COST ESTIMATION MODEL FOR ADVANCED PLANETARY PROGRAMS - FOURTH EDITION

Report No. SAI 1-120-768-C9

by

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Contract NASW-3035

April 1982

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FOREWORD

This study represents a portion of the work performed by Science Applications, Inc. within Task 2: Cost Estimation Research of Contract No. NASW-3035 for the Earth and Planetary Exploration Division (Code EL/4) of OSSA/NASA Headquarters. The results are intended for use as a decision-aiding tool to assist NASA in its development of long-range mission plans for solar system exploration.

The author wishes to express his gratitude to those individuals both within NASA and the industrial community who graciously provided the information vital to his study.

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Acronyms and Abbreviations

Database Flight Programs

M64 = Mariner Mars 1964
SUR = Surveyor
LO = Lunar Orbiter
M69 = Mariner Mars 1969
M71 = Mariner Mars 1971
PJS = Pioneer Jupiter/Saturn (10/11)
M73 = Mariner Venus/Mercury 1973
VLC = Viking Lander Capsule
VKO = Viking Orbiter
VGR = Voyager
PV = Pioneer Venus
  PVLP = Large Probe
  PVSP = Small Probe
  PVBO = Bus/Orbiter
  PVS = Science Instruments

Cost Model Categories

STD = Structure and Devices
TCP = Thermal Control, Cabling and Pyrotechnics
PRP = Propulsion
AAC = Attitude and Articulation Control
TCM = Telecommunications
ANT = Antennas
CDH = Command and Data Handling
PWR = Radioisotope Thermoelectric Generator (RTG) Power
PWS = Solar/Battery Power
ADM = Aerodeceleration Module
RDR = Landing Radar/Altimeter
IML = Line-Scan Imaging
IMV = Vidicon Imaging
PFI = Particle and Field Instruments
RSI = Remote Sensing Instruments
DSI = Direct Sensing/Sampling Instruments
SYS = System Support and Ground Equipment
L30 = Launch + 30 Days Operations and Ground Software
IDD = Imaging Data Development
SDD = Science Data Development
PGM = Program Management/Mission Analysis and Engineering
FO = Flight Operations
DA = Data Analysis

Cost Model Parameters

N = Number of Flight Qualified Units
DLH = Direct Labor Hours (1000 hours)
NRL = Non-recurring Labor Hours (1000 hours)
RLH = Recurring Labor Hours (1000 hours)
URL = Unit Recurring Labor Hours (1000 hours)
M = Subsystem Mass (kilograms)
MD = Mission Duration (months)
ED = Encounter Duration (months)
PPL = Imaging Resolution (pixels per line)

Cost Estimation Model for Advanced Planetary Programs - Fourth Edition

1. Introduction and Summary

1.1 Background and Study Objectives

In the decade of the 1980's, the United States' program for unmanned exploration of the solar system faces increased competition for the resources required for the achievement of its goals. One important implication of this situation is that the long-range mission planning process will involve a greater degree of selectivity than was seen in the past. This in turn implies that the total cost of individual missions must be forecast with a greater sense of confidence than ever before.

Several techniques are used to develop cost estimates of future missions at the pre-Phase A level of mission difinition. Engineering, or "grassroots", estimation generates cost estimates at the lowest level of the project's work breakdown structure defined at the time of the estimate. Analogy estimation derives costs by comparing mission hardware and scenario definitions with those of similar past projects and suitably adjusting the known, historical costs for such factors as differences in requirements and capabilities and for inflation. Model estimation uses cost estimating relationships (functions relating cost to requirements/capabilities), derived from historical data, to predict future costs. In essence, model estimation quantifies the analogy costing process.

For nearly a decade, Science Applications, Inc. (SAI) has been involved in cost estimation and analysis of the U.S. planetary exploration program. The work has encompassed historical cost data collection and analysis, development and refinement of a cost estimation model based on the historical data (References 1 and 2), and extensive use of the model for predicting costs of future missions.

This report discusses the development of the current version of the SAI Planetary Program Cost Model. The Model was updated to incorporate cost data from the most recent U.S. planetary flight projects and extensively revised in order to more accurately capture the information in the historical cost database. The revision was made with a two-fold objective: to increase the flexibility of the Model in its ability to deal with the broad scope of scenarios under consideration for future missions, and to at least maintain and possibly improve upon the confidence in the Model's capabilities with an expected accuracy of ±20%.

1.2 Cost Model Overview

The SAI Planetary Program Cost Model can be characterized by the following features.

- The Model is based on all relevant U.S. planetary projects from Mariner Mars 1964 through Pioneer Venus.

- Inputs to the Model are limited to information generally available at the level of pre-Phase A mission definition. Generally, these consist of estimates of spacecraft subsystem masses, design heritage, flight time and encounter duration.

- The primary output is manpower, expressed in direct labor hours. Total cost is obtained by use of appropriate conversion factors which include inflation indices.

- The Model views a mission program as consisting of two distinct phases: The Development Project, which encompasses all activity through the mission's launch + 30 days milestone and the Flight Project, which includes all activity from L + 30 days through the nominal end of mission.

- At its most detailed level, the Model deals with cost categories which are derived as compromise aggregations of the variety of work breakdown structure definitions found in the cost database.

- The Development Project is further separated into hardware-related cost categories and functional support cost categories. The hardware categories are directly related to the mission spacecraft engineering and science subsystems.

- Hardware categories are further separated into non-recurring costs (design and development) and recurring costs (fabrication and subsystem-level tests). Inheritance is assumed to affect only the non-recurring cost.

- The Model is capable of dealing with a wide variety of spacecraft designs, including inertial or spin stabilized spacecraft, atmospheric entry probes and highly automated soft landers.

1.3 Summary of Results

The model development effort resulted in an updated and revised Cost Model which adequately meets the objectives set forth in Section 1.1. Only the Development Project portion of the model was revised; cost estimates for the Flight Project are generated using algorithms from the previous version of the Model (Ref. 2).

A total of 21 revised cost categories were defined, 16 related to flight hardware and five to functional support. Two separate algorithms were derived for each hardware category: one which estimates total direct labor and another which estimates recurring labor. Non-recurring labor can be obtained by differencing the two estimates. The hardware labor algorithms are, in general, power laws or exponential functions of a single independent variable formed by the product of the number of flight units and the subsystem (category) mass.

Statistical analysis of the historical cost data resulted in a conclusion that factors derived as simple ratios can be used to convert category labor hour estimates to total cost.

An extensive error analysis of the Model measured against the programs in the database indicated that the information in the database had been captured with an average error of less than 10%. However, a simulation of the Model's performance, with number of flight units as the parameter, showed that predictions made with the Model would be highly sensitive to the number of flight units. A straight-forward adjustment procedure was devised that effectively eliminates this sensitivity but results in an increased average error of just less than 20% as measured against the database.

2. Cost Model Database

Historical cost data for thirteen unmanned lunar and planetary flight programs currently comprise the SAI cost model database. Table 1 summarizes the present status of this database. For use in model development, total program costs were segregated into two independent parts. The first, termed the development project, includes all program costs incurred through the launch + 30 days milestone. All program costs after this milestone are termed the flight project. Note that some programs in the database have multiple L + 30 milestones that are widely separated in time (e.g., Pioneer Jupiter/Saturn with launches in March, 1972 and April, 1973). This does not present a problem in segregating the costs since it is a simple matter of continuing to track hardware development of follow-on units after the first launch date. The indications in Table 1 regarding use of the data in model revision will be discussed in Section 3.

2.1 Development Project Cost Data

Cost data for the programs in Table 1 up to and including Voyager were used in developing the previous version of the SAI cost model (Ref. 2). At the time, however, the Viking Lander, Viking Orbiter and Voyager (then called Mariner Jupiter/Saturn) development projects had not been completed and the cost data used in modeling were based on estimates to complete. Thus, prior to the present model revision effort, it was necessary to analyze and reduce the actual completion costs which had been collected for these three programs into forms useful for modeling.

During this process of data reduction, two issues concerning the data and its use in modeling became apparent. First, some allocations of raw cost data into the model's cost categories did not appear to be consistent. Second, the assumption used in the previous model for separating non-recurring and recurring costs no longer appeared to be valid. Both of these issues made it necessary to reevaluate specific elements of the entire database.

Table 1

STATUS OF COST MODEL DATABASE

PROGRAM	DEVELOPMENT PROJECT (TO L+30 DAYS)	FLIGHT PROJECT (POST L+30 DAYS)	USE IN MODEL REVISION (DEVELOPMENT PROJECT)
MARINER '64	C	C	PARTIAL
SURVEYOR	C	C	PARTIAL
LUNAR ORBITER	C	C	PARTIAL
MARINER '69	C	C	TOTAL
MARINER '71	C	C	TOTAL
PIONEER JUPITER/SATURN	C	C	TOTAL
MARINER '73	C	C	NOT USED
VIKING LANDER	C	C	TOTAL
VIKING ORBITER	C	C	TOTAL
VOYAGER	C	I	TOTAL
PIONEER VENUS	C	I	TOTAL
GALILEO ORBITER	I	X	FUTURE
GALILEO PROBE	I	X	FUTURE

C: COMPLETE
I: IN PROGRESS
X: NO DATA YET

During the process of examining cost allocations, a decision was made to broaden and redefine the model cost categories. As with previous model versions, these categories are separated into two related areas: flight hardware categories and functional support categories. These categories are defined to be compatible with the wide variety of work breakdown structure definitions used by the system contractors who develop the mission hardware. Each specific category definition was arrived at through an iterative process involving both the cost data allocation and statistical modeling efforts.

