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C. Russell Joyner
Pratt & Whitney, United Technologies
West Palm Beach, Florida

Patrick M. McGinnis
Pratt & Whitney, United Technologies
West Palm Beach, Florida

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Application of ITAPS for Evaluation of Propulsion and Power at the System Level

C. Russell Joyner*, Patrick M. McGinnis†
Pratt Whitney Space Propulsion, West Palm Beach, Florida, 33410

P&W Space Propulsion has been working an effort to update our collaborative analysis and design processes for complex systems with a focus on propulsion and power for use in an Integrated Concurrent Engineering analysis and design approach. This integrated analysis and design approach (i.e. ITAPS) focuses on the formulation and validation of methodologies and processes that create a responsive and rapid advanced design and analysis environment to evaluate Aerospace systems. The ITAPS approach uses an integrated approach to examining system architectures, mission requirements and the interaction of all the elements of an Aerospace system (i.e. propulsion, power, electrical systems, vehicle sizing, and vehicle flight performance) together. This disciplined analysis capability is employed for defining and maturing integrated system concepts that could meet design requirements of future Aerospace systems being considered by the US government and the Space industry. The functional focus is on how the subsystem elements, especially propulsion and power, affect the higher-level aerospace system. The ITAPS approach uses integration of multidisciplinary design analysis tools in order to evaluate all manner of Aerospace vehicle systems. These include lower-level coupled subsystems (e.g. EHMS, power management and power systems, and the propulsion system) and higher-level total systems like expendable and reusable launch systems with all their subsystem elements. The design integration of these "system of systems" is examined at a higher system level using Phoenix ModelCenter Integration Software's ModelCenter. This paper will discuss the methodology and some examples evaluations of selected concepts relative to how the subsystem design requirements are linked to the higher vehicle system level. Also, the discussion will cover how computer design tools are "linked" together to create an integrated, functional analysis process that permits evaluation at the architectural level or at the systems level or specific subsystems of aerospace vehicles and in-space systems. The mission requirements, performance, CAD design, and cost elements of the integrated "system of systems" model will be described with discussion of how the Phoenix ModelCenter software permits a "linked" integration of system model elements. Consequently, the ITAPS approach is used to permit rapid synthesis and evaluation of the functional attributes of Aerospace vehicle systems relative to the propulsion and power system design.

Nomenclature

CAD	=	Computer Aided Design
ECLSS	=	Environmental Control and Life Support Systems
ETO	=	Earth To Orbit
GNC	=	Guidance, Navigation and Control
ITAPS	=	Integrated Total Aircraft *(Aerospace)* Power Systems
EHMS	=	Engine Health Management System, usually coupled to Vehicle Health Management System
System of Systems	=	A Multidisciplinary Approach to Obtaining a Solution to a Complex Set of Specifications Based on a Set of Capabilities, Not a Single Specific Vehicle or System

* Discipline Chief, Mission Analysis and Space Systems, PSA &I, PO 109700, MS 712-67, Senior Member.
† Senior Engineer, PSA &I, PO 109700, MS 712-67.

I. Introduction

The first step in a "systems-of-systems" evaluation is to define and then examine the functional relationships between the system elements for a given set of system design architectures. The second major step is then the quantification of the impact of design choices relative to the cost, performance, and reliability of all the system elements on the total “system-of-systems”. This system or process at Pratt & Whitney (P&W) and other United Technology Divisions is performed using Integrated Total Aircraft (Aerospace) Power Systems (ITAPS). “Aircraft” has been in the process acronym because ITAPS was first created as a process and tool to examine the synthesis of all the subsystems on miltary and commercial aircraft. It has evolved to more “Aerospace” as ITAPS as been used for systems other than aircraft. “Power” is used broadly to describe a common thread for all the system elements (e.g. propulsion, electric power, communications, EHMS, GNC) that enable an aerospace system to perform its required mission. For the remainder of this paper, ITAPS will be used in the context of “A” equaling Aerospace for any aerospace system.

ITAPS is an integrated approach to determine the functions of a complex system and then apply model-based analysis and design in a disciplined process that links legacy engineering tools along the functional interrelations for conducting system-level design studies. The objective of ITAPS is to provide an accurately defined model or system of models that represent a system-of-systems to provide quantitative solutions early in the design process. It also is employed to evaluate architectural solutions based on the system requirements assignment during the functional analysis step.

