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14. ABSTRACT
The Review of the U.S. Human Spaceflight Plans Committee found that the space exploration plans set forth in 2009 were unsustainable[1] and is forcing NASA to rethink its plans and focus on realistic estimates for its programs. The Air Force is facing similar problems due to continuing delays in completing programs and cost overruns. The Constellation program, which was to develop the Ares I, the heavy-lift vehicle Ares V, the Orion capsule, and the Altair lunar lander for manned missions to the moon, was recently cancelled by the Obama Administration in hopes that the commercial space industry can work in tandem with NASA and the Air Force to expand spaceflight[2]. As a result, the development of future launch and space vehicles necessary for spaceflight and solar system exploration will require investing precious resources in the right technology. Multidisciplinary analysis and optimization tools, specifically the Integrated System and Cost Modeling (ISCM) Tool Suite, can be used to provide performance, cost, concept of operations, and risk estimates for reusable and expendable launch vehicles for various space-based missions. A baseline reusable launch vehicle's performance was studied and optimized for minimum gross weight. The result of the study was a 39-percent reduction in weight. Four existing launch vehicles were also studied for validation and verification of the performance, cost, and operations estimates.

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Optimal Vehicle Design Using the Integrated System and Cost Modeling Tool Suite

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The Review of the U.S. Human Spaceflight Plans Committee found that the space exploration plans set forth in 2009 were unsustainable[1] and is forcing NASA to rethink its plans and focus on realistic estimates for its programs. The Air Force is facing similar problems due to continuing delays in completing programs and cost overruns. The Constellation program, which was to develop the Ares I, the heavy-lift vehicle Ares V, the Orion capsule, and the Altair lunar lander for manned missions to the moon, was recently cancelled by the Obama Administration in hopes that the commercial space industry can work in tandem with NASA and the Air Force to expand spaceflight[2]. As a result, the development of future launch and space vehicles necessary for spaceflight and solar system exploration will require investing precious resources in the right technology. Multidisciplinary analysis and optimization tools, specifically the Integrated System and Cost Modeling (ISCM) Tool Suite, can be used to provide performance, cost, concept of operations, and risk estimates for reusable and expendable launch vehicles for various space-based missions. A baseline reusable launch vehicle's performance was studied and optimized for minimum gross weight. The result of the study was a 39-percent reduction in weight. Four existing launch vehicles were also studied for validation and verification of the performance, cost, and operations estimates. The results were typically within five percent of documented values, which is acceptable for concept-level studies. The results generated from the ISCM Tool Suite provide a reliable foundation for program managers and mission planners to make decisions for both manned and unmanned space missions.

Nomenclature

ΔV	=	*change in velocity*
T/W	=	*thrust to weight ratio*

I. Introduction

The concept of multidisciplinary analysis and optimization has been around since the 1970s, beginning with the advent of computer-aided design[3]. The linking of various disciplines, such as aerodynamics, propulsion and structures, can provide rapid analysis of a system as well as optimize a system using the synergy between disciplines. However, the computer power of the 1970s limited the use of such methods. As computing power improved, the ability to link together different industry standard tools and optimize a design has become more feasible. Modeling frameworks, such as iSIGHT, AML, and Phoenix ModelCenter, have been developed to support the linkage of performance tools and optimizers. Additional tools that evaluate cost and operations have also been developed. These tools combined with the performance tools can estimate how the vehicle will perform, what the cost of development and production will be and how the vehicle design affects operations, including schedule, and facilities and labor costs. The addition of an optimizer can greatly improve the designs and integrating performance, cost, concept of operations, and risk provides a complete end-to-end view of the program.

The early design approach for highly complex systems and programs, such as space launch-systems, relied on providing a set of system requirements to multiple teams to design individual subsystems. Those requirements that were fed to teams dealing with the functional areas such as satellite bus, payload, launch options, propulsion, operations, cost analysis and other subsystems would change based on the limitation of technology and resources for

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each group. Each team had to communicate effectively with other teams to update requirement changes as well as design changes. The iteration of this process is expensive and becomes more expensive if there is lack of communication or a miscommunication between the teams. The process is time consuming and may not result in the optimum design which can lead to design changes during the program life-cycle. The process becomes even more complex if the customer changes system requirements.

The solution is to use integrated/collaborative optimizing tool-suites. Instead of relaying requirements to a myriad of design teams, the requirements are provided to a single user-interface module. The user-interface module then interfaces with an integration-core module. This integration-core module is the link between the functional elements of the program. The software is designed to automatically handle the limitations of one subsystem and provide updates to another. This solution will provide results to the design team within days, not the weeks or months typically seen in programs using the traditional design methodology.

Multidisciplinary design has an advantage over early design processes, because the multidisciplinary process will automatically link different subsystems and perform the necessary iterations. The early design process typically results in cost overruns and schedule delays, because of communication issues, unknown limitations of subsystems, and unsustainable and unrealistic requirements are discovered late in design process. Once the conceptual design is finalized, typically within a few weeks, cost estimates are applied to determine design, development and test (DDT&E), and life-cycle costs. The ability to successfully model the life-cycle cost during the conceptual-design phase is paramount. Unsustainable and unrealistic requirements and the impact of introducing new technologies are typically difficult to evaluate at the early design phase using traditional design paradigms and have a huge impact on life-cycle cost. Approximately 80 percent of the life-cycle costs are determined by the decisions made in the conceptual-design phase[4]. Modeling the effect of disciplines for a system using multidisciplinary analysis helps determine unrealistic and unsustainable requirements and the impact of technology insertion, which drives the cost of the system. Accurately estimating the life-cycle cost will ensure that programs will not reach the Nunn-McCurdy line requiring programs that exceed 125% of the original estimate to be canceled, and the program will be funded to completion.

The ISCM tool suite is designed to handle the performance, cost, operations, and risk aspects of highly complex systems. By linking the life-cycle cost model, the performance model and the operations model, a more realistic depiction of the final program can be achieved. As discussed earlier, space launch systems are highly complex systems and are dependent on reducing system mass and improving rocket efficiency to boost performance. New engine technologies, such as aerospike engines and thrust augmenting nozzles, need to be carefully considered in the scheme of the whole vehicle before investing in them. A multidisciplinary approach allows for conceptual designs that include newer technologies, the impact on the various subsystems, and overall rocket performance, to be modeled quickly. Also, multiple technology configurations can be modeled quickly. In addition to performance, these vehicle models would also contain cost estimates and operations models, and identify potential risks for the program. The integrated models can help steer the investment in new technologies, and provide decision makers with realistic estimates of the full impact of a new launch systems being introduced. The complete depiction of a program can then be compared to other designs and their associated costs in order to make more informed decisions on technology investment and the flow of development dollars. The multidisciplinary analysis and optimization will help determine an optimal design taking into consideration performance, cost, and operations for a given set of requirements. It identifies areas of risk so that mitigation plans can be put in place to minimize the impact on the program.

II. Overview of the ISCM Tool Suite

The ISCM tool suite is the continued evolution of Advatech Pacific Inc.'s (Advatech) approach of using an integrated system analysis tool suite to simulate the key aspects of a program's life cycle. The results provided by the ISCM tool suite provide supporting programmatic information for defining a system baseline and the ability to rapidly update the analysis using the latest available program information. The modules supporting ISCM currently address launch vehicles and spacecraft modeling. Further development will expand the tool suite to other systems incorporating the concepts implemented for the core modules to further support the aerospace community. The goal is to provide the industry with a flexible tool that can provide responsive turnaround and optimal vehicle designs based on customer requirements and mission constraints. The ISCM tool suite is primarily designed to support the systems engineering aspects of a design. The tool suite uses vehicle performance, weights and geometry to determine the DDT&E costs, the life-cycle costs and the concept of operations (ConOps). The modules used to develop the performance of the system use multidisciplinary analysis and optimization. Figure 1 illustrates the interactions for ISCM's modules.

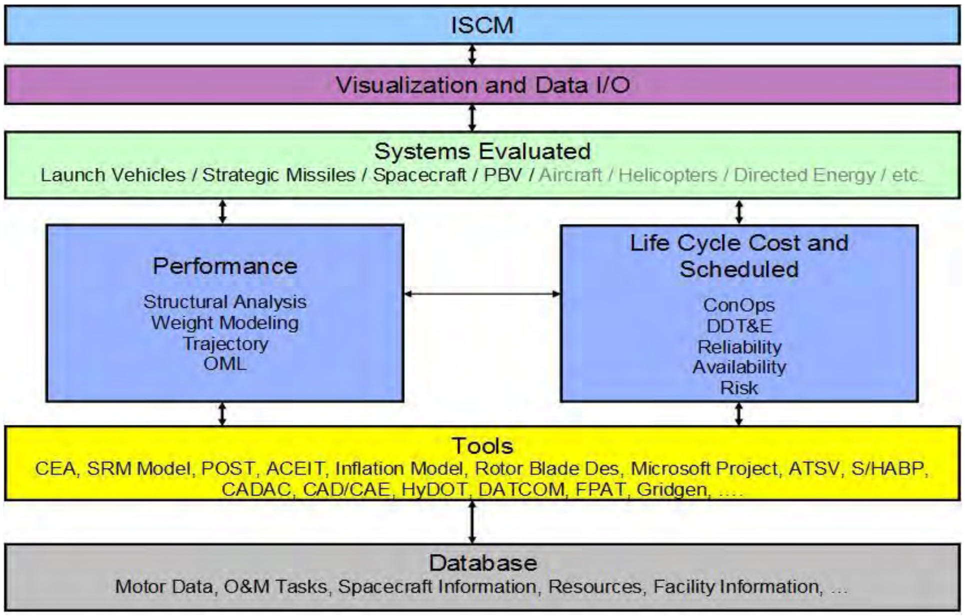

Figure 1. ISCM Architecture

As shown in Figure 1, the performance module and life-cycle costs and schedule module are linked to the tools and database modules. These tools and databases are linked using a modeling framework that incorporates an optimizer to optimize the design. The tools module contains existing industry-standard tools as well as tools developed by Advatech and the Air Force Research Laboratory (AFRL) that have been verified and validated. Some tools, such as the Program to Optimize Simulated Trajectories (POST), have their own optimization routines. In this case, the framework will size the system to the desired parameter, for example a rocket's thrust-to-weight ratio, and then use POST to optimize the trajectory. The framework will then loop through the sizing optimizer and POST until an optimum is found. The database module contains various performance, cost and operations information obtained from industry and government sources. The database module is used to derive cost estimating relationships (CERs) and determine launch availability, risk, facilities cost, labor cost and existing launch vehicle performance and related quantities.

The ISCM tool suite models multiple elements of launch vehicle and spacecraft programs including:

- performance,
- ConOps,
- development, production, and operations costs,
- schedule,
- reliability,
- availability,
- fleet readiness, and
- trajectory analysis.

Currently, the two performance modules in ISCM are the Advanced Computational Engineering Simulator – Integrated Space Engineering Tool (ACES-ISET) and the Integrated Propulsion Analysis Tool (IPAT). ACES-ISET is primarily used as a conceptual design tool for satellites. IPAT is primarily used as a conceptual design tool for launch vehicles. As a standalone tool, ACES-ISET uses elements from IPAT to model launch vehicles for satellite launches. In ISCM, the two tools are separated into modules and linked to the life-cycle cost model, which includes ConOps. A risk model is also incorporated to account for technical and schedule uncertainties. The ISCM tool suite can be used as a planning tool to support requirements definition, program planning, mission planning, systems analysis, and technology assessment. Figure 2, illustrates how the modules are currently linked.

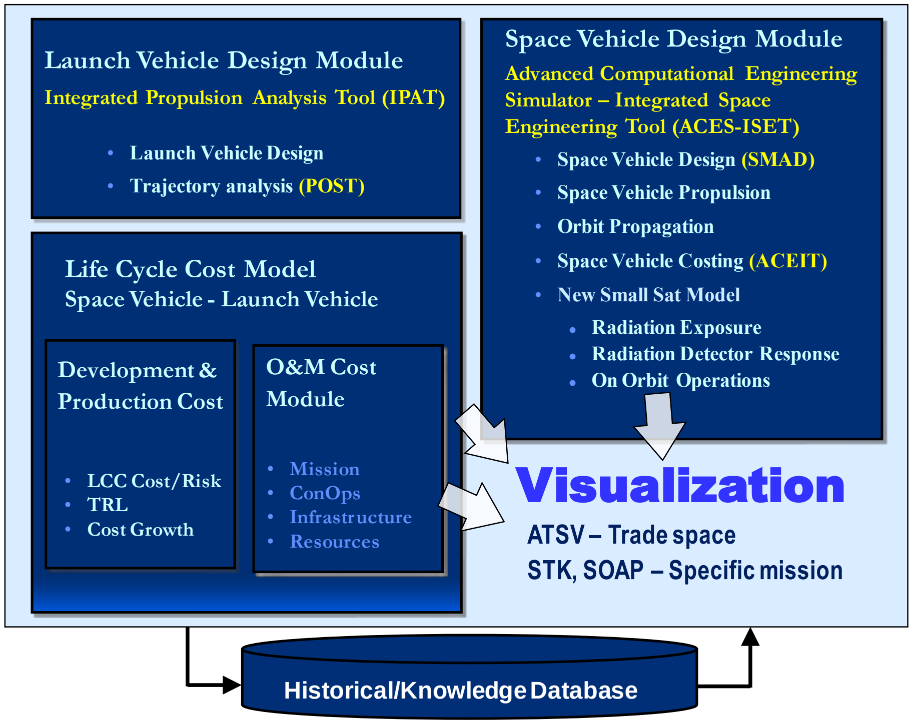

Figure 2. Space Systems Modules

The historical/knowledge database shown in Figure 2 is updated as the tool is used. The more vehicles are designed with the tool suite and followed to completion with the tool suite, the more accurate the data in the database will be. Also shown in Figure 2, are the various methods of visualization. In addition to Excel spreadsheets and the graphics displayed by the user interface, ISCM exports to the Penn State Advanced Trade Space Visualization (ATSV) tool[†], Satellite Tool Kit (STK)[‡], and the Satellite Orbit Analysis Program (SOAP)[§].

Space launch-systems provide a unique design challenge using multidisciplinary techniques. The subsystem weights and sizing are determined empirically at the conceptual-design level, not by a physics-based equation such as those used for propulsion and heating analysis. The empirical models are developed using the subsystem weights from existing launch vehicles. Due to the limited amount of information for launch vehicles in production, ISCM will update the databases that manages the empirical models with vehicles designed using the tool suite. In addition to weight and sizing, there are various physics-based analyses that must be performed. Aerodynamics, structures, propulsion performance, trajectory, and thermal analysis are all integrated into the modeling framework. The interdependencies are linked by the framework and as the requirements of one discipline change, the other disciplines are automatically aware of the change and updated.

