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Technology Estimating: A Process to Determine the Cost and Schedule of Space Technology Research and Development

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Abstract

As the premier leader in space technology research and development, NASA is investing in new technologies [1] that include 14 primary technology roadmap areas, and aeronautics [2]. Understanding the cost for research and development of these technologies and the time it takes to increase the maturity of the technology is important to the support of the ongoing and future NASA missions. Specifically, there exists a need to provide estimating capabilities for technologies in the Technology Readiness Level (TRL) range of 2 to 6. Overall, technology estimating may help provide guidance to technology investment strategies initially for NASA's Game Changing Development Program Office and similar stakeholders help improve evaluation of technology affordability, and aid in decision support.

A year-long research effort was initiated to help identify a systematic process for estimating the cost and schedule of low TRL technology research and development projects. This research project effort was complimented by phased work group sessions, multiple meetings, data acquisition and analysis, and discussions with experts in the field of technology maturation, NASA executives, technologists, analyst, principal investigators, engineers, and project/program managers.

This research report provides a summary of the framework development of a Technology Estimating process where four technology roadmap areas were initially selected to be studied. The framework includes definition of terms, discussion for narrowing the focus from 14 NASA Technology Roadmap areas to four, and further refinement to include technologies in the TRL range of 2 to 6. Included in this paper is a discussion to address the evaluation of 20 unique technology parameters that were initially identified, evaluated and then subsequently reduced in number determined suitable for use in characterizing these technologies. Further, a discussion of data acquisition effort and criteria established for data quality are provided. A summary of the findings obtained during the research including gaps identified, description of a spreadsheet-based estimating tool initiated as a part of the Technology Estimating process, and the examination of a case study are provided. Suggestions for continued investigations in this research are also addressed.

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Appendices

Introduction and Background

The need for technology estimating was addressed to the NASA Cost community in 2011Cost Symposium, where Sefcik et al., 2011 identified:

- No current Agency/Glenn Research Center database exists for estimating technology development projects,
- Data to populate such a database is in technologist's head or spread out amongst many people or in long term storage or missing/discarded due to personnel turnover or ….,
- No known good method to estimate the cost of Technology Reference Level (TRL)* advancement that is supported by actual data,
- Reduction in Agency technology projects since 2005 results in little recent data that would be available, and
- Estimates tend to be worked to the year's budget versus planning through project completion. (3)

Note: * = TRL is defined in Appendix A.

In response to the NASA Cost Community's call for implementation of a capability to provide technology estimating, this research project was initiated and sponsored by the Office of Evaluation, Cost Analysis Division in collaboration with the Space Technology Mission Directorate, Game Changing Development Program Office. The goal was to improve NASA's ability to estimate the cost of technology development and maturation. This technology estimating research involves identifying parameters that are expected to influence the cost of a technology, collecting actual data for completed technology efforts, and then conducting mathematical and statistical analyses to generate cost estimating relationships between the parameters and use these in an analysis to determine the cost and schedule of technology development.(4)

The procedural process diagram for the conduct of the research was prepared by the Cost Analysis Division and presented in Figure 1. The process was identified to include a series of workshops and internal reviews within the NASA Cost Community to elucidate issues and the development of the Technology Estimating research, provide the necessary community input and acceptance of the process, and provide a platform for the required internal peer review.

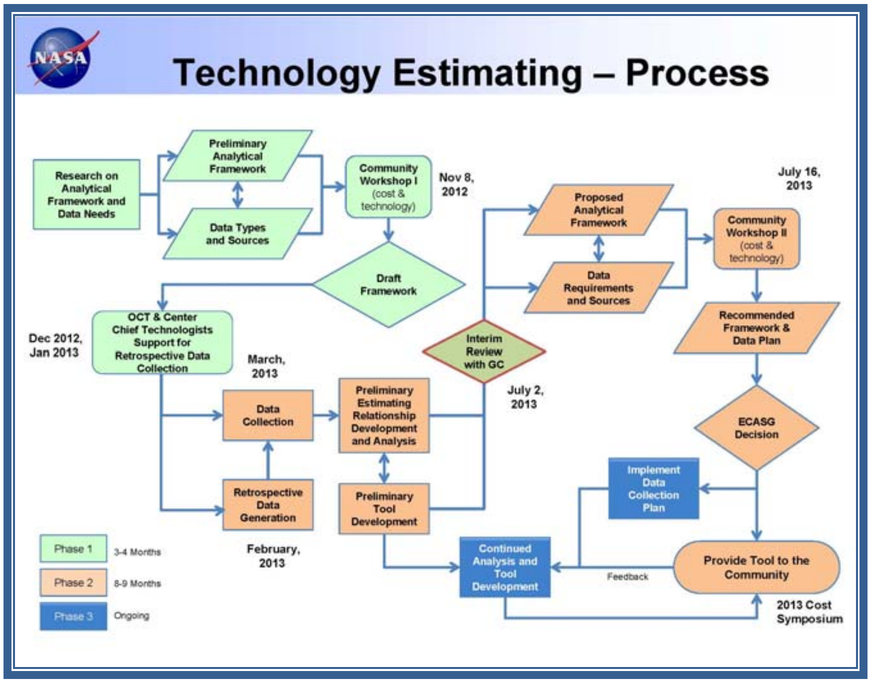


Figure 1. Technology Estimating Process Diagram, 2012-2013

Purpose

Technology has been defined in a number of ways. NASA defines it as:

"*a solution that arises from applying the disciplines of engineering science to synthesize a device, process, or subsystem, to enable a specific capability*." [1] [5]

Industry definitions include:

By Boer, 1999 "*the application of knowledge to useful objectives. It is usually built on previous technology by adding new technology inputs or new scientific knowledge*" [6], or by Van Wyk, 1999 "*Created competence as manifested in devices, procedures, and acquired human skills*".[7]

Fundamentally, given any definition, it is recognized that technology will possess a monetary cost for its research and development, and will exhibit the duration in time to achieve its full maturation in preparation for inclusion in subsequent flight projects. Both are fundamental metrics that should be known. What is the purpose then for Technology Estimating, what are the benefits, and how do we do it? The intent of this paper is to report the information accumulated and process developed so as to document the technology estimating effort.

Beltramo, 1988 identified the primary purpose of a cost estimating model is to support a decision at some level. The choice may be a "go" or "no go", alternative A versus B, design trade off at the component level, or at some other level. Under all circumstances, the user must carefully consider the assumptions inherent in the estimating to determine they are appropriate for the intended purpose.[8] Gaining an understanding of the cost and schedule of developing a technology could be critical for those who acquire technology research and development or to those who need to manage specific technology projects and technology advancement programs that manage a portfolio of technology projects. Clearly, an increased understanding of technology cost(s) or when management is involved in technology investments and how money may be spent on a single project, or either in a limited or broad portfolio of specific technologies, technology estimating should help in decision making. Oberlender et al., 2001, recognized that early estimating of projects is vital for business unit decisions that include strategies for asset development, potential project screening, and resource commitments. [9]

Benefits

We must acknowledge that the motivation for delivering or pursuing new technology research and development activities may be distinctly different for each stakeholder, and each has an opportunity to enjoy different benefits. NASA benefits were identified and discussed with technologists and the cost estimating community for this research and they are presented in Table 1.

Table 1
Benefits to NASA - Technology Estimating

NASA		Benefit
Projects and Programs	Pre-Phase A, to satisfy NPR 7120.5E, 5.f. Basis of Estimate (cost and schedule)	"The project also develops and maintains the status of a set of programmatic and technical leading indicators to ensure proper progress and management of the project. These include….. cost trends".
	Analyze technology costs to satisfy NPR 7120.5E, 8.0 Technology Readiness Assessment and Development	"Provide technology development schedules, including intermediate milestones and funding requirements, during Phases A and B for each identified technology development to achieve TRL 6 by PDR. Describe expected status of each technology development at SRR, MDR/SDR, and PDR."
	Analyze technology costs to satisfy NPR 7120.5E, 3.5 Technology Development Plan where it is required	"describe how the project will transition technologies from the development stage to the manufacturing and production phases." Technology Estimating would provide the data to evaluate the cost and schedule during the phases.
	Support NPR 7120.8 NASA Research and Technology Program and Project Management Requirements, R&T program Commitment Agreement (PCA) Template	Provide the estimated cost range for the program for the five-year period beginning in the current fiscal year at a level of detail that identifies the approved individual projects. Identify the constraints and assumptions used to develop this estimated cost range and specifically identify those assumptions that drive the range. This cost range should contain all costs necessary to perform the program, including, but not limited to, standard project activities, required technology developments, facilities costs, infrastructure costs, operations and sustainment, data analysis, and disposal. Reference the annual budget contained in the Integrated Budget and Performance Document (IBPD) for cost phasing. The cost range should be updated when program content changes, such as the addition of new projects entering implementation." Appendix D, 6.0 Cost Commitment
Task Managers, Program Managers, Principal Investigators		Provide capability and dataset to benchmark cost and schedule estimate plans against prior technology investments.
		Increase confidence in technology cost/schedule thus increasing capability to manage technology costs.
		Help analyze factors that influence technology cost and thereby reduce cost.
Technologists		Provide a capability and dataset to better anticipate the cost and schedule resources needed to mature a technology to a target TRL level.
NASA-wide		Supports need to independently assess the likelihood that various technology cost and schedule plans can be successfully met.
		Provides a tool and dataset that addresses gap in existing cost analysis methods for technologies TRL 2 to 6.
		Knowledge of Technology cost(s) and schedule increases understanding as to whether it can be affordable.
		Establishes framework for future data collection to further enhance estimating capabilities.

How you perform technology cost and schedule estimating can be a challenge. The initial challenge comes from the decision for which cost model or estimating process should be selected. The considerations made for selection must include what ultimate process is best for evaluating complex technologies, each with their own set of unique or potentially abstract conditions. Added to the challenge are potential differences in the characterization of a technology, or from one technology to another where the difference can be significant.

The difficulties and considerations made, for how to estimate technology has been addressed by Hazelrigg et al., 1991 who recognized the difficulties in estimating the cost of space technologies [10], Roy et al., 2005 recognized the need in commercial applications where a systematic approach to cost estimating of technologies in the automotive industry was needed[11], Ingalls et al., 2004 who recognized that the use of parametric estimating in budgeting, scheduling, and control of (Technology driven) projects would enhance the ability of project management organizations to effectively and efficiently utilize valuable resources,[12] and Cyr, 1988 who investigated parametric cost estimating methods for advanced space systems in the conceptual phase. [13] The Rand Corporation, 1992 while engaged in technology estimating of complex aerospace technologies, identified the need to perform estimating using parametric analysis for complex systems early in the development of advanced technologies. [14] From this community, it was evident that a technology, during its early stages of research and development, must be characterized, not only by its maturity, but by how much definition a technology was given by a thorough characterization. ***A basic assumption taken in this research was that all technologies have inherent variability.***

Determination of a Cost Estimating Process

Knowing that there was variability in the very thing we are trying to estimate, and given 14 plus one technology areas, the derivation of credible estimates seems to be a daunting task. How then do we begin to select a cost estimating process and what NASA technologies do we address? To answer these questions for technology estimating in this research, the Research Team proceeded in two steps: 1) summarize the types of cost estimating processes available; then 2) to make simple refinement of the NASA technology data based on TRL. In the first step, a short summary has been identified for five cost estimating processes, and they are presented in Table 2.

Table 2
Cost Estimating Processes – Advantages and Disadvantages
(Hazelrigg et al. 1991[10], Roy Et al. 2005 [11], Shishko et al. 2003 [15], Dumas 1979 [16], Cavalieria, 2003[17])

Cost Estimating Process	Advantages	Disadvantages
Analogy-based technique [10]	Estimate is based on degree of similarity between projects. Used when little or no data is available.	Degree of similarity is difficult to assess. Costs are subjectively adjusted up or down depending on the project complexity.
Engineering approach [11] (also known as “bottoms up”)	Method is systematic and based on elementary components.	Design or technology must be very well defined. Requires large amount of time for preparation.
Real Options Valuation [15]	Valuing projects in an environment of extreme uncertainty.	Requires extensive systems thinking and engineering analysis to build a credible simulation of alternative sample paths.
Parametric [16]	Objective, unbiased, consistent. Takes less time. Suitable for use early in project formulation with limited project definition and limited data	Assumption is that same condition(s) which governed costs in the past will be the same on each project. May exacerbate cost growth.
Artificial neural network [17]	Non-linear and parallel, can “infer” from knowledge.	Requires training, and provides “black box” solutions

After a literature review and review of the multiple analytical methods, the formalized parametric estimating techniques and data collection and analysis as outlined by the International Cost Estimating and Analysis Association in the Parametric Estimating Handbook [18] was determined to be the best option for further investigation. The selection of parametric estimating as the best choice for use in cost estimating technology is also substantiated by Thibault, 1992 who indicated that the "US Defense Contract Audit Agency believes now, as it always believed, that parametric estimating techniques using cost-estimating relationships are acceptable in the appropriate circumstances for proposing costs on government contracts."[19] Fad et al., 1988, identified that parametrics is only the cost estimating method that can function within the limited data and estimating turn-around time constraints of the new business environment.[20] The Federal Acquisition Regulations (FAR) 15.404-1(b)(2)(iii) and 4(c)(i)(C) states that parametrics are an acceptable method for performing price analysis.[21] Based on the comparison of advantages and disadvantages of various accepted estimating processes and literature review, ***parametric estimating provides the best possible solution for satisfying this technology estimating research*** given the need to perform analysis early in project definition and possessing limited data.

Scope of Technology

The second step in the cost estimating process is that we refined the NASA technologies by separating them into two classes, i.e. TRL 2 to 6; and technologies greater than TRL 6. This separation of technologies into classes was made to simplify and reduce the scope of technologies to be investigated. It is commonly recognized that technologies in the TRL range of 2 to 6 normally have limited detailed project information, while the extent of detail or information for technologies with TRL > 6 usually possesses project information in much greater detail. Technologies with TRL > 6 were also identified to have significant or extensive amount of project related information and this information has been typically and accumulated in and represented by many cost estimating cost models and data sets adopted by NASA Cost Community such as NAFCOM and REDSTAR. The investigation of TRL 1 projects was deferred in this initial study to help limit the number of potential projects and reduce the scope of the research effort.

In the Phase I Workshop, technologies with TRL range from 2 to 6 were identified to include those systems, sub-systems, parts, components and materials that were non- flight technologies. Figure 2 presents the primary scope of technologies that were investigated and provides a matrix indicating ***the technologies of interest in this research study were TRL in the range of 2 to 6.***

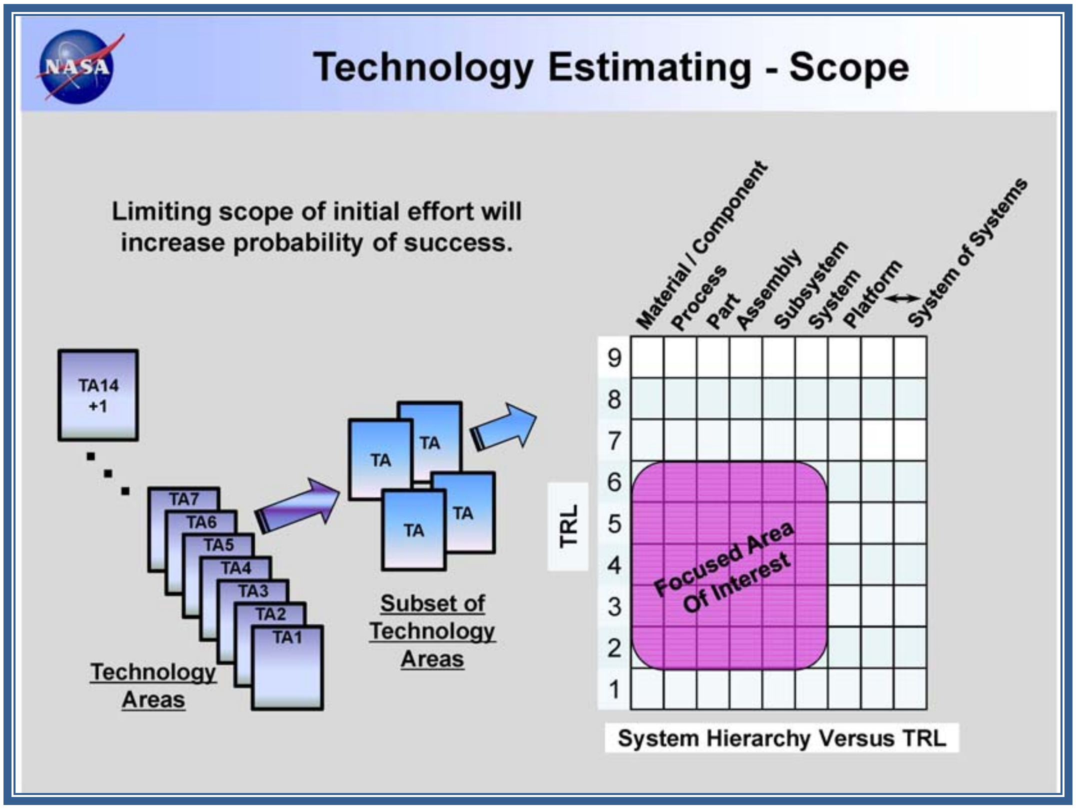


Figure 2. TRL Versus Technology Scope Classification – Presented at the Phase I Workshop

Before the Phase I Workshop, the Research Team deliberated on the extent of data that may be available in each of the respective technology areas and that several challenges may exist. Later these challenges were found to become evident during the development and investigation of the TRL 2 to 6 technology projects scope. Each of these "challenges" is listed below with a Research Team observation:

1. Technology Tracking Not Standardized

Meaning: Standardization of Technology Tracking at NASA would allow an understanding of technology and TRL progression and help refine an understanding of native problems or difficulties in certain technologies, and to help identify common issues. Tracking of technologies in successive phases or similar technologies between programs would help to understand the progression of a technology, and possible impacts to duration.

Research Observations:

a. The deployment of NASA's technology roadmap was not brought to light until at least the period of time after February 2012, when the Steering Committee for NASA Technology Roadmaps; National Research Council of the National Academies published "*NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*".(2) After this publication, NASA's technologies would then be assigned into specific Technology Areas (TAs) and these assignments were in the early process of being established. Prior to this publication therefore, no previous technology project data before February 2012 would be expected to consistently contain the formalized NASA Technology Area Roadmap designations.

b. NASA's new technology information resource (*TechPort*) was published internally to NASA on October 10, 2012. TechPort was constructed for tracking technologies and providing help standardization of the tracking of technology. After an initial survey of the data contained in *TechPort* during the first phase of this research project, only five completed projects were found to be included in the first publication, although this number was found to grow with time. Further, only five of the 20 technology estimating parameters were found common in TechPort, and many of these were not fully completed and provided as placeholder to be completed later.

c. ***Tracking technology in its early progressive stages along the path of development or where the early technology has branched to other Technology Roadmap Areas (TAs) would be a significant building block to Technology Estimating.*** Systematic tracking of technology cost and schedule efforts using the technology characterization parameters identified in this research as they could be applied to NASA and other data sources. These data sources may include the New Technology Reporting https://invention.nasa.gov/, TechPort https://techport.nasa.gov/techport/home.action, Small Business Innovation Research/ Small Business Technology Transfer (SBIR/STTR) http://sbir.gsfc.nasa.gov/SBIR/SBIR.html, Earth Science Technology Office (ESTO) Techfolio http://www.estotechnology.us/techportfolio/, One NASA Cost Engineering (ONCE), and other governmental organizations.

2. Naming system or Taxonomy of Technologies

Meaning: A naming system for technologies helps to identify where a technology fits or is attributed to the larger system or mission. Whether the particular technology is a material, part, component, etc. of a larger system, a naming system or convention was perceived to be especially helpful when multiple items are included in the construct of the technology.

Research
Observations:

a. The NASA Systems Engineering Handbook identifies systems, components, etc. as shown ballooned in red in Figure 3.[5] Beyond the Work Breakdown Structure (WBS), which is unique to each technology, NASA does not appear to have a standard taxonomy to name overall systems or components. Further, with respect this research, technology projects in the range of TRL 2 to 6 do not normally have a WBS.

