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MODELING OF TURNAROUND OPERATIONS FOR NEXT GENERATION SPACE TRANSPORTATION ARCHITECTURES

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This paper presents an approach to space transportation turnaround operations modeling using knowledge based complexity functions. This project is of significant relevance to the field of industrial engineering as it deals with knowledge based estimation of processing operations based on the design characteristics of an extremely complex product. The modeling approach uses expert's knowledge to predict the ground cycle time and costs of a new concept launch vehicle by functions that estimate the complexity and reliability of the system based on its design characteristics. The operational requirements include the interactions between the launch vehicle and its ground infrastructure: the spaceport. Finally, the paper discusses the implementation of the modeling concept into a tool called Architecture Assessment Tool - enhanced (AATe) used by NASA and its contractors.

Significance: It is imperative that space transportation systems be analyzed in the very earliest of design to ensure all life cycle costs are considered. This paper presents an approach to the operational cost and time modeling of these systems by knowledge based complexity functions and the importance of this assessment using the concept of total design.

Keywords: Operations Modeling, Space Vehicles, Design Assessment, Cost Assessment, Knowledge based Modeling.

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1. INTRODUCTION

Even in the face of recent setbacks, the human race continues to look at the skies and dream of someday establishing a human presence beyond Earth, routinely traveling to the Moon, Mars, or beyond. Recent announcements by the U.S. government for a return to the Moon and a first human landing on Mars in the relative near future demonstrate that these dreams are quite alive (Mooring 2004). While budget and technological realties may postpone the realization of these dreams for many more decades, space transportation systems provide our civilization critical capabilities including the ability to place satellites in orbit, conduct experiments in space, and repair/ service satellites already in orbit. Satellites in both Geo-synchronous Earth orbit (GEO) and Low Earth orbit (LEO) provide the information backbone essential for today's economy. Satellites (for reconnaissance, positioning, entertainment, news, communications, weather prediction, etc) are by no means the end point of the commercialization of space. Companies like Hilton Hotels, Lockheed Martin, Boeing and multiple entrepreneurs are interested in other commercial uses of space, including tourism, manufacturing, health care, and passenger transportation. Tourism and space based passenger transportation are the two areas that have the most promise with the growing number of *adventure travel* enthusiasts and the significant volume of travel between the Americas, Europe, and Asia.

The major obstacle to the continued growth and commercialization of space and the return of exploratory missions to the Moon and Mars is the cost of space transportation (Morris 2004) in conjunction with low reliability and operability (Scott 1998). The cost of moving one pound of material (payload) from the earth's surface to low earth orbit (100 miles above earth) is estimated at 6 to 10 thousand dollars (Mankins 2002), which translates into more than a million dollars per passenger. Cost estimation is a chief concern among lawmakers in the U.S., as NASA has been known for cost underestimates through most of its past programs (Morris 2004). The high costs of space transportation systems arise not only from the one-time investments required to design and manufacture vehicles, but also from the recurring systems operation and maintenance. As an example, given the Space Shuttle's planned life, most of the multi-million dollar cost required for a single Shuttle mission is directly linked to operational costs. The lesser part (in the hypothetical scenario that it was a commercial venture that had to payback investment money) would be related to the development and vehicle acquisition costs, amortized over the total number of Shuttle missions. To change this, and effectively commercialize space, a new paradigm in space transportation systems, including their design and operation, must be adopted (Mankins 2002). This new paradigm must be based on the principles of total design.

The prediction of costs and other operations related parameters for a LV architecture/concept is a complex problem. This is because launch vehicles are inherently very complex systems (Ryan and Townsend, 1998), design architectures are based on new technologies where limited cost/operations knowledge exists, and the "true" reliability, maintainability, and operability of a concept vehicle are difficult to predict. In addition, at the architectural/concept design level a limited set of design characteristics has been defined, limiting the input side of the equation. In spite of these limitations, the development of cost assessment - operation focused models is required to truly understand the affordability of new launch systems.

This paper describes a modeling approach created to capture and convey operations knowledge that vehicle designers can use early in the design process. The modeling approach was utilized in the development of a software tool called the Architecture Assessment Tool – enhanced (AATe), which can provide reusable space vehicle developers (the *users*) with a *map* of the operational requirements for a vehicle concept. These operations requirements will determine ground systems investment and operational costs given a few demand scenarios, for example the number of launch pads that must be constructed and the time required at that facility given a demand that requires 40 flights per year. The costs and performance of the ground systems is added to other costs (i.e. per vehicle cost) to provide a designer with an estimated cost to orbit vs. demand.

