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Using Technology Readiness Levels (TRLs) in UAS development

Capt.cmdr.sup.instr. Cătălin BALMUȘ, Ph.D. Candidate*

*"Carol I" National Defence University, Bucharest, Romania
e-mail: cata_afa@yahoo.com

Abstract

In the dynamic world of aeronautical technology, the development of uncrewed aircraft systems (UAS) is an area of continuous expansion and innovation. Technological progress in this sector can be measured by the Technology Readiness Levels (TRL) Scale, which provides a standardized framework for assessing the technological maturity of a product or system. The TRL scale is widely used in industry and research to guide the systematic development of new technologies from concept and initial research to operational implementation and commercialization. This scale can also be successfully used in the research, development, and deployment of an uncrewed aircraft system.

Keywords:

technology readiness levels; TRL; technological development; UAS.

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Economic growth and new technologies are increasingly linked to ever-lower energy consumption and reduced environmental impact, with an emphasis on interdisciplinarity between research, education, and commercialization of technologies. Sustainable development and technological innovation are key to meeting today's global challenges, from climate change to limited natural resources. In this context, the process of transforming an innovative idea into a widely applicable technology becomes essential for economic and social progress.

Therefore, developing technologies undergo a well-defined cycle that starts with an idea and ends with its implementation and application in various domains. This process of technological evolution was standardized by NASA in the 1970s, mainly for space exploration technologies. The initial concept of Technology Readiness Levels (TRLs) was introduced by Stan Sadin, a NASA scientist, who developed the first seven-level TRL in 1989. In the 1990s, NASA adopted an expanded version of the TRL scale that included nine levels of technology readiness. This nine-level scale has rapidly gained general acceptability throughout the aerospace industry and beyond, becoming a standard for assessing and monitoring technological progress. Over time, the use of the TRL scale has expanded across numerous industry sectors, including healthcare, energy, transportation, and information technology (Banke 2010).

The implementation of the TRL scale also helps to reduce the risks associated with technological development and supports decision-making regarding research and development investments. In addition, this methodology supports interdisciplinary and international collaboration, having a significant impact on innovation and competitiveness in the global marketplace.

Therefore, the correct understanding and application of the TRL scale are crucial for the success of emerging technologies and for achieving a balance between economic progress, environmental protection, and society's well-being. This integrated and standardized approach continues to play a vital role in shaping the future of technology and transforming innovative ideas into concrete and effective solutions.

Overview of TRLs

Technology Readiness Levels (TRLs) are a standardized methodology used to assess the stage of development and maturity of a technology during the research, development, and implementation stages. These levels are numbered from 1 to 9, where TRL 9 represents the most mature technology. The lowest level, TRL 1, shows that the information emerging from basic scientific research is taking the first step from an idea to a practical application. A technology that has reached TRL 9 is a technology that has been fully incorporated into a larger system, has been proven to work smoothly, and is considered operational. The road from TRL 1 to TRL 9 is often long and complex, involving years of research and development. This process includes testing and validating individual components, creating prototypes, and integrating them into a complete system, followed by further testing in the laboratory and real-world conditions. Only after successfully passing through all these stages can a technology be considered mature and ready for practical use.

The nine levels originally defined by NASA (Héder 2017):
Level 1 - Basic principles observed and reported
Level 2 - Technology concept formulated
Level 3 - Experimental proof of concept
Level 4 - Technology validated in laboratory
Level 5 - Validarea în mediul relevant
Level 6 - Demonstration of a system/subsystem model or prototype in a relevant environment (terrestrial or space)
Level 7 - Demonstration of a prototype in space
Level 8 - Real system finalized and „flight-qualified" through testing and demonstration (on the ground or in space)
Level 9 - Flight-proven system with successfully executed missions

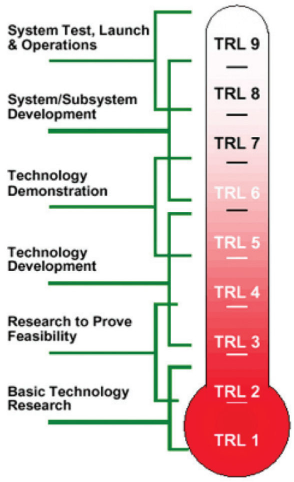

Figure 1 NASA technology readiness levels

So, levels 1 and 2 address the theoretical part of the development and have a lower cost because they are the results of scientific research programs. Level 3 also has a low cost, but TRL 4 and TRL 5 have some higher costs. Costs then increase exponentially and reach a maximum at TRL 8, which is the most costly to realize (Héder 2017). The overlooked approach of TRLs 4 to 7 can lead to what is called the "Valley of Death", where neither academia nor the private sector prioritizes investments. This is why many technologies, although promising, end their journey before deployment. In order to cover this area, additional involvement and collaborative effort are needed (TWI-Romania n.d.). Assessing the readiness of individual technologies minimizes budget and planning risks.

