

## THEORETICAL AND METHODOLOGICAL FOUNDATIONS OF TECHNOLOGY VALIDATION IN STARTUPS

Dawid ROMEK<sup>1\*</sup>, Monika KLIMOWICZ<sup>2</sup>, Kamil BROMSKI<sup>3</sup>,  
Paulina KACZOR-SZKODNY<sup>4</sup>, Katarzyna WIELGUSZEWSKA<sup>5</sup>

<sup>1</sup> Łukasiewicz – ITECH; dawid.romeek@itech.lukasiewicz.gov.pl, ORCID: 0000-0002-2658-1670

<sup>2</sup> University of Wrocław, Łukasiewicz – ITECH; monika.klimowicz@uwr.edu.pl, ORCID: 0000-0002-0605-783

<sup>3</sup> Łukasiewicz – ITECH; kamil.bromski@itech.lukasiewicz.gov.pl, ORCID: 0009-0007-0414-4326

<sup>4</sup> Instytut Medycyny Wsi im. Witolda Chodźki, Łukasiewicz – ITECH; paulina.kaczor7@wp.pl,  
ORCID: 0000-0002-0196-2549

<sup>5</sup> Łukasiewicz – ITECH; Katarzyna.wielguszewska1@iel.lukasiewicz.gov.pl

\* Correspondence author

**Purpose:** This article presents the results of desk research analysis concerning technology validation in startups, with particular emphasis on theoretical and methodological foundations of this process. The study aims to identify key trends, barriers and research gaps in technology validation processes within the start-up ecosystem.

**Design/methodology/approach:** The research employed a systematic desk research methodology, encompassing scoping review of scientific literature from databases including PubMed, Scopus, and Google Scholar, complemented by grey literature review of industry reports published between 2016 and 2025. The analysis utilized triangulation methodology, combining theoretical, methodological, and data triangulation approaches.

**Findings:** The results indicate that the lack of standardized tools for innovation assessment and limited managerial competencies in startups constitute significant obstacles to the commercialization of new technologies. Technology Readiness Levels (TRL), despite being a recognized standard, require adaptation to the specific needs of early-stage startups. The study identifies the "valley of death" phenomenon as a critical barrier between prototype development and full commercialization.

**Research limitations/implications:** The study is limited to desk research analysis and requires validation through empirical research involving accelerators, investors, and start-up founders. Future research should focus on developing standardized validation tools adapted to the Polish innovation ecosystem.

**Practical implications:** The findings provide foundations for developing a standardized technology validation tool that could serve as a "technology validation certificate" for innovative projects. This would enhance market transparency and facilitate investment decision-making processes.

**Originality/value:** This article contributes to filling the research gap concerning institutionalized technology validation support in the start-up ecosystem. It integrates perspectives from innovation management, technology transfer, and entrepreneurship research.

**Keywords:** technology validation, startups, innovation commercialization.

**Category of the paper:** Research paper.

## 1. Introduction

The contemporary innovation landscape is characterized by an intensification of technological entrepreneurship processes, in which start-up enterprises play a crucial role as catalysts for technology transfer and innovation commercialization. Despite the growing importance of the start-up sector in the global economy, these enterprises face numerous challenges related to technology validation, investment risk assessment, and adaptation of technological solutions to market requirements (Blank, Dorf, 2012; Ries, 2011).

Technology validation, understood as the process of confirming technological, market, and commercial feasibility, constitutes one of the key challenges for startups (Gbadegeshin et al., 2022). The literature indicates the existence of a significant gap between the conceptual phase of technological innovations and their successful commercialization, referred to as the "valley of death" in the technology development process (Navarro-Castillo et al., 2024). This phenomenon is particularly pronounced in deep-tech startups, which operate at the boundaries of breakthrough technological innovations and face challenges concerning both technical feasibility and commercialization possibilities (Muscio et al., 2023).

The European Commission (2017) emphasizes the importance of Technology Readiness Levels (TRL) as a fundamental tool for assessing technological maturity. However, research indicates that this framework requires adaptation to the specific needs of startups, particularly those in early development stages (Mankins, 2009). The TRL scale, originally developed by NASA for space technology assessment, has been widely adopted in innovation policy at EU, national, and regional levels, yet its application in the start-up context reveals certain limitations (Héder, 2017).

In parallel with technological validation challenges, startups must also validate their business models and market assumptions. The Lean Startup methodology, developed by Ries (2011) based on Blank's (2013) Customer Development approach, provides a systematic framework for hypothesis testing and iterative learning. This methodology emphasizes the importance of building a Minimum Viable Product (MVP) and gathering customer feedback before making substantial investments in product development (Frederiksen, Brem, 2017).

This article presents partial results of research conducted within the QualiTech project (Technology Validation Center for Start-ups), which is to provide knowledge about the current state of advancement of the start-up ecosystem and tools for their support, essential for enhancing their market competitiveness. The project addresses the scientific and research gap by analyzing the functioning of the Technology Validation Center for Start-ups as an institutional mechanism supporting validation processes in the innovation ecosystem.

