
Systemic Design Factors for Raw Materials Sovereignty: A TRL-Sensitive Taxonomy

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Abstract: Accelerating deep-tech industrialization is critical for future European prosperity and essential in the raw materials sector for meeting European raw materials sovereignty objectives. Practitioners need to understand which systemic design factors can be leveraged to accelerate deep-tech industrialization and overcome the systemic misalignments that cause breakthrough technologies to stall during the transition from laboratory research to industrial scale – a phenomenon known as the "Valley of Death". However, existing Innovation System research offers descriptive typologies but lacks prescriptive guidance, while Technology Transfer research reduces the systemic environment to a passive constant. This study develops a validated taxonomy of 14 systemic design factors for accelerating technology industrialization across six dimensions, following a Design Science Research approach. The taxonomy is grounded in systematic literature analysis and validated in six expert interviews with senior innovation managers from mining equipment manufacturers, providing prescriptive groundwork for TRL-sensitive ecosystem management.

Keywords: Innovation Ecosystem; Innovation Success Factors; Ecosystem Design; Taxonomy of Innovation; Raw Materials Sovereignty; Technology Transfer; Technology Readiness.

1 Introduction

The commercialization of deep-tech innovation – innovations characterized by significant scientific breakthroughs, high capital intensity, and prolonged development cycles – represents one of the most critical challenges for modern innovation management in science and industry alike. This challenge is particularly relevant for advanced technologies in the harsh raw materials industry as rapid technology transfer to the environments of mining is essential for meeting the objectives within the framework of the European Critical Raw Materials Act and securing industrial sovereignty (European Court of Auditors, 2026). However, breakthrough technologies frequently stall during the transition from laboratory research to industrial scale – a phenomenon known as the "Valley of Death" (Ellwood, Williams and Egan, 2022). These failures are often not a result of scientific inadequacy but of systemic misalignment and a lack of active design of the transfer environment (Schuh, Latz and Jakob, 2023; Zaitsava, Loi and Fullone, 2025).

This study addresses this challenge by developing a validated taxonomy of systemic design factors for innovation managers in the mining industry for the proactive development of innovation systems, to improve deep-tech transfer and contribute to raw materials sovereignty. The remainder of this paper is structured as follows: Section 2 provides a concise overview of the systemic challenges and resulting open research questions, section 3 describes the design science research approach and taxonomy development process applied, section 4 provides the detailed research findings and the description of the taxonomy, and in section 5 the results are discussed and concluded.

2 Background

Innovation management literature provides two primary but often disconnected streams to address this challenge: Innovation System (IS) research and Technology Transfer (TT) research. IS research offers frameworks for describing the structural components of innovation ecosystems, successfully identifying "what" elements and actors must be present and how they interact. Innovation systems are characterized by members and their activity flows, their multilateral relationships and a shared ambition for a focal value proposition to materialize (Adner, 2017). These systems are dynamic and influenced by a variety of contextual factors, requiring a co-evolution accounting for sectoral dynamics (Bergek *et al.*, 2015; Adner, 2017). Yet, while IS frameworks successfully capture structural configurations, they fall short of providing guidance on how these configurations must be actively transformed as technology matures. On the other hand, TT research focuses on describing processual transitions of innovation, often relying on the linear logic of the Technology Readiness Level (TRL) scale (Bozeman, Rimes and Youtie, 2015; Ellwood, Williams and Egan, 2022). While TT research excels at defining "when" milestones are reached, it frequently reduces systemic environments to passive contextual constants rather than designable variables (Olechowski, Eppinger and Joglekar, 2015).

There is an urgent need to understand how researchers, transfer organizations and companies can establish capabilities for managing co-evolving innovation systems (Talmar *et al.*, 2020; Schuh, Latz and Jakob, 2023). As technology moves toward industrial application, cooperation between different manufacturing companies occurs primarily during individual phases due to a lack of a holistic ecosystem approach (Riesener, Dölle and Kuhn, 2019). More research is required to examine how to advance TRL-frameworks to cater for collaborative innovation, as the TRL-framework promotes a producer-oriented mindset not suitable for today's co-creative innovation projects (Yfanti and Sakkas, 2024). Even comprehensive analyses of ecosystem management capabilities such as Altman, Nagle and Tushman (2022) neither synthesize findings into actionable guidance nor address specific dynamics of technology development across maturity stages. More recent IS research highlights the importance of co-evolution and examines how ecosystem

management must evolve (Leite *et al.*, 2025; Schieren *et al.*, 2026), yet without translating insights into frameworks that guide practitioners in designing and synchronizing system environments along technology development processes.

Enhancing innovativeness and supporting the development of innovation systems is especially important in the European raw materials industry given the tremendous strategic significance of securing raw materials for technological development and production in Europe. Increasing domestic primary production of critical raw materials is one key lever to strengthen European raw materials sovereignty (European Court of Auditors, 2026), which in turn requires fast and efficient innovation. According to Clausen and Sørensen (2022), innovation in mining is characterized technologically by advancements in digitalization, automation and electrification and systemically by high importance of the innovation ecosystem, requiring strong collaborations along value chains and explicit consideration of systemic, contextual factors to enable technological innovation for the transformation towards a green mine of the future. These contextual factors include societal dimensions such as changing work models enabled by remote-control technologies (Storey, 2025) and environmental considerations (Kashan *et al.*, 2022). This underscores the need for integrated and synchronized management of technological development and its surrounding innovation system.

By integrating the structural view of ecosystems with a dynamic perspective on technology development, this study produces a validated taxonomy of systemic design factors to support the proactive development of innovation systems. This paper therefore aims to answer the following research question: Which systemic design factors must be synchronized with Technology Readiness Levels to accelerate deep-tech industrialization in the raw materials sector?

