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# Bridging the gap: Linking prototyping and technology readiness levels for integrative product development

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Laura Rehberg, Institute of Entrepreneurship and Innovation Science (ENI), University of Stuttgart, 70569 Stuttgart, Germany. Email: st176358@stud.uni-stuttgart.de Shorter development cycles, increasing complexity due to the interaction of hardware and software and the simultaneous pressure to innovate and reduce costs lead to products being launched early that have not yet been sufficiently validated and tested. The prototyping phase is crucial to ensure maturity as a preliminary stage to series production. Although this validation is critical to ensure the maturity of the product or technology to avoid recalls, previous research has focused on exploring the phenomenon of prototyping in general. To fill this gap, we use the standardized framework of technology readiness levels and develop prototyping readiness levels that allow for a graded assessment of maturity.

Our empirical study is based on the unique case of the Boeing 737 Max 8 and a research project to develop an automated prototyping hub. Our findings show how mismanagement of prototypes and inadequate technology readiness level (TRL) assessment can lead to serious safety issues. Based on these findings, we introduce prototyping readiness levels that complement the idea of TRLs to reduce and eliminate bottlenecks and errors in the early stages of the development process.

### KEYWORDS

new product development, maturity, product development, prototype, prototyping, TRL

### 1 | INTRODUCTION AND RESEARCH GAP

Every year, numerous product recalls lead to financial losses, reputational damage and business interruptions across all industries. In January 2024, for example, the New York Times headlined that Tesla recalled 1.6 million cars in China (Bradsher, 2024) or Toyota recalled 1.8 million RAV 4 SUVs over potential fire risk in November 2023 (Mayorquin, 2023). In addition to losing customer confidence, market share can fall long term (Wowak & Boone, 2015). The reasons for defects and quality problems range from design faults and manufacturing problems to incorrect commissioning. Those responsible, such as suppliers, can also vary and may be inside or outside the company (Ni & Huang, 2018).

Therefore, companies must ensure product readiness before placing products on the market to identify and prevent product defects and safety problems proactively. This is supported by compliance with development processes and recurring quality checks. At the same time, however, increasing complexity and ever-shorter development cycles (Llopis-Albert et al., 2021) make it more difficult to adhere strictly to these. Methodological and procedural developments are therefore required to be efficient on the one hand and make the degree of maturity measurable along the development process on the other. The development landscape is divided into two areas: the new product development, which is characterized by, for example, the classic new product development process (Bessant & Francis, 1997; Tzokas et al., 2004), the product emergence process (Weber, 2009) or the V-model (D'Ambrosio & Soremekun, 2017), and the technology

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development, which is primarily controlled, for example, by technology readiness levels (TRLs) (Mankins, 1995). TRLs are used to assess the maturity of a technology and determine its readiness for use in the field (Mankins, 1995). The concept of TRL originated in the US government in the 1970s. NASA developed the levels to assess the readiness of technologies being developed for space missions.

The TRL system comprises nine levels, ranging from Level 1 (basic principles observed) to Level 9 (actual system demonstrated in an operational environment). Each level is defined by explicit criteria to evaluate the technology's maturity (Mankins, 1995).

Nevertheless, both streams are united using prototypes as an enabler. Whereas prototyping is a distinct phase in new product development, prototypes in technology development serve more as the outcome of individual phases for testing purposes in different environments. The occurrence of different types of prototypes for different purposes has also found its way into the literature and has spawned its own trend, known as prototyping research. In addition to prototyping processes (Exner et al., 2016; Warfel, 2009; Yu et al., 2018) and definitions (Houde & Hill, 1997; Rehberg & Brem, 2024), the focus is also on the purpose (Camburn et al., 2014; Jensen et al., 2016; Wall et al., 1992), design (Wall et al., 1992; Warfel, 2009) and role of prototypes (Lauff et al., 2018). Prototypes and their application are on everyone's lips, but the understanding of prototypes and their definition is very heterogeneous. Wall et al. (1992) already recognized: "Different types of prototypes are used in many different ways to address different types of questions."

Nonetheless, prototyping processes have not yet been retrospectively examined regarding the challenges or consequences of undesirable developments. As shown in Figure 1, previous research considers prototyping as part of the new product development process and concludes with the final product. This study starts precisely at this point and uses the findings on the final product to further develop prototyping as an essential phase.

Furthermore, advancing research in prototyping requires less of an isolated view of the method and more of an exploration of methods and processes in the context of real-world challenges (Elverum & Welo, 2016). New impetus is needed to optimize development processes in R&D by using prototypes as a vehicle for maturity development to identify and rectify deficiencies early.

While the integration of prototyping research into product development processes is slowly gaining momentum (e.g., [Rehberg & Brem, 2024]), its integration into technology development remains unexplored.

This study explores the symbiotic relationship through a case study approach to transfer prototyping into readiness levels, which can be applied across manufacturing industries. To fulfil this purpose, our study is based on two cases: the Boeing 737 Max 8, clearly illustrating the scope of developmental missteps (Bergstra & Burgess, 2020; Herkert et al., 2020; Zhang et al., 2022) and a research project on the development of an automated prototyping hub. With this approach, we aim to answer the following research question:

### "How can the prototypes' maturity level be measurable to efficiently ensure technology and product readiness?"

Our contribution can be summarized in two points. First, we review and analyse the decisions made during the development of the Boeing 737 Max 8 and the general challenges in developing complex products. Second, we create a process framework for structured prototype maturity development, divided into six phases: technology concept, dependency analysis, requirements, specifications, integration and testing. In this way, we help practitioners by presenting a framework that enables a maturity-level measurement of prototypes and, at the same time, optimizes the efficiency of prototyping by minimizing risks through a systematic approach. Theoretically, we contribute to the symbiosis between methods in an industrial context-based on real challenges. In doing so, we connect the literary strand between prototyping and new product development and technology processes and build a bridge between the specific requirements of industry and the generalist processes of literature. Our results strongly suggest that early recognition of risks and dependencies helps to make the development process more efficient and secure.