The decision to undertake research in this area was motivated by the rapidly growing need to support innovative enterprises in the early stages of their development, particularly through activities related to the testing, validation, and optimization of technologies characterized by

high implementation potential (Dziewit, 2024; Majewski, 2025). The significance of this research problem stems from the need for better understanding of mechanisms supporting technology transfer and optimization of decision-making processes concerning investments in innovative enterprises at early stages of their development. Previous research has primarily focused on analysing individual cases of technological validation or on theoretical models of this process, while comprehensive ecosystem analyses considering the specificity of the start-up environment and its institutional support needs remain scarce (Sanasi et al., 2023).

The choice of the topic of technology validation in start-ups is justified both by the growing role of technological entrepreneurship in the economy and by the clear research gaps identified in the literature on the subject. Previous research has focused primarily on selected elements of the process, such as assessing technological maturity in terms of TRL, implementing the Lean Startup methodology, or analysing the ‘valley of death’ phenomenon, but rarely integrating these perspectives into a uniform, coherent validation approach tailored to the specificities of young technology companies. As a result, there is a lack of standardised assessment tools that would combine technical, market and business dimensions with ecosystem conditions, while at the same time being resource-feasible for start-ups operating in conditions of high uncertainty and limited funding. The literature also emphasises that the classic TRL scale, derived from the context of large space projects, needs to be adapted to the realities of agile, iterative product development and the specificities of sectors such as software, AI and knowledge-based services, where traditional ‘laboratory evidence’ criteria do not always apply. At the same time, research on Lean Startup and experimentation in start-ups indicates that although this approach has become widespread in practice, its empirical verification and embedding in a broader framework of technological and commercial readiness assessment remain insufficient. In turn, studies on the ‘valley of death’ show the persistence of financial, organisational and regulatory barriers between the prototyping phase and scaled commercialisation, but rarely translate into operational indicators that could be directly used in the decision-making processes of investors, accelerators and public institutions. Against this background, addressing the theoretical and methodological foundations of technology validation in start-ups - considering TRL integration, the Lean Startup approach and valley of death analysis - responds to a clearly identified research gap and lays the groundwork for designing practical tools to support more effective resource allocation in the innovation ecosystem.

The structure of this article is organized as follows: section 2 describes the research methodology, including systematic literature review procedures and desk research analysis, section 3 presents a comprehensive literature review covering technology validation concepts, TRL frameworks, lean startup methodology, and the valley of death phenomenon, section 4 presents results and discussion, analysing key findings and identifying challenges and finally section 5 concludes with implications for theory and practice.

## 2. Technology validation in startups - research methodology

This research employs a systematic desk research methodology designed to identify and analyse key areas (macro-areas) for further empirical investigation. The methodological framework is grounded in the concept of methodological triangulation, understood as the application of multiple research methods to enhance validity, reliability, and completeness of research findings (Denzin, 2012). The research design incorporates three forms of triangulation. Theoretical triangulation allowed for the analysis of the phenomenon of technology validation in startups from the perspective of various conceptual frameworks (innovation ecosystem theory, entrepreneurship financing theory, technology validation concepts). Methodological triangulation was applied by complementary analytical methods (systematic literature review, desk research analysis). To answer the research questions, a variety of data sources (scientific literature, industry reports, statistical data, strategic documents) were utilized.

The main objective of the research was to verify the data contained in the source materials to identify the micro-areas of research with the greatest information potential based on the involvement of financing entities in a given industry. The study was designed to address four specific research objectives:

RQ1: to analyse the most common areas of startup activity in Poland.

RQ2: to examine the nature and type of relationships between startups and supporting/financing entities.

RQ3: to analyse trends in changes in the areas of activity and sources of startup financing.

RQ4: to identify key factors that investors and accelerators consider when evaluating startups (scalability, product, team, business model).

The systematic literature review was conducted following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines and Cochrane Collaboration standards for systematic reviews in social sciences. The theoretical foundation rests on evidence-based research principles, where systematic searching, critical evaluation, and synthesis of available literature constitute the foundation for further empirical research. The literature search was conducted across multiple databases: (1) academic databases: PubMed, Scopus, Google Scholar, (2) specialized databases: Web of Science, IEEE Xplore, (3) grey literature sources: industry reports, government documents, white papers, consulting firm analyses. The search strategy employed the following keyword combinations: "technology validation" AND "startups", "Technology Readiness Level" OR "TRL" AND "commercialization", "lean startup" AND "validation", "valley of death" AND "innovation", "technology transfer" AND "startups". The analysis encompassed publications from 2016 to 2025, allowing capture of evolving realities in the innovation ecosystem and changing needs of young technology firms. This timeframe was selected to balance contemporaneity of findings with sufficient longitudinal perspective for trend analysis.