The flight hardware-related categories are defined as follows:

- Structure & Devices - Spacecraft main structure, support trusses, adapter, scan platform, booms, solar panel structure, miscellaneous mechanisms and other hardware, ballast, bioshield, pressure vessel, landing gear, HGA structure.
- Thermal Control, Cabling & Pyrotechnics - Passive and active temperature control, cabling and wire harness, pyrotechnic devices.
- Propulsion - Propulsion system inerts.
- Attitude & Articulation Control - Celestial and inertial sensors, attitude control electronics, articulation devices and actuators.
- Telecommunication - Transponder, receiver, transmitter, telemetry, modulation/demodulation.
- Antenna - S/X antenna, omni's, low and medium gain antennas, waveguides, feeds, rotary joint.
- Command & Data Handling - Command computer & sequencer, flight data, data storage.
- Power - Solar cells & slide covers, battery, conditioning and distribution (does not include RTG units).
- Aerodeceleration - Heat shield, aeroshell, parachute and mortar.

- Radar - Altitude marking/terminal descent radar antenna(s) and electronics, radar altimeter.
- Imaging - Camera and electronics (vidicon or line scan).
- Particle & Field - Magnetometers, high-energy radiation, plasma, micrometeroid sensors.
- Remote Sensing - Radiometers and spectrometers.
- Direct Sensing & Sampling - Atmospheric and surface instruments.

Similarly, the functional support categories are defined as follows:

- Program Management/MAE - Project management and control, administration and support staff, division reps, preflight trajectory and navigation analysis, mission engineering, ephemeris development, planetary quarantine support.
- System Support & Ground Equipment - Spacecraft design teams, system configuration, system assembly and testing, quality assurance, reliability, safety, electronic parts acquisition and screening, mission and test computers, ground data system, ground data handling, ground handling equipment.
- Launch + 30 Days Operation & Ground Software - ETR operations, command team test and training, simulation, sequence development, flight command and control software.
- Image Data Development - Development of capabilities for image processing lab, image data software, imaging science team and support (pre-flight).
- Science Data Development - Development of capabilities for science teams and team support, science data processing and analysis (pre-flight).

The fully reduced and allocated cost data are presented in Appendix A for the seven major programs used in the present model development effort. Although technically speaking, Viking was a single program, the Lander capsule and Orbiter are treated separately since each system was developed under a separate contract. Conversely, all Pioneer Venus spacecraft were procured within the same system contract and therefore the functional support costs are aggregate for the entire program. No attempt was made to prorate these costs to the various spacecraft types.

Previous versions of the cost model were predicated on defining the separation of non-recurring and recurring costs as the point in time in the project schedule when the fully-assembled proof-test-model was delivered to the spacecraft test facility for initial system testing. This definition, though arbitrary, was felt to provide an adequate average basis for model development.

Recently completed development projects, however, appear to invalidate the use of this definition. Specifically, several of the major flight components of the Viking Lander were almost totally redesigned after initial system tests were started. Conversely, almost all of the Voyager flight hardware was fully fabricated well before assembly of the PTM spacecraft. Finally, the Pioneer Venus project did not fabricate PTM spacecraft. This latest case is also indicative of current and future project planning, i.e. to not fabricate, assemble and test a proof-test-model spacecraft.

Since a new definition of the non-recurring/recurring cost separation at the system level could not be found which would adequately apply to the projects in the database, it became necessary to analyze the data at the subsystem/major component level. As a result of this assessment, it was decided to separate recurring from non-recurring costs at the start of fabrication of flight qualified hardware. This new definition was applied as closely as possible to the major component level. Occasionally, there was not sufficient information to determine this breakpoint in cost. For such cases, either a single milestone in the schedule was applied to all subsystems or considerable direction was taken from the Work Breakdown Structure (WBS). For example, using WBS subaccount definitions, non-recurring could be equated with "engineering", and recurring could be equated with "manufacturing".

Table 2 presents percentage ratios of recurring labor to non-curring labor, normalized to one flight unit, for each of the hardware cost categories for the Mariner '69 (M69) through Pioneer Venus (PV) development projects. Cursory examination of this data, as exhibited by the large standard deviations, leads immediately to the conclusion that use of simple ratios for determining recurring cost from non-recurring cost, as had been used in previous model versions, would no longer be valid. A more complex functional form would be required.

2.2 Development Project Technical Data

Table 3 presents the project-related technical data used in formulating the cost model. Except for the number of flight qualified units (N) for each project and imaging resolution (PPL), all other data are subsystem masses. No other information, such as power requirements, was found to be necessary for developing the cost model algorithms.

Note that for those projects that use radioisotope thermoelectric generators (RTGs) as the main power source, the mass of the RTG units is not included. Also, for the Pioneer Venus probes, the masses of the small omni antennas are included in the telecommunication subsystem rather than considered separately in the Antenna category (ANT).

Special considerations were required for certain aspects of the Pioneer Venus program. For example, many subsystem masses of what is identified as the Bus/Orbiter are composites of averages of common hardware components plus components of each vehicle which are unique. This approach was required because of lack of resolution in the detailed cost data between bus hardware and orbiter hardware. The PV probe and orbiter science are treated together as a separate subproject because of insufficient resolution in several of the instrument contracts to allow adequate proration of costs to the appropriate PV mission.

Table 2

PERCENT RATIOS RECURRING/NON-RECURRING LABOR

HARDWARE CATEGORY	M69	M71	PJS	VLC	VKO	PVLP	PVSP	PVBO	PVS	AVERAGE	STANDARD DEVIATION
STD	17.5	10.9	44.7	12.3	20.2	77.1	16.6	32.8	-	33.0	24.2
TCP	3.6	25.1	25.9	10.3	28.9	29.9	17.3	34.5	-	28.2	21.2
PRP	9.8	12.5	46.7	11.5	20.7	-	-	55.5	-	36.9	33.7
AAC	8.1	5.9	30.9	13.5	36.7	-	-	24.2	-	23.1	14.3
TCM	3.9	10.8	53.4	16.8	28.3	48.1	27.8	42.5	-	34.4	23.4
ANT	-	14.5	16.5	16.8	35.1	-	-	26.4	-	33.0	28.4
CDH	11.0	9.6	38.4	21.1	41.4	22.5	19.6	13.4	-	26.7	17.8
PWR	-	-	43.9	8.4	-	-	-	-	-	32.2	20.6
PWS	8.5	11.2	-	-	57.7	24.9	11.4	17.7	-	21.9	18.5
ADM	-	-	-	6.0	-	33.4	17.3	-	-	18.9	13.8
RDR	-	-	-	21.0	-	-	-	-	25.4	23.2	3.1
IML	-	-	26.8	15.8	-	-	-	-	27.1	23.2	6.4
IMV	9.8	24.6	-	-	26.6	-	-	-	-	24.5	11.2
PFI	-	-	30.8	-	-	-	-	-	33.9	47.9	26.9
RSI	15.0	23.6	26.4	-	29.6	-	-	-	37.9	37.8	28.8
DSI	-	-	-	16.1	-	-	-	-	25.2	20.6	6.4

Table 3

DEVELOPMENT PROJECT TECHNICAL DATA
(masses in kilograms)

	M69	M71	PJS	VLC	VKO	VGR	PVLP	PVSP	PVBO	PVS
N	3	2	2	3	2	2	1	3	2	1
STD	127.4	156.0	62.5	210.9	280.4	277.3	132.2	42.4	141.4	-
TCP	46.2	52.0	20.0	103.9	89.9	104.3	17.3	7.7	45.8	-
PRP	19.4	87.0	11.0	79.7	177.4	49.6	-	-	19.0	-
AAC	37.5	38.0	5.7	20.3	64.9	51.3	-	-	13.9	-
TCM	37.9	36.0	10.3	25.4	50.0	53.2	6.6	2.8	12.4	-
ANT	-	4.1	5.5	8.8	6.8	5.1	-	-	3.3	-
CDH	35.7	32.0	9.4	47.8	62.0	50.0	5.2	3.9	21.0	-
PWR	-	-	17.7	86.2	-	28.9	-	-	-	-
PWS	52.8	75.0	-	-	133.1	-	15.0	5.9	37.3	-
ADM	-	-	-	214.5	-	-	108.0	24.0	-	-
RDR	-	-	-	35.4	-	-	-	-	-	9.7
IML	-	-	4.3	12.8	-	-	-	-	-	5.0
IMV (PPL)	22.5 (945)	26.0 (832)	-	-	45.4 (1182)	38.1 (816)	-	-	-	-
PFI	-	-	23.0	-	-	40.3	-	-	-	22.1
RSI	36.4	42.0	2.7	-	27.2	39.0	-	-	-	25.7
DSI	-	-	-	58.7	-	-	-	-	-	22.7

3. Model Development

Results of advanced (pre-Phase A) mission planning and analysis studies typically involve detailed recommendations regarding science rationale, trajectory analysis and mission sequencing. Mission-related hardware definitions, however, are usually not as well defined. Gross payload requirements, in such terms as net mass delivered at the target or net injected mass at Earth, can be fairly well predicted. However, detailed mass definitions at the subsystem and component level are not easily obtained. Hence, detailed mass estimates are typically generated prior to Phase B studies by a combination of selecting appropriate subsystems/components from previous successful designs and/or current designs, and use of mass scaling relationships.

This approach can generate reasonable early mass estimates and also yields information concerning design heritage. However, such an approach cannot take into account what impact technological advances and changes in general design philosophy might have on component masses. Furthermore, little, if any, information is generated regarding such details as part counts, number of spare components, reliability, power profiles, command structure, communications link parameters, etc. That is, spacecraft designs resultant from advanced studies contain none of the detailed engineering parameters required in performing a so-called bottom-up cost estimate.

