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Paper Session II-B - Simulating Shuttle and Derivative Vehicle Processing at Kennedy Space Center

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SIMULATING SHUTTLE AND DERIVATIVE VEHICLE PROCESSING AT KSC

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ABSTRACT

Rockwell International Space Systems Division is teamed with the University of Central Florida on a research project to develop an automated simulation system to model ground processing scenarios for the Shuttle and Shuttle-derived vehicles. This simulation system is necessary to evaluate launch site facilities requirements and estimate life-cycle costs of future space programs.

This paper presents the results of initial simulation modeling of the orbiter processing critical path at Kennedy Space Center (KSC). An approach is presented for the planned capabilities to simulate mixed fleet processing and to perform sensitivity, capacity, cost, and risk analyses. Potential expert system applications for the simulation system are presented, such as a resource allocation tool for stand-down periods or a long-range scheduling tool for future programs like the Space Exploration Initiative.

The simulation model will be developed using the object-oriented languages *MODSIM II* and *C++*. This model is different than other software tools currently used for planning at KSC in that it is stochastic rather than deterministic. A deterministic model assumes all parameters of the model are known constants. A stochastic system defines the operations process using an indexed collection of random variables. The modeling system will be expandable using object-oriented inheritance techniques in which facilities and vehicles are modeled as templates. This system is different from other planning systems used at KSC in that supplemental vehicle and/or facility data can be introduced during program execution. This technique allows effective modeling of dynamic launch site environments for future programs.

INTRODUCTION

The launch site manager is faced with a complex world in which to make decisions. A formal and efficient technique is needed to augment the manager's experience in decision making. The technique must be formal (precisely documented) so that it can be learned quickly and applied to new situations. The technique must be efficient so that its cost does not increase in proportion to the complexity of the situation. Computer simulation is a technique that fulfills these needs. Computer simulation is a formal decision-making aid, adaptable to the complexities and change of the launch site environment which can be developed and communicated efficiently [5].

The National Aeronautics and Space Administration (NASA) has no comprehensive means of simulating and quantitatively analyzing launch vehicle processing requirements at the KSC. Currently, ground operations planning is accomplished using computer scheduling tools. The conceptualization of future programs makes use of qualitative expert knowledge and cost modeling. Although the current approach has proven successful on the National Space Transportation System (NSTS) program with a fleet of three Space Shuttle orbiters, the Space Exploration Initiative and increased Space Shuttle launch rates will add complexity to ground processing activities. In order to manage this increase in ground processing complexity, a comprehensive simulation capability is needed. The initial goal of this project is to develop the software tools to fulfill this need. The long-term research objective is to provide the capability of modeling processing scenarios for future programs' launch vehicle requirements. Without such tools, less than optimal approaches to ground processing requirements planning will result, wasting scarce resources and subsequently losing opportunities.

SYSTEM DEVELOPMENT METHODOLOGY

The goal of this project is to develop the software tools necessary for simulating ground flow processing activities for both current and future programs at the KSC. This simulation capability will allow engineers at the NASA to effectively model and quantitatively assess the options available in the costly and complex operations involved in the ground processing of space vehicles.

The modeling capabilities that will be provided in this initial research phase include the ground processing requirements of the current Space Shuttle as well as three recently proposed Shuttle-derived vehicles. A discussion of the ground processing requirements for each of these vehicles follows. In addition the simulation system will allow the case study of mixed fleet processing operations involving these launch vehicles. The life-cycle costs of each approach will be used as an evaluation criterion [12].

The simulation system software will be developed using object-oriented software construction techniques. This software methodology was developed specifically to increase the reusability of software components. Such an approach offers a capability not available using traditional software technology -- the ability to easily modify or extend the usefulness of existing software components. The result is a flexible simulation environment not constrained by the limitations of today's software development methods. An object-oriented approach offers the capability of user modification to the simulation system software to account for facilities or scenarios not considered at the time of system development.

Tables 1 and 2 describe the capabilities of software planning tools currently used at KSC. Table 1 contains the characteristics of the Artemis scheduling tool. This is the tool currently used by the Mission Planning Office for Space Shuttle manifest planning.