Materials were included if they met the following conditions: (1) published in peer-reviewed academic journals or by recognized research institutions, (2) addressed technology validation, start-up development, or innovation commercialization, (3) published in English, Polish, or German, (4) available in full-text format, (5) available in open source, (6) possessed clear methodological framework and empirical basis. Materials were excluded based on: (1) insufficient methodological rigor or unclear research design, (2) focus exclusively on non-technology sectors, (3) Lack of relevance to start-up or early-stage venture context, (4) unavailability of full text despite database access, (5) published prior to 2016 unless seminal works providing theoretical foundations.

The desk research component involved systematic analysis of secondary sources, including industry reports, statistical databases, and organizational documentation from key ecosystem stakeholders. This approach aligns with established methodologies for secondary data analysis in entrepreneurship research (Morse et al., 2002). Grey literature sources were identified through: (1) systematic searches of major accelerator, incubator, and venture capital websites, (2) government agency and policy document repositories, (3) industry association publications and reports, (4) conference proceedings and white papers. Each source underwent quality evaluation considering authorship credibility and institutional affiliation, methodological transparency and rigor, sample size and representativeness (for empirical reports), currency and relevance to research questions and consistency with findings from peer-reviewed sources.

Following recommendations regarding research methodology impact on data quality, systematic verification procedures were applied to ensure reliability and validity of desk research findings. This included cross-referencing multiple sources for key claims, distinguishing between empirical findings and opinion-based statements, and noting limitations and caveats in source materials.

The multi-method approach combining systematic literature review with comprehensive desk research enables robust identification of research gaps and formulation of research questions for subsequent empirical investigation. This methodological design supports the development of grounded research instruments while maintaining scientific rigor and replicability.

### **3. Technology validation in startups - theoretical foundation**

Technology validation represents a multidimensional process encompassing technical, market, and commercial verification of innovative solutions. According to Wieringa (2014), technology validation requires empirical research methods that enable scaling up requirements engineering approaches. This process involves systematic assessment of whether a technology

meets specified requirements and can function effectively in its intended operational environment.

Dean et al. (2022) emphasize the role of complexity in technology validation, particularly concerning radical innovations. Their research demonstrates that higher levels of complexity in innovative technologies correlate with greater challenges in crossing the valley of death, necessitating more sophisticated validation approaches. The authors argue that effective validation must address both technical performance and market acceptance dimensions simultaneously. Muscio with the research team (2023) specifically examine technology validation in the context of renewable energy innovations, demonstrating how inadequate validation processes can create systemic barriers to innovation deployment. Their study highlights the importance of institutional support structures that facilitate validation across multiple dimensions: technical feasibility, economic viability, regulatory compliance, and social acceptance. The concept of validation extends beyond mere technical testing to encompass business model validation and market validation. Sanasi et al. (2023) investigate experimentation practices in technology-based startups after achieving initial market validation, revealing that validation is not a one-time event but rather an ongoing process requiring systematic approaches throughout the start-up lifecycle. Their research identifies specific patterns of experimentation that distinguish successful scaling ventures from those that plateau after initial validation.

The Technology Readiness Level framework, originally developed by NASA in the 1970s, provides a systematic methodology for assessing technology maturity across nine distinct levels, from basic principles observation (TRL 1) to proven system operation in actual environments (TRL 9) (Mankins, 2009). This framework has become widely adopted across government agencies, funding organizations, and research institutions as a common language for discussing technology maturity (Héder, 2017). Each TRL represents specific development milestones and evidence requirements. TRL 1-3 cover basic research and proof-of-concept activities conducted in laboratory settings. TRL 4-6 involve validation and demonstration phases, first in laboratory environments, then in relevant operational contexts. TRL 7-8 encompass prototype demonstration in operational environments and system qualification through testing. TRL 9 represents full-scale deployment and proven operation (European Commission, 2017). Salvador-Carulla et al. (2024) demonstrate that the original TRL framework requires adaptation for different contexts, particularly in implementation science and health research. Their study developed a modified TRL for Implementation Science (TRL-IS) that addresses limitations of the original framework for non-hardware technologies. This adaptation work highlights an important insight: while TRL provides valuable structure, its application must be contextualized to specific domains and technologies. For startups, several challenges emerge with TRL application. First, many startups operate in highly dynamic environments where rapid iteration and pivoting are necessary, potentially making rigid TRL progression impractical (Ghezzi, 2019). Second, startups often lack resources for

comprehensive testing required to advance through TRL levels systematically. Third, the TRL framework focuses primarily on technical maturity while underemphasizing business model viability and market readiness - factors critically important for start-up success (Leatherbee, Katila, 2020). Current studies have proposed complementary frameworks to address these limitations. The Market and Technology Readiness Level (MTRL) framework integrates both technical maturity and market readiness dimensions, recognizing that commercial success requires advancement on both axes (Bruno et al., 2020). Similarly, Lavin et al. (2022) adapted TRL concepts for machine learning systems, acknowledging that different technology domains require tailored maturity assessment approaches.