The remainder of this paper is divided as follows: Section 2 provides a description of the design process of launch vehicles and Section 3 discusses the main elements of a space transportation architecture. Section 4 presents the Space Shuttle as an example architecture, moving from design to reality without a focus on operations understanding. Section 5 describes the modeling methodology proposed in the research and Section 6 the implementation of the model into a computer tool. Section 7 describes the implications of the model and tool to the space vehicle design and assessment community, Section 8 presents the validation process and Section 9 the conclusions and future work

2. THE DESIGN OF SPACE TRANSPORTATION ARCHITECTURES

Historically, the design and analysis of space transportation architectures and vehicles has focused on the principles of the "rocket equation". The rocket equation specifies the thrust-to-weight ratios required to exit earth's gravity. Design processes that focused on the "rocket equation" have resulted in the use of complex materials and manufacturing processes, dangerous and expensive propellants, and other system elements that optimize the thrust to weight ratio given the technological limitations at the time of design. While satisfying the rocket equation will always be a necessity, a design process that focuses primarily on these parameters has so far resulted in highly expensive, complex, maintenance intensive, and often unreliable systems. Even new developments as the Space Taxi (Stanley 2000) fail to address the operational requirements and costs of space transportation architectures.

The main stages of the traditional design process for a space transportation system are shown in Figure 1. This traditional process divides knowledge use according to the stage of the development process. In this traditional approach, vehicle designs (first stage) were the result of two 'inputs': design knowledge (materials, propellants, etc) and mission requirements (payload and orbit requirements). Once the design and testing were completed, manufacturing knowledge was used to produce the vehicle to the required specifications (second stage). Finally, operations knowledge was used to manage preparation, processing, launch and recovery operations (third stage). This traditional method focused on the processes of vehicle design and mostly ignored ground operation requirements until after vehicle definition and commitment had occurred. This approach is referred to by operations designers as *the support the design view*.

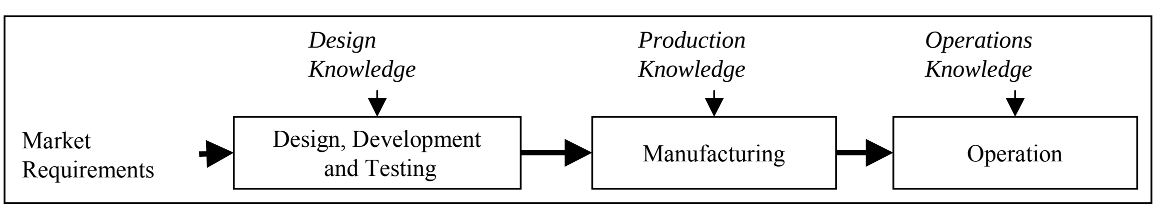


Figure 1. Traditional design and development process for space transportation systems.

A *total design* paradigm for space transportation systems is shown in Figure 2. This approach uses downstream knowledge during each stage of development. Design, manufacturing, and operations knowledge is used during the vehicle design and testing stage, and manufacturing and operations knowledge is used during the production stage. This alternative view focuses on an integrated and concurrent design process (*total design*) where the vehicle and the ground operations are simultaneously designed. Operations designers refer to this approach as *the design for support view*. The challenge is to develop models and tools by which new space transportation system concepts can be evaluated from an operational perspective early, during the design process. This evaluation must be then merged with development models such as NAFCOM (a NASA/ Air Force model for Design and Development assessment) and manufacturing assessment models as the one proposed for aircraft production (Marx et al. 1998).

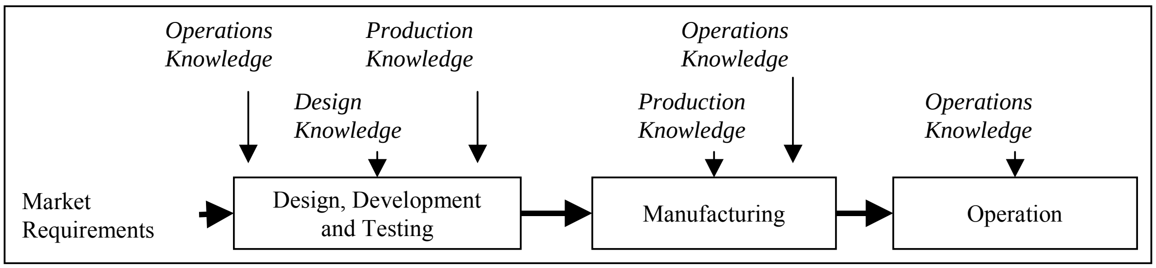


Figure 2. Total design and development process for space transportation systems.

Once operational, a space transportation system must be thought of as a marriage between flight systems working efficiently with ground systems. This requires close attention to vehicle-ground system compatibility from the conceptual design and analysis stage through detailed design. This means conceiving flight designs and analyzing them not only in the context of their payload and orbit specifications (market requirements), but continually projecting the concepts in their operational spaceport environment. Early identification and control of potential ground processing bottlenecks, flight-to-ground system incompatibilities, and excessive infrastructure is a critical requirement of the design process.

The first evaluation parameter is the realistic estimation of the potential flight rate and vehicle utilization for a space transportation concept. The flight rate and vehicle utilization are measures that the designer cannot input, but outputs can be derived from several factors including the concepts' reliability and operational requirements. The vehicle's lift capacity (pounds to orbit) combined with the flight rate (flights per year) results in the vehicle's spacelift characteristic (total pounds per year per vehicle). Realizing the concept's operational requirements is a major challenge facing space transportation systems developers given information is practically non-existent at this early evolutionary stage to construct operations models that can derive accurate flight rates and infrastructure estimates (labor, facilities, etc.).

