ESTIMATING LOGISTICS SUPPORT OF REUSABLE LAUNCH VEHICLES DURING CONCEPTUAL DESIGN

W. D. Morris, N. H. White, W. T. Davis
NASA Langley Research Center

Dr. C. E. Ebeling
University of Dayton

Paper for the
32nd Annual International Logistics Conference and Exposition
August 5-7, 1997

Abstract

Methods exist to define the logistics support requirements for new aircraft concepts but are not directly applicable to new launch vehicle concepts. In order to define the support requirements and to discriminate among new technologies and processing choices for these systems, NASA Langley Research Center (LaRC) is developing new analysis methods. This paper describes several methods under development, gives their current status, and discusses the benefits and limitations associated with their use.

Nomenclature

CER	Cost Estimation Relationships
CES	Cost Element Structure
ECLS	Environmental Control Life Support
GPOT	Ground Power-On Time, hours
IEP	Induced Environment Protection
ILS	Integrated Logistics Support
KVA	Kilovolt Amperes
L	Length, feet
LaRC	Langley Research Center
LO2	Liquid Oxygen
LH2	Liquid Hydrogen
LRU	Line Replaceable Unit
MA	Maintenance Actions
MH	Manhours
MNPWR	Number of maintenance personnel
MTBM	Mean Time Between Maintenance, hours
MTTR	Mean Time To Repair, hours
O&M	Operations and Maintenance
O&S	Operations and Support
PLS	Personnel Launch System
R&D	Research and Development
R&M	Reliability and Maintainability
RP-1	Rocket Propellant
WS	Wingspan, feet
WT	Weight, pounds

Introduction

Logistics requirements for launch systems are largely driven by the choices made during the design process and decisions about how the design will be supported in its operating environment. Methods exist to define the support requirements for new aircraft concepts,[1-2] but these are not directly applicable to new launch vehicle concepts because they are generally applied during development phases when the system is fairly well defined. As such, these methods have the advantage of well defined data and experienced logisticians to perform the analysis. Conceptual design, by its nature, provides limited vehicle definition. In such studies performed at the NASA Langley Research Center (LaRC), application of aircraft methods to launch vehicle designs has been limited both by the reduced level of definition available and by the lack of applicable historical data for reusable space vehicles. In order to define the support requirements and to discriminate among new technologies and different maintenance and operating concepts for these systems, it has been necessary to develop new analysis methods. These methods must be capable of working with a limited level of concept definition to define the support required consistent with both the design and operational concept. This paper will describe the analysis methods under development at LaRC, give their current status, and discuss the benefits and limitations of these approaches.

Early attempts to define support for conceptual launch vehicles focused on the use of discrete event simulation modeling.[3-5] Although useful in giving general insight to support requirements, the models had to be based on assumed values for turnaround time, manpower, number of facilities, etc. Historically defined support requirements were generally only available at highly aggregated levels. This level lacked the fidelity necessary to evaluate the effects of introducing new technologies and procedures to the concept and its support environment. Additional data, based on Shuttle operations, was obtained in a study specifically designed to aid in process definition, and to define manpower and task times for launch support.[6] While this information aided simulation modeling there still was no direct connection between the design and its support requirements. This linkage to the design is usually through the reliability and maintainability (R&M) requirements. In order to establish this link in the absence of historical R&M data from launch vehicles, an approach was chosen which was based on comparability to aircraft system requirements.

Aircraft data were used to formulate an R&M analysis tool based on parametric estimating relationships.[7-9] This method builds on one developed by Weber[10] for analyzing space system designs based on aircraft data. As Shuttle data became available in the post Challenger time period, several contracted studies[11-13] were also used to obtain R&M data from the Shuttle program similar to the aircraft data by using existing data sources. As these sources were not originally intended to produce R&M data, simplifying assumptions were made in order to use the available information.

The concept of defining support in terms of vehicle parameters was extended to the study of logistics resources by also determining parameters that characterize the support environment. A parametric approach to defining these resources was developed by Ebeling[14] as an extension of the R&M analysis tool.[8,9] In addition, logistics models were developed by Rockwell as a continuation of methods initially developed during their Personnel Launch System (PLS) studies.[15,16] In the following sections, this report describes several of the models that are being developed to perform operations and support analysis for conceptual systems, discusses the rationale for the methodologies, provides examples of their usage, and discusses some of the benefits and limitations of the methodologies used.

Models and Analysis Methods

At LaRC, estimation of support requirements of new systems addresses both the ground and flight operations. These include not only activities contributing to the direct cost for organizational level maintenance and servicing, but also the logistical support which includes the facilities, supplies, transportation, training, documentation, depot maintenance and management. Three criteria were established for the analysis tools that are being developed: (1) they must work with the limited data available during conceptual design, (2) they must link the design to the operations and support (O&S) environment, and (3) where possible the methods need to be based on historical data as this provides a creditable basis from which to judge new estimates of support. The approach which was chosen was that of comparability analysis in which the support requirements of future systems are defined based on similarities to known support requirements of existing systems. Two of the tools being developed are a R&M model and a logistics model. Their relationship is illustrated in Figure 1 along with the simulation model which is a standard analysis tool used by LaRC.

