# A Review of Technology Assessment Methods for Space Transportation Systems

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## Abstract

In the last decade, advances have been made in the development of quantitative technology assessment methods for use in selecting optimum technology portfolios that will enable future, large-scale space programs. Expert-based technology selection methods are being replaced with mathematically-rigorous approaches that use physics-based numerical simulation to determine technology impact sensitivities on a candidate space system. Multi-attribute utility theory is used to evaluate the top-level effect of a single technology or a combination of technologies across a set of figures of merit. These new quantitative methods can be run both deterministically and probabilistically. The latter approach has the added benefit of capturing the effects of technology performance uncertainty associated with speculative programs.

This paper reviews the development and history of technology assessment techniques that have been developed for or applied to next-generation space transportation systems. It is primarily a survey paper of past methods. Particular focus is placed on methods furthered by Georgia Tech's Space Systems Design Laboratory as well as application work performed by SpaceWorks Engineering, Inc. during the late 1990's and early 2000's. Methods reviewed include ATIMS, ATIES, TechSim, and TRIPS. Relationships between the approaches and comparisons to other technology assessment tools and methods are discussed.

## Introduction

In technological organizations, such as NASA, the U.S. Air Force, DARPA, and private aerospace industry, the job of the technology portfolio manager is demanding. The job requires the portfolio manager to select from a myriad of candidates, those technologies that will have the most positive long-term impact on the organization's mission. Budgets are invariably constrained, so not all technologies can be funded. Selecting the optimum mix of technologies that provide the highest return on investment is made more difficult by uncertainty in the candidate technology's cost and impact on the mission, interactions between combinations of technologies, political pressures to select one technology over another, and inherent risks associated with technology development. Investment decisions must be well-founded and justifiable to a number of stackholders in the overall organization. Mathematically rigorous technology assessment methods are needed to promote credibility and technical honesty in the process.

Systems engineers have responded this need by developing a number of technology assessment methods that can be advantageously applied to the technology portfolio manager's problem. Many of the methods have origins outside of aerospace (e.g operations research, business management), but have been adopted by aerospace engineers as useful methods. Other methods have been conceived and developed with a particular aerospace mission in mind.

This paper serves as a survey and historical review of technology assessment methods that have been applied to space transportation and space access missions. Particular emphasis will be placed on methods and tools that are most familiar to the author. These are ideas and applications from Georgia Tech's Space Systems Design Lab (SSDL) and SpaceWorks Engineering, Inc. (SEI) from roughly 1995 to 2005. The paper will cover both 'methods', essentially approaches, processes, ideas, and 'tools', those software codes and simulations that implement the methods to predict specific numerical results. A method may be described in text or graphical terms that outlines the process. A tool will consist of input files and control variables, an executable (often just Microsoft Excel®) and a set of numerical results.

## Terminology

Establishing a common lexicon has been one challenge for the industry, and the terminology may vary from organization to organization. Throughout this paper, the following terms and phrases will be used to describe technology assessment methods and tools.

Enabling Technology — An 'enabling' technology is one that is a prerequisite for the vehicle or component to exist as envisioned by its advocates. For example, a nuclear-thermal rocket vehicle requires a nuclear thermal rocket engine. That technology is not yet mature, so it is *enabling* for that concept. Similarly, scramjet-powered space access vehicles require maturation of scramjet engine technologies. Often then, a space transportation architecture, by virtue of the flight elements that comprise it, will be proposed with an associated list of enabling technologies that the technology manager is obligated to fund. Consideration of alternate enabling technologies is essentially consideration of alternate architecture approaches, and is a decision made by space systems architects. The technology portfolio manager does not typically have the luxury of changing his or her enabling technology set.

