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QUANTITATIVE TECHNOLOGY ASSESSMENT IN SPACE MISSION ANALYSIS

Dale C. Arney, Ph.D.

Space Mission Analysis Branch, NASA Langley Research Center, Mail Stop 462, Hampton, VA 23681, dale.c.arney@nasa.gov

Abstract

New technologies will need to be developed to create feasible concepts for NASA's ambitious missions of the future, but quantitative assessments of the impacts that technologies have on systems or architectures are sporadic and often inadequate. The Space Mission Analysis Branch at NASA's Langley Research Center is developing a quantitative technology assessment framework to address this issue with a vision of being able to understand the mission and system architecture impacts of technology development activities. A phased approach is being pursued to answer technology needs assessment and technology forecasting questions. First, the integration of subject matter experts, data collection, and data analysis techniques ensures that the framework is accessible and analyzable. Second, systems analysis determines the impact of key technologies from the first phase on systems, architectures, and campaigns. The goal of a quantitative technology assessment framework is to accelerate technology assessments, to improve the accuracy of those assessments, and to provide deeper insights into the impact of new technologies.
Keywords: technology assessment, data analysis, systems analysis

1. Introduction

NASA is currently working toward ambitious future missions such as a long-term human presence on and around the Moon leading to a human mission to Mars [1]. New technologies will need to be developed to realize feasible concepts for these ambitious goals.

Assessing the technology needs and impact in complex systems and architectures is a challenging problem that is sporadic and often inadequate. Understanding these needs and impacts depends on an understanding of where capability gaps exist and how new technologies can benefit the future missions. Subject matter experts must be engaged, and their input must be captured in a manner that enables an assessment of technologies based on their quantitative impact on the system or architecture.

This paper describes a quantitative technology assessment framework for capturing, understanding, and analyzing the mission and system architecture impacts of technology development activities. This framework is being developed in the Space Mission Analysis Branch at NASA Langley Research Center with the vision that this framework will enable better understanding of technology needs for existing mission concepts and better understanding of the impacts that new technologies can have on future concepts.

2. Background

2.1. Technology Assessment Background

Historically, NASA focuses on mission-driven technology assessment. During the conceptual design phase for a new system, designers need to understand the current capabilities of existing technology so that they may perform trade studies for different concepts. An understanding of what capabilities exist and how much development effort is required to reach new performance levels can enhance cost and schedule estimates ultimately provided to decision makers.

As outlined in Williams-Byrd et al. [2], during the Evolvable Mars Campaign, twelve teams of subject matter experts representing common capability areas, referred to as System Maturation Teams (SMTs), were created to help "formulate, guide, and resolve performance gaps associated with the identified exploration capabilities." [2] The capabilities/teams were:

1. Autonomous Mission Operations
2. Communications and Navigation
3. Crew Health and Performance
4. Entry, Descent, and Landing (EDL)
5. Environmental Control and Life Support Systems (ECLSS)
6. Extravehicular Activities (EVA)
7. Fire Safety
8. Human Robotic Mission Operations
9. In-Situ Resource Utilization (ISRU)
10. Power and Energy Storage
11. Propulsion
12. Thermal Systems

During the Evolvable Mars Campaign, technology investment decisions and trade studies were based on the input from SMTs [2, 3]. This approach leverages NASA's technical expertise and incorporates qualitative information, such as political guidance, development risk, and lessons learned. However, many discipline experts are likely unaware of all future missions under consideration, provide data at different levels that make trades difficult, and have limited time to commit to conceptual system analysis due to their obligation to advance their functional area.

Following the conclusion of the Evolvable Mars Campaign, the SMTs were disbanded. The Technology Assessment and Integration Team no longer serves as the interface between the architecture assessments and the technology development activities [4]. As illustrated in Figure 1, that function is now distributed to multiple teams across NASA.

An alternative approach for future technology assessments is defined in Williams-Byrd et al. [2] as "model-based analysis." Model-based analysis uses quantitative analysis tools to analyze the impact that specific technology improvements might have on systems or architectures. This technique has the benefit of being more objective and more repeatable than before. Performing quantitative analysis enables analysts to understand the impacts of investments throughout the entire system architecture. However, this methodology also has challenges to overcome: lack of fidelity in the model to adequately represent a technology, complexity of system architecture modeling when new operations concepts are introduced, and the lack of qualitative input from experts.