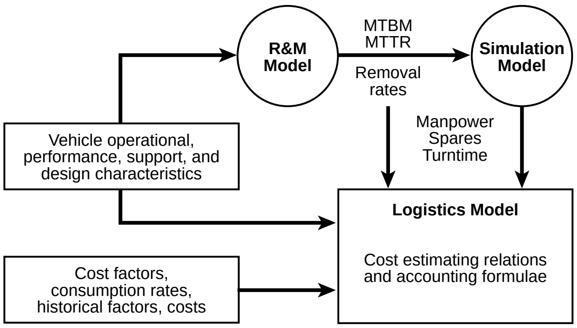


Figure 1. Relationship among conceptual models.

R&M Model

The R&M model addresses the problem of defining reasonable expectations for turnaround times and manpower requirements of conceptual vehicles. It is predicated on the assumption that these requirements should be based on the maintenance actions generated by each mission and the maintenance policy that is chosen to return the vehicle to a state of flight worthiness. The R&M model provides the critical link between the vehicle design and the operating

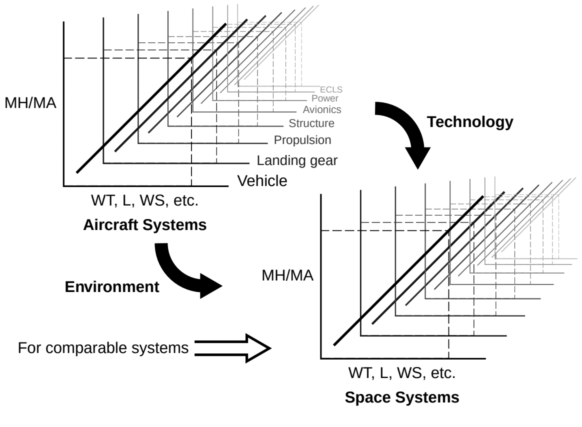
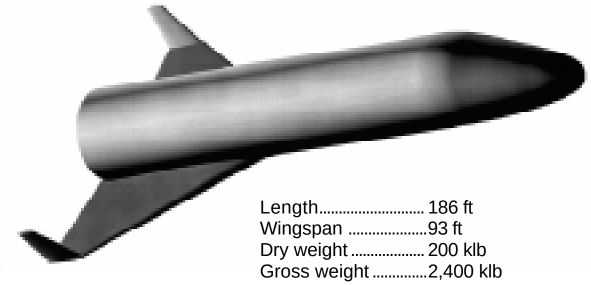


Figure 2. Reliability and maintainability model.



Length	186 ft
Wingspan	93 ft
Dry weight	200 klb
Gross weight	2,400 klb
Dual-fuel	LO2, LH2, RP-1
Seven engines	

Figure 3. Single-stage vehicle (SSV) concept.

scenario. It is based on comparability to either aircraft or Shuttle subsystem support requirements (Figure 2). The model input is matched to the level of definition available from the design team. The input requires vehicle definition (Figure 3) in terms of overall dimensions, weight, and technology if available. The output then estimates the turnaround time and manpower requirements based on the system design and choice of maintenance concept. Both aircraft and Shuttle R&M information were used in developing this model.

The number of maintenance actions and the number of maintenance manhours required for support of each subsystem are estimated based on the user's choice of comparability to either aircraft or Shuttle R&M characteristics. These are primarily the mean time between maintenance (MTBM), mean time to repair (MTTR), a technology growth factor, and the critical failure rate (Table 1). The MTBM is a measure of the system's operational reliability and is used to indicate the frequency that maintenance must be performed on a system. The MTTR is a measure of the time required for properly skilled crew with all of the necessary resources to return a system to operating status and is a measure of the systems inherent maintainability. A technology factor was developed by observing the improvement in MTBM characteristics over a period of years, then interpreting that change as a rate of enhancement that can be applied to similar subsystems. This is used to project an expected improvement in the database technologies to the time period of the study. The critical failure rate is based on the percentage of maintenance actions that have resulted in aborts out of the total number of maintenance actions for each subsystem based on aircraft data and is used to define the phased mission reliability of the system.

Table 1. Operations and Support Drivers.

Maintenance Actions (R&M)	Maintenance Policy
• MTBM • MTTR • Technology growth factor • Critical failure rate	• Ratio scheduled to unscheduled maintenance • Crew size • Ground power-on time (GPOT)

Maintenance policies (Tables 1 and 2) are input through the choices of parameters that reflect those characteristics of either Shuttle or aircraft maintenance support policies or the user can create his own policy. The primary parameters used to define the maintenance concept include scheduled maintenance hours per operating hour or alternately the ratio of scheduled to unscheduled maintenance, the crew size required to do the hands-on labor, the extent of parallel versus serially performed repair tasks, and the power-on time required for ground servicing (GPOT). The amount of scheduled maintenance performed on aircraft has been observed to be about half the unscheduled maintenance required (dependent on vehicle size). This characteristic is used to define an aircraft maintenance concept in which the amount of scheduled maintenance reflects the maturity of a system which has allowed the amount of preventive maintenance to be balanced against the risk of failed systems. Developing the same characteristic for Shuttle, scheduled maintenance is about 4 to 5 times that of the unscheduled maintenance. This is consistent with the Shuttle maintenance concept which requires extensive inspection and testing between flights in order to ensure successful system operation. The size of the crew required to support maintenance

Table 2. Characterization of Maintainance Policies.