3 Research methodology

To address the identified gap between static IS-research and linear-reactive TT-research, this study employs a Design Science Research (DSR) approach, aiming to generate a purposeful, actionable, validated and clearly defined artifact (Hevner *et al.*, 2004). Synchronizing the co-evolution of technology and its environment requires a thorough understanding of the individual factors researchers and managers can leverage, which in turn requires a comprehensive taxonomy of such factors. This taxonomy – the DSR artifact of this study – is developed following the basic principles of the extended taxonomy design process proposed by Kundisch *et al.* (2022), who refined the long-standing process proposed by Nickerson, Varshney and Muntermann (2013). The methodological approach of this study is structured into three phases:

- Phase 1: Literature selection and factor extraction
- Phase 2: Iterative taxonomy construction
- Phase 3: Empirical validation and final taxonomy design

3.1 Phase 1: Literature selection and factor extraction

Phase 1 involves a systematic literature search (Carrera-Rivera, Larrinaga and Lasa, 2022) to identify systemic design factors. The literature search was conducted in two major databases relevant for innovation and engineering, namely Scopus and IEEE Xplore, along the following focus areas:

- Innovation systems and ecosystems, ensuring coverage of the systemic lens.
- Technology readiness and maturation, ensuring coverage of the TRL lens.

To ensure relevance of the findings to current challenges, the search was limited to peer-reviewed English-language publications from 2022 onwards. Types of publications included proceedings, book chapters, and research papers.

Table 1 Literature Search

<i>Search terms</i>	<i>Details</i>	<i># Articles (gross)</i>	<i># Articles (net)</i>
Database	Scopus		
Query	(TITLE-ABS-KEY ("Innovation System*" OR "Innovation Ecosystem*")) AND (TITLE-ABS-KEY ("Technology Transfer" OR "TRL" OR "Technology Readiness Level*" OR "Valley of Death")) AND PUBYEAR > 2021 AND PUBYEAR < 2027 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "bk"))	182	118
Data base	IEEE Xplore		
Query	("Innovation System*" OR "Innovation Ecosystem*") AND ("Technology Transfer" OR "TRL" OR "Technology Readiness Level*" OR "Valley of Death")	65	63
Filter on years	From 2022 -2026		
Filter on language	Only articles in English		
Eligibility criteria	Only articles with clear link to technology development in developed industries; Only articles with focus on technology, innovation, development and (eco-) system-design factors.	181	32

Source: Authors' own illustration.

The systematic search yielded 247 papers. Following a de-duplication and formal screening process, 181 unique publications remained. Papers were screened for clear links to technological development in developed industries and containing relevant design factors; 32 papers remained covering deep-tech transfer, innovation system, and innovation ecosystem design (Table 1), providing 72 design factors after the inductive analysis.

3.2 Phase 2: Iterative taxonomy construction

Taxonomy development necessitates clear target requirements and ending criteria.

Target requirements are determined by the need for actionability: taxonomy elements must be actively influenceable and manageable by innovation managers. Factors that merely describe the state of technological maturity are therefore excluded.

Ending criteria include objective and subjective ending criteria. Objectively, factors must be grouped into dimensions that meet the requirements of being mutually exclusive and collectively exhaustive (MECE) so that each factor can be assigned to one and only one category. Subjectively, conciseness, ease of navigation and explanatory value are defined to support actionability and understanding of system design as well as the identification of a system's strengths and weaknesses. These subjective criteria informed the taxonomy's structure and granularity. Factors were iteratively consolidated; iterations alternated between conceptual-to-empirical and empirical-to-conceptual to ensure the creation of an actionable, robust and structurally sound taxonomy.

The iterative process resulted in six core categories and 14 MECE design factors organized along two conceptual dimensions, representing a deliberate design choice balancing sufficient coverage of systemic complexity with the conciseness required for practical application.

3.3 Phase 3: Empirical validation and final taxonomy design

Sector-specific actionability can only be achieved through empirical validation: following the suggestions for expert validation by Bogner, Littig and Menz (2009) and for expert validation in DSR by Venable, Pries-Heje and Baskerville (2016), six expert interviews were conducted with senior innovation and R&D managers from mining equipment manufacturers due to their pivotal role in driving technology adoption and leveraging the unused potential of available technologies in partnerships along value chains (Clausen and Sørensen, 2022). Experts were selected based on technical expertise and corporate responsibility, and vetted via a 15-minute digital pre-interview. Selected experts are described in Table 2.

Table 2 Interview Overview (anonymized)

<i>Interview</i>	<i>Company profile</i>	<i>Interviewee profile</i>
Interview A	Global provider of integrated bulk material handling and conveying systems, specializing in large-scale transport, mineral processing, and automated storage solutions for the mining industry.	Senior expert for global innovation management
Interview B	Global provider of heavy-duty equipment and transport solutions, focusing on machine intelligence and data-driven optimization for sustainable mining and construction environments.	Senior expert for smart systems
Interview C	Global manufacturer of heavy-duty surface and underground mining equipment, specializing in large-scale hauling systems and comprehensive digital management platforms.	Senior expert for global innovation projects
Interview D	Global manufacturer of heavy-duty mining equipment, specializing in autonomous haulage systems and large-scale hydraulic excavators.	Senior expert for new technologies and innovation
Interview E	Global provider of high-efficiency motor and large-drive systems, specializing in heavy-duty electrification and digital twins for mining and industrial application.	Senior expert for systems and solutions portfolio
Interview F	Global manufacturer of integrated electrification, automation, and digital solutions for the optimization of large-scale mining operations.	Senior expert for R&D & robotics

The interviews were conducted as semi-structured interviews of 75 to 90 min duration following a three-step flow:

1. Unprompted factor identification: experts described a recent innovation project and key factors for driving and hindering success.
2. Prompted taxonomy evaluation: the taxonomy was introduced and respondents asked to categorize each factor as a “critical” must-have factor, “supportive” success-factor, or “non”-factor, providing explanation and additional nuances from their mining perspective.

3. Thematic discussion: conversation on emerging themes and final considerations regarding future taxonomy potential.

The interview results were aggregated and used to sharpen, extend, or falsify the previously designed taxonomy iterations.

