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OPERATIONS ASSESSMENT OF LAUNCH VEHICLE ARCHITECTURES USING ACTIVITY BASED COST MODELS

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ABSTRACT

The growing emphasis on affordability for space transportation systems requires the assessment of new space vehicles for all life cycle activities, from design and development, through manufacturing and operations. This paper addresses the operational assessment of launch vehicles, focusing on modeling the ground support requirements of a vehicle architecture, and estimating the resulting costs and flight rate. This paper proposes the use of Activity Based Costing (ABC) modeling for this assessment. The model uses expert knowledge to determine the activities, the activity times and the activity costs based on vehicle design characteristics. The approach provides several advantages to current approaches to vehicle architecture assessment including easier validation and allowing vehicle designers to understand the cost and cycle time drivers.

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1. INTRODUCTION

The research and design of the next generation launch vehicles (LV's) continues as NASA and industry recognize the potential commercial uses of space and space-based transportation. However, these potential uses cannot be realized until the cost to access space is reduced by several orders of magnitude [1]. In order to achieve this, and based on experiences with the only existing reusable LV (Shuttle) and several expendable LV programs, the design process has evolved and parameters like operability, maintainability, and life cycle costs are critical measures of performance for the evaluation of new LV architectures [2].

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 [3], 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 are 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. Ground operations account for a large portion of the cost of shuttle and ELV's operations. In addition, models that asses early at the concept level are essential as decisions made at this stage of design typically have a significant effect on life cycle costs and other operation parameters.

The need for operation assessment models has prompted NASA's John F. Kennedy Space Center, industry, and academia to form a team (Vision Spaceport) to address these issues [4]. The efforts of the Vision Spaceport team have resulted in a prototype model toolkit that assesses the spaceport requirements driven by a LV architecture. The tools developed by this team provide a "sense of direction" Life Cycle Cost (LCC) based on costs baselines of the Shuttle program and other existing launch/transportation systems. The tools are founded on knowledge functions that map vehicle characteristics to operational functions of a spaceport [5], for example the launch function. The tools developed by this team have been used in two NASA studies; The Space Solar Power Concept Definition Study and The Space Transportation Architecture Study 99.

An alternative approach to the knowledge based functions used in the Vision Spaceport toolkit is the development of a knowledge driven Activity Based Costing (ABC) model. ABC techniques have been used in several cost estimation models for manufacturing; jobs shops environment [6], CIM (Computer Integrated Manufacturing) environments [7], and electronics manufacturing [8], and supply chain modeling. In the space vehicle operations environment, an ABC model was proposed by Christenson and Komar [9] for the modeling and analysis of reusable rocket engines. Their approach focused on detailed modeling of the activities required to turnaround reusable rocket engines, including the development of design specific schedules, resource sets, and stochastic characterizations.

In general, all of these ABC models work by first estimating the activities required to produce/operate a product/device, and then based on these, estimate the labor and other costs associated with these activities. These models addressed "well defined" environments where technology is at a mature state and the effect of design choices is well understood. The problem addressed by this research is the estimation of activities on an environment were there is limited knowledge of the activities required by a vehicle architecture, given these architectures are typically based on new and experimental technologies. This research proposes the use of expert's knowledge to estimate the activities and associated time and cost parameters. The rest of the paper is organized as follows. The first section reviews the modeling requirements for operations cost assessment of LV architecture designs. The second section presents a generic modeling methodology. The third section describes the knowledge requirements to implement the methodology. The fourth section summarizes the work and discusses directions of future work.

2. OPERATIONS ASSESSMENT MODELING OF LV ARCHITECTURE DESIGNS

The reduction of the cost to access space could open new markets and applications, as for example space tourism. To achieve the lower cost requirements of a future space transportation system, the assessment of vehicle concepts/architectures must consider all life cycle costs; design and development, manufacturing, and production. Design decisions drive to a large extent development, manufacturing, support, and operations functions, thus models based on design decision can be used to predict all of these areas. However, the complexity of this assessment process requires the development of multiple models, capable of estimating the different cost elements, for example a program development assessment model, a manufacturing assessment model, and an operations assessment model. All of these models should then be integrated to provide true life cycle costs for a space transportation system.