Enhancing Technology — Enhancing technologies are those optional technologies that can be overlaid on a proposed space architecture fro the purpose of improving its quantitative figures of merit (e.g. increased performance, increased reliability and safety, decreased cost). The general assumption made here is that a basic concept, with its prerequisite enabling technologies, can do a mission, but perhaps not most economically or reliably. *Enhancing* technologies can be overlaid to improve the likelihood of meeting mission goals. Enhancing technologies can represent large impacts to a single discipline or component of the architecture, or they may achieve a small improvement to many components of the architecture and achieve significant gains due to the positive interactions amongst the components. Many of the methods developed to date have focused on the selection of an optimal combination of enhancing technologies from a number of candidates.

k-factor — A numerical measure of the positive of negative impact of a technology on a VIF. k-factors may be deterministic or sampled from a probabilistic distribution. A typical k-factor for a propulsion system might be +10% on Isp, indicating that the application of the technology to the space transportation system is thought to improve Isp by 10%. For a given technology, a vector of perhaps 10 – 15 k-factors will be used to describe its impact on the system-level VIFs. Some k-factors may be positive, others may be negative (e.g. cost). Other organizations may refer to these impacts as technology performance metrics (TPMs) or technology technical performance metrics (TTPM). The Georgia Tech nomenclature is adopted here. Multiple k-factors can be applied to a VIF multiplicatively or additively.

n-factor — n-factors are numerical noise factors that affect the space system being simulated. n-factors are sampled from a probability distribution and represent uncontrollable uncertainties in the expected outcomes and may be the result of modeling uncertainties, incomplete knowledge of a phenomena, etc. For example, an analyst may chose to put an uncertainty distribution on the drag coefficient of a particular launch concept. Like k-factors, n-factors will influence the VIFs and ultimately affect the overall figures of merit for a system. However, they are always present in the simulation and are not optional overlays to the process.

VIF — VIFs, or vehicle influence factors, can be thought of as the disciplinary 'knobs' on a vehicle simulation. Changing a VIF will result in an increase or decrease in vehicle performance, cost, reliability, etc. For example, for space access vehicles a VIF might be the propellant tank weight per unit volume. With the baseline VIF value, the vehicle can achieve a certain payload. If a technology is applied, that technology will have a vector of k-factors that describe the trends it has on vehicle performance, cost, reliability, etc. Each k-factor will affect a corresponding VIF. A new materials technology might have a k-factor of -10% for the tank weight VIF. In a probabilistic simulation, n-factors also affect VIFs, even in the absence of enhancing technologies.

## Background

At NASA in the early to mid 1990's, the most common methods used to assess the impact of new technologies were expert-based approaches. These methods included Quality Function Deployment (QFD) and the Analytic Hierarchy Process (AHP). With both QFD and AHP, domain experts are gathered in a meeting room and technologies are systematically evaluated against various outcome criteria. The process requires each expert to judge the relative advantage of one technology over another. In AHP, for example, a question might be "Which technology is better at achieving lower costs, Tech A or Tech B?" The expert would then record a pairwise vote indicating which technology he or she thought was best, and by how much. Perhaps a value of "5" would be assigned, indicating a strong preference for Technology A. This process would be repeated for each technology until all the comparisons were recorded. If a group of experts are used to create the comparisons, then the facilitator may choose to have the group discuss the comparisons and reach consensus before the votes are recorded. Alternately, data can be collected from each expert individually and then post-processed to produce a mean score and a standard deviation. By applying a multi-attribute decision making technique (e.g. TOPSIS – the Technique for Order Preference by Similarity to the Ideal Solution), the facilitator can create a single weighted evaluation function from the individual figures of merit for each enhancing technology, and thereby rank them in order of most preferred to least preferred. AHP was commonly used by NASA technology programs. Much of the facilitation and data reduction was performed by Science Applications International Corporation (SAIC) in Huntsville, AL. The Space Propulsion Synergy Team (SPST) was also an advocate of expert-based technology assessment techniques such as QFD.

While manageable from a data collection and reduction perspective, expert-based approaches were deemed to be lacking in several areas. Foremost, the results produced were often indefensible to stakeholders that did not 'win' a pet technology project through the process. It is fair to say that the results of this process could be easily manipulated by biased experts (i.e. 'gaming' the process to achieve a desired outcome). Second, the experts are often not sufficiently knowledgeable to truly understand the magnitude of the expected impact of a technology on each of the metrics. Technology A may be thought to improve the reliability of a concept, but by how much? Is it significant or insignificant? Each expert enters his or her vote based on a rough perception of what the impact will be. A technology that has a small impact on a number of components of a system might be more important than a technology that has a large impact on one component, but this may be lost on experts whose experience is in one particular field or another. Also, expert-methods typically assess one technology at a time. The synergistic effects of multiple technologies that comprise an investment portfolio are too difficult to evaluate in this process. There are simply too many combinations. Finally, budgetary constraints are difficult to manage in an expert process. If the highest-ranking technology is unaffordable, is it fair to assume that the technology manager should go down the list until an affordable technology is found? It is equally plausible that a combination of technologies that fit within the budget will be more advantageous than the single, highest-ranking affordable technology.

