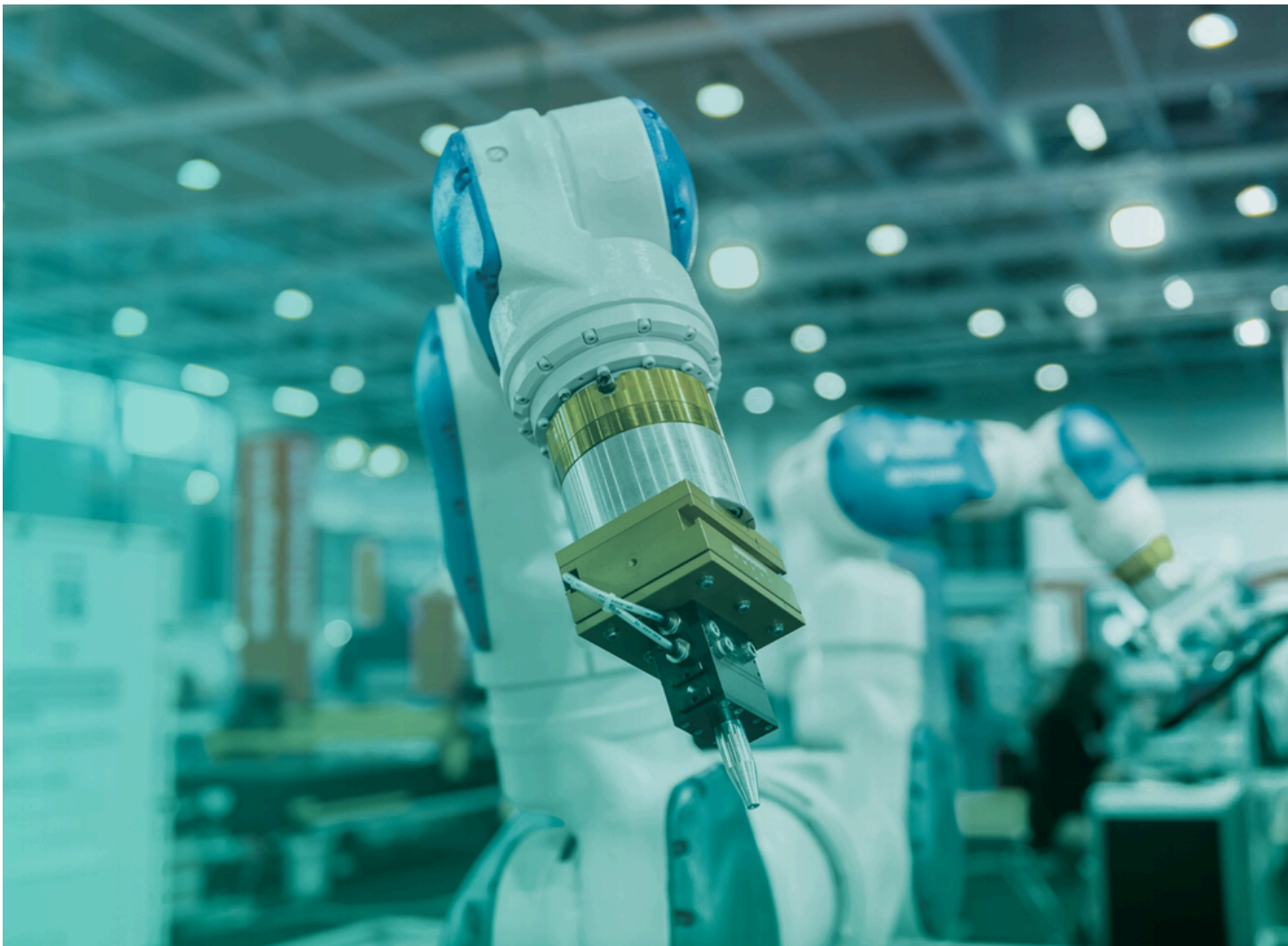


INSIDER'S PERSPECTIVE

TRL AND MRL

The art of making technology maturity transparent as basis for management decisions