The approach for achieving early "top-down" cost estimates, therefore, is to develop a cost model commensurate with the level of mission definition and related flight hardware details generally obtained from advanced mission planning studies. On the other hand, as seen in Section 2, the useful database of historical programs will provide only a relatively small sample size for statistical analysis. Therefore, the individual algorithms which constitute the model should be parsimonious, requiring the smallest possible number of estimated parameters for adequate representation. Parsimony will thus lead to uncomplicated functional forms while preserving as many statistical degrees of freedom as practical during the model fitting process. The techniques employed for model fitting are ordinary least squares regression and regression through the origin.

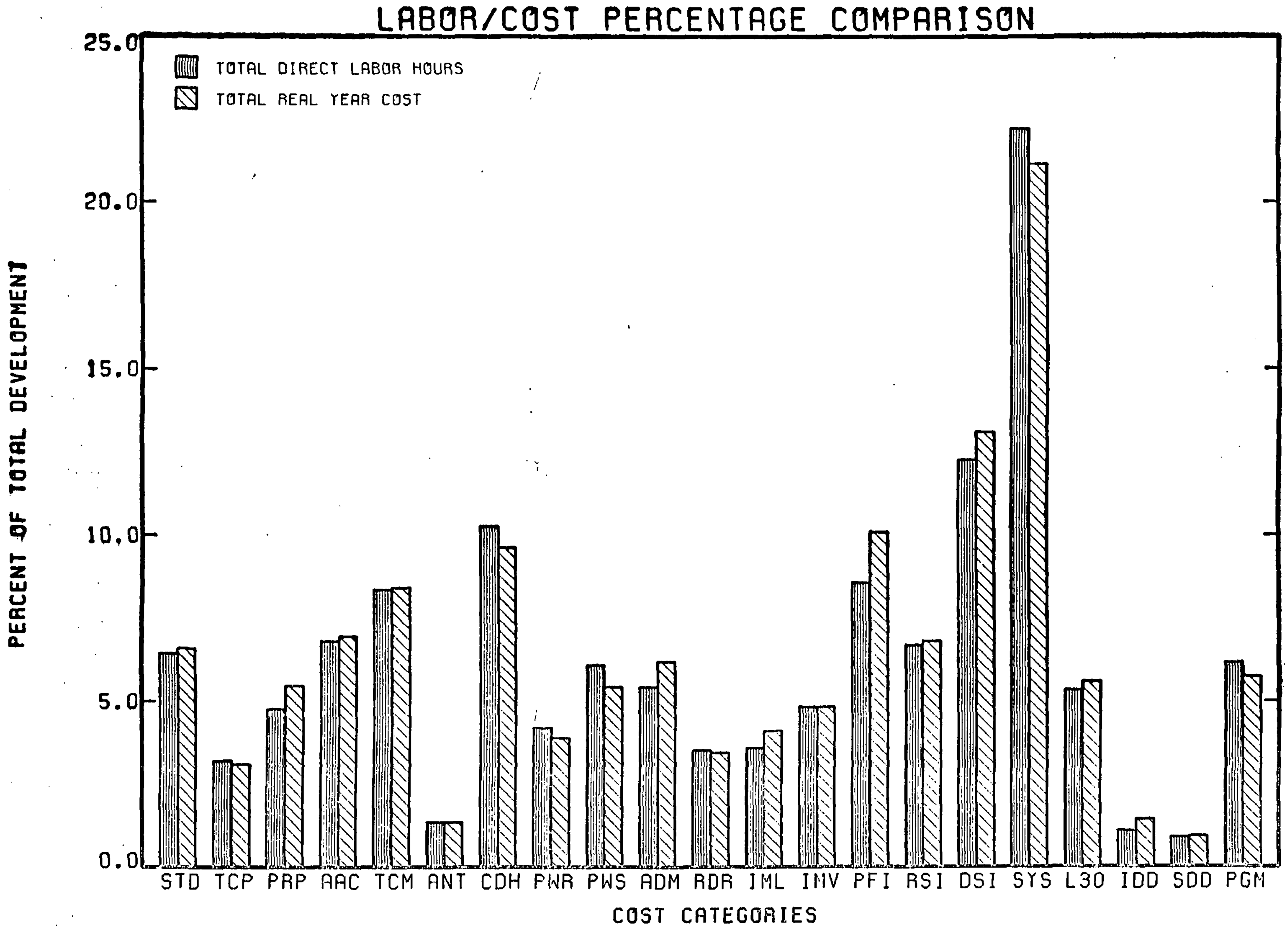
3.1 Labor/Cost Proxy Analysis

All previous versions of the SAI Cost Model have used direct labor hours as the primary dependent variable for both estimation and prediction, and the present version is no exception. The major arguments underlying the use of labor hours include decoupling of forecasts from inflation and ease in costing low volume production. Decoupling from inflation places all forecasts on a normalized, comparable basis, comparable both to past programs in the database and to other forecasts. Mass production techniques have not been utilized for deep-space missions and thus the marginal cost of mission hardware is not substantially decreased through additional production. The mission development effort is labor intensive, and therefore, the cost of mission hardware is a direct linear function of the manpower involved in design, manufacturing and testing. This implies that it may not be necessary to analyze how development cost breaks down among labor, overhead, materials, other direct charges, etc. The relationship between mission parameters and resources can be better understood and evaluated for accuracy when that resource, i.e. manpower, is modeled explicitly. Finally, forecasting manpower requirements in addition to project cost provides management with additional information to aid in the program planning process.

It is not sufficient, however to categorically state that manpower, expressed in direct labor hours, should be a reasonable and practical proxy for cost. Figure 1 compares database averages of category labor hours with category total cost, as percentages of total development project hours and cost, for each cost category. On inspection and for most categories, the correlation between labor hours and cost appears to be adequate.

This favorable comparison can be firmly established with a statistical analysis. In a statistical sense, the percentage ratios

FIGURE 1



LABOR/COST PERCENTAGE COMPARISON
TOTAL DIRECT LABOR HOURS
TOTAL REAL YEAR COST
PERCENT OF TOTAL DEVELOPMENT
25.0
20.0
15.0
10.0
5.0
0.0
STD TCP PRP AAC TCM ANT CDH PWR PWS ADM RDR IML INV PFI RSI DSI SYS L30 IDD SDD PGM
COST CATEGORIES

shown in Figure 1 are simply sample means. Therefore, a t-test(1) for equivalent means can be applied to the data. The assumptions and steps for doing so are as follows. Since the sample size is small, normality must be assumed in the data because tests for normality would not be powerful enough. (This assumption actually holds throughout the modeling process for the same reason.) A fairly powerful test is required in order to decrease the probability of incorrectly accepting the hypothesis of equivalent means. Since there is no control over sample size, the best available option is to test at a fairly high significance level. For this purpose, 20% was selected.

The t-test is based on equivalent sample variances. Therefore, an F-test(2) for equivalent variances was first performed. Results from the F-test indicate that for all 21 categories shown in Figure 1, the variances of the labor hour ratios are equivalent to those of the cost ratios at the 20% significance level, and therefore the t-test can be applied.

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(1) The t-test evaluates the statistic

$$t^* = d\ \sqrt{n}/s(d)$$

against the Student's t distribution with n-1 degrees of freedom, to test the hypothesis that two normally distributed populations with the same unknown variance have the same mean. The test is performed using n paired observations from the two samples. In the above equation

d = the mean of the differences between the two samples
n = the sample size
$s(d)$ = the standard deviation of the differences between the paired values

For a selected significance level, α, if

$$|t^*| < t(1-\alpha/2;\ n-1)$$

then we may conclude that the two sample means are equivalent.

(2) F-test, as used in this context, evaluates the statistic

$$F^* = S_1^2/S_2^2$$

against the F distribution with n-1 and n-1 degrees of freedom, to test the hypothesis that two normally distributed populations have the same variance. The test is performed using n paired observations from the two samples. In the above equation

S_1 = is the standard deviation of the first sample
S_2 = is the standard deviation of the second sample

For a selected significance level, α, if

$$F(\alpha/2;n-1;n-1) < F^* < F(1-\alpha/2;n-1;n-1)$$

then we may conclude that the two samples have the same variance.

Results of the t-test show that in 16 of the 21 categories the mean ratios of labor hours and total cost are equivalent at 20% significance. This result is fairly acceptable since at 20%, approximately 4 out of 21 categories are expected to be not equivalent purely by chance. Relaxing the level of significance to 10% results in 19 of 21 categories having equivalent means where 2 of 21 are not expected by chance.

The implications of these results are that direct labor hours should provide a good proxy to total cost as the *primary* dependent variable and that *factors derived as simple ratios should be adequate for converting from labor hours to total cost*. This latter conclusion eliminates any need to analyze the cost data in terms of breakdowns among labor, overhead, material, etc.