The ISCM tool suite process flow begins with the system requirements provided by a customer. Then the tool suite begins to design a vehicle based on those requirements. An optimization routine is used to iterate the design such that the vehicle is the optimal solution for the customer's needs and mission constraints. The process begins with the initial geometry of the vehicle, which deals with the outer mold line and flow-path geometry. The sizing of individual stages can be done manually by the designer or using a sizing routine in ISCM that uses a specified desired ΔV or T/W. The geometric properties are then passed to an aerodynamics module that calculates the aerodynamics loads and inlet performance (if necessary), in 3-degrees of freedom (DOF). These aerodynamics results are then applied to the propulsion module. This module calculates the propulsion loads, heating and performance to be passed on along with the aerodynamics to the trajectory module. The trajectory module uses the current propulsion and aerodynamic values to achieve a specified mission profile. In addition to determining flight path, the trajectory module also calculates load cases and fuel requirements. The flight path calculated by the

[†] http://www.atsv.psu.edu/index.html

[‡] http://www.stk.com/

[§] Product of the Aerospace Corporation trajectory module and the propulsion heating results are passed on to the thermal module where the temperatures experienced during flight are calculated. These temperatures are used within the structural module along with the various loads calculated by other modules to calculate material weight and empty mass properties. For hypersonic vehicles, the empty mass properties, propulsion performance values and the 3-DOF analysis are then provided to the stability and control module to provide the gain and phase margins. For a missile-type vehicle, the sensors module calculates the accuracy of the vehicle. Finally, all the data is compiled for the vehicle and provided to the costing model. Once the vehicle cost analysis has been performed, the vehicle parameters are passed on to the optimizer to improve upon vehicle weight, trajectory, propulsion, materials and cost to meet the constraints and requirements set by the customer.

The cost evaluation process for launch vehicles addresses the principal cost drivers in a program throughout the development, acquisition, and operational life-cycle of the program. Performance is linked with life-cycle cost, schedule, and risk estimates. The technologies involved in the program, both existing and proposed, are evaluated using cost growth models that correlate technology maturity and Technology Readiness Levels (TRLs) to cost and schedule growth. Cost estimates for the program include DDT&E, Operations and Maintenance (O&M), and disposal. These cost drivers are evaluated by a set of tools integrated within the modeling framework.

The DDT&E costs are determined by one of two acquisition strategies. The first acquisition strategy costs the vehicle development and production as new technology. The costs and schedules for producing the new technology vehicle are determined by using Congressional Selection Acquisition Reports (SARs) for historical programs at key systems engineering milestones. The milestones evaluated are:

- Authorization to Proceed (ATP)
- Preliminary design review (PDR)
- Critical design review (CDR)
- Flight Certification Authorization (FCA)
- Initial Operating Capability (IOC)

Cost growth factors are derived at these milestones for historical programs that have low, medium and high cost growth factors. The derived values are incorporated in the historical database. The anticipated growth rate for the program can be selected as well as the program phases to be analyzed. The second acquisition strategy is used for government furnished equipment (GFE) vehicles, such as the Minotaur launch vehicle family. The development costs are not needed for this acquisition strategy, but the external costs are included. External costs are defined as costs that are not included in the cost of the GFE. The external costs include contractor costs, refurbishment, vehicle enhancements, mission assurance, spaceport support, ground support, and other government costs.

CERs are applied at the major milestones of the work breakdown structure (WBS), such as ATP and CDR. The CERs are based primarily on subsystem weights and quantity. The CERs are refined further to account for material and configuration differences in the subsystems. The CERs are used to adjust the costs of the historical programs. Risk is applied to the costs at the major milestones to provide a low, high and most likely estimate. These risk factors are determined using a deterministic method-of-moments. The risks and costs are combined to provide an S-curve for each major design milestone. The S-curve is the probability of success versus the cost at each milestone. When the S-curve for each milestone is plotted on the same chart, the cost growth can be seen between the milestones. An example of a low-cost growth and a high-cost growth program are shown in Figure 3.

Figure 3a. Low-Cost Growth Curves

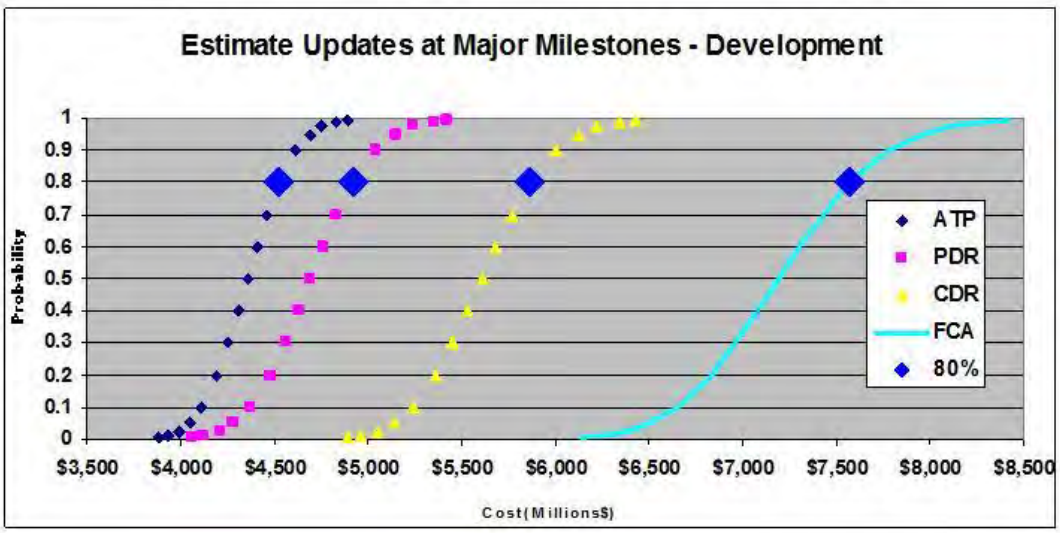

Figure 3b. High-Cost Growth Curves

The most likely cost is taken at 80 percent probability, shown in Figure 3. The 80 percent probability of success is the United States Air Force standard. For example in Figure 3b, the cost at the FCA milestone ranges from roughly $6.2B at zero percent probability to $8.4B at 100 percent probability and the most likely cost is roughly $7.5B. The shift from CDR to FCA in Figure 3b is roughly $1.7B using the 80 percent probability. This shift means that the cost of continuing the program from CDR to FCA will cost $1.7B and the cost of the program at FCA will be $7.5B with 80 percent probability. The shifts in cost in Figure 3a are not as drastic as the ones in Figure 3b, hence the classification of a low-cost growth program. The shifts are impacted by technology maturity and program complexity.

Incorporating accurate DDT&E and procurement costs are quintessential in the multidisciplinary analysis and design the space-launch system trade-space. While a vehicle can perform the mission within a given set of requirements, the cost of developing and procuring such a vehicle can be prohibitive. Evaluating the vehicle costs across the trade space allows for more informed decisions in choosing the best program. Accurate cost projections will mitigate a program's risk of reaching the Nunn-McCurdy line for Department of Defense funded programs.

An important part of the life-cycle cost for launch vehicles to evaluate is the ConOps. ConOps covers the evaluation of launch WBS, O&M, facility and labor costs, fleet readiness, availability, and reliability. The information from the performance module is passed to the life-cycle module to dynamically create a launch WBS, an O&M schedule, and facility and resource information for the desired mission. The O&M schedule and facility and resource information provide a starting point for a more detailed evaluation of the WBS and O&M. An example of the launch WBS is shown in Figure 4:

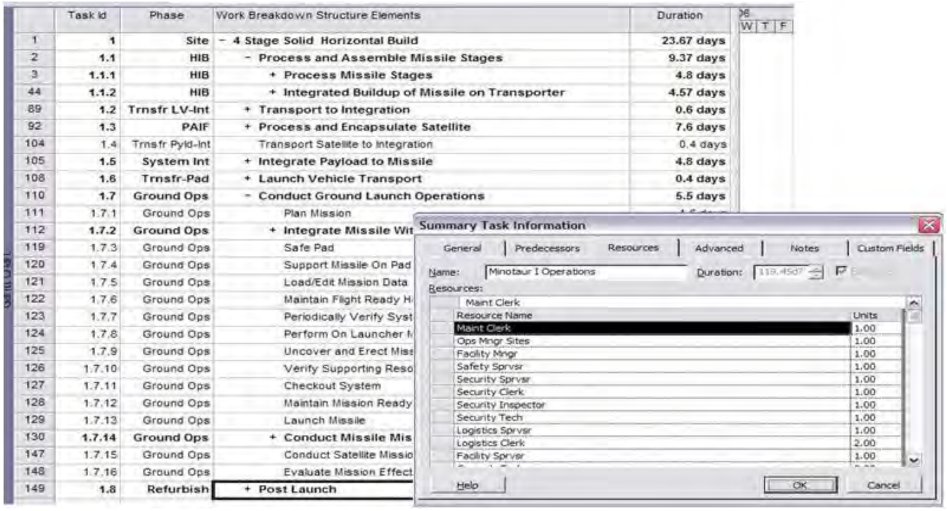

Figure 4. Sample Four Stage Rocket WBS

The launch WBS, shown in Figure 4, is dependent on mission type, launch vehicle, work schedule, and mission setup. The types of mission supported for the ConOps are:

- Planned launch rate
- Prompt global strike
- On alert
- Operationally responsive space

ConOps uses a historical database collected from many sources, including subject matter experts, regional salary tables, the Air Force Cost Construction Handbook and Department of Defense Facilities Pricing Guide to estimate the operations and facilities cost. Associated with the schedules are resources, also shown in Figure 5, broken down by labor categories, skill levels, and whether they are military, government or civilian contractors. The cost of supporting this schedule is the total salary cost for the launch vehicle location. The labor costs are determined from the WBS of launch operations and the length of program operations.

The work schedule is generated by determining how many hours per shift for each day worked per week. The schedule can be varied to determine how the work schedule impacts the launch WBS and labor costs. Build mode and launch mode will also impact the launch WBS. The build modes are vertical build and transport, horizontal build and transport, and build on the pad. The launch modes are ground launch, air launch from internal carriage, and air launch from external carriage. From the launch WBS, launch rate and fleet readiness are calculated. The facilities and support equipment quantities are a function of fleet readiness requirements and mission setup selections. Defaults for facilities and O&M tasks are provided by a default ConOps template, but can be tailored to specific launch sites and programs. The facilities cost can be analyzed as existing structures, modifications to existing structures, or structures that need to be built. Operations and sustainment factors are applied to the facilities costs for O&M to determine recurring costs.

The fleet readiness analysis is developed to support the defined launch rate and to identify the number of vehicles that need to be stored unassembled, assembled in storage, integrated with the payload, or on standby at the pad to meet the planned launch rate. The available assembly and integration cells can be varied in this analysis to determine the impact on the fleet readiness. In addition to the support level required to meet the launch rate, the analysis identifies the time it would take to reach the required state of readiness. Some situations will call for the addition of launch pads or facilities to meet the desired launch rate. The mission designer can evaluate the impact of additional cells and varied launch rates to determine how best to achieve the fleet readiness for the mission.

Launch availability is the probability of a vehicle launching on schedule. The module evaluates several factors that impact the availability of a launch. These factors are:

- Vehicle hardware

- Launch process complexity
- Facility complexity
- Weather
- Range
- Payload

The impact of each factor is determined by the historical database which contains the launch history for various launch vehicles. Launch impacts due to weather are linked to national weather databases to predict the conditions at the particular launch site and their impact on availability. In addition to the historical database, the availability is also impacted by secondary parameters that are based on engineering judgment and input from subject matter experts. These secondary parameters include the impact of a manned versus unmanned space vehicles and evaluate reusable vehicles with or without reentry, and parachute versus fly-back recovery.

Launch vehicle reliability focuses on flight failures, as they have the highest impact on overall cost. Launch failures are estimated from program start to maturity. As the program matures, the number of failures expected decreases and that decrease is incorporated in the model. Launch vehicle reliability is, in part, derived from historical launch programs such as the Delta, Minotaur, and Atlas programs. Additional evaluation criteria for launch vehicle reliability are derived from industry subject matter experts in the form of a survey. The relative impact of evaluation criteria is calculated using the Analytical Hierarchical Process (AHP). The score for each criterion is calculated based on mission designer input and relative weight. The resulting score from the survey is used to calculate an estimated failure rate and number of expected failures based on program maturity. History has shown that experienced launch teams, legacy components, and less complex launch vehicles have a higher success rate than inexperienced launch teams and newer and complex designs.

ConOps provides a comprehensive analysis of launch site operations to include in the multidisciplinary analysis of a space launch system. The mission designer has a tool to evaluate launch sites and the effects that launch rates, site facilities, and program maturity has on a desired launch campaign. The mission designer can analyze which sites and schedules can best fit the desired operation. ConOps identifies the baseline infrastructure, manpower, and launch processing activities required for launch operations of the satellite or post-boost vehicle.

III. Optimizing a Reusable Launch Vehicle (RLV) Design[5]

Fully reusable and partially reusable launch vehicle designs have been proposed not only for space transportation systems, but for responsive satellite launch and strike missions as well. A baseline reusable launch vehicle design was optimized for minimum gross-weight using the IPAT module of the ISCM tool suite. The launch vehicle must meet a variety of real-world constraints including launch azimuth, staging conditions, trajectory constraints and final orbit. The baseline vehicle, with a return-to-launch-site booster, that was analyzed is shown in Figure 5:

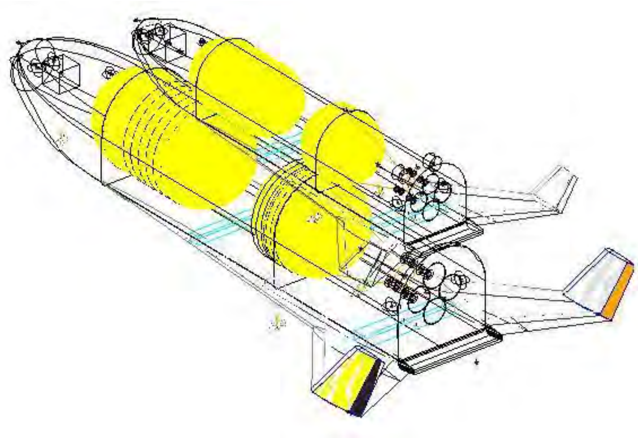

Figure 5. Baseline RLV

The vehicle shown in Figure 5 was constrained to an easterly launch from Kennedy Space Center, FL to a 100 by 100 nautical mile orbit with a 15,000 lbm payload. The gross orbiter weight for the baseline vehicle was 661,000 lbm and the gross booster weight was 2,270,000 lbm. The fuel was RP-1 with liquid oxygen used as the oxidizer.