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Introduction

Innovation-driven industries are facing a ever lasting need to balance technological ambition with feasibility. While new technologies come with competitive advantages, their path from mere concept to scalable production is often characterized by uncertainty. **Technology Readiness Levels (TRL)** and **Manufacturing Readiness Levels (MRL)** offer proven frameworks to provide enhanced transparency across this path, showing whether a product is not only **technically mature but also producible at scale**. However, maturity assessments come with their own challenges:

Complex systems, unclear scope, subjectivity, and resource misalignments frequently undermine their added-value. Effective application requires more than standardized checklists. It demands business-driven approaches adjusted to organizational goals. When embedded into product development processes, TRL and MRL foster structured decision-making, sharpen resource allocations, and strengthen risk transparency, enabling companies to transform uncertainty into strategic clarity and long-term profit.

Scope of discussion

- **Technology Maturity:** The challenges of system complexity, planning constraints, and evaluation validity
- **TRL & MRL:** The added value of standardized concepts and the pitfalls of rigid application
- **Pragmatic assessment:** Efficient methods for assessing product and process maturity
- **Integration into Product Development Planning (PDP):** Enhancing decision gates with transparency for risk-aware choices
- **Implementation & Roll-Out:** From pilot projects to sustainable operational adaption

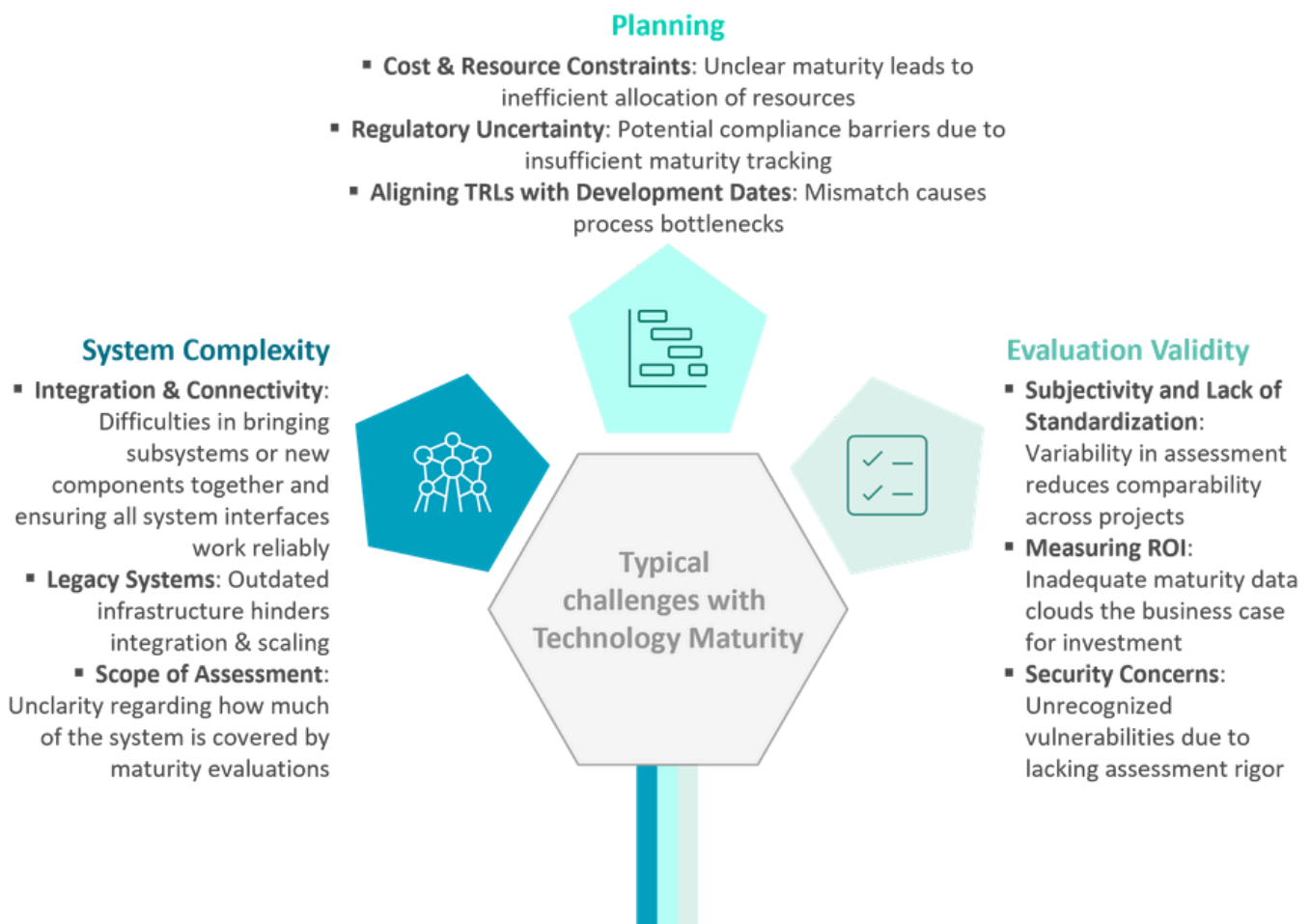
Transparency in Technology & Manufacturing Readiness