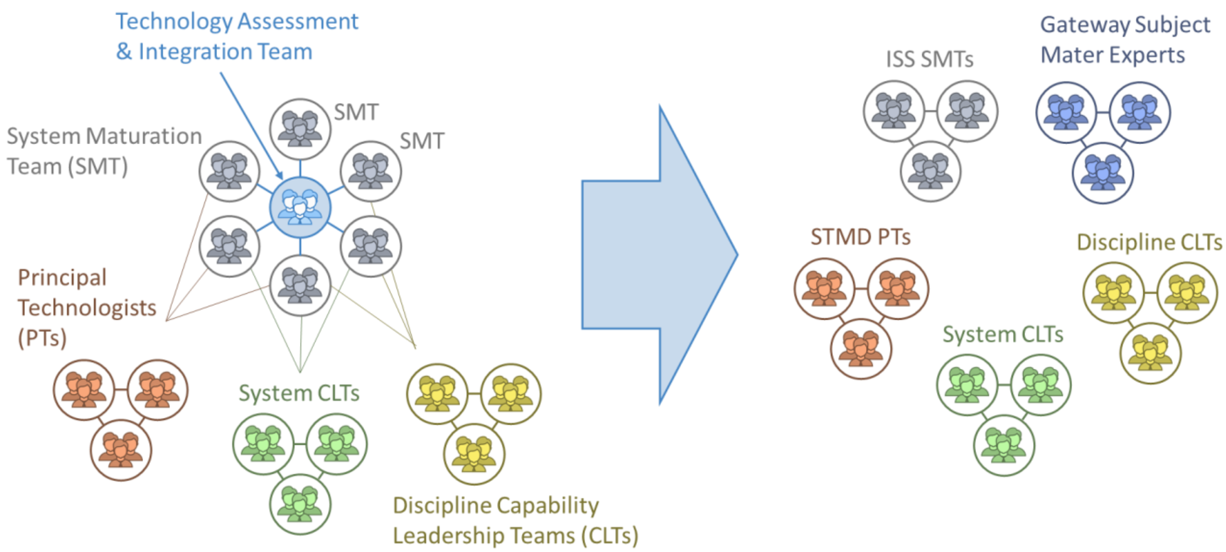

Figure 1. After the Evolvable Mars Campaign concluded, the integration between the architecture assessment and discipline experts was distributed.

Table 1. The quantitative technology assessment framework is based on the hybrid approach (replicated and updated from Williams et al. [2])

	Analysis Method		
Figures of Merit	Past Studies	Expert Input	Simulation/Analysis
Safety and Mission Success		X	X
Performance and Effectiveness			X
Programmatic Risk		X	
Affordability and Life Cycle Cost	X		X
Applicability to Other Missions	X	X	X

The quantitative technology assessment framework presented in this paper implements the "hybrid approach" recommended in Williams-Byrd et al. [2]. The hybrid approach combines subject matter expertise, historical studies, and model-based analysis as shown in Table 1 (replicated and updated from [2]). The hybrid approach requires both subject matter expert input and system analysis model development to use that input.

The quantitative technology assessment framework described in this paper helps more easily perform the technology assessments needed for NASA's future missions. The framework can retain information from previous studies, assessments, and expert inputs to maintain the connection with subject matter experts who are even more burdened now with uncoordinated requests. Maintaining that corporate knowledge in an updated, accessible, and analyzable format is more important than ever.

2.2. Technology Assessment Questions

There are three common types of technology assessment questions in space mission analysis. The first involves what this paper will refer to as "technology needs assessment," where the needed technologies to field a new system are identified. The second and third involve what this paper will refer to as "technology forecasting," where the impact of a new technology is analyzed for either an individual system or an entire architecture. The three types of technology assessment questions are described in more detail in the following sections. The goal of a quantitative technology assessment framework is to accelerate answers to all three question types, to improve the accuracy of those assessments, and to provide deeper insights into the impact of new technologies. Figure 2 presents these three questions visually.