ITAPS generates the roadmap for defining the solutions to be obtained by modeling all the system functional elements to increased levels of fidelity. System-level design solutions will result from executing the ITAPS amalgamated toolset to meet the mission or aerospace vehicle design requirements. The integrated approach transcends the usual decoupled functional discipline approach to doing isolated component design studies and then brings the component designs together to evaluate the alignment of requirements from the subsystem level to the higher aerospace vehicle system level. The ITAPS approach works for any complex aerospace system that must have absolute synergy within a system design. The ITAPS approach permits identification of design issues or noncompliance to mission requirements early in the conceptual design process and facilitates a more affordable overall design optimization down to the component level relative to cost, reliability, and performance. The first step in the ITAPS modeling process is to determine the design (mission) requirements and the aerospace vehicle (and subsystem elements) system metrics. The design requirements are used to determine the aerospace or space vehicle system type and operational functions.

Subsystem functional elements are determined and then the functional interdependencies are identified. The functional description at the system level is used to define the functional modeling requirements that make up an ITAPS integrated model. The subsystems can be examined and described by taxonomy and function. After functionality and system crossover potential is determined, the systems are modeled at the functional performance level and design trade-offs are performed to examine the impact on mass, performance, cost, complexity, and maintainability.

Once the system design requirements are isolated, figures of merit qualified, and functional analysis performed; the required system model elements are selected based upon the level of fidelity required to measure the “system of systems” against the figures of merit. These models can be Visual Basic scripts, EXCEL worksheets, C and FORTRAN subprograms and/or large monolithic legacy programs (e.g. flight mechanics codes like POST). These models and the system elements they represent are then “linked” using a integration program. This is done so that the model elements can share common parameters (i.e. Propulsion Model outputs Thrust as dependent design term, Trajectory uses Thrust as independent design term) and the interaction between model elements can be captured as the total system design is perturbed to look for design sensitivities (e.g system optimization).

Phoenix Integration Software’s ModelCenter software was chosen last year after a period of evaluation by Pratt Whitney Space Propulsion as the most user friendly, technically versatle and the “file-wrapping” tools presented more reusability for the scripts between different system models.

II. Evaluation Process and Figures of Merit

An evaluation process based upon fundamental NASA Systems Engineering (SE) guidelines is used to start the ITAPS evaluation. First in the process is the identification of the objectives and goals of the system second is the design conceptualization and next is the evaluation or design trade studies performed relative to the set of objectives or goals for the system. If the requirements for the evolution of the design to full maturity are known then it upgrades can be done in blocks. If the requirements are not fully developed, then the system can be evolved via "spirals" to obtain functionality initially and then further "spirals" are used to evolve the system to the final goals or to some extended but planned functionality. ITAPS in this case uses the Systems Engineering philosophy to form the framework for quantification of the system attributes via analysis and technical planning. The engineering tools are employed to set-up the decision-making path for the application of Systems Management. Thus ITAPS creates a disciplined approach to bridging the Systems Engineering and Systems Management elements of dealing with the interrelationships that exist in the design of complex systems. ***Figure 1*** illustrates how the ITAPS process aligns with the processes within the Systems Engineering approach to developing and evaluating system concepts to meet design requirements.

