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# AN INTEGRATED ESTIMATION AND MODELING ENVIRONMENT FOR THE DESIGN OF THE ORBITAL SPACE PLANE

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## ABSTRACT

The development of simulation models can be time consuming and highly dependant on system data being widely available. When using simulation modeling to analyze future systems, system data may not be available for the system under study and simulation results are often needed within a short time frame to support early system design efforts. This paper presents a parametric estimation/generic simulation integrated environment developed to facilitate the rapid development of valid simulation models for the Orbital Space Vehicle ground processing operations.

## 1 INTRODUCTION

When modeling future systems, such as the NASA Orbital Space Plane (OSP), input data for the simulation study may be hard or impossible to come by. Knowledge, expertise (or an expectation about a process flow), applicable resources and constraints for the future product are but half the challenge that analysts face. The other half requires estimation to populate the simulation model with the likely values or probabilities for the tasks that are planned. The creative process of design and analysis for the product or processes proposed are interconnected. Analyst usually rely on parametric estimates from similar systems or expert opinion when building these types of models. Therefore, simulation studies of future systems become lengthy projects due to the initial time investment required early on in the data collection process. In today's competitive global market, time is of an essence. If the analysis of a system is too lengthy, the opportunity to influence the design of a system decreases. Furthermore, with the current increase in technical advancement, the system may be obsolete by the time the simulation analysis is ready to provide concrete results. By expediting and facilitating the estimation of design characteristic of future systems, simulation projects can benefit from reduced development time and more accurate analytical estimations. In addition, by integrating such a tool with a generic simulation environment, simulation models of alternative scenarios can be developed quickly and more cost effectively.

There is a need for an integrated/generic simulation environment that would allow users to design a future system and rapidly run a simulation of the system. Models are built fast and hence, are more likely to answer today's questions today. The objective of this study was to develop such an environment for the Orbital Space Vehicle. The developed environment is composed of the integration of two stand alone tools. SAGE (Schedule & Activity Generator/Estimator) is used to estimate the processing characteristics of the OSP designs based on OSP vehicle design characteristics. These characteristics along with additional user input are then fed into GEM- FLO 2.5 (Generic Environment for Modeling Future Launch Operations). GEM-FLO 2.5 uses this information to populate a generic simulation model of the processing operations for the OSP design. This paper presents the methodology used to develop and validate the integrated environment. The paper begins with a summary of related literature. The next section discusses the methodology used, followed by a section that presents a discussion of various test cases, and finally, some conclusions.

## 2 LITERATURE REVIEW

A literature review was conducted in the areas related to parametric modeling & estimation and generic simulation models. In the area of parametric modeling, there are multiple examples of models that use knowledge to support design decision making. For example, Ratchev, Urwin, Muller, Pawar and Moulek (2003) present a knowledge approach to the requirement engineering of one of a kind complex systems. Their approach uses knowledge functions to facilitate matching customer requirements to product characteristics. Among the proposed applications, knowledge based models have been used in the design of protection schemes for electrical transmission systems (West, Stochan, Moyes, McDonald, Gwyn and Farell 2003) and to design intelligent CAD systems (Chen and Xu 2001). In the space operations assessment arena, the model developed by Zapata and Ruiz-Torres (1999) utilized knowledge based parametric functions to estimate cost and time required for ground operations based on the architecture design.

In the area of generic modeling, Mackulak and Lawrence (1998) expressed a need for generic/reusable models that are properly structured to provide sufficient accuracy and computer assistance. In order to respond to this need and to evaluate the advantages of generic simulation models in terms of design turnaround time, they created a model of an automated material handling system. In their study, they demonstrate that a generic model can be constructed to meet the needs of reuse for a situation with a reasonably small set of unique components and that when properly constructed a special purpose reusable model can be more accurate and efficient than new models individually constructed for each application scenario. Simulation reusability resulted in an order of magnitude improvement in design project turnaround time with model building and analysis time being reduced from over six weeks to less than one week.