Operations models (ground operations or spaceport operations) are an important part of the assessment of new vehicle architectures as they reflect a large portion of the system's recurring costs and will determine the vehicle flight rate capability. The recurring costs and the flight rate are the result of tasks or activities that are required during ground operation, for example the preparation of a payload for integration with the vehicle. Typically the cost and task duration time assessment of these processes is performed by experienced engineers who employ their knowledge of production and operations technology, methods analysis, and engineering economics to predict the probable cost and production time of a product [6], in this case a ground operation activity.

This paper describes a modeling methodology that estimates the flight rate capability and the costs associated with the spaceport operations for a LV concept/architecture. The research described here focuses solely on this area given other models have been proposed to estimate manufacturing costs/production times which could be used to model LV systems [10]. Under the scope of this research, the spaceport is the environment where a LV operates and is provided the support required to satisfy customer requirements. The spaceport is defined as the set of functions that enable a space vehicle to operate and become a space transportation system; from landing (if a RLV) to launch. This includes the processes required to prepare the vehicle for launch, the processes for payload/crew/passenger ingress and egress, the processes of integration to other elements (as in the Shuttle system), the processes required to maintain the vehicle, and the processes required to control during flight. Other functions of the spaceport include those of payload preparation, logistics, and overhaul maintenance.

3. ACTIVITY BASED MODELING OF LV ARCHITECTURES

The principles of activity based models are the assignment of flow times and costs to a product based on the activities required for its production. Each activity has an associated activity time and a set of resource requirements which determine the cost of the activity. In the operations case, the costs will be based on the activities required for ground operations and its associated activity times and other activity cost drivers.

Given the "product" is the operation of a LV concept/architecture with no existing processes (therefore the actual activity times and costs are not known), the model must predict the activities and the corresponding activity times and costs. As the information about a concept launch vehicle is limited, only top level activities can be defined. Studies from NASA and industry [11] have characterized the inputs from a LV architecture/concept required to assess its operability. While this input list is extensive, it has not been directly related to specific ground activities, and in most cases the architecture variables that drive the time and cost requirement for an activity have not been determined.

3.1 Design Driven Activities

This model characterizes a LV architecture/concept by J design variables, for example, engines of the staged combustion type, engines of the RBCC type, ceramic tile thermal protection system, etc. For each design variable j there are N_j activities required for flight readiness/operation as for example leak check, remove and repair, servicing, etc. The LV architecture/concept is also defined by K vehicle characteristics/ operational drivers α_k. Vehicle characteristics/operations drivers are for example the total area that is covered by a type of thermal protection, the weight of the vehicle, the number of fuel cells in the vehicle, etc. In addition, in some cases the operational driver is the existence of that variable in the design, thus α_k will be a binary variable. For example, a design variable could be the "existence" of life support systems on board and a possible activity is to service the systems, thus $\alpha_{life\ support} = 1$ in the case of SST and $\alpha_{life\ support} = 0$ (not true) in the case of Venture Star.