3. SPACE TRANSPORTATION SYSTEM ELEMENTS AND COSTS

A Space Transportation Architecture (STA) is defined as the combination of the vehicle (s) that physically moves people and/or objects to space with the supporting ground operating systems. The design process typically starts with the design of the vehicle, followed at much later times with the design of the spaceport environment.

3.1 Vehicle Elements and Costs

Vehicle designers develop and specify the scheme by which the elements of the vehicle will be arranged into a single integrated system; the form and shapes, the propulsion systems, the number of major systems, and the manner it is all integrated. The vehicle design will also dictate at higher levels of system definition the production processes for manufacturing and integration, and the detailed geometries of parts and subassemblies. This activity will specify manufacturing and other costs related to acquiring the first component of the STA. Tools to estimate development and manufacturing costs have been developed jointly by NASA and the Air Force, one such tool being NAFCOM.

3.2 Spaceport Elements and Costs

Vehicle designers are not typically concerned with the operations and processes required to turnaround a vehicle (test, process, maintain, and repair the vehicle systems), but their design decisions will drive these processes as a consequence of the design's complexity and technologies. For example, a single stage to orbit system does not require a mating process (union of the stages i.e. the shuttle system where the orbiter is attached to an external fuel tank and two semi-reusable solid rockets). The primary modules of the supporting operating systems - the spaceport have been defined as follows:

- *Passenger/Cargo Processing (Terminal)*: Facilities and systems required for the handling of passengers and cargo after landing, and prior to launch. Could be separated into two facilities.
- *Traffic/Flight Control*: Oversight of landing, launch, and flight operations.
- *Launch*: Vehicle departure facilities and systems.
- *Landing*: Vehicle arrival facilities and systems.
- *Vehicle Maintenance and turnaround*: Facilities and systems required to repair, inspect, and prepare the vehicle for the next launch. One such facility may be needed for each reusable stage of the vehicle.
- *Vehicle Assembly/Integration*: Facilities and systems required to combine multiple stages. Could be part of the Maintenance and Turnaround facility.
- *Vehicle Depot Maintenance*: Facilities required for the off-line repair of vehicle subsystems.
- *Expendable Elements*: Facilities required to inspect and prepare expendable items for launch.
- *Operations Management and Support*: Facilities and systems for management and engineering support.
- *Logistics*: Facilities and systems for materials acquisition, transport, storage, and disposal.
- *Spaceport Support Infrastructure*: Facilities required to support all other facilities.
- *Community Infrastructure*: Housing, medical, and other miscellaneous facilities required to sustain a community.

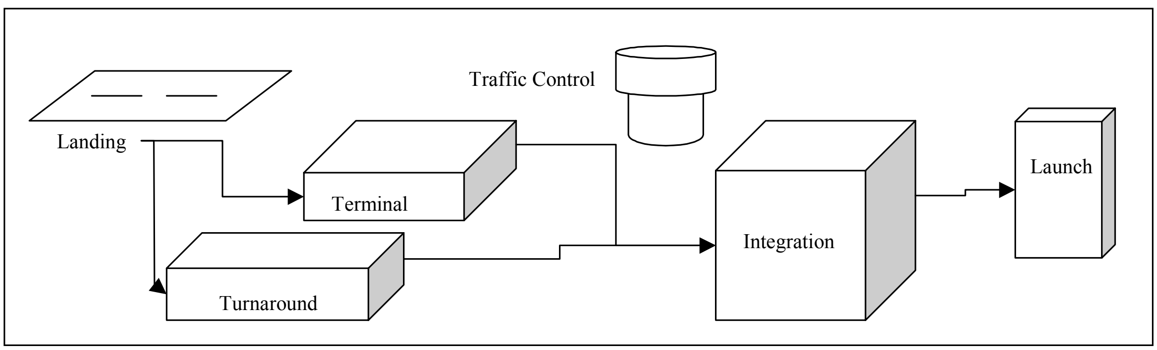


Figure 3. Spaceport functions and flows.

Several possible vehicle flows within a spaceport's basic components are illustrated in Figure 3. An airplane like vehicle that does not require major maintenance after each flight and has a single stage will move directly from landing to the terminal, and then to launch. If the vehicle does not require maintenance after each flight, but has multiple stages, then an integration function will be required which can be performed at another facility or at the terminal. Vehicles that require major maintenance and tests procedures after each flight must flow to a turnaround facility and then proceed to integration or directly to the terminal functions. The vehicle design indirectly defines which of these flows will be required between landing and launch and the time required in each of these processes.