The article is organized as follows. First, the relevant literature on technology maturity and prototyping is discussed. Second, the research design approach is highlighted. Third, the research results on prototyping readiness levels (PRLs) are presented and discussed. The paper concludes with reflections on some limitations related to the case study and future research opportunities in prototyping.

Although all aspects and applications of prototypes are equally important, in this study, we focus on the systematic development of physical prototypes. In this context, we define prototypes as preliminary models without series maturity and limited functionality. Furthermore, in the context of this paper, we define prototyping as the iterative activity of creating this prototype.



# 2 | INTERFACES BETWEEN TRLS AND PROTOTYPING

The development of mechatronic systems is becoming increasingly complex (Cornelis et al., 2022). While hardware (HW) and software (SW) were considered separately in the past, complex mechatronic systems now dominate the innovation landscape. An integrative approach to developing these is necessary because, on the one hand, several interest groups are involved in the development (Törngren et al., 2014), including considering supply chains (Ramani et al., 2022). On the other hand, SW and HW must be developed and tested together (Do & Chae, 2007), as SW cannot be considered independently, for example, due to the certification of complex systems (Youn & Yi, 2014). The basis is formed by functional and nonfunctional requirements, which have no content boundaries depending on the system (Glinz, 2007).

Nevertheless, a functional prototype must be able to cover these requirements to ensure successful testing (Li & Liu, 2008). As the time-to-market is getting shorter and shorter, methods are needed that enable an accurate simulation of HW/SW systems (Bringmann et al., 2015), which underlines the importance of efficient prototyping methods. These must also be anchored in the development processes for technologies.

The connection between prototyping and TRLs only becomes apparent on closer inspection. While prototyping is primarily used to develop new products, TRLs describe the maturity development of technologies based on nine levels (see Table 1).

Both prototyping and TRLs play critical roles in engineering. They are closely linked, as the prototyping process is an essential step in technological development to increase the TRL value of a technology and thus accelerate its time to market. In contrast to new product development, prototyping does not represent a subprocess in

TABLE 1	Technol	ogy readiness	level (TRL)	(Mankins,	1995).
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Levels (1-9)	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in a laboratory environment
TRL 5	Component and/or breadboard validation in a relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9	Actual system "flight proven" through successful mission operations

technology development. Still, it is an outcome of the level as a prototype, which is then validated in the subsequent levels in different environments (e.g., laboratory or space environment). By creating prototypes, it can be shown that the technology can be applied and has the potential to be developed further. This is important to gain the confidence of potential investors, customers and other stakeholders and to accelerate progress toward market readiness. However, the definition of the expected outcome does not allow any conclusions to be drawn about how the maturity level of the prototype itself will develop.

This is not the only limitation of the concept. One of its main criticisms is that it focuses too much on technical readiness and does not consider other factors, such as market demand or social acceptance. Over the years, the concept has been adapted and modified to assess the readiness of various technologies and other factors and concepts. For example,

- Software Technology Readiness Level (STRL) (Graettinger et al., 2002)
- System Readiness Level (SRL) (Sauser et al., 2006)
- Human Readiness Level (HRL) (Salazar & Russi-Vigoya, 2021)
- Integration Readiness Level (IRL) (Sauser et al., 2010)
- Demand Readiness Levels (DRL) (Paun, 2012)
- Manufacturing Technology Readiness Level (MTRL) (Peters, 2015)

Peters' (2015) MTRLs are based on specific manufacturing technology criteria. The HRLs were developed to address the human element throughout the lifecycle (Salazar & Russi-Vigoya, 2021). Furthermore, these also arise when there are challenges in applying the models. For example, Olechowski et al. (2015) shed light on the limitations of TRLs in terms of independent evaluation of components and the lack of consideration of incremental improvements of previous versions.

In addition, components' integration problems are the leading cause of delays and budget overruns. In addition, Sauser et al. (2006) note that while TRLs are useful as characterizations for technology development, they do not indicate how the technology is integrated into an overall system. Kujawski (2013) refers to this and evaluates SRL as potentially misleading since TRL is ordinal data. Paun (2012) takes the perspective of demand readiness, which he argues is a missing link in the TRL concepts. Mankins (2009) re-evaluated his TRL model years later and saw the differences in perception and attribution of TRLs and between subsystems and components as challenging. Furthermore, he emphasizes expected uncertainty in research and development into practices and metrics.

However, prototyping research is also characterized by different research directions. Overall, prototyping refers to an experimental phase in the product development process in which several versions or models of a product, known as prototypes, are created for various purposes. These are further developed, refined and optimized within this process phase. Therefore, prototyping is critical to the engineering design process, as it systematically demonstrates feasibility and applicability (Lauff et al., 2018; Wall et al., 1992). It involves creating a preliminary version of a product or system to test its functionality,

performance and usability (Rudd et al., 1996). However, a variety of studies have looked at prototyping in engineering design, along with its purpose, maturity development and process approach (Camburn et al., 2014; Christie et al., 2012; Exner et al., 2016; Houde & Hill, 1997; Jensen et al., 2016; Lauff et al., 2018; Wall et al., 1992; Warfel, 2009; Yu et al., 2018). Prototyping helps engineers identify and address design issues before finalizing the product, reducing the risk of costly errors in the final version (Houde & Hill, 1997). The term prototype is commonly used across different disciplines. However, a distinction is made primarily concerning the characteristics of a prototype. Beaudouin-Lafon and Mackay (2012) define a tangible artefact as one that does not require interpretation as a prototype. Ullman (2010) and Liao et al. (2009) also refer to the tangibility criterion and define a prototype as a physical model. Erichsen et al. (2019) extend this to include computer-aided design models and drawings. Wall et al. (1992) and Warfel (2009) choose a different description and characterize a prototype as the first of its kind in engineering. Furthermore, it provides information about the performance and quality of the product and the manufacturability (Warfel, 2009). Overall, a prototype contributes to a better understanding of design, functionality and usability throughout the technical design process (Otto & Wood, 2001; Ulrich & Eppinger, 2012).