4 Taxonomy development and findings

4.1 Conceptual dimensions

In the context of Technological Innovation Systems (TIS), systems are viewed, organized and managed along the level of the individual technology (micro), the interplay with a specific system surrounding the technology (meso), and the exogenous environment influencing the system in the wider context (macro) – a trifold structure rooted in evolutionary economics (Dopfer and Potts, 2004) and widely adopted in innovation system research (Hekkert *et al.*, 2007; Markard and Truffer, 2008; Geels, 2011; Bergek *et al.*, 2015). Furthermore, ecosystem design theory differentiates between structural and dynamic elements as two layers that constitute innovation ecosystems (Hekkert *et al.*, 2007; Altman, Nagle and Tushman, 2022), setting the foundation for elements to manage the required co-evolution of innovation systems as outlined in section 2.

Analyzing the 72 factors from recent literature, first iterations allowed to clearly link factors to the three levels of the TIS view. Building upon existing established mental frameworks to enhance actionability (Kundisch *et al.*, 2022), the taxonomy design follows this ontological standard and adapts the three-level-view in form of its first organizing dimension. Inspiration is drawn from ‘A taxonomy of innovation’ by Luma Institute (2014) for using action- and objective-oriented descriptors, guiding users based on their desired outcome.

The first conceptual dimension of this taxonomy adapts the three-level TIS structure (macro, meso, micro) as its organizing principle; the three resulting elements are defined as follows:

Navigating: describes the dimension encompassing factors that interact with the exogenous environment beyond direct control of the developing company. Management actions focus on successful navigation by anticipation of and increasing influence over exogenous factors.

Orchestrating: describes the dimension encompassing all factors that interact with the surrounding environment within the sphere of control of the developing company. Management actions focus on deliberate orchestration of assets, actors, resources and relationships.

Configuring: describes the dimension encompassing all factors that interact directly with the technological development within direct control of the development company. Management actions focus on outcome-oriented configuration of the development system.

During the iterative review process, factors grouped along the first dimension proved stable and mutually exclusive. A second dimension emerged from the observation that factors differ fundamentally in their management logic: some focus on structural elements, while others focus on continuous alignment as technology matures, matching the aforementioned

structural and dynamic elements of ecosystems by Hekkert *et al.* (2007) and Altman, Nagle and Tushman (2022).

The second conceptual dimension of this taxonomy builds on the structural and dynamic elements of ecosystem design theory, introducing the two layers of „setup" and „synchronization"; the six resulting taxonomy categories are defined in Table 3.

Table 3 Taxonomy Dimensions

	<i>Setup</i>	<i>Synchronization</i>
<i>Navigating (Macro)</i>	Macro Environment Establishing structural conditions for navigating the exogenous environment across funding and foresight	Normative Alignment Synchronizing technological development with evolving policy, standardization and social dynamics
<i>Orchestrating (Meso)</i>	Strategic Assets Establishing structural conditions for orchestrating technology development across infrastructure, IP and talent	Value Network Synchronizing value chains, partnerships and resources with evolving development requirements
<i>Configuring (Micro)</i>	Solution Architecture Establishing the structural conditions for configuring technologies across system design and readiness levels	Value Proposition Synchronizing the development system with its deployment environment across value capturing and technology absorption

The six categories along the two conceptual dimensions are the results of the iterative design and validation process. The structural concept emerged early on and proved to be MECE, meeting the objective ending criteria; the final definitions represent the result of the taxonomy design process, meeting the subjective ending criteria.

4.2 Contextualization and Use Cases

Before presenting the factors of the taxonomy, contextual information from the six interviews that informed the taxonomy refinement process is provided.

Interviewee A highlighted mining-operator-driven innovation processes - often with consultancy-led procurement structures - requiring proactive engagement with the mining-operators to create a thorough, future-oriented understanding of customer requirements and feed visionary, differentiating concepts into the procurement process and shape procurement requirements. Critical early development steps are customer empathy, problem understanding, market monitoring, solutions scouting and partner screening. Managing systemic readiness across multiple dimensions simultaneously is important, as is transfer of new knowledge across organizational and functional boundaries, institutionalized by a dedicated MVP Hub at Company A. Product lifecycles of 30 to 35 years create exceptionally high robustness requirements and innovations must withstand real-life interference factors from the outset, whilst usage-data integration is a structural barrier for new business and maintenance models.

Interviewee B highlighted a strong foresight practice spanning across short-, mid- (5-yr) and long-term (20-40-yr) horizons. A Design Thinking-based use case illustrated how deep operational understanding, achieved through structured site observation and cultural proximity, is a prerequisite for meaningful innovation. Certification was identified as a critical market entry condition, requiring early integration into the development process rather than late-stage validation. Among mining employees, automation is associated with job displacement, requiring proactive communication strategies and a reframing around safety, pay and job quality. A near-failure of a mature MVP due to a stakeholder's objection

underscored the integration of human and organizational factors into technical readiness assessments.

Interviewee C highlighted funding resilience requirements of long-cycle deep-tech development in mining to cater for structural, corporate evolutions. Strong business cases and continuous stakeholder buy-in are essential for maintaining development momentum in addition to technical and market factors. Tension between technical ambition and market readiness must be managed as premature investments in technology development ahead of confirmed market demand impose critical risks. If early-stage developments fail to reach commercialization, market conditions can shift and disruptive technologies can appear during the development window, rendering prior investments worthless and underscoring the necessity of continuous, systematic evaluation of commercialization potential and new technologies.

Interviewee D highlighted the absence of prototypes as defining characteristics for innovation with a prototype being the first product delivered. This fundamentally shapes requirements for systemic readiness across all development streams simultaneously. Interviewee D pointed out the potential gaps between internal readiness assessments and real-world deployment conditions as an area for improvement. Divisional business structures require overcoming corporate boundaries through deliberate knowledge management, early alignment and competency integration in dedicated “new-tech” pre-development functions for systematic technology exploration and hedging. Mindset and team culture – measured in pride and identification – are critical in an industry struggling to attract talent.