With these shortcomings for its standard technology assessment process in mind, NASA's Advanced Space Transportation Program (ASTP) office approached Georgia Tech's Space Systems Design Lab (SSDL) in early 2000 for help in developing and applying a more rigorous, physics-based simulation for evaluating enhancing technologies for next-generation space transportation concepts. The method should rely on multidisciplinary simulation to produce unbiased, defensible impact scores for individual technologies as well as multi-technology portfolios. Uncertainties should be included in the simulation. Budget constraints should be explicitly considered, both in terms of annual and cumulative outlays. A new computing tool should be developed to apply the quantitative process repeatedly and automatically.

In the mid-1990's Georgia Tech's Aerospace Systems Design Lab (ASDL) had done some pioneering work in developing quantitative, simulation-based technology assessment methods for future commercial air transport concepts. Under funding from NASA Langley and ONR, ASDL developed the TIES process – Technology Identification, Evaluation, and Selection (Ref. 1). TIES is a multi-step process for identifying design requirements, technology needs, candidate technologies, then determining compatibilities between candidate technologies. The process proceeds to a simulation phase in which the impacts of technologies on the aircraft metrics are numerically predicted, then the results are post-processed using a multi-attribute decision method such as TOPSIS to rank the most significant technologies. The simulation phase of TIES is probabilistic, and depends on fast-acting physics-based simulations. Its developers typically rely on approximate meta-models such as response surface equations to predict the outcome of the application of a given technology. To build the response surface, an aircraft synthesis code (FLOPS) and life-cycle cost code (ALCCA) were coupled and the response surface was fitted off-line, before the TIES simulation was begun. The result was a simulation that was reasonable accurate, and fast enough to support thousands of simulations in a short period of time. TIES has been successfully applied to technology assessment problems in aircraft design, missile design, and naval systems design (Refs. 2 – 3).

At Georgia Tech's Center for Aerospace Systems Analysis, the question was posed, why couldn't a process like TIES be used to assess technologies for NASA's space transportation program? The answer laid primarily in the lack of an integrated space vehicle synthesis tool to serve as the numerical 'engine' for the process. Space launch systems are highly multidisciplinary. The propellant closure process is very non-linear. Many candidate space transportation concepts are revolutionary and unique, with no historical basic for deriving weights or costs. As a result, the conceptual space vehicle design community had never really developed a multidisciplinary synthesis tool like FLOPS. Rather, teams of disciplinary engineers, each with their preferred analysis tool, were used to design the candidate concepts. These distributed closure teams were slow and cumbersome compared to a fast-acting monolithic tool like FLOPS. However, at that time the team-oriented design approach was necessary to maintain accuracy of the synthesis results. Response surface approaches at the top-level (i.e. the space vehicle-level characteristics such as payload or gross weight) were deemed inadequate.

The author and graduate students in the SSDL conceived of a compromise solution for providing quantitative technology assessment and impact analysis. First, the TIES process itself would be streamlined and modified for the space vehicle design application. ATIES (Abbreviated Technology Identification, Evaluation, and Selection) was proposed to retain only those steps of the original process that were applicable. Second, a Microsoft Excel®-based vehicle simulation capability called a ROSETTA model was proposed to serve as the probabilistic analysis engine for the process for space vehicle designs. ROSETTA models (originally called RDS models) are very fast-acting simulations that use a combination of discipline-level response surfaces and actual, full fidelity disciplinary codes. ROSETTA models have been developed for space launch systems, in-space transfer vehicles, Mars transfer vehicles, and solar sail concepts.