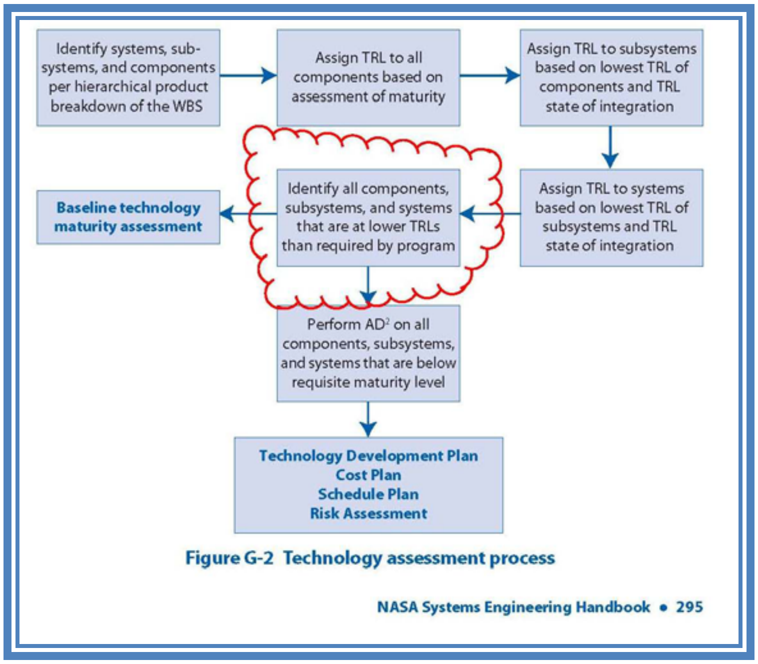


Figure 3. Reference to naming system
(From NASA Systems Engineering Handbook [5], page 295)

b. For convenience, the basis for the "Technology Scope Classification" shown on the axis of abscissas identified in Figure 2 and as presented in the Phase I Workshop was formulated by the Cost Analysis Division, and with an eye towards International Standards Organization (ISO) 27026 [22]. The ISO 27026 issued a formative naming taxonomy and tree structure for cost breakdown structure in Appendix E of ISO 27026, which was used to help formulate the "Technology Scope Classification".

3. Taxonomy of Technologies Between NASA Organizations

Meaning: A naming system for technologies that is common between NASA organizations would help translate technologies and communication across organizations. Common naming systems would improve technology estimating and data management.

Research Observation: NASA has multiple technology organizations and naming of systems between them was not observed to be standard. The common naming of items between organizations would help to retrieve information and cost and schedule data for technologies between different NASA organizations.

4. Endpoint or Disposition of the Technology

Meaning: The identification for what status the technology takes at its conclusion is important to understanding of the technology progression or if the technology has been dead-ended. The disposition of the technology is a clarification if the technology is to be tracked further or identified for how it can be progressed.

Research
Observation: NASA does require technology projects to identify the end point or disposition of the technology. Identifying this information would help to track technology and illuminate the cost and schedule impact on future similar or same projects.

The Phase I meeting confirmed that the focus of this research will include the scope for technologies with TRL range of 2 to 6 and that those technologies would be comprised of parts, materials, components, sub-systems or systems. Further, it was widely recognized within the NASA Cost Community that NASA currently has no cost estimating tool(s) for the scope of technologies within the range of TRL 2 to 6. Therefore, the focus of this Technology Estimating research project has been identified for technologies with TRL range of 2 to 6.

In summary, ***multiple cost estimating processes were identified and evaluated with respect to the advantages and disadvantages presented, and considering the scope of technology addressed, parametric estimating offers the best option for use in this research to provide cost estimates for technologies in the TRL range of 2 to 6. However, based on the extent of retrospective data received during this phase of research, the analogy based methods will be used until the data can be evaluated further for Costing Estimating Relationship (CER) development and parametric analysis using those CERs.***

Technology Areas

In 2004, the Steering Committee for NASA Technology Roadmaps; National Research Council of the National Academies published *NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space*. On December 2012, NASA rolled out the NASA strategic Space Technology Investment Plan [1]. These reports identified NASA’s 14 technology roadmap to space technology. As a finding of the Phase I Workshop, ***four technology areas were identified to be investigated for Technology Estimating***. It was resolved at the Phase I Workshop that the following technology areas, listed in Table 3, provided the highest opportunity for providing a large enough number of technology projects that could be investigated for use in the research. In addition, it was recognized that any attempt to include all 14 technology areas would be inextricably difficult within the one year term planned for this research effort. Further, the acquisition for data for all of the 14 technology areas would be a challenge within the time frame of this research.

Table 3
Phase I Workshop Results
NASA Technology Roadmap Areas Identified to be Investigated in the Technology Estimating Research

TA03	Space Power and Energy Storage
TA04	Robotics, TeleRobotics, Autonomous Systems
TA08	Science Instruments, Observatories, Sensor Systems
TA12	Materials, Structures, Mechanical Systems, Manufacturing

Parameters Used for Characterization of Technology

Describing technology such that it can be adequately measured for use in Technology Estimating was one of the principle framework topics addressed in the Phase I Workshop. The Research Team engaged a three step process for development of parameters that would be used in characterizing the technology. First, a literature search was conducted to determine those parameters that could best characterize NASA technology. The second step was to evaluate all the technology parameters in the Phase I Workshop that could best be applied for use in the cost estimating process and data collection. The third step included an evaluation of the parameters during the data collection phase, and for use in the Technology Cost and Schedule Estimating (TCASE) tool development.

It was anticipated by the Research Team that the CERs will include multiple parameters that significantly influence the cost of technology development. These included parameters such as: Technology Readiness Levels (TRL), Key Performance Parameters (KPPs), Complexity, Research & Degree of Difficulty ($R\&D^3$), Advanced Degree of Difficulty (AD^2), Implementation Readiness Level (IRL), etc. Initially, there were 13 parameters presented for consideration at the Phase I Workshop, see Figure 4.

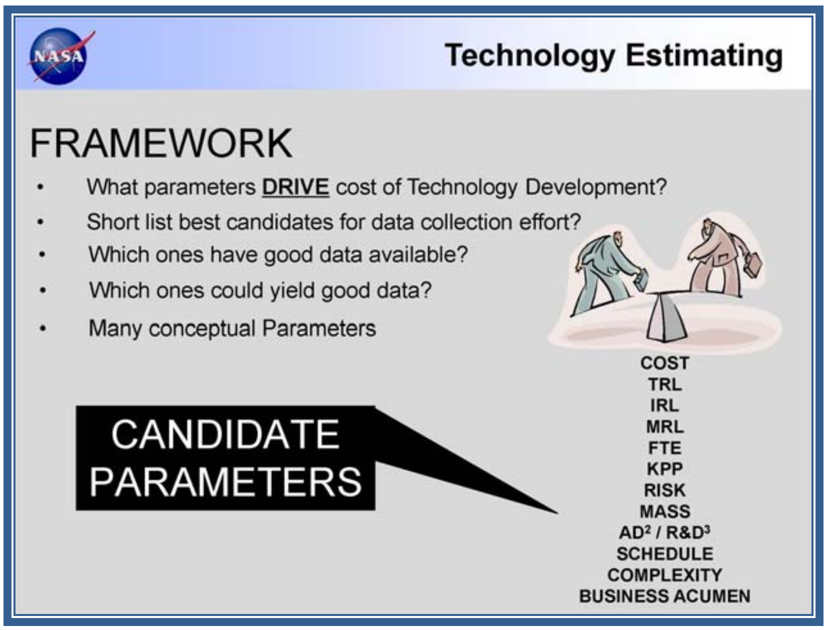


Figure 4. Initial Phase I Workshop Parameters Presented for Consideration

The advantages and disadvantages for prospective parameters presented for consideration in the Phase I Workshop and are provided in Table 4 for convenience, and also included are those parameters evaluated in the Phase II workshop.

Table 4
Parameter - Advantages and Disadvantages

Parameter	Advantages	Disadvantages
Technology Readiness Level	Experienced procedure; Assessment can affect Cost Estimate; Analysis using TRAT tool; Fast, iterative process easily repeated during development	Highly subjective; No defined process for defining TRL values; Characterize what drives the time to Technology Maturity; Difficult to measure; Risk to quality not fully developed; Identify future success?
Key Performance Parameters	Measurable performance goals that a given technology must attain to enable mission objectives; A significant advancement in the state-of-the-art	Unique to each specific system, therefor application not well defined across multiple technologies
Research and Development Degree of Difficulty	Compliments TRL by providing an accurate and effective assessment of the difficulty required for TRL advancement	Maturity of application & approach; Subjective?
Manufacturing Readiness Level	Adds analysis to determine manufacturability and identify related risks; Predicts whether or not we will be able to produce the product in the timeframe and at the rate desired with the desired quality; Identifies risks for a program office to work on.	Subjective; No defined process for defining MRL values; Information must be dug out of manufacturer Criteria for comparisons must be established
Advancement Degree of Difficulty	Prior demonstration of implementation with AD^2 analysis tool	Little demonstrated usage beyond AD^2 tool
Schedule	Defined schedule showing maturity increasing/adequate analysis and testing; High risk items, work around – Contingency development	Technology development probability of failure is similar to any project; Need defined WBS, requirements, schedule, cost, etc.
Integration Readiness Level	Enables consistent comparison of the maturity of different integration points	Insufficient for evaluating the developmental state, potential, or risk of a system
System Readiness Level (SRL)	Common platform for system development and technology insertion evaluation; Hierarchal view of technology insertion/system development assessment	System readiness (capability, maturity) may be too complex concept; Calculated from other metrics rather than objectively measured, may yield inaccurate information and non-intuitive results
Cost*	Cost is fundamental to requirements for estimating new technologies.	All costs may not be included due to shift in WBS.
Estimate vs. Actual*	Actual costs are preferred for parametric analysis.	Estimates do not meet criteria for parametric analysis.
Funding Sources*	Provides understanding of possible program funding impact to technology cost and schedule.	Multiple funding sources creates difficulties in tracking the technology costs
Push vs. pull*	Identifies the impetus for technology	Application of classification is subjective
Evolutionary vs. Revolutionary*	Identifies the level of innovation	Application of classification is subjective
Technology Area*	Segregates the technology into pre-defined road map areas	Cross referencing of technology areas can be confusing

Table 4 - Continued
Parameter - Advantages and Disadvantages

Parameter	Advantages	Disadvantages
Hardware vs. software*	Helps to illustrate the technology complexity	Software can be developed as its own parameter
Defining System Characteristics*	Characterizes technology to a greater detail	Difficult to apply consistent rationale
Level of Effort*	Defines the number of staff involved and potentially a good indicator of cost	Students, contractor staff not well identified
Unplanned Events*	Helps to illustrate emergent costs	Difficult data to acquire and information is currently not well documented
Organization(s) Involved*	Identifies the level of specialties required for a particular technology	Difficult to establish as a cost driver
Facilities and Infrastructure*	Illustrates the basis for cost	Difficult data to acquire and information is currently not well documented
Team Experience*	Exposes relation of technology complexity and ease of administration/accomplishment	May be subjective
Budget Constraints and Disruptions*	Helps to illustrate emergent costs	Difficult data to acquire and information is currently not well documented

Note: * = Identified during and after Phase I Workshop

Definition of Terms

Initiation of this research required an assessment of the language terms that the Research Team used with one another in discussions and during the many briefings made throughout this research project. It was quickly recognized that a need existed to define terms, especially prior to the Phase I workshop. The construct of the definitions were intended to have a positive impact and to help elicit meaningful discussions amongst the workshop participants and provide a near community acceptance for how to communicate issues. In addition, the definitions were intended to be provided as a supplement in the data collection process. It is noteworthy that the definitions have not gained acceptance outside this research. The definitions were changed and modified multiple times over the course of the research to evolve into those definitions now used by the Research Team and they are presented in Appendix A.

Technology Estimating

For the purposes of this research, the phrase "technology estimating" implies the estimating of the cost and schedule requirements for the development of technologies. This differs from the interpretation of "technology estimating" used throughout most of the NASA community, for the broader technology estimating term often implies the analysis and estimation of the improved technical performance of a system or architecture due to the inclusion of a given technology. The usage here of technology estimating to mean the estimating of the cost and schedule for technology maturation is limited to the cost and schedule estimating communities.

Risk

Risk may be defined as a measure for the loss of an asset or capability. Technology estimating provides the fundamental metrics that should help the technology manager reduce, eliminate or accept the risks pertaining to the development cost and schedule of a technology. The asset or capabilities that could be lost within technology development efforts include the success of the technology development effort itself. Once these risks are revealed or better understood, it will both enlighten and embolden the technology or technology portfolio manager and potentially help to support the foundation for partnership building. Partnerships that are founded on an understood cost and schedule risk will position the partnership to propel success in a technology's research and its ultimate development. NASA has clearly indicated that partnerships for technology development, transfer and mutual benefit is a key objective in the Space Technology Program.(23) As an instrumental supporting role, technology estimating capability could help reduce risk by providing cost and schedule input data to decision support systems such as those identified by Smith et al., 2004(24) and Weisbin et al., 2004, for complex technology portfolios.(25) Recognizing the full impact of cumulative risks in technologies within portfolio management could improve overall risk management and further the opportunity for success in the mission's goal.

Risk for technology projects has been addressed in the literature. (24) (25) (26) (27) ***Although it is recognized that technology risk is a driver to cost and schedule of technology, due to the results of the Phase I Workshop, it was determined that there would be a limited or no data captured in a meaningful way for retrospectively reporting the risk data in the TRL< 6 projects. Therefore, risk as a parameter for use in analyzing individual technology projects would not be addressed in this research.***

Upon completion of the Phase I Workshop, and from input by technologist during the course of the research, a total of 20 parameters evolved and were then ultimately established for characterizing technologies and then used in the data collection. Figure 5 presents the 20 parameters identified. The parameters were identified into generalized classes to include:

- Project characterization,
- Project results,
- Development metrics,
- Project execution, and
- Programmatic factors.

Each classification was devised to help capture the overall technology project diversity, variability, and technical detail. These parameters have been defined in Appendix A.

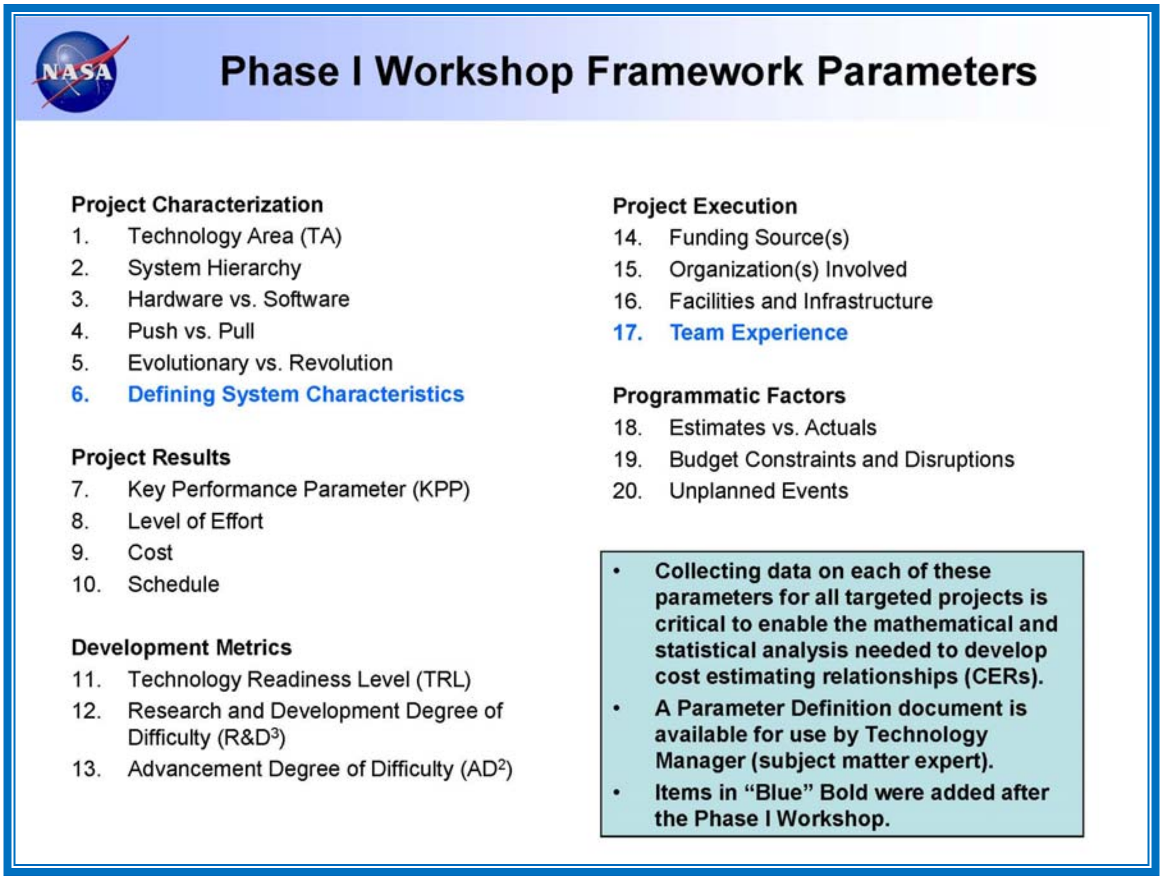


Figure 5. Technology Estimating Parameters Identified in Phase I Workshop
Used for Characterization of Technology and Data Collection

Data

Essential to this research project was the technology project data. Because limited historical data was believed to exist, or was anticipated to be available for the parameters which were expected to be significant drivers of technology development cost and schedule, a retrospective effort to gather historical data was required. Therefore, the focus of data for this research would be past projects that contained the best available information that could be readily found from online sources, embedded data in costing programs, or other Nasa Cost Analysis Division supported software.

A significant focus in this research was to obtain historical project data, retrospectively generated, which would be used to help develop a key outcome of the research. This key outcome is a consensus in the cost and technology communities about those parameters which are determined to be key drivers for technology cost. Once this consensus is obtained, the parameters would be analyzed for development of cost estimating relationships. Once these relationships and parameters could be decided upon, then future collection of data related to these parameters can then be incorporated into ongoing databases and data collection efforts such as TechPort, One NASA Cost Engineering (ONCE) and Nasa Cost Instrument Model (NICM). Over time, existing CERs can be refined and new CERs can be developed as the amount of available data to conduct the requisite analysis expands.

1. Acquisition

The acquisition of data for this research was broken down into three tasks for Technology Projects in the TRL range of 2 to 6 and the four technology roadmap TAs (3, 4, 8 and 12). These data acquisition tasks included:

- Identification of a NASA community preference for which TAs, the NASA programs might prefer to be studied first;
- Identification of the technology funding programs currently being administered by NASA as of 2012; and then
- Determine which of the available projects that could be identified by a survey given at the Phase I Workshop, and by survey of all data sources developed by exhaustive research.

The first component to data acquisition was the Research Team's task to determine if there existed an individual or most requested preference for which of TAs areas were to be studied and subsequently evaluated for different NASA programs or organizations. Based on a random survey of several technologists via informal interviews with different NASA programs, no preference was identified for one of the TAs was to be evaluated over another.

The second component to the data acquisition was the identification of technology funding programs throughout NASA, and from these, it was necessary to identify which of those would potentially possess the necessary population of technical projects with data or information that might yield names of Technology Managers, and who could provide the requisite retrospective data. Approximately 42 NASA funding programs were identified initially for use by the Research Team for retrospective data generation by the Technology Managers. Table 5 lists the funding programs identified in the research to determine the availability of data. The list was derived from those programs identified and listed in *TechPort*.

Table 5
Funding Programs Identified to Be Surveyed for Technology Estimating Data

Number	Centers & Facilities Programs
1	Advanced Exploration Systems
2	Astrophysics Research and Analysis
3	Centennial Challenges
4	Center Independent Research & Developments: GSFC IRAD
5	Center Independent Research & Developments: JPL IRAD
6	Center Independent Research & Developments: JSC IRAD
7	Center Independent Research & Developments: KSC IRAD
8	Center Independent Research & Developments: LaRC IRAD
9	Center Innovation Fund
10	Center Innovation Fund: ARC CIF
11	Center Innovation Fund: DFRC CIF
12	Center Innovation Fund: GRC CIF
13	Center Innovation Fund: GSFC CIF
14	Center Innovation Fund: JPL CIF
15	Center Innovation Fund: JSC CIF
16	Center Innovation Fund: KSC CIF
17	Center Innovation Fund: LaRC CIF
18	Center Innovation Fund: MSFC CIF
19	Center Innovation Fund: SSC CIF
20	Discovery Program
21	Earth Science Technology Office
22	Exoplanet Exploration
23	Flight Opportunities Program
24	Fundamental Aeronautics Program
25	Game Changing Development
26	Ground Systems Development and Operations
27	HELIOS
28	Mars Exploration
29	NASA Electronic Parts and Packaging Program
30	NASA Innovative Advanced Concepts
31	OSMA Software Assurance Research Program
32	Planetary Science Research
33	Planetary Science Technology Program
34	SBIR/STTR Programs
35	Small Spacecraft Technology Program
36	Space Life and Physical Sciences Research and Applications
37	Space Technology Research Grants
38	Technology Demonstration Missions
39	Phase I SBIR
40	Phase II SBIR
41	Phase III SBIR
42	Constellation ETDP (Exploration Technology Development Program)

The third component for data acquisition was an exhaustive survey of the available technology projects that may be available for use in the research. To help identify possible technology projects with a potentially rich data to help satisfy the retrospective data generation by the Technology Managers, a survey was conducted at the Phase I Workshop. The survey included a written document (form) which was developed and provided to the Phase I Workshop participants. The form is included in Appendix B. The information obtained from the survey during the Phase I workshop was promising, however the resulting number of individual Technology Projects revealed as a result of this survey were ultimately found to be limited. In addition to this survey at the Phase I Workshop, a listing of 76 prospective data sources was developed by the Research Team and is included in Appendix C. This listing was based on research of NASA programs, literature search, and from cost estimating models common to NASA and commercial industry typically used for TRL > 6 missions and projects.