This paper demonstrates how TRL and MRL create transparency that bridges technological feasibility with scalable production ability. By integrating these frameworks pragmatically into product development processes, organizations can achieve risk-aware decision-making, optimized resource allocation, and long-term strategic value.

Typical challenges with technology maturity

Lacking maturity transparency – meaning insufficient assessment of TRL and MRL – regularly results in a variety of **challenges throughout the product development process**. When manufacturers cannot reliably benchmark where their technology or systems stand, the consequences are far greater than technical uncertainty, but rather **adversely impact cost, time-to-market, and overall organizational effectiveness**.

The major challenges associated with lack of TRL/MRL transparency can be structured along three dimensions:

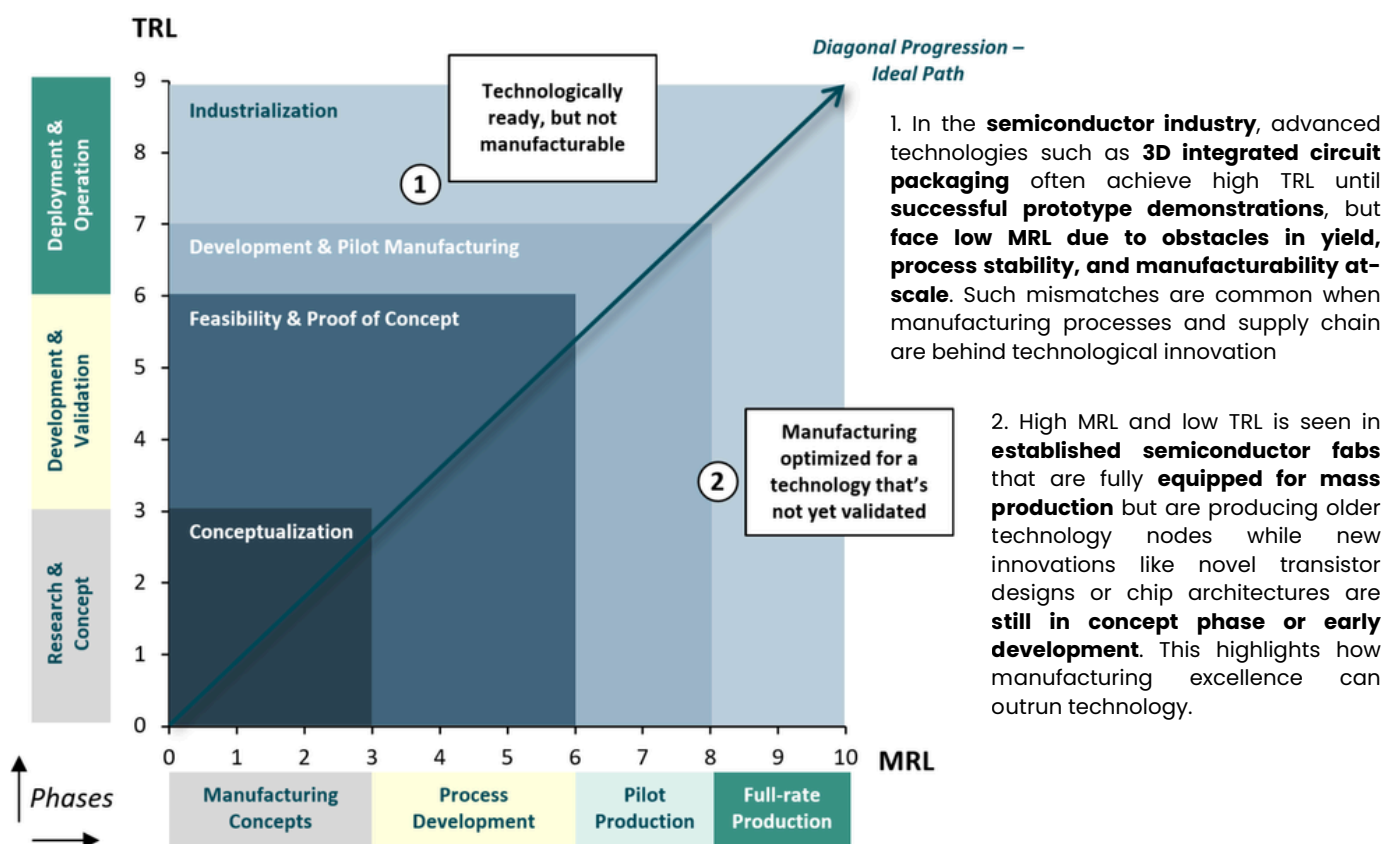


Challenges arising from limited maturity transparency

When TRL and MRL are not evaluated with sufficient precision, manufacturers face **significant technical uncertainty**. Lack of transparency complicates the integration of complex systems, especially when **legacy products** are involved. Planning may suffer through **inefficient resources allocation, regulatory uncertainty**, and non-matching between **maturity levels and development timelines**. Simultaneously, lack of evaluation validity will ultimately delay time-to-market and decrease organizational effectiveness.

TRL & MRL: The added value of standardized concepts and the pitfalls of rigid application

The universal, industry-proven frameworks **Technology Readiness Level (TRL)** and **Manufacturing Readiness Level (MRL)** provide standardized, non-correlated metrics to evaluate the maturity of both technology (product) and manufacturing (process) **through all development stages**. TRL assesses how far a technology has progressed **from idea to fully operational product**. MRL, however, tracks the ability to actually **produce it in a reliable, qualitative way, and at scale**. Both models are indispensable, as product and process maturity progress at different rates. A new product can be technologically ready (high TRL), but not manufacturable in high volumes (low MRL) – and vice-versa. Therefore, **both frameworks are essential** for cross-industry risk management and successful market roll-out. A structured manufacturing path ensures that the ability to produce in a reliable and scalable way advances in step with technological development, safeguarding the feasibility of industrial employment.