The combination of different processing times and flows is an issue that takes us to the first fundamental relationship between the vehicle and the ground operations systems: *cycle time*. The *cycle time* of a vehicle can be defined as the expected interval of time between a vehicle's landings. In the case of multi-stage vehicle, the cycle time of each stage is first determined followed by an integrated cycle time if such is appropriate (for example if integration is at the launch pad, the integrated cycle time is zero). Thus each stage has an independent cycle time and an integrated cycle time. While a typical airplane *cycle time* can be measured in hours, the *cycle time* for our current reusable STA (the Space Shuttle) is measured in months. Finally, the expected time in orbit must be established in order to determine the true vehicle utilization - the expected number of flights per vehicle per year. From the estimated processes and types of ground operations systems required, facility investment costs, operating costs, and the flight rate for a single vehicle are estimated. The costs of a STA can then be divided as follows:

- *Fixed Operational Costs*: These are the baseline operational costs required for a single flight per year. For example management, engineering, and technical staff.
- *Variable Costs*: These are flight dependent operational costs. For example fuel, replacement parts, additional staff and insurance.

- *Development Costs*: Initial costs required to develop the STA technologies required.
- *Facilities and Infrastructure Costs*: Initial costs required to build and equip the ground systems that will support the STA.
- *Vehicle Acquisition Costs*: Purchase of the vehicles.

A total cost assessment can be made for a vehicle concept by rolling up investment and operational costs, the expected life of the vehicle, and a demand for service. The demand for service (pounds per year) will determine the number of flights needed per year, and therefore the number of vehicles. As the number of flights increase, the variable cost per flight may be reduced as a result of economies of scale, or increase as a result of increased complexity. The total facilities and infrastructure costs increase with fleet size and the number of flights (i.e. number of launch pads, number of maintenance hangars), but the per flight cost will eventually decrease with an increase in the number of flights given economies of scale.

The notion of fixed and variable costs for operations can not be over emphasized. Space transportation infrastructures are currently dominated by high fixed costs and extensive operational processing times for major flight elements. A model of space transportation operations can not be a complete or correct system representation if it is to deal with flight rate issues without adequately addressing fixed and variable cost relationships.

4. AN EXAMPLE SPACE TRANSPORTATION SYSTEM: THE SPACE SHUTTLE

As large as the Shuttle contribution is to today's space transportation capability, experience gained in the development and subsequent operation of the system should provide us insight on how to utilize the concept of total design and *design for support* during early conceptual design. During conceptual design it was envisioned that the Shuttle's maintenance and servicing processes were to be simple and able to maintain an expected flight rate of ten flights per year per vehicle. It was also envisioned that the maintenance, servicing, and inspection processes would require little infrastructure. Additionally, payload integration would be simple, implying very little labor. The Space shuttle was supposed to provide significant cost reductions when compared with its predecessors systems, but this depended on a dramatic flight rate increase that was never achieved (Dinerman 2004).

By the time the Shuttle architecture (flight and ground) was in operation, the complexity of the ground infrastructure had grown to meet the servicing, inspection and checkout required by the vehicle design. While the Shuttle maintenance was envisioned as similar to an airplane, the turnaround of the orbiter is a complex endeavor with specialized and dedicated equipment that engulfs the orbiter at the Orbiter Processing Facility at the Kennedy Space Center. As a result of these additional processes, the expectation of spacelift performance of 500,000 pounds per year was well above the real performance that has averaged about 100,000 pounds per year per vehicle for the last 7 years. This is based on a stable flight rate of about two per year per vehicle. Another important shortfall from the Shuttle's concept to the developed system is the change in lift capability. The original single mission lift capability was 65,000 lbs., which was changed to 50,000 lbs. in the developed version. While this shortfall is significant (vehicle spacelift change of 150Klbs. per year), the significance of flight rate shortfall was significantly higher (vehicle spacelift change of 400Klbs. per year). This difference is quite important as it illustrates the drastic effect that flight rate shortfall can have in relation to spacelift performance.

5. MODELING APPROACH

The complexity of processing space vehicles comes from multiple factors including redundancy, lack of robustness in materials, low reliability, accessing difficulties, among many. The approach proposed in this paper and utilized in the developed computer application is based on weighted equations that relate a set of input questions into functional complexity indexes. The creation of these relationships and complexity indexes is the main building block that captures expert knowledge. To estimate complexity indexes, an extensive study was conducted where space operations experts were asked in various survey tools to relate design variables to operation costs and cycle time drivers. The goal of these activities was to imitate the process of evaluation that an expert would utilize in assessing an STA. From these surveys a set of weights that related inputs to outputs were derived and their use explained next. This approach provides a higher level of fidelity of assessment than individual experts as it separates complexity by function, and uses survey instruments that were function specific.

The inputs for each stage of an STA are combined into expert based functional complexity indexes, with most of these inputs coming from multiple-choice options, and the number of choices varies per question. There are weights associated with the options, and weights relating the design variables with the operations functions. The general formulation for the approach is as follows: there are v design variables indexed by $h \in V \equiv \{1,\ldots,v\}$ and there are f operation functions indexed by $j \in F \equiv \{1,\ldots,f\}$. Each design variable h has a unique number of design options $d(h)$ indexed by $b \in D(h) \equiv \{1,\ldots, d(h)\}$. Each design option b for a design variable h is modeled by $d_{h,b}$, where $d_{h,b}$ is a binary variable (0,1), 1 if option b is "selected", and 0 if not. The condition is that only one option can be selected, thus $\sum_{b \in D(h)} [\, d_{h,b} \,] = 1$. Each design option b

of design variable *h* has an associated option modifier $m_{h,b}$ from 0 to 1, thus each design variable *h* has a plain score ps_h from 0 to 1 as below, and its defined as $ps_h = \sum_{b \in D(h)} m_{h,b} d_{h,b}$. Each design variable *h* has an associated design weight for each operation function *j*, $w_{j,h}$. The normalized score, n_j, called the Module Assessment Index (MAI), for a function *j* is then defined as $n_j = \sum_{h \in V} w_{j,h} ps_h / \sum_{h \in V} w_{j,h}$