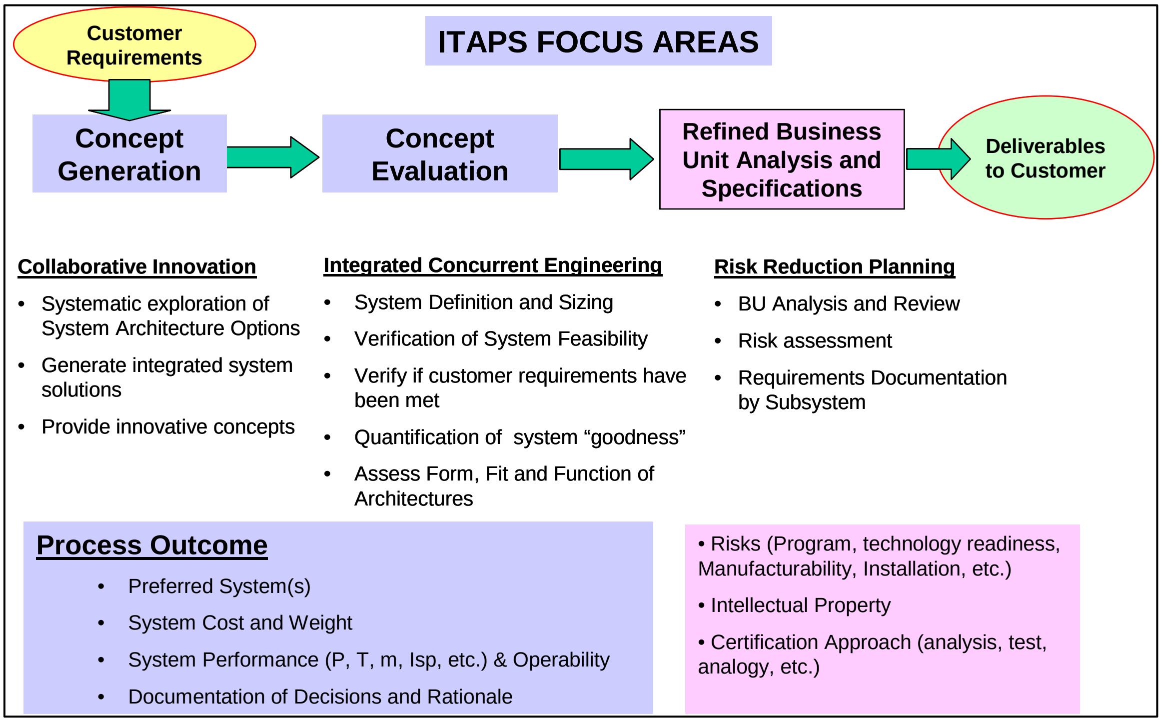

Figure 1 - ITAPS process and the Systems Engineering concept development roadmap.

Once the goals or objectives of a system or defined, a hierarchical architecture functional analysis for the system or super system is performed along with the assignment of system level design requirements. This activity under ITAPS is based on a functional analysis for the system architecture and the system elements or it can be focused on a specific system concept if it is already defined in detail. The functional analysis analyzes the performance requirements and allocates them to discrete activities. It decomposes the primary system into sub-functions using increasing levels of detail. This step in the SE process is closely tied with mission analysis efforts and architecture synthesis efforts to focus the allocation of qualitative and quantitative program goals. If done rigorously and in conjunction with other elements of the SE process, it allows early identification of critical design functions at the start of development and can be used to reduce system design risk.

ITAPS is both process and model-based analysis and design evaluation activity. It can be focused to use qualify the functions and the study of the functions of a System. It also can be focused on using legacy-engineering tools along the functional interrelations for conducting system-level studies. The objective of ITAPS is to provide a disciplined approach to determining if the complexity of a system is being captured with enough fidelity to determine the interrelationships of the system's elements. The engineering quantification focuses on accurately defined models or assemblies of models that represent the system-of-systems in order to provide quantitative solutions early in the design process for interaction between elements like the power system, propulsion, environmental controls, flight structures, etc.

The roadmap for examining the possible system solutions is obtained by modeling all the system functional elements to a high level of fidelity. System-level design solutions will result from executing the ITAPS amalgamated toolset to meet a given architecture, a defined mission or specific aerospace vehicle design requirements. The integrated approach transcends the usual decoupled functional discipline approach to doing isolated component design studies and then brings the component designs together to evaluate the alignment of requirements from the subsystem level to the higher aerospace vehicle system level. The ITAPS approach works for any complex aerospace system that must have absolute synergy within a system design. The ITAPS approach permits identification of design issues or noncompliance to mission requirements early in the preliminary design process and facilitates better overall design optimization down to the component level relative to reliability, cost, and performance. The first step in the ITAPS modeling process is to determine the mission design requirements and the aerospace vehicle (and subsystem elements) system metrics. The mission design requirements are used to determine the aerospace or space vehicle system type and operational functions.

The subsystem functional elements are determined and then the functional interdependencies are identified. The functional description at the system level is used to define the functional modeling requirements that make up an ITAPS integrated model. ***Figure 2*** illustrates the ITAPS process functional analysis diagram for an in-space system. This type of system diagram is then used to determine the required system model elements based on the functional interaction of the system elements.