BenMahmoud-Jouini and Midler (2020) take a bird's eye view of prototyping and introduce three archetypes along the development process. In the early phase of the design process, he presents the two archetypes: stimulators to stimulate creativity and demonstrators to evaluate initial concepts. After the development phase, so-called validators are used to validate specifications and ensure buildability. This perspective is extended by Dosi et al. (2020) to show that prototypes can also inhibit innovation. Building on the fundamental insights into the characteristics and use of prototypes further challenges arise in developing highly complex technologies that require SW and HW integration.

On the one hand, few empirical studies deal with highly complex physical technologies or products (Lakemond & Holmberg, 2022) or the role of prototypes in developing such (Elverum & Welo, 2015). On the other hand, there are special requirements on the part of the external authorities. For example, they defined test activities that must be carried out in the development phase to detect errors at an early stage (Woodward & Hennell, 2005).

Although prototyping and TRLs are separate concepts and research areas, they are closely linked.

While prototyping is viewed as an isolated phenomenon in prototyping research, it represents an underlying methodology in the TRLs, which is considered in the levels. Once a prototype has been successfully tested and helped improve the technology or product, the TRL level for any new technological developments can be increased as the technology or product is closer to the market. Nevertheless, the interfaces between prototyping research and TRLs are critical convergence points in the technology development process. Exploring these interfaces is essential for optimizing the effectiveness of prototyping efforts and explicitly assessing their maturity level. By strategically linking prototyping activities to the TRLs and making the maturity level of a prototype measurable, risks and misconceptions in development can be identified in a structured manner at an early stage, and costs can also be reduced in the long term. We take advantage of the disadvantage of TRLs that no comprehensive assessment of the potential risks of a technology is part of TRLs and combine this with the purpose of prototyping, which is to test and evaluate technical solutions to identify any issues that need to be resolved before the final product is manufactured.

### 3 | RESEARCH DESIGN

In this paper, technological readiness levels are examined and applied to prototypes to measure maturity development. The aim is to make development processes for technologies and products in the prototyping phase more efficient by validating and verifying assumptions at an early stage to reduce recalls or failures after commercialization.

First, case data and multiple sources describing the phenomenon from different perspectives allow a deeper understanding of the underlying mechanisms (Eisenhardt & Graebner, 2007). Second, case studies provide a holistic insight by investigating complex phenomena (Hollweck, 2016; Yin, 1994). Therefore, a case study is chosen to examine (Eisenhardt & Graebner, 2007) and understand the real-world context in which the phenomenon occurs (Hollweck, 2016; Yin, 1994).

The decision to analyse multiple groups of people within the occurring phenomenon is based on Yin's (1994) findings that they provide a more solid basis for developing theories. The research design of this paper is shown in Figure 2.

We compiled and summarized previous technology readiness and prototyping research in the first phase. By consolidating these various sources, we aimed to identify areas where existing research may need to be expanded to address real-world challenges better. To conduct the case study, Phase 2 identified cases that had challenges in development that either led to delays in the timeline (Automated 3D printing platform) or failure of the technology after commercialization (Boeing 737 Max 8).

Empirical data on the cases considered in this paper were collected from various sources. The systematic analysis and evaluation of this data in phase 3 (technical reports, documentation, field investigations) served to identify significant patterns and critical findings, which were then combined with the conclusions of the literature.

This empirical investigation enabled us to comprehensively understand the current situation in practice and the complex relationship between the concepts of TRLs and prototyping. The data analysis served as a cornerstone for deriving conclusions and insights crucial for further research into the phenomenon.

In the final step of our study, we translated the findings and patterns from the empirical data analysis into a conceptual framework called "Prototyping Readiness Levels." The insights and knowledge gained from the research and empirical analysis were translated into a structured model within this framework. The formulated PRLs are





intended to serve as a practical guide or tool, providing engineers and practitioners from different disciplines with a strategic framework to make iterative development more systematic and effective.

#### 3.1 **Research setting**

To answer the research question, we looked for development projects aimed at creating a new technology or haptic product that could be commercialized. We did not limit ourselves to one industry to avoid bias. The research framework is based on analysing secondary data for the Boeing case and qualitative analysis of a research project. In the Boeing case, 344 pages of documentation and 23 papers were analysed. Six were found to be relevant. All the data used are listed separately in Section 3.2.

The selection of cases was based on the following criteria:

- Extensive documentation of the development available/or access to documentation can be made possible
- Unrestricted viewing of all CAD models/physical prototypes, if available
- Development based on TRLs

Given the focus of our study on engineering design processes, we chose a divided research approach in two case studies to gain multiple perspectives to validate the results. We focused on gathering the decision chains during development to capture assumptions and decisions that influence the final product. For this, we chose two cases where prototypes play an essential role, and the final product interacts with a human. Accessibility to development documentation is minimal due to secrecy, so we selected the very well-documented

case of the Boeing 737 Max 8 and a research project at a research campus of a German university that focuses on developing an automated prototyping hub that enables decentralized additive manufacturing of prototypes.

The Boeing 737 Max 8 is a commercial airliner designed for medium-haul flights, capable of accommodating up to 189 passengers and flying over 6500 km. The first crash occurred on 29 October 2018, when a Lion Air 737 MAX 8 crashed into the sea off Indonesia.

The second crash occurred on 10 March 2019, when an Ethiopian Airlines 737 MAX 8 crashed in Ethiopia (National Transportation Safety Board, 2019; The federal democratic republic of ethiopia ministry of transport and logistics, 2022).