The Lean Startup methodology, articulated by Ries (2011) and building upon Blank's (2013) Customer Development framework, represents a fundamental shift in entrepreneurial practice toward systematic, hypothesis-driven experimentation. This methodology addresses the high uncertainty inherent in start-up environments by providing structured approaches to learning and adaptation (Ghezzi, 2019). At its core, the Lean Startup methodology consists of several interconnected components. First, it emphasizes the Build-Measure-Learn feedback loop, which structures the process of hypothesis testing through rapid experimentation cycles (Ries, 2011). Second, it advocates for the development of a Minimum Viable Product (MVP), the simplest version of a product that enables validated learning about customers' needs and preferences (Bocken, Snihur, 2020). Third, it introduces the concept of "pivoting" making fundamental strategic changes based on validated learning rather than persisting with initial assumptions (Shepherd, Gruber, 2021). Additionally, analysis of Frederiksen and Brem (2017) reveals that while the methodology draws on established concepts from lean manufacturing, customer development, and agile software development, its integration into a coherent entrepreneurial framework represents a meaningful innovation. However, they also note that scientific validation of the methodology's effectiveness remains limited, with much evidence being anecdotal or based on practitioner experience.

Recent research has examined how entrepreneurs implement Lean Startup practices. Ghezzi (2019) investigates digital startups' adoption of Lean Startup approaches, finding that entrepreneurs employ principles of effectuation and bricolage alongside lean practices, creating hybrid approaches adapted to their specific contexts. Leatherbee and Katila (2020) demonstrate that the method works best for early-stage teams when combined with appropriate governance structures and decision-making processes. Bocken and Snihur (2020) extend Lean Startup concepts to sustainable business model innovation, arguing that the methodology's emphasis on experimentation and iteration makes it particularly suitable for addressing complex sustainability challenges. Their research demonstrates how Lean Startup principles can be applied beyond traditional technology startups to enterprises pursuing environmental and social objectives. Critical perspectives on Lean Startup have also emerged. Some researchers question whether the methodology's emphasis on quick pivoting and minimal initial investment might lead to premature abandonment of promising but challenging innovations (Shepherd, Gruber,

2021). Others note that the approach may be less suitable for hardware-intensive or highly regulated industries where rapid iteration is constrained by physical or regulatory factors (Mansoori, Lackéus, 2020).

The "valley of death" metaphor describes the critical period in the development of innovation, located between the transition from prototype validation to initial pilot implementations and the achievement of repeatable, scalable commercialisation, in which the risk of start-up failure is highest due to the mismatch between the logic of research funding and the requirements of investors and the market, as well as the accumulation of technological, market and institutional barriers (Beard et al., 2009; Ford et al., 2007; Muscio et al., 2023; Navarro-Castillo et al., 2024).

It constitutes a complex and multidimensional phenomenon encompassing interrelated financial, organizational, institutional, and network-related barriers, whose effective mitigation necessitates coordinated and concurrent interventions across the domains of public policy, managerial practice, and innovation processes. This phenomenon represents a fundamental challenge in innovation systems, occurring at the intersection between research and development activities and commercial deployment. As Beard et al. (2009) point out this phenomenon results not from inherent market failures in R&D investment, but rather from misalignment between early-stage research funding (often government-supported) and later-stage commercialization requirements. Their economic analysis suggests that the valley of death emerges when initial research investments are made without sufficient attention to subsequent stages' investment requirements and criteria.

Based on the analysed literature, three interrelated stages of the 'valley of death' can be distinguished: (1) the transition stage from high levels of technological readiness (TRL 4-6), in which it is necessary to move from proof of concept and validation in laboratory conditions to demonstration in a relevant operational environment and to build credible technical evidence with limited resources (European Commission, 2017; Mankins, 2009; Salvador-Carulla et al., 2024), (2) the commercial gap stage, in which technologies with relatively high TRL encounter low market and business readiness - lack of a verified business model, insufficient market traction and incomplete problem -solution or product-market, despite earlier positive technical validation results (Gbadegeshin et al., 2022; Muscio et al., 2023; Sanasi et al., 2023), and (3) the scaling gap stage, in which start-ups, after achieving initial market validation, face barriers related to building organisational capacity, obtaining bridge financing between the seed and Series A rounds, developing demonstration infrastructure, and complying with complex regulatory requirements, which is particularly evident in the deep-tech and renewable energy sectors (Barron, Amorós, 2020; Dean et al., 2022; Muscio et al., 2023; Navarro-Castillo et al., 2024). The operationalisation of these stages therefore requires the distinction of at least three types of indicators: first, indicators of technological maturity, measured, among other things, by the TRL level and the scope of tests and demonstrations carried out (number of tests completed in laboratory and real-world conditions, existence of a prototype operating in the

