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Forecast of gaps in critical supplies for Rail Innovations. A pan-European approach for resilience

Veronica Elena BOCCI[1], Wolfgang REIMER[2], Meng-Chun LEE[3],
Danijela DORIC[4], Jemylia RAIMBAULT[5], Nihan AYDEMIR[6]

[1]DITECFER, Pistoia, Italy
[2]GKZ, Freiberg, Germany
[3]GKZ, Freiberg, Germany
[4]RAILENIUM, Valenciennes, France
[5]RAILENIUM, Valenciennes, France
[6]Gebze Teknikal University, Istanbul, Türkiye
Corresponding Author: Veronica Elena Bocci (coordinatore@ditecfer.eu)

Abstract

Despite the increasing competition, the European rail supply industry still holds world leadership on the market for rail products thanks to its investments in R&D. At the same time Europe is not producing around ¼ of the Railway supplies it needs; these include raw materials, intermediate products and finished products from overseas. The COVID-19 and the following crisis ("permacrisis") and the related supply disruptions—despite their difference in duration and reasons—have taught that the more you rely on Global Value Chains for your supplies, the more vulnerable you are. And in too many cases, the supply of key components and raw materials is not only very far from Europe but also concentrated in a few places, which boosts vulnerability Not only: the greater frequency and severity of climate hazards is teaching that climate change is one more source of disruptions, interrupting production, raising costs and prices, and hurting corporate resilience. Also, supply vulnerability increases proportionally with the increasing demand for Advanced Technologies and Advanced Materials necessary to deliver (also) rail innovations.

Europe's actual capacity to produce for the market the innovations its industries and Academia are developing within the 'Europe's Rail R&I programme' is therefore challenged in the project "LEADER 2030", from which this research stems. This risk, however, is not only confined within Europe but is global.

The Paper proposed by this international team offers food for thought to the audience of the WCRR and considerations about the design and resilient sourcing for rail innovations.

Keywords: Critical Supplies, Innovation, Autonomy, Resilience, Value Chain

1. Introduction

The paper aims to present the approach followed by the 'LEADER 2030' project: (i) in trying to give a name and a seize to the critical raw materials and components needed to produce the rail innovations in Europe, out of the aggregated, skyrocketing, global demand for rare earths, copper, chips etc.; (ii) in forecasting the availability of those materials and components by the time they will be needed and the supply gaps; (iii) in identifying the products subject to obsolescence driven by the upcoming innovations, with special attention to those usually delivered by smaller companies; (iv) based on the above, in providing an 'alert' to the European rail value chain five years in advance to target time of 2030, to support decision-making with policy recommendations, industrial recommendations as well as with concrete, targeted actions along the value chain.

2. Disruptions and dependencies to threaten supply of railway innovations

2.1 Definitions

According to the ISO Standard 22301:2019 'Security and resilience – Business continuity management systems – Requirements', the word ***disruption*** means: "incident, whether anticipated or unanticipated, that causes an unplanned, negative deviation from the expected delivery of products and services according to an organization's objectives". Such meaning clearly highlights the incidental nature and the effects on business processes, on a clear micro-economic scale, i.e. at company/organisation level. For a macro-economic scale analysis, we can refer to the following definition: "Supply chain disruptions are defined as unexpected and unforeseen events or circumstances that disturb the regular flow of goods and materials along the value chain" [Novoszel, L., Wakolbinger, T., 2022].

Concerning the *nature* of the incident/event, supply chains disruptions can be triggered through a variety of factors, where a series of unrelated events could effectively cause a shortage. Even though the risks might appear distinct from one another on the surface, it is the culmination of different factors affecting different stages and aspects of a business output that can constitute the disruption. Each disruption produces a wide array of impacts, which ultimately disturb the regular flow of goods and materials along the value chain. In the most recent years, the areas mostly impacted by the supply chain shocks have been:

- Logistics breakdowns – due to transportation bottlenecks, port closures, shipping rates skyrocketing, etc.
- Lack of material supplies – due to concentration of suppliers, export restrictions, closure of suppliers, climate events, etc.
- Energy security – due to oil and gas skyrocketing prices, need to change sources and suppliers, etc..

While disruptions are caused by *events*, the other risk affecting the regular supplies is ***dependencies***, which have a *more structural* cause. The European Commission defines them as: "reliance on a limited number of actors for the supply of goods, services, data, infrastructures, skills and technologies combined with a limited capacity for internal production to substitute imports" [European Commission, 2021]. The concept is valid per se also at micro-economic level (individual business level), but of course here the reference is made to the macro-economic level. For such a reason, the European Commission defines ***strategic dependencies*** as: "dependencies that are considered of critical importance to the EU and its Member States' strategic interests such as security, safety, health and the green and digital transformation' [Ibidem].

