verify that change and risk remain integrated as the system matures.
14	Work-package risk framing functioned effectively where applied yet was not universal across teams.	Create a unified Change–Risk Board that evaluates every modification with explicit assessment of risk impact and mitigation ownership.

Table 6 Cross-Organisational Alignment

	Gap	**Recommendation**
15	Alignment was initially treated as a milestone activity rather than a persistent operational function.	Maintain continuous alignment cycles with scheduled cross-partner dependency checks.
16	Internal planning assumptions diverged between cycles, interface dependencies were identified too late	Require transparent exchange of plans, constraints, and architectural assumptions to prevent divergence from remaining undisclosed.
17	Interdependency maps across work packages were incomplete or late, increasing the risk of cascading delays.	Introduce alignment indicators to detect early drift in timelines, interfaces, and operational interpretations.

18A	Reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.	Establish a multidisciplinary alignment team spanning engineering, operations, safety, and IT to ensure unified interpretation of system dependencies.
18B	Reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.	Incorporate human-centred transition discussions early to support role clarity and emotional readiness during system evolution
18C	Reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.	Implement a cross-organisational governance protocol with defined roles, escalation pathways, and synchronisation routines.

Table 7 Collaboration, Trust and Shared Delivery

19	Trust degradation emerged when information was withheld, delayed, or mediated through too few individuals.	Adopt structured trust-maintenance protocols, such as joint retrospectives after milestones.
20A	Collaboration fluctuated with interpersonal dynamics instead of being supported by structured trust-maintenance practices.	Develop dependency and responsibility maps to clarify interrelations and reduce resistance.
20B	Collaboration fluctuated with interpersonal dynamics instead of being supported by structured trust-maintenance practices.	Require early cross-functional engagement, including periodic in-person alignment sessions.
21A	Partners lacked structured mechanisms to rebuild trust after setbacks or failed tests.	Develop dependency and responsibility maps to clarify interrelations and reduce resistance.
21B	Partners lacked structured mechanisms to rebuild trust after setbacks or failed tests.	Require early cross-functional engagement, including periodic in-person alignment sessions.

Table 8 Delivery Chain, Supplier Coordination & Co-Design

	Gap	**Recommendation**
22A	The top-down requirements were cascaded without sufficient shared understanding, leading to several interpretations of the "intended system". Co-design procedures lacked uniformity among work packages.	Require joint workshops to interpret requirements and ensure that operators, IM's, and suppliers share a common understanding of functions, assumptions and constraints.
22B	The top-down requirements were cascaded without sufficient shared understanding, leading to several interpretations of the "intended system".	Implement iterative integration checkpoints (minor, frequent releases) to identify divergence early, reduce rework and stabilise interfaces.

	Co-design procedures lacked uniformity among work packages.	
23A	Relationship-building practices were uneven, leading to variable trust levels and communication gaps across supplier teams. The shared understanding of the long-term migration strategy (e.g., GoA4 evolution) was not always aligned across actors.	Integrate suppliers into long-term migration planning so technology choices align with future architectural needs rather than short-term work package constraints.
23B	Relationship-building practices were uneven, leading to variable trust levels and communication gaps across supplier teams. The shared understanding of the long-term migration strategy (e.g., GoA4 evolution) was not always aligned across actors.	Create a formal supplier engagement playbook documenting co-design expectations, communication protocols, and integration responsibilities for future projects.

Table 9 Regulation & Policy

nr	**Gap**	**Recommendation**
24	Regulatory engagement did not always precede design stabilisation, leading to interpretation gaps once system behaviour, safety logic, and interface assumptions had already been fixed.	Establish regulators as permanent contributors in early workshops on requirements definition and safety logic interpretation.
25A	Certification pathways remained largely aligned with long-lifespan rail assets, despite the introduction of digital technologies requiring more frequent updates.	Co-develop certification pathways that clarify evidence expectations, acceptable interpretations, and evaluation milestones.
25B	Certification pathways remained largely aligned with long-lifespan rail assets, despite the introduction of digital technologies requiring more frequent updates.	Conduct structured alignment sessions between EU, national and regional authorities to harmonise certification expectations and reduce conflicting interpretations.

Table 10 Passenger & Public Trust

Nr	**Gap**	**Recommendation**

26	Communication about the benefits of automation and safety principles was not embedded early in the programme.	Develop a dedicated communication plan for passengers and the public, explaining safety logic, benefits, and operational changes in accessible terms.
27A	Technical information was rarely translated into non-expert language, limiting public comprehension.	Use demonstrations, visual explainers, and open events to familiarise the public with ATO/GOA4 behaviour.
27B	Technical information was rarely translated into non-expert language, limiting public comprehension.	Ensure transparency through periodic public updates, shared performance data, and visible evidence of safety assurance.
28	Mechanisms to monitor or respond to public sentiment were limited, and opportunities for demonstrations.	Track trust indicators (public sentiment, feedback, concerns) and integrate them into migration decisions.

Table 11 Inter-governmental Alignment

Nr	**Gap**	**Recommendation**
29	EU, national and regional policies were not consistently aligned in timing, scope or regulatory emphasis, creating uncertainty for long-term planning.	Establish a structured EU–national–regional coordination forum to align strategy, timelines, and migration expectations.
30	Homologation processes differed across borders, with varying interpretations of requirements.	Co-develop synchronised homologation roadmaps to harmonise evidence requirements and reduce divergent interpretations.
31	Cross-border interoperability discussions began too late to harmonise technical and operational assumptions meaningfully.	Begin interoperability alignment early by holding joint workshops to clarify cross-border assumptions, safety logic and interface expectations.
32	Funding windows and strategic priorities were sometimes misaligned, contributing to delays and fragmented rollout trajectories.	Align funding cycles with technical migration phases to enable predictable investment and staged deployment.

Table 12 Community & Local Mobility Actors

Nr	**Gap**	**Recommendation**
33A	Engagement with local authorities and mobility actors often began after	Initiate structured engagement with local authorities at project inception, including

	technical planning, limiting flexibility to adjust test scenarios.	workshops to identify depot, crossing and test-field constraints.
33B	Engagement with local authorities and mobility actors often began after technical planning, limiting flexibility to adjust test scenarios.	Establish a continuous communication loop with local actors (biweekly or monthly touchpoints) to maintain shared awareness and rapid issue escalation.
34	Municipal expectations regarding safety, disturbance and public perception were not consistently integrated into migration planning.	Establish a continuous communication loop with local actors (biweekly or monthly touchpoints) to maintain shared awareness and rapid issue escalation.
35	Operational constraints (crossings, depot rules, noise limits) were not consistently mapped early, leading to rework and rescheduling.	Develop a Local Operational Constraints Map that must be validated and updated with municipal partners before major design or test decisions.
36	Communication cycles with local actors were irregular, reducing shared situational awareness and slowing approval processes.	Co-design test feasibility plans with municipalities to align safety expectations, public communication needs and operational restrictions.

Table 13 Cross-Sector Collaboration

nr	**Gap**	**Recommendation**
37	Engagement across sectors was not consistently organised through a dedicated knowledge-integration programme.	Create a Cross-Sector Innovation Council (CSIC): a standing body linking operators, IMs, OEMs, academia, and technology networks to coordinate innovation agendas and share frontier developments.
38A	Interfaces remained intermittent, leaving suppliers, operators, and research actors to advance innovation separately. This produced parallel work, repeated analytical effort, and missed opportunities to align emerging methods with operational deployment.	Formalise boundary-innovation workshops: conduct structured workshops to translate advances from adjacent sectors (autonomous vehicles, aviation safety, telecom networks) into rail-specific use cases.
38B	Interfaces remained intermittent, leaving suppliers, operators, and research actors to advance innovation separately. This produced parallel work, repeated analytical effort, and missed opportunities to align emerging methods with operational deployment.	Adopt joint pilots with external actors: run small-scale co-development demonstrators with research institutes or tech companies to test frontier solutions before full integration.

Table 14 Systems Engineering & Integration

nr	Gap	Recommendation
39	Systems-integration skills were not systematically retained in-house. Engineering, testing, and integration activities were frequently outsourced during peak phases and associated knowledge departed at contract completion. This loss occurred despite the long operational horizon of ETCS and ATO and the need for recurrent digital updates.	Establish a formal Systems Integration Team (SIT): a dedicated cross-domain group responsible for architecture coherence, interface definition, configuration control, and release governance.
40	Dependence on a small cadre of experts created bottlenecks and repeated upskilling cycles became necessary as external teams left.	Adopt a DevOps-style continuous integration model: introduce incremental sub-releases, enabling frequent, small-scale integration rather than medium-size “integration events.”
41A	With AI-supported logic and software updates occurring far faster than rail asset renewal, internal specialist capacity proved insufficient to support continuous system recalibration and integration oversight.	Use a unified system configuration baseline: maintain a single, source-controlled architecture map (hardware, network, software) accessible to all partners.
41B	With AI-supported logic and software updates occurring far faster than rail asset renewal, internal specialist capacity proved insufficient to support continuous system recalibration and integration oversight.	Institutionalise system-level visibility: require weekly cross-domain integration reviews to monitor impacts across signalling, onboard, network and testing environments.

Table 15 Operational Readiness (Systems Knowledge)

nr	Gap	Recommendation
42	Operational preparation and data quality sometimes did not keep pace with technical deployment.	Co-design test plans with dispatchers and field coordinators to match live network constraints.
43	Limited ability to reproduce identical test runs and irregular digital-map updates reduced reliability of test outcomes and complicated performance assessment.	Create a unified integration team covering signalling, onboard systems, traffic management, and testing coordination.

44A	Continuous synchronisation of operational data and traffic-aware test planning are required to prevent degradation of ATO behaviour and to secure credible validation results.	Use simulation with full operational parameters, including dispatching rules and real traffic behaviour.
44B	Continuous synchronisation of operational data and traffic-aware test planning are required to prevent degradation of ATO behaviour and to secure credible validation results.	Require interface documentation to state operational dependencies and procedural limits.
44C	Continuous synchronisation of operational data and traffic-aware test planning are required to prevent degradation of ATO behaviour and to secure credible validation results.	Hold regular operational–engineering alignment reviews to ensure assumptions remain consistent with day-to-day practice.

Table 16 Interpersonal, Negotiation & Soft Skills

nr	**Gap**	**Recommendation**
45	Soft-skill capabilities varied across partners, creating vulnerabilities in tasks that require cross-organisational agreement.	Develop a structured negotiation protocol for resolving cross-partner conflicts.
46A	Teams struggled to mediate conflicting priorities, facilitate discussions under pressure and distinguish relational tension from technical disagreement. Over-reliance on technical argumentation, without corresponding attention to expectations and trust, limited collaboration.	Require facilitation methods (e.g., joint issue framing, agreement mapping) for all significant disagreements.
46B	Teams struggled to mediate conflicting priorities, facilitate discussions under pressure and distinguish relational tension from technical disagreement. Over-reliance on technical argumentation, without corresponding attention to expectations and trust, limited collaboration.	Mandate interpersonal-skills training for task leaders and WP leads.
46C	Teams struggled to mediate conflicting priorities, facilitate discussions under pressure and distinguish relational tension from technical disagreement.	Focus on diplomacy, expectation management, active listening and multi-stakeholder facilitation.