The baseline design underwent iterations that featured changes in geometry and constraints. The geometric changes dealt with the wing shape, tank size and outer mold-line. The constraints that were changed involved staging velocity, thrust-to-weight ratio, target orbit and maximum acceleration. The relationship between staging velocity and maximum acceleration was studied prior to optimizing the launch vehicle and the study results were applied to the optimization of the launch vehicle. The baseline vehicle weights, staging velocity and maximum acceleration are shown in Table 1:

Table 1. Baseline RLV Staging Velocity and Weights

	Booster	Orbiter
Staging Velocity (ft/s)	7,000	7,000
Maximum Acceleration (g's)	3.5	3.5
Dry Weight (lbm)	205,570	122,292
Gross Weight (lbm)	2,269,810	661,354

The gross weight of the booster in Table 1 includes the gross orbiter weight as well. An additional study was performed on the aerodynamics of the booster to incorporate into the optimized vehicle model. The staging velocity/acceleration study provided better starting points for the optimization. The aerodynamic side-study was necessary due to failed fly-back trajectories. The vehicle design sensitivity is shown in Figure 6:

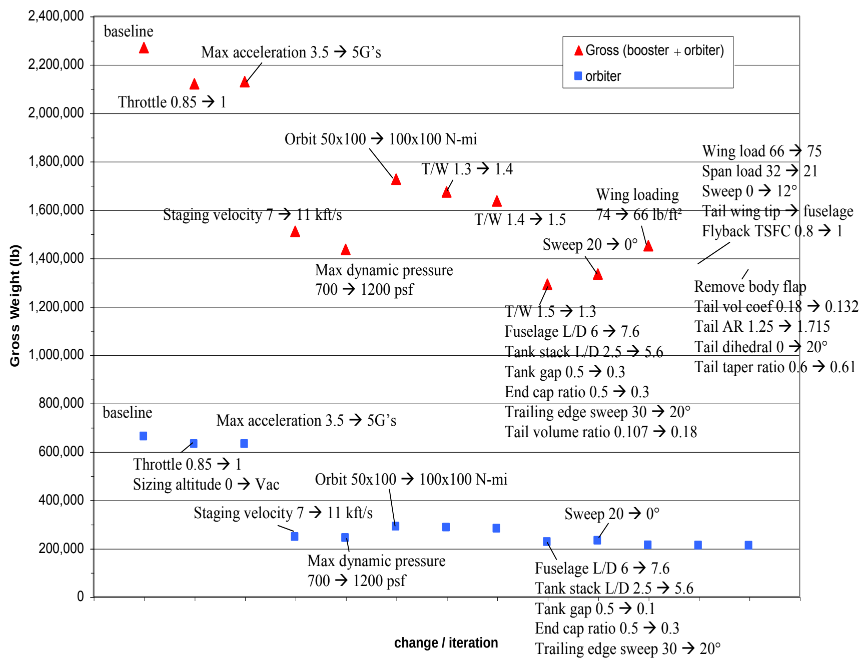

Figure 6. RLV Design Sensitivity

The points in Figure 6 illustrate the vehicle gross weights during the iteration process for various performance, trajectory and geometric constraints. The initial changes to thrust-to-weight are due to errors in the calculation. The change in orbit was due to changing from the default of 50 nmi by 100 nmi orbit to the desired 100 nmi by 100 nmi orbit.

The result of the multidisciplinary optimization routine was a 39-percent reduction in gross weight. The orbiter and booster are significantly thinner and have an improved wing shape for transonic flight. The optimized design is shown in Figure 7.

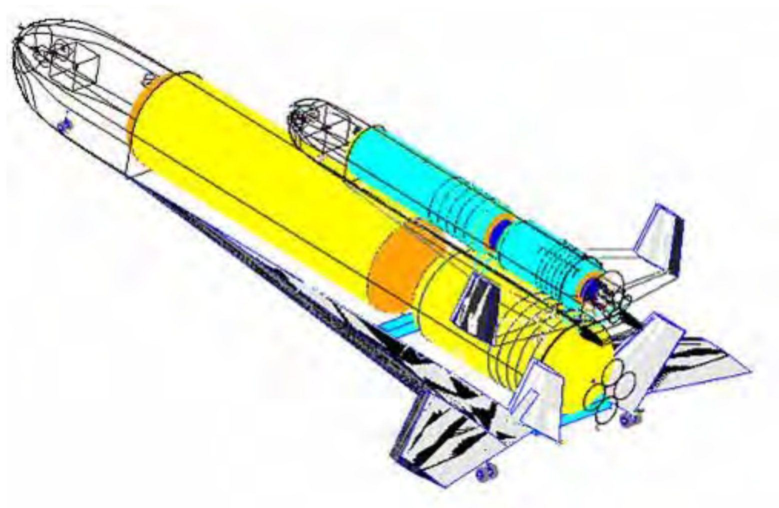

Figure 7. Optimized RLV

The reusable design shown in Figure 7 is also longer than the baseline version. This is due to the adjustment of the length-to-diameter ratio during the optimization process. The optimized design's weights, staging velocity and maximum acceleration are shown in Table 2:

Table 2. Optimized RLV Staging Velocity and Weights

	Booster	Orbiter
Staging Velocity (ft/s)	11,000	11,000
Maximum Acceleration (g's)	5.52	5.52
Dry Weight (lbm)	84,769	33,692
Gross Weight (lbm)	1,382,515	210,875

The staging velocity of 11,000 ft/s and acceleration of 5 g's in Table 2 was determined from the staging velocity/acceleration study done prior to modeling. Other staging velocity and maximum acceleration combinations were also modeled. The results of those additional models are shown in Table 3:

Table 3. RLV Weight at Various Staging Velocities

Staging Velocity (ft/s)	11,000	9,000	7,000
Acceleration Limit (g's)	5.52	5	5
Total Vehicle Weight (lbm)	1,382,515	1,463,043	1,790,531
Booster Dry Weight (lbm)	74,099	65,808	85,944
Orbiter Dry Weight (lbm)	33,337	40,985	59,082
Combined Dry Weight (lbm)	107,436	106,793	145,026

As shown in Table 3, the 11,000 ft/s velocity yielded the lowest gross vehicle weight. However, further study showed the heating environment experienced by the 9,000 ft/s and the 7,000 ft/s boosters is much more benign than the 11,000 ft/s booster. Expanding the trade space to address the pros and cons of various designs quickly is one of the main benefits of multidisciplinary analysis and optimization.

IV. Benefits of Adding Cost and Operations Modeling

The benefits of using MA&O for space launch vehicles are increased performance, rapid evaluation of the trade space, and end-to-end cost and operations evaluations. The performance optimization of an RLV was outlined in the previous section. The result of the multidisciplinary optimization was a 39-percent reduction in gross vehicle-weight. The performance model also explored other designs and examined their heating environments. The process provided a deeper look at the trade space that traditional design teams may never reach. However, cost and operations were not explored for the RLV study, because the cost and operations modules for RLVs at the time of the study were not complete and the task order did not require cost and operations modeling. Incorporating models for the cost and operations of a design allows for evaluation of a program on the whole, not just the performance aspects. These advantages are not limited to space launch vehicles and can be seen in the design of other systems, such as blended-body aircraft and hypersonic vehicles.

In general, the increased performance of a system is the main benefit of the multidisciplinary approach to design. The optimization process can find minima and maxima points in the design space that traditional design teams may never get to. The method exploits the synergy between system components and functions to increase performance while reducing system weight and cost[6]. Additionally, exploration of the system trade space can be done by modeling and simulating multiple changes over the system, as seen with the RLV study that was presented. The multidisciplinary analysis and optimization methods explore the impacts that one discipline has on another, and this interaction of disciplines allows for designers and analysts to rapidly evaluate the impact of a change to a given subsystem. Typical design teams would take weeks to assess the design space for each change. The multidisciplinary method allows for a rapid assessment of the trade space in days, not the weeks traditional design teams take.

The ISCM tool suite incorporates the additional benefits of cost, operations, and risk modeling for space vehicles and launch vehicles. Cost estimation allows for more informed decisions by managers about investment into new technologies and what programs should be funded. Combining performance, cost, operations, and risk estimates into an integrated model creates a deeper understanding of the program as a whole. ISCM's approach to a program is shown in Figure 8:

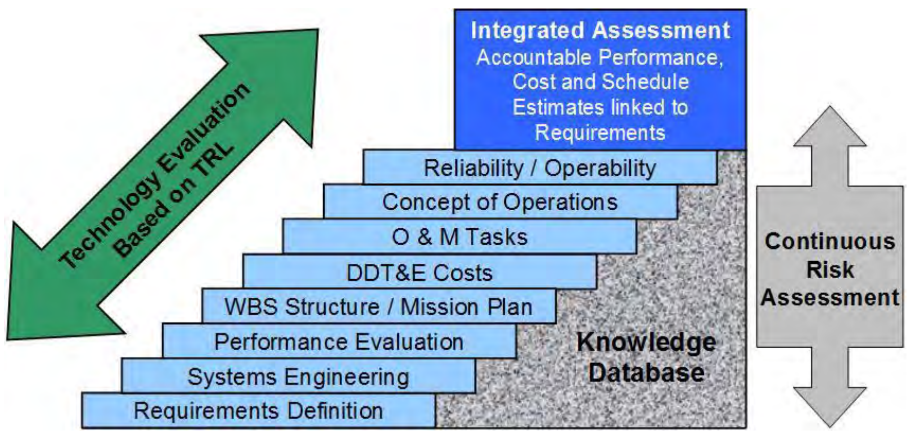

Figure 8. ISCM Integrated Assessment Approach

As shown in Figure 8, the models build on one another starting from requirements definition to reliability and operability. Performance is a small part of the overall program, but an important part in estimating the costs and ConOps. The knowledge database is linked to all steps of the program and uses information from previously modeled programs to improve the model. A knowledge database that updates with use provides improved estimates. This translates into fewer programs that exceed the Nunn-McCurdy Line and more programs on-budget.

Complete life-cycle cost estimation also assesses the operations and maintenance effects of new designs. This provides a perspective on how a new design can get the mission done and how the design affects the operations, facilities and schedule. The addition of a ConOps model to the multidisciplinary methods provides an end-to-end perspective of a program that can identify trouble spots of supporting a new design. The model can also be used to assess construction and other modifications to existing launch sites to support new vehicles. This overall view of the program and facilities and labor needs allows program managers to make a decision on a design that will not only fulfill the performance requirements of the mission, but will fulfill the operation requirements early on in the design phase. ISCM has the additional benefit of being able to fight requirement creep and immaturity. A system concept trade study and analysis will capture, develop, refine and validate system requirements. It will also identify, assess and quantify the operational, technical and programmatic impacts of requirement changes[7]. By catching unsustainable and unrealistic requirements early, the poor requirements that would lead to significant increases in life-cycle cost can be changed, improved, or eliminated.

V. Verification and Validation Study

Verification and validation of any tool is necessary to ensure the calculations and results are acceptable to use in industry. The verification and validation study in the scope of this paper provides another example of multidisciplinary analysis and an example of the cost model and operations model results for expendable launch vehicles. Four launch vehicles were chosen to verify and validate the launch vehicle module, the Integrated Propulsion Analysis Tool (IPAT), of the ISCM tool suite. The launch vehicles chosen were the Atlas V 401, Delta II 7426-10, Falcon I, and the Minotaur I. The launch systems chosen are shown in Figure 9:

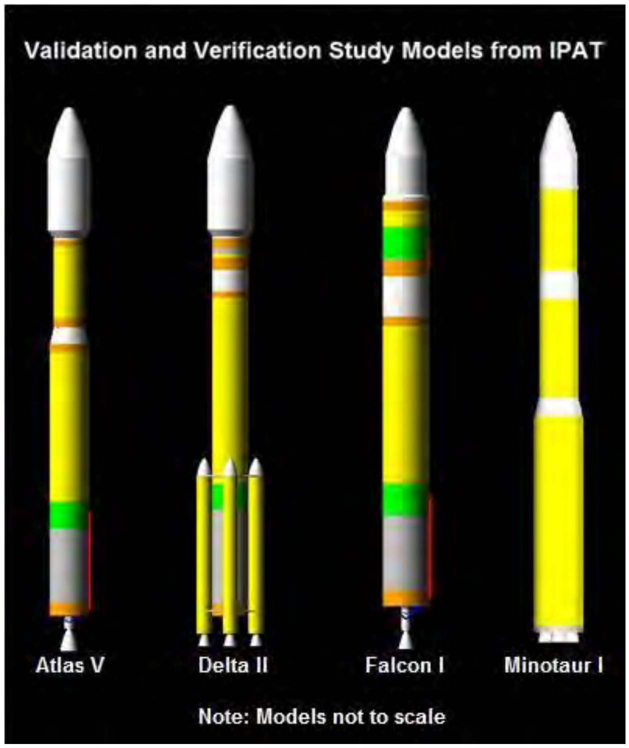

Figure 9. V&V Launch Vehicle Models

The Atlas, Delta and Minotaur were chosen due to the availability of information about them. The Falcon I was chosen to evaluate the tool's performance on a new launch vehicle concept. The performance values, the cost estimates, and ConOps were compared to published values for each launch vehicle.

The DDT&E cost estimates were generated by the Advanced Cost Model integrated into IPAT. The new technology, development and production acquisition strategy was chosen for the Atlas V, Delta II, and Falcon 1 launch vehicles and the GFE acquisition strategy was used for the Minotaur I launch vehicle. The acquisition method for the three liquid-propulsion vehicles requires a buy scenario or a production schedule to estimate the production costs. The inputs were left at their defaults for the study except for the number of launches was set to 30, which models six launches per year for five years. The GFE acquisition method for the Minotaur I also used the defaults, but modeled the production of 10 launch vehicles.

The ConOps model is used to describe the infrastructure, manpower, and launch processing functions needed to support the mission. Some operations are common between each launch vehicle, while the unique aspects are determined by options chosen by the user and additional operations can be added in the Microsoft Project WBS. The areas of ConOps modeled for each vehicle are operations flow, facilities' requirements, labor requirements, fleet readiness, reliability, and availability. The key inputs for a launch vehicle are launch vehicle type, build and launch modes, launch site facilities, number of launches over launch campaign, and support schedule.

The Atlas V payload planner's guide was used to set the constraints on the Atlas V 401 model. In some instances, a contingency weight was applied to match the weights from the tool to the documented value. The contingency weight option was used to compensate for the empirical weight estimations. As shown in Table 4, the values from IPAT match fairly well with the documented values. The green highlighted values in the IPAT values column represent the inputs into IPAT. The other values are outputs from the tool.

Table 4. Atlas V Data[8-10]

	IPAT Value	Documented Value
Performance Model		
Payload (lbm)	17,141	17,141
Fairing (lbm)	4,982	5,046
Upper Stage		
Vacuum Thrust (lbf)	22,301	22,301
C* Efficiency	0.944	*
Vacuum Isp (s)	450.5	450.5
ΔV (ft/s)	16,126	16,457
Propellant Load (lbm)	45,921.7	45,922
Contingency Weight (lbm)	-797	0
First Stage		
Sea Level Thrust (lbf)	860,344	860,344
C* Efficiency	0.943	*
Sea Level Isp (s)	311.3	311.3
ΔV (ft/s)	19,434	19,765
Propellant Load (lbm)	626,252	626,309
Contingency Weight (lbm)	-4,367	0
Advanced Cost Model		
6 Development/30 Production, 80% Probability of Success		
Total Program Cost (BY09 $)	10.17B	*
Procurement AUC (BY09 $)	339M	*
SE/PM (BY09 $)	31.85M	*
Mission Assurance (BY09 $)	1.36M	*
Mission Success (BY09 $)	4.67M	*
Award Fee (BY09 $)	10.63	*
Launch Operations (BY09 $)	99.34M	101.73M (adjusted for inflation)
GSE (BY09 $)	9.99M	*
Range (BY09 $)	3.37M	*
Group Support (BY09 $)	48.67M	*
Operations & Maintenance		
Vertical Build & Transport (days)	16	18
Facilities, 10 year maintenance	24.4M	*
Labor, 10 years	222.5M	*
Availability (%)	53	47

Note: * symbolizes documented values that were not found during the study.

The performance values in Table 4 match within two percent prior to the addition of the contingency weights, while the cost and operations values match well with the available data. The Atlas was modeled launching from Vandenberg Air Force Base to low Earth orbit for the maximum payload. The documented cost numbers for this model come from published budgets, articles and reference guides.

The Delta II model used information from the payload planner's guide as well as data from the Space and Tech website, www.spaceandtech.com, to determine the constraints. The 7426-10 version of the Delta II consists of the standard Delta II two-stage rocket with a Star 37 third stage and four GEM boosters. The documented and modeled values are shown in Table 5.