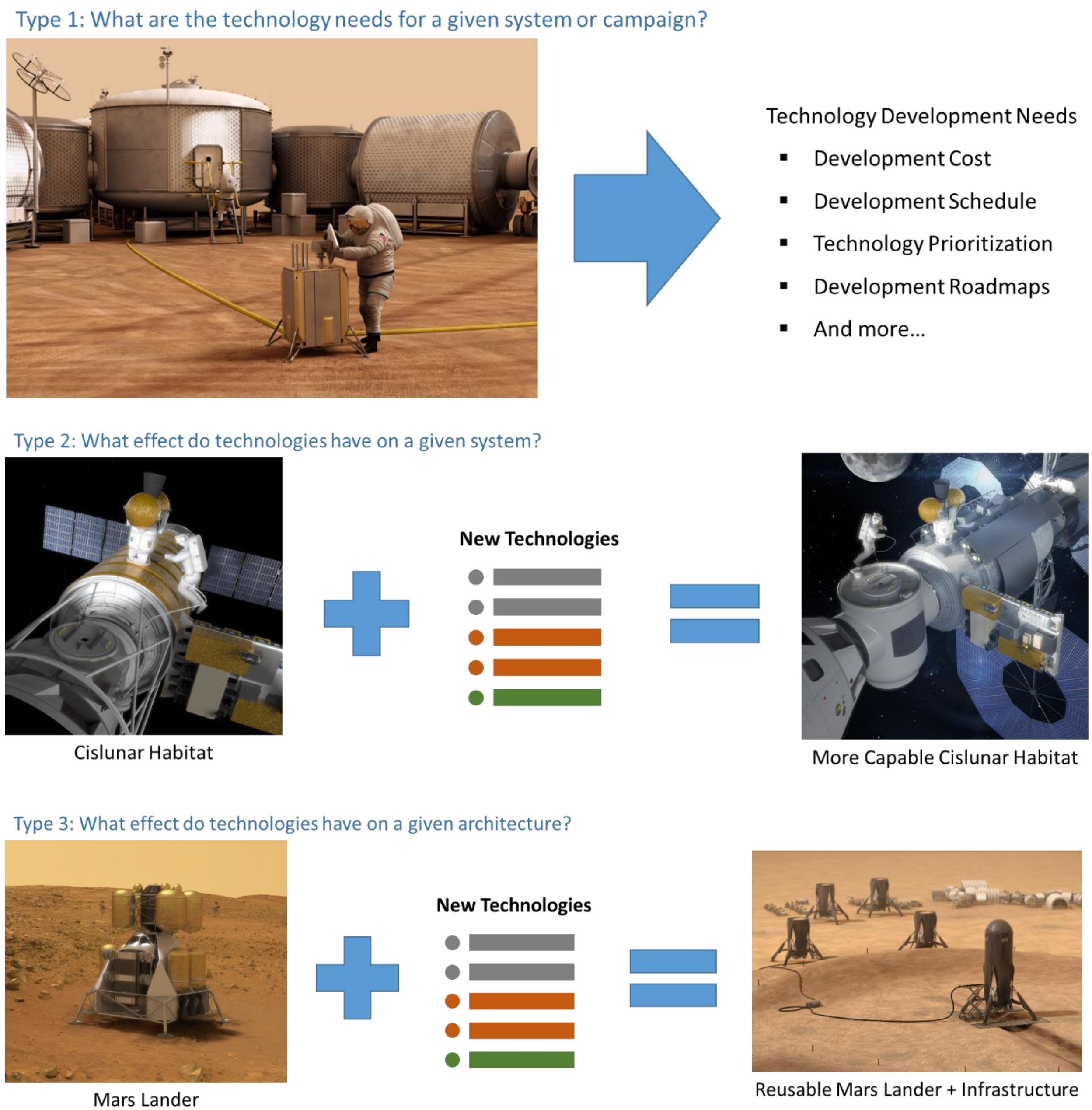

Figure 2. There are three common types of technology assessment questions in space mission analysis.

Type 1 Question: What are the technology needs for a given system or campaign?