Given the modifier and weights are all between 0 and 1, the normalized score for an operations function is between 0 and 1. Note in this application, 0 is the worst possible value and 1 the best. The approach used by the AATe is then to utilize n_j as a selector in a series of *data curves* as illustrated in Figure 5. *Data curves* in the AATe are generated based on two reference points, Space Shuttle and the Concorde Airplane (with space vehicle technology modifications). A curve is generated between the two points using a modified exponential equation. There are multiple *data curves* depending on the type of stage; data curves for stages with passengers and payload, for payload only, no payload or passengers, and so on. There are data curves for the following operational characteristics as variable costs, facility capacity (flights per facility in the case of on line functions: integration, turnaround, landing, and launch), fixed annual operations costs per facility, and facility and GSE Acquisition cost.

The approach used in the model captures additional concept information that modifies both the n_j's and the *data curves*. Non function inputs and their use in the model include the stage objective; used to select the *data curves* applicable to the architecture as vehicles with no crew or passengers have cost curves that do not include the costs of life support systems for example, and dimensions (envelope, stage, payload) as this modifies the *data curves*: larger vehicles than the baseline will require larger facilities and incur in larger costs (all other factors the same).

6. MODEL IMPLEMENTATION

The developed modeling method was implemented in a computer program called the Architecture Assessment Tool-enhanced (AATe). The AATe is a strategic- decision-making tool, which aims to help in the early vehicle development process. A suite of tools for detailed modeling is also being developed concurrently. The AATe computer application was developed in Microsoft Excel ® with a Visual Basic for Applications ® front end. The basic process performed by the AATe is to capture the inputs, load these inputs in the complexity functions generating the MAI scores that are then used in conjunction with the knowledge base to generate the performance metrics. Figure 4 illustrates the input interface. The AATe performs all file management functions typically associated with software applications as *Save*, *Load*, and *New*. Architecture files are text files saved with a specified format read by the tool. The tool has other features including sensitivity reports and the ability to compare multiple architectures simultaneously.

Menus and icons provide access to input dialogs and to output reports. The user enters inputs in two phases, a) inputs related to the overall architecture approach and b) stage independent inputs. For example, an architecture input relates to the flow and location of integration in the case of systems with multiple stages. A stage input relates to the number of engines in that stage or the need for life support (a non-crew/passengers stage does not need life support). These questions relate to several top level areas: number of stages, propulsion systems, propellants, complexity, reliability, maintainability, and support systems. For each question there are 3-10 design options in a multiple-choice fashion. While there could be many possibilities, even an infinite number, limiting the number of options simplified the formulation and knowledge acquisition process. Queries include the payload capacity of the vehicle, expected flight rate for the fleet, the vehicle's expected life, the expected development and per vehicle acquisition costs, enabling calculations such as required vehicles to meet the flight rate, and required facilities.