Table 5. Delta II Data[11-13]

	IPAT Value	Documented Value
Performance Model		
Payload (lbm)	1,979	1,979
Fairing (lbm)	2,300	2,300
Upper Stage (Star 37FM)		
Vacuum Thrust (lbf)	10,625	10,625
Vacuum Isp (s)	291.9	289.8
Propellant Load (lbm)	2350.1	2350
Second Stage		
Fuel	Aerozine	Aerozine-50
Oxidizer	NTO	NTO
Vacuum Thrust (lbf)	9,815	9,815
C* Efficiency	0.933	*
Vacuum Isp (s)	319.4	319.2
ΔV (ft/s)	10,090	*
Propellant Load (lbm)	13,235	13,236
Contingency Weight (lbm)	928	0
First Stage		
Vacuum Thrust (lbf)	200,000	200,000
C* Efficiency	0.857	*
Vacuum Isp (s)	301.5	301.7
ΔV (ft/s)	18,703	*
Propellant Load (lbm)	211,321	211,220
Contingency Weight (lbm)	-3,149	0
Advanced Cost Model		
6 Development/30 Production Vehicles, 80% Probability of Success		
Total Program Cost (BY09 $)	3.81B	*
Procurement AUC (BY09 $)	189.23M	166.23M (adjusted for inflation)
SE/PM (BY09 $)	17.8M	*
Mission Assurance (BY09 $)	0.8M	*
Mission Success (BY09 $)	2.6M	*
Award Fee (BY09 $)	5.9M	*
Launch Operations (BY09 $)	55.5M	58.26M (adjusted for inflation)
GSE (BY09 $)	5.6M	*
Range (BY09 $)	1.9M	*
Group Support (BY09 $)	27.2M	*
Operations & Maintenance		
Build on Pad (days)	31	35
Facilities, 5 Year Maintenance (BY09 $)	27.4M	*
Labor, 5 Years (BY09 $)	121.4M	*
Availability (%)	40.7	42.4

Note: * symbolizes documented values that were not found during the study.

The values in Table 5 for IPAT match well, within two percent for performance, with the documented values. The cost numbers estimated by the IPAT module use the 80-percent probability. As shown in Table 2, the procurement cost is higher than the documented cost. The higher cost is attributed to the probability setting of 80 percent.

The Falcon I launch vehicle model was constructed using the payload planner's guide and SpaceX's responsive launch demonstration report. The streamlined operations of the Falcon I caused a greater gap between the modeled and documented costs, but the values for performance matched within two percent. The values are shown in Table 6:

Table 6. Falcon 1 Data[14-17]

	IPAT Value	Documented Value
Performance Model		
Payload (lbm)	800	800
Fairing (lbm)	332	320
Upper Stage		
Vacuum Thrust (lbf)	6,900	6,900
C* Efficiency	0.847	*
Vacuum Isp (s)	317	317
ΔV (ft/s)	15,723	*
Propellant Load (lbm)	8,900	8,900
Contingency Weight (lbm)	221	0
First Stage		
Sea Level Thrust (lbf)	78,000	78,000
C* Efficiency	0.853	*
Vacuum Isp (s)	300	300
ΔV (ft/s)	13,824	*
Propellant Load (lbm)	37,383	47,380
Contingency Weight (lbm)	-1,133	0
Advanced Cost Model		
6 Development/30 Production Vehicles, 80% Probability of Success		
Total Program Cost (BY09 $)	2.91B	*
Procurement AUC (BY09 $)	96.5M	10.9M (Falcon 1e launch price)
SE/PM (BY09 $)	9.1M	8.8M
Mission Assurance (BY09 $)	0.4M	*
Mission Success (BY09 $)	1.3M	*
Award Fee (BY09 $)	3.0M	*
Launch Operations (BY09 $)	28.3M	24.2M
GSE (BY09 $)	2.8M	*
Range (BY09 $)	1.0M	3.046M
Group Support (BY09 $)	13.9M	*
Operations & Maintenance		
Build on Pad (days)	22	7
Facilities, 5 Year Maintenance (BY09 $)	44.1M	*
Labor, 5 Years (BY09 $)	93.3M	*
Availability (%)	71.3	20

Note: * symbolizes documented values that were not found during the study.

As shown in Table 6, the procurement costs are vastly different, over $80 million. The other documented costs are within reason. The other difference of note is the build time. The difference of 15 days can be contributed to lean nature of SpaceX's operations.

The Minotaur I model was constructed using the International Reference Guide to Space Launch Systems. The reference guide also provided cost estimates. The type of values calculated for the Minotaur I's performance and cost were different than the previous vehicles. The difference in performance is due to the difference in type of propulsion. The previous vehicles use liquid-fueled rocket engines while the Minotaur I uses solid rocket stages and was evaluated using existing motors from the IPAT database. The values for the vehicle performance, cost, and operations of the Minotaur I are shown in Table 7.

Table 7. Minotaur I Data[12, 18-19]

	IPAT Value	Documented Value
Performance Model		
Payload (lbm)	538.33	418
Fairing (lbm)	373	427
<u>Fourth Stage</u>		
Average Thrust (lbf)	7121.19	7200.0
Vacuum Isp (s)	290.1	290.1
Nominal Burn Time (s)	67.38	69.6
Propellant Weight (lbm)	1699	1699
Propellant Mass Fraction	0.859	0.86
Empty Weight (lbm)	278	278
Stage Weight (lbm)	1977	1977
<u>Third Stage</u>		
Average Thrust (lbf)	33450.05	34500.0
Vacuum Isp (s)	289.0	289.0
Nominal Burn Time (s)	70.75	72.5
Propellant Weight (lbm)	8589	8633
Propellant Mass Fraction	0.899	0.900
Empty Weight (lbm)	962	918
Stage Weight (lbm)	9551	9551
<u>Second Stage</u>		
Average Thrust (lbf)	60360.59	60300.0
Vacuum Isp (s)	287.5	287.5
Nominal Burn Time (s)	60.26	65.54
Propellant Weight (lbm)	13753	13753
Propellant Mass Fraction	0.886	0.890
Empty Weight (lbm)	1753	1524
Stage Weight (lbm)	15506	15506
<u>First Stage</u>		
Average Thrust (lbf)	174856.50	178000.0
Vacuum Isp (s)	237.0	237.0
Nominal Burn Time (s)	58.03	60.8
Propellant Weight (lbm)	45830	45830
Propellant Mass Fraction	0.900	0.900
Empty Weight (lbm)	5055	4955
Stage Weight (lbm)	50885	50885
Advanced Cost Model		
Total Program Cost (BY09 $)	179.084M	194.3M-228.6M
Single Launch Cost (BY09 $)	20.524M	19.4M-22.8M (adjusted for inflation)
Contractor (BY09 $)	10.987M	*
Enhancements (BY09 $)	0.518M	*
Mission Assurance (BY09 $)	1.728M	*
Mission Success (BY09 $)	1.037M	*
Mission Support (BY09 $)	0.216M	*
Booster Refurbishment (BY09 $)	0.518M	*

Note: * symbolizes documented values that were not found during the study.

Table 7. Minotaur I Data Continued

	IPAT Value	Documented Value
Spaceport (BY09 $)	0.648M	*
Range (BY09 $)	2.591M	*
Group Support (BY09 $)	0.432M	*
Risk – 10% (BY09 $)	1.866M	*
Operations & Maintenance		
Horizontal Build/Transport (days)	32.11	45
Facilities, 10 years (BY09 $)	20.0M	*
Labor, 10 years (BY09 $)	177.3M	*
Availability (%)	84	20

Note: * symbolizes documented values that were not found during the study.

As shown in Table 7, the availability of the Minotaur I launch vehicle is predicted to be much greater than the documented values have shown. The difference is due to the limited number of Minotaur I launches that have taken place. The total program cost was assumed to be between 10 times the lowest and 10 times the highest single launch costs, because only 10 Minotaur I vehicles were modeled.

The performance models in IPAT are accurate, generally within two percent, due to their years of development. With the weight models at that level of accuracy the predictions for conceptual vehicle design have a greater fidelity. Additionally, for modeling existing vehicles, the contingency weight capability can be used to match known weights exactly, which allows for accurate performance analysis.

For the cost and operations estimates, the results are generally less accurate than the performance estimates due to the complexity of the relations and number of variables involved. However, the better the data is that is used to build the models, the more reasonable the estimates become. For conceptual design, where the tool suite will primarily be used to perform trade studies between different potential concepts, the estimates should prove useful to compare relative costs of different approaches.

VI. Conclusion

The design of space launch vehicles can benefit from the use of multidisciplinary optimization and analysis. The subsystems can be linked using modeling frameworks. The link between subsystems allows the designer to see the effects of requirements throughout the system in a timely manner. The traditional method of design teams takes weeks to assess the impact of requirements and requirement changes. The multidisciplinary process will reduce design times and can produce results in days. The minima and maxima of various systems can be found using this method where design teams may never find those optimal points in a design.

The addition of cost, operations, and risk modeling in a tool suite, like ISCM, allows for an end-to-end evaluation of a system. The cost modeling of new systems will reduce the number of programs that cross the Nunn-McCurdy Line and produce more programs that are on-budget. The complete end-to-end view provides the complete picture and identifies areas of risk so that mitigation plans can be implemented to minimize the impact of these risks. The designers and program managers will have complete view of how requirements and new technologies affect the program on a global scale. This leads program managers to invest precious dollars into the right technologies and designs.

The performance of an RLV design concept was optimized for minimum gross weight using the ISCM tool suite. The result was nearly a 40-percent reduction in overall weight. The four areas of performance, cost, operations, and risk also underwent a verification and validation process using four existing launch vehicles. The Atlas V, Delta II, Minotaur I, and Falcon I vehicles were chosen and the results were encouraging. The performance values generated by ISCM's multidisciplinary process matched within two percent of published values. Cost and operations values matched well with the published values that were available. The biggest difference in cost and operations was found with the Falcon I. This is attributed to the shift SpaceX has made from traditional launch vehicle operations.

The ISCM tool suite incorporates four key areas of design (performance, cost, operations, and risk). The ISCM tool suite addresses the need for a tool that can provide evaluations of a space system's performance, cost, ConOps, and risk. The application of multidisciplinary methods in ISCM for space systems enable mission designers and program managers to identify unsustainable and unrealistic requirements early in the design process and complete a systematic evaluation of the program early in the pre-acquisition phase minimizing the cost overruns and schedule delays being experienced today. The methodology of the evaluation of designs can be expanded to other systems such as air and ground assets and provide a complete tool suite for the acquisition process. The modular approach to ISCM allows for easy integration of industry tools to expand ISCM's evaluation to more systems. The ISCM tool suite provides a benefit to the aerospace industry by modeling a system from conceptual design to program retirement.

Future Work

Currently the ISCM tool suite addresses space launch systems and space vehicles. The cost modeling capabilities for those systems are being expanded. Specifically, the DDT&E cost evaluation and operations and maintenance evaluation for partial and fully reusable launch vehicles are being developed. The ConOps for the space vehicles is also being addressed and new technologies being developed by the Air Force are being incorporated into the tool. As with any modeling and simulation software, the tool suite needs to undergo a complete verification, validation and accreditation. This can be done in part by demonstrating the tool suite's capabilities on an Air Force acquisition program. Additional systems will also be added to the tool suite as needs and customers become available for them. The types of systems to be developed in the foreseeable future are shown in Figure 10:

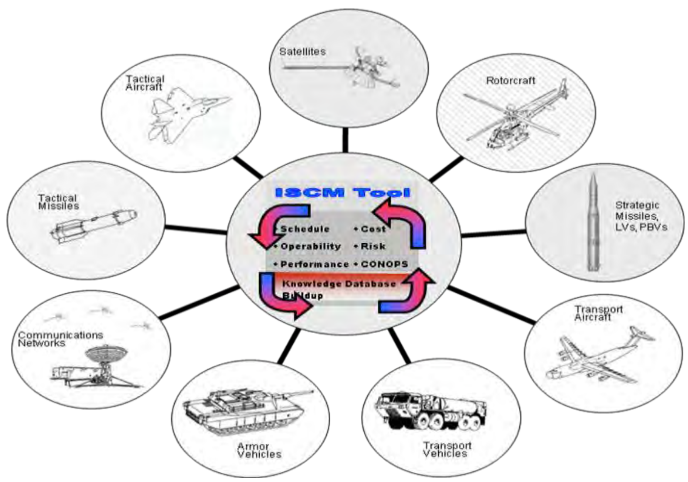

Figure 10. Systems to be supported by ISCM

As shown in Figure 10, the systems include space assets, air assets and ground vehicle assets. The multidisciplinary analysis and optimization methodology and modular approach used for the space launch systems and space vehicles will be applied to the proposed systems.

Acknowledgments

The author would like to acknowledge the Air Force Research Laboratory Space Vehicle Directorate and Propulsion Directorate Assessment and Analysis branch in supporting the development of the ISCM tool suite. This work was conducted under contract FA9300-06-D-0003 for the Air Force Research Laboratory – Edwards AFB. The publication of this document does not indicate endorsement by the Air Force Research Laboratory – Edwards AFB, nor should the contents be construed as reflecting the official position of that Agency. This material may be reproduced by or for the U.S. Government pursuant to the copyright license under the clause at DFARS 252.227-7013.