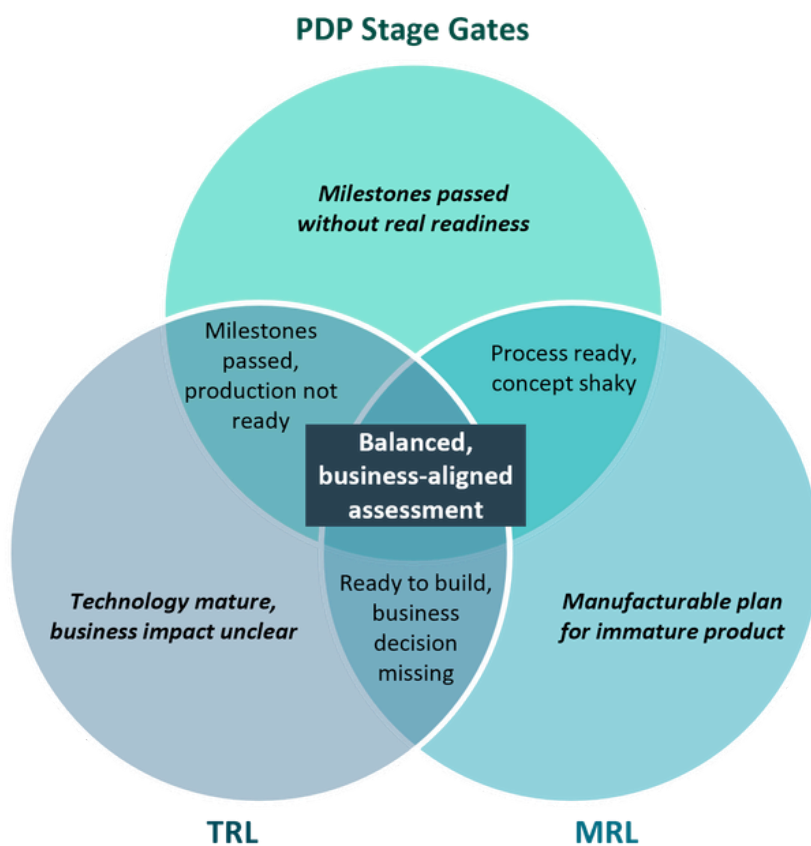


The matrix shows MRL (x-axis) and TRL (y-axis) across the phases Conceptualization, Development and Pilot Manufacturing, and Industrialization. The ideal path follows the diagonal, where manufacturing and technology progress in parallel, achieving maturity together. Deviations highlight risks: a high TRL but low MRL signals a product that is technically ready but not manufacturable at scale. While high MRL with low TRL indicates misaligned process investment. This framework illustrates the complementary yet non-correlated nature of TRL and MRL for managing readiness throughout the lifecycle.

Typical challenges with TRL & MRL

The application of TRL and MRL **adds significant value to product development processes** while raising challenges and undesirable complexity that need to be avoided carefully. Although maturity models deliver transparency regarding the state of technology, their implementation is most effective when specifically tailored to the individual business model and its organization's objectives.

A common pitfall is an **over-reliance on theoretical methodologies** without matching them to practical realities, resulting in unwieldy processes that are disconnected from actual operational needs. In this context, an inordinate focus on standardized documentation or **rigid evaluation criteria can turn TRL and MRL assessments into administrative undertakings**, ultimately diminishing their impact and reducing the engagement of program teams and decision-makers. **Maturity assessments should directly contribute to key decisions** and risk management, promoting product maturity and manufacturing.



Practical Considerations:

- **Adapt TRL/MRL** to the context and priorities of the business
- **Use as supporting tool for transparency**, not as administrative burden
- **Extension of PDP** milestones rather than duplication
- **Balance technology maturity evaluation** with costs, risks, and integration aspect

Avoiding pitfalls: The intersection of PDP, TRL, and MRL

Illustration of the overlap and distinct challenges of integrating Product Development Process (PDP) milestones, TRL and MRL. True business value is achieved when technical maturity, manufacturability, and business decision points align. Non-overlapping areas show common pitfalls for each dimension.

Decision based on transparent risk

Executive management provides itself with a decisive leverage when product and manufacturing transparency shapes business decisions, particularly through structured maturity assessments. **By revealing and quantifying risks, transparency enables executives to prioritize initiatives in their portfolio or roadmap with greater confidence.**

Rather than relying on ambitious or trend-driven assumptions, executives can dedicate resources to technologies and projects that demonstrate both technical feasibility and production readiness, **safeguarding against overvalued or immature technologies** and mitigating the risk of significant investment decisions.

Furthermore, the maturity assessment **provide the necessary clarity for buy or make decisions**, revealing not only the maturity level of internal development but also the maturity level available on the market.

Beyond individual projects, **transparent maturity evaluations significantly elevate governance quality.** They ensure capital allocation to objective evidence, align diverse stakeholders on the same facts, and increase information against market volatility, ultimately **strengthening long-term value creation.**

On operation level, significant strategic advantages derive from the transparency of products and manufacturing processes, in particular to **prioritize resource allocation** – ensuring that limited operational capacity is directed toward concepts with highest impact on **cost efficiency, time-to-market, and quality reliability.** This enables to focus development resources on opportunities in which transparent maturity **accelerating progress in critical areas** to add value while **reducing the risk of unforeseen challenges during scaling.**

Well-optimized resources could enable the simultaneous evaluation of multiple development concepts side by side and identify those with higher maturity and lower implementation risk.

Furthermore, the maturity transparency sharpens decisions regarding the manufacturability throughout the development cycle and **uncovers**

potential gaps in process stability or scalability early on. This enables go/no-go and redesign decisions before costly escalation, giving Operations a proactive role in shaping feasible production scenarios. The combined effect is a targeted, **risk-aware allocation of resources** that maximizes maturity and supports robust, scalable production outcomes.