target environment, compliance with minimum regulatory requirements) (European Commission, 2017; Heder, 2017; Lavin et al., 2022); secondly, market validation and business model indicators, referring to the Lean Startup logic - the number of iterations of the Build-Measure-Learn cycle, the presence and quality of the Minimum Viable Product (MVP), the number of tested hypotheses regarding customer segments and value propositions, early traction indicators (e.g., pilot agreements with customers, retention rate, willingness to pay) and the presence or absence of a 'pivot' decision (Blank, 2013; Ries, 2011; Frederiksen, Brem, 2017; Ghezzi, 2019; Leatherbee, Katila, 2020); thirdly, indicators of organisational and ecosystem capabilities, including the structure and complementarity of the founding team's competencies (balance of technical and business competencies), access to a network of partners and complementary resources (accelerators, incubators, industrial partners, open innovation strategies), the level of funding obtained at subsequent stages (proof-of-concept grants, bridge financing, capital rounds) and the intensity of institutional support (mentoring, testing infrastructure, validation programmes) (Barron, Amorós, 2020; Gbadegeshin et al., 2022; Navarro-Castillo et al., 2024; Dziewit, 2024; Majewski, 2025). In this perspective, the 'valley of death' is not synonymous with the technology validation process itself or the TRL framework, but refers to a specific section of the innovation development path where the disproportion between growing requirements for technical, market and organisational requirements and the availability of capital, managerial competence and ecosystem resources leads to an increased likelihood of project failure; thus, TRL provides a measure of 'what' has been achieved in technical terms, Lean Startup describes 'how' iterative market validation takes place, while the concept of 'valleys of death' determines 'where' along this path the risk of failure is greatest and what configurations of indicators (technological, market and organisational-institutional) signal the approach of critical points. Adopting such a distinction between concepts and indicators, based on the analysed research, allows for an in-depth analysis of validation mechanisms in start-ups: it enables the identification of projects that are 'stuck' at high TRL levels, but with low market validation and weak organisational capabilities, as well as those which, despite their lower technological maturity, are strongly embedded in the ecosystem and have a better-prepared business model, and thus have a better chance of successfully crossing the 'valley of death'.

For young companies requires the simultaneous development of technology, a business model, and organizational capabilities. Gbadegeshin et al. (2022) develops a comprehensive model for helping high-tech startups overcome the valley of death, identifying several critical success factors. These include: securing adequate early-stage funding, developing strong entrepreneurial team capabilities, establishing strategic partnerships with industry players, and maintaining clear focus on customer needs throughout development. The author emphasizes that crossing the valley of death requires simultaneous attention to technological development, business model refinement, and resource mobilization. Additionally, Barron and Amorós (2020) examine entrepreneurial programs designed to bridge the valley of death,

analyzing specific mechanisms through which accelerators and incubators help startups navigate this critical period. Their research identifies key support elements including mentorship, networking opportunities, structured validation processes, and phased funding approaches. However, they also note significant variation in program effectiveness, with success depending heavily on quality of mentorship and relevance of industry connections.

Muscio et al. (2023) specifically investigate the valley of death in the EU renewable energy innovation system, demonstrating how regulatory fragmentation, lack of demonstration facilities, and insufficient bridge financing create systemic barriers to innovation deployment. Their research highlights the need for coordinated policy interventions addressing multiple dimensions of the valley of death simultaneously. From this perspective, the study conducted by Navarro-Castillo et al. (2024), which examines open innovation strategies as critical mechanisms for overcoming the valley of death in new technology-based firms, constitutes a valuable contribution to the field. Their qualitative research with Spanish startups reveals that successful firms actively leverage external knowledge sources, strategic partnerships, and ecosystem relationships to compensate for internal resource limitations. The study emphasizes that crossing the valley of death increasingly requires ecosystem-level capabilities rather than solely firm-level resources.

#### **4. Findings and discussion**

The systematic literature review revealed several critical insights regarding technology validation in startups, organized around four thematic areas: TRL operationalization and validation tools, commercialization challenges despite positive validation, limited managerial competencies in startups and methodological challenges in innovation research.

Despite TRL being a recognized standard for technology assessment, significant challenges emerge in its application to start-up contexts. The literature consistently indicates that the TRL framework, designed originally for large-scale NASA projects with substantial resources and long development cycles, requires substantial adaptation for resource-constrained start-up environments (Mankins, 2009; Héder, 2017). Salvador-Carulla et al. (2024) demonstrate that TRL adaptations are possible and can improve framework utility for specific contexts. Their work on TRL-IS (TRL for Implementation Science) shows that successful adaptation requires removing inappropriate elements (such as laboratory testing requirements for non-hardware innovations) and adding context-specific criteria. For startups, similar adaptations might include: (1) adjusting evidence requirements to reflect resource constraints, (2) incorporating business model validation alongside technical readiness, (3) allowing for iterative, non-linear progression through levels, (4) integrating market feedback mechanisms at earlier stages.