Interviewee E highlighted the significance of trusted partnerships with mining operator customers: full access to mission-critical operational environments and emergency situations enabling a first-hand, deep understanding of valuable problems and being considered as a solution provider. Customer proximity and trust must be deliberately cultivated over time through offerings creating recurring site visits and engagement, to generate operationally sensitive insights. Innovative technologies should be communicated as concrete operational benefits at early stages to secure demand before formal procurement decisions are made, placing emphasis on connecting technology development with commercial functions. Focused research partnerships – consortia of two to three partners with complementary skills – enable fast, application-oriented development.

Interviewee F highlighted two main innovation drivers, namely efficiency and safety, that underly all innovation platforms across electrification, robotics and digitization, and the need for early inter-organizational collaboration to cover and integrate all required competencies. Innovation must begin outside-in: starting from customer-validated innovation platforms, scouting for existing solutions beyond mining and assembling the right consortia before development commences. The interviewee emphasized that consortium success is determined not by formal partner structures but by the people involved and the openness of the collaborative culture – stable consortia with the right individuals outperform formally well-structured but culturally closed partnerships.

The use cases presented above illustrate the diversity of systemic conditions under which deep-tech development unfolds in the mining industry. Recurring themes emerged around customer proximity, organizational resilience, modular development logic, and the importance of proactive ecosystem engagement.

4.3 Taxonomy Factors: Definitions and Empirical Grounding

The following section presents the 14 taxonomy factors as results of the iterative artifact development process, grounded in systematic literature analysis, expert contextualization and the prompted evaluation results summarized in Table 4.

Figure 1 visualizes the final taxonomy for systemic co-evolution. Each design factor is grounded in literature, contextualized through expert insights and formally defined below.

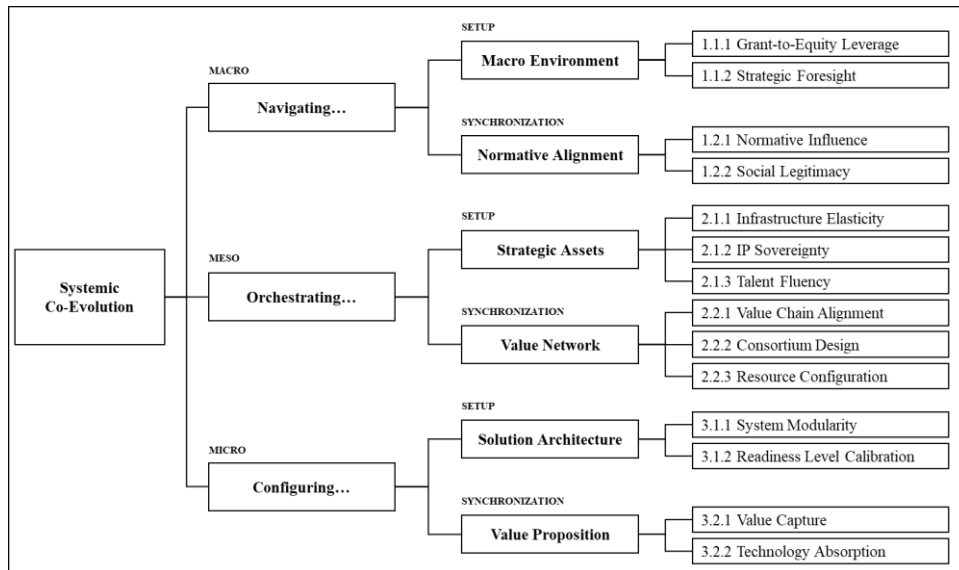


Figure 1 – Taxonomy for Systemic Co-Evolution

1.1.1 Grant-to-Equity Leverage

Literature highlights the role of targeted, public private funding for acceleration (Blundi *et al.*, 2022, p. 225; R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 3) and overcoming TRL adoption barriers (H. Chaimae, A. Mohammed and B. Oumaima, 2025, p. 645), helping to de-risk fundamental research for private commercialization (R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 6). In the mining context, this capability manifests in the ability to structurally connect cross-sectoral technology platforms with application-oriented R&D. By anchoring public funding to platform-level objectives rather than isolated projects, mining OEMs can ensure that academically funded research progressively feeds into proprietary development pipelines (Interview A, B).

Grant-to-Equity Leverage is defined as the capability to shape, secure, and leverage public financing instruments to cover CAPEX-intensive development phases and generate IP and commercial results.

1.1.2 Strategic Foresight

Literature suggests the anticipation of market and technology trajectories to inform present-day development decision and backcast TRL achievement goals from desired end-states (S. Saito *et al.*, 2022, p. 3; Knop, Olko and Brzóška, 2025, p. 522), ensuring development priorities are anchored in a long-term understanding (R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 2). In the mining context, foresight only becomes actionable when mapped against concrete customer requirement trajectories across short-, mid-, and long-term horizons – moving beyond broad trend monitoring toward platform-level prioritization that directly guides development investment decisions (Interview A, B, C).

Strategic Foresight is defined as the capability to systemically define customer need platforms, anticipate long-term geopolitical, technological and macroeconomic scenarios to derive actionable innovation strategies.

1.2.1 Normative Influence

Literature considers policy regulations a barrier to innovation (B. M. Mdau and S. Grobbelaar, 2025, p. 5; Akritidi and Kanavos, 2026, p. 95), requiring companies to actively participate in policy making and alignment for successful commercialization (Chen *et al.*, 2022, p. 11; Pushpanathan and Elmquist, 2022, p. 9), to engage along policy lifecycles (Dehler-Holland, 2025, p. 16) and to support the development of targeted regulations suitable for emerging technologies (Díez-Hernández *et al.*, 2026, p. 13). Furthermore, adhering to standards (B. M. Mdau and S. Grobbelaar, 2025, p. 5) and shaping new standards and interfaces with other products or technologies in coordinative processes (Pushpanathan and Elmquist, 2022, p. 11) are highlighted. In the mining context, regulatory and industry standards are primarily shaped by mining operators, not equipment manufacturers. OEMs must cultivate strategic partnerships with operators to gain indirect influence and must be able to identify emerging technology domains where standards are not yet set but can have a disruptive potential (Interview A, C, D, E).

Normative Influence is defined as the capability to actively align technological development paths with evolving regulatory frameworks and to proactively shape compliance and norming conditions through direct engagement or strategic positioning within customer partnerships.