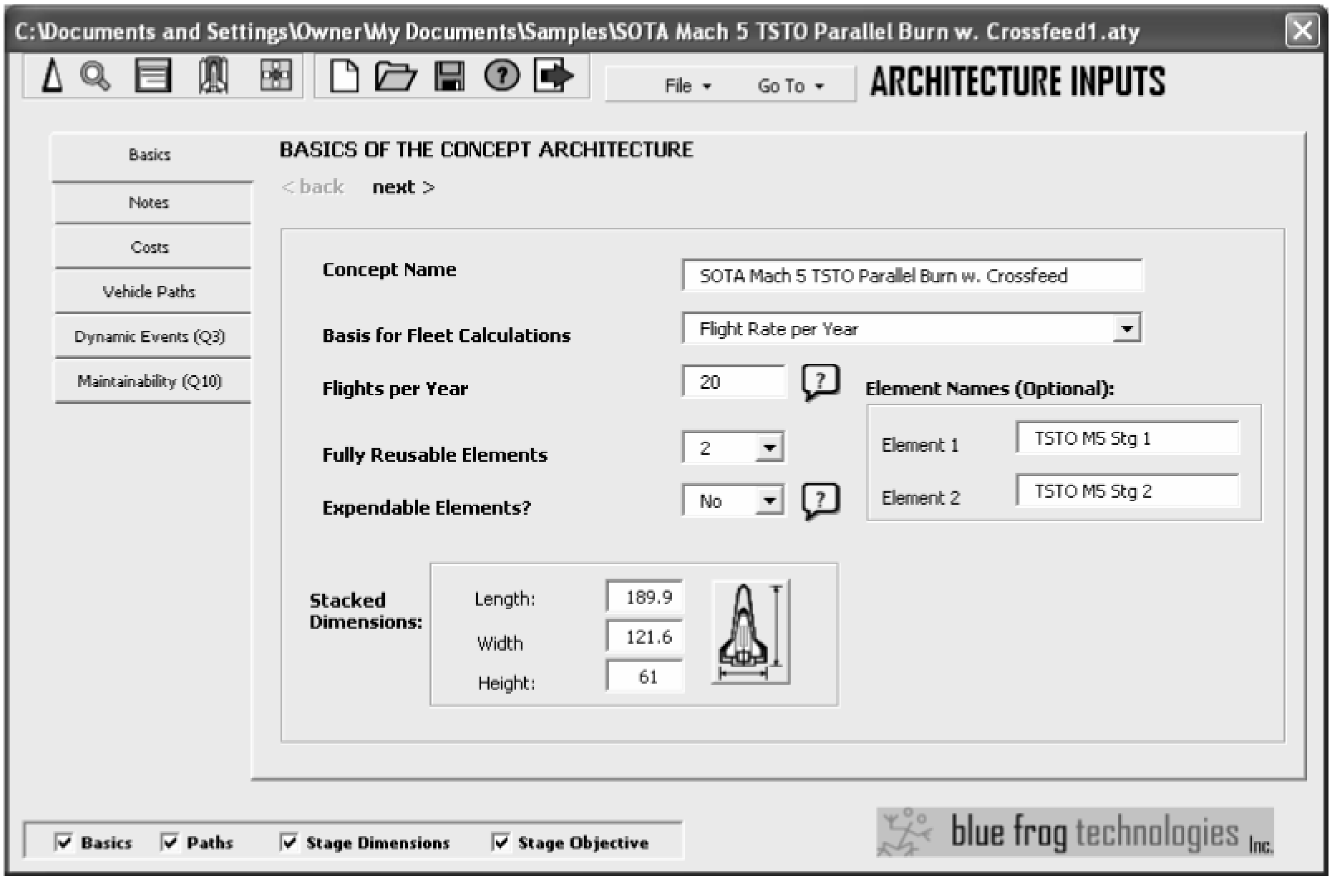
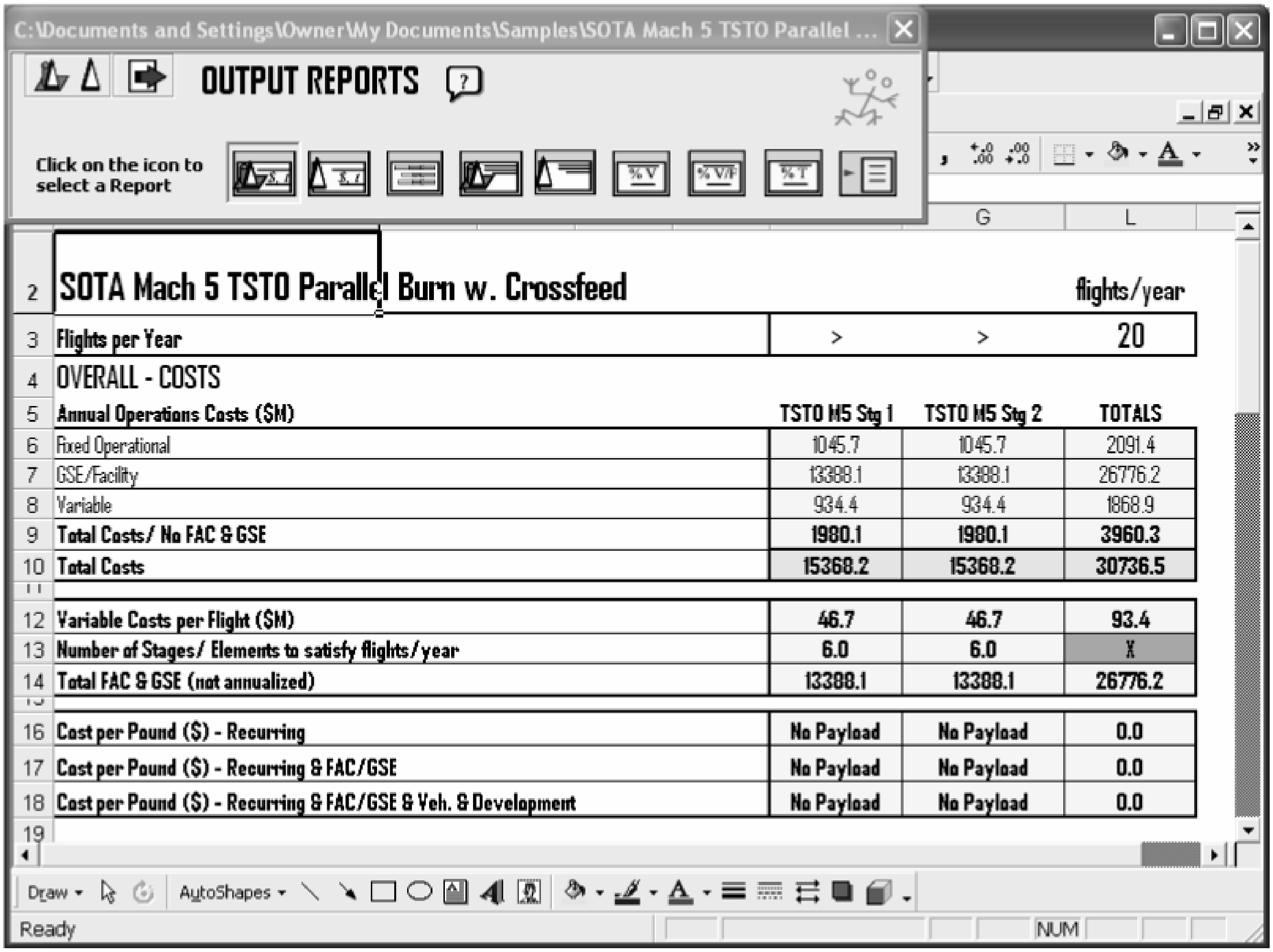