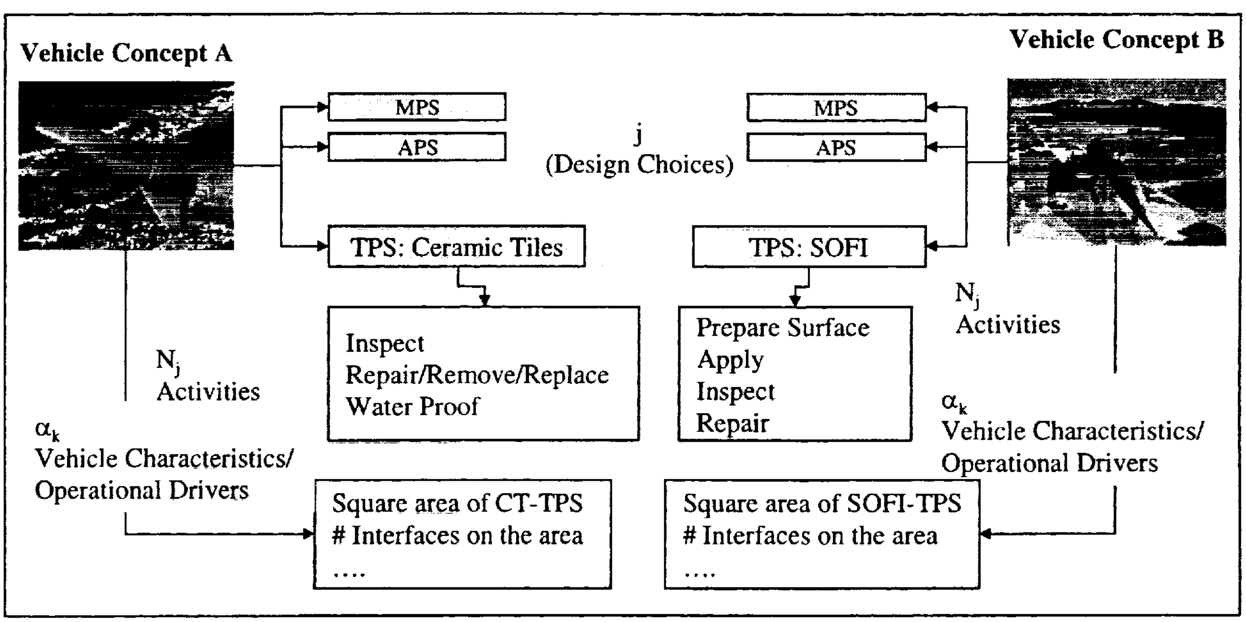

Figure 1. Example design driven activities

Figure 1 illustrates the approach for two concepts. Each design concept is based on several design choices, for example the type of engine used for the main propulsion system (MPS), the type (if any) of its auxiliary power system (APS), and the type of thermal protection system (TPS) covering its exterior surfaces. In the example shown, vehicle concept A uses ceramic tiles as a thermal protection system, while concept B uses SOFI (spray on foam insulator) for thermal protection. The activities for each approach are different and similarly, the vehicle characteristics/operations drivers of interest are different.

3.2 Estimating Operational Cost

To determine the operational cost, it is assumed that each activity n of design variable j, referred to as j(n), has an associated cost $C_{j(n)}$ which is a function of one or more vehicle characteristics/ operations drivers (1a). The cost function for activities could have different forms as required by the activity, including formulation as a linear equation (1b) or as non linear equation (1c).

$$C_{j(n)} = f(\alpha_k) \tag{1a}$$

$$C_{j(n)} = \Omega + \Psi\alpha_x + \Delta\alpha_y \tag{1b}$$

$$C_{j(n)} = \Omega + \Psi\alpha_x/\alpha_y + \Delta(\alpha_y)^2 \tag{1c}$$

Note: Ω, Ψ,and Δ are constants or functions.

For example, the cost of inspecting a thermal protection system (TPS) of ceramic tiles may be formulated by $20,000 + $150 x area of ceramic tile TPS. The $20,000 may be cost of setting up the equipment and the $150 may be associated with the labor and overhead cost per square foot of ceramic tiles TPS that is inspected.

By adding up the cost for all the activities, the total operations cost per flight, C_{ops} , can be formulated (2).

$$C_{ops} = \Sigma_{m=1..J} \{\Sigma_{t=1..Nm} C_{m(t)}\} \tag{2}$$

3.3 Estimating Ground Cycle Time

The flight rate is an important characteristic of flight systems which is tightly related to ground operations. Estimating the flight rate is important as it will help estimate the number of vehicles required to satisfy customer demand forecasts, and also estimate the proper allocation of design, development, and manufacturing costs to ground activities. The flight rate is the inverse of the total flow time of a vehicle over the length of a year, where the total flow-time is the time a vehicle spends in the ground (ground cycle time) and in space (flight time).