In the summer of 2000, the combination of ATIES and ROSETTA were proposed to NASA ASTP (Advanced Space Transportation Program) as a viable method for replacing its current expert-based technology ranking process. Science Applications International Corporation (SAIC) in Huntsville, AL was selected as the prime contractor for the Integrated Technology Assessment Center (ITAC) – a multi-organization team of contractors, consultants, and academic institutions. As originally conceived, ITAC was to use the ATIES/ROSETTA process to evaluate a range of technologies and space concepts from various sources throughout the industry. Georgia Tech and SpaceWorks Engineering, Inc. (SEI) were involved in the center at its beginning, but left the organization after less than one year over financial issues, creative differences, and changes in project leadership. ITAC continued to operate for a few years before being terminated by NASA (Refs. 4 – 5).

After ITAC, Georgia Tech SSDL and SEI continued to work in the technology assessment field for NASA and Air Force programs. The remainder of this paper is a survey and review of methods and tools developed from 2000 to 2005.

## ATIES

Abbreviated Technology Identification, Evaluation, and Selection (ATIES) is a derivative of and a streamlining of the original and larger TIES process created by Mavris and Kirby. ATIES was developed by Charania (Ref. 6) in early 2000 as an appropriate subset of steps for space transportation. In the space transportation conceptual design community, the need and requirements are generally known to the designers (i.e. 20,000 lb of payload to orbit). Therefore the step related to characterizing the mission need and need for technologies was eliminated from the original process. Similarly, technology identification steps designed to gather information on technologies was omitted. The applicable technologies are also generally known. Other key steps of the process were retained – technology compatibility matrices, technology impact matrices, fast-acting probabilistic simulation, and post-processing via weighted combinations of figures of merit (FOMs). For the latter step, Georgia Tech generally employed TOPSIS. One significant step was added to the original TIES as an enhancement. As technology combinations are created (e.g. Tech A + Tech E + Tech F), an available budget filter is immediately applied that eliminates any combination that does not fit under annual or cumulative budgets. In our applications, this filter resulted in a significant decrease in numbers of portfolios that needed to be evaluated and this saved time and computational effort. A schematic of the steps of the ATIES process is shown in Figure 1. Other examples of its application can be found in References 7 and 8.

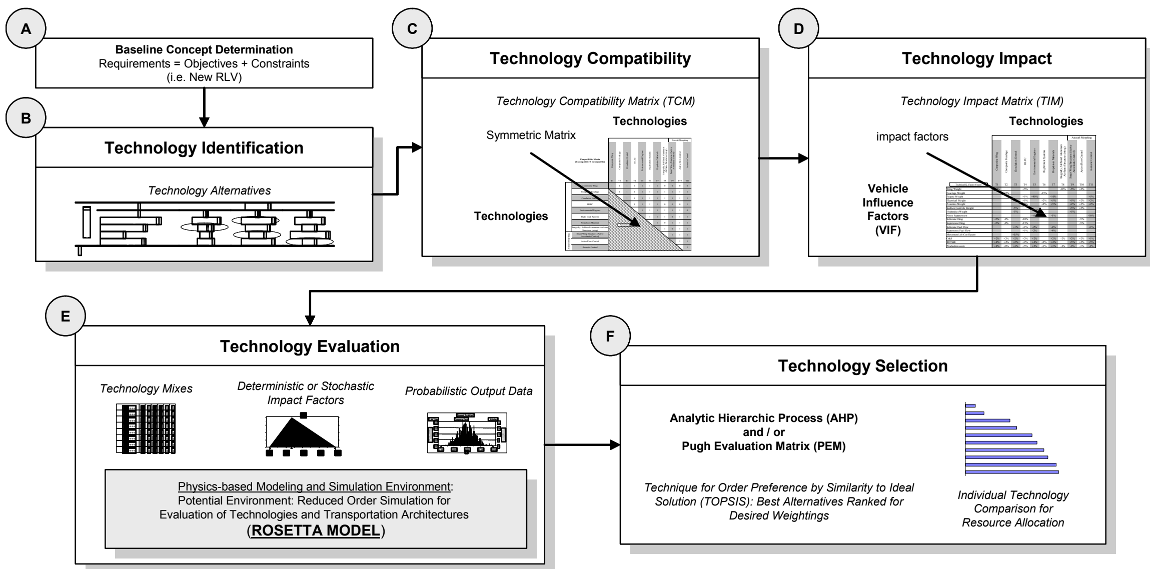


Fig. 1. Process flow for the ATIES process.