1.2.2 Social Legitimacy

Literature highlights the importance of addressing and overcoming customer acceptance barriers on systemic and communicative level (B. M. Mdau and S. Grobbelaar, 2025, p. 5) and of screening of social risks before scaling (Díez-Hernández *et al.*, 2026, p. 13). In the mining context, social legitimacy includes two distinct but interdependent levels. Externally, automation technologies face persistent association with workforce displacement, requiring proactive communication strategies that reframe technological advancement in terms of safety improvements and job quality rather than efficiency alone. Internally, the industry's struggle to attract new talent creates an equally critical legitimacy challenge – innovative technologies must be positioned not only as operationally beneficial but as signals of an evolving, attractive industry identity (Interview B, C, D, E).

Social Legitimacy is defined as the capability to proactively shape public perception and societal acceptance of emerging technologies by addressing social risks, reframing narratives and positioning technological advancement as aligned with broader societal values.

2.1.1 Infrastructure Elasticity

Literature highlights creating experimental infrastructure and performing trials and pilots. (T. Norp *et al.*, 2024, p. 1113; N. Tachaboon and T. Piyatamrong, 2025, p. 483; R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 4). Especially for research-intensive innovation, access to highly specialized labs (H. I. Hibino, S. Miyashita and S. Sengoku, 2022, p. 3; M. Bliemel *et al.*, 2026, p. 872), regulatory sandboxes for customer co-creation under controlled but realistic conditions (Pushpanathan and Elmquist, 2022, p. 5; V. Fedák, R. Hudák and F. Jakab, 2022, p. 157), and digital-twin-in-the-loop validation before field trials (G. Sadovskii *et al.*, 2025, p. 5) are mentioned as important factors. In the mining context, real-world demonstrations and generation of certification- and sales-relevant proof points are important. Combining in-lab and on-site testing is required, supported by a shift from physical to software-based testing and adoption of digital twins and 3D pit modelling. Balancing structural, synergetic environments and project-specific ad-hoc testbeds as well as negotiating protected experimental real-world environments are important (Interview A, B, C, D, E).

Infrastructure Elasticity is defined as the capability to strategically design, access and reconfigure physical and virtual testing environments that enable real-world technology testing outside normal regulatory constraints across TRL stages.

2.1.2 IP Sovereignty

Literature highlights the importance of active IP management whether in combining IP for joint exploitation (Pushpanathan and Elmquist, 2022, p. 5; Sarpong *et al.*, 2025), for defining ownership in joint development efforts (K. A. Bello, M. G. Kanakana-Katumba and R. W. Maladzhi, 2025, p. 4), when handing out challenges to external co-creation teams (Li and Li, 2026, p. 10), or for effective IP transfer from academia to industry (R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 3). In the mining context, the strategic importance of IP orchestration is amplified by a consolidated market structure with dominant central players, where IP documentation and protection represent critical competitive assets. Experts emphasized treating IP strategy as a design discipline from the concepting stage rather than an administrative afterthought – actively structuring ownership, licensing and joint development agreements in anticipation of future collaboration architectures (Interview A, B, C).

IP Sovereignty is defined as the capability to actively design and reconfigure IP ownership and licensing structures and protect IP in joint development agreements in alignment with evolving collaboration requirements and competitive positioning across TRL stages.

2.1.3 Talent Fluency

Literature highlights the significance of people for facilitating knowledge transfer across organizational boundaries (F. Asplund *et al.*, 2022, p. 6; V. Fedák, R. Hudák and F. Jakab, 2022, p. 157; R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 5; M. Bliemel *et al.*, 2026, p. 872), of addressing the fundamental mismatch between academia's focus on long-term theoretical knowledge and industry's demand for market-driven, timely application (K. A. Bello, M. G. Kanakana-Katumba and R. W. Maladzhi, 2025, p. 4) and the significance for evolving human resources, competencies and management models when adopting new technologies (G. Sadovskii *et al.*, 2025, p. 5). In the mining context, a limited talent pool requires proactive close collaboration between HR and development functions to manage team composition and emerging skill requirements. Emphasis is placed on interdisciplinary skills and people who can derive solutions from customer problems. Protected team structures are identified as an organizational prerequisite, enabling the development of new competencies, team culture and cohesion (Interview A, B, C, D, E, F).

Talent Fluency is defined as the capability to acquire and develop specialized human capital with deep technical skills and interdisciplinary skills and integrate them into high-performing teams.

2.2.1 Value Chain Alignment

Literature highlights the management of all relevant aspects along the value chain for successful development and introduction, from supply infrastructure (B. M. Mdau and S. Grobbelaar, 2025, p. 5), cooperations with up- and downstream partners, investors and customers (Li and Li, 2026, p. 11), or exchange interfaces and data (G. Sadovskii *et al.*, 2025, p. 5). In the mining context, value chain integration operates along three distinct but interdependent imperatives: early customer integration to ensure solution design is anchored in real operational requirements, early supplier integration to secure parts availability, cost structure assumptions and supply forecasting, and the deliberate definition of interaction and data exchange points along the value chain. (Interview B, C, D).

Value Chain Alignment is defined as the capability to strategically time and manage the integration of customers, suppliers and partners across material, data and operational interfaces to ensure solution relevance, supply security and interoperability across TRL stages.

2.2.2 Consortium Design

Literature highlights collaboration within innovation ecosystems and strategic partnerships (N. Yıldırım and D. Tunçalp, 2023, p. 2608; H. Chaimae, A. Mohammed and B. Oumaima, 2025, p. 645). Coordination of individual innovation ecosystems in a Hub and Spokes structure is suggested, to centralize coordination of activities and creating a “one-stop-shop” for solution design (T. Norp *et al.*, 2024, p. 1111). Universities are widely regarded

as important actors in consortia for facilities and knowledge transfer (V. Fedák, R. Hudák and F. Jakab, 2022, p. 154; N. Yıldırım and D. Tunçalp, 2023, p. 2617; Braslina *et al.*, 2025, p. 652; Gonzalez-Urango, Mu and Corona-Sobrino, 2025, p. 9; R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 6). In the mining context, experts described a sequential orchestration logic beginning with a thorough understanding of customer requirements, followed by systematic mapping of internal and external capabilities, before deciding how to structure collaboration and with whom. This customer-centric sequencing – rather than opportunistic partnership formation – determines both partner selection criteria and the appropriate degree of alignment versus control within any development consortium (Interview A, B, D, E).