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Optimal Vehicle Design Using the Integrated System and Cost Modeling (ISCM) Tool Suite

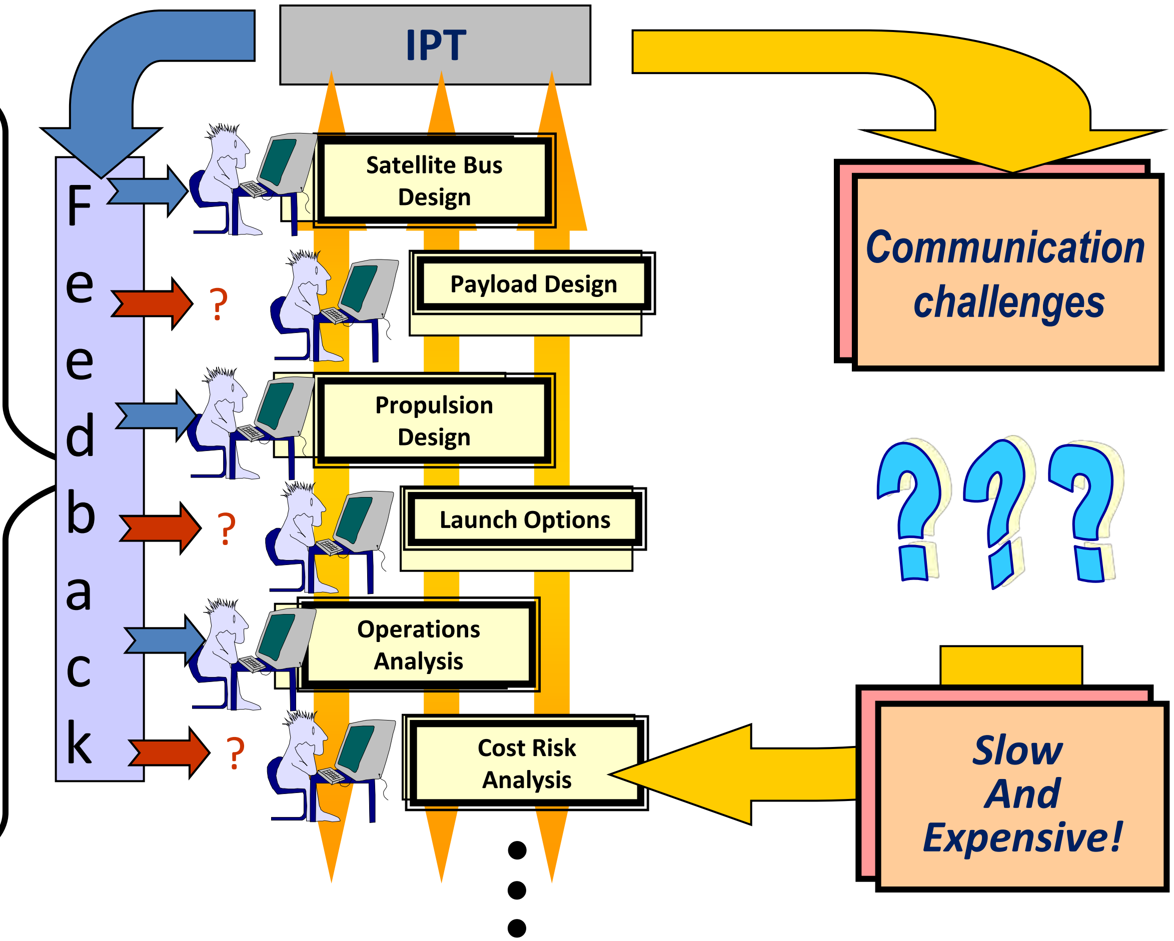
Presenter: Michael O'Such

Early Design Methodology

<u>Early Design Challenges</u> of High-Performance Complex Systems

Mission/System Requirements

- Operational Assumptions, Conditions and Constraints
- Size, weight, power
- New technology insertion
- Performance
- Schedule
- ⋮



Cost Growth Factors

- At least 80% of the life-cycle cost is determined by decisions made in the conceptual design phase[1]
  - Presence of overstated and unstable requirements that are difficult to evaluate during source selections
  - Optimistic Estimates
  - Inadequate pre-acquisition planning and risk reduction
- Historical programs have seen significant increases in cost and schedule as they transition from system-need definition to system delivery and initial operating capability

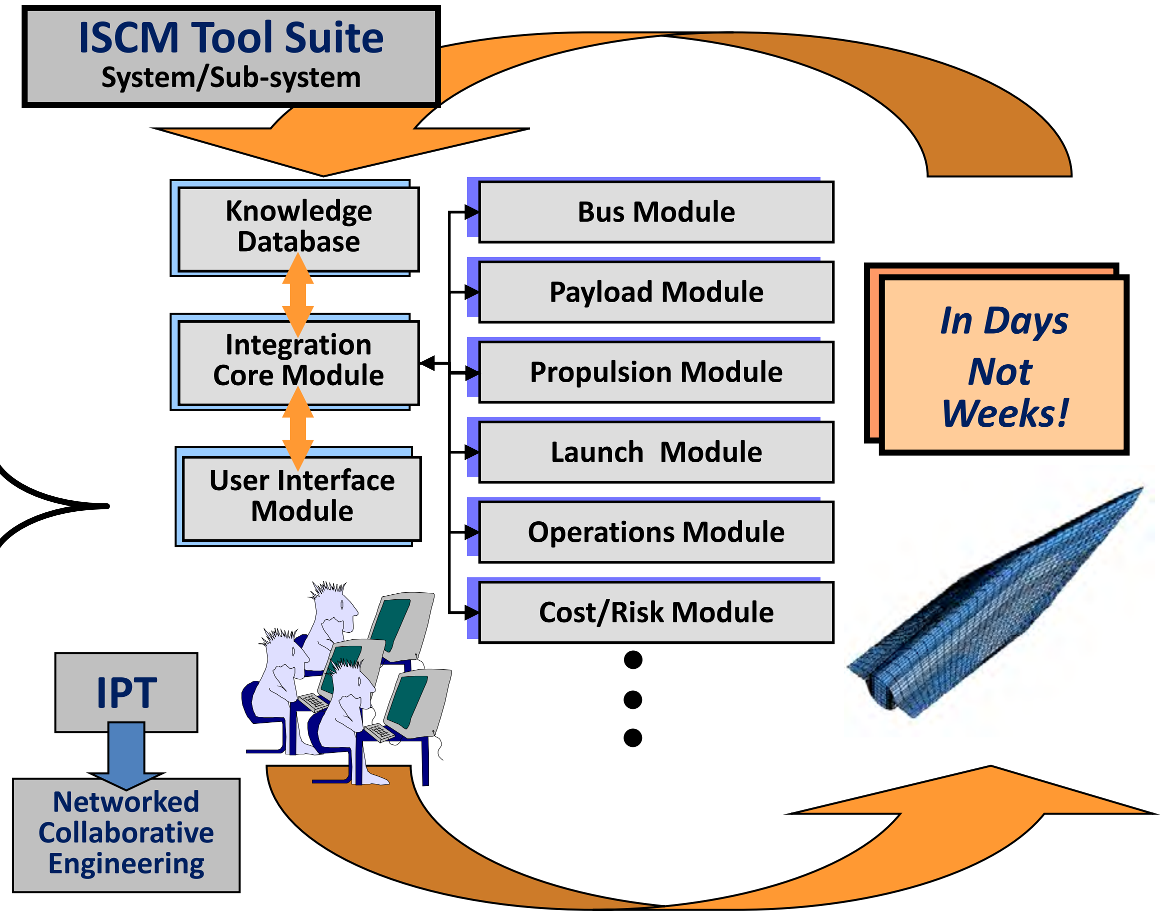
[1]Blair, J. C., George C., *Launch Vehicle Design Process: Characterization, Technical Integration, and Lessons Learned*, Marshall Space Flight Center, AL, 2001.

ISCM MA&O Design Process

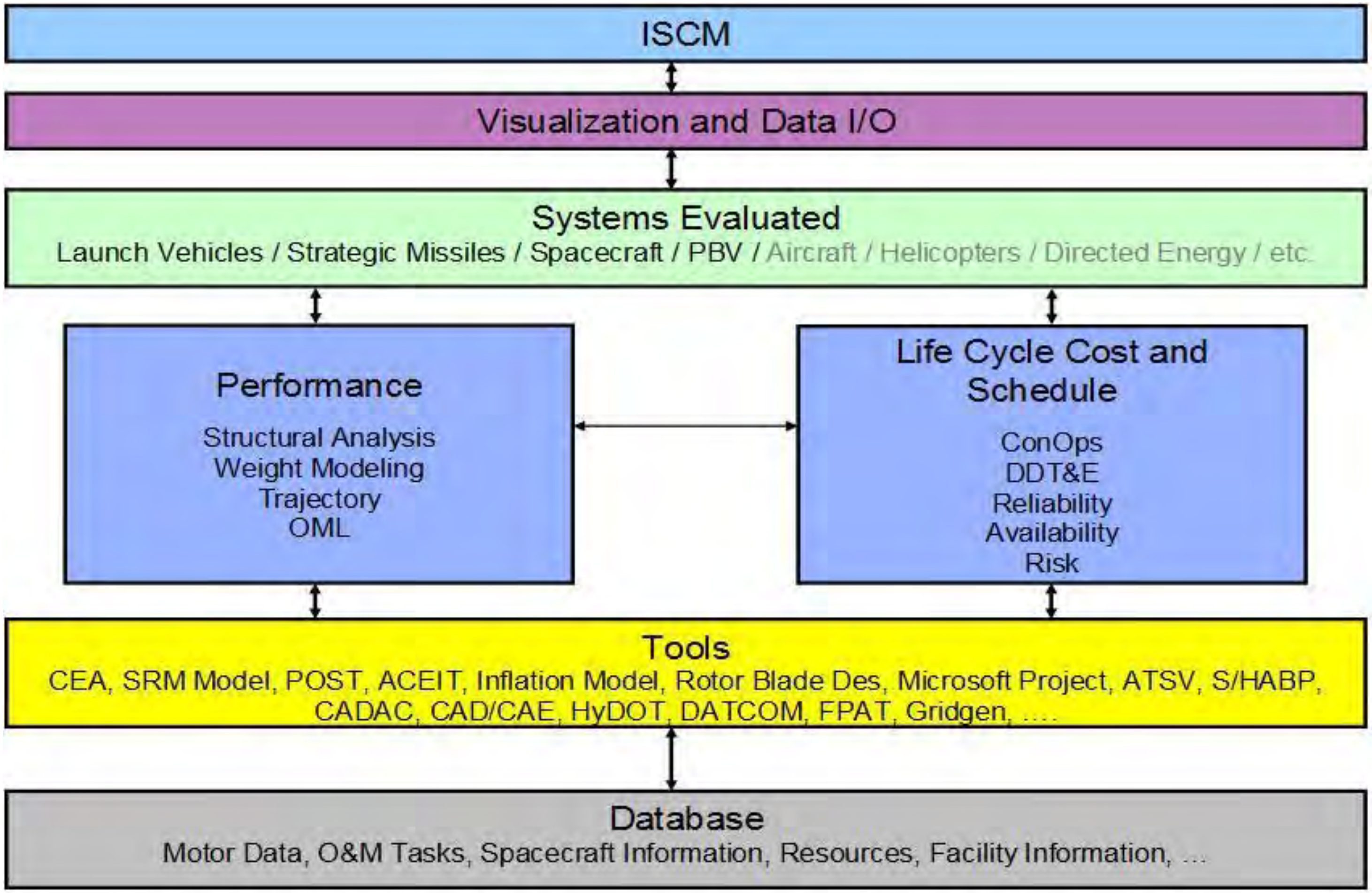
Solution to Early Design Challenges of High-Performance Complex Systems

Mission/System Requirements

- Operational Assumptions, Conditions and Constraints
- Size, weight, power
- New technology insertion
- Performance
- Schedule
- •
- •
- •



ISCM Architecture Overview



Space Mission Modules Overview

Launch Vehicle Design Module

Integrated Propulsion Analysis Tool (IPAT)

- Launch Vehicle Design
- Trajectory analysis **(POST)**

Life Cycle Cost Model

Space Vehicle - Launch Vehicle

Development & Production Cost

- LCC Cost/Risk
- TRL
- Cost Growth

O&M Cost Module

- Mission
- ConOps
- Infrastructure
- Resources

Space Vehicle Design Module

Advanced Computational Engineering Simulator – Integrated Space Engineering Tool (ACES-ISET)

- Space Vehicle Design **(SMAD)**
- Space Vehicle Propulsion
- Orbit Propagation
- Space Vehicle Costing **(ACEIT)**
- New Small Sat Model
  - Radiation Exposure
  - Radiation Detector Response
  - On Orbit Operations

Visualization

ATSV – Trade space

STK, SOAP – Specific mission

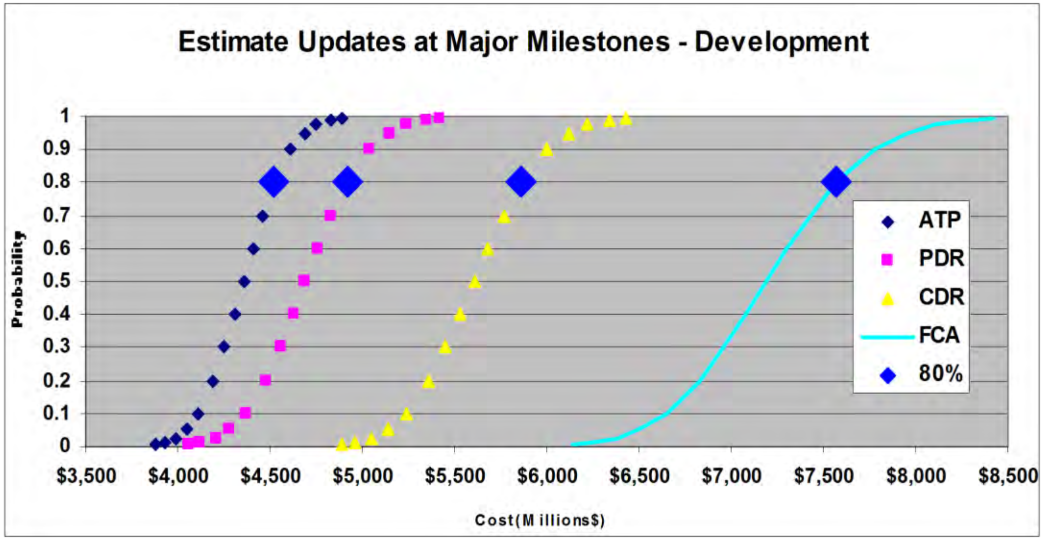
Historical/Knowledge Database

Launch Vehicle Design Overview

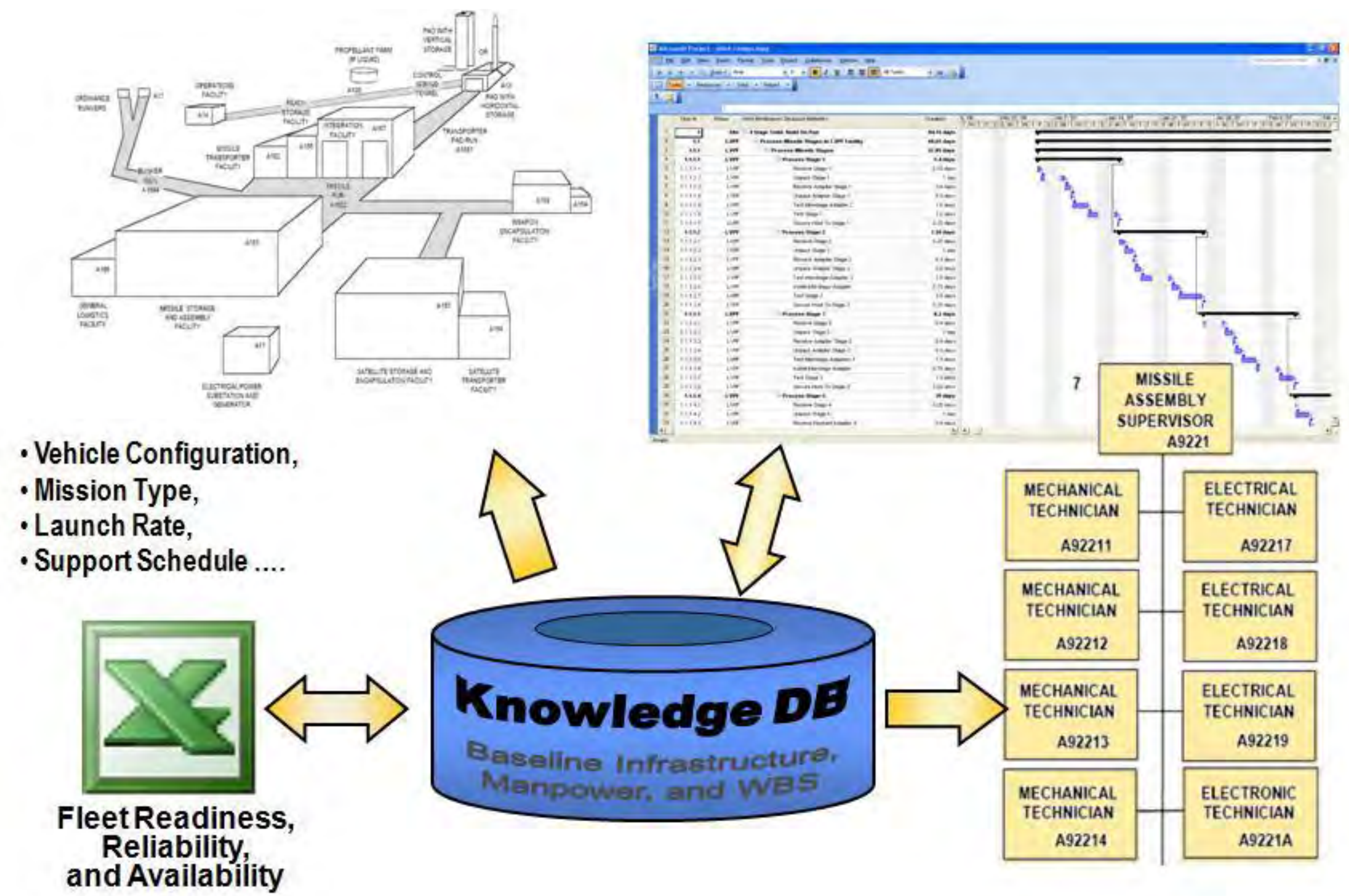
- Developed for rapid assessment of launch vehicle designs for Air Force Research Laboratory – Assessment and Analysis Branch
- Various propulsion types modeled:
  - Liquid
  - Solid
  - Hybrid
  - Air-breathing
  - Rocket-based combined-cycle
- Various vehicle types modeled:
  - Expendable Launch Vehicle (ELV)
  - Reusable Launch Vehicle (RLV)
  - Strategic Missiles including ICBMs
  - Common Aero Vehicle (CAV)
- Integration of over 20 industry standard tools including CEA, POST, MINIVER, Missile-DATCOM
- Advanced Cost Model (ACM) used to estimate development and production costs