	Aircraft	Shuttle
Ratio of scheduled to unscheduled maintenance	55%	400%
Typical number of maintenance actions per mission:		
Unscheduled	<10	1000
Scheduled	<10	1600
Percentage of induced maintenance actions	22%	36%
Makeup of maintenance crews (typical)	Techs Crew chief	Techs Quality Safety Test Cond Eng
Size of maintenance crew (typical)	2-3	4-9

on each subsystem reflects the number of unique skills required for that technology. For aircraft, this normally involves a crew chief and one or two technicians with specialized skills required for the task. For Shuttle, the crews frequently are made up of a test conductor, a systems, quality, and safety engineer, and a technician. This crew size and makeup reflects a maintenance concept driven by complex vehicle and ground systems designs, and frequently requires engineering effort to support the maintenance activities. As the system matures and maintenance problems and processes become well documented, the need for unique solutions from engineering support should lessen as repair methods become ‘standardized.’ This should substantially reduce the number of maintenance activities and reduce the need for large crew sizes and engineering support. The current maintenance concept used on Shuttle requires extensive periods of time when the power is on for the flight systems while they are being tested. This increased time of operation and increased exposure to induced damage has a direct effect on the amount of maintenance required.

The R&M model input is matched to the level of definition available from the weights and sizing model used by the design team. This model is used to develop the vehicle dimensions and subsystem weights based on the vehicle performance requirements. The R&M model input (Figure 4) requires vehicle definition in terms of overall dimensions, weight, and technology if available. Individual subsystem weights and other characteristics can also be used to provide better definition. The differences in mission length and the space environment are accounted for by the model when using the aircraft data. The Shuttle R&M data already reflects the effects of the space environment and mission lengths typical for space vehicles. However, the user must still adjust the Shuttle values to account for the physical characteristics which are different from the Shuttle’s system and to account for any differences in the mission environments. The model can then be used to estimate the turnaround time and manpower requirements based on the system design and choice of maintenance concept.

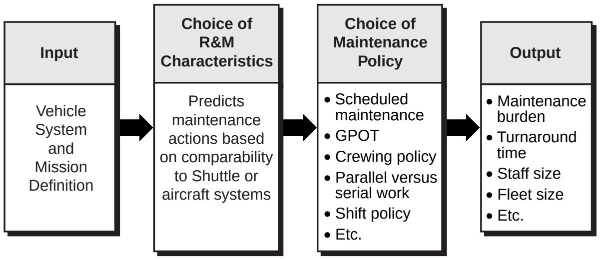


Figure 4. Analysis process for R&M model.

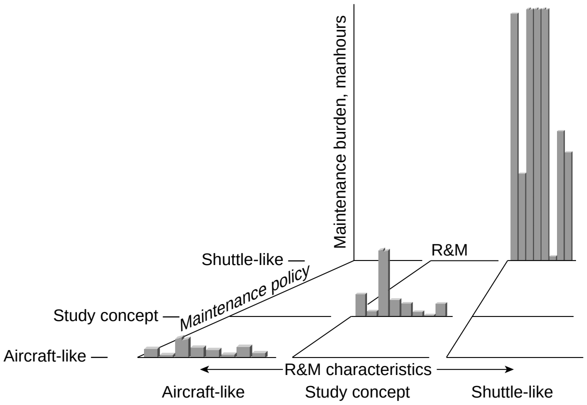


Figure 5. Maintenance burden as a function of R&M and maintenance concept characteristics.

Once a scenario is built based on the vehicle description, weights, and flight rate objectives, runs are then made with the model in order to define the R&M characteristics of the concept for two bracketing conditions (Figure 5). First it is defined based on comparability to Shuttle R&M characteristics and support concepts; then based on comparability to aircraft characteristics and support concepts. (For those systems for which there are no comparable aircraft systems, assumptions of improvements are made based on the Shuttle values.) This creates a range of R&M parameters between the currently demonstrated capability of Shuttle (Shuttle values), and a set of values characteristic of aircraft. In general, the Shuttle R&M values represent the current capability and the aircraft values the potential goals for new launch vehicles. The R&M model results then provide an initial level of comparison for new

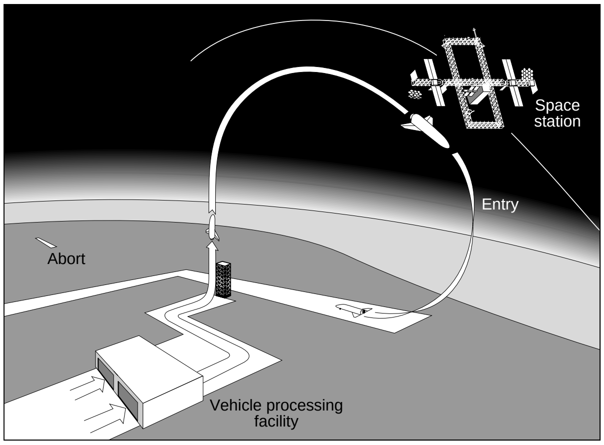


Figure 6. Operating scenario.

systems. For better insight, these results can be used as input to other models for more detailed analysis.