	Over-reliance on technical argumentation, without corresponding attention to expectations and trust, limited collaboration.	
47A	Progress often depended on a small number of individuals with strong interpersonal abilities, creating bottlenecks and reducing programme resilience.	Document negotiation outcomes with traceable decision logs. This reduces repeated disagreements and ensures continuity even when personnel change.
47B	Progress often depended on a small number of individuals with strong interpersonal abilities, creating bottlenecks and reducing programme resilience.	Require issue owners to verify whether the dispute is technical or relational before triggering formal escalation.
47C	Progress often depended on a small number of individuals with strong interpersonal abilities, creating bottlenecks and reducing programme resilience.	Introduce a formal "alignment session" mechanism before critical milestones. These sessions ensure partners articulate assumptions, constraints and concerns openly.

Table 17 Data, Software & Testing Competence

nr	**Gap**	**Recommendation**
48	Specialised skills in data configuration, software behaviour analysis and validation are sometimes limited and concentrated in a small number of individuals.	Establish a dedicated system-integration and testing team. Similar to a DevOps model, this group maintains configuration oversight, supervises test environments and ensures continuity across releases.
49	The programme demonstrated a structural need for dedicated specialists in GoA 4 configuration integrity across simulation and field environments. Lacking this proficiency, processes slowed and it was harder to identify the source of problems.	Adopt a strict small-increment release strategy. Require that new features or components be introduced in isolated increments to make failures identifiable and manageable. Implement mandatory pre-validation of every component before system integration.
50	A defined specialist track, supported by continuous training and clear role allocation, is required to ensure sufficient capacity for future automated testing and data-centric verification task.	Ensure redundancy for critical simulation and testing infrastructure.

Table 18 Leadership & Training Capability

	Gap	Recommendation
51A	Leadership practices and training provisions were not consistent across teams.	Institutionalise psychological safety practices.
51B	Leadership practices and training provisions were not consistent across teams.	Require leaders to open meetings with uncertainty statements, encourage dissent and normalise the reporting of issues without penalty.
52A	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Embed structured reflective routines.
52B	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Conduct mandatory retrospectives after every major test, demonstration, or release, documenting lessons and actions.
52C	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Adopt transparent decision-making protocols.
52D	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Begin operator and engineer training during early requirements definition, rather than after system development, to reduce resistance and support faster adoption.
53A	Digital role competence development fell behind with technical progress, leaving operators and engineers underprepared for data-driven decision-making tasks.	Develop a forward-looking digital skills framework.
53B	Digital role competence development fell behind with technical progress, leaving operators and engineers underprepared for data-driven decision-making tasks.	Define future competencies for ATO/GoA4 operations, including system integration, data interpretation, testing logic, and automation supervision.
54A	Training remained largely reactive with no shared competency framework.	Begin operator and engineer training during early requirements definition, rather than after system development, to reduce resistance and support faster adoption.
54B	Training remained largely reactive with no shared competency framework.	Create a joint cross-organisational training academy. IM–RU–OEM partners should co-develop simulation-based training to build common situational awareness and technical fluency.

Table 19 Driver & Operator Adaptation Skills

nr	Gap	Recommendation
55	Operators were at times engaged only after major requirements and procedures had been set, limiting their influence on operational concepts and reducing readiness.	Engage drivers and operators from the outset.
56	Training occasionally began after technical configurations were fixed, narrowing preparation for supervision and fallback functions.	Include them (drivers) in use-case definition, requirement reviews, and early testing to ensure operational realism.
57A	Role definition was not always explicit, creating uncertainty about authority and task boundaries.	Implement clear role-framing protocols.
57B	Role definition was not always explicit, creating uncertainty about authority and task boundaries.	Communicate explicitly how the operator's role will evolve (e.g., supervision tasks, fallback responsibilities).
58	Communication on unresolved system questions was sporadic, encouraging informal interpretation.	Create a human-centric adaptation roadmap. Align technical milestones with workforce adaptation milestones to prevent bottlenecks.
59	Feedback channels existed informally but were not consistently integrated into design cycles.	Establish an operator feedback loop. Use structured interviews, test ride-along sessions and periodic workshops to surface concerns early.
60	When the human implications of automation were not addressed, resistance surfaced later in testing, slowing acceptance and diminishing confidence in migration processes.	Communicate uncertainties transparently. Acknowledge what is not yet known to reduce speculation and strengthen trust.

Table 20 Stakeholder involvement

	Gap	Recommendation
61	Access restrictions related to credentials, intellectual property, and siloed organisational processes hinder open coordination.	Engage stakeholders and decision-makers early in the process. Implement a structured and transparent stakeholder engagement process from the start of the project, including mandatory early review checkpoints synchronised with key lifecycle milestones.

62A	Some stakeholders are overrepresented while others are underrepresented, often based on perceived early-stage relevance, which leads to biased or incomplete requirements.	Create inclusive forums for continuous collaboration where roadmaps, deliverables, and risks are jointly defined.
62B	Some stakeholders are overrepresented while others are underrepresented, often based on perceived early-stage relevance, which leads to biased or incomplete requirements.	Use structured decision-making methods (e.g., MCA) to systematically integrate stakeholder priorities and reduce bias.
63A	Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges.	Use structured decision-making methods (e.g., MCA) to systematically integrate stakeholder priorities and reduce bias.
63B	Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges.	Promote open communication while managing confidentiality constraints.
63C	Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges.	Ensure documentation of stakeholder inputs and decisions is accessible to strengthen trust and shared accountability.
64	The uneven or late engagement causes redesign, resistance in later phases, and inefficient migration planning.	Early and sustained alignment significantly improves migration success by limiting redesign and organisational resistance.

Table 21 Adoption of formal methods

	Gap	**Recommendation**
65	Despite clear advantages, formal methods such as model-based systems engineering adoption continues to face cultural and organisational resistance, partly due to the perception that formal methods are overly complex or suitable only for specialists.	Position formal methods adoption as a strategic priority starting at tendering and early design phases.
66	The railway sector lacks harmonised standards and interoperable tooling across suppliers and operators, complicating model exchange and integration. Although other industries	Develop harmonised, interoperable toolchains supported by clear guidelines.

	widely apply formal methods, the railway domain has not yet institutionalised comparable practices.	
67A	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Invest in change management programs that include role based training and internal FM champions to shift organisational culture.
67B	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Use demonstrators and pilot projects to provide tangible evidence of benefits and build stakeholder confidence.
67C	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Collaborate with regulatory and safety bodies to establish formal acceptance criteria and integrate FM into certification processes.
67D	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Emphasise modular design and interface specifications aligned with FM principles to support scalable, flexible migration underpinned by trusted validation throughout the lifecycle.

Table 22 Incremental Certification in Modular Development

	Gap	**Recommendation**
68	There is no widely accepted incremental or component level certification framework tailored to ATO systems developed iteratively.	Establish a structured modular certification route that enables component level approvals and staged integration validation.
69A	Without a consistent modular certification pathway, integration risks build up toward the end of the project.	Select and implement a technology stack standardised across projects early in the initiative and pilot certification on smaller representative subsystems to uncover issues early.
69B	Without a consistent modular certification pathway, integration risks build up toward the end of the project.	Ease the certification of software and tools later in the process since they use the same technology stack.
70	The variety of tools and technologies complicates efficient certification even further.	Select and implement a technology stack standardised across projects early in the initiative and pilot certification on smaller representative subsystems to uncover issues early.

71	Late-stage monolithic certification, unclear communication of certification limits, and uncoordinated approaches amplify these challenges.	Collaborate closely with certification authorities to evolve regulatory processes that acknowledge iterative and modular development practices, reducing time to market and cost while ensuring safety and compliance.
72	Late-stage monolithic certification, unclear communication of certification limits, and uncoordinated approaches amplify these challenges.	Clear documentation and shared understanding of certification boundaries help stakeholders plan and execute migration steps more effectively while minimising rework and delays.

Table 23 Change management

nr	**Gap**	**Recommendation**
73	In practice, change management efforts are often insufficient or fragmented.	Invest in dedicated change management strategies that secure leadership buy-in and provide tailored training across roles.
74	Leadership engagement is limited, role-specific training is lacking and communication is unclear.	Enhance the change readiness in companies by encouraging a culture of openness and collaboration.
75	Demonstrators to showcase the benefits of new methods are scarce.	Leverage pilot projects and demonstrators to demonstrate value and build confidence.
76A	Additional barriers include stakeholder silos, political considerations, intellectual property concerns and regulatory complexity.	Establish clear communication channels and cross-organisational forums to break down silos.
76B	Additional barriers include stakeholder silos, political considerations, intellectual property concerns and regulatory complexity.	Implement gradual integration phases that bridge legacy and new systems to mitigate resistance.
77	Without addressing these human and organisational factors, technical innovations risk poor adoption or underutilisation.	Addressing both culture and technology is essential for sustainable migration and deployment success.

Table 24 Deliverable Dependencies

nr	**Gap**	**Recommendation**
78A	R2DATO needs to keep working towards a harmonised methodology to	Continue to enhance collaboration and communication across work packages.

	model, track and sequence dependencies between deliverables across work packages.	
78B	R2DATO needs to keep working towards a harmonised methodology to model, track and sequence dependencies between deliverables across work packages.	Develop and implement a standardised, project-wide methodology for mapping and sequencing inter-work package deliverables, right from the start.
79A	Communication is sometimes fragmented; ownership of dependencies is unclear, and potential delays can propagate unnoticed.	Establish centralised tools and communication channels for real-time tracking of dependency status and changes.
79B	Communication is sometimes fragmented; ownership of dependencies is unclear, and potential delays can propagate unnoticed.	Assign clear responsibility owners for key dependencies to manage and coordinate delivery proactively.
80.A	Risks of duplicated work, overlooked interdependencies, and misalignment between planned and actual delivery, undermining deployment success.	Support iterative, parallel execution of independent or loosely coupled deliverables.
80.B	Risks of duplicated work, overlooked interdependencies, and misalignment between planned and actual delivery, undermining deployment success.	Implement systematic monitoring to enable early risk detection and collaboratively define mitigation plans to prevent cascading schedule impacts.
80.C	Risks of duplicated work, overlooked interdependencies, and misalignment between planned and actual delivery, undermining deployment success.	By fostering disciplined coordination practices, R2DATO can reduce integration risks and ensure smooth migration execution.

Table 25 Interfaces

nr	**Gap**	**Recommendation**
81	FP2-R2DATO and the broader European railway domain currently lack a harmonised, open interface framework with clear ownership, version control, and change governance.	Develop and institutionalise a European reference that defines standardised, testable interface contracts with explicit ownership, versioning and change management.
82	Disparate interface implementations and multiple protocol versions from	Embed these interfaces as contractual requirements and certify compliance to build stakeholder trust.

	different suppliers create compatibility issues	
83A	The absence of contractual clarity over interface responsibilities and evolving specifications hampers coordinated integration and delays delivery.	Promote open communication protocols and provide tools and guidelines for interface validation.
83B	The absence of contractual clarity over interface responsibilities and evolving specifications hampers coordinated integration and delays delivery.	Close collaboration among system integrators, suppliers, infrastructure managers and regulators is essential to align interface standards and enable seamless multi-vendor migration and deployment.