To help acquire the needed data for the research, a Data Collection Sheet was prepared by the Research Team and consisted of an Excel® spreadsheet in three printable sheets and included in Appendix D. In preparation of the collection sheet format, the Research Team generally followed the NASA's TechPort for its sequence of information as presented on the web page. In addition, the data collection effort generally followed the principles as outlined by Meisel, 1988, who identified three key requirements for obtaining the correct model input data: (1) finding the right experts, (2) asking the right questions, and (3) transforming the question responses correctly into data compatible with the model input format. [(28)]

The format of the data collection sheet along with the instructions for preparing answers was discussed and modified at least four times by the Research Team. After resolving many concerns, the data collection sheet was then used in at least three separate and individual interviews with Technology Managers for preliminary testing. The format of the data collection sheet consisted of pull down menus where possible so as to aid the Technology Manager in making a response. File extension naming of the data collection sheets also provided very helpful in identifying the correct projects with the respective Technology Manager and accountability. The data collection sheets were also made suitable for data retrieval into an Integrated Technology Project Database which was used as a data source to the *Technology Cost and Schedule Estimating* (TCASE) tool.

Overall, data collection followed guidelines as identified by established methodologies [(29)(30)] including structure in the document, pre-testing with sample technologist, and including wording or sequence to help reduce bias.

2. Sources of Data

The existing data sources identified in the first phase of the research were compiled and investigated in detail. Those with reliable cost and schedule information were selected for use as supporting data for the TCASE framework. The specific data sources are identified below, along with the year the data source was produced, and the number of entries (i.e. technology data projects) contained in each. Included are those 3,178 data found as listed in Table 5, by SpaceWorks, 2012 [(31)]

Table 5
Data Sources Used in this Research [31]

Short Name	Description	Year	Entries
ETDP	NASA Exploration Technology Development Program	2012	42
ESTO	NASA Earth Science Technology Office	2012	138
SBIR	Current NASA SBIR Technologies	2012	51
GCD	Game Changing Development Program Office Technology Projects	2012	35
ESMD	NASA Exploration Systems Mission Directorate ESAS Technologies	2005	304
Tech Tool Box	ATLAS (Advanced Technology Lifecycle Analysis System)	2002	6
Ext Tech Data	Tauri Group research into External Government Technologies (EGT within the MATCH relational database)	2012	28
Cx ETDP	Constellation Exploration Technology Development Program	2007	19
NTID	NASA Tech Inventory Database	2004	991
Hist SBIR STTR	Historical SBIR and STTR data	2012	1191
RLV Tech DB	NASA RLV Technology Database	1993	64
HEOMD TechDev Team	Estimates of HEOMD needed technology developments	2012	78
ETDP from MATCH	Mapping Applicable Technology To Exploration Challenges	2007	21
External from MATCH	Mapping Applicable Technology To Exploration Challenges	2007	192
JSS TBCC	NASA/Air Force Joint Systems Study TBCC Technologies	2010	18

SpaceWorks, 2013, provided a frequency analysis of 643 technology projects investigated for all technology areas, Figure 6 to identify if the source of data were rich with the 18 parameters of interest, and then only for the four selected technology areas were presented in Figure 7.

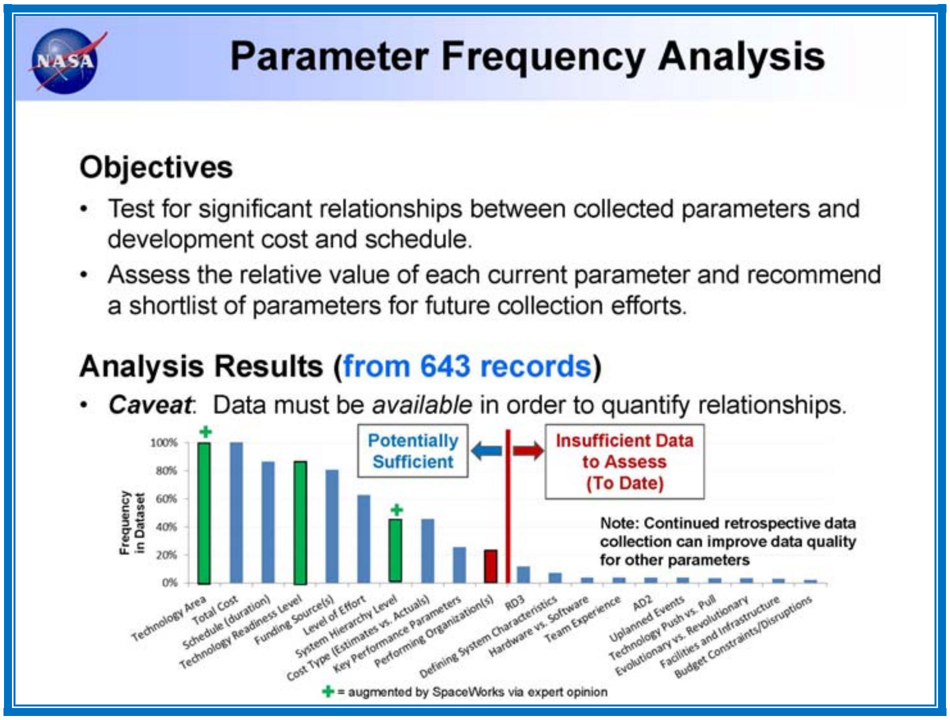


Figure 6. Data Frequency – 20 Parameters
(Figure from SpaceWorks, [31] 2013)

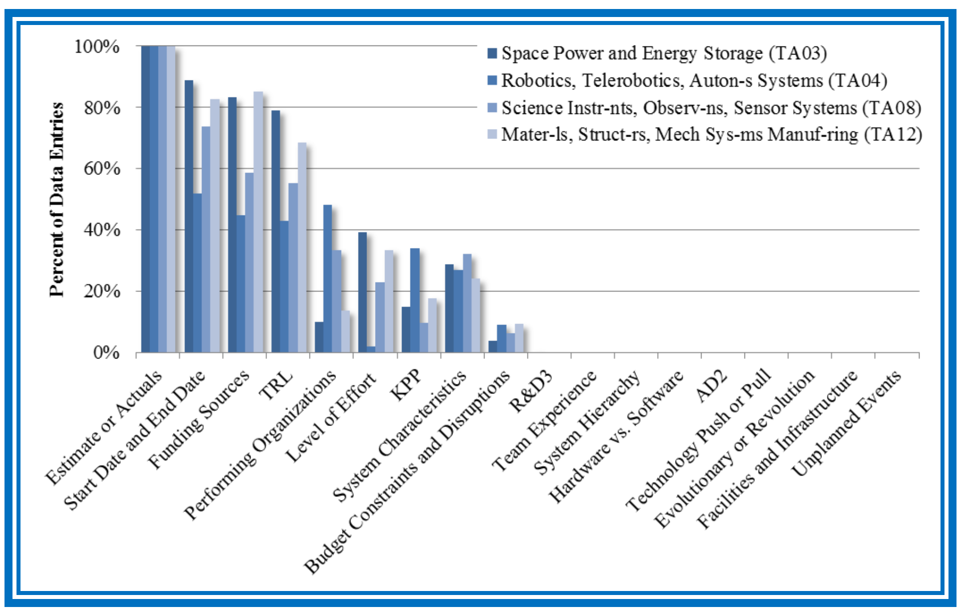


Figure 7. Data Richness - Data in four Technology Areas (3, 4, 8 & 12) and 18 Parameters
(Figure from SpaceWorks, [31] 2013)

As indicated in Figures 6 and 7, many parameters were found to be absent in the historical data for all the data sources investigated and specifically these included: team experience, system hierarchy, hardware vs. software, R&D^3, AD^2, push vs. pull, evolutionary vs. revolutionary, and unplanned events.

Upon completion of an evaluation by the Research Team of all the data sources, it was revealed that the SBIR Phase III, ETDP, ESTO and GCDPO programs retained the highest potential sources of data to be used for retrospective data generation to be used in the research and for evaluation of the 20 parameters for possible CER development. This was due to the nature that much of the project information was available on-line or as a downloaded document with cost and schedule data furnished to the Research Team. These four sources of data for these projects were identified in Table 6. These specific programs were found to have many of the data and parameters of interest to the research which included published: cost and schedule data, TRL, project descriptions, technology area identified, and the names of Principal Investigators or Project Managers and contributor contractors. Initially, 229 technology projects were identified individually as containing potentially high value data. Multiple contacts were made with technologists where the Technology Managers reside to request assistance for their support to supply the needed data.

Table 6
Sources of Technology Projects TRL 2 to 6 Used for Evaluation of the 20 Parameters
SBIR Phase III, EDTP, ESTO and GCPDO Programs

Funding Program	Media	Point of Contact	Notes
SBIR Phase II & III	List from Electronic Handbook	Provided by Mederos, L. and Jahns, G. C.	Cost and schedule data provided
ETDP	CD	Fitzgerald, J. and Law, R. C. provided duplicate copy of the ETDP information. Formal copy of the data was included in *Windchill*™ as indicated by Hall, K. L. but not readily accessible.	Partial cost and schedule data available. ETDP data was headed to National Archives.
ESTO	On Line	On Line at http://www.estotechnology.us/techportfolio/ and Komar, G. J.	Cost and Schedule data provided separately.
Game Changing Development Program Office	NX	Koca, M. E. and Brooks, C. E.	Cost and schedule data available.

Beginning May 21, 2013, 178 of the Technology Managers for 229 targeted Technology Projects were provided a data collection sheet to be used for retrospective data generation. The balance of the 51 technology projects were found to have Technology Managers who were no longer associated with the project or not found, or no records were found to be available to make for a viable data collection response making these data of no value. As of June 20, 2013, 37 data collection sheets were prepared by the Technology Managers and returned to the Research Team. A copy for each of the electronic data collection sheets for responses received from the Technology Manager are included in Appendix D. Where telephone contact with the Technology Managers were necessary to aid in the completion of the data collection sheets, GAO structured interviewing techniques and guidelines [(28)] were implemented to help provide explanations that were uniform and to provide clear explanations or instructions to avoid disruption of data quality, avoid introduction of bias, or to not interfere with the cognitive decision process of the Technology Manager. [(28-29)]

An informal survey of the Technology Managers, who provided their input to the data collection sheet, or their facilitators related to the data collection activity generally, indicated the following:

- "This is a very important process, and we need it",
- "Insufficient time to accomplish this data collection effort with all the other work being done",
- "It takes from one to two hours to complete the data collection sheet for a project",
- "The technology project is old and I cannot remember, or files not available",
- "The project is 10 years old", and
- "A WBS will be needed to complete the data collection sheet".

Data collection from established sources in this research proved exceedingly difficult and the uniform documentation of the data in a useable format overall was found not well established. A notable exception, the data acquired from the SBIR Electronic Handbook, was superior to this research in that it contained a systematic categorization of the many parameters of interest and the data were presented on an Excel® spreadsheet. The Game Changing Development Program Office data were found to contain the highest level of parameters of interest to the Research Team and the technology project data were found archived as slides in Microsoft™ Power Point® on LaRC's NX on-line project archival system. The ETDP data was found to be located on NASA's Windchill® system and designated to be headed for the National Archives. An attempt was made to intercept it for use in this research and fortunately, a copy of the ETDP data was made available to the Research Team before its' archival. The ESTO project information was rich in data and found on an on-line web site quad sheets in Adobe™ PDF® format. These ESTO project data were then converted to Microsoft Word® documents for extraction to the Integrated Data Base.

Appendix B of the Parametric Handbook identifies that ***data should be collected for all technology projects centrally and maintained in a manner that provides a complete audit trail with dates, so that cost can be adjusted for inflation.*** [(21)] A good example for how project metrics are documented for large mission level projects was NASA's ONCE and CADRe. It was unfortunate however that the ONCE/CADRe system did not afford a suitable data base for this research. ONCE and CADRe is supported by requirements included with NASA policy for NASA Procedural Requirements (NPR) 7120.5 projects in excess of $250 million. It is recognized that Technology projects of TRL range of 2 to 6 are below that dollar threshold and may be managed at a different level under multiple funding programs. Each of these lower TRL technology projects has been founded on programs that have different documentation requirements and none were required to be centrally located in a data base. It was also observed that Technology Projects with TRL < 6 in this research do not normally have a work breakdown structure in which data can be acquired. Further, programmatic information related to skill of the technology team, infrastructure requirements, delay(s) to the project, significant change(s) in the project, and tracking the project were obscure.

3. Pre-Completed Data

Contact with several NASA organizations revealed that the time for generation of the retrospective project data into the data collection sheet by the Technology Manager was a perceived burden to their time applied to their required duties. In an effort to help reduce this time burden, the Research Team attempted to obtain total project costs and the beginning and end dates for the project from the respective funding organization. In addition, an effort was made to retrieve the technical paper(s) published for 82 technical projects. The technical paper(s), where found were researched to determine if they contained any one of the 20 project parameters to be evaluated for characterization of the technology. The information contained in the technical paper(s) was then translated back to the project Data Collection sheets along with the cost and schedule information as provided. The Technology managers were then asked to back check the pre-completed data collection sheet for accuracy.

It is important to note that the NASA *Aeronautics and Space Database* was the primary research source for investigating technical publications related to the technology project along with the LaRC OCIO Technical Library resources and E-Databases. At times, this effort was augmented by courtesy use of the *Old Dominion University Library* on-line resources.

The following was learned from this pre-completion effort for the data collection sheet:

- The technology presentation for each project was researched. Some technology projects only had a power point presentation associated with the technology project as if they had been given to a professional technical group or symposium. The value for obtaining parameters from this source was found to be of low or no/questionable data value, and the data collection sheet was not pre-completed.

- The technology paper for each project was researched. Technology projects at times had one or more technical papers associated with the technology project. Most papers were found to consistently contain rich information with respect to the 20 parameters of interest. The value for obtaining data for the estimating parameters and retrospectively generating the data into the data collection sheet was found to be of high to medium data value.

- During the research, the technical papers did not always possess the same title as the funded research project title.

- Tracking the technical paper to the parent funded research project title was at all times not possible. The funding contract number did not appear in the technical paper.

- A question was identified that could not be resolved within the scope of this effort to understand if a series or successive technical papers were connected to the parent funding contract. Currently, progression of the technology could only be tracked by the technical paper’s publication date. It was unresolved in this limited time to determine if the primary technology branched into other technology applications or Technology Areas.

- The TRL progression and cost per year was input as an estimate to the pre-completed Data Collection sheets by the Research Team as a straight-line interpolation,
- Review of the technical papers did not reveal if a cost was associated with use of a facility for the project. When costs are reported in pre-completed data collection sheets for use of facility, they were estimated by the Research Team.

- Review of the technical papers did not reveal how many Full Time Employees (FTEs) were included for a technology. The numbers of FTEs were estimated on the Data Collection Sheets by the Research Team based on the number of technical paper contributors.

- Typically, the pre-prepared data collection sheet, if not checked or confirmed by the by the Technology Manager, was ultimately identified to be of “no/questionable value” data and was not used.

- Between the initiation of data collection in March, and through June 2013, approximately 17% of the Technology Managers responded even though the Data Collection Sheets were pre-completed for their review and back-checking. By Mid-September 2013, the response rate was approximately 31%. The participation by the Technology Managers was gained from direct contact via emails and phone calls.

4. Data Quality

Data to be used in the research must be satisfactory for use in the development of the cost estimating relationships that are included in the parametric analysis. Multiple screening criteria were established in a written document titled *Technology Estimating Data Quality and Screening Methodology* and the data was checked for general accuracy. The *Data Quality and Screening Methodology* document has been included in Appendix E.

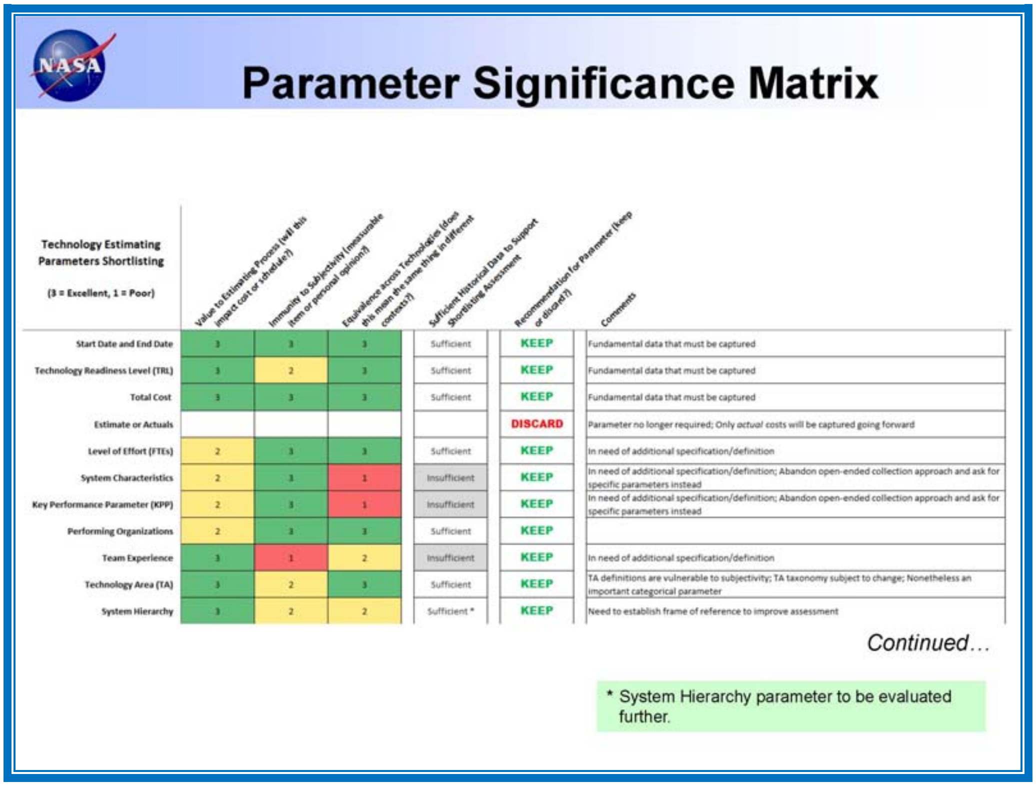
5. Parameters Evaluation and Screening

During the Phase I workshop, 20 parameters (See Figure 4) were established for the characterization of Technology projects. These parameters were classified into categories for Project characterization and results, development metrics, project execution, and programmatic factors. Recognizing the variability of technology, and the goal of determining which one of these parameters drive cost an effort was made to understand and confirm what it is we are trying to accomplish. The Research Team focused on a path to understand what the fundamental drivers to technology cost and schedule were and how best do we help assign these drivers a place in the parametric analysis to provide an estimate and schedule.

The parameters were evaluated to determine if they retained either a qualitative or quantifiable objective and the results are provided in Table 7. The qualitative and quantitative aspect of each parameter was analyzed with a discussion indicated.