Table 2 contains the characteristics of the Ground Operations Cost Model (GOCM). GOCM was originally developed on the *Lotus 1-2-3* spread-sheet application program.

Table 3 shows the launch vehicle processing simulation system characteristics. This is a stochastic model; it contains random variables to describe launch vehicle processing durations. The two software tools discussed above are deterministic, they do not account for chance or probability.

Table 1. Artemis Characteristics

ARTEMIS
• Scheduling tool • Deterministic model • User needs to receive training • All analyses manually manipulated • Tool assumes fixed assets • Output is "waterfall" type milestone charts • Output accuracy depends on users' knowledge • Best used for near-term planning

Table 2. GOCM Characteristics

GROUND OPERATIONS COST MODEL (GOCM)
• Spread-sheet algorithm • Deterministic model • User must understand computer spread-sheet techniques • All analyses manually manipulated • Facility capacity not considered • Output is scenario cost profile • Can be used for near- or long-term planning

Table 3. Launch Vehicle Processing Simulation System Characteristics

LAUNCH VEHICLE PROCESSING SIMULATION SYSTEM
• Object-oriented simulation model • Stochastic (or probabilistic) model • User friendly front end -- Menu-driven -- Graphical user interface • Easily expandable system -- Facilities and vehicles modeled as templates -- Object-oriented inheritance capability • System capabilities: -- Sensitivity analysis (mapping) -- Capacity analysis -- Cost analysis -- Risk analysis -- Mixed fleet processing • Best used for long-term planning

Software Methodology. The design of the simulation system using object-oriented software construction techniques reduces the difficulties involved in simulating complex ground processing scenarios. In this case the system architecture is based on the classes of data (i.e., objects) the system manipulates as opposed to the functions the system is required to perform. The rationale for this approach follows from the observation that as software system requirements change or evolve, the functions that the system performs may change drastically; however, the classes of data that the system manipulates remain much more stable. In the object-oriented design of such a system, more flexibility is returned. The goal of this approach is to allow the software system to be easily extended to improve its functionality, or reused in other systems. Ideally the extension or reuseability of the software does not require a knowledge of the details of system implementation. The ability to develop software in this manner enables software components to be packaged so that others can modify and incorporate them into their products. This ease of reusability is currently lacking in traditional software technology [10].

GROUND PROCESSING REQUIREMENTS

This research project will initially address the ground processing requirements for the Space Shuttle, shown in Figure 1. KSC has primary responsibility for prelaunch checkout, launch, ground turnaround operations, and support operations for the Space Shuttle and its payloads.

Figure 1. Space Shuttle

Space Shuttle Processing. The functional flow block diagram in Figure 2 shows the Space Shuttle ground processing in current practice. Solid rocket motor segments are shipped by rail from the contractor/refurbishment facility to KSC. The segments are transported in a horizontal position with transportation covers. Upon arrival the segments are off-loaded, rotated, and placed in the vertical attitude at the Rotation, Processing, and Surge Facility (RPSF). Receiving inspection is then accomplished. After build-up of the aft booster assemblies, the solid rocket motor segments are transported, in serial order starting with the aft end, to the Vehicle Assembly Building (VAB) for solid rocket booster (SRB) stacking. The inert elements (forward skirt, frustum, nose cap, electronics, and aft skirt) are shipped from various facilities to the VAB. A complete set of two SRB's is integrated on the Mobile Launch Platform (MLP) in the VAB. Once stacking operations are completed, a SRB alignment check is performed. The external tank (ET) is transported by barge to the KSC Turn Basin, then off-loaded onto a wheeled transporter and moved to the VAB. After satisfactory checkout of the tank's systems, the ET is mated to the SRB flight set on the MLP.