The foresight study "Supply chain analysis and materials demand forecast in strategic technologies and sectors in the EU" [JRC, 2023] assesses supply chain dependencies and forecasts materials demand until 2050 in the European Union, as well as its materials needs and vulnerabilities and the potential supply chain bottlenecks in key strategic technologies—most of which relevant to the rail value chain: Li-on batteries; Fuel cells; Electrolysers; Traction motors; Data transmission networks; Data storage and servers; Additive manufacturing (3D printing); Robotics; Drones.

In the next paragraphs the risk forecast takes into consideration the impact of both types of causes—disruptions and dependencies— on the investments in innovations for the transformation of European railways.

2.2 The European rail market demand

For the scope of this research, the 'market demand' is represented by the innovations targeted by the Europe's Rail programme of the European Union, which has been investing around 1.2 billion euros in research and innovation for the period 2021-2027 and which follows a previous investment of almost 1 billion euros in the period 2014-2020 under the Shift2Rail programme. The ongoing innovations are classified in seven 'Flagship Areas', covering all aspects of railway transformation sought in Europe:

1. Flagship Area 1 (FA1) 'Network Management, Planning, and Control & Mobility' is implemented through the Flagship Project (FP) **FP1 'MOTIONAL - Mobility Management in a Multimodal Environment and Digital Enablers'**. Among the key innovations here is the **European Rail Traffic Management System (ERTMS)** and the ERTMS Level 3 has been identified as the core technology to achieve the 2030 future rail objectives.

2. Flagship Area 2 (FA2) 'Digital & Automated up to Autonomous Train Operations' is implemented through the **FP2 'R2DATO - Rail to Digital Automated up to Autonomous Train Operation'**. It involves development of key innovations around (i) *Advanced Signalling, Control and Automation*: focus is on advanced **Automatic Train Control (ATC)**, encompassing Automatic Train Protection (ATP), Automatic Train Supervision (ATS), and Automatic Train Operations (ATO) integrated with ERTMS/ETCS standards for hybrid-level autonomy (HL3) and Level 3 (L3) moving block operations; (ii) *Seamless Communication and Connectivity*: focus is on **Continuous Train-to-Ground Communication** as Reliable communication systems through Next-Generation Communication Systems like 5G and FRMCS (Future Railway Mobile Communication System).
3. Flagship Area 3 (FA3) 'Intelligent & Integrated Asset Management' is implemented through the corresponding **FP3 'IAM4RAIL - A Holistic and Integrated Asset Management for Europe's Rail System'**. The key innovation here is the Integrated Asset Management System (IAMS), which applies to both rail infrastructure and rolling stock. IAMS is designed to enhance maintenance efficiency and manage lifecycle costs effectively through **predictive and condition-based monitoring**.
4. Flagship Area 4 (FA4) 'A Sustainable and Green Rail System' is implemented through the corresponding **FP4 'RAIL4EARTH - Sustainable and Green Rail Systems'**. It focuses on driving environmentally friendly and energy-efficient innovations within the European railway sector. Its primary objective is to significantly **reduce the environmental impact of rail operations and infrastructure**, enhancing energy efficiency, reducing environmental impact, and improving resource use across the rail network.
5. Flagship Area 5 (FA5) 'Sustainable Competitive Digital Green Rail Freight Services' System' is implemented through the corresponding **FP5 'TRANS4M-R - Transforming Europe's Rail Freight'**. Its primary objective is to enhance the competitiveness and sustainability of rail freight services through digitalization and green technologies, and the key innovation is an Intelligent Train System, which incorporates advanced functionalities like **Digital Automatic Couplers (DAC)** and seamless rail freight.
6. Flagship Area 6 (FA6) 'Regional Rail Services / Innovative Rail Services to Revitalize Capillary Lines' is implemented through the corresponding **FP6 'FUTURE - Delivering Innovative Rail Services to Revitalize Capillary Lines and Regional Rail Services'**. Its primary objective is to rejuvenate regional rail services and capillary lines by adopting cutting-edge technologies and strategies, aiming to increase accessibility, operational efficiency, and sustainability in regional and rural areas through a **low-cost technical and operational framework for low density lines** to reduce the cost per kilometre both in terms of CAPEX and OPEX while increasing customer satisfaction as a European solution.
7. Flagship Area 7 (FA7) 'Innovation on new approaches for guided transport modes' is implemented through the corresponding **FP7 'PODS4RAIL'**. Its primary goal is to explore and develop the **next generation of flexible, and high-speed guided transport systems** based on a fully automated multi-modal mobility system for passengers and goods which is sustainable, interconnected, digital, on-demand, standardised, scalable and suitable for all transport modes.