In Type 1 questions, performance metrics are defined that are required to perform a mission, and the technology assessment consists of determining what new technologies (along with their development cost, schedule, etc.) are required to achieve those metrics. Type 1 questions require a database of technology information from subject matter experts and a level of detail on the system, architecture, or campaign to determine the technology needs.

Examples of Type 1 questions include:

- For a given human Mars campaign, what are the capability gaps that need to be closed? What are the high priority developments, development cost, and development schedule to close those gaps? [2, 3]
- For a cislunar habitat (e.g. Gateway), what are the capability needs, development cost, and schedule for given baseline and alternative concepts?
- For a set of Earth orbital spacecraft and mission concepts, what are the synergies and gaps in technology development activities required to support those disparate missions?

Type 2 Question: What effect do technologies have on a given system?

Type 2 questions are common in many fields where a feasible operational concept can be improved (better cost, safety, etc.) by adding a new technology. Type 2 questions require a systems analysis capability that can incorporate the improvements of the technology. This is typically accomplished with multipliers on performance parameters within the systems analysis capabilities. Therefore, the systems analysis capability must be structured around the performance parameters, and the technologies' impacts on those performance parameters must be understood.

Examples of Type 2 questions include:

- In aeronautics, how do given engine technologies improve noise, fuel efficiency, and other metrics for a given class of commercial aircraft [5]
- How do different life support technologies (impacts mass, level of closure, reliability, etc.) impact the design and performance of a deep space habitat?

Type 3 Question: What effect do technologies have on a given architecture?

Type 3 questions are similar to Type 2 questions, but apply to the impacts that a technology has on an entire architecture instead of a single system within a defined architecture. When technologies are added that fundamentally change the operational paradigm, it is difficult to quantitatively assess the impact that technology has on the overall system architecture because the trade space is intractable. Type 3 questions require architecture trade space exploration and the systems analysis that can incorporate the technology impacts on performance parameters.

Examples of Type 3 questions include:

- How does in-space assembly impact the design, deployment, and operations of a human Mars architecture? [6]
- What is the total impact on reducing time of flight (via new propulsion technologies) for human Mars missions (benefit, cost, risk, technology, etc.)? [7]

3. Phased Approach

A phased approach is being pursued to develop the capability to answer all three question types. First, the integration of subject matter experts, data collection, and data analysis techniques across the NASA technology portfolio will ensure that the framework is up to date and accessible for analyses. Second, systems analysis is used to assess the impact of key technologies from the first phase on systems, architectures, and campaigns.

Phase 1: Data Collection and Analysis

The first phase involves creating a means to rapidly access and analyze the data from technologists and subject matter experts. However, these experts are likely unaware of all future missions under consideration and have limited time to commit to conceptual system analysis due to their obligation to advance their functional area. Therefore, capturing the state of the functional areas, current developments, and future expected capabilities in a manner that is easily accessible for conceptual design is crucial.

The quantitative technology assessment framework incorporates a structured approach to collect, organize, and clean data from subject matter experts, technologists, and others. This approach creates a flexible and searchable record for state-of-the-art for a given capability. To facilitate this, an ontology for technology assessment was established, and a relational database was constructed to store the resultant framework. The ontology must be flexible to accommodate multiple functional areas and types of capabilities, and it must capture the functional needs, state-of-the-art performance, and other parameters in a structured, repeatable manner. Figure 3 presents a graphical representation of the ontology used in the quantitative technology assessment framework.

In this ontology, *Disciplines* are large groups of functional areas, analogous to the System Maturation Teams [2, 3], and broadly contain functions related to a domain of expertise. These broad groupings help to categorize the aspects of technology performance into logical groups. The current list of Disciplines in the database are listed below, but the list will expand as more information is collected:

- Communications
- Navigation
- Entry, Descent, and Landing (EDL)
- Environmental Control and Life Support System (ECLSS)
- Extravehicular Activity (EVA)
- In-Situ Resource Utilization (ISRU)
- Power and Energy Storage
- Propulsion
- Cryogenic Fluid Management (CFM)
- On-orbit Servicing, Assembly, and Manufacturing (OSAM)