Brown & Powers (2000) generated a generic maintenance simulation model design to support a model of Air Force Wing operations and the maintenance functions associated with them. The model was also designed to be generic enough to be used in military applications as well as the commercial world. The simulation tool used was Arena by Rockwell Software and Excel/VBA for model input/output data. In addition, a Visual Basic Input Form also feeds into the model providing additional values (specified by the user) that control the timing of simulation events and the length of the simulation run. As some of the lessons learned, they found that the generic nature of the model required large quantities of input leading to a substantial amount of time consumed in setting up the model and manipulating the data.

The Winter Simulation Conference of 2000 session on composable, reconfigurable simulations exposed a series of papers (Diaz-Calderon, A., Paredis, C. J. J., and Khosla, P. K. 2000; Kasputis, S. and Ng, H. C. 2000; Davis, P. C., Fishwick, P. A., Overstreet, C. M., and Pegden, C. D. 2000; Son, Y. J., Jones, A. T., and Wysk, R. A. 2000) that addressed advantages of generic models such as reduced simulation analysis time, reduced monetary investment and model reuse.

This paper describes a methodology that merges parametric estimation with generic modeling in order to simulate valid models of future systems in a short timeframe with significant reduction on simulation analysis time and monetary investment.

## 3 METHODOLOGY

The methodology used to develop the integrated environment consists of 4 major steps:

- Development of estimation tool (SAGE)
- Modify GEM-FLO 2.0 to handle OSP vehicle configurations
- Integrate SAGE and GEM-FLO 2.5
- Validate environment
- Run Scenarios.

### 3.1 Development of SAGE

The objective of SAGE is to estimate the ground processing characteristics of an OSP vehicle design. SAGE translates the design of a space vehicle system into operational requirements by combining available operational data with results obtained from an expert based model that follows the reasoning and thought processes used by experts. The model combines vehicle characteristics into indexes linked to processing activities for particular system types (i.e. processing activities related to thermal protection systems, ascent propulsion, and payload processing). Based on the design specifications; reliability, maintainability, and supportability scores are determined for each vehicle system (i.e. main propulsion). These scores are then used to modify the ground system indexes (i.e. main propulsion inspection and maintenance). Designs that are simpler, more robust and/or easier to maintain will result in shorter processing times, or in the elimination of activities. Figure 1 presents a flowchart of the driving components in SAGE.

#### 3.1.1 User Inputs

SAGE defines a vehicle design by a set of system objects. Objects relate to physical components/characteristics of the design or to an approach used throughout the system.

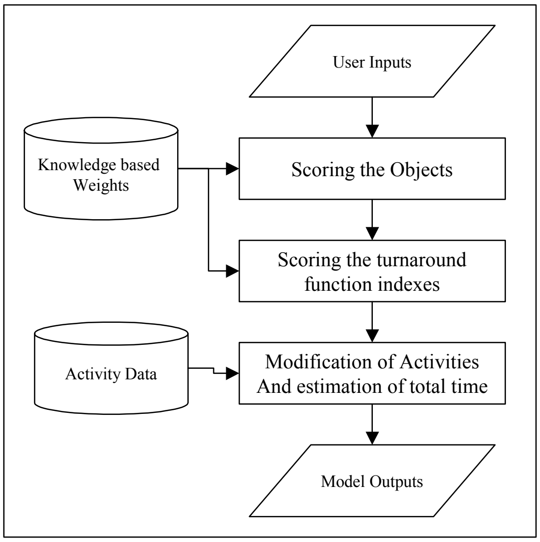


Figure 1: SAGE Components

There are three object types: basic, optional single use, and optional multi-use. The basic objects serve to define the design in terms of overall reliability and maintainability, size of the vehicle, integration approach to other elements, and spaceport approach. The optional single use object relates to physical components that can be part of the design. Only one single use object can be added to an element. For example, if the vehicle has a crew, the user must add the crew/passengers object, if there is a payload bay, the payload object and so on. The final type of object is the optional – multiple use. The design in Figure 2 includes one Ascent Propulsion object and two container objects (one for liquid oxygen and one for liquid hydrogen).