It is important to make the distinction that ATIES is a process and not a software tool. It is simply a set of steps on a flow chart, that when applied (even “manually”) to a space technology investment problem, will result in data that is useful to the decision-maker regarding the relative value of various technology portfolios. It does, however, depend on a physics-based simulation (box E). We chose to use a fast-acting ROSETTA model as the quantitative engine for our analyses. See the description of a ROSETTA model below.

## ATIMS

ATIMS (the ASTP Technology Investment Management System) was a software environment for implementing the ATIES process originally conceived in the spring of 2000 by the author with assistance from Mr. Eric Hyde of NASA's Marshall Space Flight Center. ATIMS was a control panel of sorts that was designed to assist the technology portfolio manager with interfacing the probabilistic analysis with the ROSETTA model numerical engine. In a comprehensive GUI, speedometer-type gauges were to allow the user to establish lower and upper bounds and most-likely values for triangular distributions on each k-factor. Further, the user would be allowed to choose from a series of ROSETTA models (then called RDS models) upon which to perform the technology analysis.

ATIMS was proposed as a core piece of the ITAC project. ATIMS was to be coded by SAIC personnel, using their experience in creating custom software code for NASA and the DoD. However, as the ITAC contract got underway, it became apparent that the resources necessary to fully implement such a tool would be more than the contract could afford. Simpler alternatives were available for executing the process and these were more typically employed. At Georgia Tech and SpaceWorks Engineering, the ATIES process was implemented using a series of spreadsheets for forming candidate technology portfolios and Decisioneering's Crystal Ball® Monte Carlo driver integrated directly with an Excel-based ROSETTA model. ATIMS development was abandoned in 2001.

SAIC subsequently developed the FASTPACT software environment as a simpler alternative to ATIMS. FASTPACT was built in Phoenix Integration's ModelCenter® framework and used separate disciplinary models to evaluate the impact of enhancing technologies on space transportation vehicles (Ref. 5). Each discipline of the multidisciplinary closure process is a component in ModelCenter® (typically an Excel component) and they are linked together to iterate toward a closed vehicle. As technologies are added or program factors are changed, the vehicle can be re-closed using FASTPACT. Computational overhead for iterative processes in ModelCetner® can be large for probabilistic simulations, so FASTPACT is often run deterministically to save analysis time.

## ROSETTA

ROSETTA (Reduced-Order Simulation for Evaluation of Technologies and Transportation Architectures) models are Microsoft Excel® workbooks consisting of several interlinked worksheets, each representing a particular discipline in the overall process (Fig. 2). ROSETTA models were proposed in 2000 as a way to rapidly approximate the multidisciplinary process required to synthesize or "close" a space transportation concept. Excel's internal iterations and often the Solver function are used to change the vehicle scale factor and economic parameters until the available propellant mass fraction and the required propellant mass fraction are equal and the economic performance targets are met.