Consortium Design is defined as the capability to systematically identify, select and involve complementary partners based on customer-centric requirement analysis and capability mapping, structuring trusted development consortia with deliberate alignment over control across TRL stages.

2.2.3 Resource Configuration

Literature highlights transformational leadership and project management capabilities for innovation programs (N. Yıldırım and D. Tunçalp, 2023, p. 2608), coordinated by dedicated innovation project managers (S. Ozcan, A. Stornelli and C. Simms, 2024, p. 9933), and the critical role of cross-functional embedment within organisations (N. Tachaboon and T. Piyatamrong, 2025, p. 482) and the tailored configuration of teams and resources (Pushpanathan and Elmquist, 2022, p. 5; B. M. Mdau and S. Grobbelaar, 2025, p. 5). In the mining context, demonstrating progress to internal and external stakeholders and constant business case evaluation enables resilience and the ability to configure team and resources as required throughout development phases (Interview A, B, C, D, E).

Resource Configuration is defined as the capability to actively configure and sustain the human, financial and organizational resources required for long-cycle development programs, maintaining commitment and resilience through systematic progress demonstration and continuous evaluation across TRL stages.

3.1.1 System Modularity

Literature highlights modular product design with minimal dependencies to reduce friction and costs (B. M. Mdau and S. Grobbelaar, 2025, p. 5; G. Sadovskii *et al.*, 2025, p. 5), and its role in contributing to the emergence and control of innovation ecosystem focusing on technology development for respective modules (Pushpanathan and Elmquist, 2022, pp. 11–12). In the mining context, modularity is highlighted for fast, iterative testing of components and features, whilst keeping an economically viable product base with high shares of scalable equal parts (Interview A, B, C, D, E, F).

System Modularity is defined as the capability to design modular product- and system-architectures with clearly defined interfaces, enabling fast iterative development, scalable customization and deliberate control over ecosystem participation.

3.1.2 Readiness Level Calibration

Literature highlights readiness level assessments across various dimensions (S. Ozcan, A. Stornelli and C. Simms, 2024, p. 9927, 2024, p. 9933; G. Sadovskii *et al.*, 2025, p. 5; H. Chaimae, A. Mohammed and B. Oumaima, 2025, p. 645), and balancing technological novelty, industry maturity, and ecosystem building strategies (Li and Li, 2026, p. 12), to avoid overinvesting in technology development and ensuring successful customer deployment (G. Sadovskii *et al.*, 2025, p. 5). In the mining context, technology, service and commercial readiness streams must be simultaneously validated at defined gates. Early demand creation is needed, making sales readiness an explicit and parallel development stream alongside technical readiness (Interview A, B, C, D, E).

Readiness Level Calibration is defined as the capability to simultaneously assess and synchronize multiple readiness dimensions to ensure holistic deployment readiness and early demand creation.

3.2.1 Value Capture

Literature highlights value capturing along development phases (S. Ozcan, A. Stornelli and C. Simms, 2024, p. 9927; B. M. Mdau and S. Grobbelaar, 2025, p. 5) through early value proposition definition (Anderson *et al.*, 2022, p. 7) and rigorous evaluation of sales hypotheses and value delivery systems and partners (Pushpanathan and Elmquist, 2022, p. 11; Hubert, 2023, p. 3445; N. Tachaboon and T. Piyatamrong, 2025, p. 481; R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 4). In the mining context, close relationships between OEM and operator are crucial to generate required insights, and value capturing must be designed beyond the first customer for scaling (Interview A, B, C, E).

Value Capture is defined as the capability to define and adjust the commercial business model for value capturing (customer-orientation) under uncertainty.

3.2.2 Technology Absorption

Literature highlights technological absorption through cultural tech-openness, monitoring and scouting (H. -C. Huang, H. -Y. Shih and T. -H. Ke, 2024, p. 2072), noting its importance before commencing work (S. Saito *et al.*, 2022, p. 3; R. Sotelo, G. Lefebvre and A. Chen, 2025, p. 4), to sharpen innovation platforms and concepts (J. Kim and Y. Geum, 2025, p. 3395). In the mining context, tech-absorption is particularly critical in early development phases and enabled by systematic scanning and evaluation of external technologies and securing of access rights before technological consolidation (Interview A, B, C, D, F).

Technology Absorption is defined as the capability to systematically monitor, scout and selectively integrate external technologies into the development process.