The cost of logistics support will also be driven by the operating scenario chosen for the concept (Figure 6). By relating logistics support to both vehicle and program characteristics, logistic costs elements will be sensitive to both vehicle design and its operating environment. That is a primary objective of the logistics model.

The logistics elements are but one part of the overall cost of a new system. In order to ensure that all cost are accounted for a cost element structure (CES) was defined. This CES was based upon a three-axis work breakdown structure (Figure 7) consisting of the configuration axis in which the vehicle's design is specified, the cost axis in which the cost of the elements are defined, and the function axis in which the elements required to implement and operate a new system over its life-cycle are defined. From this model, a linear CES was developed (Table 3) which represents the activities required to operate and support a space launch system.

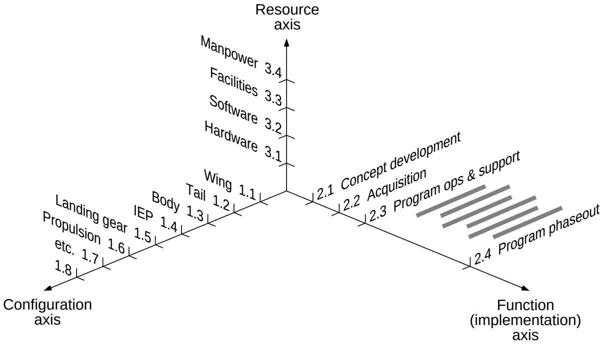


Figure 7. Work breakdown structure.

Logistics Model

Logistics modeling is based on defining those elements typically associated with operating and supporting a system, including facilities, supplies, transportation, training, documentation, maintenance and management. Several different approaches were taken to compute these estimates. One approach is based upon a set of parametric relationships, the other is an accounting methodology. The primary estimating method chosen for each of the elements is illustrated in Table 4. In addition to the Logistics Support elements, the logistics model addresses organizational level maintenance and the System Support elements. Program support and R&D are based on historical costs. Lack of existing data does not currently allow definition of the remaining Operations elements within the model.

Table 3. CES for Launch Vehicle Operations & Support

2.3.1	Operations
2.3.1.1	Refurbishment
2.3.1.2	Organizational maintenance
2.3.1.3	Processing operations
2.3.1.4	Integration operations
2.3.1.5	Payload operations
2.3.1.6	Transfer
2.3.1.7	Launch operations
2.3.1.8	Mission operations
2.3.1.9	Landing/recovery/receiving operations
2.3.1.10	Non-nominal operations
2.3.2	Logistics Support
2.3.2.1	Depot maintenance
2.3.2.2	Modifications
2.3.2.3	Spares
2.3.2.4	Expendables
2.3.2.5	Consumables
2.3.2.6	Inventory management & warehousing
2.3.2.7	Training
2.3.2.8	Documentation
2.3.2.9	Transportation
2.3.2.10	Support equipment
2.3.2.11	ILS management
2.3.3	System Support
2.3.2.1	Support
2.3.2.2	Facility O&M
2.3.2.3	Communications
2.3.2.4	Base Operations
2.3.4	Program Support
2.3.5	R&D

Parametric Approach: The parametric approach consists of deriving regression equations which predict directly certain logistics support requirements as functions of vehicle design parameters, support policies, and operational characteristics. These equations are generally based upon a comprehensive historical database consisting of a variety of military aircraft. In the parametric approach, primary use is made of cost estimation relationships (CER) obtained by using multiple regression techniques to fit historical cost data to one or more vehicle design or performance variables. Parametric estimating methods provide a statistical basis for establishing a relationship between costs and one or more "cost-drivers." For these parametric equations, the independent variables chosen for use are limited to only those parameters which can be determined or estimated early in the conceptual phase of the study. With the dependent variable as cost, independent

Table 4. Cost Elements Estimation Methods.