3.2 Functional Forms

Having argued that 1) the type and amount of independent variables for cost prediction of advanced planetary missions is limited, 2) that the cost category algorithms should be parsimonious, and 3) that cost category direct labor hours should be the primary dependent variable, the following general relationships are postulated. For the flight hardware categories (subsystems), total direct labor hours (DLH) is a function of the number of flight qualified units (N) and the subsystem mass (M):

$$\text{DLH} = F(N, M) \quad ,$$

with separate functions independently derived for each category. For the functional support categories, total labor hours is postulated to be a function of the total hardware labor hours (all categories):

$$\text{DLH} = G(\Sigma\text{DLH hardware}).$$

Table 4 presents examples of some of the functional forms that were analyzed for possible relevance to the cost model. The single parameter type functions attempt to capture the separation between non-recurring and recurring costs by modeling each quantity separately. The dual parameter functions essentially ignore this separation and

Table 4

EXAMPLES OF POSSIBLE FUNCTIONAL FORMS

Single Parameter Functions

1) $DLH = NRL + N*URL$

where $NRL = f(M)$

$URL = k*NRL$, k constant

2) same as 1) except $URL = g(M)$

3) $DLH = (NRL + URL) + (N-1) * URL$

where $(NRL + URL) = f(M)$

functions $f(M)$ and $g(M)$ are of the general forms $a + bM$, aM^b or $\exp(a + bM)$

Dual Parameter Functions

4) $DLH = a + bN + cM$

5) $DLH = aN^b M^c$

6) $DLH = a + b(NM)$

7) $DLH = a(NM)^b$

8) $DLH = \exp[a + b(NM)]$

9) $DLH = aM^b + cNM^d$

10) $DLH = (a + bN) M^c$

attempt to directly model category total cost. Function types 1 through 8 in Table 4 can be fitted using the standard techniques of ordinary least squares regression. In some cases regression through the origin was used. This technique constrains, on an a priori basis, the estimate of "a" to be zero in function 6 and to be one in function 7 for example. Function types 9 and 10 can only be fitted by using non-linear regression and were only briefly examined.

3.3 Test Statistics

In order to identify which of the possible function forms best fit the database, some statistical measures of goodness-of-fit are required. For this purpose, two standard measures were used during the regression analysis: the correlation coefficient of the fitted data and the t-statistic of the parameter estimates. (The t-statistic in this context is defined as the parameter estimate divided by the standard error of the estimate. It should not be confused with the t-test described in Section 3.1, although it is evaluated in a similar manner.)

These measures are fairly adequate for determining a best fit of the data at the individual category level, but are not sufficient for analyzing model performance at the project level. Therefore, two additional measures were defined for use at both the category and project levels: the mean percentage error (MPE) and mean absolute percentage error (MAPE). Given a theoretical function of the form

$$y_i = a + b\,x_i \ , \quad i = 1 \ , \ \ldots \ , \ n$$

the fitted function is then

$$\hat{y}_i = \hat{a} + \hat{b}\,x_i \ ,$$

and the residual errors due to the fitting process are

$$\hat{e}_i = y_i - \hat{y}_i \ .$$

The two measures are then simply defined as

$$\text{MPE} = \frac{1}{n} \Sigma \frac{\hat{e}_i}{y_i}$$

and

$$\text{MAPE} = \frac{1}{n} \Sigma \left| \frac{\hat{e}_i}{y_i} \right| \ .$$

Mean percentage error can be viewed as an indication of bias in the fitted function. Mean absolute percentage error can be viewed as an indication of the gross error inherent to the fitted function and thus the confidence with which it can be used in making forecasts.

Specific cutoff values of these statistical measures were not used during the modeling process. For the most part, the "best fit" functions were chosen on the combined basis of having the highest correlation and t-statistics and lowest MPE and MAPE. However, certain qualitative, or subjective measures were also applied, such as a desire to avoid negative constants in linear (straight-line) fits.

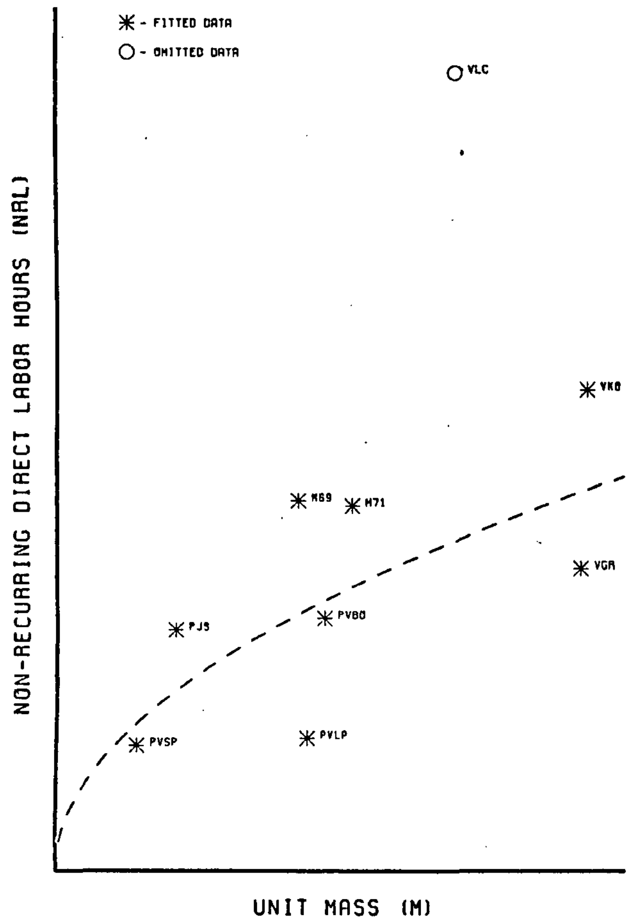
4. Model Analysis

The first model formulation analyzed was the single parameter type, which separately models non-recurring and recurring labor hours, for the obvious reason that this form had been successfully modeled in previous versions. Briefly, however, it was now found that algorithms based on non-recurring labor as a function of subsystem mass had poor correlation and unacceptably large percentage errors. Furthermore, as might be expected from the data in Table 2, recurring labor could not be expressed as a constant fraction of non-recurring labor. Algorithms of recurring labor as a function of subsystem mass did have moderate correlation and marginally acceptable percentage errors.

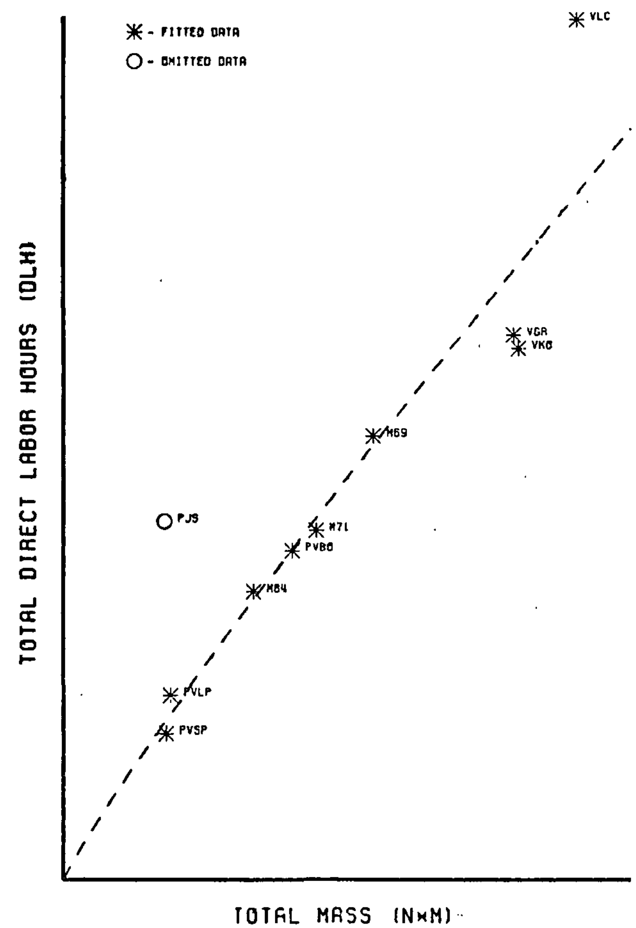
Reexamination of the cost data allocations did not reveal any obvious discrepancies to which the poor correlation could be attributed. Therefore, it seemed apparent that a new model formulation would have to be investigated. Consequently, a wide variety of theoretical functions based on the dual parameter formulation were analyzed. Multiple linear type functions, i.e. having two independent variables, exhibited moderately good correlation, but, in general, the strongest correlation was observed in algorithms that modeled category total labor as a function of a single variable formed by the product of subsystem mass and the number of flight units. Simply restated, total cost is a strong function of total mass. This is merely a statement of observed correlation in the data and is not necessarily evidence of a fundamental relationship.

Figure 2 illustrates the preceding discussion with the structure and devices hardware category as an example. Each graph shows the sample data and the fitted function, in each case a power law. Considerable scatter and thus poor correlation can be seen in Figure 2a, non-recurring labor versus unit mass. By comparison, a significant trend is observed in Figure 2b, total labor versus total mass. Similarly strong correlations between total labor and total mass were observed for most all other hardware cost categories.

Structure & Devices



a) Non-recurring labor fitted function and data



b) Total category labor fitted function and data

Figure 2. Comparisons of Different Functional Forms for Structures & Devices Cost Category

All of the available information in the database was not used in developing the cost model algorithms. The earliest projects, specifically Mariner '64, Surveyor and Lunar Orbiter, were largely excluded from the modeling effort because of the early technology status inherent in these projects. Exceptions to exclusion were made when a specific cost category data point correlated strongly with the data from later projects. Conversely, if a data point from the later projects was observed to be an obvious outlier from a significant trend, that data was excluded from the regression. An example of this is seen in Figure 2b in which Mariner '64 is included among the fitted data but Pioneer Jupiter/Saturn is excluded. This selective use of the data is not arbitrary. Data included from earlier programs may indicate that the effort required to design, fabricate and test the particular subsystem is somewhat independent of the technology in use. Data excluded from recent programs indicates either extreme cost overruns for high outliers or extremely high heritage for low outliers.

The decision to eliminate outliers led to the complete exclusion of Mariner '73 from the modeling process. This is not surprising since this particular project used a considerable amount of residual hardware from previous Mariner projects. Specifically, all hardware category costs for Mariner '73 were observed to lie well below trends indicated by the other projects in the database.