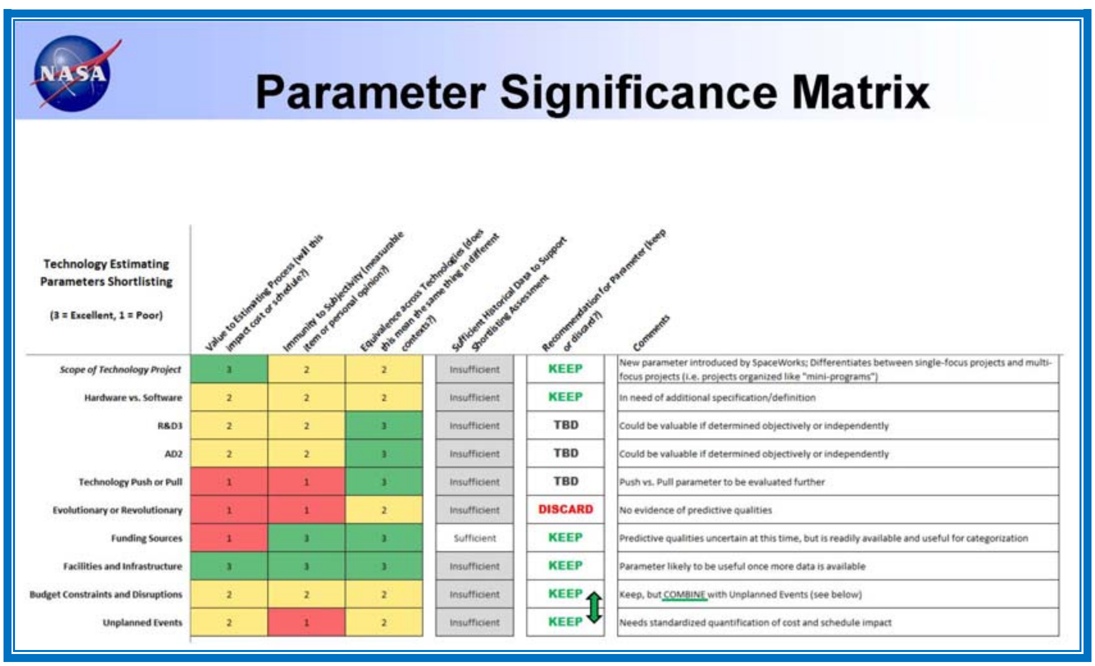
Table 7 **Technology Characterization Parameters – Analysis**			
Project Characterization	**Parameter Value**	**Metric (Quantifiable or Qualitative)**	**Discussion**
Technology Area (TA)	1 through 15	Quantifiable	Easy parameter to assess for first level TA, however the secondary, tertiary levels of TA were at times difficult to apply.
System Hierarchy	Hardware/Material, Component/Part, Assembly, Sub-system, System	Qualitative	The hierarchy was easy to apply and helps to classify the technology.
Hardware versus Software	All hardware/No software, High hardware/Low software, Medium hardware/Medium software, Low hardware/High software, No hardware/All software	Qualitative	The amount of hardware versus software was found difficult to quantify with great accuracy. The level of programming hours, lines of code, extent of computer applications must be addressed in order to determine its total cost driving implications to the Technology. Parameter should be expanded to include software as a separate parameter.
Push versus Pull	Either	Qualitative	The determination of the intent whether a project was push versus pull could not be fully discerned from the data.
Evolutionary versus Revolutionary	Either	Qualitative	The determination of the intent whether a project was evolutionary versus revolutionary could not be fully discerned from the data.
Defining System Characteristics	Description of project in terms of length, mass, volume, power, etc.	Quantifiable	Parameter was a significant contributor to the analysis as a means to describe the technology however at the level of limited data for a specific TA.
Project Results			
Key performance Parameter (KPP)	Description of project performance or distinct capability	Quantifiable	The parameter was a significant contributor to the analysis as a means to describe the technology however at the level of limited data for a specific TA.
Level of Effort	Full time employees	Quantifiable	The parameter was considered a significant contributor to the research.
Cost	Total cost in dollars	Quantifiable	The parameter was considered a significant contributor to the research.
Schedule	Total project duration in years	Quantifiable	The parameter was considered a significant contributor to the research.
Development Metrics			
Technology Readiness Level (TRL)	1 through 9	Qualitative	The parameter is a significant contributor to the analysis however the TRL determination may is subjective.
Research & Development Degree of Difficulty ($R\&D^3$)	1 through 5	Qualitative	The parameter was found difficult to apply.
Advancement Degree of Difficulty (AD^2)	1 through 9	Qualitative	The parameter was found difficult to apply.
Project Execution			
Funding Sources	Number and identification	Qualitative	The parameter was found easy to apply.
Organizations Involved	Identification of NASA organizations, Universities, contractors, etc.	Qualitative	The parameter was found easy to apply.
Facilities and Infrastructure	Description of laboratories, aircraft, or other special facilities required.	Quantifiable	The parameter was found easy to apply.
Team Experience	Little or no team experience, Experience conducting research but little or no experience with specific technology, Experience with research of this specific technology, Experience with this specific technology and innovative team	Quantifiable	The parameter was found easy to apply
Programmatic Factors			
Estimates versus Actuals	Either	Quantifiable	The parameter was found easy to apply.
Budget Constraints and Disruptions	Description of any budget constraints or disruptions which may have influenced the project	Qualitative	The parameter was found easy to apply.
Unplanned Events	Description of any events which may have influenced the project	Qualitative	The parameter was found easy to apply.

An analysis was conducted of the 20 parameters further using a weighting scheme and the results are presented in Figures 8a and 8b.



Technology Estimating Parameters Shortlisting (3 = Excellent, 1 = Poor)	Value to Estimating Process (will this impact cost or schedule?)	Immunity to Subjectivity (measurable item or personal opinion?)	Equivalence across Technologies (does this mean the same thing in different contexts?)	Sufficient Historical Data to Support Shortlisting Assessment	Recommendation for Parameter (keep or discard?)	Comments
Start Date and End Date	3	3	3	Sufficient	KEEP	Fundamental data that must be captured
Technology Readiness Level (TRL)	3	2	3	Sufficient	KEEP	Fundamental data that must be captured
Total Cost	3	3	3	Sufficient	KEEP	Fundamental data that must be captured
Estimate or Actuals					DISCARD	Parameter no longer required; Only *actual* costs will be captured going forward
Level of Effort (FTEs)	2	3	3	Sufficient	KEEP	In need of additional specification/definition
System Characteristics	2	3	1	Insufficient	KEEP	In need of additional specification/definition; Abandon open-ended collection approach and ask for specific parameters instead
Key Performance Parameter (KPP)	2	3	1	Insufficient	KEEP	In need of additional specification/definition; Abandon open-ended collection approach and ask for specific parameters instead
Performing Organizations	2	3	3	Sufficient	KEEP	
Team Experience	3	1	2	Insufficient	KEEP	In need of additional specification/definition
Technology Area (TA)	3	2	3	Sufficient	KEEP	TA definitions are vulnerable to subjectivity; TA taxonomy subject to change; Nonetheless an important categorical parameter
System Hierarchy	3	2	2	Sufficient *	KEEP	Need to establish frame of reference to improve assessment

Figure 8a. Parameter Analysis Using a Rating Scheme



Technology Estimating Parameters Shortlisting (3 = Excellent, 1 = Poor)	Value to Estimating Process (will this impact cost or schedule?)	Immunity to Subjectivity (measurable item or personal opinion?)	Equivalence across Technologies (does this mean the same thing in different contexts?)	Sufficient Historical Data to Support Shortlisting Assessment	Recommendation for Parameter (keep or discard?)	Comments
Scope of Technology Project	3	2	2	Insufficient	KEEP	New parameter introduced by SpaceWorks; Differentiates between single-focus projects and multi-focus projects (i.e. projects organized like "mini-programs")
Hardware vs. Software	2	2	2	Insufficient	KEEP	In need of additional specification/definition
R&D3	2	2	3	Insufficient	TBD	Could be valuable if determined objectively or independently
AD2	2	2	3	Insufficient	TBD	Could be valuable if determined objectively or independently
Technology Push or Pull	1	1	3	Insufficient	TBD	Push vs. Pull parameter to be evaluated further
Evolutionary or Revolutionary	1	1	2	Insufficient	DISCARD	No evidence of predictive qualities
Funding Sources	1	3	3	Sufficient	KEEP	Predictive qualities uncertain at this time, but is readily available and useful for categorization
Facilities and Infrastructure	3	3	3	Insufficient	KEEP	Parameter likely to be useful once more data is available
Budget Constraints and Disruptions	2	2	2	Insufficient	KEEP	Keep, but COMBINE with Unplanned Events (see below)
Unplanned Events	2	1	2	Insufficient	KEEP	Needs standardized quantification of cost and schedule impact

Figure 8b. Parameter Analysis Using a Rating Scheme

Each parameter was individually evaluated and documented with an evaluation narrative and included in Appendix F. The evaluation conducted used the premise that a schedule and cost driver was a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost, and to qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense. The following is a detailed summary of the parameter evaluation:

A statistical analysis was conducted to evaluate the parameters and the results are included in Figure 9.

Analysis of Variance (ANOVA) Results

Parameter	Likelihood of Relationship between Parameter and Cost?	Comments
Technology Area (TA)	**Significant** (p-value ≈ 0.00) Samples: 605 historical + 38 retrospective	
Total Cost	-	*This is an output (predicted) parameter*
Schedule (duration)	-	*This is an output (predicted) parameter*
TRL (i.e. TRL Start➡End)	**Significant** (p-value ≈ 0.00) Samples: 485 historical + 37 retrospective	
Funding Source(s)	-	Insufficient commonality/uniformity within data to conduct test
Level of Effort	-	*Not an independent parameter*
System Hierarchy Level	**Significant** (p-value = 0.03) Samples: 213 *augmented* + 26 retrospective	Further evaluation is required
Cost Type (Estimates vs. Actuals)	-	*Intended for classification of data only; Not predictive*
KPP	-	Insufficient commonality/uniformity within data to conduct test
Performing Organization(s)	**Insignificant** (p-value = 0.43) Samples: 605 historical + 38 retrospective	

Note: It is common practice to look for a p-value <= 0.05 (i.e. 5%) before declaring that there is a significant underlying relationship between groups of data.

Figure 9. Analysis of Variance Results

With the addition of retrospective data, additional analysis is expected to be conducted to determine the significance of the parameters to be evaluated further.

Based on the analysis conducted, the parameters were screened and the recommended parameters were then identified in the Phase II Workshop. Based on the workshop results, the following parameters are recommended to be used for Technology Estimating, Figure 10, and those items identified with a "star" are already included in TechPort.

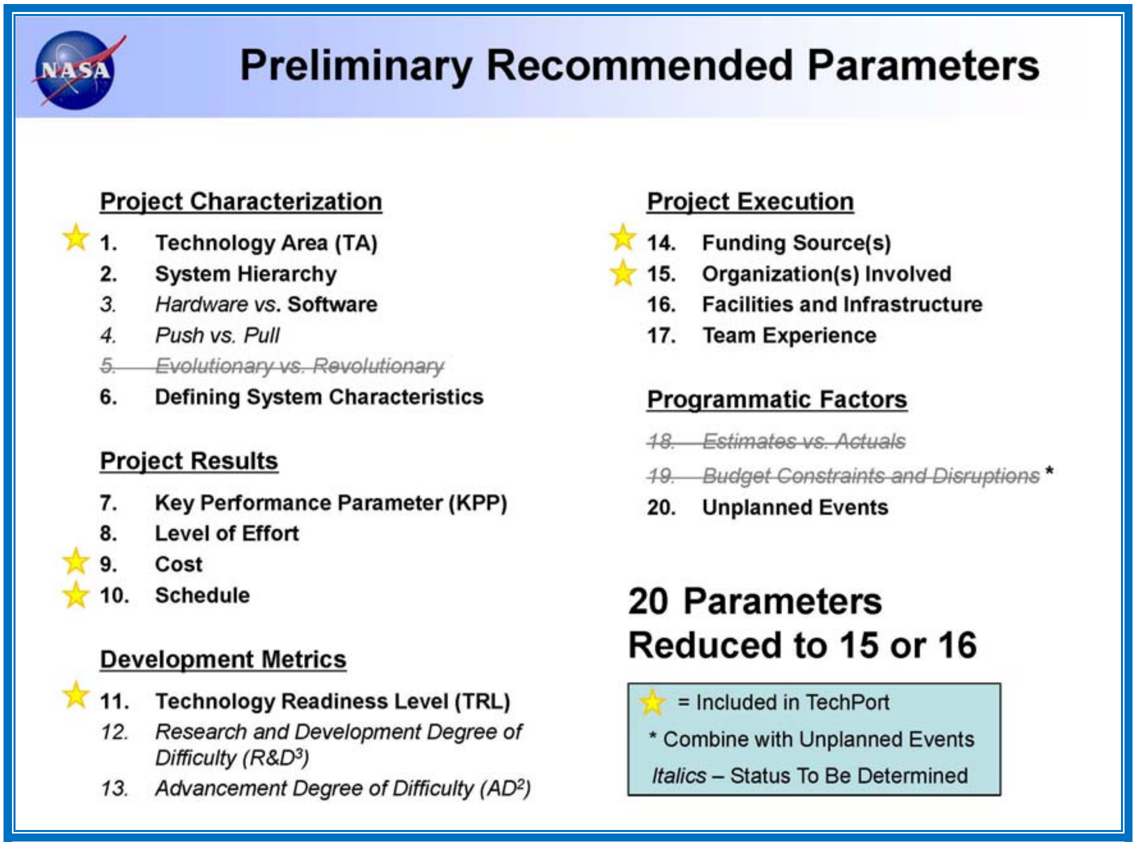


Figure 10. Preliminary Recommended Parameters

Several parameters were identified to be evaluated further. The parameter hardware versus software has been identified to have the hardware term eliminated and the software parameter term could include:

1. Brief description of software and its use,
2. Source lines of code,
3. Function point count,
4. Object class count,
5. Number of screens,
6. Language,
7. Application type,
8. Build environment,
9. Target environment,
10. Reliability, Maintainability,
11. Degree of reuse or COTS,
12. Number FTEs, and
13. Team experience.

Estimating Tool

Development of a tool to aid in the preparation of an estimate must include a sober consideration for its intended accuracy. Oberlander et al., 2001, identified that the accuracy of an estimate is measured by how well the estimated cost compares to the actual total installed cost. Oberlander's research identified that the accuracy of an early estimate depends on four determinants: (1) who was involved in preparing the estimate: (2) how the estimate was prepared; (3) what was known about the project; and (4) other factors considered while preparing the estimate. Further, his research team defined the estimate as the point in time when the estimate was performed, i.e. estimate that has been prepared from inception of the project up to and including funding approval.[9] ***The Technology Estimating research has determined that the estimating process presented herein is initially conceived as a predictive estimate performed at the inception of the technology, and based on the level of confidence indicated with the number of similar projects included and with reference to their respective analogies of projects. Ultimately, it is desired that the process will lead to development of Cost Estimating Relationships and Parametric analysis to be developed later***.

The credibility of an estimate is a highly desirable but intangible characteristic that is often touted but can only be achieved through demonstrated performance or through verification or validation. Determining the credibility of an analogy based or parametric model whether (1) to verify the cost of a program for a higher command, or (2) to develop a cost estimate, or (3) to evaluate a cost proposal requires the same type of information. The responsible person, or group(s), accepting the output of the model must feel comfortable with the information being provided. Fad, et al. 1988, indicated that this can only come from a moderate understanding the model being used, information pertaining to its technical validity, confidence in the people using it, and the track record of both. [20] Colmer, et al., 1999, recognized that although cost estimation techniques can make forecasts using very little data, it is a mistake to place great reliance on these estimates without a firm grasp of the estimate limitations, assumptions, and risks. All too often a number (or cost estimate) created has a life of its own and continues to mislead. It should be borne in mind that new technologies have been developed before. Experience on how this affected cost is still relevant, especially as it is likely that some parts of the product will be little changed by these developments. A sufficiently long term historical perspective and a broad view of industry may well reveal trends and analogies of value to the estimator.[32] ***It is recognized in this research that development of a technology estimating process and tool will evolve to a higher levels of credibility once the commitment in this research continues and the level and number of data required on which the technology estimates are based becomes increasingly established. The high level of credibility anticipated to be required for users will continue as a function of the long term and perpetual commitment to data acquisition and its maintenance.***

The TCASE tool was developed in Microsoft Excel® from the modeling architecture functional diagram developed and presented in Figure 11. The tool allows the user to define a new technology project for the purpose of cost and schedule estimation by entering inputs for the different estimating parameters identified during the study. To familiarize the user with the tool, a User's Manual is included in Appendix H. Based on these inputs; the tool presents analogous historical technology projects from the database of collected project data. From these analogies, a statistical distribution of cost and schedule predictions can be generated.

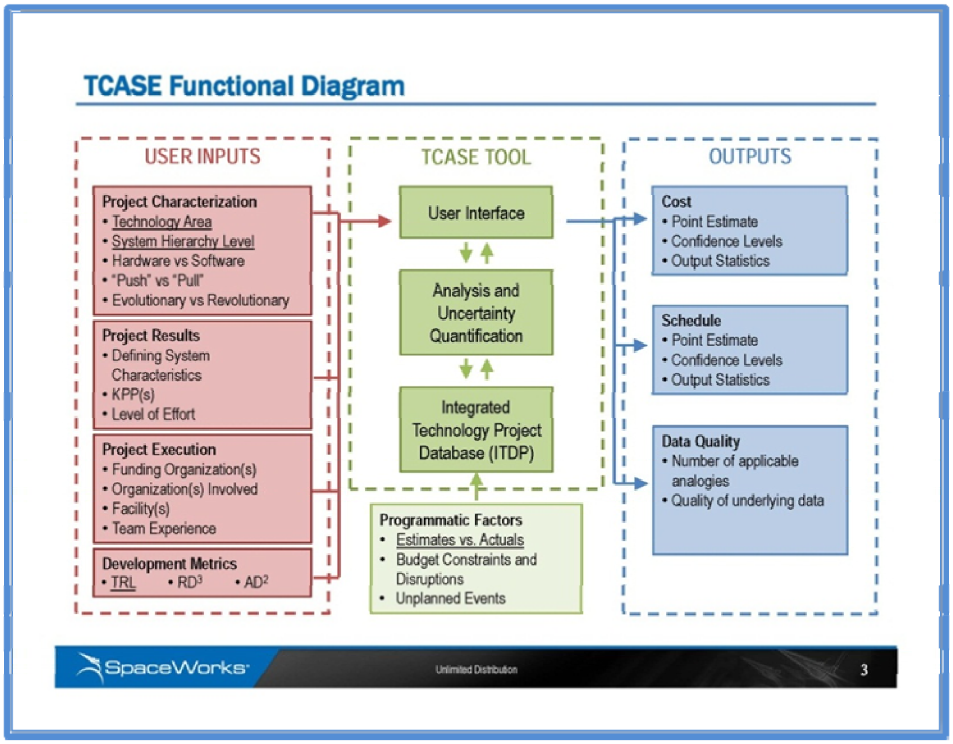


Figure 11. Architecture of the Technology Estimating Tool TCASE
(Figure from SpaceWorks,[33] 2013)

The front end of the TCASE tool was updated to reflect the development of the analytical framework. The Project Inputs section reflects the latest technology cost and schedule estimating parameters, and the analogies section was expanded to include the parameters associated with the analogous technology projects. The front end is shown on Figures 12a and 12b.