Table 26 Standards and procedures

nr	**Gap**	**Recommendation**
84A	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Engage early with cross-border stakeholders and participate in EU-level regulatory harmonisation efforts to promote consistent requirements interpretation and regulatory alignment.
84B	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Deploy domain-expert translators as needed and establish bilingual documentation standards to ensure clarity.
84C	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Prioritise model-based, executable specifications to minimise ambiguity.

Table 27 Testing Environments

	Gap	Recommendation
85	The railway domain currently lacks harmonised, cross-organisational digital test environments.	Develop interoperable, accessible shared (ATO) test environments that incorporate realistic digital twins and simulation interfaces.
86A	This fragmentation leads to isolated testing, inconsistent toolchains, and late discovery of incompatibilities, increasing project risk and costs.	Promote cross-stakeholder collaboration on tool standardisation and testing procedures.
86B	This fragmentation leads to isolated testing, inconsistent toolchains, and late discovery of incompatibilities, increasing project risk and costs.	Institutionalise shared testbeds as integral components of safe, efficient migration and deployment.
86C	This fragmentation leads to isolated testing, inconsistent toolchains, and late discovery of incompatibilities, increasing project risk and costs.	Leverage demonstrators and pilot projects to validate approaches and build trust.
87	Legacy constraints and intellectual property concerns further complicate the establishment of shared platforms.	Establish governance and data-sharing agreements to ensure effective use of test environments.

Table 28 Interoperability

nr	Gap	Recommendation
88A	No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.	Develop a baseline for modelling languages and interoperability standards for tools used by all ATO stakeholders.
88B	No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.	Establish an authoritative semantic data model with standardised APIs and rigorous version control.

88C	No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.	Promote early and continuous cross-stakeholder collaboration to evolve and maintain these standards, enabling robust integration across organisations and ensuring future-proof migration paths.

4.3 BRIDGING GAPS

Which methods described in Chapter 3 can help mitigate the gaps identified in D33.1, and—where possible—to what extent or in what way? Tables 29 and 30 show the gap-recommendation combinations that can be addressed by multiple or just one of the studied methods: these gaps can be bridged by the mentioned method(s).

In Table 31 to 34, the gap-recommendation combinations are shown from a different point of view. Table 31 shows the recommendations that are specific to FP2-R2DATO, while Table 32 shows the recommendations that are relevant to the System Pillar. The remainder of the recommendations are to be addressed by human initiative. In Table 33 these are listed in combination with a suggested method. Table 34 shows the recommendations to be addressed by human initiative where the gaps cannot be bridged by any of the mentioned methods.

Table 29 Bridging gaps with multiple methods

nr	Gap	Recommendation	Use of method	How/To what extent
1	Strategic plans were not consistently updated as conditions shifted.	Institute a structured annual roadmap review that integrates regulatory interpretation updates, operational feedback from test corridors, and assessed system maturity, ensuring the plan remains aligned with evolving conditions.	1) DevOps “mindset” 2) Deployment Strategies and Roadmapping Framework	1) DevOps encourages & uses continuous planning rather than quarterly or annual planning 2) The roadmapping framework is dynamic in terms of content and planning.
2	While implementation progressed, partners continued to rely on assumptions set earlier, leading to divergence between planned automation levels and actual readiness.	Define capability targets in incremental stages rather than fixed end-states to accommodate changes in signalling dependencies, operational readiness, and technology development.	1) Formal Methods 2) Deployment Strategies and Roadmapping Framework	1) Specification of requirements to avoid diverging assumptions 2) The method is based on stakeholders’ engagement at all stages, which supports in convergence between planning and actual readiness.
6	The digital map was not always current and missing or outdated data elements directly influenced DATO responses, complicating fault attribution.	Update the digital map and associated register on a continuous cycle, ensuring alignment between trackside configuration, TMS logic and ATO data inputs.	1) DevOps 2) Formal Methods	1) Supporting continuous cycle 2) Interface specification (Architecture) and version management

7 A	Critical interdependencies—especially those involving signalling transitions, braking curves, operational procedures and supplier-specific behaviours—were underestimated.	Develop a long-term, system-of-systems DATO integration plan that covers signalling, onboard systems, operational rules, traffic management and safety-case requirements across their full lifecycle.	1) DevOps "mindset" 2) Architecture 4evolution 3) Formal Methods 4) Deployment Strategies and Roadmapping Framework	1) DevOps *de-risks integration* by doing it continuously instead of late in the lifecycle 2) Architecture 4evolution allows to select a SW Architecture oriented for a continuous cycle of software updates, recycling, issues management and continuous operation among cooperative modules. 3) Formal methods for system architecture specification and early testing 4) The method integrates multi-disciplinary systems and topics into one coherent framework and explores long-88term integration in case of new technological developments.
7 B	Critical interdependencies—especially those involving signalling transitions, braking curves, operational procedures and supplier-specific behaviours—were underestimated.	Introduce early dependency-mapping and interface-control processes, ensuring that all partners identify and review.	1) Formal methods 2) Deployment Strategies and Roadmapping Framework	1) System Architecture definition 2) Most of the sub-methods within the main method involve the Delphi approach at an early stage, which supports in strengthening dependencies and in building consensus and agreement among all partners.
8	Several technical decisions were driven by immediate constraints rather than long-term migration logic, leading to incompatible interfaces, duplicated effort and delays in achieving stable ATO–ETCS interaction.	Anchor all major technology decisions to a modular migration roadmap to avoid short-term optimisations that undermine long-term compatibility.	1) Architecture 4evolution 2) Deployment Strategies and Roadmapping Framework	1) Architecture 4evoution deals with modular migration with swift module replacement, deployment, and risk management, and allows for planned software deployments that guarantee interoperability across modules in the long-term. 2) The method helps in understanding what is already achieved to avoid duplicated efforts and to steer technological decisions towards a term-defined modular migration roadmap.
15	Alignment was initially treated as a milestone activity rather than a persistent operational function.	Maintain continuous alignment cycles with scheduled cross-partner dependency checks.	1) Formal Methods 2) Deployment Strategies and Roadmapping Framework	1) Architecture design with clear interfaces. 2) A roadmap is not a static output; it needs continuous alignment with various stakeholders, especially as the project or topic of interest progresses.

16	Internal planning assumptions diverged between cycles, interface dependencies were identified too late	Require transparent exchange of plans, constraints, and architectural assumptions to prevent divergence from remaining undisclosed.	1) DevOps 2) Formal Methods	1) The planning stage of DevOps allows for a backlog of clear plans, constraints, and architectural assumptions whose changes are safely stored in a repository. The repository is also capable of tracking changes as the project is developed further, allowing for the participants to look up to a centralised source of truth. 2) Architecture design with clear interfaces and requirements specification
22	The top-down requirements were cascaded without sufficient shared understanding, leading to several interpretations of the "intended system". Co-design procedures lacked uniformity among work packages.	Require joint workshops to interpret requirements and ensure that operators, IMs, and suppliers share a common understanding of functions, assumptions and constraints.	1) DevOps 2) Formal Methods	1) DevOps allows for a common source of truth with a repository of documents and code. The repository is not constrained to a document size or number limit and every actor can generate a discussion surrounding their interpretation of a document *before* they act upon it. The changes tracking built into the repository might also ensure that every actor (operator, IM's, suppliers) is capable of coping with the changes in the interpretation of a requirement 2) Requirements Engineering, Architecture design
51 A	Leadership practices and training provisions were not consistent across teams.	Institutionalise psychological safety practices.	1) DevOps "mindset" 2) People Oriented Change Management	1) DevOps culture is to remove silos and makes alignment a continuous operational process. 2) The Role of Leadership - Ethical Leadership, which builds trust and positive relationships between leaders and employees
51 B	Leadership practices and training provisions were not consistent across teams.	Require leaders to open meetings with uncertainty statements, encourage dissent and normalise the reporting of issues without penalty.	1) DevOps "mindset" 2) People Oriented Change Management	1) DevOps culture is to remove silos and makes alignment a continuous operational process. 2) The Role of Leadership - Ethical Leadership, which builds trust and positive relationships between leaders and employees

58	Communication on unresolved system questions was sporadic, encouraging informal interpretation.	Create a human-centric adaptation roadmap. Align technical milestones with workforce adaptation milestones to prevent bottlenecks.	1) Deployment Strategies and Roadmapping Framework 2) People oriented Change Management	1) The roadmapping framework supports the involvement of humans and adaptation with technical milestones. 2) Transparent communication and early engagement are promoted to support smooth migration to enhance acceptance and readiness.
61	Access restrictions related to credentials, intellectual property, and siloed organisational processes hinder open coordination.	Engage stakeholders and decision-makers early in the process. Implement a structured and transparent stakeholder engagement process from the start of the project, including mandatory early review checkpoints synchronised with key lifecycle milestones.	1) Deployment Strategies and Roadmapping Framework 2) People oriented Change Management	1) The framework aims at engaging stakeholders from the beginning of the project, and the resulting roadmap highlights key milestones and review checkpoints, with a highlight on what relates to the critical path. 2) Early engagement of end-users to improve quality as well as trust and ownership.
67 A	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Invest in change management programs that include role based training and internal FM champions to shift organisational culture.	1) Formal methods (partly) 2) People Oriented Change Management	1) Showcase benefits 2) Model for acceptance of (technological) change
67 B	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Use demonstrators and pilot projects to provide tangible evidence of benefits and build stakeholder confidence.	1) Formal methods (partly) 2) Deployment Strategies and Roadmapping Framework	1) Showcase benefits 2) The developed roadmap aims at defining the gaps and step-changes to reach demonstrators and pilot projects that consequently lead to the final deployment of the investigated system or technology.
67 C	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Collaborate with regulatory and safety bodies to establish formal acceptance criteria and integrate FM into certification processes.	1) Formal Methods 2) Deployment Strategies and Roadmapping Framework (Partly)	1) Provide official models for reference testing 2) Regulatory and safety bodies are defined as stakeholders in the definition of acceptance criteria and decision-making.
87	The railway domain currently lacks harmonised, cross-organisational digital test environments.	Develop interoperable, accessible shared (ATO) test environments that incorporate realistic digital twins and simulation interfaces.	1) Formal Methods 2) DevOps	1) Provide official models for reference testing. 2) It requires consistent test environments, uses simulations and supports formal methods inside pipelines