Even though non-recurring cost could not be successfully modeled, this quantity in terms of labor hours was still needed in order to apply inheritance algorithms (see Appendix C). These algorithms were developed on the premise that design and hardware heritage affects only the non-recurring portion of development costs. Developing new inheritance algorithms which would operate on total category cost was beyond the scope of the current model development effort. Thus, a procedure was needed to extract the non-recurring portion from the total labor estimate. As was previously mentioned, the recurring cost data exhibited moderately good correlation with subsystem mass. Obviously, then, an estimate of non-recurring labor could be recovered by differencing the total labor and recurring labor estimates. During the process of analyzing recurring costs, a slight improvement in correlation was observed between total recurring cost and total mass over that of single-unit recurring cost and unit mass. Algorithms of total recurring labor as a function of total subsystem mass were therefore developed. An estimate of single-unit recurring cost can be obtained by simply dividing by the number of flight units.

In the functional support categories, costs for system support and ground equipment and for launch + 30 days operations and ground software were found to correlate well with the sum of flight hardware category costs. Costs for pre-launch development of capabilities for imaging data processing and for non-imaging science data analysis were observed to correlate with imaging system resolution and non-imaging science payload mass, respectively. Finally, the cost of program management correlated well with the sum of all other category costs, both hardware and support functions.

Table 5 summarizes the complete set of algorithms developed during the modeling process. The flight project algorithms from the previous model version are also presented. Graphs of the data and fitted functions together with associated statistics are presented in Appendix B. Figure 3 is a flow diagram illustrating the key elements of the cost model.

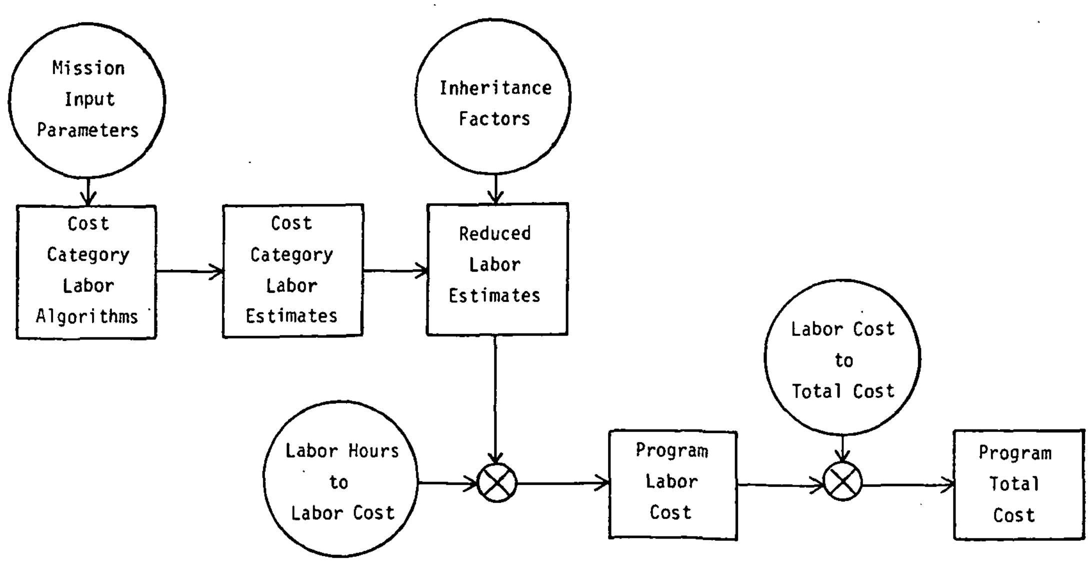


Figure 3. Cost Model Schematic

Table 5

Summary of Cost Model Algorithms

Development Project - Flight Hardware

Structure & Devices

$$DLH = 1.626\ (N * M)^{0.9046}$$

$$RLH = 1.399\ (N * M)^{0.7445}$$

Thermal Control, Cabling & Pyrotechnics

$$DLH = \exp\ (4.2702 + 0.00608\ N * M)$$

$$RLH = 3.731\ (N * M)^{0.6082}$$

Propulsion

$$DLH = 56.1878\ (N * M)^{0.4166}$$

$$RLH = 1.0\ (N * M)^{0.9011}$$

Attitude & Articulation Control

$$DLH = 21.328\ (N * M)^{0.7230}$$

$$RLH = 1.932\ (N * M)$$

Telecommunications

$$DLH = 4.471\ (N * M)^{1.1306}$$

$$RLH = 1.626\ (N * M)^{1.1885}$$

Antennas

$$DLH = 6.093\ (N * M)^{1.1348}$$

$$RLH = 3.339\ (N * M)$$

Command & Data Handling

$$DLH = \exp\ (4.2605 + 0.02414\ N * M)$$

$$RLH = \exp\ (2.8679 + 0.02726\ N * M)$$

RTG Power

$$DLH = 65.300\ (N * M)^{0.3554}$$

$$RLH = 7.88\ (N * M)^{0.7150}$$

Solar/Battery Power

$$DLH = \exp\ (3.9633 + 0.00911\ N * M)$$

$$RLH = \exp\ (2.5183 + 0.01204\ N * M)$$

Aerodeceleration Module

$$DLH = 3.481\ (N * M)^{0.8416}$$

$$RLH = 4.662\ (N * M)^{0.5}$$

M in kilograms
DLH, RLH in 1000 hours
MD, ED in months

Table 5 (continued)

Summary of Cost Model Algorithms

Landing Radar/Altimeter

$$DLH = 11.409\ (N * M)^{0.9579}$$
$$RLH = 1.2227\ (N * M)^{1.2367}$$

Line-Scan Imaging

$$DLH = 10.069\ (N * M)^{1.2570}$$
$$RLH = 1.989\ (N * M)^{1.4089}$$

Vidicon Imaging

$$DLH = 4.463\ (N * M)^{1.0369}$$
$$RLH = 1.0\ (N * M)^{1.1520}$$

Particle & Field Instruments

$$DLH = 25.948\ (N * M)^{0.7215}$$
$$RLH = 0.790\ (N * M)^{1.3976}$$

Remote Sensing Instruments

$$DLH = 25.948\ (N * M)^{0.5990}$$
$$RLH = 0.790\ (N * M)^{0.8393}$$

Direct Sensing/Sampling Instruments

$$DLH = 6.173\ (N * M)^{1.2737}$$
$$RLH = 1.0\ (N * M)^{1.4200}$$

Development Project - Support Functions

System Support & Ground Equipment

$$DLH = 0.36172\ (\Sigma\, DLH\ hardware)^{0.9815}$$
$$DLH = 0.5095\ (\Sigma\, DLH\ hardware)\quad \boxed{\text{Viking Class Missions}}$$

Launch + 30 Days Operations & Ground Software

$$DLH = 0.09808\ (\Sigma\, DLH\ hardware)$$

Imaging Data Development

$$DLH = 0.00124\ (PPL)^{1.629}$$

Science Data Development

$$DLH = 27.836\ (\text{non-imaging science mass})^{0.3389}$$

Program Management/MA&E

$$DLH = 0.10097\ (\Sigma\, DLH\ \text{all categories})^{0.9670}$$

Flight Project

Flight Operations

$$DLH = \left(\frac{\Sigma\, DLH\ Hardware}{3100}\right)^{0.6} (10.7\ MD + 27.0\ ED)$$

Data Analysis

$$DLH = 0.425\ (DLH\ Flight\ Operations)$$

4.1 Labor/Cost Conversion Factors

As was demonstrated in Section 3.1, simple conversion factors, derived as average ratios, are all that are needed to convert category direct labor hours into category total cost. Two independent factors were derived for this purpose: the first converts labor hours to labor cost while the second converts labor cost to total cost. These conversion factors are presented in Table 6 for all cost categories.

Derivation of the labor cost to total cost factors was straightforward, involving simple ratios of the allocated cost data. However, derivation of the labor hours to labor cost factors first required elimination of the effects of inflation inherent in the raw cost data. For this purpose, the NASA R & D Escalation Indices for Space Systems Development (February 1979) were used to adjust the annual funding for each category in each project to a fiscal year 1977 basis. Once this was accomplished, simple ratios were again used to derive the conversion factors. Projects completed prior to 1970 were not included in this process because such projects, having median funding nearly a decade or more from the basis, would introduce too much variance in the ratios.

4.2 Error Analysis

The first step in analyzing model performance was to test the model against the development projects in the database. In order to obtain global, consistent measures of model performance, the error analysis was confined to the seven major projects contributing to the model development. Errors from cost categories excluded from the regression analysis (such as PJS structure and devices) are included in the global error analysis.

Table 7 summarizes the percentage residual errors at the hardware level (i.e. exclusive of the support categories) of the seven projects. Also shown for comparison are the hardware level residual errors obtained from a model based on separate algorithms for non-recurring

Table 6

Labor/Cost Conversion Factors

Cost Category	Labor Hours to Labor Cost (FY77 dollars/manhour)	Labor Cost to Total Cost
Development Project		
Structure & Devices	10.45	3.303
Thermal Control, Cabling & Pyrotechnics	10.26	3.317
Propulsion	10.54	3.616
Attitude & Articulation Control	10.63	3.347
Telecommunications	9.99	3.352
Antennas	9.96	3.466
Command & Data Handling	9.68	3.163
RTG Power	9.51	3.177
Solar Battery Power	10.41	3.148
Aerodecleration Module	10.73	3.296
Landing Radar/Altimeter	10.08	3.158
Line-Scan Imaging	10.57	3.604
Vidicon Imaging	9.52	3.586
Particle & Field Instruments	10.62	3.395
Remote Sensing Instruments	10.65	3.286
Direct Sensing/Sampling Instruments	9.55	3.454
System Support & Ground Equipment	10.55	3.076
Launch + 30 Days Ops & Ground S/W	10.71	3.214
Image Data Development	11.46	3.130
Science Data Development	12.76	3.987
Program Management/MA & E	11.57	2.685
Flight Project		
Flight Operations	10.44	3.247
Data Analysis	10.44	3.425

Table 7

Comparison of Hardware - Level Residual Percentage Errors

Hardware Project	Total DLH Model	Separate NRL/URL Model
M69	1.8	26.4
M71	-3.1	-4.1
PJS	17.1	26.2
VLC	-1.2	19.8
VKO	-5.4	9.3
VGR	3.0	8.4
PV	-8.6	-19.4
MPE	0.6	9.5
MAPE	5.7	16.2

and recurring labor. The global errors, MPE and MAPE, support expectations based on the individual algorithm correlations: a model formulated on estimation of total category DLH would exhibit less bias and higher confidence than a model based on separate NRL and URL algorithms.