Table 4 Interview Results

<i>Item</i>	<i>Interview A</i>	<i>Interview B</i>	<i>Interview C</i>	<i>Interview D</i>	<i>Interview E</i>	<i>Interview F</i>
1.1.1	Supportive External funding is supportive for transversal-topics; IP-build-up a must	Critical Lobbying for key topics; build consortia for cross-sectional topics & add on owned-IP; particularly relevant for emerging technology domains	Supportive Less relevant; great ideas can be funded internally	Non Not relevant; inhouse R&D; no focus beyond core product	Non Not relevant; timelines don't allow for generating competitive advantages	Supportive Budgets must come from within; external funds support consortia building but not development
1.1.2	Critical Focus on long-term prioritization along horizons; based on customer-centric innovation platforms & respective market monitoring	Critical Becomes actionable by focusing on customer need platforms & defining how they will evolve over all horizons	Critical Focus on detailed customer requirements & development criteria; specific, actionable focus on present issues; long-term areas might be roughly mapped	Supportive Large trends monitored but divisional freedom limited; main observation points are short-term demand- & supply-oriented	Supportive Important for focusing on the right problems; short-term focus most crucial (3–5-year planning cycles)	Critical Building & revising customer-centric innovation platforms for next ~5yrs
1.2.1	Supportive A is a supplier; mining operators shape policy; strategic partnerships & conversations allow steering	Critical Monitor challenges & apply implications to long- / mid- / short-term scenarios; proactive, early norm shaping important; standardization bodies help spread awareness & build demand	Critical Certification priorities based on core-markets; reactive, customer triggered; little influence; customers & operators have standards in place; relevant for automation & electrification	Critical Important to understand & adhere to all compliance aspects early; active norm shaping not always necessary	Critical Permitting must be considered early in processes and gates; norming not relevant – lengthy processes & no disruptive norms in sight	Supportive Scalability of basis technology across various industries & technological applications must be ensured; part of commercial awareness within teams
1.2.2	Supportive Must include ESG: feeds into legitimacy strategy of operators (sustainability goals & assessments)	Supportive Automation is associated with job losses; must be addressed as part of launch strategy; new tech can make industry attractive	Critical Workforce requires change management for increased acceptance of automation & autonomy	Critical Important for future talent attraction; industry struggles to attract new talent	Critical Includes skills & appeal of industry; communication of positive societal impact	Non Technological acceptance is driven by customer needs around efficiency and safety improvements
2.1.1	Supportive Requirements difficult to foresee; partnerships & access are important	Critical Sandboxes for demonstration of results & benefits & certification; adjust testing routines to new	Critical Important to test with & without customers early & generate proof points; 3D pits, digital modelling &	Critical Fast testing cycles; generation of early proof points; simulation environments & tool-chains	Critical Essential for fast market introduction; ideally in unregulated scenarios; access to mission-critical customer processes; design trusted	Critical Testing at mining-sites under real conditions enabled by trusted partnerships; laboratory testing and

2.1.2	Critical IP documentation for external exchange & protection (especially in small mining world with dominant central players)	technologies; shift from physical to software-based testing	digital twins highly important for development	important; evaluation of synergy-potential against ad-hoc approaches	partnerships for physical and operational proximity	on-site testing in most realistic environments
2.1.3	Critical Projects stall without the right people & experts; capability includes scouting & integration	Critical Involve IP unit early at concepting stage; leverage own technologies for trades & licensing; IP as design discipline not admin	Critical IP protection essential; restrictive communication based on classification system	Supportive Not as a metric but as a supportive competence	Supportive IP does not equal success; right strategies for protection and use matter more than metrics	Critical Mainly IP protection within consortia and against operators; IP must remain with OEM;
2.2.1	Supportive Dual-sourcing strategies; data integration; defined interaction points with operators	Critical People are prerequisite for progress; requires proactive scouting across global development networks; turn tacit into explicit knowledge as people move on	Critical Close connection to HR; strategic talent development for new tech requirements; ambidexterity & protected team development	Critical Team composition & culture critical; pride & identification within the team should be used as KPIs	Critical Creating and developing the right talent base and team composition critical for fast and successful development	Critical People composition & culture (“get shit done”); attitude and experience; 2-3 people who can think from customer problem to concept suffice
2.2.2	Critical Customer centricity & needs; two steps: monitoring & scouting; co-development creates speed; what exists should be bought; dissemination of knowledge	Critical Involve right players once requirements are identified; strategically design trusted partnerships for insight generation	Critical Early parts & supplier sourcing key to secure cost structure & supply assumptions	Critical Highly important on supplier & demand side; prototype is the first product – no room for error	Supportive Customer proximity key to identify upcoming innovation platforms; supplier transparency supports forecasting	Supportive Main issues occur at intersection of development to industrialization.
2.2.3	Critical Customer centricity & needs; two steps: monitoring & scouting; co-development creates speed; what exists should be bought; dissemination of knowledge	Critical Stay tech-open; create partnership & alignment rather than control	Supportive C is a highly vertically integrated company; little need for external ecosystem or network; connect the right people internally	Critical Close co-development with tech suppliers as tech development at supplier level may show positive ROI decades later; internal collaboration through informal exchange & clear documentation	Supportive Strong in-house competencies reduce consortia dependency; use research partners i.e. (application-focused) universities; customer closeness via sales and service teams underleveraged	Critical constituted by open climate and the right people (not partners); can be facilitated by public funding; access to internal knowledge & exchange part of culture
3.1.1	Critical Skills require change from early to later stages: seamless change from systemic thinkers to topic experts	Supportive Requires strategic involvement of key decision makers; late-stage stakeholder objections can stall or derail mature developments	Critical Critical for budget release; ongoing accurate business case evaluation; include resilience in case of company or market shifts	Critical Progress demonstration as key mechanism for budget & stakeholder management	Critical Business case with clear evaluation criteria; focus on scalability & early value demonstration	Critical availability of the tech of choice; freedom to staff, develop & test
3.1.1	Critical Enablement of various & fast exploration iterations (change, test,	Critical Design, test, learn requires modular thinking & architecture	Critical Setting clear interfaces & modular testing as structural foundation of	Critical Reduction of costs & resources required for changes; independent	Critical Modular architecture is standard & a must-have; 60-80% of parts must	Supportive Dependent on type of technology and product

	validate) up to hard development gates		the NPI process; safety-critical redundancy requirements must be embedded from the outset	modules allow scalability & high adoption rates	be scalable for customization & feature extension	
3.1.2	Critical All relevant ensured to be ready at hard gates; integrated development & launch preparation	Critical Solution- & service-readiness-levels ensure sales & aftersales are aligned & prepared	Critical Requires structure & clear gates to understand & define what needs to happen when	Critical Prototypes are first products, exchange & client-side feedback required; clear definitions of finished states	Critical Clear PLM with stage-gates, quality gates & milestones; adherence to technical specs	Supportive Changes with maturity; first focus on tech and concepting; other RL must start at the right time
3.2.1	Critical Clear definition of tailored value capturing model; direct involvement of sales (awareness & adoption)	Critical Combine customer insight & value proposition design; requires trusted partnerships & strategic planning; Understand operational environment to add value	Critical Clear understanding of commercialization – pricing models & demand	Supportive Important to understand & tackle the right customer problems; ensure willingness to pay	Critical Scalability across multiple customers & competitive solutions; ongoing business potential analysis	Critical Clearly defined value model required; customer insights and working business model as foundation
3.2.2	Supportive Important during exploration before design freeze: focus on customer needs; adoption supported via MVP-team	Critical Create exclusive rights to use technologies early; consider acquisition strategies for start-ups & new tech	Supportive Tech-openness at early stages; dependent on in-house competencies & supply structure; align with risks at client sites	Critical Important to scan new technologies and select for testing and iterations; involve structural client feedback	Supportive Conservative - solutions don't evolve once customer is convinced; new technologies must be communicated as benefits early	Critical involves constant scouting; involves designing the organization so R&D can seamlessly flow into production

Source: Interview results, authors' own illustration.