Cost Element		Estimation Method
2.3.1 Operations		
2.3.1.1	Refurbishment	Historical factor
2.3.1.2	Organizational maintenance	CERs & R&M model
2.3.1.3	Processing operations	Not addressed
2.3.1.4	Integration operations	Ô
2.3.1.5	Payload operations	Ô
2.3.1.6	Transfer	Ô
2.3.1.7	Launch operations	Ô
2.3.1.8	Mission operations	Ô
2.3.1.9	Landing/recovery/ receiving operations	Ô Ô
2.3.1.10	Non-nominal operations	Ø
2.3.2 Logistics Support		
2.3.2.1	Depot maintenance	CERs or accounting
2.3.2.2	Modifications	Historical factor
2.3.2.3	Spares	CERs or accounting
2.3.2.4	Expendables	CER
2.3.2.5	Consumables	Accounting
2.3.2.6	Inventory management & warehousing	Accounting
2.3.2.7	Training	Accounting
2.3.2.8	Documentation	CERs or accounting
2.3.2.9	Transportation	Accounting
2.3.2.10	Support equipment	CERs or historical factor
2.3.2.11	ILS management	Historical factor
2.3.3 System Support		
2.3.2.1	Support	CERs
2.3.2.2	Facility O&M	CERs
2.3.2.3	Communications	Historical factor
2.3.2.4	Base Operations	Historical factor
2.3.4 Program Support		Historical cost
2.3.5 R&D		Historical cost

variables such as weight, length, thrust, volume, quantities, etc. are used as cost-drivers. Most of the CER's used in the model have been derived from aircraft data. These equations work to the extent that the aircraft design and performance characteristics are consistent with those being defined for the space vehicle. When this is not the case, an alternate approach is needed.

Accounting Methodology: The accounting methodology provides a way of incorporating actual aircraft and Shuttle data into the analysis. This is accomplished in part by deriving historical factors for the parameters used to define the cost elements. A set of equations were written such that the values selected for independent parameters could be used to characterize the support environment as either based on Shuttle logistics support or military aircraft logistics support. This work was predicated on the assumption that these differing values would characterize the two different (aircraft verses Shuttle) approaches to logistics support. Each of the elements for logistics support were initially defined using the accounting methodology. The definitions were in terms of the costs drivers unique to each element.

Both the organizational and depot maintenance support costs are a function of the number of maintenance actions required, the time required to repair, the manpower required, the frequency of replacement parts, as well as the flight rate for the fleet of vehicles. The supply support includes the cost of buying, storing and managing spares and consumables. The spares cost are a function of the total number of LRUs on a vehicle, removal and condemnation rates, the time required for the repair cycle on these parts, the flight rate, and the sparing policy. The consumables and expendables costs are primarily a function of the flight rate. The inventory management cost is a function of the cost to stock and maintain the spares inventory. Training cost are a function of the number of courses, the cost required to develop and administer the training as well as the number of personnel and the time required to take the training. These are a function of both the design and the maintenance policy. At this time computer based training is not accounted for by the model. Documentation costs include the development, publication, and updating of the maintenance manuals. These are driven by the number of systems on the vehicle, the number of unique reparable line replaceable units (LRU), and the number of pages required in the manuals. At this time the model does not account for electronic documentation. The transportation cost includes both transport of the vehicle to the launch site and the cost of transporting spares to and from the depot site. The cost of support equipment is currently based on Shuttle support equipment for both environments. The cost of equipment is assumed to be proportional to the Shuttle's based on vehicle size, turnaround time, and flight rate. Currently the Integrated Logistics Support (ILS) management costs are computed as a percentage of the other logistics elements.

In some cases historical cost factors are based upon Shuttle data and in other cases they reflect an average aircraft value. Some estimates are also based upon direct analogy using cost data obtained from the Shuttle program. Adjustments may then be made for differences in size, number of engines, performance, etc. For some subsystems and functions this approach may provide the only means for obtaining a cost estimate since the Shuttle is the only vehicle of its type and purpose.

The logistics model typically uses the output from the R&M model as input. These are primarily the turnaround time, the hands-on vehicle level crew requirements and the fleet size. Program input requires definition of the year on which the technology is based and the planned operating life. The model also requires inputs of overall vehicle weights, mission description phase times and propellant types. In addition, the support and operating scenario is described in terms of launch and landing sites, manufacturing site, and depot location (for determining transportation cost). The model uses this information to estimate both the non-recurring and recurring cost to establish and operate the system over its life cycle. The independent parameters used by the model are chosen to describe the support environment as either similar to aircraft or Shuttle.

Fundamental to the model is the assumption that the organizational support requirements are driven by the unscheduled maintenance requirements of the design. Both the time and personnel required to return it to flight status are also driven by the maintenance concept that has been assumed for this system in the R&M model. In addition the number of systems and subsystems that must be supported are drivers in the logistic support. Both the number of removals and the repair cycle time and personnel are primary drivers in the depot level of logistics support.