The next step in the error analysis was to determine the global errors at the development project level in terms of both percentage labor hours and total cost. Estimates of support function labor, for the most part, are based on the summation of hardware category labor. Thus errors in hardware labor estimates would be expected to propagate through the support functions. Also, the factors to convert from labor hours to total cost are simple averages and the variances implicit in such averages would also be expected to propagate through the conversion to cost. These considerations imply that the global errors at the project cost level might be worse than those observed at the hardware labor hours level.

Table 8 presents a summary of the global errors at the project level. The first grouping, termed "Fitted", are those errors which are obtained when the actual hardware level labor is used to estimate

Table 8

Global Percent Error Summary

		Fitted			Estimated		
		Hardware	Support Functions	Total Project	Hardware	Support Functions	Total Project
LABOR HOURS	MPE	0.6	-6.8	-1.5	0.6	-8.7	-2.1
	MAPE	5.7	12.5	6.4	5.7	14.3	7.0
TOTAL COST	MPE	1.5	-5.5	-0.8	1.5	-6.3	-1.1
	MAPE	6.9	12.3	7.3	6.9	16.5	8.2

the function labor. The group labeled "Estimated" is the errors observed when the estimated hardware labor is used. The conclusion from these results is that use of estimated hardware labor in the function algorithms and averaged conversion factors has only marginal effect on the hardware level global errors. The model as formulated captures the database with a marginally conservative bias of approximately 1% overestimation and a gross error less than 10%.

Appendix D contains the details of the error analysis from which the results in Table 8 were obtained.

4.3 Simulation Analysis

The error analysis discussed in Section 4.2 provides an assessment of how well the model has captured the data from which it was developed. However, it provides little information regarding how well the model will perform in practical applications.

Because of the large number of input variables, a parametric analysis of the model would be cumbersome to perform and difficult to evaluate. Monte Carlo simulation can provide a feasible method for assessing the overall performance of the model. By artificially viewing subsystem masses as stochastic variables, the simulation reduces to selecting probability distributions which adequately express these variables, and randomly sampling from these distributions. A simplifying assumption is made that individual subsystem masses are independent of other subsystem masses. The sampled masses from each trial of the simulation can be input to the model in a deterministic fashion and the model output can then be averaged over the number of trials. Given a fixed number of trial runs, the number of flight units becomes the only control parameter.

Selecting probability distributions is the only matter of speculation. Both uniform and triangular probability density functions were used to assess what affect, if any, such different assumptions might have on the outcome. Figure 4 below represents a typical triangular probability density function.

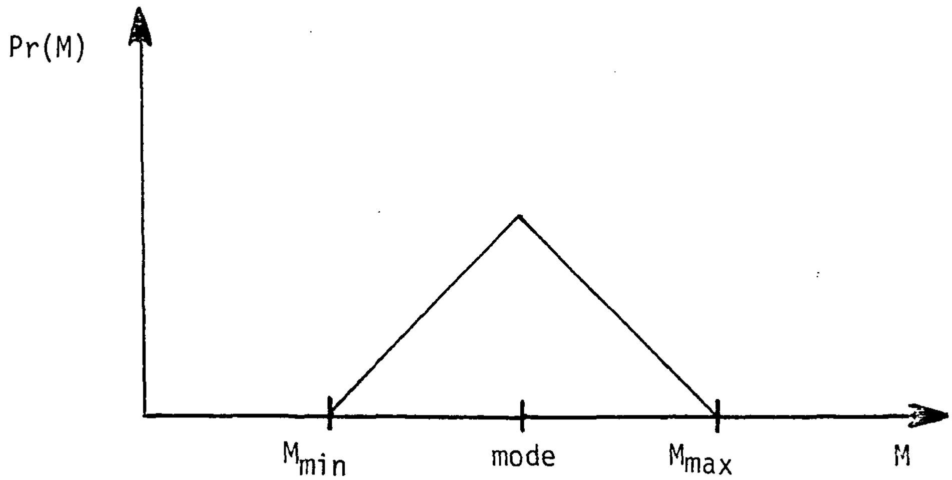


Figure 4. Subsystem Mass Probability Density Function

The lower and upper bounds, M_{min} and M_{max}, for each hardware cost category were chosen as the smallest and largest subsystem masses observed in the historical database from Table 3. Three different modes were analyzed for the triangular pdf's: 25%, 50% and 75% of the difference between M_{min} and M_{max}. The number of flight units was systematically varied from one to five and 1000 trials were run for each case. Only the hardware total labor was analyzed since the support categories are direct functions of this quantity and their inclusion would not provide additional information.

For purpose of comparison, a simulation of the previous version of the SAI Cost Model was also made. Table 9 summarizes the results of the two model simulations with number of flight units as the parameter. That the total simulated mass is the same for each respective pdf attests to the fact that to maintain consistency the same pseudo-random number stream was used in each case.

The first point to notice in the data is that the results from using different probability distributions are consistent. Therefore, any conclusions which may be drawn from the analysis are not dependent upon the assumptions used to randomly select subsystem masses.

The major result indicated by the data in Table 9 is the non-linear increase in total labor as a function of the number of flight

Table 9

Summary Results of Cost Model Simulation Analysis

Model Formulation	PDF	Average Simulated Total Mass (kgs)	Average Hardware Total Labor (1000 hours)				
			N=1	N=2	N=3	N=4	N=5
New	Uniform	574	2136	3847	6392	12005	28643
	Triangular 25%	502	1966	3401	5173	8084	14519
	Triangular 50%	575	2150	3792	5940	9759	18781
	Triangular 75%	648	2331	4215	6916	12367	26772
Previous	Uniform	574	3438	3846	4254	4662	5069
	Triangular 25%	502	3219	3599	3980	4360	4741
	Triangular 50%	575	3485	3898	4312	4725	5138
	Triangular 75%	648	3736	4180	4625	5069	5513

Averages of 1000 trials for each pdf

units. Figure 5 is a plot of the data for the 50% triangular pdf. The increase in labor for the previous model is linear, which is consistent with intuitive expectations, ignoring such factors as economy of scale. Since the hardware cost category algorithms of the new model are a mix of power laws and exponentials, the increase in labor as a function of flight units was not expected to be exactly linear. However, the highly positive slope of the function in Figure 5 was not expected.

To investigate this further, simulations were also made of models based on formulations 2 and 3 in Table 4. Results of these simulations are shown as the hashed region in Figure 5. These results exhibit consistency with the results from the previous model simulation: increase in total labor is a linear function of the number of flight units.

4.4 Error Analysis Revisited

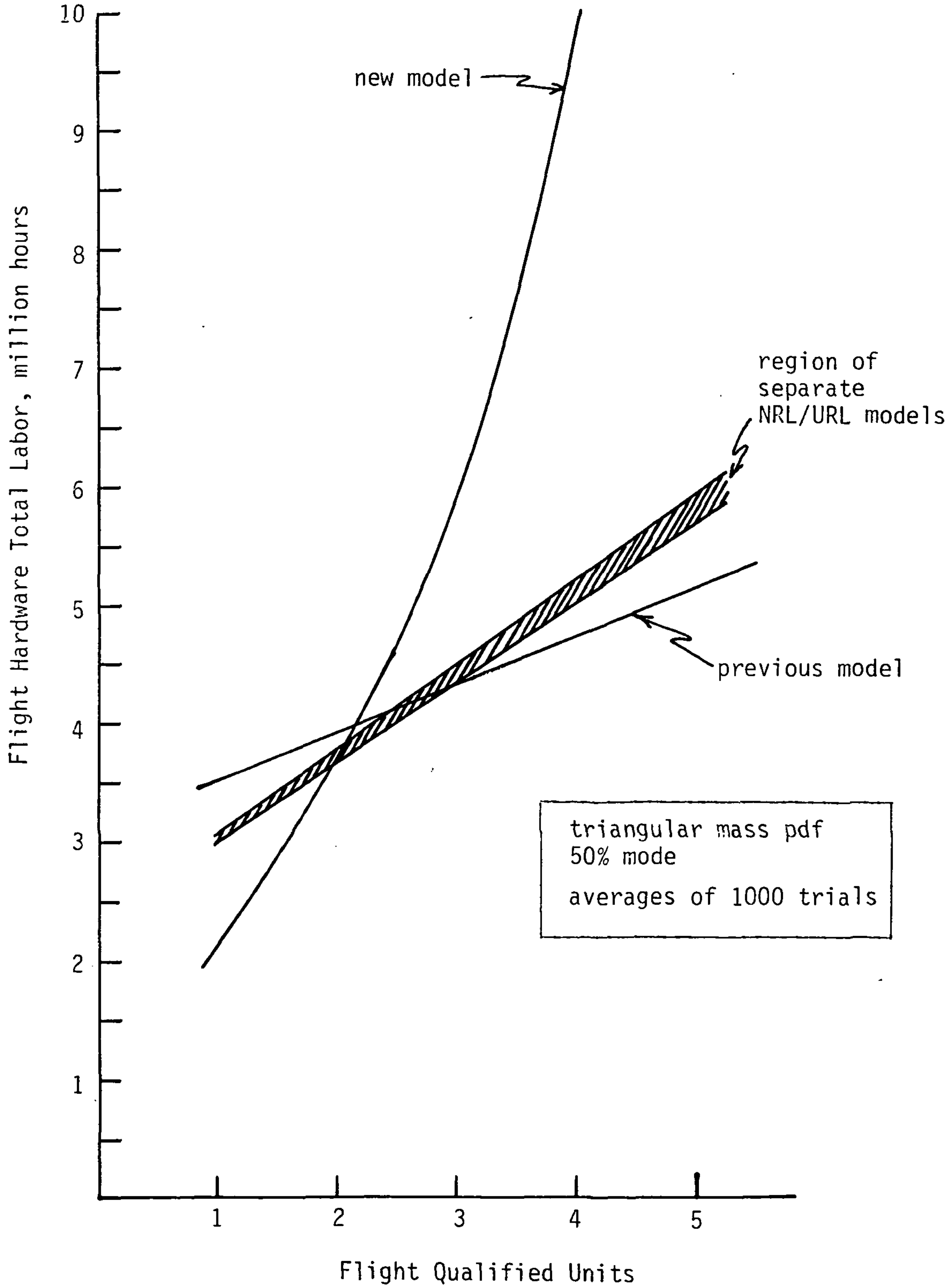
From the previous discussion, it appears that the model formulation, as presented in Table 5, is highly sensitive to the number of flight units. A procedure is needed to reduce this sensitivity while maintaining the high correlation of the category algorithms with the database. Two considerations indicate that such a procedure may be feasible. Of the ten hardware systems in Table 3, five consisted of two flight qualified units. Furthermore, at N=2, results of the new model simulation are very near to the other model simulation results. This suggests a procedure which may be termed anchoring and adjustment, that is, to anchor an initial cost estimate at two flight units and adjust this estimate up or down by the appropriate amount of recurring cost. Expressed mathematically, the procedure is