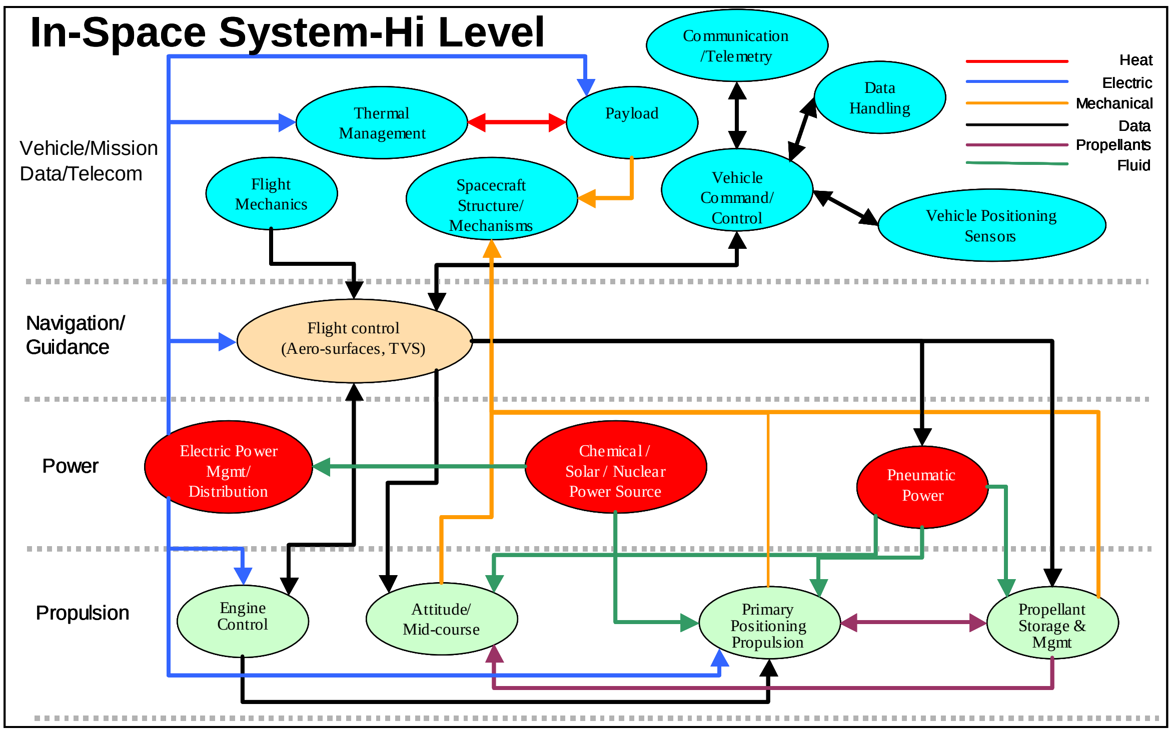

Figure 2 - ITAPS functional analysis diagram.

Each of the elements that make up a aerospace system like; structure and tankage, GNC, ECLSS, power and propulsion for any flight system of in-space exploration systems would be defined based on defined architectures. The systems would be examined and described by taxonomy and function. After *functionality* and system crossover potential (*integration areas*) is determined, the systems are modeled at the functional performance level and design trade-offs are performed to examine the impact on mass, performance, cost, complexity, and maintainability. ***Figure 3*** shows the step where under ITAPS the functional analysis results are used to describe the elements that need to be modeled and then the sub-elements that are also modeled like the ECLSS, power system, propulsion system, thermal management system and the vehicle flight structure. This example shows the breakout of the propulsion model sub-element and the required lower-level system models required to describe the total system to a higher-level of fidelity.