Cost Estimation Overview

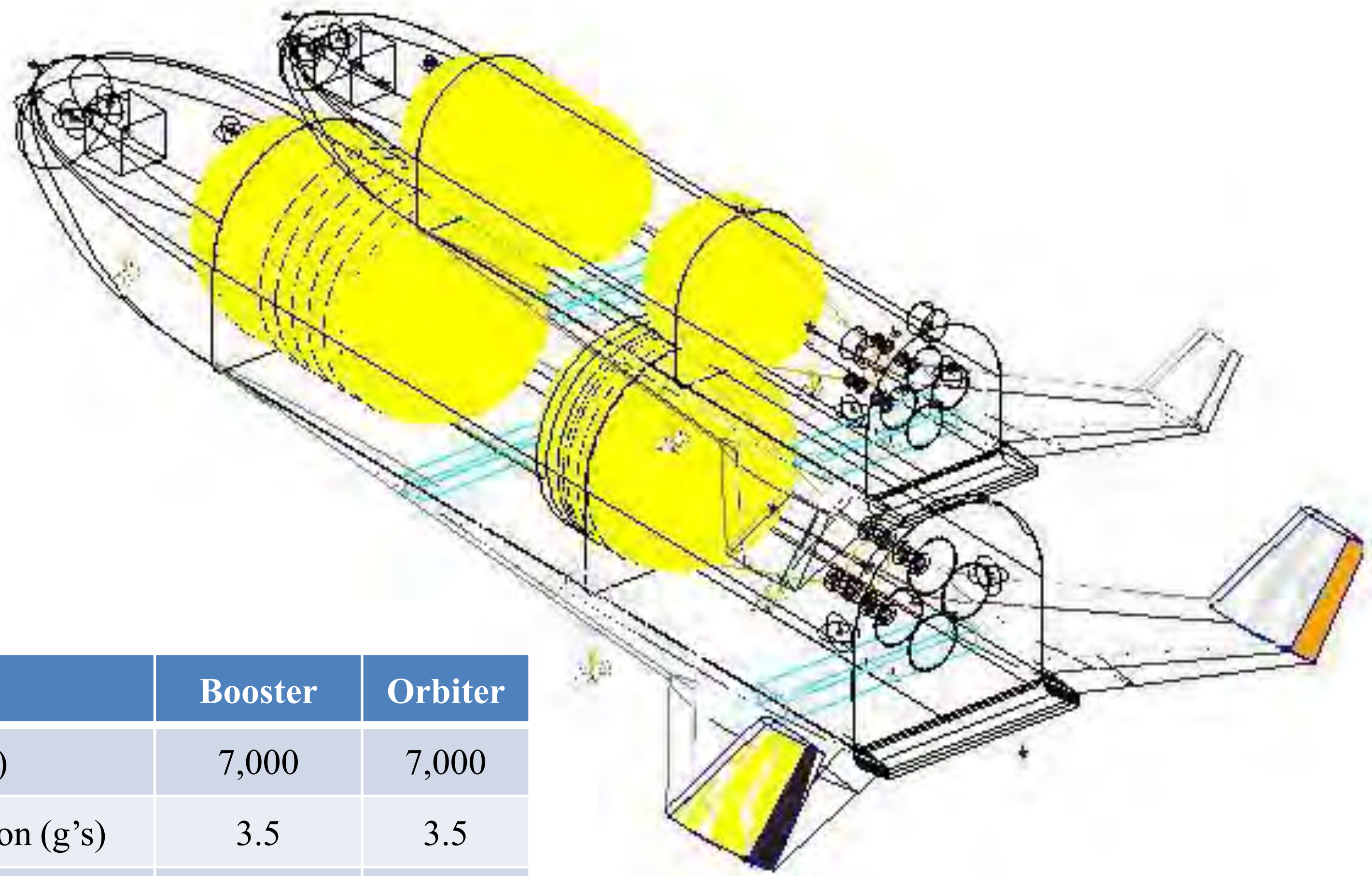
- Design, Development, Test, and Evaluation costs of launch vehicles
- Acquisition strategies
  - New technology development and production
  - Government Furnished Equipment (GFE)
- Based on TRL and historical program cost and schedule information from Selected Acquisition Reports
- Cost Estimating Relationships primarily based on system weight and quantity, refined to account for differences in
  - Material selections
  - Nozzle configuration
  - Tank configuration
  - Engine chamber pressure, fuel mixture variations
  - Pressurization system



Concept of Operations Overview

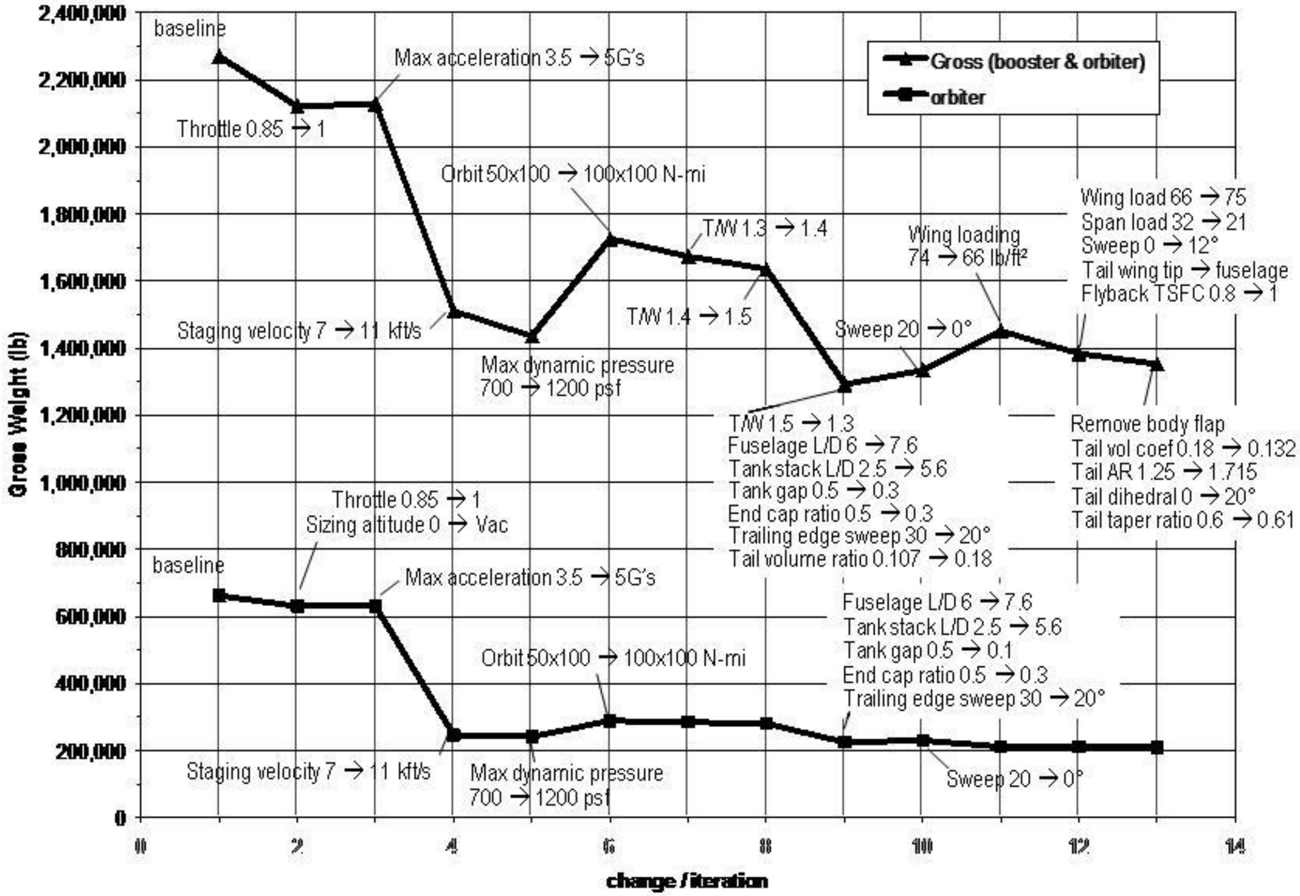


Baseline Reusable Launch Vehicle

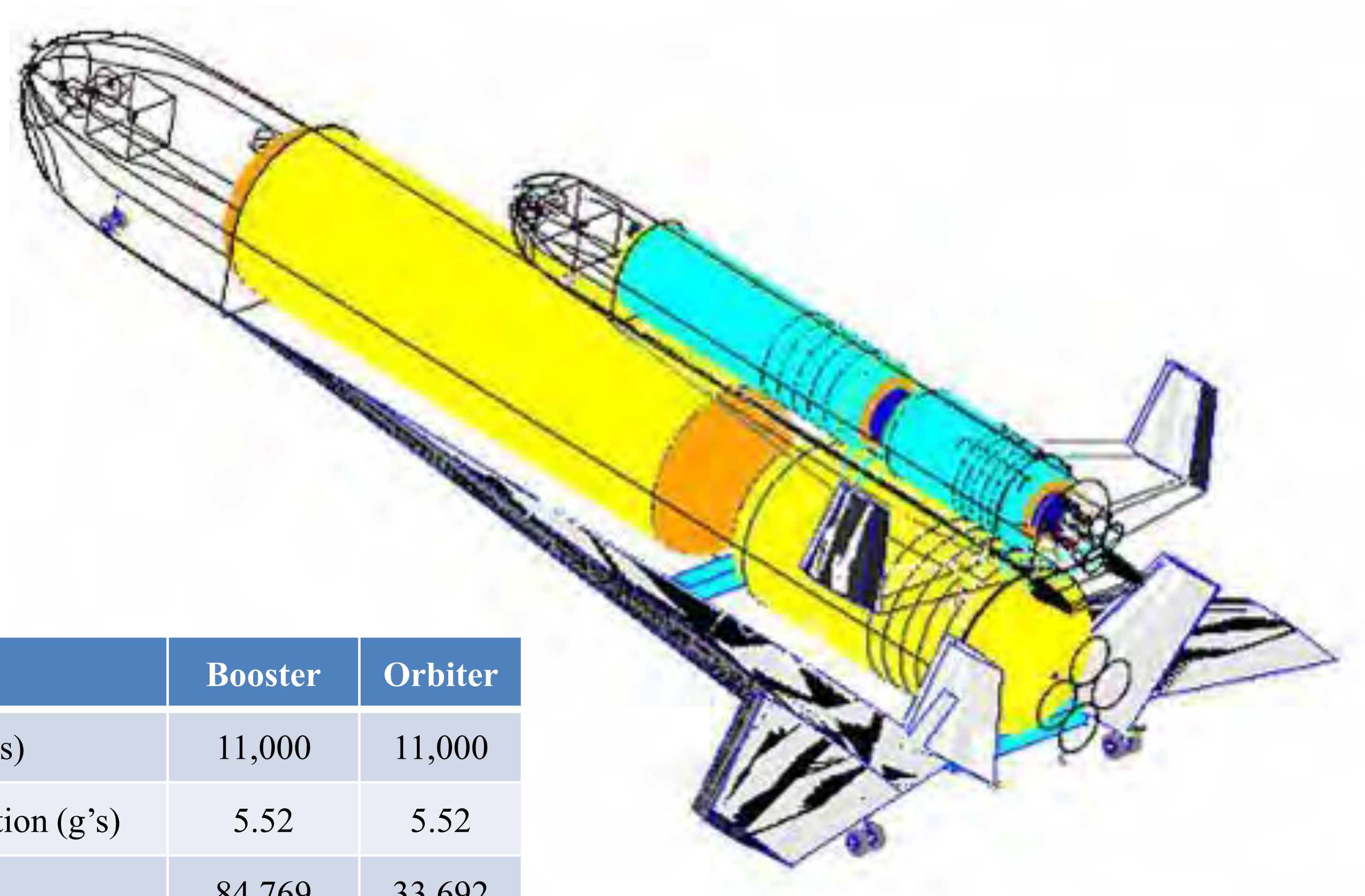


	Booster	Orbiter
Staging Velocity (ft/s)	7,000	7,000
Maximum Acceleration (g's)	3.5	3.5
Dry Weight (lbm)	205,570	122,292
Gross Weight (lbm)	2,269,810	661,354