Results

An illustration of the approach used to estimate logistics costs is given in Figure 8 where the general flow of input and output data is shown for a typical subsystem. Vehicle design, performance and operational characteristics are entered into the R&M model. If comparability to an aircraft electrical subsystem is assumed, parametric equations will convert vehicle and subsystem parameters (e.g. dry weight and Max KVA) into R&M parameters such as MTBM, maintenance hours per maintenance action (MH/MA), average crewsize, scheduled maintenance hours per operating hour, and removal rate (fraction of removals per maintenance action). (Alternatively, if desired, corresponding shuttle derived parameters can be applied.) These R&M parameters along with an operational scenario which includes the mission length and mission rate (missions per year) can be converted into estimates of subsystem turntimes, MTTR, spares requirements, and maintenance personnel requirements. For example, minimum maintenance personnel is determined from

$$\frac{\left((\text{active operating time/MTBM}) \times (\text{MH/MA})\right) \times \text{mission rate}}{12 \text{ months} \times \text{direct labor hours available/month/person}}$$

Using the Poisson probability distribution with a mean equal to the average number of demands during the repair cycle time, spare levels are computed to satisfy a specified fill rate. Subsystem turntime is based upon the elapsed time to complete both scheduled and unscheduled maintenance using an average crew size, the assigned number of crews, and the computed maintenance hours. The analyst can control turntimes by varying the number of assigned crews. However, this may be at the expense of increasing the number of maintenance personnel if the assigned personnel exceed the minimum number required based upon the computed maintenance hours.

Similar values are computed for all subsystems composing the vehicle. A range for the overall vehicle turntime is found by assuming subsystem maintenance tasks are performed both in series and in parallel with a user specified weighted average used to estimate the most reasonable time. Vehicle turntime may also include payload integration time and time on the launch pad.

The output from the R&M model as well as many of the vehicle and subsystem input parameters are entered into the logistics model along with cost rates and usage factors (Figure 8). The model will then compute the annual cost for each category within the CES. For example, organizational level maintenance costs will include a rollup of all subsystem maintenance personnel obtained from the R&M model using:

direct labor cost = avg tech salary ($/hr) ¥ 2080 (hr/yr)
¥ manpower (from R&M).

The technician labor rate can be adjusted to current or then year dollars based upon a specified discount rate. Organizational maintenance overhead costs are then added to the direct labor cost. Total spares and expendables costs are computed in a similar manner.

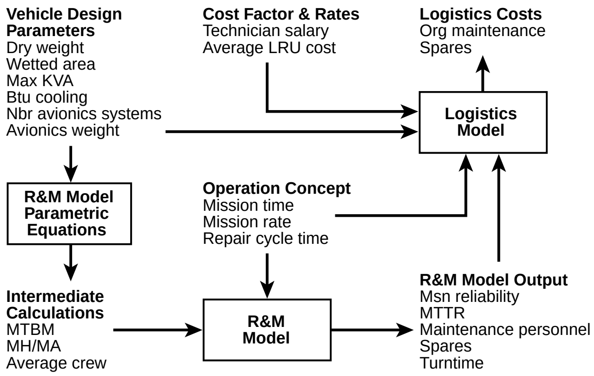


Figure 8. Typical subsystem.

Other costs are determined parametrically within the model. For example, facility support parametric estimating relationships were developed to estimate the yearly cost to operate, repair and maintain the facilities necessary to support the processing of new launch vehicle designs. The costs include those allocated to the personnel assigned to the maintenance and operation of real property facilities and related management and engineering support work and services. The costs also include those associated with materials, contract and other expenses associated with maintenance of real property facility assets. The cost data used to develop the parametric cost estimating relationships were the total yearly aggregated cost for a specific aircraft. As an example, the equation for processing facility personnel cost was found to be:

$$\text{Personnel } \$ = \left(174,077 - \frac{1010 \times 10^4}{\text{length} + \text{wingspan}}\right) \times \text{nbr vehicles}$$

Still other logistics costs are based upon a cost accounting approach using current cost rates or, in many cases, historical Shuttle values. For example, consumables such as fuel and oxidizer costs are based upon the consumption rate, flight rate and the current or projected cost structure. The life support system (ECLS) costs are computed from values based upon shuttle experience, but adjusted for the number of crew, mission duration and the flight rate.

The model will combine and roll-up all costs to correspond to the CES. Only cost computed by the logistics model are shown in the example output in Table 5.

Table 5. Example CES Summary Output.

	CES	Annual Cost, $M
2.3.1 Operations		
2.3.1.1	Refurbishment	0.00
2.3.1.2	Organizational maintenance	1.87
2.3.1.3	Processing operations	—
2.3.1.4	Integration operations	—
2.3.1.5	Payload operations	—
2.3.1.6	Transfer	—
2.3.1.7	Launch operations	—
2.3.1.8	Mission operations	—
2.3.1.9	Landing/recovery/ receiving operations	—
2.3.1.10	Non-nominal operations	—
2.3.2 Logistics Support		
2.3.2.1	Depot maintenance	3.57
2.3.2.2	Modifications	0.00
2.3.2.3	Spares	4.39
2.3.2.4	Expendables	0.00
2.3.2.5	Consumables	19.96
2.3.2.6	Inventory management & warehousing	4.32 2.3.2.7
Training	.03	
2.3.2.8	Documentation	13.98
2.3.2.9	Transportation	.01
2.3.2.10	Support equipment	25.22
2.3.2.11	ILS management	9.53
2.3.3 System Support		
2.3.2.1	Support	17.08
2.3.2.2	Facility O&M	84.08
2.3.2.3	Communications	1.84
2.3.2.4	Base Operations	7.38
2.3.4 Program Support		—
2.3.5 R&D		—
Total		193.26

Example Trade-Off Analysis

With the capability to relate logistics costs to vehicle design, performance, and operational paramet-ers, meaningful trades can be performed using these models. Currently the analysis techniques include varying one or more of these input parameters and determining the effect these changes have on R&M parameters and the various logistics support cost. As an example, varying the mission length will increase maintenance actions per mission (MA), maintenance hours (MH) and spares requirements as shown in Figure 9. This, of course, will result in an increase in main-tenance personnel costs, spares costs, and other related logistics costs.