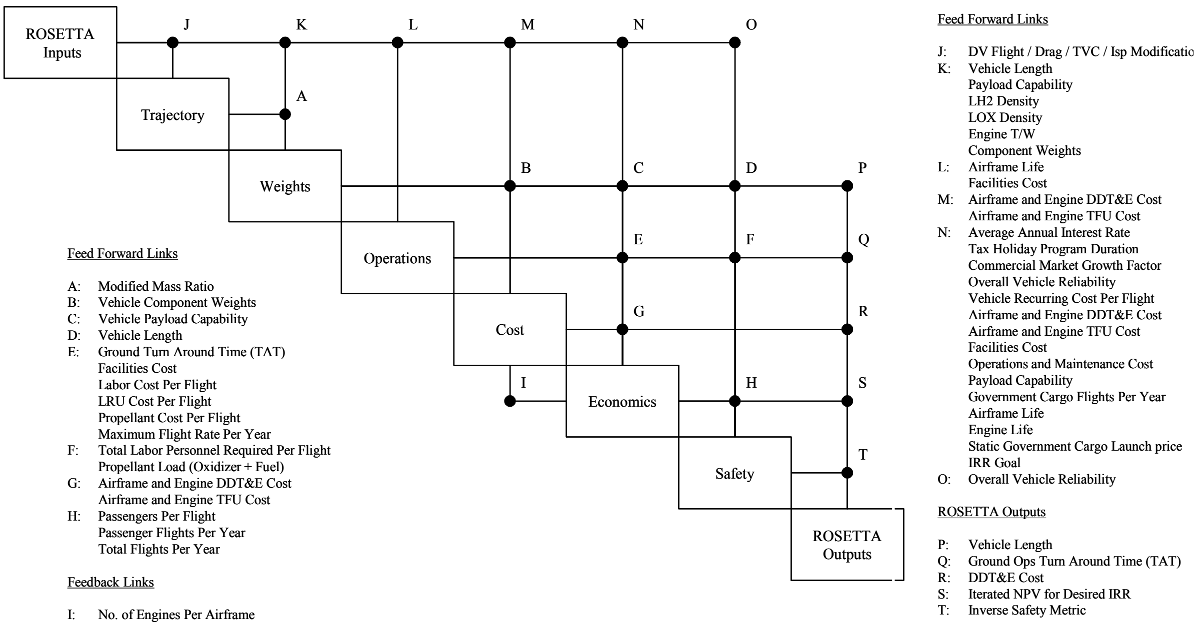


Fig. 2. Typical DSM for a Space Transportation Synthesis Process (for ROSETTA).

ROSETTA models are the equivalent of FLOPS and ALCCA in the original TIES process. The standard, team-oriented design process for advanced space transportation is much too slow and labor intensive to support probabilistic evaluation. ROSETTA models use a combination of meta-models (e.g. for trajectory and ground operations analyses) and existing spreadsheet models included intact (e.g. economics and weight estimation) to create a reasonably accurate approximation that can be executed repeatedly in a direct Monte Carlo process. Coupling variables between disciplinary worksheets are linked directly to other worksheets to speed execution time. Depending on complexity, ROSETTA models may take less than a second to up to 10 seconds to run. Georgia Tech and SpaceWorks Engineering have created ROSETTA models for reusable launch vehicle, in-space transfer vehicles, space solar power Mars vehicles, bi-modal NTR concepts, and solar sail-powered interstellar concepts.

## TechSim

TechSim is a joint development of Georgia Tech SSDL and SpaceWorks Engineering, Inc. TechSim is a fully-automated technology evaluation environment for determining the optimum mix of enhancing technologies when applied to an advanced space transportation concept. TechSim was conceived in 2003 and developed in 2004 as an environment to automate the selection of technologies subjected to a limited technology budget. It is implemented using Phoenix-Integration's ModelCenter® design integration environment (Fig. 3).