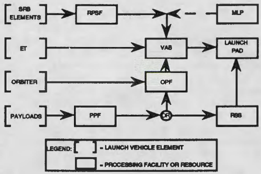

Figure 2. Current Space Shuttle Processing Flow

The Orbiter Processing Facility (OPF) is used to process the orbiter vehicle between missions. Following landing from a space mission, usually at Edwards Air Force Base (EAFB), the orbiter is ferried on its 747 Shuttle carrier aircraft (SCA) to KSC and towed to the OPF. Initial OPF operations start with a series of vehicle access operations. Routine post-flight deservicing/servicing and checkout is performed. Any required vehicle modification or deficiency resolution is worked in parallel with OPF operations whenever possible. Routine preflight servicing is performed and if no cargo is to be installed in the OPF, the orbiter is closed-out and towed to the VAB [4,8].

Payloads may be shipped to KSC via air, sea, rail, or highway transportation. Payloads are processed either horizontally or vertically at one of the payload processing facilities (PPF) located at KSC, at Cape Canaveral Air Force Station, or at a commercial facility adjacent to KSC. Horizontally processed payloads, usually integrated into the Spacelab module at the Operations and Checkout building, are moved via the canister/transporter to the OPF for vehicle integration into the payload bay. Vertically processed payloads are moved via the canister/transporter to the Payload Changeout Room in the Rotating Service Structure (RSS) at the launch pad. Vertical payloads are integrated into the orbiter payload bay at the pad [4,7,8].

INITIAL SIMULATION MODEL

Figure 3 depicts the current Space Shuttle processing critical path flow that was derived from Figure 2. An initial NSTS processing critical path simulation model has been developed in the *SLAM* simulation language. Historical NSTS processing data from missions STS-1 through STS-31R were collected and incorporated into this critical path simulation model. STS-1 OPF (531 days) and VAB (33 days) processing times were excluded from the data base used for the critical path simulation model because they were considered maverick data points. STS-1 data included completion of orbiter vehicle construction activities which are not part of standard NSTS vehicle processing. The critical path flow shown in Figure 3 includes historical processing time modes (not the means) and maximum and minimum observations. The MLP delay time includes post-launch MLP refurbishment, and then booster stacking (missions STS-27R through STS-31R mode = 39 days) and SRB/ET mate and closeout (16 days) when a VAB high bay becomes available.

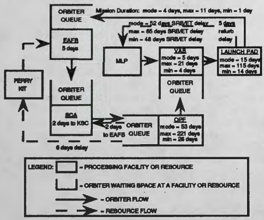

Figure 3. Current Space Shuttle Processing Critical Path Flow

NSTS critical path *SLAM* simulation model output is shown in Table 4. Each run of the simulation model was for a ten year period. Deterministic values were assigned for the number of: orbiters, OPF bays, VAB bays, MLP's, launch pads, EAFB crews, ferry kits, and SCA's for each simulation run in Table 4. The orbiter queue capacity was modeled as unlimited because it was assumed temporary shelters could be used to store orbiters. Simulation model output for average missions per year and average time that an orbiter waits for an OPF bay is shown in Table 4 for each run number. The deterministic (Det.) output was calculated by using the mean historical processing time for each facility or resource. The random output was calculated by fitting the triangle distribution to the facility or resource historical processing time characteristics shown in Figure 3. The simulation model randomly selects processing times from that distribution.

The triangle distribution was used instead of the normal distribution because a triangle distribution defines practical distribution limits; whereas using the normal distribution could have resulted in negative processing times in some instances when processing time samples where randomly selected from as little as two standard deviations (-2σ) away from the mean.

Some initial conclusions from the critical path simulation model output are:

- With current facilities (i.e., two OPF bays and three MLP's) and three orbiters, the best *average* flight rate that could be expected (based on historical processing data) is six to eight missions in a year (see simulation run #2).

- The new orbiter and OPF bay should provide capability for an average of nearly eight to ten flights per year (or better if historical processing times can be improved upon, see simulation run #8).

- Adding a fourth MLP is better than adding a fourth OPF bay with four or more orbiters for increasing average flight rate, but there is little effect on flight rate for either choice for less than four orbiters (see simulation runs # 11 - 20).

- The launch processing system with three or four OPF bays and three MLP's almost saturates at four orbiters and the average flight rate will not increase much past ten flights per year unless a new MLP is added or processing times are improved (see simulation runs #6 - 15). Little improvement is shown according to the simulation by adding a fourth OPF bay without a fourth MLP.