Table 6. Annual Operations and Support Costs in Millions of Dollars.

MTBM factor	MTTR factor	Orgn	Depot	Spares	Expend	Ware-house	ILS mgt	Sys Spt	Total
1.00	1.0	12.7	.021	14.1	.071	.61	17.03	91.81	136
1.20	.9	12.4	.016	12.0	.055	.52	16.85	91.77	134
1.50	.8	12.0	.012	10.3	.042	.44	16.71	91.71	131
1.75	.7	11.6	.010	8.8	.035	.38	16.58	91.67	129
2.00	.5	11.4	.009	8.1	.030	.35	16.53	91.64	128

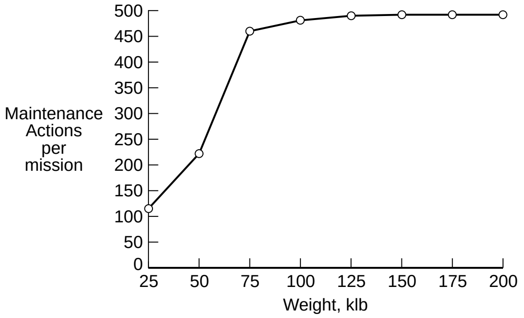


Figure 10. Maintenance actions required per mission as a function of vehicle size for an example mission.

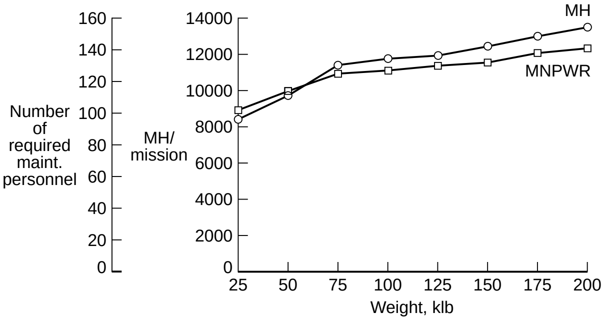


Figure 11. Maintenance manhours and support personnel as a function of vehicle size for an example mission.

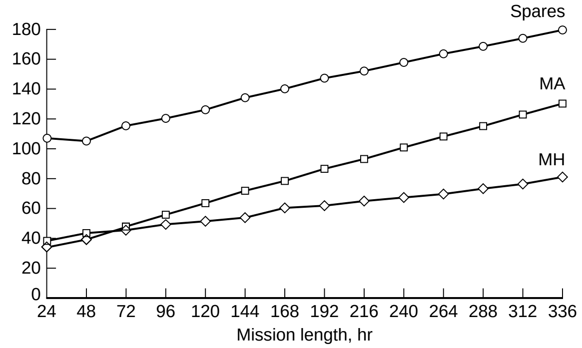


Figure 9. Support requirements as a function of mission length.

Figures 10 and 11 illustrate the effect that overall vehicle size has on the support requirements. Size in-crease is shown as measured by dry weight (with other dimensions increasing proportionately) in order to provide a larger payload to orbit. Figure 10 illustrates the increased number of maintenance actions due to the vehicle growth and its effect on overall reliability. Figure 11 shows the impact on maintainability of this growth in terms of the number of maintenance man-hours and personnel required for support. The rapid growth in the number of maintenance actions, leveling off above one hundred thousand pounds reflects the underlying aircraft data base. The support manpower does not increase at the same rate as the number of maintenance actions. The maintenance manpower per maintenance action for the smaller systems appears to be higher than for the larger systems. This figure indicates the level of savings in manpower support for the larger systems delivering larger payloads.

Table 6 illustrates the effect that systematic changes in vehicle R&M due to design changes have on logistics support costs as measured by the MTBM and MTTR. For the scenario being analyzed, a total cost savings of over 8 million dollars a year would be observed if the reliability were doubled (MTBM) and maintainability halved (MTTR) from the baseline estimate as a result of design changes such as reducing subsystem complexity, adopting new technologies, increasing the use of modularization, improving parts and material selections, and changing to a predominately remove and replace maintenance concept.

Other trade-off analyses of interest might include changes in the mission rate of the fleet. With a baseline rate of 20 missions per year, the graph shown in Figure 12 with the cost data depicted in Table 7 was developed showing the increase in logistics support costs as the mission rate increases. The most sensitive cost cate-gories are shown separately.