Table 30 Bridging gaps with one method

nr	Gap	Recommendation	Use of method	How/To what extent
3	When revisions did not occur, coordination slowed and corrective work increased, revealing that static roadmaps are incompatible with the continuous evolution characterising DATO environments.	Use scenario-based migration assessments to evaluate alternative progression paths, enabling timely adjustment when underlying assumptions shift.	Deployment Strategies and Roadmapping Framework	The method aims at providing scenario-based roadmapping and migration strategies with dynamic modules related to content, gaps, paths and time.
4	Validation practices differed across partners and datasets lacked consistent traceability and version control.	Maintain a single validated reference dataset for all integration and performance assessments.	DevOps	DevOps pipelines support "single source of truth," automated checks, and controlled configuration updates — exactly what your data issues require.
5	Test comparisons were occasionally drawn between fundamentally different operational conditions—for example, scheduled services versus inserted test trains—leading to misleading performance interpretations.	Restrict comparative testing to equivalent operational contexts to prevent inaccurately inferred performance differences.	Formal Methods	Requirement specification
9	The absence of a unified learning mechanism contributed to repeated deviations, loss of continuity during staff transitions and delays in refining operational and technical standards.	Establish mandatory learning reviews after every major test, deviation, or integration issue, with clearly assigned ownership and follow-up actions.	Deployment Strategies and Roadmapping Framework	The method aims at developing future/follow-up actions that need to be completed and to investigate the various uncertainties that might arise at each identified step-change or action.
10	Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams	Integrate short, facilitated storytelling exchanges after major tests to capture tacit insights before they dissipate.	Deployment Strategies and Roadmapping Framework	*Only partially solved because documentation remains a personal contribution that must be done to ensure that knowledge is transferred, regardless of the used tool.* The method incorporates best practices and lessons learned from previous studies, to expand the analysis on the basis of existing insights.
13	While structured mechanisms existed, engagement was uneven, and several late adjustments	Conduct regular cross-partner governance reviews to verify that change and risk remain	Deployment Strategies and Roadmapping Framework	The involved stakeholders include governance reviewers and the roadmap is built dynamically to

	required substantial rework due to absent early synchronisation between change proposals, safety implications, and operational constraints.	integrated as the system matures.		accommodate changes as the system evolves.
18 A	Reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.	Establish a multidisciplinary alignment team spanning engineering, operations, safety, and IT to ensure unified interpretation of system dependencies.	Deployment Strategies and Roadmapping Framework	Supports multi-disciplinary decision-making and interpretation
18 B	Reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.	Incorporate human-centred transition discussions early to support role clarity and emotional readiness during system evolution	People oriented Change Management	Early engagement of end-users supports development of readiness to change.
22 B	The top-down requirements were cascaded without sufficient shared understanding, leading to several interpretations of the "intended system". Co-design procedures lacked uniformity among work packages.	Implement iterative integration checkpoints (minor, frequent releases) to identify divergence early, reduce rework and stabilise interfaces.	Deployment Strategies and Roadmapping Framework	The roadmap results from the framework provide iterative integration milestones to identify changes and rework the defined step-changes and interfaces.
23 A	Relationship-building practices were uneven, leading to variable trust levels and communication gaps across supplier teams. The shared understanding of the long-term migration strategy (e.g., GoA4 evolution) was not always aligned across actors.	Integrate suppliers into long-term migration planning so technology choices align with future architectural needs rather than short-term work package constraints.	Deployment Strategies and Roadmapping Framework	The framework involves all stakeholders, including suppliers, at all stages and at different time horizons (e.g. short-term, medium-term and long-term). This ensures that choices remain aligned with future needs as the project evolves.
24	Regulatory engagement did not always precede design stabilisation, leading to interpretation gaps once system behaviour, safety logic, and interface assumptions had already been fixed.	Establish regulators as permanent contributors in early workshops on requirements definition and safety logic interpretation.	Deployment Strategies and Roadmapping Framework	Involvement of various types of stakeholders at all stages including workshops and interpretation of results

25	Certification pathways remained largely aligned with long-lifespan rail assets, despite the introduction of digital technologies requiring more frequent updates.	Co-develop certification pathways that clarify evidence expectations, acceptable interpretations, and evaluation milestones.	Formal methods	Use formal methods in certification processes.
29	EU, national and regional policies were not consistently aligned in timing, scope or regulatory emphasis, creating uncertainty for long-term planning.	Establish a structured EU–national–regional coordination forum to align strategy, timelines, and migration expectations.	Deployment Strategies and Roadmapping Framework	The framework is structured to join various stakeholders at different levels to align on strategy, timelines and expectations.
30	Homologation processes differed across borders, with varying interpretations of requirements.	Co-develop synchronised homologation roadmaps to harmonise evidence requirements and reduce divergent interpretations.	Deployment Strategies and Roadmapping Framework	The framework can be applied to any type of roadmap with clear objectives and criteria to converge interpretations and consensus.
32	Funding windows and strategic priorities were sometimes misaligned, contributing to delays and fragmented rollout trajectories.	Align funding cycles with technical migration phases to enable predictable investment and staged deployment.	Deployment Strategies and Roadmapping Framework	Funding cycles can be adjusted to various step-changes and stages of the deployment strategy.
33	Engagement with local authorities and mobility actors often began after technical planning, limiting flexibility to adjust test scenarios.	Initiate structured engagement with local authorities at project inception, including workshops to identify depot, crossing and test-field constraints.	Deployment Strategies and Roadmapping Framework	The framework aims at engaging local authorities and stakeholders at all stages from the start to end.
35	Operational constraints (crossings, depot rules, noise limits) were not consistently mapped early, leading to rework and rescheduling.	Develop a Local Operational Constraints Map that must be validated and updated with municipal partners before major design or test decisions.	Formal Methods	Define operational requirements
36	Communication cycles with local actors were irregular, reducing shared situational awareness and slowing approval processes.	Co-design test feasibility plans with municipalities to align safety expectations, public communication needs and operational restrictions.	Deployment Strategies and Roadmapping Framework	The framework includes stakeholders at all levels and aims at addressing multiple criteria related to any field such as safety, public needs and operational concerns.

38	Interfaces remained intermittent, leaving suppliers, operators, and research actors to advance innovation separately. This produced parallel work, repeated analytical effort, and missed opportunities to align emerging methods with operational deployment.	Formalise boundary-innovation workshops: conduct structured workshops to translate advances from adjacent sectors (autonomous vehicles, aviation safety, telecom networks) into rail-specific use cases.	Formal methods	Architecture design
40	Dependence on a small cadre of experts created bottlenecks and repeated upskilling cycles became necessary as external teams left.	Adopt a DevOps-style continuous integration model: introduce incremental sub-releases, enabling frequent, small-scale integration rather than medium-size "integration events."	DevOps	DevOps culture emphasises "continuous learning" via retrospectives, blameless culture and shared knowledge
42	Operational preparation and data quality sometimes did not keep pace with technical deployment.	Co-design test plans with dispatchers and field coordinators to match live network constraints.	DevOps	DevOps methodology support operations involved early in test design, shared responsibility and continuous feedback loops.
43	Limited ability to reproduce identical test runs and irregular digital-map updates reduced reliability of test outcomes and complicated performance assessment.	Create a unified integration team covering signalling, onboard systems, traffic management, and testing coordination.	DevOps	The gap aligns with DevOps principles like cross-functional teams, environment parity and versioning of digital maps & datasets.
44	Continuous synchronisation of operational data and traffic-aware test planning are required to prevent degradation of ATO behaviour and to secure credible validation results.	Use simulation with full operational parameters, including dispatching rules and real traffic behaviour.	DevOps	DevOps principles like cross-functional teams, continuous integration, automated pipelines, monitoring, and feedback loops will help increasing the maturity.
48	Specialised skills in data configuration, software behaviour analysis and validation are sometimes limited and concentrated in a small number of individuals.	Establish a dedicated system-integration and testing team. Similar to a DevOps model, this group maintains configuration oversight, supervises test environments and ensures continuity across releases.	DevOps	The proposed action is a DevOps practice in itself.

49	The programme demonstrated a structural need for dedicated specialists in GoA 4 configuration integrity across simulation and field environments. Lacking this proficiency, processes slowed and it was harder to identify the source of problems.	Adopt a strict small-increment release strategy. Require that new features or components be introduced in isolated increments to make failures identifiable and manageable. Implement mandatory pre-validation of every component before system integration.	DevOps	How DevOps helps: CI/CD pipelines ensure every change is validated before integration; Incremental releases make root-cause analysis far easier; Environment parity (field–sim–test) is a core DevOps objective; Automated tests catch conflicts before they reach simulation or track.
50	A defined specialist track, supported by continuous training and clear role allocation, is required to ensure sufficient capacity for future automated testing and data-centric verification task.	Ensure redundancy for critical simulation and testing infrastructure.	DevOps (partly)	DevOps defines clear roles and works with infrastructure redundancy as well.
52	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Adopt transparent decision-making protocols.	Deployment Strategies and Roadmapping Framework	The framework provides a structured approach for non-biased decision-making.
53 A	Digital role competence development fell behind with technical progress, leaving operators and engineers underprepared for data-driven decision-making tasks.	Develop a forward-looking digital skills framework.	People oriented Change Management	One of four key determinants of technology acceptance is Facilitating Conditions: how users perceive the organisational and technical infrastructure available to support the use of the technology (like resources, knowledge and compatibility).
53 B	Digital role competence development fell behind with technical progress, leaving operators and engineers underprepared for data-driven decision-making tasks.	Define future competencies for ATO/GoA4 operations, including system integration, data interpretation, testing logic, and automation supervision.	People oriented Change Management	One of four key determinants of technology acceptance is 'Facilitating Conditions: how users perceive the organisational and technical infrastructure available to support the use of the technology (like resources, knowledge and compatibility).
55	Operators were at times engaged only after major requirements and procedures had been set, limiting their influence on operational concepts and reducing readiness.	Engage drivers and operators from the outset.	Deployment Strategies and Roadmapping Framework	The framework integrates any type of stakeholders including drivers and operators at all stages.

56	Training occasionally began after technical configurations were fixed, narrowing preparation for supervision and fallback functions.	Include them (drivers) in use-case definition, requirement reviews, and early testing to ensure operational realism.	People oriented Change Management	Early engagement of end-users can support acceptance of new technology.
57 B	Role definition was not always explicit, creating uncertainty about authority and task boundaries.	Communicate explicitly how the operator's role will evolve (e.g., supervision tasks, fallback responsibilities).	People oriented Change Management	Readiness for change is (among other factors) influenced by how the change is communicated, timeliness and transparency are key.
59	Feedback channels existed informally but were not consistently integrated into design cycles.	Establish an operator feedback loop. Use structured interviews, test ride-along sessions and periodic workshops to surface concerns early.	DevOps	DevOps uses shared dashboards (e.g. Kanban, dependency maps) and promotes open communication cycles.
60	When the human implications of automation were not addressed, resistance surfaced later in testing, slowing acceptance and diminishing confidence in migration processes.	Communicate uncertainties transparently. Acknowledge what is not yet known to reduce speculation and strengthen trust.	People oriented Change Management	Readiness for change is (among other factors) influenced by how the change is communicated. Transparent communication is vital for creating trust.
62 A	Some stakeholders are overrepresented while others are underrepresented, often based on perceived early-stage relevance, which leads to biased or incomplete requirements.	Create inclusive forums for continuous collaboration where roadmaps, deliverables, and risks are jointly defined.	Deployment Strategies and Roadmapping Framework	The framework aims at building continuous collaboration based on roadmapping where risks and deliverables are jointly integrated.
62 B	Some stakeholders are overrepresented while others are underrepresented, often based on perceived early-stage relevance, which leads to biased or incomplete requirements.	Use structured decision-making methods (e.g., MCA) to systematically integrate stakeholder priorities and reduce bias.	Deployment Strategies and Roadmapping Framework	The framework is structurally based where the MCA is used as one of the main decision-making methods for addressing stakeholders' priorities with minimised bias.
63 A	Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges.	Use structured decision-making methods (e.g., MCA) to systematically integrate stakeholder priorities and reduce bias.	Deployment Strategies and Roadmapping Framework	The framework is structurally based where the MCA is used as one of the main decision-making methods for addressing stakeholders' priorities with minimised bias.