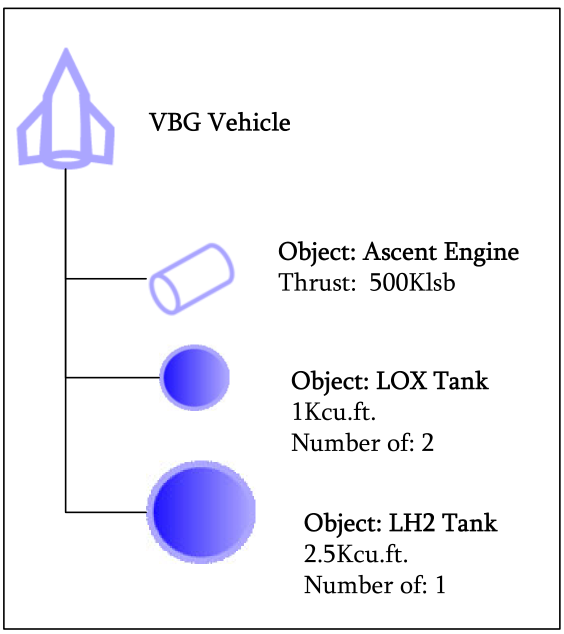


Figure 2: Example of Vehicle Objects

Objects are defined by qualitative inputs and quantitative inputs. Qualitative inputs define the technologies and options that characterize the object. For example, a payload bay has a qualitative input related to its level of standardization and an input specifying the type of connections between the payload compartment and the vehicle' systems (i.e.. liquids and gases). Quantitative inputs can be used to define the number of units that are linked to an object. A quantitative input for a thermal protection system (i.e. metallic tiles) could be the surface area covered by this specific type of thermal protection material

### 3.1.2 Scoring the Objects

Each object is scored independently based on *expert determined* weights that link all the qualitative inputs. Each option (within one of the qualitative inputs) has expert based predetermined values. The multiplication of the weights by the input values selected by the user is then divided by the sum of the weights to get a normalized object score. Finally, the quantitative inputs are used to scale the size of the object.

### 3.1.3 Scoring the Processing Function Indexes

Object scores are then combined with a second set of *expert based* weighs that relate object types to each of the processing function indexes. This process links objects that are related to each type of ground process. For example, all the ascent propulsion type objects and orbit type propulsion objects in the vehicle design are linked to the propulsion inspection and maintenance turnaround index and to the facilities preparation turnaround index.

### 3.1.4 Modification of Activities and Estimation of Total Time

Once the ground functions have been calculated based on the design characteristics, each of the activities related to a function is modified by the ground system index. The model keeps all precedence relationships across activities, preventing sequence changes to the turnaround activities. Finally, the total top-level times are estimated considering all ground systems operations. The model utilizes historical data from eight shuttle flows (about fifteen thousand activities), where engineers and managers at the Kennedy Space Center (McCleskey 2004) analyzed this data in order to relate each activity in the flow to a ground system function.

### 3.1.5 Outputs

The model generates eight top-level time estimates for a) main processing activities, b) integration time to an expendable/ other reusable activities, and c) launch activities. In addition, the user is asked to provide an estimate in terms of annual flight rate, which allows the estimation of the size of the fleet and the number of facilities required per module (main processing facility, integration facility, launch facility). The time and resource information is then passed to the simulation model via an exported file.

It is important to note that SAGE contains variables that cumulatively expose the user to the challenge of diverse design choices, multiple combinations of which can yield diverse solutions. For example, an object my be less reliable, but more easily maintained, or vice versa. Object count, reflecting on overall system complexity, can be increased for an operable technology, versus having a lowered complexity for an in-operable technology. In this and many other combinations, SAGE output results require analytical and design expertise to interpret while adding knowledge and expert understanding.