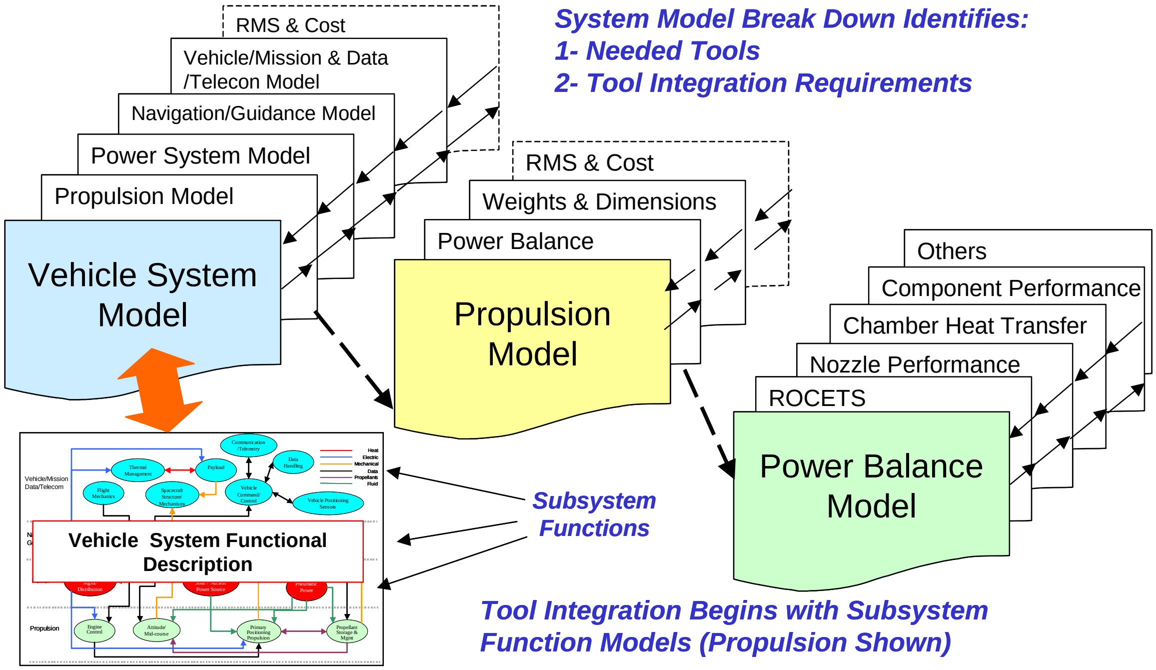

Figure 3 - ITAPS functional analysis used to guide determination of models for ModelCenter.

The functional and system architectures analysis figures of merit are typically cost, mass, performance, maintainability and integrated system reliability. These can be calculated based on algorithms describing each subsystem element (e.g., vehicle system model, power model, propulsion model, cost model) and captured for evaluation. For example, the primary figure of merit can be maximization of system affordability within a fixed cost profile by focusing on decreasing the total integrated system development or acquisition cost, while examining secondary figures of merit such as decreasing overall system mass, or increasing overall system performance, or improving the overall integrated system's reliability and maintainability.

The figures of merit are examined based on how they affect the architectures that are comprised of specific system design synergies. ***Figure 4*** illustrates the ModelCenter tool used to evaluate figure of merits after the functional elements are modeled and integrated into an integration software tool known as ModelCenter™. Pratt Whitney uses the Phoenix Integration Software's ModelCenter program to perform integrated functional analysis and to perform system analysis to determine the impact of subsystem design at a higher architecture and vehicle systems level.