Takeaway

TRL and MRL frameworks should be customized to business needs, ensuring they steer focus towards value creation and avoid burdensome or purely theoretical assessments disturbing the business.

Efficient approach in determining TRL & MRL

Robust and pragmatic methods for determination of the product maturity (TRL) and the production maturity (MRL) of the associated manufacturing process are crucial to drive projects towards an industrialization. An effective maturity assessment strategy focus only on key dependencies and risks rather than exhaustively covering every aspect. Hands-on experienced structures are required to allow a fast and reliable assessment delivering relevant insights, preventing process inflation and ensuring a tool for business empowerment.

TRL Assessment: Function-Feature breakdown & critical dependency identification

The product's TRL should not be approached as a single measure. Rather, it should be derived by decomposing the breakdown into its discrete functions and features supporting them, base for the methodology. The TRL assessment is likewise derived from the maturity of product features. For each feature-function pairing, critical dependencies are mapped after identification of technology interdependencies and direct interfaces.

In the approach, each function is systematically divided into subfunctions. If an interaction or interface to a feature is identified, the pair is investigated regarding its maturity and assessed regarding the TRL definition previously shown. Based on all assessed pairs of a feature, the "lowest" TRL is escalated for the overall rating. In practice, the function-feature pair ratings also allows to note the technology status shortly.

Definition

Function: describes the technological task or operating result that the product should achieve in its final application.

Feature: refers to a unique technological characteristic, sub-system, or capability of the product that operationalizes these functions and provides demonstrable added value in terms of performance, usability, or integration.

Feature		Feature 1	Feature 2	...
Function		TRL 3	Escalated TRL (lowest conservative approach)	
Function 1	Subfunction 1.1	TRL 3 Short Reasoning	TRL of the Function-Feature relation with a short reasoning for documentation and later reassessment	
	Subfunction 1.2	No Function-Feature Relation		
	Subfunction 1.3	TRL 4 Short Reasoning		
Function 2	Subfunction 2.1	TRL 3 Short Reasoning		
	Subfunction 2.2	No Function-Feature Relation		
	Subfunction ...	TRL 5 Short Reasoning		
...	...	TRL 4 Short Reasoning		

Product maturity based on technological function-feature relations, defined on subfunction level.

MRL Assessment: Process chain breakdown & production tool considerations

Similar to the product technology, the manufacturing process requires an efficient and pragmatic approach to evaluate maturity e.g., by starting to map the complete process chain with the required tools.

Process Block	Process Block 1		Process Block 2	
	MRL 6		Escalated MRL (lowest conservative approach)	
Sub Process	Name Subprocess Step	Name Subprocess Step		
Production Tool	MRL 6	MRL 4	MRL of the subprocess based on status of the process step development and involved production tools	
Current Status	Production Tool status description	Production Tool status description		
	Subprocess status description	Subprocess status description		

Exemplary breakdown of the approach in maturity evaluation of the process chain and process step incl. required tools.

This needs separating the process into distinct subprocess steps. For each subprocess step of a process block, the MRL is determined on the maturity of the subprocess step. Also, a short documentation of the status can be added incl. the specifically needed tools. The maturity assessment is done based on the definition shown in previous sections. For a process block, the “lowest” MRL is conservatively transferred for the overall MRL assessment.

Takeaway

Product Technology: Utilization of a function-feature breakdown to assign TRL at the subfunction level, highlight of critical technology dependencies and identification of lowest maturity areas for focused development.

Manufacturing Technology: Structured assessment around subprocess steps and the required tools with assignment of MRLs based on the lowest maturity of the involved elements for a risk-focused assessment.

Efficient approach in determining TRL & MRL

A thoughtful integration of TRL & MRL into the existing Product Development Process (PDP) is crucial to enable maturity transparency throughout the product development phases. Rather than establishing new gates to the PDP, **TRL and MRL enrich established decision points** with a clear perspective on the technological maturity and manufacturing capabilities at this stage. In best-practice approaches, **TRL and MRL are integrated** in the PDP providing the structure from concept to the industrial stage.