5 Discussion & Conclusion

This study set out to answer the following research question: Which systemic design factors must be synchronized with Technology Readiness Levels to accelerate deep-tech industrialization in the raw materials sector? The primary outcome is a validated, sector-specific and industry-oriented taxonomy of precisely these systemic design factors: it provides a prescriptive structure instead of descriptive typologies as a comprehensive and actionable set of 14 distinct and nuanced factors. Section 5 is structured as follows: a short discussion of the theoretical contribution, a short discussion of empirical findings and practical implications, followed by limitations, future research and a conclusion.

5.1 Theoretical Contribution

This study challenges the prevailing assumption that deep-tech transfer is primarily a challenge of linear technological maturation. By integrating the structural view of IS research with the dynamic perspective of TT research, the taxonomy overcomes the structural bias of IS research and the linear-reactive logic of TT research.

The developed taxonomy contributes to the body of knowledge in three ways: a) it provides an actionable structure of systemic design factors, b) it serves as prescriptive groundwork for TRL-sensitive system management, and c) it provides the necessary dimensions to categorize and localize systemic barriers, offering a strategic path toward accelerating European technological sovereignty in the raw materials sector.

The analysis further suggests that the current body of research does not cover all relevant factors equally: several factors – in particular on macro and micro levels – are empirically validated but theoretically underrepresented in recent literature. Furthermore, practitioners stress the importance of customer- and market centricity and a clear focus on value and outcomes as a prerequisite for success: a perspective widely unaddressed in IS and TT research – pointing to clear directions for future theoretical development.

5.2 Practical Implications

The empirical validation revealed several findings that extend beyond the theoretical framework and carry direct practical relevance.

Factor relevance corresponds with the strategic foresight horizon of the organization: the capacity to leverage public funding presupposes a sufficiently long planning horizon to identify, shape and capitalize on funding opportunities – making Grant-to-Equity Leverage a strategic orientation rather than a purely financial capability (Observation 1). Factor relevance varies systematically with actor type: macro-level synchronization factors were rated critical primarily by OEMs with sufficient market position to shape regulatory environments, while component suppliers rated these as supportive or non-relevant – suggesting the taxonomy may serve as a foundation for actor-specific design guidance (Observation 2). A consistent meta-theme across all interviews directly validates the central premise of this taxonomy: technical readiness alone is insufficient for successful industrialization – organizational culture, stakeholder management and customer proximity frequently determine success or failure independently of technical maturity (Observation 3). Factor relevance for IP Sovereignty reveals divergent patterns that reflect different innovation strategies. Organizations pursuing a technology-outside-in approach for emerging technologies emphasize strategic IP acquisition, while organizations maintaining broad in-house solution portfolios focus on protection within consortia (Observation 4). Finally, a notable cross-interview finding concerns the strategic significance of close, trust-based relationships along the value chain. Experts consistently emphasized proximity to customers beyond transactional exchange as a prerequisite for accessing operationally

sensitive insights, defining first solutions for later scaling and gaining access to real-world application scenarios (Observation 5).

For the academic community, the central lesson for researchers and transfer managers is the necessity to shift from purely descriptive typologies toward a prescriptive science of system engineering: ecosystem should not be perceived as an exogenous given. The developed taxonomy can be utilized as a structured foundation for identifying systemic gaps and evolutionary steps.

For industry managers, the study offers a pragmatic shift in perspective: the "Valley of Death" is reinterpreted as a synchronization gap rather than a mere funding deficit. Successful deep-tech industrialization requires proactive management of the systemic environment as a co-evolutionary process – ensuring that corporate capabilities for ecosystem design along the taxonomy factors are sufficiently developed and that ecosystems evolve parallel with technical maturity rather than reactively following it. The taxonomy provides a structured foundation for identifying and localizing systemic gaps and prioritizing management interventions across all relevant dimensions.

5.3 Limitations, Future Research and Conclusion

This study has several limitations. The empirical validation is based on six expert interviews drawn exclusively from mining equipment manufacturers, limiting generalizability across actor types and value chain positions. The perspectives of mining operators, deep-tech start-ups and transfer intermediaries remain unrepresented. The literature search was deliberately constrained to publications from 2022 onwards, ensuring currency but potentially excluding relevant foundational contributions. Finally, the deliberate reduction to 14 factors prioritizes actionability – the taxonomy represents a purposeful design choice based on objective and subjective ending criteria.

Future research should prioritize three directions. First, research should empirically investigate how factor criticality and management logic shift across TRL stages – from early-stage research through applied development to pre-commercial demonstration. Second, the validation sample should be extended to include mining operators, deep-tech start-ups and transfer intermediaries, allowing for actor-specific factor relevance profiles and a more comprehensive understanding of systemic design priorities across value chain positions. Third, research should focus on the development and empirical validation of a TRL-sensitive capability assessment tool that operationalizes the 14 factors across maturity stages, enabling organizations to systematically diagnose systemic gaps and prioritize interventions.

Ultimately, this research concludes that the systemic environment of deep-tech development is not an exogenous given but a designable variable, and that its co-evolution with technology maturity is an organizational competency that should be systematically managed. By providing a validated taxonomy of 14 systemic design factors, this study offers the necessary foundation for a TRL-sensitive approach to ecosystem management in the raw materials sector.

The authors used Omnifact Claude 4.6 Sonnet to improve the language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final version of the paper.

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