63 C	Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges.	Ensure documentation of stakeholder inputs and decisions is accessible to strengthen trust and shared accountability.	Formal Methods	Architecture designs as same basis
64	The uneven or late engagement causes redesign, resistance in later phases, and inefficient migration planning.	Early and sustained alignment significantly improves migration success by limiting redesign and organisational resistance.	DevOps	DevOps supports: Early supplier involvement, Iterative design and release cycles, Co-development & shared interface testing
65	Despite clear advantages, formal methods such as model-based systems engineering adoption continues to face cultural and organisational resistance, partly due to the perception that formal methods are overly complex or suitable only for specialists.	Position formal methods adoption as a strategic priority starting at tendering and early design phases.	Formal Methods	Clear requirements management for deliveries
66	The railway sector lacks harmonised standards and interoperable tooling across suppliers and operators, complicating model exchange and integration. Although other industries widely apply formal methods, the railway domain has not yet institutionalised comparable practices.	Develop harmonised, interoperable toolchains supported by clear guidelines.	Formal methods	Define clear standards. Develop algorithms to “translate” from one tool to the other. Long-term: compromise on common tooling, provide official reference models along with standards that allow to test conformity
67 D	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Emphasise modular design and interface specifications aligned with FM principles to support scalable, flexible migration underpinned by trusted validation throughout the lifecycle.	Formal methods	Showcasing benefits is part of Formal Methods.
68	There is no widely accepted incremental or component level certification framework tailored to ATO systems developed iteratively.	Establish a structured modular certification route that enables component level approvals and staged integration validation.	Formal Methods	Provide official models for reference testing

71	Late-stage monolithic certification, unclear communication of certification limits, and uncoordinated approaches amplify these challenges.	Collaborate closely with certification authorities to evolve regulatory processes that acknowledge iterative and modular development practices, reducing time to market and cost while ensuring safety and compliance.	Formal Methods	Provide official models for reference testing; different models for different stages
72	Late-stage monolithic certification, unclear communication of certification limits, and uncoordinated approaches amplify these challenges.	Clear documentation and shared understanding of certification boundaries help stakeholders plan and execute migration steps more effectively while minimising rework and delays.	Formal Methods	Formal methods can be used to define subsystems that can also be tested and certified with the defined interfaces.
73	In practice, change management efforts are often insufficient or fragmented.	Invest in dedicated change management strategies that secure leadership buy-in and provide tailored training across roles.	People oriented Change Management	The Role of Leadership: Leaders who actively promote change and remove barriers facilitate employees' adoption of automation and digital tools. Leadership styles that have proven to be effective in boosting readiness for change: Ethical Leadership and Transformational Leadership.
74	Leadership engagement is limited, role-specific training is lacking and communication is unclear.	Enhance the change readiness in companies by encouraging a culture of openness and collaboration.	People oriented Change Management	The Role of Leadership: Leaders who actively promote change and remove barriers facilitate employees' adoption of automation and digital tools. Leadership styles that have proven to be effective in boosting readiness for change: Ethical Leadership and Transformational Leadership.
76 B	Additional barriers include stakeholder silos, political considerations, intellectual property concerns and regulatory complexity.	Implement gradual integration phases that bridge legacy and new systems to mitigate resistance.	Deployment Strategies and Roadmapping Framework (Partly)	The framework can support in building a roadmap with gradual phases to bridge any gaps, including the ones related to legacy and new systems.

77	Without addressing human and organisational factors, technical innovations risk poor adoption or underutilisation.	Addressing both culture and technology is essential for sustainable migration and deployment success.	People oriented Change Management	From UTAUT follows that technology must be both user-friendly and perceived as improving job performance as well as being supported by other colleagues (social influence) Also a positive perception of the availability of organisational and technical infrastructure to support the use of the technology, plays a part. The concept of IRTC sheds light on how readiness for technological change is shaped through close working relationships, employees often develop shared attitudes that shape their collective readiness.
79 A	Communication is sometimes fragmented; ownership of dependencies is unclear, and potential delays can propagate unnoticed.	Establish centralised tools and communication channels for real-time tracking of dependency status and changes.	Formal Methods	Architecture design to make dependencies and their ownership explicit
79 B	Communication is sometimes fragmented; ownership of dependencies is unclear, and potential delays can propagate unnoticed.	Assign clear responsibility owners for key dependencies to manage and coordinate delivery proactively.	Architecture 4evolution	Prescribes clear responsibilities
81	FP2-R2DATO and the broader European railway domain currently lack a harmonised, open interface framework with clear ownership, version control, and change governance.	Develop and institutionalise a European reference that defines standardised, testable interface contracts with explicit ownership, versioning and change management.	Formal Methods	Provide official models for reference testing
82	Disparate interface implementations and multiple protocol versions from different suppliers create compatibility issues	Embed these interfaces as contractual requirements and certify compliance to build stakeholder trust.	Formal Methods	Provide official models for reference testing
83 A	The absence of contractual clarity over interface responsibilities and evolving specifications hampers coordinated	Promote open communication protocols and provide tools and guidelines for interface validation.	Formal Methods	Requirements Engineering and interface definitions (architecture design)

	integration and delays delivery.			
83 B	The absence of contractual clarity over interface responsibilities and evolving specifications hampers coordinated integration and delays delivery.	Close collaboration among system integrators, suppliers, infrastructure managers and regulators is essential to align interface standards and enable seamless multi-vendor migration and deployment.	Formal Methods	Requirements Engineering and interface definitions (architecture design) and multidisciplinary teams.
84 A	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Engage early with cross-border stakeholders and participate in EU-level regulatory harmonisation efforts to promote consistent requirements interpretation and regulatory alignment.	Formal Methods	Provide official models for reference testing
84 B	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Deploy domain-expert translators as needed and establish bilingual documentation standards to ensure clarity.	Formal Methods	Provide official models for reference testing
84 C	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Prioritise model-based, executable specifications to minimise ambiguity.	Formal Methods	Provide official models for reference testing

86 A	This fragmentation leads to isolated testing, inconsistent toolchains, and late discovery of incompatibilities, increasing project risk and costs.	Promote cross-stakeholder collaboration on tool standardisation and testing procedures.	DevOps principles	Like, implementation of Continuous Integration, shared pipelines, automated regression testing
88 A	No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.	Develop a baseline for modelling languages and interoperability standards for tools used by all ATO stakeholders.	Formal Methods	Formal Methods can provide such a tool.
88 B	No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.	Establish an authoritative semantic data model with standardised APIs and rigorous version control.	Formal Methods	Provide official models for reference testing
88 C	No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.	Promote early and continuous cross-stakeholder collaboration to evolve and maintain these standards, enabling robust integration across organisations and ensuring future-proof migration paths.	Deployment Strategies and Roadmapping Framework	The method aims at enhancing collaboration among various types of stakeholders to enable robust and efficient migration strategies across multiple organisations.

Table 31 R2DATO/Project-specific

nr	**Gap**	**Recommendation**	**Use of method**	**How/To what extent**
7 A	Critical interdependencies—especially those involving signalling transitions, braking curves, operational	Develop a long-term, system-of-systems DATO integration plan that covers signalling, onboard systems, operational rules, traffic	1) DevOps "mindset" 2) Architecture 4evolution 3) Formal Methods 4) Deployment Strategies	1) DevOps *de-risks integration* by doing it continuously instead of late in the lifecycle 2) Architecture4evolution allows for a continuous cycle of software updates, recycling,

	procedures and supplier-specific behaviours—were underestimated.	management and safety-case requirements across their full lifecycle.	and Roadmapping Framework	issues management and continuous operation among cooperative modules. 3) Formal methods for system architecture specification and early testing 4) The method integrates multi-disciplinary systems and topics into one coherent framework and explores long-88term integration in case of new technological developments.
10 D	Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams	Implement a learning-maturity metric to monitor whether lessons are being captured, interpreted and institutionalised across the DATO ecosystem.		
27 A	Technical information was rarely translated into non-expert language, limiting public comprehension.	Use demonstrations, visual explainers, and open events to familiarise the public with ATO/GOA4 behaviour.		
38 B	Interfaces remained intermittent, leaving suppliers, operators, and research actors to advance innovation separately. This produced parallel work, repeated analytical effort, and missed opportunities to align emerging methods with operational deployment.	Adopt joint pilots with external actors: run small-scale co-development demonstrators with research institutes or tech companies to test frontier solutions before full integration.		
46 B	Teams struggled to mediate conflicting priorities, facilitate discussions under pressure and distinguish relational tension from technical disagreement. Over-reliance on technical argumentation, without corresponding attention to expectations and trust, limited collaboration.	Mandate interpersonal-skills training for task leaders and WP leads.		
52 B	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Conduct mandatory retrospectives after every major test, demonstration, or		

		release, documenting lessons and actions.		
53 B	Digital role competence development fell behind with technical progress, leaving operators and engineers underprepared for data-driven decision-making tasks.	Define future competencies for ATO/GoA4 operations, including system integration, data interpretation, testing logic, and automation supervision.	People oriented Change Management	Unified Theory of Acceptance and Use of Technology (UTAUT): One of four key determinants of technology acceptance is Facilitating Conditions: how users perceive the organisational and technical infrastructure available to support the use of the technology (like resources, knowledge and compatibility).
67 A	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Use demonstrators and pilot projects to provide tangible evidence of benefits and build stakeholder confidence.	1) Formal methods (partly) 2) Deployment Strategies and Roadmapping Framework	1) showcase benefits 2) The developed roadmap aims at defining the gaps and step-changes to reach demonstrators and pilot projects that consequently lead to the final deployment of the investigated system or technology.
69 B	Without a consistent modular certification pathway, integration risks build up toward the end of the project.	Ease the certification of software and tools later in the process since they use the same technology stack.		
75	Demonstrators to showcase the benefits of new methods are scarce.	Leverage pilot projects and demonstrators to demonstrate value and build confidence.		
76 B	Additional barriers include stakeholder silos, political considerations, intellectual property concerns and regulatory complexity.	Implement gradual integration phases that bridge legacy and new systems to mitigate resistance.	Deployment Strategies and Roadmapping Framework	The framework can support in building a roadmap with gradual phases to bridge any gaps, including the ones related to legacy and new systems.
78 B	R2DATO needs to keep working towards a harmonised methodology to model, track and sequence dependencies between deliverables across work packages.	Keep developing and implementing a standardised, project-wide methodology for mapping and sequencing inter-work package deliverables, right from the start.		
80 B	Risks of duplicated work, overlooked interdependencies, and misalignment between planned and actual delivery, undermining deployment success.	Implement systematic monitoring to enable early risk detection and collaboratively define mitigation plans to prevent cascading schedule impacts.		