### 3.2 GEM-FLO 2.5

GEM-FLO is a generic discrete event simulation platform designed to accept any reusable launch vehicle design characteristics and operational inputs (such as processing times, event probabilities, required resources, and transportation times) and automatically generate a simulation model of the system. Once the simulation model is executed, it will provide multiple measures of performance including operations turnaround time, expected flight rate, and resource utilizations, thus enabling users to assess multiple future vehicle designs using the same generic tool.

GEM-FLO was developed to serve as a test bed for comparing competing designs of next generation vehicle architectures. GEM-FLO provides a common ground to compare the operational performance and costs of the proposed designs in a timely manner. When designs were proposed for the OSP vehicle, a similar tool was needed to compare the different OSP designs (Figure 3).

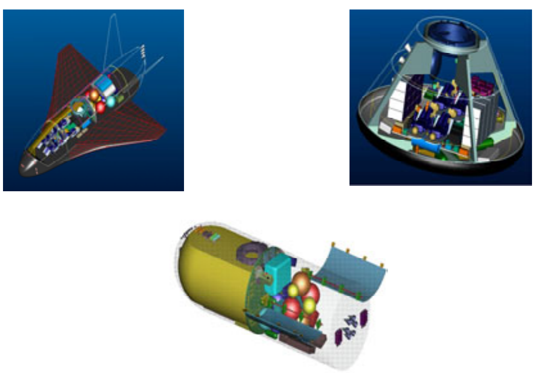

Figure 3: OSP Vehicle Design

The proposed OSP vehicle's operational flow differ slightly from other designs (including the shuttle) in two areas (see Figure 4). First, an OSP vehicle should always be available on orbit to serve as a rescue vehicle. Rescue vehicles have a predetermined maximum and minimum stay window at which time it will wait until another OSP vehicle is ready to replace it. The second difference, lies in the different designs integration locations. Different design configurations may be integrated either at the pad or at an integration facility. In order to accommodate these modifications, the latest version of GEM-FLO, GEM-FLO 2.0, was modified. An important modification was the ability to run multiple configurations (such as the Delta and Atlas) with distinct processing characteristics in the same model run. The conceptual flow diagram of the OSP vehicle design is presented in Figure 4.

In order to model the rescue vehicle replacement after an extended stay, synchronization logic was incorporated in the model. A rescue vehicle should be replaced no later than the maximum time allocation. Therefore, new missions (immediately after creation) would check the state of the rescue mission on orbit, if the worst case time estimation for the new mission total processing, integration and launch time falls within the replacement timeframe, the new mission is tagged as a replacement mission.

In order to elicit the required information from users, GEM-FLO 2.0 uses a graphical user interface designed to use the RLV domain terminology. This user interface, therefore, allows the system experts to enter information into the generic simulation using terminology with which they are familiar. This same system specific terminology is used by GEM-FLO when displaying the output results from running the model (Steele, Mollaghasemi, Rabadi and Cates 2002). Modifications were made in GEM-FLO 2.5 to reflect the design characteristics present within OSP designs. The most glaring modification was the hierarchical re-design of the GUI. With the ability to model unique process configurations within one model, activities such as integration and launch were now designed to be configuration dependent.

### 3.3 Integration

The integration of SAGE and GEM-FLO 2.5 allowed for the use of both tools at the same time. This gave users the flexibility to perform analysis of OSP vehicle designs faster and more accurately. However, integration was also done in a way to avoid hindering the ability to run both tools individually, if need be. Users would input the vehicle design characteristics into SAGE. Based on these design characteristics, SAGE will then provide estimates for times (processing, integration and pad times), the number of Flight Hardware Elements (FHE) required per FHE type, and the new mission arrival rate. GEM-FLO 2.5 can then be loaded with a design specific session. SAGE outputs are imported into a GEM-FLO scenario by the simple click of a button.