To determine the ground cycle time, it is necessary to first estimate the time of each of the activities required by the design. It is assumed that each activity n of design variable j, referred to as j(n), has an associated task time $T_{j(n)}$ which is a function of one or more vehicle characteristics/ operations drivers (3a). Similar to the cost function, the task time for an activity could have different forms as required by the activity, including formulation as a linear equation (3b) or as non linear equation (3c).

$$T_{j(n)} = f(\alpha_k) \quad (3a)$$

$$T_{j(n)} = E + \Gamma\alpha_x + \Pi\alpha_y \quad (3b)$$

$$T_{j(n)} = E + \Gamma\alpha_x/\alpha_y + \Pi\alpha_y^{\,2} \quad (3c)$$

Note: E, Γ,and Π are constants or functions.

For example, the time to inspecting a thermal protection system (TPS) of ceramic tiles may be formulated by 24 hours + 0.5 hours x area of ceramic tile TPS, where 24 hours may be the time required to set up the equipment and 0.5 hours is the time required to inspect per square foot of ceramic tiles TPS given a full capacity of resources (multiple inspecting resources working in parallel).

To determine the overall flow-time and therefore the flight rate, a network of the activities is modeled. This is based on the assumption that spaceport (ground operations) is a network of Q stations, where each station has an unlimited amount of processors. The model also assumes that each activity j(n) is assigned to one of the Q buckets by variable $b_{j(n)}$, of range1 to Q based on expert's knowledge. At the top level, stations could be defined by the major spaceport functions as landing, turnaround, integration, launch, and traffic control during flight. Each processor at a station can only complete activities for one design variable, thus the lead time at each station is determined by the longest set of activities for a design variable system assigned to it. This assumes that the resources assigned to each subsystem are independent are there are no scheduling conflict constraints. The lead time of the network is the sum of lead times for all the stations.

The cycle time for subsystem j at station q, $CT_{q,j}$ is:

$$CT_{q,j} = \Sigma_{\,t=1..Nj} \left(T_{j(t)} \text{ if } b_{j(t)} = q, 0 \text{ otherwise} \right) \quad (4)$$

The cycle time for a station q, CT_q is:

$$CT_q = \text{Max}_{\,m=1..J}\ CT_{q,m} \quad (5)$$

The ground operations cycle time is:

$$GCT = \Sigma_{\,d=1..Q}\, CT_d \quad (6)$$

Figure 2 illustrates an example of how the process works for a specific station. Let's assume there are only three design options for the turnaround module (TPS = Thermal Protection System, MPS = Main Propulsion System, CT = ceramic tiles, B = Blankets, RBCC = rocket based combined cycle). Each of these choices have an associated set of activities, activity times, and activity costs (I = inspect, r/r/r = repair/replace/remove, WP = water proof, S = safe, S/C = service/closeout). The sum of the three activities for the TPS-ceramic tiles design choice is the one that determines the turnaround cycle time.