PLANNED SIMULATION CAPABILITIES

The object-oriented simulation system is being developed on a Sun Sparc 4 workstation network located at the University of Central Florida. The major advantage of object-oriented programming is that the simulation system is easily expandable because of inheritance capability where facilities and launch vehicles are modeled as templates. The object-oriented programming languages *MODSIM II* and *Concurrent C++* are being used for system development. The object-oriented system will have its validity tested against the verified *SLAM* critical path model.

Table 4. Critical Path SLAM Simulation Model Results

Sim. Run #	Input Number of: Orbiters	OPF Bays	VAB Bays	MLPs	Launch Pads	EAFB Crews	Ferry Kits	SCAs	Simulation Output: Avg. Missions per Year: Det.	Random	OPF Wait Time (Days): Det.	Random
1	2	2	2	3	2	1	1	1	5.4	4.5	0.0	0.0
2	3	2	2	3	2	1	1	1	8.0	6.2	0.7	10.5
3	4	2	2	3	2	1	1	1	9.3	7.1	10.4	24.7
4	6	2	2	3	2	1	1	1	9.3	7.6	82.6	82.9
5	8	2	2	3	2	1	1	1	9.3	7.6	151.4	165.6
6	2	3	2	3	2	1	1	1	5.4	4.5	0.0	0.0
7	3	3	2	3	2	1	1	1	8.1	6.3	0.0	0.0
8	4	3	2	3	2	1	1	1	10.0	7.8	0.4	1.3
9	6	3	2	3	2	1	1	1	10.1	8.8	1.5	7.7
10	8	3	2	3	2	1	1	1	10.1	8.6	5.5	11.0
11	2	4	2	3	2	1	1	1	5.4	4.5	0.0	0.0
12	3	4	2	3	2	1	1	1	8.1	6.3	0.0	0.0
13	4	4	2	3	2	1	1	1	10.0	7.9	0.0	0.0
14	6	4	2	3	2	1	1	1	10.1	8.7	0.5	1.0
15	8	4	2	3	2	1	1	1	10.1	8.7	1.3	2.4
16	2	3	2	4	2	1	1	1	5.4	4.5	0.0	0.0
17	3	3	2	4	2	1	1	1	8.1	6.4	0.0	0.0
18	4	3	2	4	2	1	1	1	10.7	8.3	0.3	1.9
19	6	3	2	4	2	1	1	1	13.4	10.3	1.6	18.6
20	8	3	2	4	2	1	1	1	13.4	10.8	4.0	42.1
21	2	4	2	4	2	1	1	1	5.4	4.5	0.0	0.0
22	3	4	2	4	2	1	1	1	8.1	6.4	0.0	0.0
23	4	4	2	4	2	1	1	1	10.7	8.4	0.0	0.0
24	6	4	2	4	2	1	1	1	13.4	10.7	0.4	2.4
25	8	4	2	4	2	1	1	1	13.4	11.1	1.0	5.3

The launch vehicle processing simulation system logic flow chart is shown in Figure 4. The simulation system will have a user friendly front end consisting of a graphical user interface. This interface will pictorially represent the KSC launch site through presentation graphics and animation. Typical inputs to the menu-driven front end will permit the user to choose:

1) any number (or type) of launch vehicles, OPF bays, VAB bays, MLP's, launch pads, EAFB crews, ferry kits, and SCA's;
2) waiting space (queue) capacity;
3) processing time duration and distribution (constant or random) for each activity, and;
4) initial placement of launch vehicles and launch site configuration.

Typical simulation output will permit the user to determine:

1) nominal processing times for varying fleet sizes (and mixes);
2) facility utilization and optimization;
3) effects of exceptional events and schedule disruptions (for risk analysis);
4) potential processing flow bottleneck locations, and;
5) optimal strategies for minimizing processing delays and life-cycle costs.