Optimization Iterations

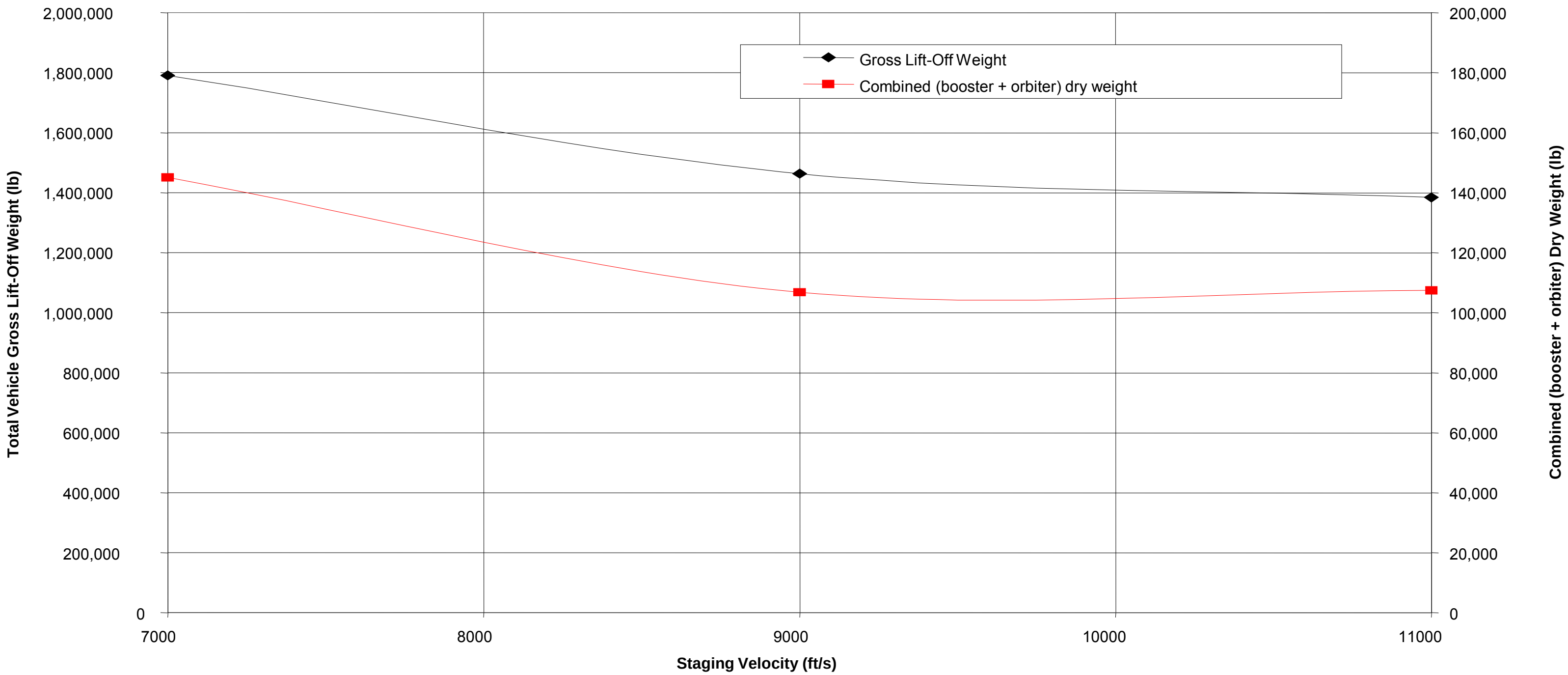


Optimized Reusable Launch Vehicle



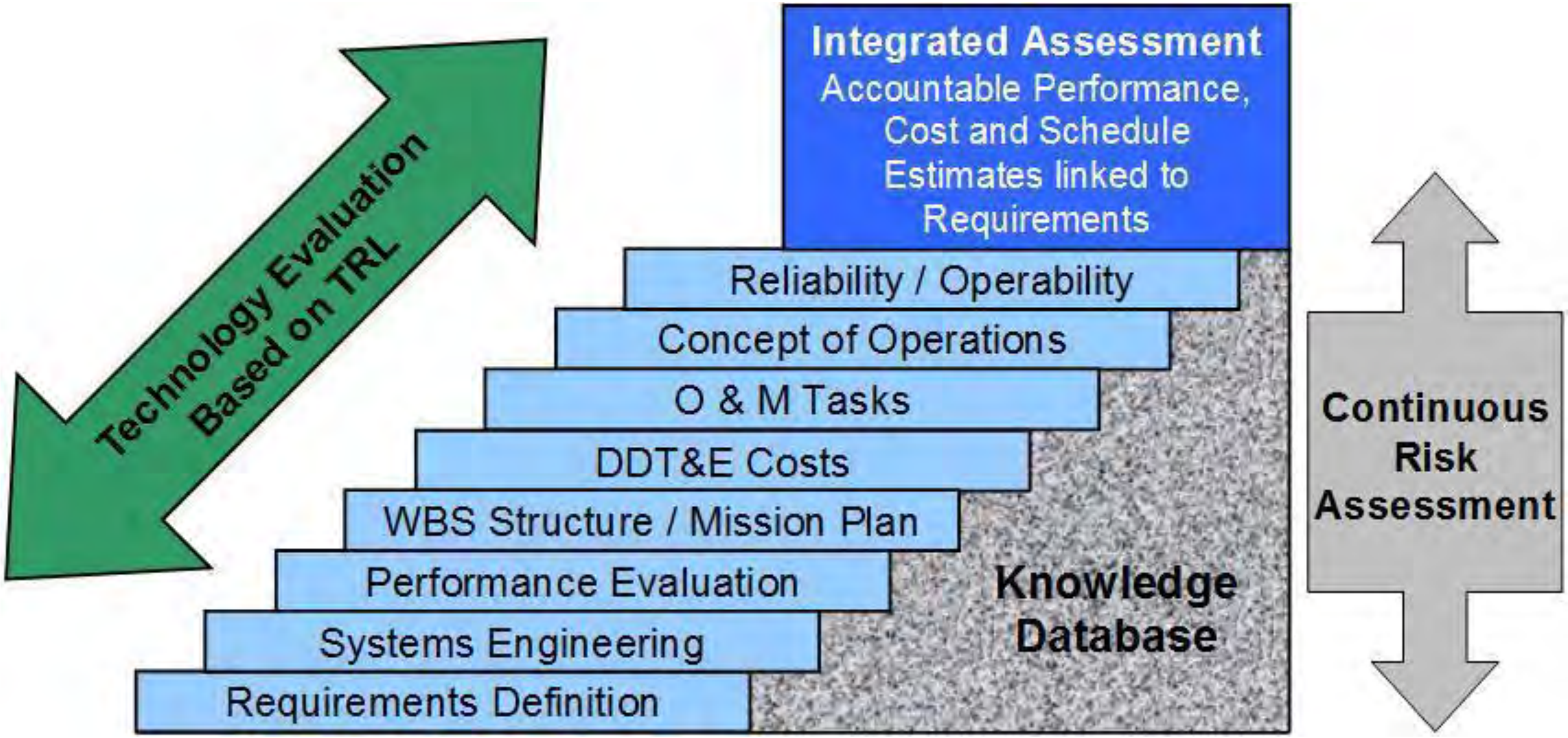
	Booster	Orbiter
Staging Velocity (ft/s)	11,000	11,000
Maximum Acceleration (g’s)	5.52	5.52
Dry Weight (lbm)	84,769	33,692
Gross Weight (lbm)	1,382,515	210,875

Staging Velocity Trade Space



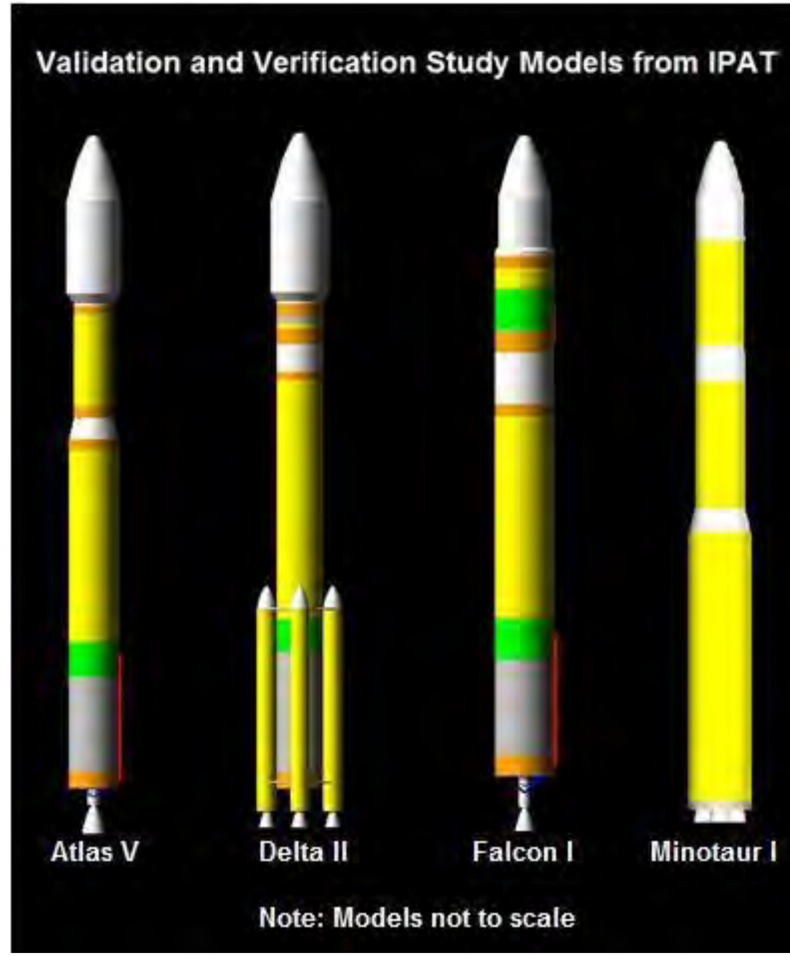
Staging Velocity (ft/s)	7,000	9,000	11,000
Acceleration Limit (g's)	5	5	5.52
Total Vehicle Weight (lbm)	1,790,531	1,463,043	1,382,515
Booster Dry Weight (lbm)	85,944	65,808	74,099
Orbiter Dry Weight (lbm)	59,082	40,985	33,337
Combined Dry Weight (lbm)	145,026	106,793	107,436

Integrated Assessment Approach

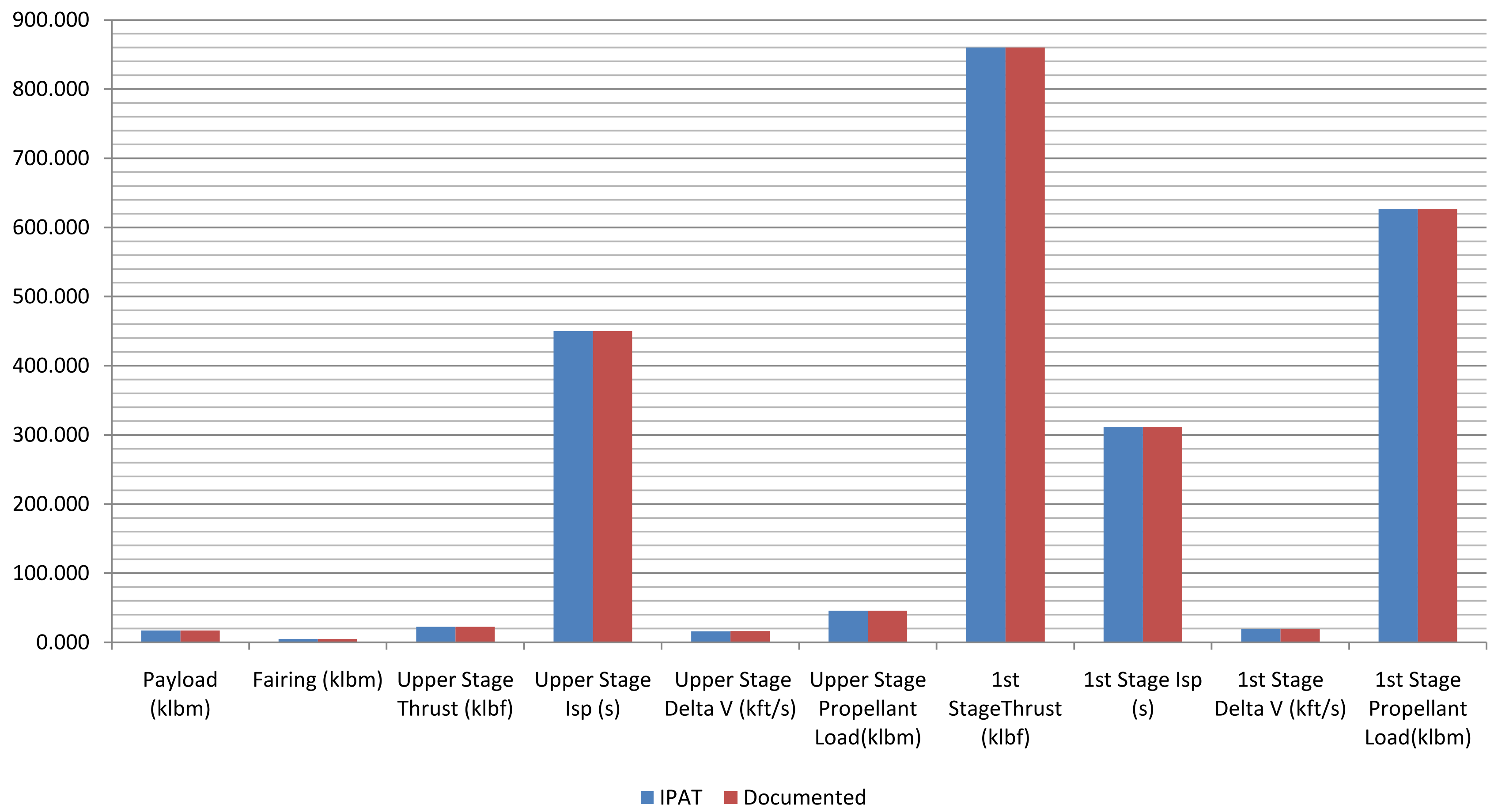


Verification and Validation Study

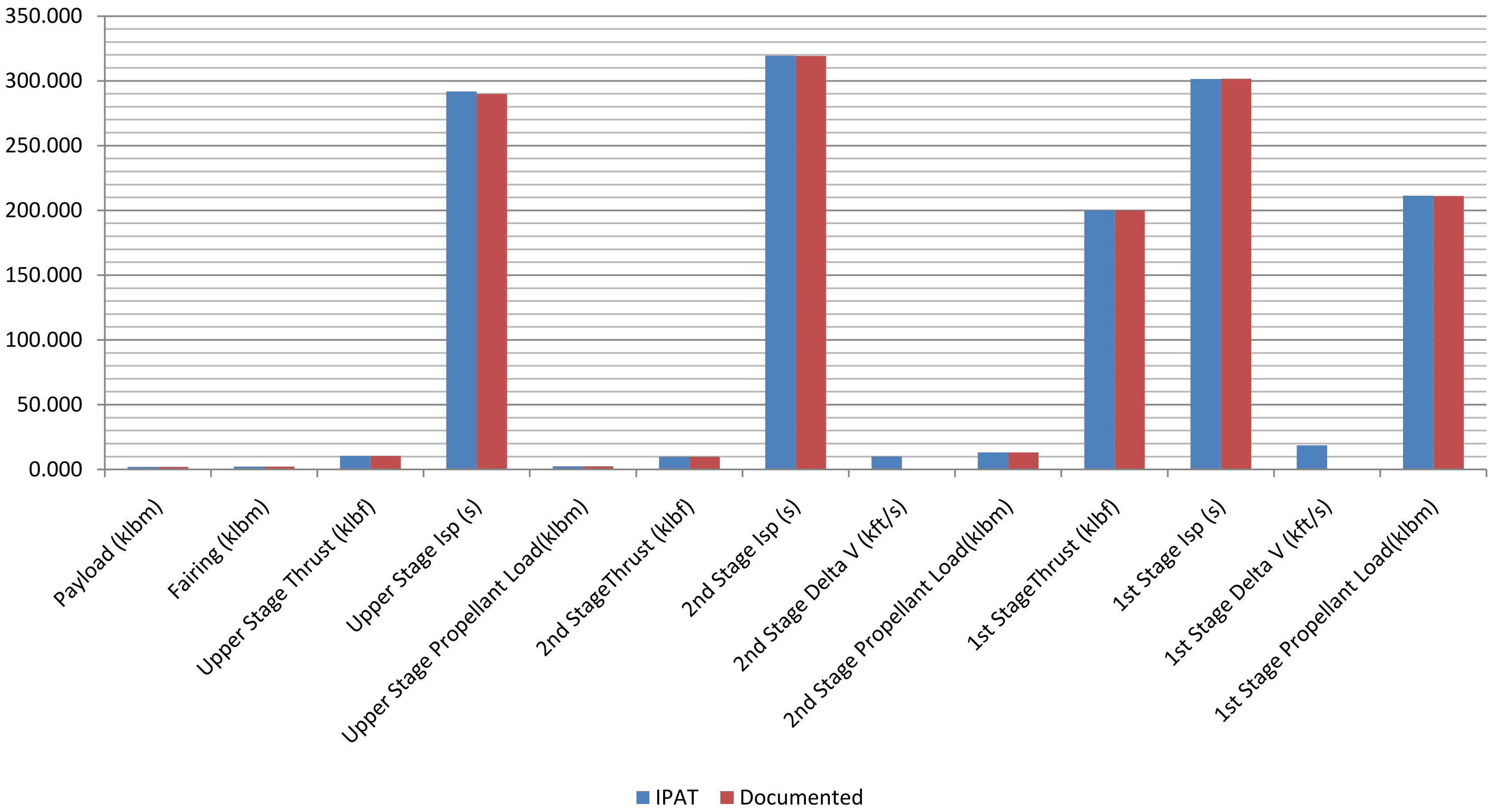
- Four vehicles modeled in IPAT
- Performance, cost, and operations modeled
- Compared to documented values from manufacturers and other published sources
- Performance values generally matched within 2%
- Cost and operations values matched well with available information