Figure 4. AATe Input Form.

As the vehicle information is entered, the data is fed to the module functions and the Module Assessment Indexes determined. As discussed in the modeling approach, the MAI's define the characteristics of the ground systems at a module level for each stage. For example, the cargo processing module has a function that combines all inputs relevant to the type of cargo and passengers, the technologies used to load cargo and passengers, the level of standardization of cargo shapes, the vehicle cargo bay technologies and position, etc. Inputs related to avionics and propulsion for example, have little or no bearing in what type of cargo processing facility is needed, and therefore are not included in that module's function.

For each of the twelve modules identified in Section 3.2, various facility types were defined based on a worldwide benchmark of ground operating systems (NASA, European Space Agency, China Space Agency). The definition at this level includes a simple description of the facilities, the cycle time (if applicable), the investment costs (facility and equipment), the fixed operational costs (materials and labor) for a single flight, and the variable operational costs (materials and labor) -for each additional flight. While the benchmarks defined existing operating systems, optimistic, but probable, extrapolations were developed to generate the low cost-fast turnaround facility types. In all cases, there was a large range between the low cost, fast turn-around facilities, airport like, and the shuttle like facilities, very expensive and long turn-around with about two orders of magnitude separating them in terms of costs and cycle times.

Total expected annual payload demand is entered by the user, or alternatively a flight rate per year can be entered. Using this information a lower bound number of vehicles is calculated for a fixed number of flights. The number of stage-vehicles and/or integrated vehicles and the estimated processing times are then used to determine the capacity required for each module type, i.e. number of launching facilities. This information is then integrated to roll-up formulas that calculate the measure of performance of greatest interest: dollars per pound. Figure 5 illustrates one of the output reports from this process.



C:\Documents and Settings\Owner\My Documents\Samples\SOTA Mach 5 TSTO Parallel ...

OUTPUT REPORTS

Click on the icon to select a Report

2	SOTA Mach 5 TSTO Parallel Burn w. Crossfeed			flights/year
3	Flights per Year	>	>	20
4	OVERALL - COSTS			
5	Annual Operations Costs ($M)	TSTO M5 Stg 1	TSTO M5 Stg 2	TOTALS
6	Fixed Operational	1045.7	1045.7	2091.4
7	GSE/Facility	13388.1	13388.1	26776.2
8	Variable	934.4	934.4	1868.9
9	Total Costs/ No FAC & GSE	1980.1	1980.1	3960.3
10	Total Costs	15368.2	15368.2	30736.5
12	Variable Costs per Flight ($M)	46.7	46.7	93.4
13	Number of Stages/ Elements to satisfy flights/year	6.0	6.0	X
14	Total FAC & GSE (not annualized)	13388.1	13388.1	26776.2
16	Cost per Pound ($) - Recurring	No Payload	No Payload	0.0
17	Cost per Pound ($) - Recurring & FAC/GSE	No Payload	No Payload	0.0
18	Cost per Pound ($) - Recurring & FAC/GSE & Veh. & Development	No Payload	No Payload	0.0

Figure 5. Example Output Report.

7. MODEL IMPLICATIONS

The leap from the multi-attribute utility function to single vehicle outputs occurs based on a series of tables which represent levels of improvement in two major ways from the baseline - improvements in complexity and reliability. Consider that a perfectly reliable Shuttle would still be extremely complex. Even if no parts failed during turnaround, the remaining tasks (for example, connecting multiple interfaces, handling multiple elements, hazardous operations, multiple connections that must be broken and verified each flight) would still leave a vehicle unlikely to be anywhere near aircraft like in it’s operations or turnaround time. The inverse is also true. Consider a highly simplified, highly integrated vehicle, with few different interfaces, or fluids, and with simple preparations for launch. It would, if as undependable as Shuttle hardware, require many removal and replacements of faulty hardware, and also be in no way aircraft like in its operations or turnaround time.

The AATe concept of single stage/vehicle productivity is a cornerstone here. Just as an aircraft has inherent characteristics of reliability, maintainability and overall operational support required, apart from whether it is part of a fleet or not, so too a reusable launch vehicle concept has similar stand-alone characteristics. This model captures design choices, and, after generating an estimation of single vehicle outputs (timelines, single string facility and operational costs, and single vehicle flight rate capability per year), goes forward to calculate fleet operations - multiple vehicles and facilities meeting a yearly spacelift scenario of pounds per year to orbit.