This unique case needs to be scientifically investigated for several reasons. First, following the two crashes attributed to flight control SW problems, the safety of the Boeing 737 Max 8 has been called into question. It is crucial to understand how these problems occurred and how they can be avoided in the future. Second, the Boeing 737 Max 8 resulted from an extensive development, prototyping and testing phase. A thorough analysis can help to understand where errors occurred during the process and how they can be avoided. Third, this case has been intensely researched, and the lessons learned are accessible. Mistakes in development that lead to accidents or fatalities are otherwise rarely made public. Therefore, this case provides a fruitful basis for further research into prototyping as part of product development. Overall, a scientific investigation of the Boeing 737 Max 8 is essential to ensure that errors during the development, prototyping and testing phases can be avoided in the future and to ensure the safety of highly complex SW-driven products.

In addition, the research project "Automated 3D Printing Platform" aims to offer prototyping as a service.

With the help of the developed platform, customers should be able to order 3D prints directly via a web interface by uploading the print order via the portal. The platform itself consists of several 3D printers, which are connected via a rail system. After completion of the print job, the component is picked up via the printing plate and stored via a rail system. To ensure integrated development, the tasks were allocated to the project team members according to their other functions at the start of the project. The milestones were monitored based on deadlines for the respective installation managers. Communication within the project was ensured through weekly team meetings.

The project was analysed over the entire development process and the individual TRLs 1–6.

### 3.2 | Data collection

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We opted for case studies with two different scenarios. One case represented a disastrous outcome, while the other illustrated a successful completion of the product development process. Our selection aimed to contrast the impact of wrong decisions or misleading assumptions during the prototyping phase. We sought to gain fundamental insights into the effects of such errors in the prototyping process through data collection (see Table 2).

### 3.3 | Reports/documents on Boeing 737 Max 8

In the case of the Boeing 737 Max 8 accident, the data are primarily based on the reports published by the Ministry of Transport and

#### **TABLE 2**Overview of data sources.

Logistics of the Democratic Republic of Ethiopia and the National Transportation Safety Board. Within this framework, 344 pages of documentation were studied and analysed. The focus was put on the course of the accident and the erroneous decisions in the development that led to the accident.

### 3.4 | Previous research on the Boeing 737 Max 8

Since few accidents are as well-documented as the Boeing 737 Max 8, we analysed previous research on the subject and the damage analysis published by the authorities.

For this purpose, we searched for "Boeing 737 Max 8" in Google Scholar and identified referenced papers using the snowball method. Six articles were identified as relevant to understanding the context of what happened during the development.

# 3.5 | Field research of the automated 3D platform project

The development of an automated 3D printing platform was followed, documented and analysed over 6 months. During this period, field visits were made to observe the platform's development, and meetings were held to monitor discussions on further development and possible misconceptions. The goal was to exchange with the participants to understand the decisions better. In addition, prototypes that were not used were analysed and evaluated for reasons why they were not applicable.

	Data source	Method/type of data	Purpose
Case 1: Boeing 737 Max 8	Reports/documents on Boeing 737 Max 8	Published reports on the occurrence of accidents and damage reports	- Gain an understanding of the accident situation from the point of view of the authorities.
	Previous research on Boeing 737 Max 8	Research paper that analysed and evaluated the accident occurrence	<ul> <li>Understand and consolidate derivations that researchers have made based on published findings.</li> </ul>
Case 2: Automated 3D platform	Field research of automated 3D platform project	Observation of ad hoc meetings of the project team, visits to the plant, observation of the progress during the development phase and analysis of CAD models/ prototypes	<ul> <li>Gain a technical understanding of the platform, which formed the basis for the informal interviews.</li> <li>Analyse the prototypes/implemented solutions in the platform to identify the development progress and associated challenges.</li> </ul>
	Project team members	Nine informal interviews during visits were documented as notes and summaries.	-Gain an understanding of decisions that have been made. - Identify challenges during development. - Understanding the path to finding solutions
	Documentary and press release	Officially published product videos, reports and news.	- Secondary data is used to put the whole project and the original objective in context to the final solution at an earlier stage.

### 3.6 | Project team members

In addition to the CAD models, unstructured interviews were conducted with the developers to identify incorrect assumptions made during the prototyping phase, as in the first case. The interviewees were exclusively members of the development team with an engineering background. To ensure an open exchange, no formal interview guide was used, and the focus was on an informal discussion to keep barriers low, aiming to get unfiltered explanations of development progress and potential missteps. The thematic focus was as follows:

- Which prototypes were used in which phases?
- What characteristics did the prototypes need to have in each phase?
- Were there delays in development?
- What were the reasons for these delays?
- What role did the prototypes play in eliminating identified misconceptions?
- In retrospect, what should have been considered to ensure a more efficient maturity-level development?

### 3.7 | Documentary and press release

Public product videos and documentation about the project were studied to contextualize the progress of goals and decisions. This documentation helped to gain a basic understanding of the project and its goals and provided input for interactions with the project team.

### 4 | FINDINGS

# 4.1 | Technical analysis—Challenges in the development phase based on the TRLs

The technical analysis of the cases has shown that challenges in TRL 5 have arisen in both cases (see Figure 3). In the case of Boeing, the technical problems appeared to have been resolved, but it became apparent after the product was placed on the market that the technical solution was inadequate. In contrast, in the case of the automated 3D printing platform, countermeasures were taken during development. Here, an incorrect assumption at the beginning led to a delay in the transition from virtual to physical prototypes. The assumptions had to be reformulated, resulting in a shift in the development timeline.

In the first case, during the TRL-5 tests, it was shown that installing the new LEAP-1B engine led to a nose-up moment (ANU) of the aircraft when operated at a high angle of attack (AOA) and medium Mach numbers. As a result, aerodynamic modifications were made. A stability enhancement feature (Manoeuvring Characteristics Augmentation System [MCAS]) was introduced to improve flight characteristics and reduce the tendency to pitch up at high AOA after investigating various options to correct this problem (National Transportation Safety Board, 2019).