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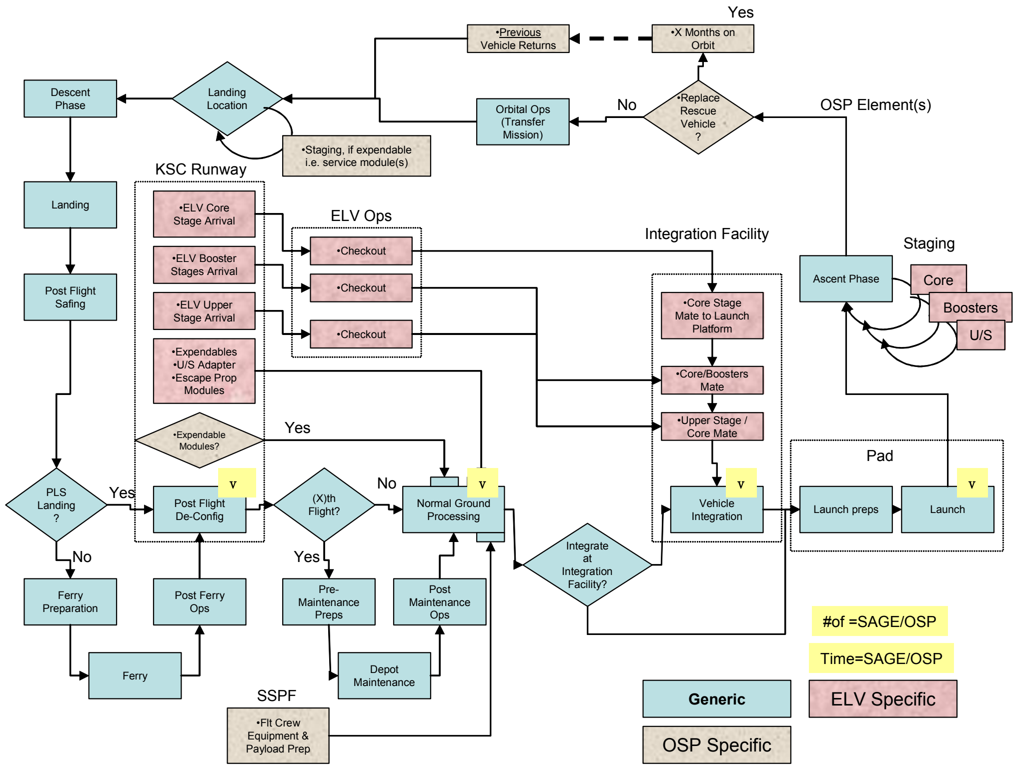


Figure 4: Conceptual Flow Diagram of OSP Vehicle Activities

### 3.4 Environment Validation

Validation of future systems is always a challenge since there is no actual system to compare the model results against. During validation efforts, modelers are interested in validating the data used throughout the model as well as the model logic itself. To validate the data used in a model of a future system, modelers can turn to subject matter experts to look at the model results and verify that these results are close to what they would expect based on their experience. The validation of the modeling logic can be accomplished by running a similar scenario of an actual (not future) system. For the validation of the environment presented in this paper both techniques were used. Three different OSP vehicle design scenarios were created: OSP on Atlas V, OSP on Delta and a combination of OSP on Deltas and Atlas V. The model was ran measuring metrics such as flight rate per year and average cycle time. Subject Matter Experts were then consulted to verify that the result were close to their expectation. Another measure of validation was to run a scenario using data from the Space Shuttle and compare these results to historical data available for these performance measure for the shuttle program. The results of the validation exercises resulted in a valid model.

## 4 SCENARIOS TESTED

The following scenarios were designed and ran using the SAGE/GEM-FLO 2.5 Integrated Environment:

- OSP on Delta
- OSP on Atlas V
- OSP on Delta or Atlas V.

The OSP on Delta and Atlas V are similar scenarios that follow the flow chart presented in Figure 4. The main difference between these two scenarios is the location where the Delta and Atlas V elements get integrated with the OSP element. This logic has an effect on how SAGE generates the top level time estimates from the OSP design. While the ground operation activities for integration and launch depend on the design characteristics, where these activities occur depend on the flow path.