This previous concept, single vehicle productivity, cannot be stressed often enough. In many operations cost modeling exercises, a typical, and flawed, assumption is to model fleets, on the assumption that single vehicle characteristics are non-representative of eventual economics and operations. A further, albeit misinterpreted, assumption is that flight rate drives down costs dramatically, and therefore fleets and high flight rates can be *skipped to* in a model of future RLV operations.

This is similar to the assumption that if one vehicle can not produce enough flights at a certain cost, perhaps two will. The result is the elastic set of facilities, which, once chosen, seem to support any flight rate desired and any number of vehicles. The often overlooked flaw is that the single vehicle characteristics must encompass and enable a high flight rate and low cost capability - from the very first vehicle. The amortization of costs, be they for additional vehicles, more infrastructure or increased operations, cannot occur quickly without single vehicle characteristics which, besides low cost acquisition, include rapid turnaround at low manpower in minimal facilities. This enables high flight rates at low costs.

The AATe model attempts to capture the effects of both complexity and reliability improvements that together define a future reusable launch vehicle, by building on a strong foundation of operational knowledge gained from Shuttle as well as advanced reusable launch vehicle studies. Together these knowledge bases define to what degree and where improvements need to be applied. The cornerstone concepts of the model are:

1. The AATe model of spaceport operations revolves around an understanding of **single vehicle productivity** as outlined previously.
2. Lack of data down to subsystems levels for Shuttle, combined with a need to explore improvements which occur across sub-system and existing technology boundaries, will make **knowledge capture** a crucial component of future modeling efforts. This will be so especially until future reusable launch vehicles come on line, not as demonstrators, but as operational systems of vehicles and associated infrastructure, operating in real environments.
3. Operations cost modeling for space transportation is a required **mechanism of feedback** between designers and operators. It is therefore necessary to develop models that go beyond the "usual suspects" currently emphasized by operations models - weight and size.

8. VALIDATION AND USE

A team made up from government and industry experts was charged with the task of examining the logic and validity of the modeling approach and input-output process. While the Space Shuttle is the only 'real world' reusable space transportation system that can be used to validate the model, logic and experience were used to determine the ability of the tool to predict operational requirements. The goal of the validation process is to verify that the tool's cost and time estimates were similar in terms of order of magnitude and ranking (space van has significantly lower per pound costs than space ferry) to those made by a group of experts. While the tool generates cost outputs to the cent level, the value of the estimate is if the assessment is to $400 per pound versus $2000, and that architecture *Y* is better than *Z* by several thousands dollars per pound. Differences in results among different analysis techniques may be as high as +/-25 % percentage points and are acceptable to decision makers at this level of assessment.

To accomplish the validation objectives, a number of space transportations concepts were defined and assessed independently by the AATe and experts and the results compared. The results of this exercise, in terms of order of magnitude validated the ability of the tool to assess transportation architectures. Further, the AATe estimates were compared to those generated by another operations assessment tool developed by scientists at the Marshall Space Center (NASA), and the results were similar in terms of order of magnitude and ranking of architectures – a key objective of early assessments is to rank concepts as to determine funding for detailed design. For example, an architecture was analyzed by several experts and estimated to take 60-80 days between flights and a cost 10%-15% lower than the Shuttle baseline, while the AATe estimated 76 days and a cost 5% lower than the Shuttle baseline. In a second architecture, experts estimated a 20-30 day turnaround and a 30%-40% savings, while the AATe estimated a 22-day turnaround and a 25% savings. These are acceptable differences (experts vs. AATe) as the objective of the validation is to corroborate the AATe generates performance measures that are comparable to those of expert teams at least in order of magnitude.

The AATe has been and is currently used to assess future space transportation architectures by engineers and managers at NASA, Boeing, Lockheed-Martin, Orbital Sciences, and multiple other NASA contractors and space related organizations. Some NASA studies, which have used AATe assessments, include the Space Solar Power (SSP) study that considered alternatives to launch a fleet of energy generating satellites, the Highly Reusable Space Transportation (HRST) study, and the recently completed assessment of architectures for the Orbital Space Plane (OSP).

9. CONCLUSIONS AND FUTURE WORK

To make the dreams of space access a reality, future space transportation systems must be designed to be cost effective and reliable. The design and development of cost effective and reliable designs requires a change in the design process, one that uses existing knowledge about operations to provide insights into the operational characteristics of new designs. The total costs of a future space transportation architecture can only be determined if there is an understanding of its operational requirements and flight rate. By combining operational requirements and flight rate estimates, the proposed tool is able to provide a performance map to vehicle designers. The proposed modeling approach allows a functional/knowledge-based analysis of future designs in order to predict operations and costs and add value to the early decision making process. The modeling approach has been implemented into a computer tool called the AATe. Future work plans to use the methodology developed for the AATe to develop a more 'detailed level' tool which has more input requirements from the user and more detailed operational functions, but which then provides additional insights on the operational requirements for the concept vehicle.

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