2.3 Criticalities in the rail value chain: Methodology and first results

In order to identify criticalities along the value chain involved in the production and delivery of the target rail innovations, the following methodology was followed:

- Identify Innovations: Each FP's main innovation (and its more advanced version when the case) was identified based on official documentation and industry inputs.
- Break Down Functionalities: Per each main innovation, core functionalities and sub functionalities were outlined.
- Detail Products and Components: From the identified functionalities, relevant products were broken down into sub-assemblies and their respective hardware and software components, isolating hardware for further analysis.
- Extract Raw Materials: Components were mapped to their required raw materials, focusing on rare earth

elements crucial for advanced rail technologies.

- Categorize Needs and Potentially Obsolete Components: Each FP was analysed for new material requirements compared to previous technologies, as well as components likely to become obsolete.
- Likelihood of Technology Implementation by 2030: Assessed the probability of each innovation reaching operational status by 2030 based on its projected Technology Readiness Level (TRL), as detailed in Europe's Rail Multi-Annual Work Programme.
- Criticality of Raw Material Demand on the Sourcing Chain by 2030: Analysed the criticality of raw materials based on demand trends and the likelihood of related innovations being implemented, identifying potential supply chain risks by 2030.

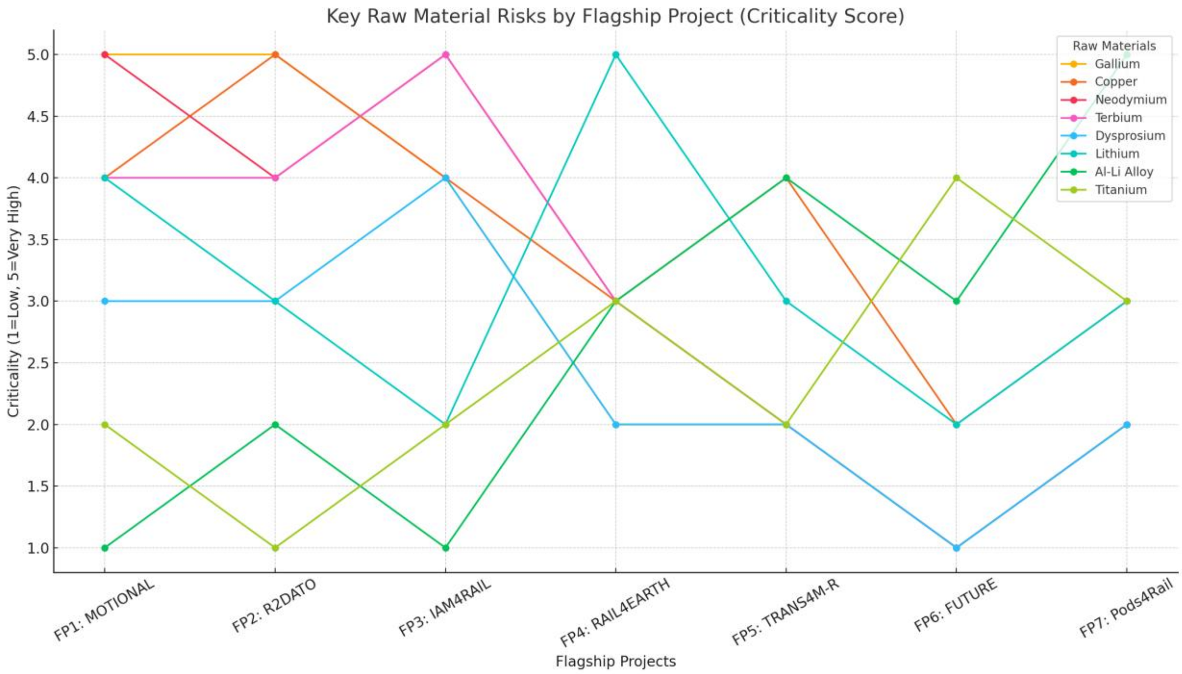

Figure 1: Criticality scoring of each Flagship Project

The Figure 1 summarises the risks associated to the realisation of each Flagship Project as result of the need for critical raw materials to produce the innovations of each FP. Findings include:

- Gallium, Copper, Neodymium, and Terbium show high criticality across the first three Flagship Projects (FP1–FP3).
- Lithium and Aluminium-Lithium alloys gain prominence particularly in FP4 (Green rail systems), FP5 (Freight transformation), and FP7 (New railway systems, Modular pods).
- Titanium appears with medium importance in later projects, especially for modular and lightweight infrastructure.
- Critical raw material reliance generally decreases from FP1 to FP7 in terms of legacy metals but increases for high-performance and rare earth materials in advanced modular solutions.