80 C	Risks of duplicated work, overlooked interdependencies, and misalignment between planned and actual delivery, undermining deployment success.	By fostering disciplined coordination practices, R2DATO can reduce integration risks and ensure smooth migration execution.		
85	The railway domain currently lacks harmonised, cross-organisational digital test environments.	Develop interoperable, accessible shared (ATO) test environments that incorporate realistic digital twins and simulation interfaces.	1) Formal Methods 2) DevOps	1) Provide official models for reference testing. 2) It requires consistent test environments, uses simulations and supports formal methods inside pipelines
86 C	This fragmentation leads to isolated testing, inconsistent toolchains, and late discovery of incompatibilities, increasing project risk and costs.	Leverage demonstrators and pilot projects to validate approaches and build trust.		
88 A	No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.	Develop a baseline for modelling languages and interoperability standards for tools used by all ATO stakeholders.	Formal Methods	Formal methods can provide such a tool.

Table 32 System Pillar Relevant

nr	**Gap**	**Recommendation**	**Use of method**	**How/To what extent**
25 A	Certification pathways remained largely aligned with long-lifespan rail assets, despite the introduction of digital technologies requiring more frequent updates.	Co-develop certification pathways that clarify evidence expectations, acceptable interpretations, and evaluation milestones.	Formal methods	Use formal methods in certification processes.
25 B	Certification pathways remained largely aligned with long-lifespan rail assets, despite the introduction of digital technologies requiring more frequent updates.	Conduct structured alignment sessions between EU, national and regional authorities to harmonise certification expectations and reduce conflicting interpretations.		

30	Homologation processes differed across borders, with varying interpretations of requirements.	Co-develop synchronised homologation roadmaps to harmonise evidence requirements and reduce divergent interpretations.	Deployment Strategies and Roadmapping Framework	The framework can be applied to any type of roadmap with clear objectives and criteria to converge interpretations and consensus.
31	Cross-border interoperability discussions began too late to harmonise technical and operational assumptions meaningfully.	Begin interoperability alignment early by holding joint workshops to clarify cross-border assumptions, safety logic and interface expectations.		
39	Systems-integration skills were not systematically retained in-house. Engineering, testing, and integration activities were frequently outsourced during peak phases and associated knowledge departed at contract completion. This loss occurred despite the long operational horizon of ETCS and ATO and the need for recurrent digital updates.	Establish a formal Systems Integration Team (SIT): a dedicated cross-domain group responsible for architecture coherence, interface definition, configuration control, and release governance.		
41 A	With AI-supported logic and software updates occurring far faster than rail asset renewal, internal specialist capacity proved insufficient to support continuous system recalibration and integration oversight.	Use a unified system configuration baseline: maintain a single, source-controlled architecture map (hardware, network, software) accessible to all partners.		
66	The railway sector lacks harmonised standards and interoperable tooling across suppliers and operators, complicating model exchange and integration. Although other industries widely apply formal methods, the railway domain has not yet institutionalised comparable practices.	Develop harmonised, interoperable toolchains supported by clear guidelines.	Formal methods	Define clear standards. Develop algorithms to “translate” from one tool to the other. Long-term: compromise on common tooling, provide official reference models along with standards that allow to test conformity

67 D	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Emphasise modular design and interface specifications aligned with FM principles to support scalable, flexible migration underpinned by trusted validation throughout the lifecycle.	Formal methods	Showcase benefits
68	There is no widely accepted incremental or component level certification framework tailored to ATO systems developed iteratively.	Establish a structured modular certification route that enables component level approvals and staged integration validation.	Formal Methods	Provide official models for reference testing
69	Without a consistent modular certification pathway, integration risks build up toward the end of the project.	Select and implement a technology stack standardised across projects early in the initiative and pilot certification on smaller representative subsystems to uncover issues early.		
70	The variety of tools and technologies complicates efficient certification even further.	Select and implement a technology stack standardised across projects early in the initiative and pilot certification on smaller representative subsystems to uncover issues early.		
71	Late-stage monolithic certification, unclear communication of certification limits, and uncoordinated approaches amplify these challenges.	Collaborate closely with certification authorities to evolve regulatory processes that acknowledge iterative and modular development practices, reducing time to market and cost while ensuring safety and compliance.	Formal Methods	Provide official models for reference testing; different models for different stages
72	Late-stage monolithic certification, unclear communication of certification limits, and uncoordinated approaches amplify these challenges.	Clear documentation and shared understanding of certification boundaries help stakeholders plan and execute migration steps more effectively while minimising rework and delays.	Formal Methods	Formal Methods can be used to define subsystems that can also be tested and certified with the defined interfaces.
81	FP2-R2DATO and the broader European railway domain currently lack a harmonised, open interface framework	Develop and institutionalise a European reference that defines standardised, testable interface contracts with	Formal Methods	Provide official models for reference testing

	with clear ownership, version control, and change governance.	explicit ownership, versioning and change management.		
82	Disparate interface implementations and multiple protocol versions from different suppliers create compatibility issues	Embed these interfaces as contractual requirements and certify compliance to build stakeholder trust.	Formal Methods	Provide official models for reference testing

Table 33 Human initiatives supported by methods

nr	Gap	Recommendation	Use of method	How/To what extent
3	When revisions did not occur, coordination slowed and corrective work increased, revealing that static roadmaps are incompatible with the continuous evolution characterising DATO environments.	Use scenario-based migration assessments to evaluate alternative progression paths, enabling timely adjustment when underlying assumptions shift.	Deployment Strategies and Roadmapping Framework	The method aims at providing scenario-based roadmapping and migration strategies with dynamic modules related to content, gaps, paths and time.
4	Validation practices differed across partners and datasets lacked consistent traceability and version control.	Maintain a single validated reference dataset for all integration and performance assessments.	DevOps	DevOps pipelines support "single source of truth," automated checks, and controlled configuration updates — exactly what your data issues require.
5	Test comparisons were occasionally drawn between fundamentally different operational conditions—for example, scheduled services versus inserted test trains—leading to misleading performance interpretations.	Restrict comparative testing to equivalent operational contexts to prevent inaccurately inferred performance differences.	Formal Methods	Requirement specification
7 B	Critical interdependencies—especially those involving signalling transitions, braking curves, operational procedures and supplier-specific behaviours—were underestimated.	Introduce early dependency-mapping and interface-control processes, ensuring that all partners identify and review.	1) Formal methods 2) Deployment Strategies and Roadmapping Framework	1) System Architecture definition 2) Most of the sub-methods within the main method involve the Delphi approach at an early stage, which supports in strengthening dependencies and in building consensus and agreement among all partners.

9 A	The absence of a unified learning mechanism contributed to repeated deviations, loss of continuity during staff transitions and delays in refining operational and technical standards.	Establish mandatory learning reviews after every major test, deviation, or integration issue, with clearly assigned ownership and follow-up actions.	Deployment Strategies and Roadmapping Framework	The method aims at developing future/follow-up actions that need to be completed and to investigate the various uncertainties that might arise at each identified step-change or action.
10 A	Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams	Integrate short, facilitated storytelling exchanges after major tests to capture tacit insights before they dissipate.	Deployment Strategies and Roadmapping Framework	*Only partially solved because documentation remains a personal contribution that must be done to ensure that knowledge is transferred, regardless of the used tool.* The method incorporates best practices and lessons learned from previous studies, to expand the analysis on the basis of existing insights.
13	While structured mechanisms existed, engagement was uneven, and several late adjustments required substantial rework due to absent early synchronisation between change proposals, safety implications, and operational constraints.	Conduct regular cross-partner governance reviews to verify that change and risk remain integrated as the system matures.	Deployment Strategies and Roadmapping Framework	The involved stakeholders include governance reviewers and the roadmap is built dynamically to accommodate changes as the system evolves.
15	Alignment was initially treated as a milestone activity rather than a persistent operational function.	Maintain continuous alignment cycles with scheduled cross-partner dependency checks.	1) Formal Methods 2) Deployment Strategies and Roadmapping Framework	1) Architecture design with clear interfaces 2) A roadmap is not a static output; it needs continuous alignment with various stakeholders, especially as the project or topic of interest progresses.
16	Internal planning assumptions diverged between cycles, interface dependencies were identified too late	Require transparent exchange of plans, constraints, and architectural assumptions to prevent divergence from remaining undisclosed.	1) DevOps 2) Formal Methods	1) The planning stage of DevOps allows for a backlog of clear plans, constraints, and architectural assumptions whose changes are safely stored in a repository. The repository is also capable of tracking changes as the project is developed further, allowing for the participants to look up to a centralised source of truth. 2) Architecture design with clear interfaces and requirements specification

18 A	Reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.	Establish a multidisciplinary alignment team spanning engineering, operations, safety, and IT to ensure unified interpretation of system dependencies.	Deployment Strategies and Roadmapping Framework	*Partially due to the need of human initiative first* Supports multi-disciplinary decision-making and interpretation
18 B	Reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.	Incorporate human-centred transition discussions early to support role clarity and emotional readiness during system evolution	People oriented Change Management	Early engagement of end-users supports development of 'readiness to change'.
22	The top-down requirements were cascaded without sufficient shared understanding, leading to several interpretations of the "intended system". Co-design procedures lacked uniformity among work packages.	Require joint workshops to interpret requirements and ensure that operators, IMs, and suppliers share a common understanding of functions, assumptions and constraints.	1) DevOps 2) Formal Methods	1) DevOps allows for a common source of truth with a repository of documents and code. The repository is not constrained to a document size or number limit and every actor can generate a discussion surrounding their interpretation of a document *before* they act upon it. The changes tracking built into the repository might also ensure that every actor (operator, IM's, suppliers) is capable of coping with the changes in the interpretation of a requirement 2) Requirements Engineering, Architecture design
22	The top-down requirements were cascaded without sufficient shared understanding, leading to several interpretations of the "intended system". Co-design procedures lacked uniformity among work packages.	Implement iterative integration checkpoints (minor, frequent releases) to identify divergence early, reduce rework and stabilise interfaces.	Deployment Strategies and Roadmapping Framework	The roadmap results from the framework provide iterative integration milestones to identify changes and rework the defined step-changes and interfaces.
23	Relationship-building practices were uneven, leading to variable trust levels and communication gaps across supplier teams. The shared understanding of the long-term migration strategy (e.g., GoA4 evolution) was not always aligned across actors.	Integrate suppliers into long-term migration planning so technology choices align with future architectural needs rather than short-term work package constraints.	Deployment Strategies and Roadmapping Framework	The framework involves all stakeholders, including suppliers, at all stages and at different time horizons (e.g. short-term, medium-term and long-term). This ensures that choices remain aligned with future needs as the project evolves.