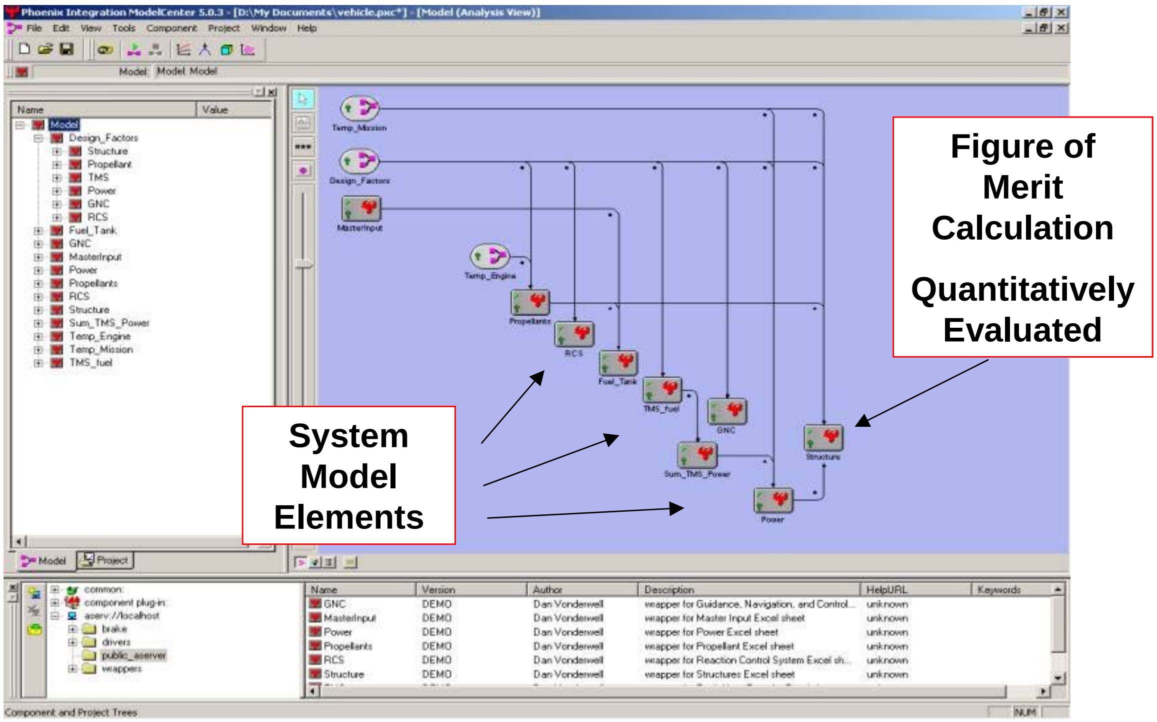

Figure 4 - Figures of Merit are evaluated under ITAPS using ModelCenter.

III. ModelCenter and Enterprise Analysis Server as The "Foundation" for the ITAPS System Modeling

Phoenix Integration offers three products that comprise their process integration suite. Pratt Whitney has focused on utilizing ModelCenter, Analysis Server and Analysis Manager. At the heart of this integrated toolset is ModelCenter. In ModelCenter "wrapped" applications are accessed to build an engineering process model. Enterprise Analysis Server is used to facilitate the creation of wrappers for the modeling applications that are accessed in ModelCenter. Finally, process models (built in ModelCenter) are run under the ModelCenter environment to perform functional analysis and design trade studies.

ModelCenter uses a graphical user interface or visually based approach to perform the model element integration. Used under the ITAPS process, it permits quick modeling of complex systems using models that already exist or the analysis manager can combine legacy programs with models that need to be developed to describe some system element. ModelCenter's hierarchy structure permits the system manager or engineer to perform complex design trades to determine how the overall system is interacting. This permits faster modeling and design optimization for system concepts that have complex elements and where the evaluation process changes frequently.

ModelCenter works by setting up an environment by which you construct the System as a series of "linked" elements with a simple interface. You can then connect to your applications that are wrapped with the Enterprise Analysis Server to build a system model or functional process. You can also set up the System model to do automated process evaluations or parametrics on the independent variables that are defining a System model. The results are viewed directly in ModelCenter, but are automatically generated in export files for plotting or examining in programs like Microsoft's EXCEL.

Pratt Whitney has found Phoenix Integration's ModelCenter software to be a most flexible and cost effective integration software for the integration of design and analysis tools and processes for a low cost PC-workstation IT architecture. Pratt Whitney Space Propulsion is adopting ModelCenter across the engineering organization for most disciplines that includes performance analysis, mechanical design, and cost and reliability analysis. The ModelCenter Software is being used to integrate key applications (e.g. MATLAB, UNIGRAPHICS, Excel, FORTRAN analysis programs, etc.) so that the electronic exchange of key design data between the "tools" is possible.

IV. Examples of ITAPS Approach With ModelCenter for Systems of Systems Analysis

Among the applications that ModelCenter has been used in systems of systems analysis, two examples are provided here. P&W has used the code to facilitate the analysis of upper stage performance on a variety of launch vehicles. ***Figure 5*** shows two EELV derivatives that have been modeled and analyzed. The purpose of this analysis is to determine the sensitivity of the two vehicles to thrust and propellant load. Each chart shows the sensitivity to either 100 klbs or 150 klbs of propellant for either the Atlas or Delta derived vehicles. Furthermore, the thrust sensitivity is shown for one, two, or three RL60 derived engines.

The advantage to the use of this tool for analysis is profound. Literally hundreds of individual cases could be run in less than an hour that would have taken days were each case run individually. In addition, the resulting data is available very easily for post processing. The capability for running a large amount of trades in a short amount of time is critical in this time of changing requirements for payload performance.

Furthermore, a large number of runs are necessary to use Design of Experiment (DoE) methods for robust design, response surface equations, and Monte Carlo analysis. This process will allow for the automatic generation of a suite of data from designs which have had its variables perturbated for the sensitivity analysis required for these methods.