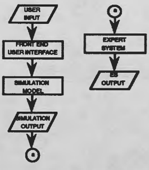

Figure 4. Simulation System Logic Flow Chart

FUTURE GROUND PROCESSING REQUIREMENTS

The development of a Shuttle-derived vehicle launch system has been proposed by NASA as one possible near-term solution to the demand for a moderately-priced heavy lift capability required by the Space Exploration Initiative [9]. A reduction of the life-cycle costs of such a program is made possible through the use of existing NSTS resources where applicable, and through the addition of new facilities as appropriate. By making use of proven Shuttle technology, this approach minimizes the risks associated with a newly designed system, and takes advantage of the nation's substantial investment in the current Shuttle infrastructure (e.g., launch pads and servicing facilities) [2,12,15].

Shuttle Orbiter Modification Processing. The functional flow block diagram in Figure 5 addresses the discontinuity that orbiter modifications pose to routine OPF processing. A new facility is proposed to handle the extensive modifications, structural inspections, and maintenance planned over the lifetime of each Shuttle orbiter. This concept treats the orbiter as a stand alone element, much like the SRB's, Space Shuttle main engines, and payloads. The orbiter design contractor/manufacturer has the vehicle expertise and is responsible for orbiter configuration. This new facility is called the Orbiter Mod Facility (OMF).

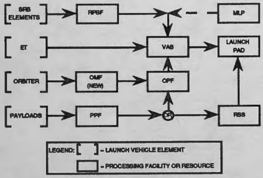

Figure 5. Shuttle Orbiter Modification Processing Flow

Shuttle-C Processing. The Space Transportation System Cargo Element, or Shuttle-C, is a largely expendable, unmanned launch system capable of carrying 80,000 to 140,000 pound payloads into low earth orbit (see Figure 6). It uses existing and modified Space Shuttle qualified systems and the established NSTS infrastructure. The Shuttle-C boattail consists of a simplified Shuttle orbiter aft fuselage utilizing two existing Space Shuttle main engines. The boattail is topped by a payload carrier (new element) [2,6,11,15]. A NASA plan uses the Shuttle-C to transport the Space Station Freedom assemblies to orbit [5,9].

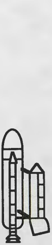

Figure 6. Shuttle-C

In the Shuttle-C functional flow block diagram shown in Figure 7, a new Cargo Element Processing Facility (CEPF) replaces the OPF of the earlier Shuttle processing scenario presented in Figure 2. This new CEPF is needed so as not to impact planned NSTS manifests by using critical path OPF processing capacity for Shuttle-C preflight processing. This approach also avoids shutting down an OPF high bay for Shuttle-C facility modifications. Other vehicle elements are processed identically to current NSTS procedures. Since the Shuttle-C vehicle envelope is no larger than the Space Shuttle's, it will fit in a VAB vehicle integration cell with some modification requiring extension of current work platforms allowing cargo element access.

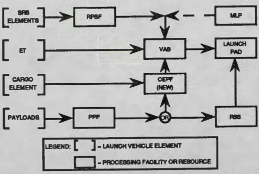

Figure 7. Shuttle-C Processing Flow

There is at least one Shuttle-C ground processing constraint to using current NSTS launch pad facilities. The lower 60 feet of the payload bay can be loaded horizontally in the CEPF or vertically in the RSS Payload Changeout Room at the launch pad; however, the upper 22 feet of the payload bay must be loaded horizontally in the CEPF because the RSS Payload Changeout Room will not reach above the Space Shuttle payload bay envelope [2,5,6,11,15].

Shuttle-C Block 1 Processing. Space Exploration Initiative studies are considering the Shuttle-C with Block 1 modifications as the lunar heavy lift launch vehicle (see Figure 8). This vehicle would ferry the spacecraft and assemblies required to build a manned moonbase [9].

Figure 8. Shuttle-C Block 1

Ground processing activities for the Shuttle-C Block 1 will be similar to those of the Shuttle-C with the addition of some new facilities. The intended cargo for Shuttle-C Block 1, payloads supporting lunar system outpost and operations, will require the new Lunar Payload Processing Facility (LPPF) shown in Figure 9. The Shuttle-C Block 1 will use the CEPF for cargo element processing and payload integration along with the Shuttle-C.