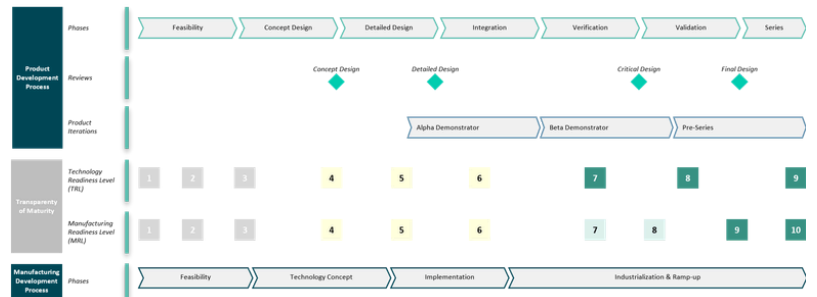
Takeaway

TRL and MRL providing maturity grades at gate decisions without adding new process steps, enabling a **proactive risk management and fostering trust across stakeholders**. They are not intended to add further gates in PDPs

Also, the integration should consider the **product iterations throughout the PDP** (e.g., Beta, Pilot products) with the therefore required technology and manufacturing readiness. Product iterations often represents hardware handovers between stakeholders e.g., from R&D to Engineering and later Operations, requiring a high grade of transparency.

The provided transparency enriches the PDP with a **risk assessment component for mitigation of technology challenges or manufacturing constraints** at an early stage. Of high importance is the understanding that not meeting

the requested TRL and MRL target automatically need to result in a gate rejection. Instead, the documentation **enables a knowledge-driven decision taking** based on residual risks and outstanding developments. It allows to manage expectations as well as agree on necessary mitigation strategies.



Schematic Product Development Process (PDP) enriched with TRL & MRL maturity grades for increased transparency on challenges and risks throughout the product development.

Stakeholder management

The successful implementation of TRL and MRL depends fundamentally on the systematic management of stakeholders across all organizational levels. Alignment and **active involvement** are essential to ensure that maturity **assessments are perceived as instruments for value creation** rather than as administrative burden. Effective stakeholder management not only improves implementation but also manages expectations and maximizes organizational benefits.

Different groups contribute to and benefit from maturity assessments in distinct ways: (1) **Senior executives** rely on transparent insights to guide portfolio steering and strategic investment decisions.

(2) **Operational managers** employ TRL and MRL to prioritize initiatives and allocate scarce resources efficiently. (3) **Project teams** depend on standardized criteria that reduce ambiguity and enhance cross-functional communication. Addressing these varying needs requires **positioning TRL and MRL as value-adding tools** tailored to the perspectives of each stakeholder group.

Furthermore, cross-departmental and organizational-level communication of risks, coupled with targeted support for operational execution, is critical for embedding TRL and MRL into daily practice. Such measures ensure legitimacy, foster trust, and establish the conditions for long-term effectiveness.

Pilot project

A pilot project provides a solid mechanism to integrate TRL and MRL into established PDP. It enables **controlled testing within existing structures** and builds momentum for the organization-wide roll-out.

To ensure feasibility, pilot projects must be carefully chosen to exhibit **representative characteristics of typical use cases** while remaining manageable in scope. Its effectiveness depends on clear objectives, realistic evaluation criteria, and strong stakeholder alignment across functional boundaries. By fulfilling these conditions, the pilot provides a robust foundation for assessing the value of TRL and MRL as

transparent decision-making inputs. Empirical results from the pilot can demonstrate tangible benefits, such as **improved risk transparency** and more effective communication across stakeholders, while simultaneously highlighting **potential implementation challenges**.

The lessons learned in this stage are essential for refining the framework and ensuring internal credibility. On this basis, a successful pilot concludes as a validated proof of concept, thereby enabling the systematic and sustainable integration of TRL and MRL into the organization's product development processes.

Roll-out

The organization-wide roll-out of TRL and MRL requires a **structured change management approach**. The successful institutionalization depends on clear communication of the purpose — *value creation through transparency rather than bureaucracy* — as well as the **active involvement of key stakeholders** from the outset. **Visible sponsorship** at the leadership level is essential to **secure legitimacy**, while **feedback loops** at the application level reinforce adoption and continuous improvement.