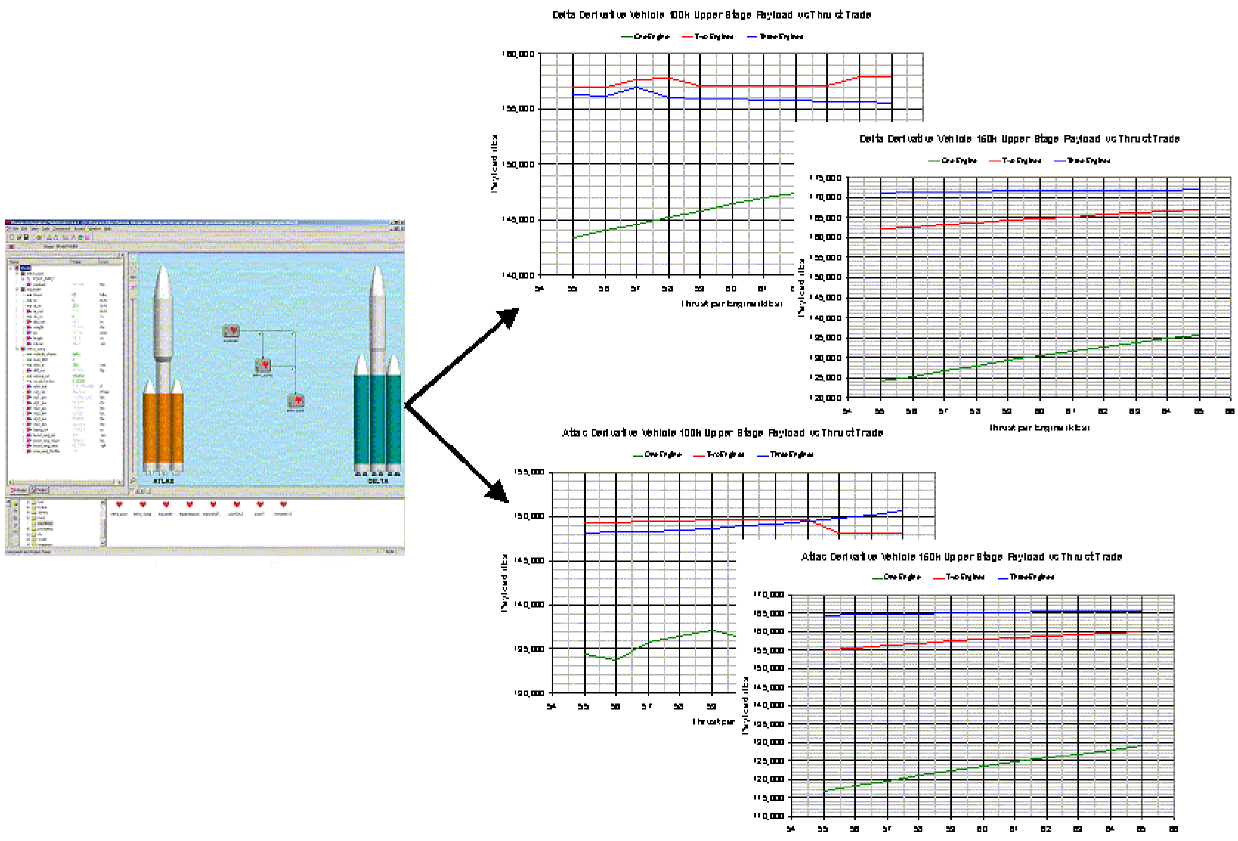

Figure 5 – ETO Launcher Upper Stage Sensitivity Analysis Using ModelCenter

The second example provided demonstrates how P&W has linked Computer Aided Design (CAD) software to the system analysis process. ***Figure 6*** shows how ModelCenter manipulates variables in EXCEL that are used in the generation of a macro in UNIGRAPHICS. This macro is then used to make changes to the modeled structure of a design. UNIGRAPHICS has been used in this application because of its utility both to design parts and facilitate the manufacture of those parts.

The example provided is a model of a nominal Bimodal Nuclear Thermal Rocket (BNTR) interplanetary vehicle. The model has the capability of changing either or both propellant tank lengths and volumes, the radiator surface area, and virtually all dimensions of the BNTR engine including the number of engines used. The engine modeled here is a representation of the P&W TRITON engine.

While the below figure has illustrated how this application can be used for interplanetary vehicles, P&W has pursued efforts to gain the capability of generating quick models of rocket engines as well. This would allow quick conceptual designs of engines, which could provide the designer with valuable information such as weight, length, and volume of an engine to determine the feasibility of a configuration under consideration. Modeling of the vehicle as well extends this capability to engine-vehicle integration. This facilitates the determination of engine requirements that are based on vehicle and mission needs.