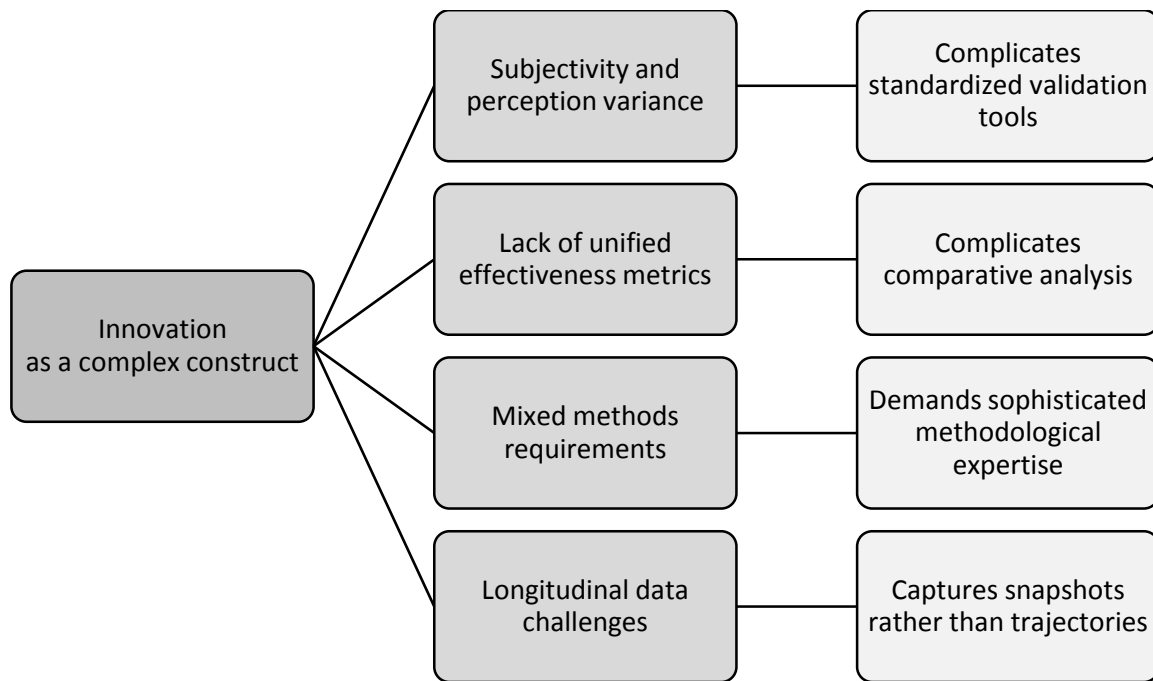
However, such adaptations remain largely theoretical, with limited empirical validation of modified TRL frameworks specifically designed for start-up ecosystems. This represents a significant gap between policy requirements (many funding programs require TRL assessment) and practical applicability for early-stage ventures.

A recurring pattern in the literature indicates that positive technological validation (high TRL) does not guarantee commercial success. Multiple studies document instances where technically mature technologies fail to achieve market adoption (Muscio et al., 2023; Gbadegeshin et al., 2022). This disconnect highlights the multidimensional nature of innovation success. The "valley of death" phenomenon manifests precisely at this juncture - between prototype development and full commercialization (Barron, Amorós, 2020). Research by Beard et al. (2009) suggests this gap results from fundamental misalignment between technical development logic and commercial deployment requirements. Technologies may achieve technical readiness without achieving market readiness, regulatory compliance, or business model viability. Sanasi et al. (2023) provide nuanced understanding of post-validation experimentation, demonstrating that even after achieving initial market validation, startups face substantial challenges in scaling. Their research identifies specific patterns: successful scaling ventures continue systematic experimentation focused on operational efficiency and market expansion, while plateauing ventures often revert to ad-hoc decision-making.

The literature consistently identifies managerial capability gaps as significant barriers to effective technology validation. Young firms often lack experience in validation processes, impeding collaboration with research institutions and navigation of commercialization pathways (Gbadegeshin et al., 2022; Navarro-Castillo et al., 2024). Specific competency gaps identified include limited understanding of R&D funding mechanisms and application processes, insufficient knowledge of intellectual property protection strategies, inadequate financial management capabilities for phased development, weak strategic planning skills for long-term technology development and limited ability to effectively communicate technical concepts to non-technical stakeholders (investors, customers, partners).

These gaps are particularly pronounced in university spin-offs and deep-tech startups, where founding teams typically possess strong technical expertise but limited business experience (Muscio et al., 2023). The literature suggests that accelerator programs, mentorship, and entrepreneurship education can partially address these gaps, though effectiveness varies significantly across programs (Barron, Amorós, 2020).

Multiple studies acknowledge fundamental methodological challenges in researching innovation and validation processes. Innovation represents a complex, multidimensional construct that resists simple measurement (Shepherd, Gruber, 2021). Key challenges are presented in the graph below.



**Figure 1.** Methodological challenges in innovation research and validation processes.

Source: own elaboration.