Maturity levels become effective only when they are **integrated into governance structures** and aligned with strategic priorities such as investment decisions and risk management. **Sponsors should exemplify the desired behavior**, for instance by demanding

maturity-based insights in portfolio reviews, thereby ensuring adoption cascades throughout the organization. Sustainable implementation further **requires capability building across teams**. Training formats — including e-learning, workshops, and playbooks — support consistent application, while systematic feedback from ongoing projects enables framework refinement and enhances credibility over time.

For TRL and MRL to provide true value, they must be **applied consistently across both new and running projects**. Selective use undermines comparability and erodes trust. Standardized templates, review criteria, and reporting dashboards facilitate alignment across the portfolio and enable cross-project benchmarking.

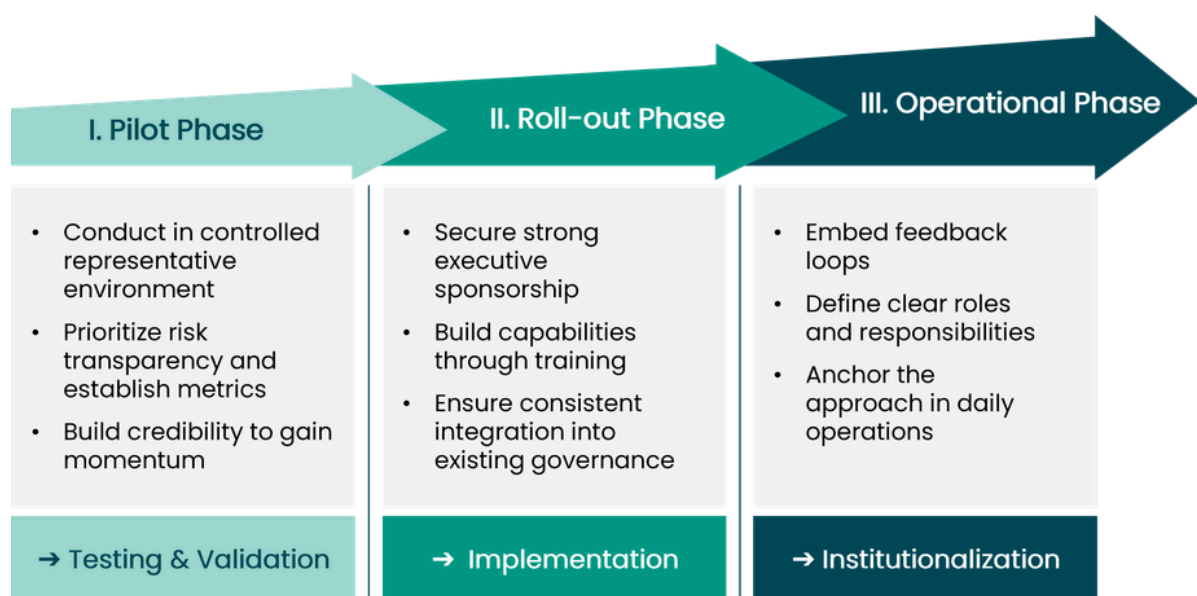
Finally, the roll-out must maintain a **balance between maturity assessment and operational efficiency**. Assessments should be seamlessly **integrated into existing gate reviews** and calibrated to project phase and criticality. This ensures transparency and risk control without slowing down development progress or adding unnecessary complexity.

Operationalization

Building on the preceding pilot phase and the structured company-wide roll-out, operationalization marks the transition of TRL and MRL from project-based implementation to institutionalized practice within organizational processes. At this stage, **the framework is embedded into governance structures**, thereby ensuring **alignment with strategic decision-making** rather than being perceived as an administrative burden.

Sustained application requires the establishment of standardized templates, assessment criteria, and reporting mechanisms to **guarantee comparability across the portfolio**. **Executive management** must consistently **request TRL and MRL metrics**, which should be firmly integrated into **reporting routines**.

Furthermore, **clearly defined roles and responsibilities** are essential to secure accountability and to ensure the continuity of the process. **Embedded feedback loops** provide the foundation for **continuous refinement and adaptive learning**. Through this institutional anchoring, TRL and MRL evolve into enduring instruments of transparency, risk management, and evidence-based decision-making, thereby consolidating their long-term organizational relevance and effectiveness.



Phased implementation model illustrating the transition to the operational integration of TRL and MRL.

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