After its successful maiden voyage on 29 January 2016, the plane was ultimately grounded due to a fatal accident caused by the adjustments made to the aircraft's aerodynamics following the engine upgrades. After intensive investigations, several factors were identified that could have contributed to the accidents. One of the leading causes was the MCAS, which was activated in both crashes. This system was introduced to prevent the aircraft from stalling, but it was later found to malfunction under certain conditions, contributing to the crashes (Sgobba, 2019). The system failed to recognize all scenarios during the flight. As a result, the SW could only incompletely and partially incorrectly assign the requirements (Zhang et al., 2022). In addition, it was designed to pivot the horizontal stabilizer and push the nose of the aircraft down to prevent a stall. In operation, however, the range of motion exceeded more than four times what was initially specified in the safety analysis document (Gates, 2019). Crash investigations revealed that the 737 Max's MCAS received incorrect data from a single angle of attack (AOA) sensor. The difference between the left and right angles of attack was about 20° for the Lion Air flight and about 59.2° for the Ethiopian Airlines flight 302, each of which caused the aircraft's control computer to push the nose down (National Transportation Safety Board, 2019). The pilots had difficulty regaining control of the plane, possibly because they were unprepared for the risk.

As a result of the crashes, the FAA and other regulatory authorities worldwide suspended the Boeing 737 Max 8 flight permit. Boeing has since made extensive changes to the aircraft, including necessary SW updates and training to ensure flight safety (National Transportation Safety Board, 2019; The federal democratic republic of ethiopia ministry of transport and logistics, 2022).

The investigations also raised allegations that Boeing had misled the FAA during the certification of the 737 Max and had prioritized profits over aircraft safety (Herkert et al., 2020).

In the case of the Automated 3D printing platform, the incorrect assumptions from TRL 1 did not lead to a failure of the system as they could be rectified in the transition between TRL 4 and TRL 5. At its core, the automated 3D printing platform consists of purchased 3D printers on the HW side, which are to be connected via a specially developed solution to receive print jobs decentral and to be able to print them at any time. The central assemblies for realizing this challenge are visually broken down in Figure 4.

The rail system serves as the basic infrastructure that ensures the movement and alignment of the various mechanisms and components within the prototyping hub. It thus forms the basis for the integration of the 3D printers and the storage of the finished printed components. At the same time, the axes ensure seamless movement within the installation space and form a link between the rail system and the grip mechanism. However, the axial degrees of freedom also represent a limiting factor in the development of the other assemblies.

The central role of the grip mechanism is to pick up the finished prototypes and store them in the warehouse. This is

	TRL Level	Technical Problem	Solution	Consequence	Summary
Case 1: BOEING 737 MAX 8	TRL 5	Installation of LEAP-1B engine leads to nose-up moment (ANU) when aircraft is operated at too high angle of attack (AOA) and medium Mach numbers	Stability enhancement feature (Maneuvering Characteristics Augmentation System (MCAS))		
	TRL 9			Crash/ system not able to recognize all scenarios during the flight. As a result, the software only incompletely and partially incorrectly assigns the requirements	Failed software/hardware integration leads to accidents and suspension of flight permit for the Boeing 737 Max 8
<b>Case 2:</b> AUTOMATED 3D PRINTING PLATFORM	TRL 1	Incorrect technical assumptions in TRL 1 that were only identified at a later level.	•		
	TRL 4-5	The transition phase from digital to physical prototypes failed.	Reformulation of assumptions from TRL 1 and return to previous TRLs	Delay in the development process	The grip mechanism cannot be realized via servo motor as assumed/ Regression is needed.

FIGURE 3 Challenges in the development phase.



FIGURE 4 Overview assemblies.

particularly important to optimize the throughput times of the 3D printers, offer a time-independent service and avoid congestion in production. This is supported by electronics and SW that act

as a nervous system and ensure the control and automation functions essential for the prototyping hub's smooth operation and functionality.

Together, the assemblies form a comprehensive system that combines mechanical, technological and functional aspects. Although the assemblies appear to stand alone, they all contribute significantly to the functionality of the prototyping platform and must be considered and developed in an integrated manner.

The specifications were formulated in TRL 1 as part of the technology concept at the beginning of the development. For example, since the innovation is based on the gripping mechanism on the HW side, it was defined at an early stage that a servo motor would control this. The development of this assumption along the TRL (1-6) is described in the following Figure 5.

Dependencies and risks often remain undiscovered until they cause a delay in production or a failure. No delays occurred within the digital phase, where only the team was responsible for progress. The transition from SW to HW and the associated dependencies on suppliers and machines caused a bottleneck between TRL 4 and TRL 5. Although iterations are not directly provided for in the framework of the TRLs, iteration was necessary, which led to a significant delay in the schedule. The reason was a wrong assumption formulated initially and concerned the most critical assembly, the gripping mechanism. Delivery problems also slowed down the process. Since the risk was not announced in TRL 2 and TRL 3, no adjustments could be made in advance.

In summary, the technical analysis shows that the challenge lies primarily in implementing and validating technical assumptions in both cases. In the case of the Boeing 737 Max 8, the technical solution was assessed as suitable but was not sufficiently tested. In the case of the 3D automated platform, incorrect assumptions were made at the outset, which only became apparent during the transition between the digital and physical prototypes.

Based on this, we can extract three critical lessons learned from both cases:

 Deploy earlier in the development phase: Prototypes should be used early in the development phase to detect misconceptions and test functionality and safety mechanisms. In this way, potential problems and errors can be identified and rectified before the product goes into production.  Test more comprehensively: Prototypes should be tested in extensive test scenarios to ensure they work in different environments and situations.

This can also help simulate unforeseen events and ensure the aircraft is safe and reliable. In particular, the interaction between HW and SW must be analysed at an early stage in various defined test cases.

 Review regulary: Prototypes should be reviewed regularly to meet standards, requirements and specifications. Any problems should be promptly corrected before the product goes into production.