$$DLH_a = DLH(2,M) + (N-2) * RLH(2,M)/2$$

where DLH(2,M) and RLH(2,M) are the algorithms of Table 5 evaluated for N=2. The correct sign for the adjustment term is automatically accounted for in the (N-2) factor. For N=1, the recurring cost of one unit is subtracted from the estimate and for $N \geq 3$ the appropriate cost is added. For N=2, the initial estimate is unaltered.

Figure 5

Comparative Summary Results of Simulation Analysis



Simulations of the new model based on this procedure were performed and are plotted as the upper bound of the hashed region in Figure 5.

The error analysis of the model database performed in Section 4.2 was reassessed using the adjustment procedure described above. Table 10 summarizes the results of this analysis. The estimated errors from Table 8 are repeated for comparison with the errors arising from the adjustment procedure. The adjusted errors show that, due to the adjustment procedure, the model still has relatively low bias, but the gross error has increased. Development projects in the database with other than two flight units contribute to this increase in mean absolute percentage error. Despite the factor of two increases, the gross errors of both labor hours and total cost are still within the acceptance limit of 20%.

4.5 Benchmark Tests

The last step in analyzing model performance was to run benchmark tests of the model against project costs from other sources. Two sources for such tests are available: actual costs of past projects not included in the model database, and independent project estimates of current and future programs.

For the first case, one project is readily available from the SAI cost database, specifically, Mariner Venus/Mercury 1973. This particular project readily lends itself to the benchmark tests since no data from it was used during model development, yet it was accomplished during the same time period as those projects in the model database. Two projects were selected for the second case: the Galileo Probe to Jupiter and the Venus Orbital Imaging Radar (VOIR) spacecraft. The estimated total development cost for the Galileo Probe was obtained from the POP 80-2 fiscal year cost estimates in Reference 3, adjusted to FY'82 constant dollars. The benchmark cost of the VOIR development project was obtained from a JPL cost review (Reference 4). The cost of the synthetic aperture radar system is not included in either the benchmark cost or the model cost estimates.

Table 10

Revised Global Percent Errors

		Estimated			Adjusted		
		Hardware	Support Functions	Total Project	Hardware	Support Functions	Total Project
Labor Hours	MPE	0.6	-8.7	-2.1	4.7	-2.1	2.8
	MAPE	5.7	14.3	7.0	16.5	19.8	16.2
Total Cost	MPE	1.5	-6.3	-1.1	2.1	-5.5	-0.3
	MAPE	6.9	16.5	8.2	16.0	22.7	17.0

Table 11 summarizes the results of the benchmark tests. All costs are given in fiscal year dollars appropriate to the particular benchmark cost. Subsystem-level heritage was taken into account in generating all model estimates. Estimates from the cost model are shown first without using the flight unit adjustment procedure. The model estimate for Mariner '73 is well within acceptable error limits. However, the initial estimates for Galileo Probe and VOIR are significantly below the benchmark costs. Applying the adjustment procedure has no affect on the Mariner '73 estimate since two units are costed, but the estimates for Galileo Probe and VOIR are now both within acceptable limits.

Based on the previous analyses, it appears that the revised model performs well for applications involving either two flight units or one flight unit with the adjustment procedure. Firm conclusions cannot be made for applications involving three or more flight units since appropriate benchmark projects are not available to test such cases.

Considering the results of the benchmark tests, although limited in number and scope, together with the results of the database error analysis, the uncertainty of cost predictions obtained from this model can be stated as follows. Flight hardware mass estimates associated with future missions have uncertainties which can vary greatly depending on the design concept and degree of heritage. Thus, for mission concepts that generally fall within the scope of missions in the model's database, the estimated uncertainty in cost predictions is approximately $\pm$20%. For mission concepts which are outside the scope of the database missions yet can be costed with this model (e.g. penetrators or rovers), the uncertainty of cost predictions cannot be estimated and must be treated on an individual basis.

Table 11

Summary Results of Benchmark Tests

Development Project/ Source	Flight Units	Benchmark Cost	Model Cost Estimate	Estimated Error	Adjusted Model Cost Estimate	Estimated Error
Mariner '73 SAI Database	2	$130M FY77	$137M FY77	-5%	$137M FY77	-5%
Galileo Probe POP 80-2	1	$108M FY82	$ 75M FY82	31%	$109M FY82	-1%
VOIR JPL Cost Review	1	$218M FY80	$157M FY80	28%	$226M FY80	-4%

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5. Sample Applications

Two sample applications of the cost model are presented to illustrate its applicability to a variety of project implementation concepts and mission scenarios.

The first example is a comet rendezvous mission using a low-thrust trajectory with the stage concept for solar electric propulsion. The mission is the Halley Flyby/Tempel 2 Rendezvous as defined in Reference 5 .

The following two pages present completed input data worksheets for this mission. The first worksheet defines the project scenario and provides necessary guidelines for generating the cost estimate. The guidelines indicate that only the Mission Module spacecraft and its associated mission operations are to be costed. The second worksheet presents subsystem mass estimates for the Mission Module flight hardware together with estimates of the inheritance classifications for each subsystem.

Figure 6 presents the computer-generated output of the cost model, showing the raw, detailed cost estimates for the Halley/Tempel 2 Mission Module hardware development and for the mission flight operations and data analysis. Within the Development Project subheading, the first group of columns display individual category labor hour and cost estimates without accounting for inheritance. The last three columns show labor and cost estimates after factoring in the effects of inheritance. The estimated cost of hardware design and fabrication is approximately $134 Million, after an estimated 30% savings due to inheritance. The cost reduncing effects of heritage in the flight hardware propagate into the functional support categories and the flight project categories so that the total development is estimated to cost $214 Million and the total program is estimated at $292 Million, without contingency. Table 12 summarizes the cost estimate in a format which is typical of actual reporting practices. "Science Development" includes the instrument hardware and imaging and science data development

SAI PLANETARY PROGRAM COST MODEL

Input Data Worksheet Page 1

Project Scenario Definition

MISSION*: *Halley Flyby/Tempel 2 Rendezvous*

HARDWARE CONFIGURATION:

SPACECRAFT ELEMENT*	NO. OF UNITS*	DESIGN HERITAGE
Mission Module	*1*	*NASA Standard, Galileo, Voyager Viking*

LAUNCH VEHICLE: *Shuttle/IUS*

FLIGHT MODE*: *Solar Electric Propulsion*

MISSION PROFILE:

LAUNCH NO.	LAUNCH DATE*	FLIGHT TIME*	ENCOUNTER TIME*
1	*July, 1985*	*48 MOnths*	*25 months*

BASE FISCAL YEAR*: FY *1982*

COST SPREAD OPTION PROJECT START DATE:

SPECIAL COST GUIDELINES:

Costs of SEP Stage, SEP Operations, and Halley Probe not included.

Module power via Stage.