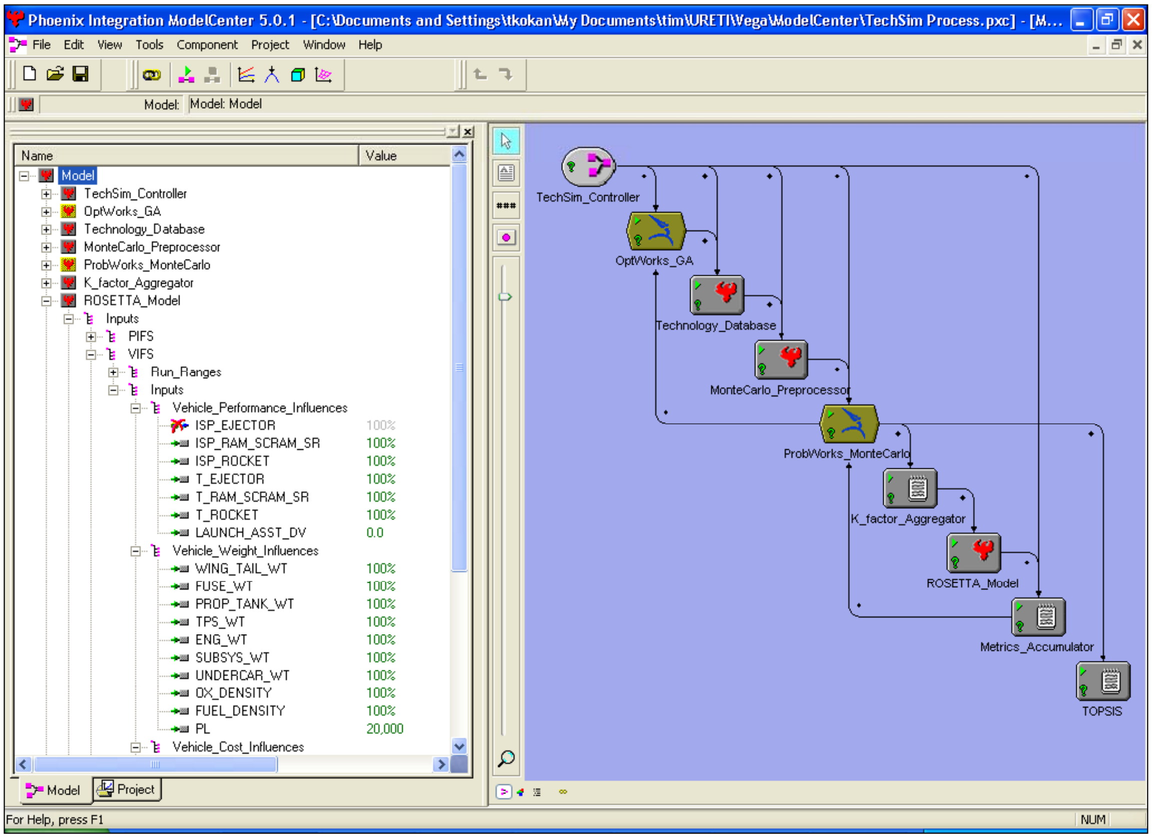


Fig. 3. Screenshot of TechSim Tool in ModelCenter®.

TechSim utilizes contributions previously discussed. A ROSETTA model is used as the fast-acting numerical simulation for the process. ATIES serves as the underlying process. A technology database of k-factors (low/most likely/high) for each VIF is included.

Given a potential portfolio of enhancing technologies, TechSim has software routines that test for inter-technology compatibility and budgetary constraints. If the portfolio is deemed viable, it is simulated probabilistically by sampling from the distributions of each technology's k-factors and then predicting the distributions of the resultant figures of merit using a direct Monte Carlo simulation driving the ROSETTA model through approximately 1000 numerical replications. Using a user-inputted desired confidence level for each figure of merit (e.g. 90th-percentile life cycle cost), the FOMs are combined into an overall evaluation criterion (OEC) using a series of weighting factors designed to represent the inputs of various constituents in the technology selection process. If the number of viable technology portfolios is manageable (say 10 – 20) then TechSim can simulation each one and then rank the resulting OECs by the best to worst. If the number of viable technology portfolios is large (100's or more), then TechSim uses a Genetic Algorithm to guide the selection of the most optimal technology portfolio. Obviously, the GA-driven process with an imbedded Monte Carlo simulation for each test case is very time-consuming computationally. Some initial work was performed to investigate parallel computation of each member of the GA population, but at the time ModelCenter® was unable to support this requirement.

TechSim is a very complete system for selecting the optimum combination of technologies for a given vehicle concept subject to a technology budget constraint. However, it still has weaknesses that need to be addressed. One, TechSim really only evaluates the overlay of enhancing technologies on a single vehicle. Multiple vehicles cannot be simultaneously evaluated, not can the system evaluate the vehicle in the context of an overall campaign. Also, TechSim does not evaluate enabling technologies. Rather, enabling technologies are inherited directly from the choice of the advanced vehicle that is being simulated. As NASA's interest in space transportation turned from technology-driven concepts such as reusable spaceplanes to more near-term concepts such as heavy-lift rockets, work on vehicle-level technology assessment methods has recently slowed.

## TRIPS

The most recent research at Georgia Tech's SSDL has been in the area of technology roadmapping. TRIPS (Technology Roadmapping and Investment Planning System) is a roadmapping (scheduling and planning) process and software tool that is currently in development (Ref. 9). TRIPS is positioned to address a weakness in the way our previous methods looked at technology investment. In previous methods, the focus was on selecting the best mix of technologies for a portfolio based solely on their most-likely impact on a particular vehicle. Little thought was given to the risk of actually maturing the technology, the uncertainty of its development schedule and the impact on the program milestones, and the need for redundancy in a technology manager's portfolio. Selecting a technology for funding at a nominal level is no guarantee that it will mature on time and within schedule, and have the desired impact of the system.