The TRL scale was adopted in Europe by the European Commission in 2011, following a study on Key Enabling Technologies (KETs) for their potential impact in enhancing Europe's industrial and innovation potential. It was proposed to set up a high-level expert group tasked with developing a coherent European strategy for development, which recommended that the TRL scale be used as a tool to assess project outcomes and expectations (European Commission 2011).

The TRL scale has been widely adopted at the EU level as a decision-making tool for funding investments in research, development, and innovation in major programs. Also in the European Union's "Horizon 2020" research and innovation funding program "Horizon 2020" from 2014 -2020, the TRL scale has been a requirement of the funding application helping the evaluator to assess the specific level of each stage and allowing the transition to the next stages (Bruno *et al.* 2020, 370).

EARTO (European Association of Research and Technology Organizations) has observed an increased use of the TRL scale as a planning tool for innovation management and thus adapted it to fit the EU-wide research, development, and investment goals (EARTO 2014):

TRL 1 – Observations of basic principles: at this stage, the focus is on the scientific understanding of a process or material.

TRL 2 – Technological concept is established: possibilities for application of the basic principles are identified. First production principles and possible markets are defined.

TRL 3 – Experimental proof of concept: based on preliminary studies, research and development of the project starts at the laboratory level and the first discussions about the main beneficiaries or customers take place.

TRL 4 – Technology validation in the laboratory: the technology is validated through laboratory trials. Production principles are identified and market studies are carried out. TRL 4-6 represents the link between scientific research and engineering, from development to demonstration. TRL 4 is the first step in determining whether individual components will work together as a system.

TRL 5 – Testing the prototype in a relevant environment: the system is tested in the environment for which it has been designed and connected to the necessary technological infrastructure. Processes are prepared for larger-scale production. The major difference between TRL 4 and 5 is the increased fidelity of the system and its operation in a relevant environment (for which it was designed). The scientific risk should be completed at the end of TRL 5. The demonstrated results should be final and statistically relevant.

TRL 6 – Demonstration of technology viability in an operational environment: the prototype system is verified. Examples may include a prototype system/model that is produced and demonstrated in a simulated environment. It is an important step in demonstrating the usefulness of a technology. Examples include manufacturing the device on a pilot production line. In TRL 6 the actual development of the technology as an operational system starts. The difference between TRL 5 and TRL 6 lies in the transition from the laboratory level to the engineering level and thus to the identification of the scaling factors that will enable the design and production of the final system.

TRL 7 – Demonstration of the model system and prototype in an operational environment: significantly increases technological maturity. Demonstration of the functionality of a real system prototype in a relevant/operational environment is required. The final design is practically complete.

TRL 8 – System complete and validated: the system/model is produced and qualified. The technology is proven functional and TRL 8 is the end of system development. Products can be mass-produced and actual manufacturing costs are determined.

TRL 9 – Current system validated in an operational environment: The system/model is proven and ready for full commercial deployment

Applications of TRLs in different industries

Industry and other government organizations have adapted the definitions for certain TRLs to suit their own needs, but their general scale fits very well with the original scale created by NASA.

Technology Readiness Levels are not just limited to space exploration or aerospace technologies. They are used in a variety of industries, including energy, health, transportation, and information technologies. In the energy industry, TRL can be used to assess the maturity of carbon capture and storage or renewable energy technologies. For example, the U.S. Department of Energy uses a Technology Readiness Assessment Guide to describe the energy requirements to be met (U.S. Department of Energy 2011).

In healthcare, TRLs can be used to assess the maturity of a new drug or new medical technology. Medical products require TRLs definitions and descriptions that are appropriate and unique to the technologies on which they are based and that take into account healthcare regulations. Recognizing these factors, the U.S. Army Medical Research and Materiel Command (USAMRMC) has established specific definitions, descriptions, and processes for TRL levels in the field (Tier7 2018).

TRL levels can also be used in the context of open innovation. Open innovation is a paradigm that assumes that firms can and should use ideas from both inside and outside, as well as solutions from the internal and external market to promote their technologies. Open innovation encourages collaboration, sharing ideas, and integrating knowledge from different sources. This can include collaboration with other companies, research institutions, universities, or even end-users (Innovating Society n.d.). In the context of open innovation, TRLs can be a useful tool to facilitate collaboration between different organizations. For example, a company may decide to collaborate with a research institute to develop a new technology. In this case, TRLs can be used to assess the stage of development of the technology and determine what resources are needed to advance the technology to the next TRL level.