Gallium Arsenide (GaAs)	**Copper (Cu)**	**Neodymium (Nd)**	**Terbium (Tb)**	**Dysprosium (Dy)**	**Lithium (Li)**	**Al-Li Alloy**
High-frequency communication systems	Wiring and connectors across all systems	Magnetic sensors (FP1, FP3, FP4)	Fiber optic signal amplification (FP1, FP3)	Magnet stabilization for sensors (FP3)	Battery-electric propulsion (FP4, FP6)	Lightweight pod structures (FP5, FP6,

(FP1, FP2)	(FP1–FP7)					FP7)
AI edge processing & signal amplifiers (FP2)	Track circuits (phased out in FP1, FP2)	High-performance actuators (FP2)	Real-time information systems (FP4)	Real-time monitoring systems (FP3)	Portable power units (FP1, FP3)	
Digital twins & predictive maintenance (FP3)	High-efficiency motors (FP4)		Light and acoustic sensors (FP4)			
Semiconductor-based controls (FP4)	Data processing and electronics (FP3, FP5)					
RFID & communication modules (FP5)						

Table 1: Examples of usage of critical raw materials for rail innovations

The Table 1 provides examples of specific components of rail innovations requiring the most critical raw materials, emphasizing e.g. that gallium will become fundamental for the railway sector and 'critical' also under the point of view of *dependencies*. The primary producer of gallium arsenide (GaAs) is in fact China, which accounts for most of the world's gallium production. In August 2023, China's Government implemented gallium export controls, requiring licensing procedures to be carried out by China's gallium exporters. Other producers include Japan, Germany, Kazakhstan, and Ukraine.

Given the growing global demand for gallium, 'resilience recipes' such as boosting recycling efforts and/or researching alternative materials for substitution will become key not only for Europe but for the US and all countries home to rail industries. This will surely become one of the most important trends in the coming years. Similar considerations will be made by the LEADER 2030 project for each material resulting as critical for the target rail innovations.

Obsolete Component/System	Reference	Obsolete Component/System	Reference
Manual Brake Testing Systems	FP5	Manual Ticketing Systems	FP6
RFID-Based Tracking	FP5	Copper Track Circuits	FP1
Fixed Freight Wagons	FP5	Old Semiconductors (BJTs, MOSFETs)	FP1, FP2
Manual Driving Interfaces	FP2	Cast Iron Engines	FP4, FP5
Analog Signalling Systems	FP1	Steel-Based Coupling	FP5
Diesel Locomotives	FP4	Paper-Based Maintenance Tools	FP3

Table 2: Examples of components/systems which will become obsolete as the rail innovations will enter the market

Table 2 provides examples of components/systems which will become obsolete as 2030 approaches and the new rail innovations will enter the European market. Resilience of the rail value chain means alerting the producers of those components/systems about market changes, to enable product adaptation or transformations beforehand.

4. Conclusion

The paper shows the following trends concerning the rail innovations developed in Europe:

1. Massive Technological Transformation Across the Rail Sector
   - Full digitalization, automation, and AI integration are core to all Flagship Projects (FPs) in Europe.
   - Innovations like ATO (Automated Train Operation), FRMCS, AI-driven maintenance, Digital Twins, and Modular Pods will redefine operations and infrastructure.
2. Critical Dependence on Strategic Raw Materials
   - High-risk raw materials such as Gallium, Copper, Neodymium, Terbium, Dysprosium, Lithium, and Aluminum-Lithium alloys are essential across multiple FPs.
   - These materials face “High” to “Very High” criticality, especially in FP1–FP3, with major sourcing risks forecasted if demand spikes simultaneously.
3. Supply Chain Disruptions and Strategic Autonomy Risks
   - Europe’s rail innovation agenda is exposed to global supply chain pressures.
   - A major recommendation is enhanced European sourcing autonomy and circular economy practices to mitigate risk.
4. Innovation Interdependencies Across FPs
   - Later FPs (FP6–FP7) rely on foundational technologies developed in FP1–FP5 (e.g. Pods4Rail (FP7) leverages digital comms from FP1, AI control from FP2, and lightweight materials from FP4–FP5). This could enhance vulnerabilities in supplies—or, conversely, boost the ‘critical mass’ effect.
5. Phasing Out of Legacy Infrastructure
   - Dozens of traditional components and materials (e.g., diesel engines, cast iron, copper track circuits, BJTs, manual systems) are being systematically replaced with digital or green alternatives.
   - This transition will require coordinated phase-out strategies to avoid stranded assets.
6. Opportunities for European OEMs, Tier 1–3 Suppliers, and Small and Medium-sized Enterprises (SMEs)
   - There is a market opening for providers of high-performance electronics, AI software, composite structures, and eco-propulsion systems.
   - But this comes with a need for skills reskilling, CAPEX reinvestment, and standardized platforms to integrate innovations across rail types.
7. Ultimately, the paper shows the importance of intelligence analysis at both industrial and policy level and at scale, as it fosters value chain preparedness and resilience. The LEADER 2030 project findings, including the forecast on availability of raw materials in the next 20+ years, will contribute to supply autonomy in Europe also thanks to exploitation actions. International cooperation in this field is desired.

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