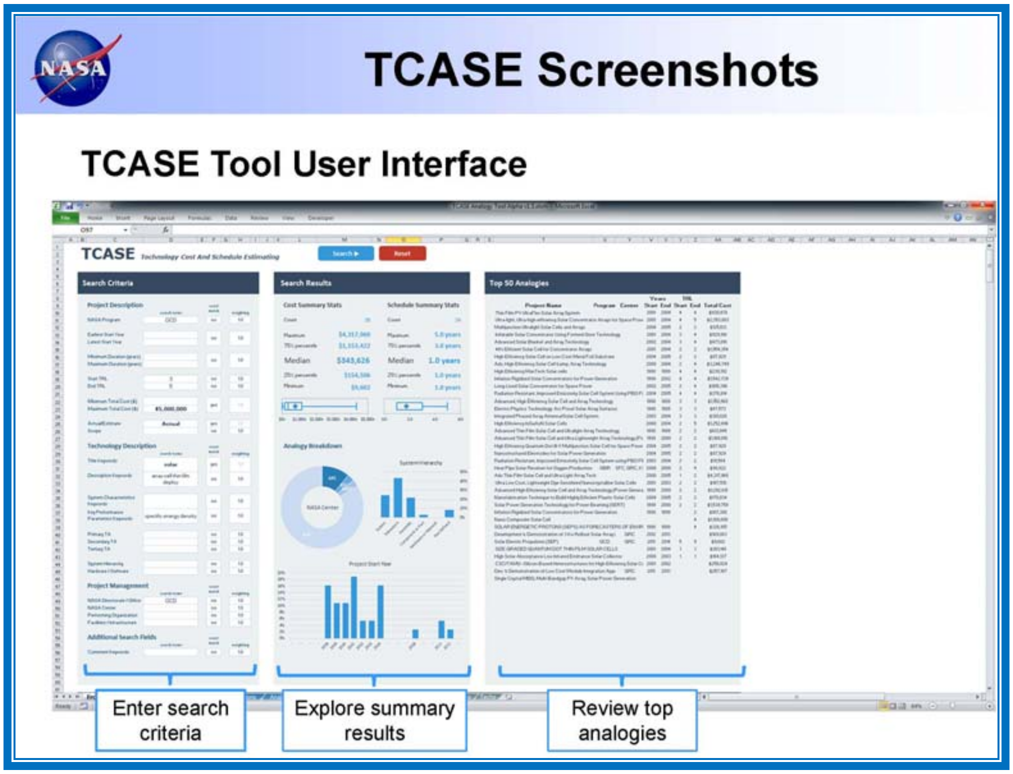


Figure 12a. Front End View of TCASE
(Figure from SpaceWorks Phase II Workshop, [33] 2013)

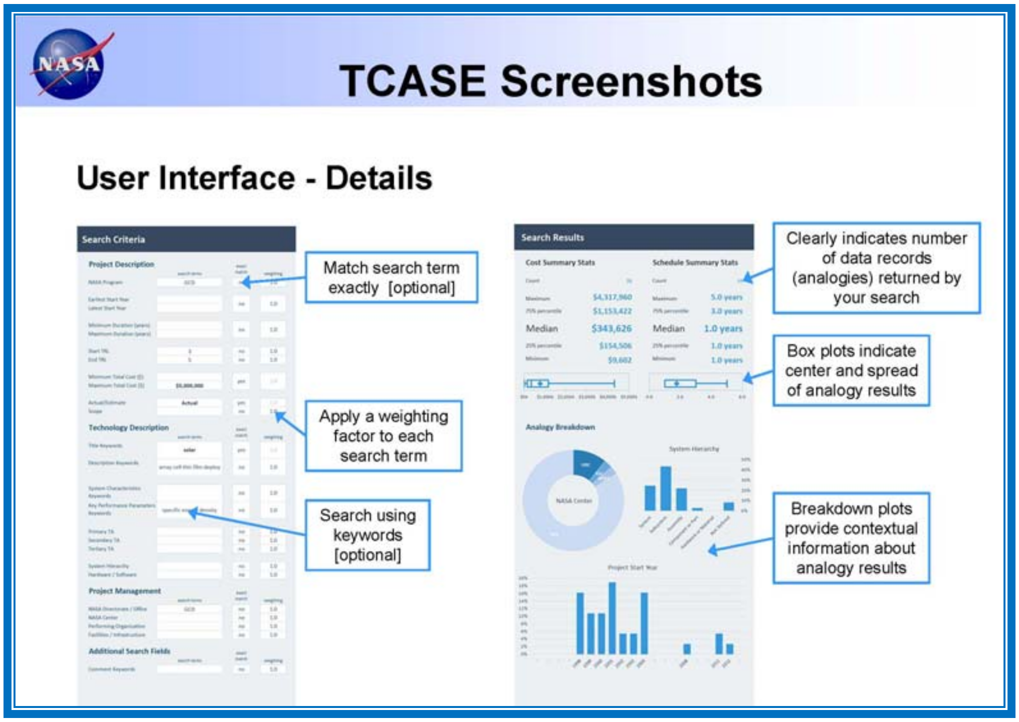


Figure 12b. Front End View of TCASE
(Figure from SpaceWorks Phase II Workshop, [33] 2013)

Importing and Exporting Technology Project Data Collection Worksheets was addressed by the Research Team in consideration of current and future applications for updating the TCASE with data. The data collection sheet can be used by the technologists for recording the parameters associated with their technology projects. In order to easily incorporate new data into the existing dataset, the processes of importing data from the datasheets to the database, and exporting data from the database to the datasheets, were automated through a set of Excel® VBA macros.

To import data from a completed data collection sheet, the VBA macros parse the datasheet, collect the parameter data from the different fields, and store this data in memory. The macros then print the data into a new row of the database, with each field from the datasheet corresponding to a column of data in the database. To export data from the database, this process is reversed. The macros read the parameter data from a single row in the database, and print this data into the appropriate fields in the datasheet. The macros are designed to import and export multiple technology projects simultaneously. To import multiple datasheets, all of the datasheet files are placed in the same folder; the macros open every datasheet identified in the folder and print the parameter data to multiple rows in the database. Conversely if multiple projects are to be exported from the database, the macros read multiple rows from the database, create a new datasheet file for each row, and print the parameter data for the projects into their associated datasheets.

Calibration, verification, validation and accreditation of the model were addressed by the Research Team. As this research will introduce the viability of the technology estimating process and TCASE tool for only four TAs, full accreditation was not anticipated to be fulfilled. Verification and validation of the TCASE however will be accomplished by continued investigation of case studies. Documentation on model verification and validation is usually critical in convincing users of the "correctness" of a model and its results, and should be included in the simulation model documentation. Calibration is the process of adjusting a model's parametric values to reflect an organization's cost and product history. The calibration process converts a general model into one developed exclusively for the organization's application. Validation is the process or act of demonstrating a model's ability to function as a credible forward estimating tool or system. Validation is performed for all parametric estimating techniques (e.g., CERs, models). (18)

Verification and validation steps generally considered and applied the following after Sargent, 2000 to TCASE:

1. Apply a test case as a study to identify that the cost and schedule estimates are at least bracketed within the range of costs for analogous projects.
2. The amount of accuracy required of the model's output variables for the model's intended application is dependent upon the input data.
3. Test, wherever possible, the assumptions and theories underlying the model.
4. In each model iteration, perform at least face validity analysis of the conceptual model.
5. In each model iteration, at least explore the model's behavior using the computerized model.
6. In at least the last model iteration, make comparisons, if possible, between the model and system behavior (output) data for several sets of experimental conditions.
7. Develop validation documentation for inclusion in the simulation model documentation.
8. Over a period of time, a schedule model upgrades will be ultimately developed for periodic review of the model's validity. (34)

The TCASE analytics was based on work by Opricovic et al. (2006) VIKOR method for multi-criteria decision making analysis which is an effective tool in multi-criteria decision making, particularly in situations where the decision maker is not able, or does not know to express his/her preference at the beginning of system design. The obtained compromise solution could be accepted by the decision makers because it provides a maximum group utility of the ''majority'', and a minimum individual regret of the ''opponent''. The compromise solutions could be the base for negotiation, involving the decision makers' preference by criteria weights. (35)

The Exact Match parameter can be set to either yes or no. If set to yes, then that particular search term will be treated as a filter, meaning that any project in the database that does not contain that search term in the specified field will not be returned as a viable result.

The Weighting parameter can be used to establish the relative importance of each search term (e.g. assigning a weighting = 1.0 for Title Keywords and a weighting of 2.0 for Primary TA would indicate that matching the Primary TA search term is twice as important as matching the Title Keywords).

The two parameters listed under Search Settings (Minimum Score for Analogy Matching and Maximum Number of Analogies in Results) are optional parameters that can be used to limit the number of results returned by a particular search. Lowering the minimum score or raising the maximum number of analogies will increase the number of results returned, and vice versa.

Findings

The following findings were provided:

1. ***A basic assumption taken in this research was that all technologies have inherent variability.***

2. ***Parametric estimating provides the best possible solution for satisfying this technology estimating research.***

3. ***The technologies of interest in this research study were TRL of range 2 to 6.***

4. ***Tracking technology in its early progressive stages along the path of development or where the early technology has branched to other Technology Roadmap Areas (TAs) would be paramount as a significant building block to Technology Estimating.***

5. ***Multiple cost estimating processes were identified and evaluated with respect to the advantages and disadvantages presented, and considering the scope of technology addressed, parametric estimating offers the best option for use in this research to provide cost estimates for technologies in the TRL range of 2 to 6. However, based on the extent of retrospective data received during this phase of research, the analogy based methods will be used until the data can be evaluated further for Costing Estimating Relationship (CER) development and parametric analysis using those CERs.***

6. ***Four technology areas were identified to be investigated for Technology Estimating.***

7. ***Although it was recognized that technology risk is a driver to technology cost and schedule, due to the results of the Phase I Workshop it was determined that there would be a limited***

or no data captured in a meaningful way for retrospectively reporting the risk data in completed projects. Therefore, risk as a parameter for use in analyzing individual technology projects would not be addressed in this research.

8. ***A significant focus in this research was to obtain historical project data, retrospectively generated, which would be used to help develop a key outcome of the research. This key outcome is a consensus in the cost and technology communities about those parameters which are determined to be key drivers for technology cost. Once this consensus is obtained, the parameters would be analyzed for development of cost estimating relationships. Once these relationships and parameters could be decided upon, then future collection of data related to these parameters can then be incorporated into ongoing databases and data collection efforts such as TechPort, One NASA Cost Engineering (ONCE) and Nasa Cost Instrument Model (NICM).***

9. ***Data should be collected for all technology projects centrally and maintained in a manner that provides a complete audit trail with dates, so that cost can be adjusted for inflation.***

10. ***The Technology Estimating research has determined that the estimating process presented herein is initially conceived as a predictive estimate performed at the inception of the technology, and based on the level of confidence indicated with the number of similar projects included and with reference to their respective analogies of projects. Ultimately, it was desired that the process will lead to development of Cost Estimating Relationships and Parametric analysis to be developed later.***

11. ***It was recognized in this research that development of a technology estimating process and tool will evolve to a higher levels of credibility once the commitment in this research continues and the level and number of data required on which the technology estimates are based becomes increasingly established. The high level of credibility anticipated to be required for users will continue as a function of the long term and perpetual commitment to data acquisition and its maintenance.***

12. ***The Research Team identified gaps during the conduct of the research. These included:***
    a. ***Cost and schedule data for some Technology Projects were not readily available in an accessible open source or not available at all.***
    b. ***Research papers for the Technology project were attempted to be used to help satisfy Technology Estimating data collection effort. Technology Projects did not always have a research paper.***
    c. ***Verifiable means to track a technical paper back to the funded research project was not found.***
    d. ***Where multiple technical papers were produced, no means existed to verifiably track to the funded research project.***
    e. ***Since this research was conducted primarily for completed projects, not all of the completed projects were assigned to a NASA Technology Roadmap Area.***
    f. ***Tracking low TRL projects through the system to a higher level was not possible.***

g. Although TechPort was released during the course of the research, TechPort data could not be used exclusively as it understandably had not been backfilled with completed projects.
h. The SAP system was initiated on or about 2003. Cost data for Technology Projects before 2003 is not readily available.
i. TechPort could be optimized further to include additional parameters data, requiring a log in to view the specific parameter.

13. Improvements to the TCASE tool may include:
a. An investigation should be made to determine if it would be useful to have the option of selecting one analogy and pulling up all of its available data into one tab/sheet rather than using its ID to search the database. The Research Team will investigate to determine if this data base query capability for one analogy can be provided in future version of the tool.
b. Annotating the percentage as a score of parameter "hits" as relevance, and/or
c. Listing the parameters with a ranking for each or say using a top to bottom score for each parameter in the analogous project.
d. System Hierarchy for the project as the system level down approach to the Hardware/Material level was addressed however, some of the data in the TCASE model appears inconsistent with this breakout. Some projects seem to include much more cost beyond just an integrated system/spacecraft level. The TCASE should be refined further with respect to the data according to the system Hierarchy.
e. The Research Team should identify if there is a way to identify the technology data that's been validated for cost, schedule, TRL, and other parameters.
f. The Research Team will verify that the tool data base does not have duplicates.
g. The Research Team will verify that TRLs listed in the data base appear correct and that lower TRL at the end of the project are consistent with the actual project results, or the project will be eliminated from the data base.

Suggestions

The following next steps are suggested and include follow-on research:

(Year 2013 to 2014)
– Continue push to collect any remaining retrospective data from historical NASA technology projects.
– Data Analysis to consolidate parameters selected for use.
– Further TCASE Model development in the four TAs.
– Investigate use of TechPort for data repository.
– Begin analysis of Data for the remaining TAs.

(Near Term)
– Refine Data /Quality Requirements.
– Continue TCASE Model use within NASA Cost Community for Beta Testing.
– Develop CERs for use in Parametric Analysis.
– Initiate Technology Estimating data input requirements /management requirements to TechPort.

(Long Term)

- Include balance of Technology Areas (1, 2, 5, 6, 7, 9, 10, 11, 13, and 14).
- Configure data pull from data sources such as TechPort.
- Maintain and Update Data and TCASE Model.
- Refine tool for NASA-wide deployment and use by Technologist, Management, and Projects.

Conclusion

The Technology Estimating process has been evaluated to determine its feasibility for providing a means to estimate technology. Based on the preliminary research, the process was determined to be a viable means to help determine the cost and schedule of technology for four of the 14 NASA Roadmap Technology Areas if the data was centralized, verifiable, and maintained. The research for Technology Estimating should continue to help refine and expedite the initial efforts initiated in this research.

The following conclusions have been derived from the research:

1. This Technology Estimating Research project addresses a gap in the NASA cost estimating capabilities for technologies in the range from TRL 2 to 6.

2. The data collection work in the research has yielded valuable information from available sources, although only for a small subset of targeted parameters. These initial results have afforded the development of a useful analogy based estimation tool. However, retrospective data collection has been challenging and efforts are continuing, to enable rigorous analysis of parameters.

3. A preliminary recommendation has been identified for data parameters to be used in the development of CERs to be applied to cost estimating using parametric analysis.

4. The future goal, pending further analysis of all parameters, will lead to CER development and evolving capabilities from an analogy based cost estimating tool now to a parametric analysis tool for the initial four technology areas investigated, i.e. TA3, TA4, TA8 and TA12.

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APPENDIX A

Definitions

TECHNOLOGY ESTIMATING RESEARCH PROJECT

Introduction and Definitions

Date: March 18, 2013; Revised June 21, 2013

The NASA HQ, Cost Analysis Division is performing research to improve the capabilities for estimating the cost and schedule of TRL 2 to 6 technology projects. For this research, the Research Team has helped to define the following 20 parameters.

PARAMETERS

1. Start Date and End Date

The beginning and end date of the project. These dates will be used to determine the duration in years and months of the technology development project.

2. Technology Readiness Level (TRL)

A systematic measurement system that supports assessment of the maturity of a particular technology and the consistent comparison of maturity between different types of technologies.(1) The Technology Readiness Level (TRL) describes the stage of maturity in the development process from observation of basic principles through final product operation. The exit criteria for each level documents that principles, concepts, applications or performance have been satisfactorily demonstrated in the appropriate environment required for that level. TRL is measured on a scale of increasing maturity from 1 to 9 as shown in the following Table 1. (2)

Technology Readiness Level
Table 1

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of	Documented description of the application/concept that addresses feasibility and benefit.

		available to support the conjecture.	algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	
3	Analytical and experimental critical function and/or characteristic proof-of concept	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experiment al results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/subsys tem model or prototype demonstration in a relevant environment (ground or space)	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully	Documented test performance demonstrating agreement with analytical predictions.

		environmental conditions.	demonstrated.	
7	System prototype demonstration in a space environment	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and “flight qualified” through test and demonstration (ground or space)	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system “flight proven” through successful mission operations	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

Note: The Technology Readiness Assessment Tool (TRAT, can be found at https://trl.msfc.nasa.gov/), developed by NASA Marshall Space Flight Center is available. If desired, the tool can assist in conducting an assessment of the beginning and ending TRL.

3. Total Cost

Total dollars required to complete the technology development project. This data will be provided by year. Cost represents total cost of labor, materials, travel, testing and equipment, etc. and should also include (and separately identify) facilities and infrastructure capital investments made as part of the research project (if any).

4. Estimate or Actuals

A categorization of the data.

- **Actuals:** Data collected from realized, historical technology development projects
- **Estimate**: Data from studies, projections, and other sources that have not yet been realized

5. Level of Effort

A measure (in total work-years) of personnel workload required in terms of Full Time Equivalents (FTE) for civil servants, or Work Year Equivalent (WYE) for contractors. One work-year represents a single project staff member (either civil servant or contractor) working full time on the project for one year. For example, if a project has two individuals working full time during a three month period of performance, then the project has 0.5 work-years.

6. Key Performance Parameter (KPP)

Those capabilities or characteristics associated with the technology that is considered to be the primary objective of the technology development effort. Technology development programs seek to improve the current state-of-the-art, so the advancement of a program can be measured by the percentage improvement in one or more KPPs.[3]

KPP information can include:

- Description of KPP and units
- Current value for state-of-the-art at the start of the project
- Demonstrated achievable value at the end of the project

For example, a jet engine propulsion technology development activity might have the goal to improve Specific Fuel Consumption (SFC). Thus SFC would be a KPP for this technology, the units would be defined (for example, g/[N*s]), along with values for state-of-the-art at the beginning of the project, and the demonstrated achievable improved value at completion of the project would be entered. The data would then be used to determine the percent improvement in the KPP as a result of the technology development project.

7. Performing Organization

A list of the names of the agencies, organizations, or companies conducting the technology development project. The number of organizations involved will be determined from this list and used as a data parameter.

8. Team Experience

Experience of the team conducting the research may be a big factor in how long the project takes and what it will cost.

Four categories of research team experience are identified, as defined below. Research team experience is to be assessed at the beginning of the technology project. The categories and definitions are:

1. The team has little or no experience conducting research.
2. The team has experience conducting research, but little or no experience with this specific technology.
3. The team has experience conducting research on this specific technology
4. The team has experience conducting research on this specific technology and ALSO has incorporated members from outside the field(s) of research who can bring new ideas and sources of innovation to the team.

9. Technology Area (TA)

The fourteen areas of space technology research being pursued within NASA, plus the fundamental research area of aeronautics. Each technology area has an associated development roadmap. The list of space technology areas and their supporting roadmaps was developed by NASA and reviewed and validated by the National Research Council (NRC). This process began in 2010 and was completed in a final report in early 2012. [(4)] The space Technology Areas have 3 levels, [(5)] which will be available to the Technology Manager in pull-down menus for entry in the data sheet. Aeronautics is normally not addressed within the Space Technology Roadmap TA taxonomy, but is included here for information as an additional ("+1") area to fully represent the technology research pursued at NASA.

14+1 TECHNOLOGY AREAS Table 2	
TA #	**Description**
TA01	Launch Propulsion Systems
TA02	In-Space Propulsion Technologies
TA03	Space Power and Energy Storage
TA04	Robotics, Telerobotics, Autonomous Systems
TA05	Communication and Navigation
TA06	Human Health, Life Support, Habitation Systems
TA07	Human Exploration Destination Systems
TA08	Science Instruments, Observatories, Sensor Systems
TA09	Entry, Descent, and Landing Systems
TA10	Nanotechnology
TA11	Modeling, Simulation, Information Tech
TA12	Materials, Structures, Mechanical Systems, Manufacturing
TA13	Ground and Launch Systems Processing
TA14	Thermal Management Systems
(+) 1	Aeronautics

10. System Hierarchy

The scope of the technology project in terms of its application of a vehicle or system. The project can be classified in one of the following five tiers [(6)] as shown on Table 3. If the technology is a process or software, the tier indicates at which level of the system hierarchy the process or software is applied. The tiers are:

System Hierarchy Table 3			
No.	**Tier**	**Definition**	**Example**
1	System	An integrated set of constituent elements that are combined in an operational or support environment to accomplish a defined objective	A spacecraft or launch vehicle stage
2	Subsystem	A portion of a system	A satellite's propulsion system or launch vehicle's propulsion system
3	Assembly	A set of components (as a unit) before they are installed to make a final product	A satellite's thruster or launch vehicle's engine turbo-machinery
4	Component / Part	A portion of an assembly	A satellite's propellant valve or a launch vehicle's engine injector
5	Hardware / Material	An item or substance used to form a component	Alloy, polymer, screws, bolts, pipes, semiconductor chips

11. Hardware vs. Software

A top-level assessment of whether the end application of the technology is:

- **Hardware:** The physical items necessary for conducting an activity, as distinguished from the theory and design that make the activity possible. Examples include mechanical equipment, tools, implements, instruments, devices, sets, fittings, trimmings, and assembled collections of those items.