# 4.2 | Data analysis and formulation of aggregated dimensions

The analysed data clearly show that despite the differences between the cases regarding scope, context and success, three aggregate dimensions are groundbreaking (see Table 3).

### 4.3 | Project frame and dependencies evaluation

Assessing the project framework and dependencies is a fundamental cornerstone of project management for a new technology or product. A comprehensive analysis of the structural framework and the available resources framework conditions such as time, costs and deadlines. In addition, dependencies must also be analysed at an early stage. These include dependencies on suppliers, internal dependencies (in the case of component-based development), installation space dependencies and HW-/SW-related dependencies. This way, potential bottlenecks and risks can be considered early, especially concerning risk management strategies.

### 4.4 | Product specifications and incident records

Product specifications form the basis for every type of development in the industry. Especially for communication with stakeholders, they



FIGURE 5 Technology readiness level (TRL) 1–6 of the prototyping hub.

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### TABLE 3 Data analysis of the case study.

First-order code	2nd order themes	Aggregated dimension	
Statements about the composition of the people involved (e.g., project team, engineers)	Initial project contextual details	Project frame and dependencies evaluation	
Description of the time course of the development/project			
Explanation assumptions made in the development phase	Project history and influences		
Explanation of interdependencies (e.g., suppliers)			
Initial technical description of the product	Product documentation and considerations in the	Product specifications and	
Influencing factors (e.g., safety, requirements from authorities, stakeholders)	development phase	incident records	
Description of technical incidents software-related	Technical incident reports		
Descriptions of technical incidents hardware-related			
Description of technical errors of a component	Technical anomalies documentation	Technical issue management	
Description of technical failures of a system			
Changes in the approach in the development phase (e.g., based on unavailability of components and resources)	Development adaptations and remediation actions		
Contributing factors (e.g., technical decisions) that cause delay/incidents			
Description of mitigation measures after an error has been detected			

are a crucial element for technically precise communication. Here, a product or component's requirements, functionalities, regulatory requirements and features are specified. They serve as a reference point to ensure the final product meets the requirements. The prototypes are developed and tested based on this specification, so it is essential to document all incidents that occur, such as deviations, misconceptions, bugs and integration errors.

### 4.5 | Technical issue management

Building on the documentation of incidents, technical problem management is required to systematically analyse and resolve technical problems during the development, testing or implementation phase. This includes a structured approach to handling issues, root cause analysis and the prioritization and evaluation of scenarios. These, in turn, must consider the dependencies defined in the project framework at the beginning and the product specification.

### 5 | DISCUSSION

The results of these studies have shown that incorrect risk assessments and assumptions in the development process can lead to delays and, in the worst case, to accidents. Prototyping as a supporting method can help identify risks early, but it is not emphasized in the TRLs. They focus primarily on technical readiness and neglect the critical aspect of component integration and interaction. However, considering the complexity of technologies and products, this integrative view is essential. Furthermore, risk assessment and mitigation of potential uncertainties are not reflected in the TRLs. Nevertheless, the results of the case studies have shown that it is crucial to identify potential risks, especially in the early stages of development. This includes considering multiple stakeholders influencing the product or the development process, for example, suppliers, end users and authorities.

### 5.1 | PRL framework

The case study findings and previous research have laid the foundation for developing the PRL framework (see Figure 7), which complements the TRLs and extends their application scope. To achieve this (see Figure 6), the aggregated dimensions and critical lessons learned were divided into different phases and stages.

On the other hand, the substantive aspects were placed in chronological order to ensure that each aspect was thoroughly addressed. Together, these elements form a comprehensive prototyping framework that guides the entire process from start to finish. The following illustration shows the framework in detail (see Figure 7).

The framework consists of four areas: the scope, the standards, the comprehensive testing and the supporting activities. It describes the maturity-level development over time.

The respective areas (1–3), in turn, contain the assigned PRLs that are required to achieve them. These are extended by supporting activities (4) and the associated **P**rototyping **S**upporting Levels (PSLs). The case study has clearly shown that incident tracking and issues management are essential.

Furthermore, the critical lessons learned from the findings must be reflected in the PRLs to fulfil this. In contrast to the TRLs,



FIGURE 6 Transformation of findings into prototyping readiness level (PRL) framework.



FIGURE 7 prototyping readiness level (PRL) framework.

prototyping is defined more broadly and includes the development of technology concepts.

Furthermore, the sequence of PRLs is linear, with validation loops that check the assumptions made in previous PRLs and ensure that the assumptions continue to be met (BenMahmoud-Jouini & Midler, 2020). If these are not fulfilled, it is possible to return depending on the error or incorrect assumption. The extent to which this is possible depends on the project and its complexity. Technical and financial constraints may be factors.

The first aggregated dimension from the case study "Project frame and dependencies evaluation" forms the starting point of the PRL framework (PRL 0). The definition of the project framework is a nontechnical requirement, which, as the study has shown, is fundamental to develop a technology concept. The following Table 4 describes the individual technical Levels (1–6).

Developing a technology concept (PRL 1) includes the initial research and the functionalities and technologies to be integrated. This also contains the evaluation of which components should be developed in-house and which should be sourced from suppliers (see Table 3) (Ni & Huang, 2018). This step is essential to identify critical components. Crises such as the worldwide shortage of semiconductors, which have led to delivery problems in the automotive industry, show this step's importance (Ramani et al., 2022). No haptic prototype is created at this level because the concept or idea is still in the initial development phase (Rehberg & Brem, 2024).