*Subjectivity and perception variance:* assessments of innovation degree, market potential, and technological maturity often vary substantially across evaluators (Ghezzi, 2019). What one investor considers breakthrough innovation; another may view as incremental improvement. This subjectivity complicates development of standardized validation tools.

*Lack of unified effectiveness metrics:* the literature reveals absence of consensus regarding appropriate metrics for assessing validation effectiveness: should success be measured by subsequent funding raised? Survival rates? Revenue generation? Patent awards? Different stakeholders prioritize different metrics, complicating comparative analysis (Frederiksen, Brem, 2017).

*Mixed methods requirements:* effective innovation research typically requires integration of quantitative and qualitative approaches - triangulation that demands sophisticated methodological expertise and substantial resources (Denzin, 2012). Many studies rely on single-method approaches, potentially missing important nuances.

*Longitudinal data challenges:* understanding validation effectiveness requires tracking ventures over extended periods, yet such longitudinal data remain scarce. Most studies capture snapshots rather than developmental trajectories (Sanasi et al., 2023).

The TRL framework provides several valuable contributions to technology validation. It provides a unified tool for assessing technological maturity, enabling risk management and resource allocation, and is widely accepted by funding agencies and investors, allowing for project comparison at different development stages. It facilitates communication among stakeholders and creates a structured pathway from basic research to commercialization. However, the TRL model does not always work well for startups: resource requirements,

especially at higher TRL levels, often exceed start-up capabilities, and the linear progression conflicts with the iterative, pivot-oriented approach typical of startups. The system primarily focuses on technical validation, neglecting business model and market readiness. Evidence requirements designed for large organizations may be impractical for resource-constrained ventures, and the classic TRL does not address projects typical for software, AI, or services. An alternative is the Lean Startup methodology, which emphasizes experimentation, rapid prototyping, and the Build-Measure-Learn cycle. It allows for continuous validation, integration of customer feedback, and pivot-or-persevere decisions based on real data. Its value lies in minimizing resource expenditure, testing key hypotheses, and enabling fast business adaptation. Combining TRL with Lean Startup may constitute a comprehensive validation tool, integrating technical assessment with market readiness. Such integration enables development based on both technological evidence (TRL) and market tests (Lean Startup), benefiting both dimensions of innovative project development.

The analysis identifies significant challenges and barriers to technology validation in startups, operating at both ecosystem and individual levels. At the ecosystem level, institutional fragmentation is a key issue: accelerators, incubators, and government programs often operate independently, applying inconsistent criteria and requirements. This creates confusion and administrative burdens for startups, hindering their access to support and validation resources (Muscio et al., 2023). Despite the growth in early-stage funding, systematic financing gaps persist, especially between seed funding and Series A investment, forming a "valley of death" that corresponds to critical validation stages (Gbadegeshin et al., 2022). Regulatory uncertainty is another major barrier, as rapidly evolving technologies often outpace regulatory frameworks. This leads to ambiguity about compliance, making it difficult for startups to validate their products and achieve commercialization, particularly when relevant regulations are unclear or absent (Navarro-Castillo et al., 2024).

At the start-up level, several common challenges impede effective validation. Resource constraints, both financial and human, limit the ability to conduct comprehensive validation activities, forcing startups to prioritize which validations to pursue (Leatherbee, Katila, 2020). Capability gaps further complicate the process: technical founders may lack business development skills, while business-oriented founders may not fully grasp technical validation requirements. Additionally, pressure for rapid progress, driven by investor expectations and competitive pressures, often creates tension between thorough validation and the need for quick market entry. This can result in premature commercialization or insufficient validation (Shepherd, Gruber, 2021).

Knowledge and information asymmetries are also significant. Investors struggle to assess the true validation status of early-stage technologies, particularly in emerging domains, and startups may overstate their progress or maturity (Ghezzi, 2019). Early-stage customers face uncertainty about product reliability and company viability, and inadequate validation evidence can impede initial customer acquisition. Furthermore, limited information sharing among

support organizations means that validated best practices and lessons learned often remain localized, rather than diffusing across the ecosystem, which limits collective learning and improvement. These barriers collectively undermine the effectiveness of technology validation processes and hinder the successful scaling and commercialization of innovative start-up projects.

## 5. Conclusions

This systematic review of literature and desk research analysis reveals that technology validation in startups represents a complex, multidimensional challenge requiring integration of technical, market, and business model assessment approaches. While existing frameworks such as TRL and Lean Startup provide valuable foundational tools, significant gaps persist between these frameworks and the practical needs of early-stage technology ventures.