- **Software:** Computer programs, procedures, scripts, rules, and associated documentation and data pertaining to the development and operation of a computer system. Software includes programs and data. This also includes COTS, GOTS, MOTS, reused software, auto generated code, embedded software, firmware, and open source software components.(7)

12. Research and Development Degree of Difficulty (R&D^3)

A top-down assessment of the anticipated difficulty likely to be encountered over the course of a technology maturation project (e.g. from the beginning TRL to end TRL). (9) R&D^3 is a qualitative evaluation of the probability of success of the development project. R&D^3 is assessed on a scale of increasing difficulty from 1 to 5 as shown on Table 4:

Research and Development Degree of Difficulty Table 4		
R&D^3	**Definition**	**Probability of Success**
1	A very low degree of difficulty is anticipated in achieving research and development objectives for this technology.	≥ 95%-99%
2	A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology.	≥ 90%
3	A high degree of difficulty anticipated in achieving R&D objectives for this technology.	≥ 80%
4	A very high degree of difficulty anticipated in achieving R&D objectives for this technology.	~ 50-60%
5	The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required.	≤ 30%

13. Advancement Degree of Difficulty (AD^2)

A bottoms-up assessment of the anticipated difficulty over the course of a technology maturation project (e.g. from the beginning TRL to end TRL). [9] AD^2 is determined through consideration of cost, schedule, and risk across several dimensions, including:

- Design and Analysis
- Manufacturing
- Software and Development
- Test and Evaluation
- Operations
- AD^2 is intended to be determined using the AD^2 calculator found at https://trl.msfc.nasa.gov/, or with a resulting value on a scale of increasing difficulty from 1 to 9 as shown on Table 5:

Advancement Degree of Difficulty

Table 5				
AD^2	**Definition**	**Risk**	**Category**	**Success Chance**
1	Exists with no or only minor modifications being required. A single development approach is adequate.	0%		Guaranteed Success
2	Exists but requires major modifications. A single development approach is adequate.	10%		
3	Requires new development well within the experience base. A single development approach is adequate.	20%		
4	Requires new development but similarity to existing experience is sufficient to warrant comparison across the board. A single development approach can be taken with a high degree of confidence for success.	30%	Well Understood (Variation)	Almost Certain Success
5	Requires new development but similarity to existing experience is sufficient to warrant comparison in all critical areas. Dual development approaches should be pursued to provide a high degree of confidence for success.	40%	Known Unknowns	Probably Will Succeed
6	Requires new development but similarity to existing experience is sufficient to warrant comparison on only a subset of critical areas. Dual development approaches should be pursued in order to achieve a moderate degree of confidence for success. (Desired performance can be achieved in subsequent block upgrades with high confidence.	50%		
7	Requires new development but similarity to existing experience is sufficient to warrant comparison in only a subset of critical areas. Multiple development routes must be pursued.	70%		
8	Requires new development where similarity to existing experience base can be defined only in the broadest sense. Multiple development routes must be pursued.	80%	Unknown Unknowns	High Likelihood of Failure (High Reward)
9	Requires new development outside of any existing experience base. No viable approaches exist that can be pursued with any degree of confidence. Basic research in key areas needed before feasible approaches can be defined.	100%	Chaos	Almost Certain Failure (Very High Reward)

Note: If needed, the AD^2 Calculator is a tool that can assist the Technology Manager in conducting an objective assessment. The AD^2 calculator is co-located with TRAT.

14. Technology Push or Pull

- **Technology Push:** Technologies that seek to meet long term goals by taking advantage of emerging or radically different ideas or approaches. Push technologies inspire new and different Missions and Mission Architectures to accomplish strategic long-term goals. [10]

- **Technology Pull:** Technologies that support or enable specific functions, capabilities or performance levels, for a defined mission, that is not achievable by proven, existent approaches. Pull technologies are motivated by the specific needs for missions, where the missions are developed by enterprise organizations to satisfy long-term strategic goals. [10]

15. Evolutionary or Revolutionary

- **Evolutionary:** An incremental or stepwise improvement from a more mature, less advanced technology.

- **Revolutionary:** A fundamentally new concept without a direct analogy, or a disruptive new innovation that is a significant advancement from an existing analogy.

16. Funding Sources

A list of the names of the organization(s), program(s), or contract(s) providing funding to the technology development project.

17. Facilities and Infrastructure

A list of the facilities and major infrastructure items required in the support of the technology development project. These could include: commercial or government laboratories, buildings, test stands, wind tunnels, etc. The number of facilities and infrastructure items will be determined from this list and used as a data parameter.

18. Budget Constraints and Disruptions

A list of the external constraints and disruptions to the resources required for the technology development project that may have negatively influenced the required project cost or schedule. For disruptions that influenced schedule, such as a break in funding between phases, the duration of these disruptions should be included. The number of total budget constraints and disruptions will be determined from this list and used as a data parameter.

19. Unplanned Events

A list of events outside of the control of the technology development project that had a negative effect on the required project cost or schedule. Examples include natural disasters, realignment of government or organization priorities, retirement or reassignment of key personnel, strikes, embargos, or testing incidents or accidents, etc. The number of total unplanned events will be determined from this list and used as a data parameter.

20. Defining System Characteristics

Technical parameters or characteristics that broadly define the scope of the technology project, but are not objectives of the technology development effort. For example, consider an energy storage technology development project with the objective of increasing Li-ion battery subsystem reliability to a goal value of 99.9%. In this case, parameters such as the energy density and the efficiency of the test battery are not direct objectives for improvement, but they may still be listed as Defining System Characteristics. (The battery subsystem reliability, on the other hand, should be listed as a Key Performance Parameter.)

References

1. Mankins, J., "Technology Readiness Levels: A White Paper," April 1995, NASA Office of Space Access and Technology, Advanced Concepts Office.
2. “Technology Readiness Level (TRL) Descriptions”, Appendix B, Small Business Innovative Research (SBIR) Solicitation, referenced December 11, 2012, http://sbir.gsfc.nasa.gov/SBIR/sbirsttr2012/solicitation/forms/appendix_B.pdf
3. “NASA Systems Engineering Processes and Requirements”, NPR 7123.1A, Nov 2009
4. Talbert, T., “Space Technology Roadmaps: The Future Brought To You By NASA”, Referenced 12/4/2012, from http://www.nasa.gov/offices/oct/home/roadmaps/index.html.
5. “Space Technology Roadmaps: Technology Area Breakdown Structure”, NASA, referenced December 11, 2012, http://www.nasa.gov/pdf/501627main_STR-Int-Foldout_rev11-NRCupdated.pdf
6. U.S. Congress, Office of Technology Assessment, The National Space Transportation Policy: Issues for Congress, OTA-ISS-620 , Washington, DC, U.S. Government Printing Office, May 1995
7. “ NASA Software Engineering Requirements”, NASA Procedural Requirements NPR 7150.2A, Office of the Chief Engineer, Effective November 19, 2009, http://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7150_002A_&page_name=AppendixA&search_term=software
8. Mankins, J., "Research and Development Degree of Difficulty: A White Paper," March 1998, NASA Office of Space Access and Technology, Advanced Concepts Office.
9. Bilbro, J., "Using the Advancement Degree of Difficulty (AD^2) as an input to Risk Management, Technology Maturity Conference, Virginia Beach, VA, Sept 8-12 2008. URL For TRAT including TRL and AD^2 found at https://trl.msfc.nasa.gov/.
10. Office of the Chief Technologist (OCT) Definitions, NASA, January 2011

APPENDIX B

Survey Form

Technology Estimating - Data Source Survey

NASA HQ Office of Evaluation, Cost Analysis Division, Technology Cost and Schedule Estimating Research Project

(Version: Rev A, Issue Date 11-15-2012)

Data Source Name

	Respondent	Data Source POC
Name		
Organization		
Email Address		
Work Phone		

Description

Tech Area(s)

Type of Data (Respond as applicable):

Historical Actual ☐ Historical Estimates ☐ Number of Projects ____ Ea. Active Projects ☐

Technology Project Size, Each (Mark all that apply)

Less than $1M ☐ $1M to $250M ☐ Greater than $250M ☐

Tracked Technology Parameters (Mark all that apply):

Cost ☐	TRL ☐	Technology Area ☐	Facilities & Infrastructure Reqr'mnts ☐	Complexity ☐	FTEs ☐
Schedule ☐	R&D [3] ☐	Tech. Proj. Tier /Scope ☐	Funding Source ☐	Push vs. Pull ☐	Unplanned Events ☐
Programmatic Risk ☐	A&D [2] ☐	Δ or TRL Progression ☐	Agencies/ORG/Companies Involved ☐	Funding Source ☐	Actual vs. Estimates ☐

Perfomance Characteristics / KPPs, status and goal, per TA ☐	Evolutionary Vs. Revolutionary ☐
Capture progression/Change of Parameters over time ☐	Budget Constraints & Disruptions ☐
Projected Metric & Theoretical Limit ☐	SOP & SOA at start of Tech. Development ☐

KPPs (list or describe)

Other (describe)

Platform (e.g. MS Excel)

Date Created

Update Frequency

Last Update

Data Sensitivity (Mark all that apply)

SBU ☐ Classified or Restricted ☐ Contractor Proprietary ☐

Other (describe)

NOTES:

1. You may print this sheet, hand write the answers, and then electronically scan it for email.
2. Please complete form and email to Stuart.Cole@nasa.gov. Call at 757-951-7403 if there are any questions.
3. Multiple sheets are acceptable.
4. Complete the information to the best of your knowledge, cite sources for future reference.
5. The purpose of the "Survey" is to obtain the best characterization of the data that is availiable.

APPENDIX C

List of Data Sources

	Tier	Data Source Name	Full Name
	Primary Sources		
1	I	NTID	NASA Tech Inventory Database
2	I	Cx ETDP Portfolio	
3	I	ARC/Mathias Lunar Surface Data	
4	I	External Gov Tech Maturation Data	Tauri Group research into External Gov Technology Tech Maturation data
5	I	Sefcik Analysis	GRC Analysis of NTID
6	I	ESMD R&T Tech Data Sheets (2006)	
7	I	RLV Tech DB (1993)	NASA RLV Technology Database 1993
8	I	HEOMD TechDev Team	
9	I	ATLAS/TITAN	Advanced Technology Lifecycle Analysis System
10	I	High Speed Research Program (80s-90s)	Wilhite led High Speed Research Program
11		National Aerospace Plane	
12		NASA SBIR/STTR	
13	I	HEOMD NSPIRES	
14	I	SMD NSPIRES	
15	I	TBCC Tech Assessment (2010)	Turbine Based Combined Cycle Tech Assessment Technology Data Sheets 2010
16	I	HLS ACENT	DARPA/NASA Horizontal Launch Study ACENT Follow-On
17	I	Gryphon Phase 2A Technologies	Gryphon Study Phase IIA High Speed Flight Experiments Concept Study Technologies
18	I	PIT	Program Integration Tool
19	I	GCD Project Snapshot	
20	I	TechPort	
21	I	START	Strategic Assessment of Risk and Technology
22		DLR Data set	
23		IDA Dataset	
24		DoD Technology Mall	
	Tools and Templates		
25	I	TCE	Technology Cost Estimator
26	I	AFRL Technology Calculator	
27	I	Bilbro Technology Calculator	Technology Assessment Calculator
29		Bilbro AD^2 Calculator	
30	I	DHS SS&T Readiness Level Calculator	
31		NAVAIR spreadsheet	
32		NICM Template	
33		DARPA Business Acumen Assessment	
34		RI3 Guidebook from Airforce	
35	II	AFRL Projects	
36	II	DARPA Projects	
37	II	DOD/Army SBIR/STTR	

38	II	DOD/MDA SBIR/STTR	
39	II	DOD/Navy SBIR/STTR	
40	II	DOD/USAF SBIR/STTR	
41	II	DOE Projects	
42	II	NASA NIAC I and II	
43	II	NASA OCT (Early Stage, Game Changing, Cross Cutting)	
44	II	NASA SBIR/STTR	
45	II	NRL Projects	
46	II	NSF Grants	
47	II	NSF SBIR/STTR	
48	II	SBIR "Enhancement Awards"	
49	I	CADRe	Cost Analysis Data Requirement
50	III	Advanced Product Design Team (Team X) Cost Model	Advanced Product Design Team (Team X) Cost Model
51	III	ALS/ADP Cost Model	ALS/ADP Cost Model
52	III	A-PICOMO	Aerospace Picosatellites Cost Model
53	III	BOE Tool	Basis of Estimate Tool
54	III	CEV TRL Summary/Details	
55	III	ChiCoMo	Chicago Cost Model
56	III	ICSAT	Integrated Cost and Schedule Analysis Tool
57	III	MATCH Database	Mapping Applicable Technology To Exploration Challenges
58	III	MICM	Multivariable Instrument Cost. Model
59	III	NAFCOM 2011	NASA / Air Force Cost Model
60	III	NAFCOM/REDSTAR	
61	III	NICM	NASA Instrument Cost Model
62	III	Parametric Cost Modeling for Space Telescopes	Parametric Cost Modeling for Space Telescopes
63	III	PMCM	Planetary Mission Cost Model
64	III	PRICE TruePlanning	PRICE TruePlanning
65	III	PRICE-H	PRICE for Hardware
66	III	PSCM	Passive Sensor Cost Model
67	III	QuickCost 5.0	QuickCost 5.0
68	III	SEER-EOS (formerly SEER-Spyglass)	SEER for Electro Optical Sensors
69	III	SEER-H	SEER for Hardware, Electronics, & Systems
70	III	SEER-IC	SEER for Integrated Circuits
71	III	SEER-MFG	SEER for Manufacturing
72	III	SEER-SEM	SEER for Software
73	III	Sensat	Sensor Satellite Expert System
74	III	SICM	Scientific Instrument Cost Model
75	III	SSCM10	Small Satellite Cost Model 2010
76	III	VIEW	VIEW

APPENDIX D

Data Collection Sheets

Data Collection Sheets are available from the Cost Analysis Division.

APPENDIX E

Technology Estimating Data Quality and Screening Methodology

To: Doug Comstock, CAD

From: Research Team

Re: Technology Estimating Data Quality and Screening Methodology

Date: January 30, 2013; Revised June 10, 2013

The purpose of this paper is to help elicit discussion leading to formulation of a method for screening data for this research. The purpose for screening data is to obtain quality Technology data in the Technology Estimating research project. The screening methodology is also intended to provide guidance for selection of data to be used in the effort, and which data should be applied, or discarded.

Currently, based on the Phase I meeting, technology project data is to be obtained for low TRL (2 to 6) technology projects and for NASA Technology Roadmap areas defined by TA 03, 04, 08, and 12. There are 20 parameters to be investigated for each of the technologies and to help determine Cost Estimating Relationships. The effort to determine CERs from these 20 parameters generally requires generation of the information from persons intimately knowledgeable of the project.

Generally, the research effort is to help define which of the 20 parameters are beneficial to use for development of CERs. In addition, development of a model requires use of data that has been carefully reviewed by the Research Team for any inconsistencies or are poorly developed which might lead to misleading conclusions as to which of the parameters are of benefit towards the preparation of a point cost and schedule estimate with a reported accuracy range.

Initially, for analysis of the 20 parameters, it is perceived that the data used in the model will help lead development and reporting of the cost and schedule accuracy range based on the quality data used. It is proposed that this accuracy range should perceptively change with the quality of data used.

Upon completion of the data collection process with the Technology Managers expected in the 1st Quarter 2013, it should become apparent which of the 20 parameters will be eliminated. The elimination of any parameter for use in the model will need to be documented. The determination should include a narrative for why the parameter was eliminated, discuss any misconceptions, the “feel” as it would apply, or list other shortcomings/notes/comments in definition or interpretation by any of the Technology Research Team or research participants.

SCREENING CRITERIA

1. Technology Projects would be categorized into high, medium, low, or no/questionable value.
2. **High value**: Technology projects could be identified as high value would be completed work showing TRL progression from TRL 2 to TRL 6 and/or beyond. These projects most likely would be represented by:
    - SBIR/STTR projects Phase III
    - ESTO,
    - EDTP,
    - Game Changing Development Program Office projects,

Data would be used to satisfy or resolve of the 20 parameters would be generated by Technology Managers and/or those persons with direct project knowledge.

3. **Medium value**: These Technology Project data includes some or satisfy part of the 20 parameters without confirmation by a Technology Manager or project knowledgeable person. These data would be obtained from currently published or documented resources and include description of the technology, TA identification, beginning and end costs, dates, and TRL. The medium value data would include a citation for the source from where it was derived, i.e. traceable.

4. **Low value**: The Low value Technology Projects data include any one of the following:
    - Un-traceable with no citation for source of data,
    - FY dollars are not identified,
    - Project data does not indicate the total project time,
    - Project is active and a Technology Manager can or cannot be found to verify the data,
    - Technology Manager can verify project future end point costs, TRL progression,
    - Only one cost is provided.

5. **No/Questionable value**: These criteria include technology data where anyone of the following applies:
    - Traceability does not exist,
    - The project is active, and no Technology Manager cannot be found to verify the data,
    - The origin of the data is in question,
    - Beginning or end cost data has not been provided,
    - No TRL data exists,
    - Project descriptions are not well defined,
    - No TA data, or
    - Basic technology project data is in question.

The No/Questionable project data should not be used in the research.

APPENDIX F

Parameter Evaluation Narrative

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Characterization	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Technology Area (TA)	Qualitative	High	Yes	Yes	Yes

1. Technology areas in secondary and tertiary breakdown were sometimes difficult to apply in all cases.
2. This parameter only applied to recent projects as the 14 TA Roadmap was promulgated within the last two years.
3. TA significantly helps to refine the Technology however branching TAs can or may be questioned.
4. Different individual TAs are expected to have generally different schedule and costs.
5. This parameter is included in TechPort.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Characterization	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
System Hierarchy	Qualitative	Med.	Yes	Yes	Yes

1. This parameter was not applied easily by Technology Managers.

EXAMPLE: If a satellite (mission i.e. “platform” or “system of systems”) had multiple sub-systems comprising the total science package, it could not readily be determined that a technology was itself a complete system or was it to be included in the larger science system or platform.

2. Would benefit from a standard reference to help clarify appropriate level in the hierarchy.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Characterization	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
~~Hardware vs.~~ **Software**	Qualitative	Low	Yes	Yes	Yes

1. Recommend that "Hardware" should be dropped as it does not provide significant correlation to amount or extent of software in all technologies.
2. **Suggested Typical software cost drivers include:** Source lines of code, Function point count, Object class count, Number of screens, Language, Application type, Complexity (various measures),Build environment, Target environment, Reliability, Maintainability, Degree of reuse or COTS, Number FTEs, Team capability.
3. Software development can be expected to be significant in the range of TRL 5 to 6.
4. Technology papers indicate sometimes one or two persons exclusively dedicated to software. And extent of software can be major influence to cost and success of the technology.
5. Data may exist as part of NPR 7150.2A software management.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Characterization	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Push vs. Pull	Qualitative	High	No	No	TBD

1. The parameter goes to <u>intent</u> of the Technology initiation and that determination can be quite difficult to determine and is possibly only known by a few, may never be documented, or is obscure.
2. If there is push then only a few discrete projects may be classified and these may be an exception.
3. If there is a push, then this parameter might be added later.
4. Currently, this parameter is recommended to be evaluated further.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Characterization	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Evolutionary vs. Revolution	Qualitative	Low	No	No	No

1. The parameter goes to intent of the Technology initiation and that determination can be quite difficult to determine and is possibly only known by a few, may never be documented, or is obscure.
2. If there is revolutionary technologies then only a few discrete projects may be classified and these may be an exception.
3. Currently, this parameter is recommended to be eliminated.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Characterization	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Defining System Characteristics	Quantifiable	Med.	Yes	Yes	Yes

1. Provides the detailed characterization of TAs.
2. Helps to characterize between technologies in same TA and for branching technologies from a single TA.
3. This parameter includes mass, volume, power, etc.
4. With future data, the characterizations could reveal for some TAs i.e. 08 Instrumentation, that they follow Moore's Law where "number of transistors on integrated circuits doubles approximately every two years" or possess smaller volumes, and less mass due to increased computing capability.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Results	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Key Performance Parameter (KPP)	Quantifiable	High	Yes	Yes	Yes

1. This parameter includes any and all project objectives.
2. The KPPs provide significant and relevant data about the project and its intended functional objectives.
3. This parameter provides the description in sufficient detail to compare it against similar technology projects.
4. This parameter also provides technical details such that branching applications may be understood.
5. When adequate data is provided, technologies with similar objectives may be compared by their respective schedule and cost.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Results	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Level of Effort	Quantifiable	High	No	Yes	Yes

1. This parameter includes manpower estimate for NASA but does not capture the cost of contractors, universities, students, etc.
2. A consideration should be made to add the capture the contracting costs in WYEs.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Results	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Cost	Quantifiable	High	Yes	Yes	Yes

1. This parameter includes the total cost (actual).
2. It is suggested that the cost per year be obtained and identified with the respective year.
3. The cost that should be identified is the cost in the management information

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Results	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Schedule	Quantifiable	High	Yes	Yes	Yes

1. This parameter includes the total duration (actual).
2. It is suggested that the total duration be identified by beginning and end dates.
3. The duration that should be identified is the time in the management information system, i.e. SAP or by official execution documents, i.e. traceable and input to the TechPort.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Development Metrics	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Technology Readiness Level (TRL)	Qualitative	High	Yes	Yes	Yes

1. This parameter includes the Technology Readiness Level as it is submitted by the Technology Manager, PI, PM or Technical Paper.
2. It is suggested that the TRL for a technology be assessed by a unbiased referee.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Development Metrics	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Research and Development Degree of Difficulty ($R\&D^3$)	Qualitative	Low	Yes	Yes	TBD

1. This parameter was difficult to administer.
2. The use of this parameter in this research was impeded by subjectivity.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Development Metrics	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Advancement Degree of Difficulty (AD^2)	Qualitative	Low	Yes	Yes	TBD

1. This parameter was difficult to administer.
2. The use of this parameter in this research was impeded by its subjectivity.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Execution	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Funding Source(s)	Qualitative	High	Yes	Yes	Yes

1. Comments from Technology Managers revealed that certain funding sources such IRAD programs do not provide enough time in the funding program to fully accomplish the Technology project efforts.
2. NASA undergoes a mix of funding programs, i.e. ETDP to GCPDO, etc. and the funding sources help to identify tracking of the technology and for branching of the technology.
3. Tracking technologies from lower TRL to higher TRL, or from incubation to mission level or cessation, is an imperative for NASA technology infusion.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Execution	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Organization(s) Involved	Qualitative	High	No	No	Yes

1. Identification of organizations involved helps to identify tracking of the technology and for branching of the technology.
2. The identification of organizations and points of contact is an imperative for tracking technology.
3. There could be a schedule or driver if a certain organization is identified with the Technology.
4. The parameter is included in TechPort.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Execution	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Facilities and Infrastructure	Quantifiable	High	Yes	Yes	Yes

1. Identification of the facilities or infrastructure goes directly to the schedule and cost driver of a technology.
2. The use of aircraft for testing was expected to be a large expenditure however it was not documented.
3. Some laboratories were noted in the literature to be specialized and there should have been a cost associated with these labs.
4. Certain University test facilities by were noted in discussion with Technology Managers to severely impact the delivery date of a technology project. These types of changed conditions would be noted in project administration records and should be identified.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Project Execution	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Team Experience	Quantifiable	High	Yes	Yes	Yes

1. Identification of the team structure goes directly to the schedule and cost driver of a technology.
2. The team structure was not well documented in any of the data sources.
3. The team makeup would be noted in project administration records and should be identified.