Technology Readiness Levels also play a crucial role in funding decisions for technology development. Investors and funding agencies often use TRLs to assess the risk associated with investing in a particular technology. A technology with a high TRL may be considered less risky because it has already gone through numerous stages of testing and validation. In contrast, a technology with a low TRL may be considered more risky because it may require more research and development before it is ready for commercial deployment.

Example of a TRL scale for the development of a UAS

The TRL scale for UAS starts with fundamental research and ends with full system operationalization. Each TRL level represents a critical step in the technology validation and verification process, ensuring that innovations are not only feasible but also applicable and effective in real missions. The TRL scale therefore serves as a roadmap for engineers and researchers, indicating the key steps and criteria needed to turn a potentially revolutionary idea into a viable solution:

TRL 1 – Fundamental Research: At this level, research is conducted to understand the phenomena and scientific principles that will be the foundation of UAS technology. For example, the aerodynamic characteristics of different structural elements of aircraft may be studied or new materials for aircraft construction may be analyzed. It is a phase of exploration and accumulation of knowledge needed to progress in technological development.

TRL 2 – Concept and Applicability: Having established fundamental principles, researchers begin to develop technological concepts and assess their viability. At this level, mathematical modeling and computer simulations can be performed to test different UAS configurations and identify the most promising development directions.

TRL 3 – Proof of Concept: Here, technology concepts are put through initial tests to verify that they work as expected. Small-scale prototypes or individual components may be used to demonstrate the feasibility of ideas. For example, flight tests may be conducted with scale models to assess aerodynamic behavior.

TRL 4 – Component Testing: At this level, individual UAS components are created and tested in a controlled laboratory environment. Endurance tests, engine tests, functional tests of sensors and navigation systems or data links as well as the evaluation of the integration of different subsystems may be performed.

TRL 5 – Integration and testing in a relevant environment: Components and subsystems are integrated into a prototype which is then tested in an environment that mimics real operational conditions. This step is crucial to assess how the system works as a whole and to identify any compatibility or performance issues.

TRL 6 – Prototype Demonstration: A functional prototype of the UAS is built and tested under conditions that simulate the operational environment. This is when it is verified that the system can perform the missions for which it was designed, including launch, flight, and recovery.

TRL 7 – Advanced Prototype Testing: The prototype is now being tested in an environment that comes as close as possible to real operational conditions. Extensive flight tests are performed to assess performance in different scenarios and to ensure that the system is robust and reliable.

TRL 8 – Final System: The UAS is now fully developed and undergoes final testing to confirm that it meets all specified requirements. This level includes obtaining the necessary certifications and preparing for serial production.

TRL 9 – Operationalization: At the last level, the UAS is used in real missions and demonstrates that it can operate efficiently and safely under the conditions for which it was designed. This is the final test of successful technology development, demonstrating that the system is ready for large-scale deployment.

This TRL scale is an example and offers a clear picture of the step-by-step development process from initial research to operational deployment of UAS technology. Each TRL level is essential to ensure that the final system is safe, efficient, and ready for the challenges of the real operational environment.

Importance and challenges of TRLs

Assessing technology readiness is essential to understand the risks associated with developing and deploying a new technology. A technology with a low TRL may have great potential but also significant risks, as many aspects of the technology may still be unknown or unresolved. On the other hand, a technology with a high TRL is closer to being ready for commercial deployment, but may still require significant investment to bring it to market.

TRLs provide an objective method of assessing the maturity of a technology, and investors and funding agencies can use TRL levels to assess the risks and opportunities associated with investments in emerging technologies.

Although the TRL scale is a useful tool for assessing technology maturity, it also has some limitations. For example, the TRL scale does not take into account the commercial or economic aspects of technological development. A technology may have a high TRL, but be commercially unsustainable due to high production costs or lack of market demand. Other challenges in using TRLs:

- the TRL scale does not take into account social or ethical aspects of technological development;
- TRLs assessment can be subjective as it depends on the interpretation and experience of the evaluators;
- testing and validating a technology to achieve higher TRL levels can be costly and time-consuming;
- TRL is not directly applicable to all technology domains. Some technologies may have particularities that do not fit neatly into this scale.

Conclusions

Technology Readiness Levels are an essential tool for assessing technological maturity and managing the risks associated with the development and implementation of new technologies. However, it is important to understand that the TRL scale is only one of many tools available for technology assessment and that it should be used in combination with other methods and tools to get a complete picture of the potential and risks of a new technology. Despite the criticisms, the TRL scale remains an essential tool in assessing technological maturity. As technology continues to evolve at a rapid pace, the TRL scale may need to be adapted or modified to keep pace with these changes. For example, new TRL levels could be added to reflect new stages of technological development or specific TRL scales could be developed for different technological domains.

Despite criticism, TRLs remain a valuable tool for assessing technological maturity. Understanding and correctly applying TRL can help manage the risks associated with the adoption and deployment of new technologies.

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