The components and their interfaces are defined in the following step of the dependency analysis (PRL 2) (Törngren et al., 2014). The

#### TABLE 4 Prototyping readiness levels (PRLs).

Levels (1-6)	Description
PRL 1: Technology concept	<ul> <li>Basic research</li> <li>Functionalities are identified.</li> <li>Technical assumptions have been formulated.</li> <li>Critical component/assembly is identified.</li> <li>Supplier overview</li> </ul>
PRL 2: Dependency analysis	<ul> <li>The component overview is created.</li> <li>Identification of dependencies/risk management</li> <li>Planning procurement</li> <li>Validation of technology concept</li> <li>Consolidation of results</li> </ul>
PRL 3: Requirements definition	<ul> <li>Definition of functional and nonfunctional requirements</li> </ul>
PRL 4: Specifications development	<ul> <li>Detailed technical description based on requirements</li> <li>Definition of test cases</li> <li>Simulation HW/SW</li> </ul>
PRL 5: Integrative prototype	• Integrative prototype for testing software and hardware and the interaction of these
PRL 6: Testing	<ul> <li>Ensuring functionality</li> <li>Testing quality requirements (e.g., standards)</li> <li>Testing for the fulfillment of requirements (PRL 3) and specifications (PRL 4)</li> </ul>

Abbreviations: HW, hardware; SW, software.

Boeing 737 Max 8 case has shown that the interaction of components and a low consideration of the effects of SW on HW can lead to severe problems (Cornelis et al., 2022). With the completion of the second phase, a basic understanding of the technology exists to build a prototype and test the SW.

The SW and HW requirements are developed in PRL 3. As also shown in the case study (Aggregated dimension: Product specifications and incident records), this step is particularly critical because it forms the basis for the SW's design, implementation and testing on the HW. The requirements must not only be clear, precise and complete but also measurable, testable and verifiable.

The development of highly complex products with a high proportion of SW increases the need for more precise specifications, as the Boeing 737 Max 8 case shows (see Table 3). The specifications (PRL 4) are derived from the functional and nonfunctional requirements (Glinz, 2007). They also include detailed technical descriptions, architecture diagrams, interface descriptions, data models and other technical details. At this point, initial simulations of HW/SW can be used to test and refine the previously defined requirements (Bringmann et al., 2015).

The next step (PRL 5) includes building an integrative prototype with which the HW, the SW and the interaction of these can be tested in PRL 6. The SW can never be tested or certified as a standalone module, making an integrative approach essential (Youn & Yi, 2014). Integrating HW and SW is significant in prototyping (Do & Chae, 2007) and, according to the critical lessons learned from the case study, is also crucial for the completion of development.

Based on the evidence from previous research (Liao et al., 2009; Otto & Wood, 2001; Rudd et al., 1996; Ullman, 2010; Ulrich & Eppinger, 2012) and the findings from this article, we define an integrative prototype as a physical object consisting of HW and SW that enables near-series testing and validation of the functional requirements of HW and SW to contribute to the validation of the functionalities from the requirements.

Due to the increasing number of modules and the growing number of suppliers, integration problems often occur, which must also be identified (PSL 2) and resolved (PSL 1) during testing (see Table 3) before the product goes into manufacturing or series production.

In addition, supporting activities consist of technical issues management and improvements (PSL 1) and incident records (PSL 2). These indicate when the user may have to return to a previous phase because an unforeseeable problem has arisen. For example, in the case of issues that occur during comprehensive testing. These must be documented (PSL 2) (e.g., via Jira) and resolved accordingly. This sometimes requires an adjustment, for example, in the technology concept, which means that the framework user should return to PRL1 and go through and validate it again. Possible risks that cannot be validated before testing must be documented as part of PSL 1 and verified as part of testing.

### INTEGRATION OF PRLS IN TRLS

PRLs represent a methodology for making the maturity level of prototypes measurable. They can, therefore, be used on their own but can also be integrated into TRLs in the development (see Figure 8) of a new technology or in other development processes dedicated to new product development.

As they are limited in scope, it is recommended that they be used as a complement to existing processes.

The integration of PRLs into TRLs is phase-related. Therefore, ensuring TRL 1–3 must consider the fulfillment of PRLs 1–4. In contrast to the TRLs, the PRLs are developed iteratively (see Figure 7).

This makes defining assumptions within the PRLs possible, which can then be validated, tested and rejected before the transition to the next TRL occurs.

Additionally, PRLs can be integrated into all existing processes or used as a supplementary method to ensure the maturity level of prototypes. The advantage is that implemented process landscapes do not have to be fundamentally changed but methodically expanded. The precise assignment and measurability of the prototype also facilitate communication and enable precise issue tracking through the accurate assignment of the level. Furthermore, the systematic approach of PRLs supports the early identification of risks and dependencies in the early phases of development. The case studies showed that it is not only the functionality of the components in the assemblies that is important but also how they are put together. Validation loops can be used to check assumptions and specifications repeatedly. In this way, unexpectedly incorrect assumptions cannot be avoided, but they are detected earlier. A systematic approach and the involvement of relevant stakeholders make it easier to overcome bottleneck



FIGURE 8 Integration of prototyping readiness levels (PRLs) in technology readiness levels (TRLs).

effects and, in the best case, even avoid them. Although the two cases are different in nature and characteristics, it became clear how essential prototypes are in developing new products to detect design errors. In the case of an airplane, the complexity is much higher, and safety is of paramount importance, but there are analogies between the two cases. For example, it is crucial to consider the human factor in prototype research. Human decision-making and training are critical aspects of prototyping, as exemplified by the lack of adequate pilot training and the failure of the automated system to provide sufficient feedback to the pilots.

The stages of prototyping readiness presented in this paper can be seen as complementary to existing research and provide a detailed view of assessing prototype maturity. The stages are structurally organized linearly but include an iterative validation of assumptions from previous stages. In addition, the risk assessment aspect is integrated into the phases. The study of the two cases helps to extend the knowledge of prototyping research beyond this case study. As part of this case study, the available findings were used to develop PRLs based on the TRLs (Mankins, 1995). These are relevant to all companies that manufacture physical products, for which prototyping is a component of new product development.