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Programmatic Factors	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Estimates vs. Actuals	Quantifiable	High	Yes	Yes	No

1. This parameter is recommend for elimination as all cost data collection in the future must be based on <u>actuals</u> and <u>traceable</u> data.
2. Estimates should be replaced with actual data acquired from the project management information system (SAP) with actual costs broken down.
3. A qualification to this cost data is that funding dollars should be broken down by yearly expenditures if possible and the funding year cost date be identified

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Programmatic Factors	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Budget Constraints and Disruptions	Qualitative	Low	Yes	Yes	No

1. This parameter is recommend for elimination as a single parameter and included with Unplanned Events.
2. Project managers do not conclude that budget constraints or disruptions in budgeting will impact the project.
3. Budget constraints or disruptions are difficult to use as a qualification.
4. This parameter would or should be included in the "unplanned event"

Schedule/Cost driver: a parameter that tends to increase or decrease schedule/cost or is highly correlated with schedule/cost

To qualify as a cost driver, a parameter must be a significant predictor of schedule/cost at least in the statistical sense

Programmatic Factors	Metric Attribute	Rank Ease of Administration Low, Med. High	Schedule Driver	Cost Driver	Recommended for Use in Future Data Collection
Unplanned Events	Qualitative	High	Yes	Yes	Yes

1. This parameter includes any and all events significant to the capture of any or all impacts to the project such as change orders, requirements change, or unforeseen conditions.
2. It is suggested that this parameter be changed to read "significant events".

APPENDIX G

Technology Cost and Schedule Estimating (TCASE) Tool

The tool is available from the Cost Analysis Division.

APPENDIX H

User Manual
Technology Cost and Schedule Estimating (TCASE) Tool

User Manual

TCASE

Technology Cost and Schedule Estimating

Beta Version

Document Revision 0.3

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Developed by:

SpaceWorks Software
A Division of SpaceWorks Enterprises, Inc. (SEI)

Funded by:

NASA Cost Analysis Division (CAD) and Game Changing Development (GCD) Program Office

User Manual

Contents

TCASE: *Technology Cost and Schedule Estimation*

Introduction

NASA and SpaceWorks have identified a need within the cost and schedule estimating community to rapidly assess the cost and schedule associated with maturing technologies along the Technology Readiness Level (TRL) scale. In response to this need, SpaceWorks has developed a Microsoft Excel® based software application called the Technology Cost and Schedule Estimation (TCASE) tool.

TCASE generates anticipated ranges of cost and schedule duration for a technology development project by drawing analogies to historical and current project. Data for historical and current projects is stored in an accompanying database. The tool is specifically designed to examine technologies in the range of TRL 2 through TRL 6.

At the end of this first year of research and development (September 2013), a prototype version of TCASE will be delivered to our research sponsors for testing and evaluation. The long-term goal of this research project is position TCASE as an everyday tool used by the NASA cost estimating and technology assessment communities.

List of TCASE Worksheets

The TCASE Excel® workbook contains several worksheets that the user should become familiar with. The content and function of each is explained here.

Worksheet Name	Description
Front End	The primary point of interaction with the TCASE tool. Enter search criteria, perform project analogy searches, view statistical results, and examine the top analogies.
Analogy Manager	View all analogy results returned by a search. Turn individual analogies ON or OFF as desired. View additional detailed information about each analogy result.
Data Viewer	View detailed information for a single analogy result / technology project record. Display is optimized for human viewing, as opposed to Database sheet (see below) which is optimized for software performance.
Data Importer	Import Technology Project Data Collection Sheets into the TCASE database.
Data Exporter	Export data records from the TCASE database to the Technology Project Data Collection Sheet format.
Database	Collection of over 1,700 historical technology development project data records. Analogous projects are drawn from this database when user executes a search.
Similarity Matrices	User-defined matrices define relative similarity between different TRLs and between different System Hierarchy levels. Required for proper implementation of analogy matching algorithm.

Front End Worksheet

The Front End worksheet serves as the basic interface with the TCASE tool. The sheet is neatly divided into 3 sections: Search Criteria, Statistical Results, and Top Analogies. A screenshot can be found in Figure 2 on the following page.

Search Criteria

TCASE offers tremendous flexibility in the use of exact match filters and/or weighted search terms to enable you to obtain the most desirable set of analogy results. There are a few basic guidelines to keep in mind when inputting search criteria:

- It is not necessary to fill out all of the Search Criteria search terms – you may use as many or as few as you like. As an extreme example, executing a search with no search terms will simply return the entire analogy database!
- To enter multiple search terms in a single field, simply separate each with a space. Multiple terms will be processed as a Boolean OR search (e.g. a Description Keywords search for HYDROGEN ROCKET will identify projects that contain HYDROGEN and/or ROCKET in the description field).
- The Exact Match parameter can be set to either yes or no. If set to yes, then that particular search term will be treated as a filter, meaning that any project in the database that does not contain that search term in the specified field will not be returned as a viable result.
- The Weighting parameter can be used to establish the relative importance of each search term (e.g. assigning a weighting = 1.0 for Title Keywords and a weighting of 2.0 for Primary TA would indicate that matching the Primary TA search term is twice as important as matching the Title Keywords).
- The 2 parameters listed under Search Settings (Minimum Score for Analogy Matching and Maximum Number of Analogies in Results) are optional parameters that can be used to limit the number of results returned by a particular search. Lowering the minimum score or raising the maximum number of analogies will increase the number of results returned, and vice versa.

Statistical Results

The Statistical Results section will display summary statistics and graphical outputs based on the data returned by your most recent search. These results constitute some of the most significant outputs of the TCASE tool, so we'll take a moment to review them in detail here:

- Summary statistics can be found at the top of the Statistical Results section. These statistics are presented in 2 columns: 1 for cost and 1 for schedule. The count statistic indicates the number of analogies returned by your search that contain data for that metric (data for cost and/or data for schedule duration). Some records in the database may include cost data but not schedule data, or vice versa – thus, the 2 counts may be different numbers! Below the count statistic are some familiar measures of center and spread, including $25^{th}/75^{th}$ percentile values, median value, mean value, maximum, and minimum. Finally, a box plot (aka "box-and-whiskers") is provided for each column. If you are unfamiliar with the box plot format, please refer to Figure 1 on the following page.

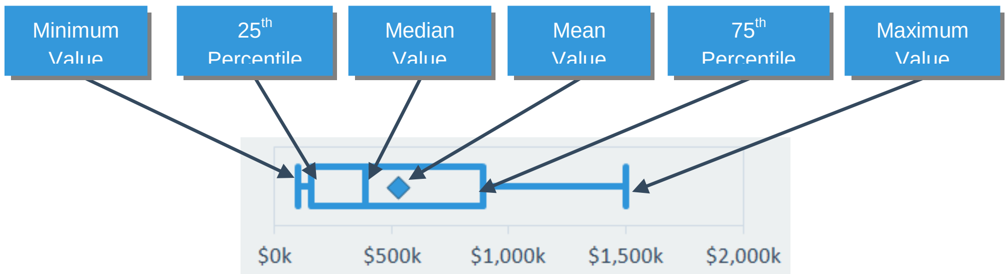


Figure 1. Definition of box plot as used in the TCASE tool.

- Below the summary statistics, you will find several plots in the Analogy Breakdown section. These plots are intended to provide some contextual information about the analogy results returned by your search. At a glance you can see the prevalence of various Lead NASA Centers, System Hierarchy Levels, and Project Start Years within your results set.

Top Analogies

After a database search has been executed, the resulting analogous project results will be displayed in 2 locations in TCASE: (1) the Top Analogies section of the Front End, and (2) the Analogy Manager worksheet. The purpose of the Top Analogies sections is simply to give the user an overview, in list format, of the highest ranking analogous projects from the most recent search. Up to 50 of the highest ranking results can be displayed here. A comprehensive and more detailed list of the analogy results can be found on the Analogy Manager worksheet.

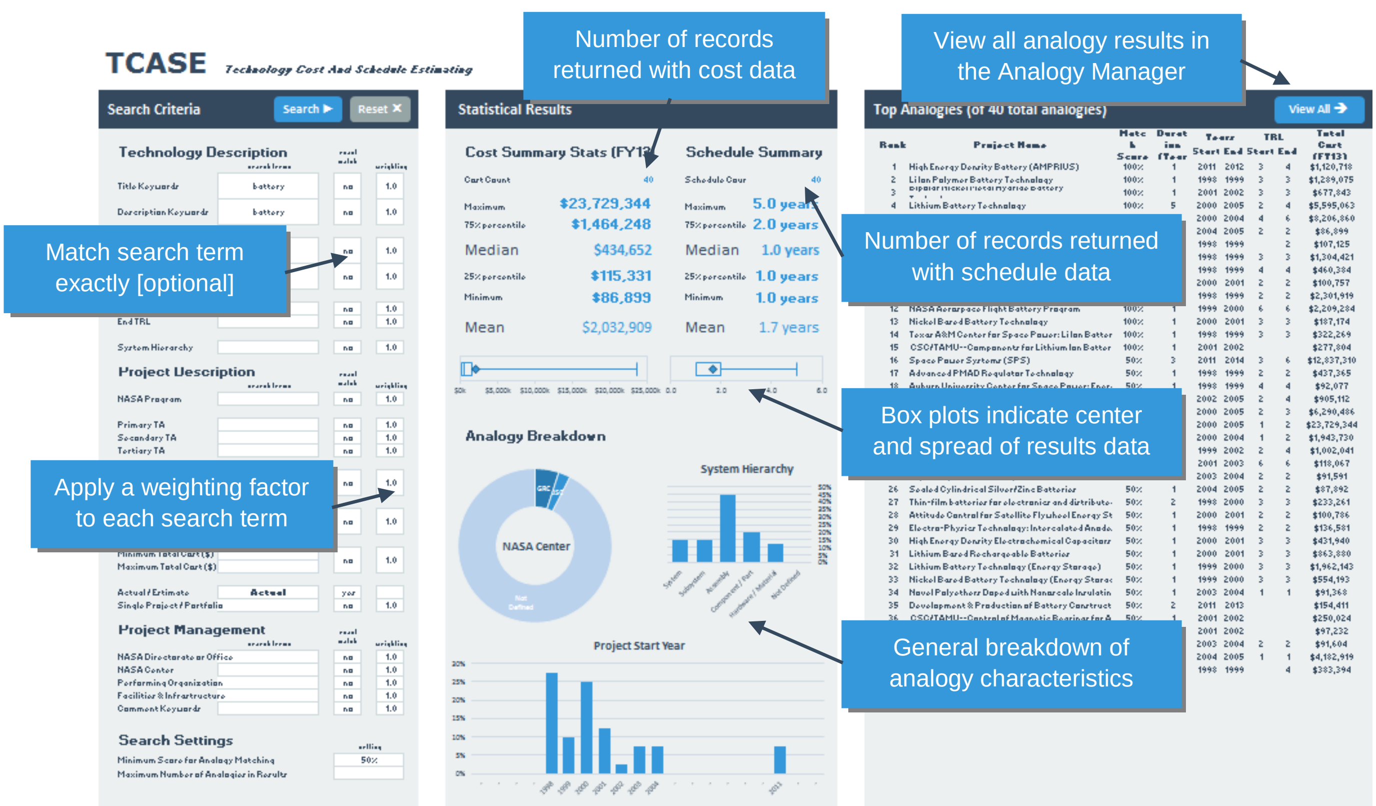
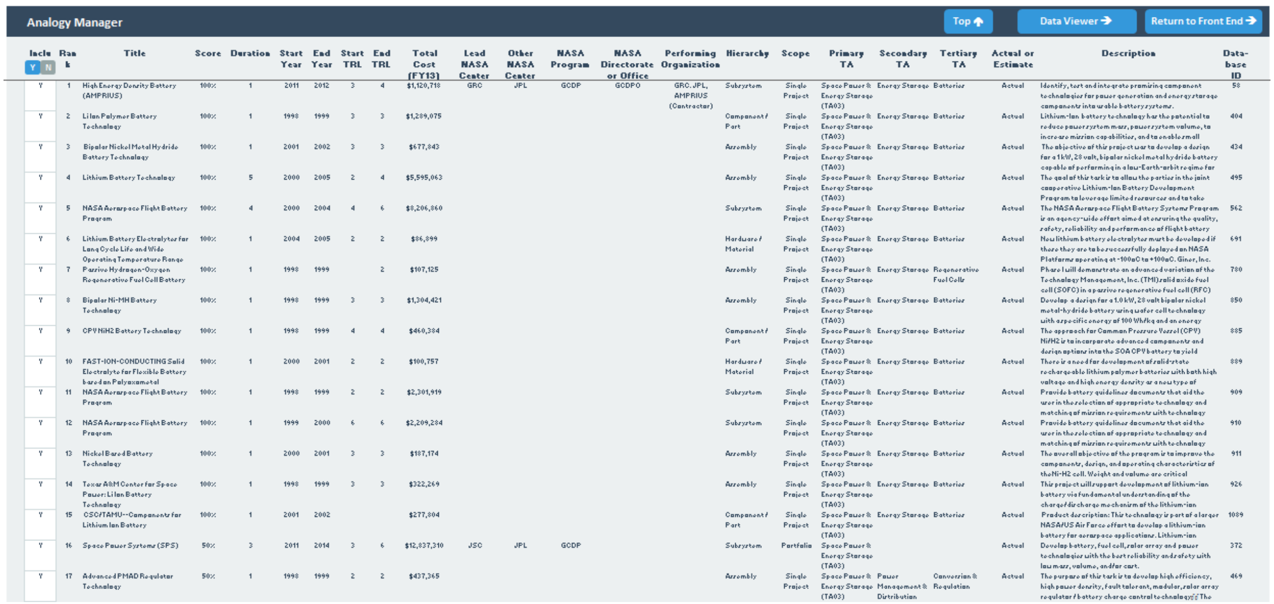


Figure 2. TCASE Front End Worksheet.

Analogy Manager Worksheet

The Analogy Manager worksheet is a dynamic sheet containing a list of *all* analogous projects returned by the most recent user search. In some ways, the Analogy Manager is similar in function to a results webpage on Google or Bing. Whereas the Front End worksheet displays summary information such as statistics and up to 50 of the top analogy results, the Analogy Manager displays a simple list of *all* technology project analogies that met the user's search criteria. A screenshot of this worksheet is shown below in Figure 3.



Include (Y / N)	Rank	Title	Score	Duration	Start Year	End Year	Start TRL	End TRL	Total Cost (FY13)	Lead NASA Center	Other NASA Center	NASA Program	NASA Directorate or Office	Performing Organization	Hierarchy	Scope	Primary TA	Secondary TA	Tertiary TA	Actual or Estimate	Description	Database ID
Y	1	High Energy Density Battery (AMPRIUS)	100%	1	2011	2012	3	4	$1,120,718	GRC	JPL	GCDP	GCDPO	GRC, JPL, AMPRIUS (Contractor)	Subsystem	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	Identify, test and integrate promising component technologies for power generation and energy storage components into usable battery systems.	58
Y	2	Li Ion Polymer Battery Technology	100%	1	1998	1999	3	3	$1,289,075						Component / Part	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	Lithium-Ion battery technology has the potential to reduce power system mass, power system volume, to increase mission capabilities, and to enable small	404
Y	3	Bipolar Nickel Metal Hydride Battery Technology	100%	1	2001	2002	3	3	$677,843						Assembly	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	The objective of this project was to develop a design for a 1 kW, 28 volt, bipolar nickel metal hydride battery capable of performing in a low-Earth-orbit regime for	434
Y	4	Lithium Battery Technology	100%	5	2000	2005	2	4	$5,595,063						Assembly	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	The goal of this task is to allow the parties in the joint cooperative Lithium-Ion Battery Development Program to leverage limited resources and to take	495
Y	5	NASA Aerospace Flight Battery Program	100%	4	2000	2004	4	6	$8,206,860						Subsystem	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	The NASA Aerospace Flight Battery Systems Program is an agency-wide effort aimed at ensuring the quality, safety, reliability and performance of flight battery	562
Y	6	Lithium Battery Electrolytes for Long Cycle Life and Wide Operating Temperature Range	100%	1	2004	2005	2	2	$86,899						Hardware / Material	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	New lithium battery electrolytes must be developed if there they are to be successfully deployed on NASA Platforms operating at -100oC to +100oC. Giner, Inc.	691
Y	7	Passive Hydrogen-Oxygen Regenerative Fuel Cell Battery	100%	1	1998	1999		2	$107,125						Assembly	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Regenerative Fuel Cells	Actual	Phase I will demonstrate an advanced variation of the Technology Management, Inc. (TMI) solid oxide fuel cell (SOFC) in a passive regenerative fuel cell (RFC)	780
Y	8	Bipolar Ni-MH Battery Technology	100%	1	1998	1999	3	3	$1,304,421						Assembly	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	Develop a design for a 1.0 kW, 28 volt bipolar nickel metal-hydride battery using wafer cell technology with a specific energy of 100 Wh/kg and an energy	850
Y	9	CPV NiH2 Battery Technology	100%	1	1998	1999	4	4	$460,384						Component / Part	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	The approach for Common Pressure Vessel (CPV) Ni/H2 is to incorporate advanced components and design options into the SOA CPV battery to yield	885
Y	10	FAST-ION-CONDUCTING Solid Electrolyte for Flexible Battery based on Polyoxometal	100%	1	2000	2001	2	2	$100,757						Hardware / Material	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	There is a need for development of solid-state rechargeable lithium polymer batteries with both high voltage and high energy density as a new type of	889
Y	11	NASA Aerospace Flight Battery Program	100%	1	1998	1999	2	2	$2,301,919						Subsystem	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	Provide battery guidelines documents that aid the user in the selection of appropriate technology and matching of mission requirements with technology	909
Y	12	NASA Aerospace Flight Battery Program	100%	1	1999	2000	6	6	$2,209,284						Subsystem	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	Provide battery guidelines documents that aid the user in the selection of appropriate technology and matching of mission requirements with technology	910
Y	13	Nickel Based Battery Technology	100%	1	2000	2001	3	3	$187,174						Assembly	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	The overall objective of the program is to improve the components, design, and operating characteristics of the Ni-H2 cell. Weight and volume are critical	911
Y	14	Texas A&M Center for Space Power: Li Ion Battery Technology	100%	1	1998	1999	3	3	$322,269						Assembly	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	This project will support development of lithium-ion battery via fundamental understanding of the charge/discharge mechanism of the lithium-ion	926
Y	15	CSC/TAMU--Components for Lithium Ion Battery	100%	1	2001	2002			$277,804						Component / Part	Single Project	Space Power & Energy Storage (TA03)	Energy Storage	Batteries	Actual	Product description: This technology is part of a larger NASA/US Air Force effort to develop a lithium-ion battery for aerospace applications. Lithium-ion	1089
Y	16	Space Power Systems (SPS)	50%	3	2011	2014	3	6	$12,837,310	JSC	JPL	GCDP			Subsystem	Portfolio	Space Power & Energy Storage (TA03)			Actual	Develop battery, fuel cell, solar array and power technologies with the best reliability and safety with low mass, volume, and/or cost.	372
Y	17	Advanced PMAD Regulator Technology	50%	1	1998	1999	2	2	$437,365						Assembly	Single Project	Space Power & Energy Storage (TA03)	Power Management & Distribution	Conversion & Regulation	Actual	The purpose of this task is to develop high efficiency, high power density, fault tolerant, modular, solar array regulator / battery charge control technology. The	469

Figure 3. TCASE Analogy Manger Worksheet.