In light of the identified research gaps, the development of future empirical research on technology validation in start-ups, focused on a multidimensional, integrated approach to TRL, market validation and the ‘valley of death’ phenomenon, is of particular importance. Firstly, it is reasonable to conduct longitudinal studies tracking validation paths from the early stages of technology development to scaling attempts, which will allow for the identification of critical points, risk factor configurations and patterns of transition through successive ‘valleys of death’ in various sectors, including in particular deep-tech (Muscio et al., 2023; Navarro-Castillo et al., 2024; Sanasi et al., 2023). Second, research is needed on the design, testing, and quasi-experimental evaluation of integrated validation tools that combine a modified TRL framework with Lean Startup methodology and additional dimensions of market, organisational, and regulatory readiness (Bruno et al., 2020; Lavin et al., 2022; Ries, 2011; Shepherd, Gruber, 2021). Third, the ecosystem conditions for effective validation require further analysis - comparative studies between countries and regions could reveal best practices in the coordination of accelerators, incubators, funds and public institutions, as well as the role of open innovation strategies in bridging resource and information gaps (Barron, Amorós, 2020; Gbadegeshin et al., 2022; Dziewit, 2024; Majewski, 2025). Another important trend is in-depth research into the structure and dynamics of managerial competencies in founding teams, considering the specific nature of academic spin-offs and their relationship with validation and investment decisions (Ghezzi, 2019; Leatherbee, Katila, 2020; Muscio et al., 2023). Finally, studies on the actual decision-making practices of investors are needed - comparing declared criteria with the actual use of validation evidence - which will enable better alignment of the designed validation tools with the needs of the capital market and increase their usefulness for stakeholders in the innovation ecosystem.

This study contributes to entrepreneurship and innovation management literature in several ways. It provides integrated analysis of technology validation across multiple theoretical perspectives, bridging traditionally separate literature streams on technology assessment (TRL), entrepreneurial methodology (Lean Startup), and innovation financing (valley of death). The research identifies specific gaps where existing validation frameworks inadequately address start-up needs, particularly concerning resource constraints, iterative development approaches, and business model validation alongside technical assessment. It establishes methodological foundation for further empirical research on technology validation in start-up ecosystems, utilizing triangulation approaches that enhance validity and reliability.

For startups, validation should be recognized as an ongoing, multidimensional process that goes beyond technical testing. Combining adapted TRL approaches with Lean Startup principles for business model validation is recommended. Start-ups should actively seek ecosystem support from accelerators, incubators, and research institutions, and systematically document validation evidence to facilitate communication with investors and secure future funding. For investors and accelerators, developing nuanced assessment frameworks that incorporate both technical and business dimensions is crucial. Structured support for validation activities, not just funding, should be provided, with clear criteria and expectations for validation evidence. Sharing validated assessment approaches across the ecosystem can help reduce information asymmetries. Policymakers should support the development of standardized validation tools tailored to start-up contexts, facilitate greater coordination among ecosystem support institutions, address financing gaps at critical validation stages, and invest in validation infrastructure such as testing facilities, demonstration environments, and proof-of-concept funding. The study's limitations - reliance on secondary sources, geographic focus on European and North American contexts, and exclusion of very recent developments - suggest the need for further primary empirical research and broader contextual analysis.

Future research opportunities in technology validation for startups include several key directions. Empirical validation studies should be conducted, tracking startups longitudinally through their validation processes to identify success factors, common pitfalls, and critical turning points. Such research would provide actionable insights into the practical challenges and effective strategies for validation in real-world contexts. There is a need to develop and test integrated validation frameworks that combine technical, market, and business model dimensions. These frameworks should be validated through action research or quasi-experimental designs to assess their effectiveness in supporting start-up success and improving the reliability of validation outcomes. Comparative ecosystem analysis offers a valuable opportunity to examine how different national and regional innovation ecosystems structure their validation support mechanisms. By identifying best practices and transferable lessons, researchers can help harmonize and optimize validation approaches across diverse contexts. Sector-specific validation research is warranted to investigate whether validation requirements and approaches differ systematically across technology domains such as software, hardware,

biotech, and clean tech. This would enable the development of domain-adapted frameworks that address the unique challenges and opportunities in each sector. Institutional analysis should focus on the role of accelerators, incubators, and other intermediary organizations in facilitating validation. By identifying organizational practices that most effectively support start-up validation needs, researchers can provide evidence-based recommendations for improving the design and delivery of ecosystem support services. Finally, investor decision-making research should examine how investors assess validation evidence when making funding decisions. Comparing stated criteria with revealed preferences will help clarify the real-world impact of validation activities on investment outcomes and inform the development of more effective validation tools and processes. These research directions collectively promise to deepen our understanding of technology validation and enhance its practical application for startups, investors, and policymakers.

Technology validation represents a critical yet undertheorized aspect of start-up development. As innovation ecosystems mature and competition intensifies, systematic approaches to validation become increasingly important for both start-up success and efficient resource allocation across the ecosystem. This study provides foundation for developing such systematic approaches, grounded in theoretical frameworks while addressing practical needs of entrepreneurs, investors and support organizations.

The path forward requires collaboration among researchers, practitioners, and policymakers to develop, test, and refine validation approaches that balance rigor with resource efficiency, standardization with contextual adaptation, and technical assessment with market and business model validation. Only through such comprehensive, integrated approaches can the innovation ecosystem effectively support the transition of promising technologies from concept to commercial reality.

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