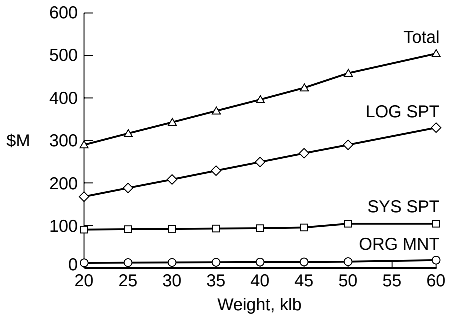


Figure 12. Costs as a function of mission rate.

Table 7. Costs ($M) versus Missions per Year

MSN/YR	ORG MNT	LOG SPT	SYS SPT	TOTAL
20	11.9	167.6	90.1	290
25	12.4	188.1	91.0	316
30	12.7	208.1	91.8	343
35	13.1	228.8	92.6	369
40	13.6	249.2	93.3	396
45	13.9	269.8	95.1	424
50	14.6	289.6	104.0	458
60	18.2	330.1	104.0	504

Other trade-offs are possible. The examples provided are only illustrative of the analysis capabilities available using the R&M and logistics cost models. Current research is seeking ways to increase the fidelity and scope of these models.

Benefits and Limitations

The purpose of these models is to provide insight into the effects of design and maintenance concept choices on the operations and support requirements of conceptual systems. They primarily provide guidance to the magnitude and direction of change that can be expected in turntime, manpower, resources, and costs of decisions made during the conceptual phase of development. Since they are based on historical data they also provide estimates relative to the experience of operational aircraft and launch vehicles. In general these models are expected value models and do not account for the variance that occurs in operational systems. However, with the use of simulation modeling, variability in failure rates, repair times, mission lengths, and resource availability and their effects on mission rates, turntimes, and personnel and spares requirements can be modeled. When available, the results of the simulation model cost drivers can replace the R&M model results for better fidelity.

The R&M model focuses on the maintenance and support of the launch vehicle up to launch. It does not address payload operations, launch or mission support although these can be accounted for with input from other sources. The model provides a means to combine data from diverse sources, Shuttle and aircraft, and from different time periods. It allows the user to make the comparisons in the same time frame and to account for the differences in growth rate of different technologies. The logistics model expands on this basic comparison to show the effects of design and support decisions on areas that are not directly related to the design concept. When historical data can be used, both modeling approaches benefit from the roll-up of support costs data that might otherwise be overlooked or lost since it is beneath the level of definition available during conceptual analysis.

The obvious differences between aircraft design parameters and operating environments and that of a launch vehicle is always a limiting factor in using the parametric approach. Unfortunately, since the Shuttle is the only manned launch vehicle thereby providing a sample size of one, it is not possible to develop similar parametric relationships based upon launch vehicles. Although the methodology accounts for these environmental differences, it would be far better if R&M factors and support costs were available for several different launch vehicle designs and operating concepts. On the other hand, reliance on historical Shuttle R&M parameters and support costs in developing cost accounting relationships, while providing in some cases the only means of estimating certain support requirements, does not provide a high degree of confidence for performing design-cost trade-offs. This is particularly true when the conceptual design or operational and support environment varies considerably from that of the Shuttle. However, as noted earlier, the models can be utilized in both an aircraft and shuttle mode to “bracket” the answer and, in any case, it is the relative differences and not the absolute costs which are typically more important in performing the conceptual design of the next generation of launch vehicles.

Validation of these models is difficult because of lack of independent data. What information that is available has generally been used to develop the algorithms used in the models. The R&M model was validated against independent aircraft parameters using data from a different time period. The results provided R&M parameters within 20% for 3 specific aircraft. The model could only be verified for the Shuttle data in a test case compared with the top level information that is known. The manpower requirements for Shuttle had to be inferred from system level data for each of the underlying subsystems. In general, cost information necessary to calibrate each of the logistic cost elements was not available and the model can only be used to infer the effects of changes to the design or support environment. The nonparametric logistics algorithms used were based on the experience and intuitive judgment of those who have worked the Shuttle and aircraft programs. They are not curve fit to empirical data.

These models illustrate the potential for defining support requirements during the conceptual design process. However, they have of necessity been developed with less than the desired level of data from the Shuttle program. Lack of comparability with aircraft operations prevents the alternative parametric approach. As more of this type of information becomes available, the models will need to be updated to provide results based on the most currently demonstrated capabilities and support policies. Operations and support analysis and estimations for future launch vehicles has always been somewhat of a subjective area. Through this process, the level of subjectivity can be reduced by providing results based on design, maintenance, and operating and support histories. These add validity to the results because they are traceable to demonstrated capability. These methods allow the user to define the support based on what can reasonably be achieved with current technologies and support policies. Only then can rationale judgment be made as to the potential improvement and value of introducing new technologies and support practices.

Summary/Conclusions

Methods have been presented which are under development for defining support requirements during the conceptual design phase. These analysis methods are based on comparability to support requirements for current operational aircraft and launch vehicles. The methods form a basis for providing relative support estimates for new launch vehicle designs and operating scenarios. The relative changes to support requirements developed by these models can be used to help discriminate among new designs and support concepts. The benefits and limitations of these approaches to defining support for new launch vehicles have been discussed.

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