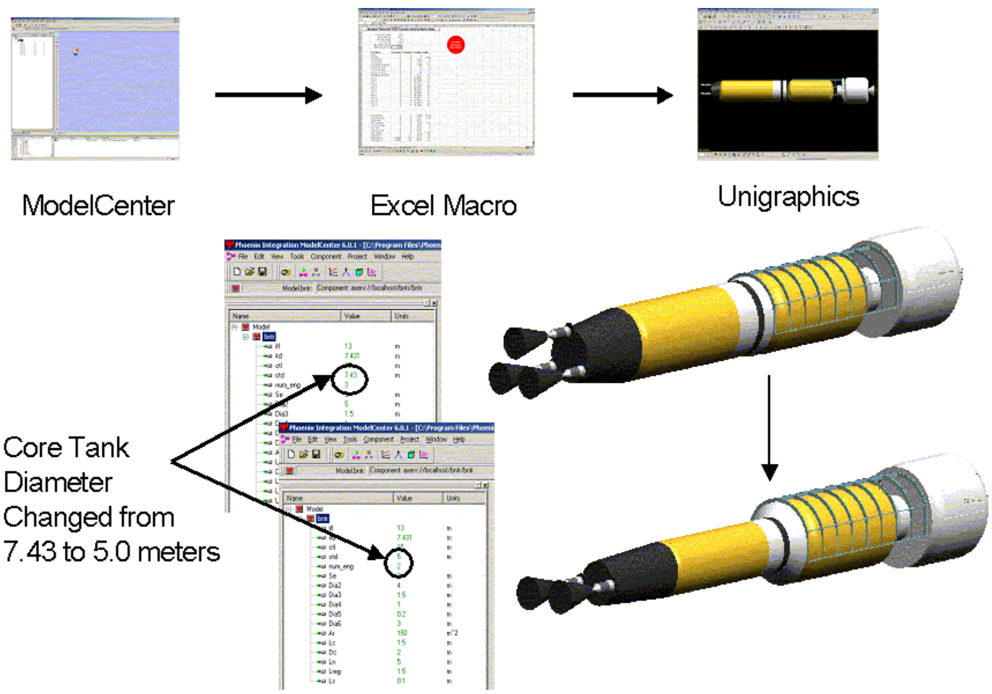

Figure 6 – Unigraphics Linked to ModelCenter

V. Summary

This paper has described ITAPS as it is employed at Pratt Whitney Space Propulsion. ITAPS is a disciplined process for evaluation of a "system of systems" at various stages of its development and design. ITAPS uses a Systems Engineering doctrine as the basis of the disciplined approach to determine the functional attributes of the super-system and the other system elements and for determining how to model the system. Pratt Whitney Space Propulsion has employed Phoenix Integration Software's ModelCenter as the current integration software for performing the quantification of the interrelationships between the system's elements and as the "visualization tool" to do parametric design trades on the system.

Prior ITAPS efforts have included hypersonic vehicle trades that examined the integrated effects of optimizing the engine concepts, thermal management systems, and fuel supply system together. During NASA 2GRLV efforts, an internal study at Pratt Whitney examined propulsion options for boost and second stage of a two-stage to orbit design using ITAPS and ModelCenter.

Recently, the examination ETO launch vehicle integrated effects, focusing on the upper-stage propulsion requirements was performed using ITAPS and ModelCenter. Also, current efforts have included the examination of propulsion analysis data exchange with CAD software for rapid parametric scaling, geometry-packaging of advanced nuclear propulsion systems using coupled vehicle and propulsion CAD models, integrated lander sizing models and their thermal management systems, and the integration of innovative combined propulsion and power on human exploration vehicles for the Moon-Mars Exploration Enterprise. These current ITAPS validation efforts and design studies providing new ways to improve the methodology for exchanging analysis and design data between modeling tools and how the analysis of the system elements affects the vehicle packaging geometry.

Additionally, newly calibrated liquid rocket and nuclear thermal rocket detailed development and acquisition cost models as well as updated reliability and logistics models are being included in the ITAPS analysis environment to do total system cost optimization as part of the higher level “systems of systems” analysis activity.

When complete at the end of the third quarter of 2004, a rapid response, reusable analysis tool-set will be in use examining architectures and systems that are part of the Project Constellation and Project Prometheus program activities.

Acknowledgments

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