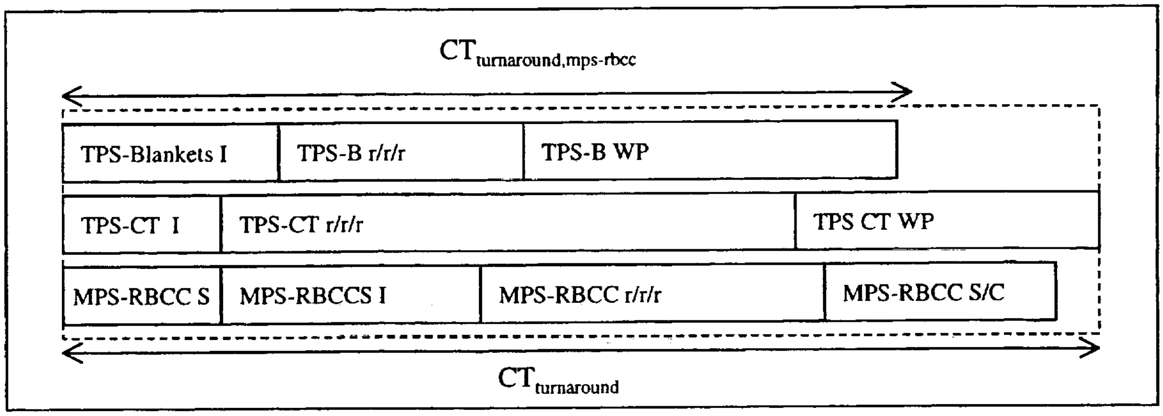

Figure 2. Example: Cycle Time for the Turnaround station

Figure 3 shows an example for the total vehicle flow-time given a set of six stations: TC = traffic control during flight, Ld = Landing operations, Turnaround operations, payload de-mate operations, payload integration operations, and launch operations. In the illustrated network, two stations are parallel: turnaround and P/L de-mate and all other processes are sequential. Note that within each station there are one or more design driven activity sets as in Figure 2.

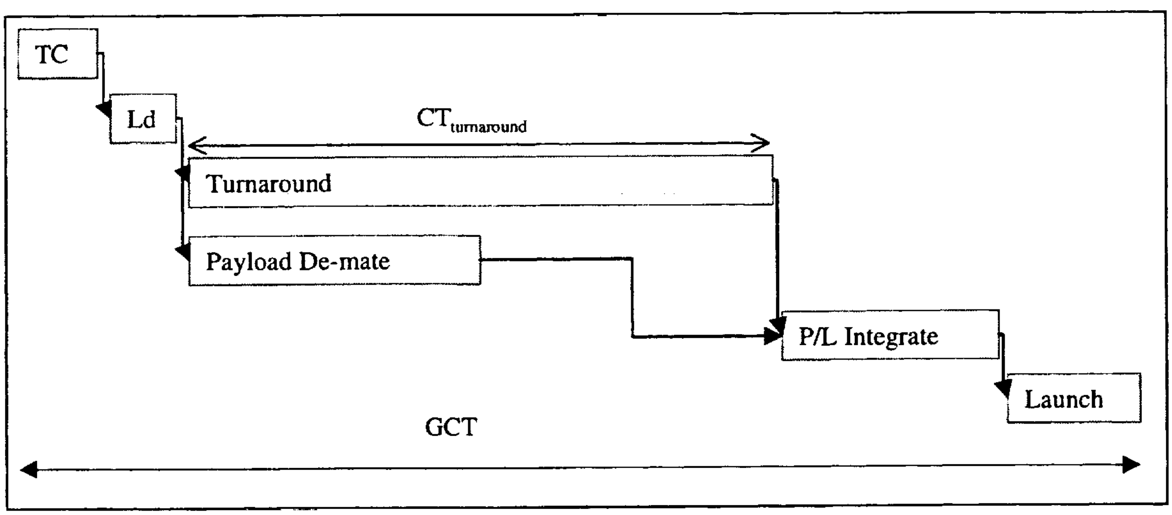

Figure 3. Total flow-time example

3.4 Knowledge Requirements

The implementation of the described model requires an extensive knowledge base. The generation of this knowledge base will require the development and validation of a knowledge capture process which allows experts from launch and design centers to participate on its development. Figure 4 shows the main knowledge elements required for the development of the model. First, a set of vehicle design options, focusing on the operational drivers, must be developed. For each of these design options, a set of activities must be defined as in section 3.1. The next step is to define the cost and time of each activity based on one or more vehicle characteristics/operations drivers as described in sections 3.2 and 3.3. The model development also requires the organization of the spaceport by stations and the assignment of activities to these stations as described in section 3.3. Finally, an area of additional research is in the development of environment scenarios, where the activities, times, and costs, required by a design choice change with improvement in reliability, vehicle life, and technology, and reductions in complexity, similar in operations to an airplane.