TRIPS attempts to simulate the technology maturation process. Each technology in the portfolio has a certain chance to advance toward its planned performance goals (k-factors) as a result of an increment of funding. However, there is a probabilistic risk that the technology will fail to mature (e.g. a test malfunction, a budget overrun, inability to achieve goals) These risks are modeled as uncertainty distributions, but are ultimately related to the technology's Research and Development Degree of Difficulty (R&D$^3$) and the required jump in Technology Readiness Level (TRL). The goal is to allow the TRIPS simulation to select an optimum portfolio of enabling *and* enhancing technologies, with necessary redundancy, to achieve a high confidence that a desired capability can be achieved. For example, the development of a propulsion technology might increase a vehicle's reliability toward a desired goal. However, the development of that technology is uncertain and highly risky. A better portfolio might carry two or three backup technologies that can achieve the same goal, at least partially through development. These managed technology portfolios are also subject to budgetary constraints of course, and this is part of the overall optimization.

Preliminary work has resulted in a proof-of-concept of the TRIPS system, but additional research is needed to mature the idea to a useful process and software tool. Work on TRIPS was begun in 2004 under NASA URETI funding to the University of Florida and the Georgia Institute of Technology. Until the fall of 2005, funding was provided under NASA MSFC's Advanced Technology Lifecycle Analysis System (ATLAS) program. The ATLAS project was terminated by NASA in late 2005.

## Summary

This paper provided a survey and summary of technology assessment methods applicable to the analysis of optimum technologies for advanced space transportation systems. Particular emphasis was placed on methods and tools created and used at Georgia Tech's Space Systems Design Lab (SSDL) and SpaceWorks Engineering, Inc. (SEI) during the period 1995 to 2005. These are the methods with which the author is most familiar.

ATIES is an adaptation of the more comprehensive TIES process created at Georgia Tech's Aerospace Systems Design Lab (ASDL) for aircraft applications. ATIES contains those steps deemed most applicable to space vehicle technology assessment and provides the basic process upon which our subsequent tools are based. The fact-acting multidisciplinary ROSETTA model provides a physics-based vehicle synthesis capability that approximates the more detailed team-oriented design process often used in industry. However, a ROSETTA model is fast enough to be used at the core of the probabilistic ATIES process (a few seconds of CPU time per evaluation). TechSim is a ModelCenter®-based simulation capability that implements ATIES. TechSim uses ROSETTA models to generate closed vehicle designed rapidly. Optimum enhancing technology portfolios can be selected (using a GA optimizer if necessary) based on the highest overall evaluation criterion score across multiple weighting scenarios (TOPSIS).

The most recent work turns attention to management of the technology maturation phase of a project. TRIPS considers both risk and redundancy in the selection of an optimum technology portfolio. Like TechSim, TRIPS is a probabilistic process, explicitly simulating uncertainty in technology development cost and schedule. Additional research is necessary to move TRIPS past the proof-of-concept stage. An ultimate goal is to combine the TechSim and TRIPS tools into a large technology assessment capability that spans technology development and life-cycle impact.

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The author would like to thank those colleagues and graduate students who have contributed to the advancement of the technology assessment methods described here. Notably, A.C. Charania provided the primary intellectual contribution for ATIES. Reuben Rohrschneider, Leland Marcus, John Bradford, John Weglian, A.C. Charania, and David Way were all instrumental in developing the ROSETTA concept. Jimmy Young, Ian Clark and Matthew Graham contributed to TechSim. Ian Clark has been the lead developer of TRIPS.

The author would also like to thank NASA's Garry Lyles and Eric Hyde for their early support of quantitative technology assessment methods being applied to space transportation systems. Through 2003, NASA MSFC's Mark Prill served as the point-of-contact for this work under NASA's University Research, Education and Technology Institutes (URETI/CUIP) program. More recently, support has come from ATLAS project sponsored by John Mankins at NASA HQ and led by Dan O'Neil from NASA MSFC.

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