In addition to containing a comprehensive list of results, the Analogy Manager worksheet includes a feature to include or exclude individual analogy results from the statistical calculations on the Front End sheet. In other words, if the user discovers one or more analogy results that he or she finds undesirable or inappropriate, these offending results may be omitted by selecting "N" (i.e. "No") in the column labeled "Include". The Summary Statistics section will instantly and automatically reflect changes due to any such data exclusions.

Data Viewer Worksheet

The Data Viewer worksheet offers a user friendly way to view the contents of a particular technology project data record from the database. The sheet contains a single input cell labeled "Enter Database ID". Simply enter the Database ID corresponding to the project record in question, and all data from that record will be displayed in a clearly labeled and organized table. A screenshot of the Data Viewer is provided in Figure 4 on the following page.

<u>**Note**</u>: The Data Viewer is a read-only utility and is not the appropriate place to attempt to edit a database record. The Database worksheet is the master location for all project data records.

Figure 4. TCASE Data Viewer Worksheet.

Data Importer Worksheet

From time to time it will be necessary to add new technology project data to the TCASE database. The Data Importer worksheet is designed to make this task much more efficient than manual data entry. The current version of TCASE is only capable of automatically importing data from specially formatted Technology Project Data Collection Sheets. Future versions of this application may be capable of interfacing with other input file formats. A screenshot of the Data Importer is provided below in Figure 5.

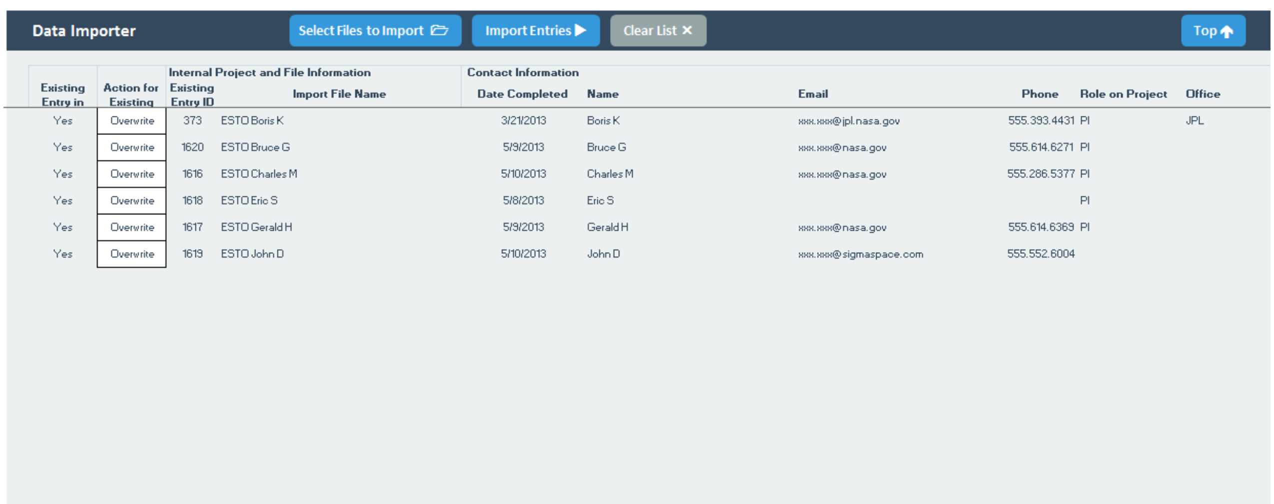


Figure 5. TCASE Data Importer Worksheet.

To use the Data Importer, start by clicking the 

button. You should see a standard file browser interface. Navigate to the location of the Technology Project Data Collection Sheet or Sheets that you wish to import (you may select multiple files in the browser by holding the CTRL key while clicking) and then click Open. You will now see one or more rows of data appear in the Data Importer – 1 row corresponding with each imported project.

TCASE will display a warning message if the name of any imported project appears to match the name of a project already in the database. Examine the column titled “Existing Entry in Database” to identify which project(s) may already exist. For each affected project, you may choose to either overwrite the existing data record in the database or create a new entry.

Once you are satisfied with the project data to be imported, click the 

button to make the specified changes and/or additions to the TCASE database.

Data Exporter Worksheet

The Data Exporter worksheet (see Figure 6) is designed to export one or more project data records from the TCASE database to a new Technology Project Data Collection Sheet. To begin using the Data Exporter, first open the Database worksheet in TCASE. To the left of each record in the database you will see a column entitled “Export Y/N”. Simply identify the project record(s) you wish to export and change the value in the “Export” column to Y for each.

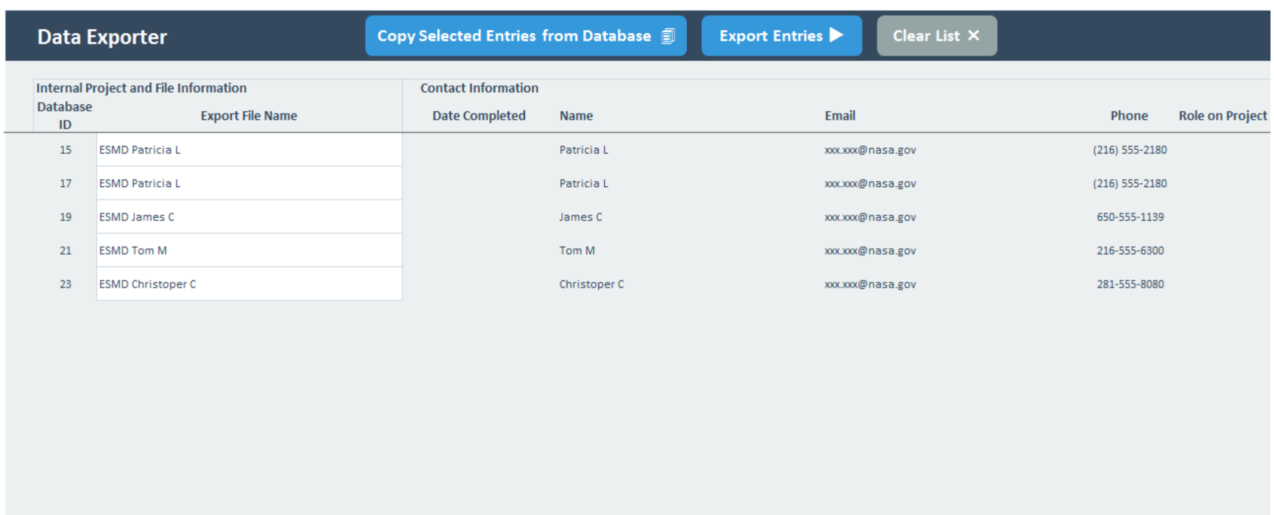


Figure 6. TCASE Data Exporter Worksheet.

Once all desired projects have been identified and marked with a Y, open the Data Exporter worksheet and click the 

button. Doing so will copy each marked database record into the Data Exporter as a new row in the list of projects. Take a moment to review the “Export File Name” for each project.

These have been created automatically, but you are free to change the file name at your discretion. Once you are satisfied with the list of projects to export and the export file names, simply click the **Export Entries ▶** button and a set of new Technology Project Data Collection Sheets will be created. Newly created Technology Project Data Collection Sheets will be saved in a subfolder within the directory where the TCASE Excel workbook resides. One sheet will be created for each technology project that you have exported.

Database Worksheet

As the name suggests, the Database worksheet is the core database that supports all other TCASE functionality. Out of the box, so to speak, the TCASE database contains more than 1,700 rows of data (aka “records” or “entries”) each of which includes up to 184 different data fields. The number of data records can be expanded – TCASE includes a Data Importer utility that allows a user to add new data records from Technology Project Data Collection Sheets. If you take a moment to browse the Database worksheet, you will notice that many data fields contain no data – perhaps half of all data fields in the database are empty. In some cases the empty cells indicate that that data field was not required for that particular project, while in other cases it represents incomplete information available about the project. As the TCASE research project continues, one objective is to improve the overall data quality in the database. A screenshot of a small portion of the TCASE database is shown below in Figure 7.

Return to Front End ➔

Export	Internal			Project Description					
Y N	ID	Office	Organization	Project Title	NASA Program	Start Date	End Date	Start TRL	End TRL
N	0001	MXT	GRC	Fuel Cells - Primary Fuel Cell	ETDP, ETDD, GCD	10/1/2008	9/30/2013	3	5
N	0002		ARC/Mark Schwabacher	Autonomous Systems	GCDP	10/1/2011	9/30/2014	4	6
N	0003	Bldg 4201 / Room 222	MSFC - ZP30	Adjustable Grazing X-Ray Optics	GCDP	10/1/2012	9/30/2016	2	4
N	0004	DSI	GRC	Advanced Composites Technologies, 3.0 - Structural Concepts Deve	ETDP	10/1/2008	9/30/2010	3	4
N	0005	Research Directorate	LaRC	Lightweight Structures - 3.4 Lightweight Window Materials	ETDP	10/1/2009	9/30/2010	3	4
N	0006	5490	GSFC	Optically Modulated Miniature Magnetometer (OMMM) (NNG11VMSBIR Contract # NNG11\		9/30/2011	3/31/2013	2	5
N	0007	LARC-A3	Game Changining Developmer	Space Synthetic Biology (SSB)	GCDP	10/1/2011	9/30/2014	2	5
N	0008		GRC	Passive PEM Fuel Cell Power System	ESMD	6/27/1905	7/2/1905	4	6
N	0009		NASA Glenn	Advanced Rechargeable Lithium-ion Battery (Advanced lithium)	ESMD	6/27/1905	7/1/1905	3	6
N	0010		NASA Glenn	Advanced Lithium Primary CFx Battery Technology	ESMD	6/27/1905	7/1/1905	4	6
N	0011		NASA Glenn Research Center	Compact/Deployable Thin-Film Solar Arrays	ESMD	6/27/1905	7/2/1905	4	6
N	0012		GRC	High Efficiency, Thin-Film, Flexible, Poly-Crystalline III-V Multi-Jun	ESMD	6/27/1905	7/4/1905	2	6
N	0013		GRC	Lunar Outpost 4.0 Power:Lunar Surface Reactor Power System	ESMD	6/27/1905	7/6/1905	2	6
N	0014		Glenn Research Center	Modular Power Distribution Unit with Universal Source Regulatior	ESMD	6/27/1905	7/1/1905	3	6
N	0015		GRC	PEM Fuel Cell System for AEVA Applications	ESMD	6/27/1905	7/1/1905	4	6
N	0016		NASA Glenn Research Center	Solar Array Space Environmental Effects and Mitigation Activities f	ESMD	6/27/1905	7/1/1905	3	6
N	0017		GRC	Solid Oxide Fuel Cell (SOFC) System for AEVA Applications	ESMD	6/27/1905	7/4/1905	3	6
N	0018		NASA Glenn Research Center	Wide Temperature Power Electronic Materials, Components and Ci	ESMD	6/28/1905	7/4/1905	3	6
N	0019		ARC	Robotics for Mars and Lunar Habitation	ESMD	6/29/1905	7/5/1905	4	6
N	0020		JPL	Robotics for Mobile Lunar and Mars Exploration	ESMD	6/26/1905	7/1/1905	4	6
N	0021		NASA Glenn	Advanced Rechargeable Lithium-ion Battery (Liquid electrolyte)	ESMD	6/27/1905	7/1/1905	3	6
N	0022		GRC	Radioisotope Thermophotovoltaic (RTPV) Energy Conversion	ESMD	6/27/1905	7/2/1905	3	6
N	0023		JSC	Robotics for In-Space Operations	ESMD	6/28/1905	7/3/1905	4	6
N	0024		NASA Glenn Research Center	Aerospace Flywheel Technology Project	ESMD	6/27/1905	7/1/1905	4	6
N	0025		NASA Glenn Research Center	Solar Array Designs/Mechanisms Using SOA Cell Technology for Lu	ESMD	6/27/1905	6/30/1905	3	6

Figure 7. TCASE Database Worksheet.

Practically speaking, a typical user will not have much need to access the Database worksheet directly. All analysis functions take place on the Front End and Analogy Manager worksheets. A more advanced user may wish to export data from the TCASE database using the Data Exporter described in the previous section. However, as we have seen even the Data Exporter requires only minimal user interaction with the database.

It is possible to edit the TCASE database directly on the Database worksheet, although **such edits must be conducted with great care and should only be attempted by an experienced user with a backup file**. For example, it is possible to delete an unwanted row from the TCASE database by clicking on the row number and using Excel’s “Delete” function. It is also possible, although somewhat riskier, to insert a new row and manually fill it with valid data for a new project record.

Similarity Matrices Worksheet

The Similarity Matrices worksheet contains 2 matrices used during the TCASE analogy matching process. These matrices are used to determine a degree of similarity between levels in the Technology Readiness Level (TRL) and System Hierarchy parameters.

The default similarity matrix for TRL is show in Figure 8 below. Interpreting the matrix is fairly straightforward. If for example we were interested in determining the similarity score between a TRL of 4 and a TRL of 7, we would look for the intersection of row 4 and column 7 and find a value of 0.2. Values along the diagonal of the matrix are equal to 1.0 since they occur at the intersection of identical values. The similarity matrices are user-editable, if desired.

TRL

	1	2	3	4	5	6	7	8	9
1	1.0	0.8	0.5	0.2	0.0	0.0	0.0	0.0	0.0
2	0.8	1.0	0.8	0.5	0.2	0.0	0.0	0.0	0.0
3	0.5	0.8	1.0	0.8	0.5	0.2	0.0	0.0	0.0
4	0.2	0.5	0.8	1.0	0.8	0.5	0.2	0.0	0.0
5	0.0	0.2	0.5	0.8	1.0	0.8	0.5	0.2	0.0
6	0.0	0.0	0.2	0.5	0.8	1.0	0.8	0.5	0.2
7	0.0	0.0	0.0	0.2	0.5	0.8	1.0	0.8	0.5
8	0.0	0.0	0.0	0.0	0.2	0.5	0.8	1.0	0.8
9	0.0	0.0	0.0	0.0	0.0	0.2	0.5	0.8	1.0

Figure 8. TCASE Similarity Matrix for TRL.

Frequently Asked Questions

- **What is the origin of the technology development cost and schedule data in the TCASE database?**
  The TCASE Database includes over 1,700 records from more than 60 sources. These sources include historical databases such as NTIS and MATCH, project records such as GCD and ETDP, SBIR records, and data solicited from technology managers during this current research period (2012-2013). More information can be found in Appendix B of this manual.

- **Has the cost data in the TCASE database been normalized?**
  Yes. All costs in the TCASE database have been normalized to FY2013 dollars.

- **Does the TCASE tool utilize cost estimating relationships (CERs)?**
  No, not at this time. TCASE uses an analogy-based approach to provide a likely range of cost and schedule for a particular type of technology development project. Future work plans call for a transition to CER-based parametric estimation methods if and when sufficient data is available to support that approach.

- **My search returned more than 50 analogous projects, but only the top 50 are shown in the Top Analogies section. Where can I view the full results?**
  Select the Analogy Manager worksheet to view the full list of analogous projects.

- **My search returned several projects that I believe are poor analogies for my estimating scenario. How can I improve the results?**
  You have several options to refine your search. First, you might revise your search criteria, setting one or more of your search terms to "Exact Match" in order to impose a hard filter. Alternatively, you may view the Analogy Manager worksheet where you have the option to manually include or exclude each analogous project returned by TCASE. With a few clicks you can toss out one or more analogous projects that you feel are improperly skewing your results. The effects of any changes made on the Analogy Manager tab will be reflected in the results on the Front End as soon as you return to that worksheet.

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Appendix A - Running a Simple Search

1. Open the MS Excel® workbook entitled **TCASE Analogy Tool Beta v0.50.xlsm** and access the *Front End* worksheet.

2. Adjust parameters in the Search Criteria section as desired. Some parameters accept text inputs, others accept numerical inputs, and some are set via a pull-down menu. Relative weightings may be applied to your parameters to reflect their importance in your search.

3. Click the [Search ▶] button to run the TCASE search algorithm and generate analogous project results. *

4. Review the outcome of your search in the Statistical Outputs section and the Top Analogies section of the *Front End* worksheet.

5. To refine your search, simply edit the parameters in the Search Criteria section and click the [Search ▶] button again. If you would like to start a completely new search, click the [Reset] button and return to step **2** above.

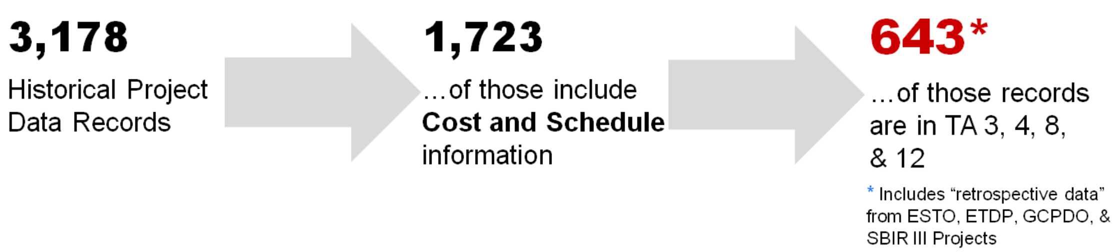
* <u>Important Notes</u>: The TCASE tool utilizes VBA macros during normal operation. Macros must be enabled in the user's local copy of Excel. Excel's Automatic Calculation setting must also be turned on.

Appendix B – Sources of Data Used in TCASE

Early in the TCASE research project, the team identified more than 70 sources of historical technology project data. These sources included broad databases such as NTIS and MATCH, and also numerous individual project records from programs such as Game Changing Development (GCD) and the Exploration Technology Development Program (ETDP), to name a few. The table below lists some of the largest sources of technology project data.

Short Name	Description	Year	Number of Entries
ETDP	NASA Exploration Technology Development Program	2012	42
ESTO	NASA Earth Science Technology Office	2012	138
SBIR	Current NASA SBIR Technologies	2012	51
GCD	Game Changing Development Technology Projects	2012	35
ESMD	NASA Exploration Systems Mission Directorate ESAS Technologies	2005	304
Tech Tool Box	ATLAS (Advanced Technology Lifecycle Analysis System)	2002	6
Ext Tech Data	Tauri Group research into External Gov Technology Tech Maturation data	2012	28
Cx ETDP	Constellation Program Technology Portfolio	2007	19
NTID	NASA Tech Inventory Database	2004	991
Hist SBIR STTR	Historical SBIR and STTR data	2012	1191
RLV Tech DB	NASA RLV Technology Database	1993	64
HEOMD TechDev Team	Estimates of HEOMD needed technology developments	2012	78
ETDP from MATCH	Mapping Applicable Technology To Exploration Challenges	2007	21
External from MATCH	Mapping Applicable Technology To Exploration Challenges	2007	192
JSS TBCC	NASA/Air Force Joint Systems Study TBCC Technologies	2010	18

Not every technology project data record contained the critical cost and schedule duration values needed for use in TCASE. As indicated in the figure below, about half of the total records collected were suitable for use in TCASE (1,723 out of 3,178). Thus, the database embedded in TCASE contains records for 1,723 historical and current technology development projects.



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14. ABSTRACT
NASA is investing in new technologies that include 14 primary technology roadmap areas, and aeronautics. Understanding the cost for research and development of these technologies and the time it takes to increase the maturity of the technology is important to the support of the ongoing and future NASA missions. Overall, technology estimating may help provide guidance to technology investment strategies to help improve evaluation of technology affordability, and aid in decision support. The research provides a summary of the framework development of a Technology Estimating process where four technology roadmap areas were selected to be studied. The framework includes definition of terms, discussion for narrowing the focus from 14 NASA Technology Roadmap areas to four, and further refinement to include technologies, TRL range of 2 to 6. Included in this paper is a discussion to address the evaluation of 20 unique technology parameters that were initially identified, evaluated and then subsequently reduced for use in characterizing these technologies. A discussion of data acquisition effort and criteria established for data quality are provided. The findings obtained during the research included gaps identified, and a description of a spreadsheet-based estimating tool initiated as a part of the Technology Estimating process.

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Affordability; Analysis; Cost; Decision support; Estimating; Schedules; TCASE; Technologies; Technology readiness level

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