NSTS work platforms in the VAB cannot accommodate the Shuttle-C Block 1 envelope, therefore a new vehicle integration cell is required. In the concept diagramed in Figure 9, all ET processing and checkout activities are moved out of the VAB to a new ET Processing Facility (ETPF). High bay #2 in the VAB is then modified into the Shuttle-C Block 1 vehicle integration cell. In addition a new Booster Stacking and Integration Facility (BSIF) is proposed to move the hazardous stacking operations out of the VAB. This concept helps promote the integrate/transfer/launch plan desired to increase parallel ground processing activities. If payloads are not integrated into the vehicle in the CEPF, a new launch pad mobile service structure (MSS) is required [9].

Shuttle-Z Processing. Previous Lunar/Mars mission studies emphasized the need for a large heavy lift capability which considers reusability. The concept of a Shuttle-derived vehicle with a third stage transfer vehicle was called "Shuttle-Z" by the Code Z Working Group of the NASA Office of Exploration. This vehicle is being considered for the Mars heavy lift launch vehicle which will be used to transport the spacecraft and assemblies required to establish a Mars outpost (see Figure 10) [9,13].

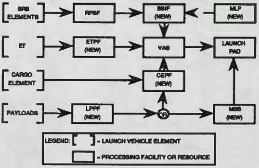

Figure 9. Shuttle-C Block 1 Processing Flow

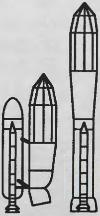

Figure 10. Shuttle-Z (Side-Mount and In-Line Versions)

The functional flow diagram of the final launch vehicle type considered in this initial research effort, the Shuttle-Z, is shown in Figure 11. The ET processing is the same as that of the Shuttle-C Block 1. Shuttle-Z payload processing requires a new Mars Payload Processing Facility (MPPF) to handle the oversized cargo the Shuttle-Z is expected to carry into orbit. In this concept a new Shuttle-Z processing facility, the Cargo Carrier Processing Facility (CCPF), is required for cargo carrier processing and payload integration. The CCPF is needed because the OPF and the CEPF processing capacity is needed to support the NSTS and Shuttle-C planned manifests. This concept modifies high bay #4 in the VAB to serve as the Shuttle-Z vehicle integration cell.

Finally, if payloads are not integrated into the vehicle in the CCPF, a MSS capability would be required at the launch pad [1,6,9,13].

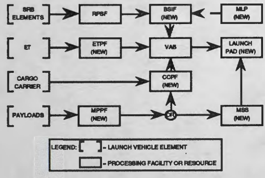

Figure 11. Shuttle-Z Processing Flow

POTENTIAL FUTURE ENHANCEMENTS

Figure 4 shows how an expert system could be added to the launch vehicle processing simulation system. Some potential expert system applications:

Table 5. Future Applications

A. Evaluation of simulation results. User inputs a scenario description into the simulation system using the graphical user interface. Simulation system generates the simulation results. Expert system results evaluator provides evaluation of results based on expert knowledge base and provides recommendations for improvements to increase launch rate or lower life-cycle costs.
B. Long-range scheduling applications (i.e., scheduling impact analysis). User inputs schedule scenario description into the simulation system using the graphical user interface. Simulation system generates the simulation results. Expert system schedule builder evaluates the simulation results and provides recommendations for improvements based on expert knowledge base. A new schedule scenario description is input into the simulation system and the cycle repeats until an optimal result is obtained.
C. Resource allocation tool for stand-down periods. Menu-driven front end allows user to establish initial stand-down conditions such as location of vehicles. Expert system makes recommendations on where to move or store vehicles or resources during the stand-down period.
D. Risk analysis tool. Probabilities of undesirable events are programmed into the model. When an undesirable event occurs during program execution (such as loss of a launch pad), the expert system makes work-around recommendations and calculates the event's effect on flight rate and life-cycle costs.
E. Iconic programming tool. Expert system automatically generates a launch vehicle processing simulation program from iconic representations of launch site facilities, resources, and vehicles represented in the graphical user interface.

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