24	Regulatory engagement did not always precede design stabilisation, leading to interpretation gaps once system behaviour, safety logic, and interface assumptions had already been fixed.	Establish regulators as permanent contributors in early workshops on requirements definition and safety logic interpretation.	Deployment Strategies and Roadmapping Framework	Involvement of various types of stakeholders at all stages including workshops and interpretation of results
32	Funding windows and strategic priorities were sometimes misaligned, contributing to delays and fragmented rollout trajectories.	Align funding cycles with technical migration phases to enable predictable investment and staged deployment.	Deployment Strategies and Roadmapping Framework	Funding cycles can be adjusted to various step-changes and stages of the deployment strategy.
33	Engagement with local authorities and mobility actors often began after technical planning, limiting flexibility to adjust test scenarios.	Initiate structured engagement with local authorities at project inception, including workshops to identify depot, crossing and test-field constraints.	Deployment Strategies and Roadmapping Framework	The framework aims at engaging local authorities and stakeholders at all stages from the start to end.
35	Operational constraints (crossings, depot rules, noise limits) were not consistently mapped early, leading to rework and rescheduling.	Develop a Local Operational Constraints Map that must be validated and updated with municipal partners before major design or test decisions.	Formal Methods	Define operational requirements
36	Communication cycles with local actors were irregular, reducing shared situational awareness and slowing approval processes.	Co-design test feasibility plans with municipalities to align safety expectations, public communication needs and operational restrictions.	Deployment Strategies and Roadmapping Framework	The framework includes stakeholders at all levels and aims at addressing multiple criteria related to any field such as safety, public needs and operational concerns.
38 A	Interfaces remained intermittent, leaving suppliers, operators, and research actors to advance innovation separately. This produced parallel work, repeated analytical effort, and missed opportunities to align emerging methods with operational deployment.	Formalise boundary-innovation workshops: conduct structured workshops to translate advances from adjacent sectors (autonomous vehicles, aviation safety, telecom networks) into rail-specific use cases.	Formal methods	Architecture design
40	Dependence on a small cadre of experts created bottlenecks and repeated upskilling cycles became necessary as external teams left.	Adopt a DevOps-style continuous integration model: introduce incremental sub-releases, enabling frequent, small-scale integration rather than medium-size “integration events.”	DevOps	DevOps culture emphasises “continuous learning” via retrospectives, blameless culture and shared knowledge

42	Operational preparation and data quality sometimes did not keep pace with technical deployment.	Co-design test plans with dispatchers and field coordinators to match live network constraints.	DevOps	DevOps methodology support operations involved early in test design, shared responsibility and continuous feedback loops.
48	Specialised skills in data configuration, software behaviour analysis and validation are sometimes limited and concentrated in a small number of individuals.	Establish a dedicated system-integration and testing team. Similar to a DevOps model, this group maintains configuration oversight, supervises test environments and ensures continuity across releases.	DevOps	The proposed action already is a DevOps practice
52 C	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Adopt transparent decision-making protocols.	Deployment Strategies and Roadmapping Framework	The framework provides a structured approach for non-biased decision-making.
55	Operators were at times engaged only after major requirements and procedures had been set, limiting their influence on operational concepts and reducing readiness.	Engage drivers and operators from the outset.	Deployment Strategies and Roadmapping Framework	The framework integrates any type of stakeholders including drivers and operators at all stages.
56	Training occasionally began after technical configurations were fixed, narrowing preparation for supervision and fallback functions.	Include them (drivers) in use-case definition, requirement reviews, and early testing to ensure operational realism.	People oriented Change Management	Early engagement of end-users improves quality and help develop acceptance trust and ownership.
57 B	Role definition was not always explicit, creating uncertainty about authority and task boundaries.	Communicate explicitly how the operator's role will evolve (e.g., supervision tasks, fallback responsibilities).	People oriented Change Management	Readiness for change is (among other factors) influenced by how the change is communicated.
58	Communication on unresolved system questions was sporadic, encouraging informal interpretation.	Create a human-centric adaptation roadmap. Align technical milestones with workforce adaptation milestones to prevent bottlenecks.	1) Deployment Strategies and Roadmapping Framework 2) People oriented Change Management	1) The roadmapping framework supports the involvement of humans and adaptation with technical milestones. 2) Transparent communication and early engagement
59	Feedback channels existed informally but were not consistently integrated into design cycles.	Establish an operator feedback loop. Use structured interviews, test ride-along sessions and periodic workshops to surface concerns early.	DevOps	DevOps uses shared dashboards (e.g. Kanban, dependency maps) and promotes open communication cycles.

60	When the human implications of automation were not addressed, resistance surfaced later in testing, slowing acceptance and diminishing confidence in migration processes.	Communicate uncertainties transparently. Acknowledge what is not yet known to reduce speculation and strengthen trust.	People oriented Change Management	Readiness for change is (among other factors) influenced by how the change is communicated. Transparent communication is vital for creating trust.
61	Access restrictions related to credentials, intellectual property, and siloed organisational processes hinder open coordination.	Engage stakeholders and decision-makers early in the process. Implement a structured and transparent stakeholder engagement process from the start of the project, including mandatory early review checkpoints synchronised with key lifecycle milestones.	1) Deployment Strategies and Roadmapping Framework 2) People oriented Change Management	1) The framework aims at engaging stakeholders from the beginning of the project, and the resulting roadmap highlights key milestones and review checkpoints, with a highlight on what relates to the critical path. 2) Early engagement of end-users improving quality as well as trust, ownership and acceptance.
62 B	Some stakeholders are overrepresented while others are underrepresented, often based on perceived early-stage relevance, which leads to biased or incomplete requirements.	Use structured decision-making methods (e.g., MCA) to systematically integrate stakeholder priorities and reduce bias.	Deployment Strategies and Roadmapping Framework	The framework is structurally based where the MCA is used as one of the main decision-making methods for addressing stakeholders' priorities with minimised bias.
63 A	Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges.	Use structured decision-making methods (e.g., MCA) to systematically integrate stakeholder priorities and reduce bias.	Deployment Strategies and Roadmapping Framework	The framework is structurally based where the MCA is used as one of the main decision-making methods for addressing stakeholders' priorities with minimised bias.
63 C	Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges.	Ensure documentation of stakeholder inputs and decisions is accessible to strengthen trust and shared accountability.	Formal Methods	Architecture designs as same basis
64	The uneven or late engagement causes redesign, resistance in later phases, and inefficient migration planning.	Early and sustained alignment significantly improves migration success by limiting redesign and organisational resistance.	DevOps	DevOps supports: Early supplier involvement, Iterative design and release cycles, Co-development & shared interface testing
67 A	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Invest in change management programs that include role based training and internal FM champions to shift organisational culture.	1) Formal methods (partly) 2) People Oriented Change Management	1) Showcase benefits 2) Models for acceptance of change show that social factors play a large part.

67 C	Formal acceptance processes remain underdeveloped, and change management, training, and safety integration efforts are often insufficient.	Collaborate with regulatory and safety bodies to establish formal acceptance criteria and integrate FM into certification processes.	1) Formal Methods 2) Deployment Strategies and Roadmapping Framework (Partly)	1) Provide official models for reference testing 2) Regulatory and safety bodies are defined as stakeholders in the definition of acceptance criteria and decision-making.
73	In practice, change management efforts are often insufficient or fragmented.	Invest in dedicated change management strategies that secure leadership buy-in and provide tailored training across roles.	People oriented Change Management	Leadership plays a part in trust and acceptance.
74	Leadership engagement is limited, role-specific training is lacking and communication is unclear.	Enhance the change readiness in companies by encouraging a culture of openness and collaboration.	People oriented Change Management	Leadership plays a part in trust and acceptance.
77	Without addressing these human and organisational factors, technical innovations risk poor adoption or underutilisation.	Addressing both culture and technology is essential for sustainable migration and deployment success.	People oriented Change Management	Social influence and perception of organisational and technical infrastructure available to support the use of the technology play a part in successful deployment. The concept of IRTC sheds light on how readiness for technological change is shaped through close working relationships, employees often develop shared attitudes that shape their collective readiness
79 B	Communication is sometimes fragmented; ownership of dependencies is unclear, and potential delays can propagate unnoticed.	Assign clear responsibility owners for key dependencies to manage and coordinate delivery proactively.	Architecture 4evolution	Prescribes clear responsibilities
79 B	The absence of contractual clarity over interface responsibilities and evolving specifications hampers coordinated integration and delays delivery.	Close collaboration among system integrators, suppliers, infrastructure managers and regulators is essential to align interface standards and enable seamless multi-vendor migration and deployment.	Formal Methods	Requirements Engineering and interface definitions (architecture design) and multidisciplinary teams.

84 A	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Engage early with cross-border stakeholders and participate in EU-level regulatory harmonisation efforts to promote consistent requirements interpretation and regulatory alignment.	Formal Methods	Provide official models for reference testing
84 B	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Deploy domain-expert translators as needed and establish bilingual documentation standards to ensure clarity.	Formal Methods	Provide official models for reference testing
84 C	Currently, no formal guidance or best practices exist for managing multilingual technical communication or for aligning disparate national regulations in safety-critical railway projects. This absence leads to inconsistent interpretations, integration obstacles, and extended project timelines.	Prioritise model-based, executable specifications to minimise ambiguity.	Formal Methods	Provide official models for reference testing
86 A	This fragmentation leads to isolated testing, inconsistent toolchains, and late discovery of incompatibilities, increasing project risk and costs.	Promote cross-stakeholder collaboration on tool standardisation and testing procedures.	DevOps principles	Like, implementation of Continuous Integration, shared pipelines, automated regression testing

88C	No agreed baseline exists for modelling languages or minimum interoperability standards for tools within the railway domain. This results in substantial differences in tools, software, and modelling approaches, complicating collaboration and integration.	Promote early and continuous cross-stakeholder collaboration to evolve and maintain these standards, enabling robust integration across organisations and ensuring future-proof migration paths.	Deployment Strategies and Roadmapping Framework	The method aims at enhancing collaboration among various types of stakeholders to enable robust and efficient migration strategies across multiple organisations.

Table 34 Pure human initiative

nr	**Gap**	**Recommendation**
9B	The absence of a unified learning mechanism contributed to repeated deviations, loss of continuity during staff transitions and delays in refining operational and technical standards.	Require that lessons directly inform updates to procedures, standards, operational logic and migration planning.
10B	Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams	Introduce structured knowledge-transfer mechanisms—such as cross-team briefings and retrospectives—to reduce dependence on individual memory.
10C	Post-test insights were unevenly documented, reflection routines varied widely, and several lessons remained siloed within individual teams	Create an interactive shared cross-partner lessons-learned repository with traceability, accessibility and consistent documentation requirements.
11	Risk escalation and ownership did not consistently align with change decisions.	Define clear escalation paths and decision authorities to ensure accountability when risks evolve across subsystems.
12	Some risks remained embedded in project layers, delaying visibility for operational stakeholders.	Conduct regular cross-partner governance reviews to verify that change and risk remain integrated as the system matures.
14	Work-package risk framing functioned effectively where applied yet was not universal across teams.	Create a unified Change–Risk Board that evaluates every modification with explicit assessment of risk impact and mitigation ownership.
17	Interdependency maps across work packages were incomplete or late, increasing the risk of cascading delays.	Introduce alignment indicators to detect early drift in timelines, interfaces, and operational interpretations.