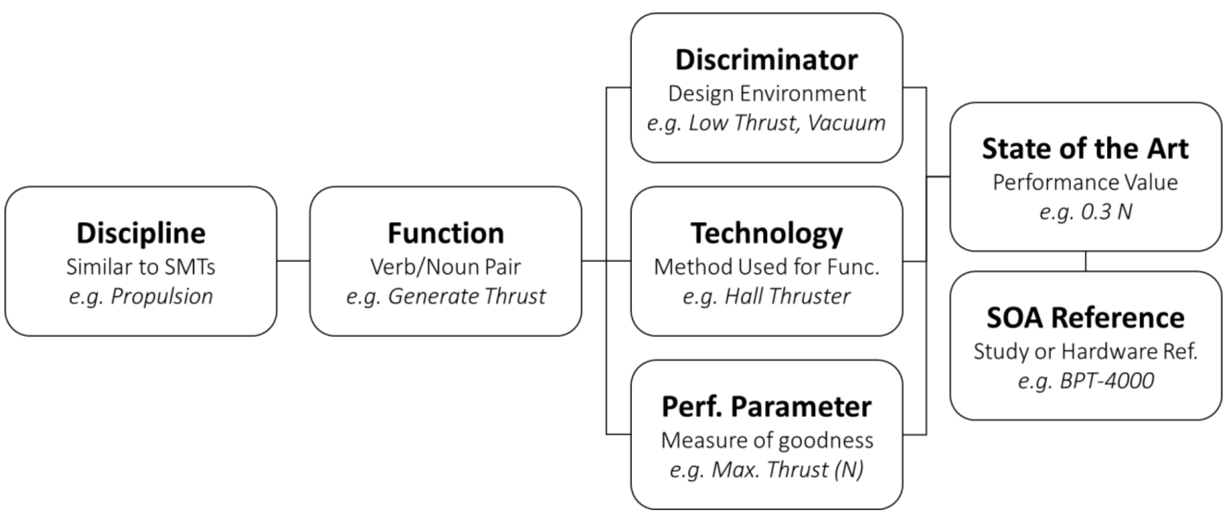

Figure 3. The ontology for the quantitative technology assessment framework organizes technologies by their functional areas.

Within each Discipline, *Functions* perform specific actions to meet a mission need. For example, within the ECLSS discipline, “remove carbon dioxide” would be a function. Functions are also known as “capabilities,” and they remain agnostic to the physical solution to perform that function.

For each Function, there are two primary elements that determine the technology need. The first is the *Discriminator*, which captures the dependence of technology performance on the environment or use case in which the system operates. For example, the distance from the Sun impacts the performance of solar panels to generate power. The second element of a Function is the *Technology*, which is the type of physical solution used to perform the function.

Each Function has a set of *Performance Parameters* which describe the metrics that define the performance of a given system. When incorporating systems analysis, the model(s) use these performance parameters to determine the performance impact of a given technology on the solution. Finally, the *State-of-the-Art* value of a Performance Parameter is unique to a given Technology and Discriminator based on the *State-of-the-Art Reference*, which is the reference to a system that has been developed or studied.

This framework creates an accessible database to inform conceptual studies quickly and gain insights without a significant burden on subject matter experts. The framework currently supports two initial use cases, enumerated below, but could expand to support other use cases, such as tracking evolution of technology development or predictions of unknown technology developments based on existing developments. The initial use cases of the framework are:

1. **Preservation of and access to institutional knowledge:** A critical feature of the database is that it provides a formal way to document technology performance as it relates to the system, architecture, or campaign being analyzed. This task can prove especially challenging when the original analyst or subject matter expert is no longer available to reference. Providing a standard structure for use helps to preserve and reduce barriers to access institutional knowledge. Trade studies can also be performed with less initial input from subject matter experts, and when they are involved, their contribution is more efficient and useful.
2. **Mission specific performance gap analysis:** The framework is able to quickly find and compare technology performance requirements for conceptual design studies. An analyst can query, sort, and filter the database, extracting the performance parameters for various technology options to determine if the current state-of-the-art can support the mission. The database allows for search by any combination of filters and can compare existing entries with specific performance targets.