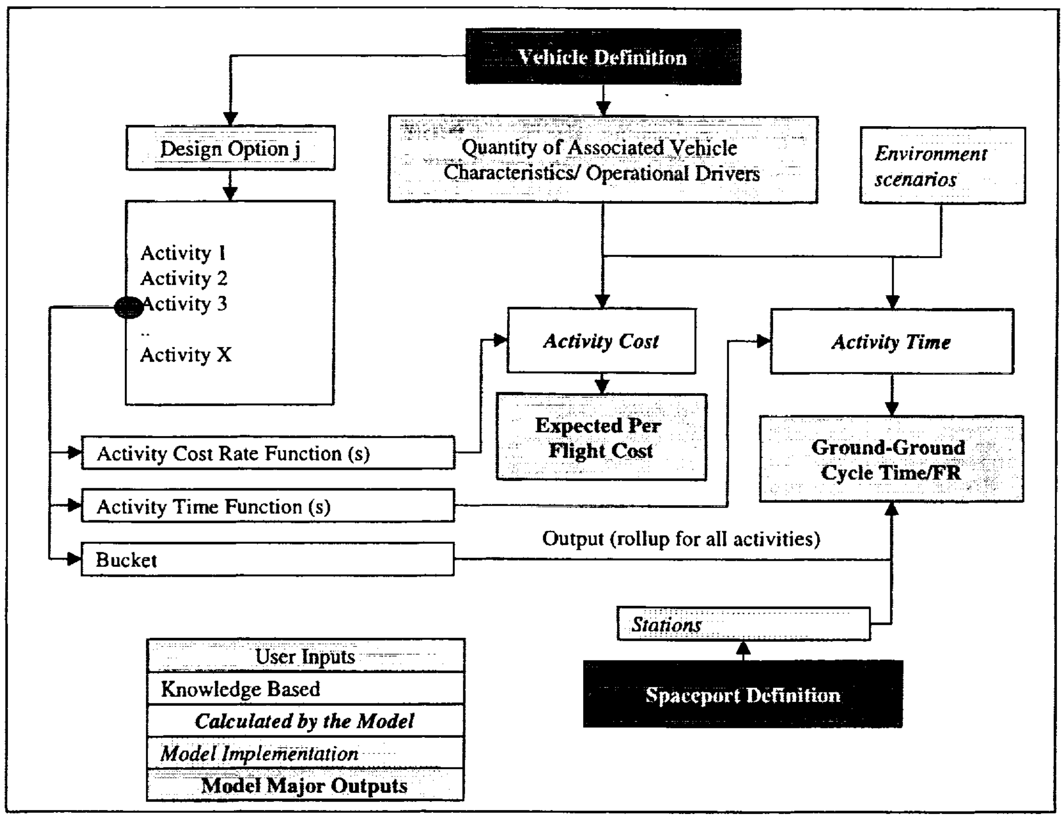

Figure 4.Knowledge requirements

4. RESULTS AND FUTURE WORK

The use of an Activity based costing model to asses the operational requirements of new products is not a new concept and could be applied to the assessment of new launch vehicle architectures. By using the knowledge of experts in the areas of spaceport operations and vehicle/technology designers, design driven activities can be determined, and from there, the time and cost of the activity. The approach allows vehicle designers to better understand (by looking at the output) the cost and cycle time drivers as they can easily observe which design driven activities have the highest costs and task times. In addition, this approach fosters the development of additional operations knowledge as it "forces" operations experts to predict the activities (and their cost and time characteristics) that new technologies will require in the context of the spaceport.

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