19	Trust degradation emerged when information was withheld, delayed, or mediated through too few individuals.	Adopt structured trust-maintenance protocols, such as joint retrospectives after milestones.
18 C	Reliance on a small number of individuals to translate expectations across organisations compounded delays and diluted trust.	Implement a cross-organisational governance protocol with defined roles, escalation pathways, and synchronisation routines.
20 A	Collaboration fluctuated with interpersonal dynamics instead of being supported by structured trust-maintenance practices.	Develop dependency and responsibility maps to clarify interrelations and reduce resistance.
20 B	Collaboration fluctuated with interpersonal dynamics instead of being supported by structured trust-maintenance practices.	Require early cross-functional engagement, including periodic in-person alignment sessions.
21 A	Partners lacked structured mechanisms to rebuild trust after setbacks or failed tests.	Develop dependency and responsibility maps to clarify interrelations and reduce resistance.
21 B	Partners lacked structured mechanisms to rebuild trust after setbacks or failed tests.	Require early cross-functional engagement, including periodic in-person alignment sessions.
23 B	Relationship-building practices were uneven, leading to variable trust levels and communication gaps across supplier teams. The shared understanding of the long-term migration strategy (e.g., GoA4 evolution) was not always aligned across actors.	Create a formal supplier engagement playbook documenting co-design expectations, communication protocols, and integration responsibilities for future projects.
26	Communication about the benefits of automation and safety principles was not embedded early in the programme.	Develop a dedicated communication plan for passengers and the public, explaining safety logic, benefits, and operational changes in accessible terms.
27 B	Technical information was rarely translated into non-expert language, limiting public comprehension.	Ensure transparency through periodic public updates, shared performance data, and visible evidence of safety assurance.
28	Mechanisms to monitor or respond to public sentiment were limited, and opportunities for demonstrations.	Track trust indicators (public sentiment, feedback, concerns) and integrate them into migration decisions.
33	Engagement with local authorities and mobility actors often began after technical planning, limiting flexibility to adjust test scenarios.	Establish a continuous communication loop with local actors (biweekly or monthly touchpoints) to maintain shared awareness and rapid issue escalation.
34	Municipal expectations regarding safety, disturbance and public perception were not consistently integrated into migration planning.	Establish a continuous communication loop with local actors (biweekly or monthly touchpoints) to maintain shared awareness and rapid issue escalation.
41 B	With AI-supported logic and software updates occurring far faster than rail asset renewal, internal specialist capacity proved insufficient to support continuous system recalibration and integration oversight.	Institutionalise system-level visibility: require weekly cross-domain integration reviews to monitor impacts across signalling, onboard, network and testing environments.

44 B	Continuous synchronisation of operational data and traffic-aware test planning are required to prevent degradation of ATO behaviour and to secure credible validation results.	Require interface documentation to state operational dependencies and procedural limits.
44 C	Continuous synchronisation of operational data and traffic-aware test planning are required to prevent degradation of ATO behaviour and to secure credible validation results.	Hold regular operational–engineering alignment reviews to ensure assumptions remain consistent with day-to-day practice.
45	Soft-skill capabilities varied across partners, creating vulnerabilities in tasks that require cross-organisational agreement.	Develop a structured negotiation protocol for resolving cross-partner conflicts.
46 A	Teams struggled to mediate conflicting priorities, facilitate discussions under pressure and distinguish relational tension from technical disagreement. Over-reliance on technical argumentation, without corresponding attention to expectations and trust, limited collaboration.	Require facilitation methods (e.g., joint issue framing, agreement mapping) for all significant disagreements.
46 C	Teams struggled to mediate conflicting priorities, facilitate discussions under pressure and distinguish relational tension from technical disagreement. Over-reliance on technical argumentation, without corresponding attention to expectations and trust, limited collaboration.	Focus on diplomacy, expectation management, active listening and multi-stakeholder facilitation.
47 A	Progress often depended on a small number of individuals with strong interpersonal abilities, creating bottlenecks and reducing programme resilience.	Document negotiation outcomes with traceable decision logs. This reduces repeated disagreements and ensures continuity even when personnel change.
47 B	Progress often depended on a small number of individuals with strong interpersonal abilities, creating bottlenecks and reducing programme resilience.	Require issue owners to verify whether the dispute is technical or relational before triggering formal escalation.
47 C	Progress often depended on a small number of individuals with strong interpersonal abilities, creating bottlenecks and reducing programme resilience.	Introduce a formal “alignment session” mechanism before critical milestones. These sessions ensure partners articulate assumptions, constraints and concerns openly.
52 A	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Embed structured reflective routines.
52 B	Communication during plan adjustments was intermittent, and retrospectives were held irregularly.	Begin operator and engineer training during early requirements definition, rather than after system development, to reduce resistance and support faster adoption.

54	Training remained largely reactive with no shared competency framework.	Begin operator and engineer training during early requirements definition, rather than after system development, to reduce resistance and support faster adoption.
57 A	Role definition was not always explicit, creating uncertainty about authority and task boundaries.	Implement clear role-framing protocols.
63 B	Formal co-design frameworks are limited or insufficiently embedded, resulting in misaligned expectations and integration challenges.	Promote open communication while managing confidentiality constraints.
76 A	Additional barriers include stakeholder silos, political considerations, intellectual property concerns and regulatory complexity.	Establish clear communication channels and cross-organisational forums to break down silos.
78 A	R2DATO needs to keep working towards a harmonised methodology to model, track and sequence dependencies between deliverables across work packages.	Continue to enhance collaboration and communication across work packages.
80 A	Risks of duplicated work, overlooked interdependencies, and misalignment between planned and actual delivery, undermining deployment success.	Support iterative, parallel execution of independent or loosely coupled deliverables.

Based on the results from the analysis in this chapter, the outcomes show that there is no single method that can address the full complexity of DATO migration. Instead, a combined approach, integrating technical methodologies with strong human-centred governance, is essential for achieving scalable and cross-border deployment of future train operations. As illustrated in Figure 5, the Deployment Strategies and Roadmapping Framework is an overarching layer that can address the DATO migration challenges. It supports the determination of where and when the other models and methods can be applied. The integration with other methods directly supports policy, regulation, and behavioural adaptation. The framework supports conducting structured alignment sessions between EU, national and regional authorities to harmonise certification expectations and reduce conflicting interpretations, as well as co-developing synchronised homologation roadmaps to harmonise evidence requirements and reduce divergent interpretations. While each method in Figure 5 addresses a specific domain, the Deployment Strategies and Roadmapping Framework coordinates their application, aligns stakeholders, manages uncertainty and structures long-term migration pathways for DATO.

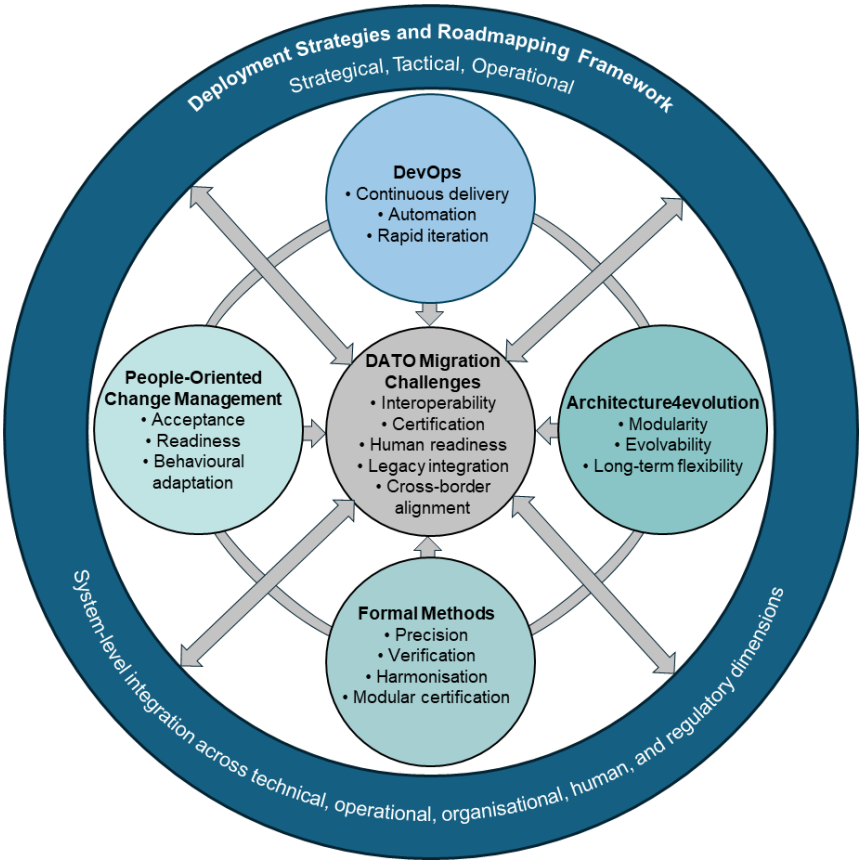


Figure 5 Overarching Deployment Strategies and Roadmapping Framework that integrates DevOps, Architecture4evolution, Formal Methods and People-Oriented Change Management

5 CONCLUSIONS

In this deliverable, an aggregation and further consolidation of the gaps and recommendations from D33.1 has been made. The main objective is to find supporting methods in bridging these gaps and endorsing the recommendations.

Several recommendations (17 in total) are supported by more than one method, for example "Develop a long-term, system-of-systems DATO integration plan that covers signalling, onboard systems, operational rules, traffic management and safety-case requirements across their full lifecycle" that is supported by four of the discussed methods.

Other recommendations (62 in total) were supported by only one method. For example, using scenario-based migration assessments to evaluate alternative progression paths is supported by the Deployment Strategies and Roadmapping Framework. Other (20) recommendations supported solely by this method collectively call for an adaptive and collaborative migration approach that continuously tests assumptions, captures learning early, aligns diverse stakeholders, harmonises regulatory and funding timelines, and integrates local, operational, and technical perspectives from the outset, to ensure that decisions are transparent, evidence-based, and coordinated across organisations and governance levels. Another example is "Develop a Local Operational Constraints Map that must be validated and updated with municipal partners before major design or test decisions" that is only supported by Formal methods.

A total of 79 recommendations is supported by one or more of the studied methods and 57 recommendations are not supported by any of the methods in the scope of WP33.

From a different point of view, the same recommendations are clustered in three categories. First, a set of 18 recommendations are specifically directed to FP2-R2DATO, for example "Define future competencies for ATO/GoA4 operations, including system integration, data interpretation, testing logic, and automation supervision." Many of these recommendations can be seen as encouragement or affirmation of the current way of working, others may be needing extra attention in the 2nd and 3rd Waves of ERJU.

The second category is a set of 15 recommendations that are relevant to the work of the System Pillar, for example "Develop harmonised, interoperable toolchains supported by clear guidelines". These recommendations could serve to support the work of the System Pillar and enhance collaboration between the Innovation Pillar and the System Pillar in the 2nd and 3rd Waves of ERJU.

Finally, the largest set of recommendations (83 in total) are those depending on human initiative, 47 of which are supported by one or more of the studied methods, while 36 of those are supported by none of the methods. For example, "Maintain a single validated reference dataset for all integration and performance assessments." is supported by DevOps. Recommendation "Promote open communication while managing confidentiality constraints." is a clear example of human initiative that is not supported by any of the methods.

The results show that DATO migration requires a combined technical and governance approach, as no single method can address its full complexity. The Deployment Strategies and Roadmapping Framework provides the overarching structure that aligns the individual methods, harmonises regulatory expectations, and guides long-term migration pathways.

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