The technology database can be accessed within the Space Mission Analysis Branch through an Application Programming Interface (API) or web interface, as shown in Figure 4. To access and interact with this API, a Python module was developed to create and read information from the database without using the browser interface. The API and Python helper functions allow programmatic access to the technology information and can sync well with the systems analysis models.

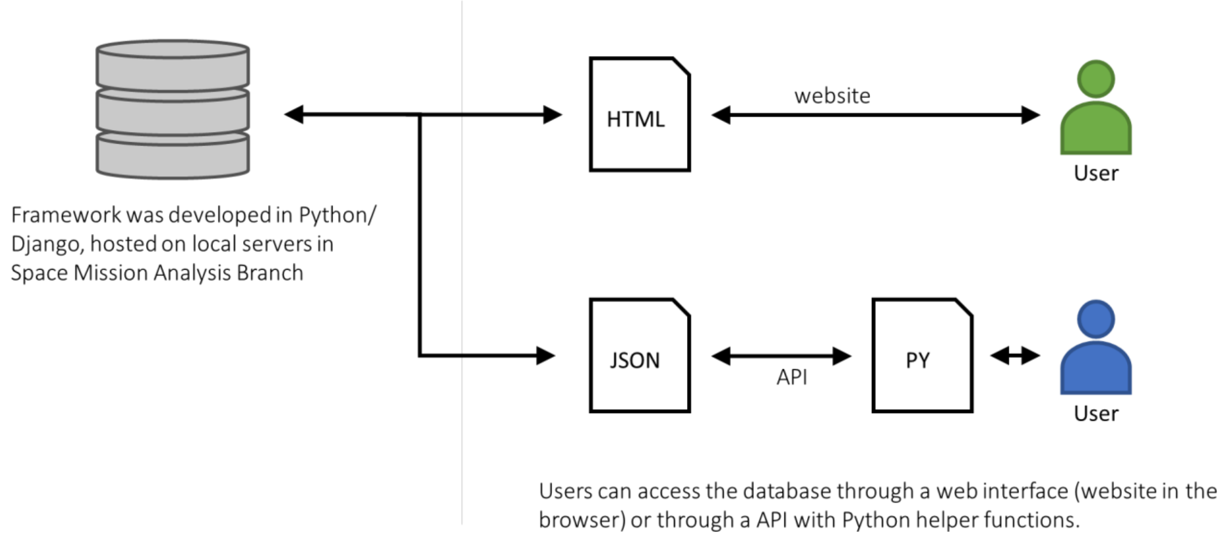

Figure 4. The framework enables the database to be queried through a browser using the web interface or programmatically with an API and Python helper functions.

Phase 2: Systems Analysis

The second phase of the quantitative technology assessment framework involves developing modular systems analysis tools that can be used in and tailored to various applications. These tools assist in answering technology forecasting questions, where the impact of a technology must be understood on the metrics (mass, power, volume, cost, etc.) of a system. The tools ideally interface with the technology database to extract relevant performance parameters for the technology or technologies being analyzed.

The current focus of work in this area is creating models to analyze systems that support ongoing work [8]. These models include propulsive vehicles, habitats, landers, and ISRU infrastructure. Where possible, the models are modular so they can be used in conjunction with each other in different architectures. They also utilize or, in some more challenging cases, will utilize the performance parameters defined in the technology assessment framework so they can interface programmatically with the technology database.

Many activities answering Type 2 and Type 3 questions have used custom-made models and technology performance parameters [5, 6, 7, 9], but this framework would allow more flexibility and rapid iteration during the concept design and trade studies.

4. Conclusions

The goal of a quantitative technology assessment framework is to accelerate answers to all three technology assessment question types, to improve the accuracy of those assessments, and to provide deeper insights into the impact of new technologies. The phased approach presented in this paper creates a structured approach to answer technology needs assessment and technology forecasting questions. The integration of subject matter experts, data collection, and data analysis techniques across the NASA technology portfolio will ensure that the framework is current and accessible for analyses. Incorporating systems analysis tools assesses the impact of key technologies on systems, architectures, and campaigns. This quantitative technology assessment framework is being actively developed as NASA’s technology assessment activities evolve, and the structured approach is well-suited to that evolution.

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