Once the OSP design has been analyzed by SAGE, the user can export a file that will be read by GEM-FLO based on one of the three scenario combinations. The user can export one or all scenarios from the same form to data files that will be read by GEM- FLO.

Once in GEM-FLO 2.5 users can import scenario estimates (such as: processing times for turnaround, integration and launch, inter-arrival time of a mission and number of elements required per flight hardware element) from SAGE or can define/modify the scenario details trough the GUI (see Figure 5). Information such as the number of distinct flight hardware elements (i.e. 2 elements for OSP and Delta scenario), OSP element characteristics (i.e. number of available OSP vehicles, reusable or expendable, etc..) and processing details (i.e. processing time per activity, number of facilities and resources needed, etc) can be specified per flight hardware element. Users can also specify the window timeframe for which a replacement vehicle can stay on orbit. Integration and Launch details are configuration dependent, therefore, users can specify the integration location, launch location and launch time per configuration. This becomes important when modeling the OSP on Delta/OSP on Atlas V multiple configuration scenario.

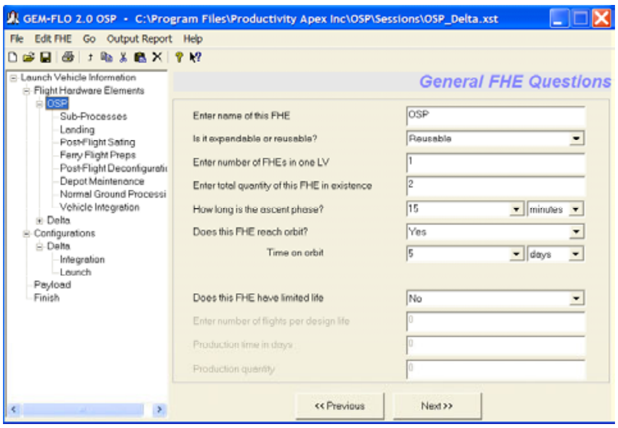


Figure 5: GUI for OSP on Delta Scenario

## 5 DISCUSSION

The measures of performance of interest for these scenarios are the number of successful flights per year, the average cycle time for a flight (from launch to launch), the average on-orbit stay for rescue vehicles and the percentage of time that replacement vehicles overstay the specified on-orbit window timeframe. By tracking these measures of performance, designers can answer questions regarding fleet size (number of OSP vehicles, Delta and Atlas V elements) and resource requirements. By performing "what if scenario" runs designers can determine:

- How many OSP vehicles are needed to meet a 6 flights per year schedule?
- How does the rescue vehicle on-orbit extended stay affect the number of flights per year?
- How many Integration/Turnaround/Launch facilities are required to support a specific fleet size?

The integration of the operations assessment model (SAGE), which translates a vehicle design to time and processes, to the simulation model (GEM-FLO) which uses these estimates to analyze total system performance allows answering these questions early on in the design phase of the program. By answering these questions early on, designers can modify their designs to improve operations performance and to efficiently use the available resources. Furthermore, an integrated estimation/ modeling environment such as this one can provide support throughout the entire life cycle of the program since it allows for system change, even dramatically, while still preserving the usefulness and reusability advantages of generic simulations. The product and process aspects of this work represent two of the parameters most often considered in maintaining competitiveness, with the third being an organizational aspect that has to do with "how or by who" the processes are implemented.

## 6 CONCLUSION

The future of space transportation will depend on the decisions of today. As designs that will replace the Space Shuttle system are being evaluated, consideration of the process times for maintenance and repair is paramount, as this will dictate the ability of the design to meet flight rate expectations and will directly affect life cycle costs. The presented methodology integration of a design assessment model that generates times and processes, to a simulation model that estimates system performance allows the fast assessment of vehicle design in relation to operations. The end objective of these efforts is to allow designers to perform a concurrent design that considers all life cycle stages and thus achieves the goal of higher reliability and reduced costs for space transportation.

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