# 6 | THEORETICAL AND MANAGERIAL IMPLICATIONS

Product recalls not only cost companies money but often also damage their reputation. As the Boeing 737 Max 8 case has shown, the development phase is crucial for validation and testing to detect and correct errors. The study presents a novel prototyping framework with significant theoretical and practical implications. It shows that a dedicated consideration of the prototyping phase and the associated maturity-level development could be beneficial for optimized control of the development progress. The prototype readiness levels (PRLs) are based on the structural approach of the TRLs but form their maturity assessment, which could be integrated into various development processes as part of the prototyping phase as a methodology for progress assessment.

PRLs represent an extension for prototyping research. While previous research has focused on various aspects of the definition (e.g., [Beaudouin-Lafon & Mackay, 2012; Houde & Hill, 1997; Rehberg & Brem, 2024]), the processual procedures (e.g., [Wall et al., 1992; Warfel, 2009; Yu et al., 2018]) and the purposes and applications of prototyping (e.g., [Houde & Hill, 1997; Lauff et al., 2018]), this study brings out a further aspect: the measurable maturity-level development. As Lauff et al. (2018) noted, the prototyping phase is at the heart of any development process. It is, therefore, essential to research each influencing factor separately. The two case studies clarified how incorrect assumptions can lead to delays or accidents. This study deals with the effects that development decisions have on the product. It links the identified patterns to a framework that combines the existing methodology of TRLs with the methodology of prototyping. Based on these findings, the PRLs provide a theoretical foundation for assessing and managing prototype readiness and maturity, which could ultimately lead to more successful innovation and a safer product. Overall, integrating prototyping techniques with the TRLs offers a significant opportunity to improve the quality of the development process.

Therefore, we suggest that we might learn from practice by reviewing failed or significantly delayed projects to identify weaknesses in process flows, which could enrich research.

The results of this study also have several interesting implications for practitioners. First, this study suggests that prototyping is not just a mere method but an important tool to identify risks early and independently and to reduce bottlenecks in the development process. In addition to the factors mentioned above, it may also be beneficial to consider the human factor and the impact of the decisions it makes as essential elements for efficient product development. The introduction of the PRL framework offers a targeted approach to assessing the maturity of prototypes, which makes it easier to evaluate development progress in the prototyping phase. By combining this methodology with established development processes, companies can reduce risks at an early stage and develop more efficiently. However, this may require rethinking process steps or integrating PRLs into existing processes, which may require top management commitment. It is becoming increasingly clear that there is a great deal of value to be gained from prototyping and that managers would benefit from having access to processes and guidelines for this. One of the more challenging aspects is the impact of technological progress and the regulatory influences that come with it. The sheer volume of SW makes it necessary to rethink development and the processes used. Aspects such as integrating SW and HW and the associated risks are expanding the types of decisions that need to be made. The introduction of PRLs considers this aspect and validates decisions in phases. While the extension of process steps, in this case, the prototyping process, initially means additional work, it increases efficiency by minimizing risks in subsequent phases. Instead, focusing on the earlier development phase may be beneficial to ensure targeted development and a safe product.

### 7 | LIMITATIONS AND FURTHER RESEARCH

This study also has its limitations. Due to the availability of data where development delays or failures occur after entry into service, the data basis focuses on the specific case of the Boeing 737 Max and the results of a research project at a German university. Based on the results, PRLs were developed to support companies and research groups in the development of projects by making the maturity development of prototypes measurable.

Nevertheless, stand-alone PRLs cannot capture the degree of technological maturity, which is crucial for assessing the overall maturity of a technology. It is, therefore, advisable to integrate PRLs into existing processes as a supplementary framework. An integrative approach is crucial. Otherwise, separate frameworks may lead to duplication of effort, especially given the overlap in content between the two maturity-level concepts. Furthermore, assessing the effort involved in introducing PRLs is not considered. The possible trade-off between increasing the safety of the product/technology and possibly more extended prototyping phases needs to be evaluated in future research. This also applies to the evaluation of possible further areas of application. The results in this study are primarily aimed at the development of functional prototypes, which are characterized by similar conditions to those described in the two cases. The development of service or UX prototypes, for example, would require a different process due to the distinct nature of the final product.

Further research should include empirical studies to validate the effectiveness of introducing PRLs in different industries and contexts. In addition, the role of other factors, such as team dynamics, organizational culture and legal frameworks, in the success of prototyping and the evaluation of PRL should be considered as part of further research. This also applies to the impact of new technologies, such as

artificial intelligence and blockchain, on prototyping and the general parameter complexity of research projects. We believe that the current approach to measuring prototype maturity makes an essential contribution to resource- and time-efficient prototype development.

In addition, the respective process step should examine different methods and tools and their suitability. The industrial perspective in various sectors and the influence of suppliers can also be a fruitful research approach. For example, developing small series in the automotive industry requires new processes and production technologies in terms of efficiency.

Based on the results of the case studies, we recommend expanding prototyping research in general to include the aspect of the complexity of a product or technology and the integration of HW and SW. This also involves incorporating the state of the art in prototyping research across disciplines and investigating and re-evaluating existing methods and tools for dealing with complexity to support practitioners in managing, using and developing complex systems. Exploring integration issues can also contribute to the further optimization of prototyping. Whereas HW and SW development was separate in the past, today, cross-disciplinary development must be considered in research to provide innovative solutions. Introducing PRLs is a starting point for rethinking prototypes and their maturity assessment. However, research must not stop at this point. Still, it must be complemented by validation and testing methods such as simulation and virtual prototyping to improve the efficiency of prototype evaluation at the different PRL stages. However, we also recommend that practitioners take up and establish the complexity and the associated new findings in research. Existing approaches must be reviewed regarding the changed requirements. Although introducing new methods requires time and effort, it pays off if the processes are successfully implemented and practiced. This also includes implementing the PRL framework in the prototyping phase to assess the maturity level systematically.

Adapting and refining the PRLs to the specific industry and project requirements are also advisable. Defining clear and achievable milestones and success criteria for each PRL gives developers clear guidelines. Examining the relationship between PRLs, success criteria, milestones and project outcomes, in turn, provides valuable information for research.

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### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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