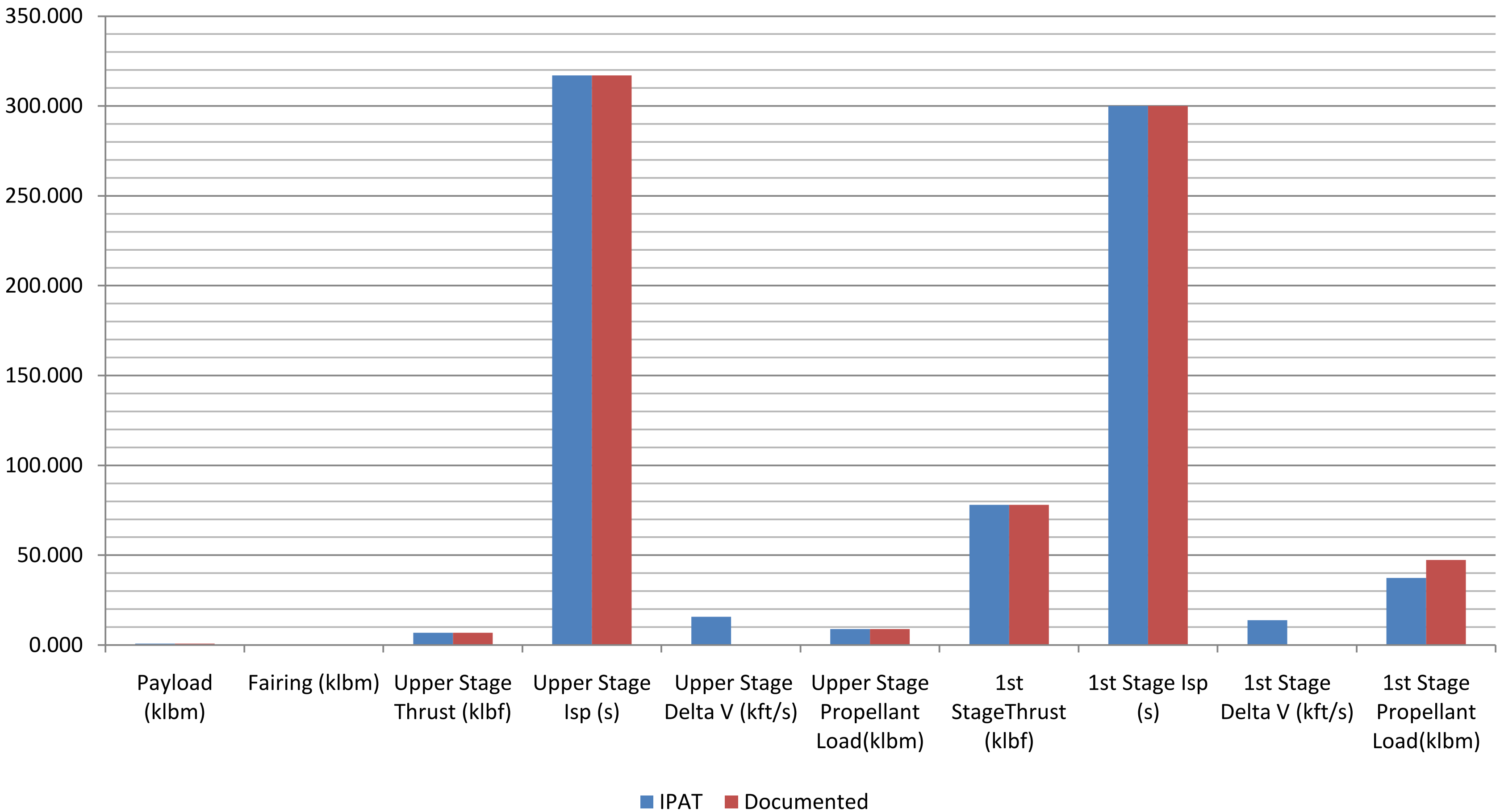
Atlas V Performance Values



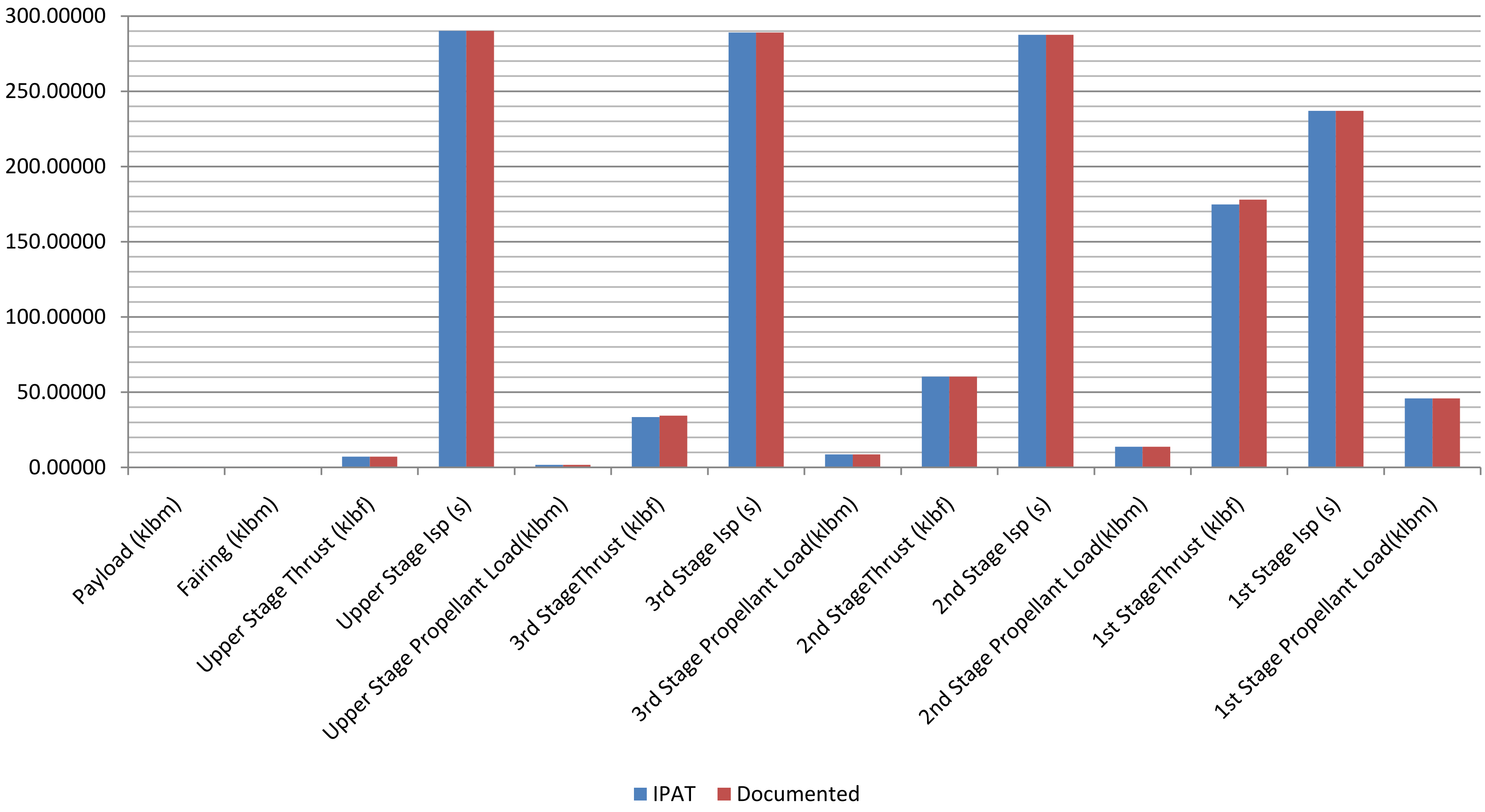
Delta II Performance Values



Falcon 1 Performance Values



Minotaur I Performance Values



Atlas and Delta Costs

	IPAT Value (BY09 $)	Documented Value (BY09 $)
Atlas V New Development	6 Development/30 Production, 80% Probability of Success	
Total Program Cost	10.17B	*
Procurement AUC	339M	*
Launch Operations	99.34M	101.73M
Delta II New Development	6 Development/30 Production, 80% Probability of Success	
Total Program Cost	3.81B	*
Procurement AUC	189.23M	166.23M
Launch Operations	55.5M	58.26M

Falcon and Minotaur Costs

	IPAT Value (BY09 $)	Documented Value (BY09 $)
Falcon 1 New Development	6 Development/30 Production, 80% Probability of Success	
Total Program Cost	2.91B	*
Procurement AUC	96.5M	10.9M (Falcon 1e)
Launch Operations	28.3M	24.2M
Minotaur I GFE Acquisition	10 Launches	
Total Program Cost	179.08M	194.3M-228.6M
First Launch Cost	20.52M	19.4M-22.8M
Last Launch Cost	16.67M	19.4-22.8M

Operation Evaluation

Vehicle	Build Mode	Estimated Duration (days)	Documented Duration (days)
Atlas V	Vertical Build & Transport	16	18
Delta II	Build on Pad	31	43
Falcon 1	Build on Pad	22	7
Minotaur I	Horizontal Build & Transport	32	45

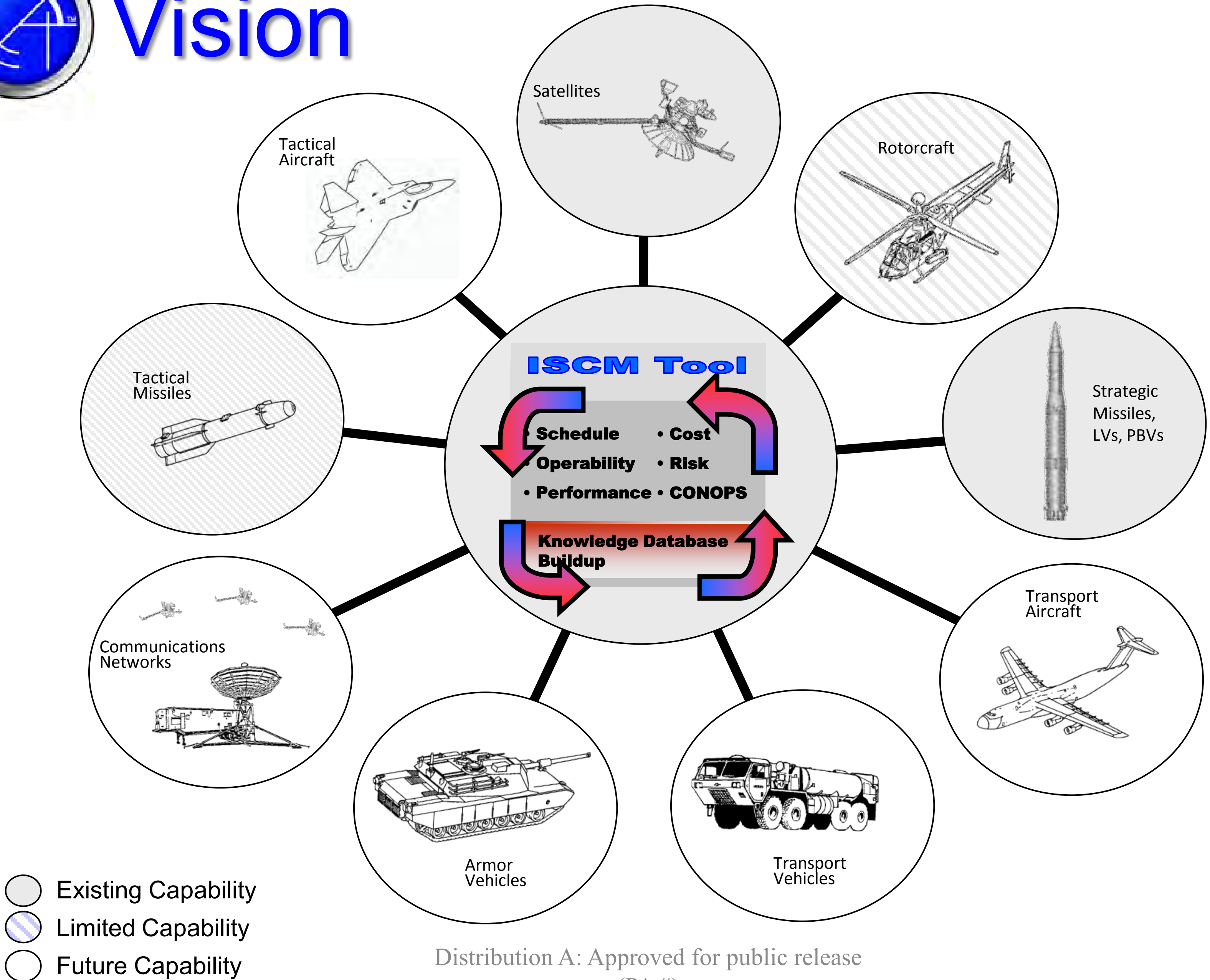
Conclusion

- The design of space launch vehicles can benefit from a integrated multidisciplinary analysis and optimization approach
- Incorporation of cost and operations models allows for end-to-end modeling of programs
- The ISCM tool suite models four keys areas of design: Performance, Cost, Operations, and Risk, and providing modeling and optimization of the complete program from end-to-end
- The MA&O process reduced the weight of a baseline RLV design by 39 percent
- V&V of the ISCM tool suite matched performance values within two percent of documented values and cost and operations values generally matched available values

Future Work

- Continue to expand cost modeling capabilities and incorporate new technologies
  - Fully implement cost models for fully and partially reusable vehicles
  - ConOps modeling for satellites/space vehicles
  - IHPRPT concepts, new propellants, new materials, etc.
- Complete Verification, Validation, & Accreditation of the Tool Suite
  - Coordinate with the Air Force and other customers to obtain data
- Demonstrate the tool capabilities on an Air Force acquisition program starting in the pre-acquisition phase
  - Continue performing studies for AFSPC, AFGSC, and ORS Office, excellent way to VV&A tool and identify improvements
- Expand the Tool Suite to address new systems

Vision



Satellites
Rotorcraft
Tactical Aircraft
Strategic Missiles, LVs, PBVs
Tactical Missiles
ISCM Tool
• Schedule • Cost
• Operability • Risk
• Performance • CONOPS
Knowledge Database Buildup
Communications Networks
Transport Aircraft
Armor Vehicles
Transport Vehicles
Existing Capability
Limited Capability
Future Capability

Questions?

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