Apply 20% APA/Reserve

*Necessary Information

SAI PLANETARY PROGRAM COST MODEL

Input Data Worksheet Page 2

Flight Hardware Definitions

SPACECRAFT ELEMENT: *HF/T2R Mission Module*

			INHERITANCE CLASS PERCENT BY MASS				
			BLOCK BUY	EXACT REPEAT	MINOR MOD	MAJOR MOD	NEW DESIGN
ENGINEERING:							
Structure & Devices:	199.3	kg	0.0	0.0	33.0	33.0	34.0
Thermal, Cabling & Pyro:	65.0	kg	0.0	0.0	33.0	33.0	34.0
Propulsion Inerts:	-0-	kg					
Att & Articulation Control:	59.5	kg	33.6	49.4	6.0	0.0	11.0
Telecommunications:	40.7	kg	20.9	50.6	28.5	0.0	0.0
Antennas:	6.2	kg	0.0	0.0	100.0	0.0	0.0
Command & Data Handling:	45.4	kg	0.0	100.0	0.0	0.0	0.0
Power*: Solar ✓ RTG ___	18.6	kg	0.0	0.0	0.0	0.0	100.0
Aerodeceleration:	-0-	kg					
Landing Radar/Altimeter:	15.0	kg	0.0	0.0	0.0	0.0	100.0
SCIENCE							
Imaging Mass:	32.0	kg	0.0	33.2	0.0	0.0	66.8
Imaging Resolution:	800	PPL	Vidicon ___	CCD ✓	Fax ___		
Particle & Field:	82.2	kg	0.0	9.5	23.1	27.2	40.2
Remote Sensing:	11.0	kg	0.0	0.0	40.9	0.0	59.1
Direct Sensing:	-0-	kg					

*For RTG Power Systems, do not include mass of RTG units

LABOR & COST PREDICTION RUN -- Ø8-APR-82

Program: Halley/Tempel 2 Mission Module First Launch: July 1985 Fiscal Year 1982 $M

DEVELOPMENT PROJECT

1 Flight Unit(s)

Category	MASS kgs	DLH khrs	RLH khrs	NRLH khrs	COST $M	INHERITANCE CLASS (%) BS	ER	MiM	MaM	DLHI khrs	NRLHI khrs	COSTI $M
STRUCTURE & DEVICES	199.3	3Ø5.7	6Ø.4	245.3	17.31	Ø.Ø	Ø.Ø	33.Ø	33.Ø	281.4	221.Ø	15.94
THERMAL, CABLING & PYRO	65.Ø	121.7	36.Ø	85.7	6.8Ø	Ø.Ø	Ø.Ø	33.Ø	33.Ø	113.2	77.2	6.32
ATT & ART CONTROL	59.5	56Ø.5	115.Ø	445.5	32.71	33.6	49.4	6.Ø	Ø.Ø	228.Ø	113.1	13.31
TELECOMMUNICATIONS	4Ø.7	494.8	151.7	343.2	27.19	2Ø.9	5Ø.6	28.5	Ø.Ø	259.7	1Ø8.1	14.27
ANTENNAS	5.2	85.4	2Ø.7	64.7	4.84	Ø.Ø	Ø.Ø	1ØØ.Ø	Ø.Ø	69.2	48.5	3.92
COMMAND & DATA HANDLING	45.4	529.7	1Ø4.5	425.1	26.61	Ø.Ø	1ØØ.Ø	Ø.Ø	Ø.Ø	189.6	85.Ø	9.52
SOLAR/BATTERY POWER	18.6	64.2	9.7	54.4	3.45	Ø.Ø	Ø.Ø	Ø.Ø	Ø.Ø	64.2	54.4	3.45
LANDING RADAR/ALTIMETER	15.Ø	255.6	41.Ø	214.6	13.35	Ø.Ø	Ø.Ø	Ø.Ø	Ø.Ø	255.6	214.6	13.35
VIDICON IMAGING	32.Ø	272.8	6Ø.2	212.6	15.28	Ø.Ø	33.2	Ø.Ø	Ø.Ø	216.3	156.1	12.12
PARTICLE & FIELD INST	82.2	536.3	493.8	42.5	31.72	Ø.Ø	9.5	23.1	27.2	53Ø.Ø	36.3	31.35
REMOTE SENSING INST	11.Ø	194.8	47.4	147.4	11.18	Ø.Ø	Ø.Ø	4Ø.9	Ø.Ø	179.7	132.4	1Ø.32
TOTAL HARDWARE	574.9	3421.4	114Ø.3	2281.1	19Ø.43					2387.Ø	1246.7	133.87
(Percent Cost Reduction												29.7%)
SYSTEM SUPRT & GRND EQPT		1Ø64.9			56.73					748.Ø		39.83
LAUNCH+3ØDAYS & GRND S/W		335.6			18.95					234.1		13.22
IMAGE DATA DEVELOPMENT		66.5			3.91					52.7		3.1Ø
SCIENCE DATA DEVELOPMENT		123.7			1Ø.32					12Ø.1		1Ø.Ø2
PROGRAM MANAGEMENT/MA&E		382.Ø			19.47					273.1		13.92
TOTAL DEVELOPMENT		5394.1			299.79					3815.Ø		213.96
(Percent Cost Reduction												28.6%)

FLIGHT PROJECT

	MSSN DUR mo	ENCT DUR mo	DLH khrs	COST $M	DLHI khrs	COSTI $M
MISSION OPERATIONS	48.Ø	25.Ø	1261.1	7Ø.13	1Ø16.1	56.51
DATA ANALYSIS			536.Ø	31.44	431.8	25.33
TOTAL PROGRAM			7191.1	4Ø1.36	5263.Ø	295.79
(Percent Cost Reduction						26.3%)

Figure 6. Cost Model Output for Halley/Tempel 2 Mission Module

categories. "Spacecraft" includes the engineering subsystem categories and the system support category. With contingency, this program is estimated to cost $355 Million.

Table 12. Cost Summary for Halley Flyby/Tempel 2 Rendezvous

	FY1982 $M
Program Management/MA&E	13.9
Science Development	66.9
Data Analysis	25.3
Spacecraft	119.9
Launch + 30 Days Operations	13.2
Mission Operations	56.5
Subtotal	295.8
APA/Reserve (@ 20%)	59.2
Total	355.0

The second sample application deals with a multi-mission project to deliver atmospheric entry probes to the outer planets Saturn, Uranus and Neptune. The project implementation scenario is based on an assumption that all six spacecraft (three probes and three probe carriers) are developed under a single hardware system contract. The probe design is assumed to rely heavily on the current Galileo Probe with suitable modifications for use at the other giant outer planets. The carrier design is assumed to benefit from the contractor's experience in designing low-cost spinning spacecraft. Other guidelines include a presumption that the project is charged for RTG units, 15% contingency is to be applied, and only the development cost, i.e. costs to launch + 30 days, is to be estimated.

Figure 7 presents the cost model output for the Outer Planet Probes Development Project. Hardware cost categories are shown separately for the two different spacecraft. Functional categories, however, are shown as totals for the overall development effort and not prorated to each spacecraft. The total development is estimated at approximately $277 Million without contingency. Table 12 summarizes the development

SAI PLANETARY PROGRAM COST MODEL

Input Data Worksheet Page 1

Project Scenario Definition

MISSION*: *Outer Planet Probe Project*

HARDWARE CONFIGURATION:

SPACECRAFT ELEMENT*	NO. OF UNITS*	DESIGN HERITAGE
Probe	*3*	*Galileo Probe*
Probe Carrier	*3*	*Contractor's design base*

LAUNCH VEHICLE: *Shuttle/IUS*

FLIGHT MODE*: *Jupiter Swingby*

MISSION PROFILE:

LAUNCH NO.	LAUNCH DATE*	FLIGHT TIME*	ENCOUNTER TIME*
1	*April, 1992 (Saturn)*		
2	*Jan, 1994 (Uranus & Neptune tandem launch)*		

BASE FISCAL YEAR*: FY *1982*

COST SPREAD OPTION PROJECT START DATE:

SPECIAL COST GUIDELINES:

System contract for six spacecraft

Costs to Launch + 30 days only

3 RTG's @ $10M/unit

15% APA/Reserve

*Necessary Information

SAI PLANETARY PROGRAM COST MODEL

Input Data Worksheet Page 2
Flight Hardware Definitions

SPACECRAFT ELEMENT: *Probe*

		INHERITANCE CLASS PERCENT BY MASS				
		BLOCK BUY	EXACT REPEAT	MINOR MOD	MAJOR MOD	NEW DESIGN
ENGINEERING:						
Structure & Devices:	58.4 kg	0.0	100.0	0.0	0.0	0.0
Thermal, Cabling & Pyro:	23.9 kg	0.0	100.0	0.0	0.0	0.0
Propulsion Inerts:	-0- kg					
Att & Articulation Control:	-0- kg					
Telecommunications:	12.9 kg	0.0	65.0	35.0	0.0	0.0
Antennas:	-0- kg					
Command & Data Handling:	15.6 kg	0.0	65.0	35.0	0.0	0.0
Power*: Solar ✓ RTG ___	13.4 kg	0.0	100.0	0.0	0.0	0.0
Aerodeceleration:	91.9 kg	0.0	65.0	35.0	0.0	0.0
Landing Radar/Altimeter:	-0- kg					
SCIENCE						
Imaging Mass:	-0- kg					
Imaging Resolution:	-0- PPL	Vidicon ___	CCD ___	Fax ___		
Particle & Field:	-0- kg					
Remote Sensing:	6.9 kg	0.0	100.0	0.0	0.0	0.0
Direct Sensing:	21.4 kg	0.0	62.8	37.2	0.0	0.0

*For RTG Power Systems, do not include mass of RTG units

SAI PLANETARY PROGRAM COST MODEL

Input Data Worksheet Page 2

Flight Hardware Definitions

SPACECRAFT ELEMENT: *Probe Carrier*

INHERITANCE CLASS PERCENT BY MASS

		BLOCK BUY	EXACT REPEAT	MINOR MOD	MAJOR MOD	NEW DESIGN
ENGINEERING:						
Structure & Devices:	183.6 kg	8.2	1.0	0.0	90.3	0.0
Thermal, Cabling & Pyro:	52.6 kg	0.0	0.0	0.0	100.0	0.0
Propulsion Inerts:	16.2 kg	87.0	1.8	0.0	11.2	0.0
Att & Articulation Control:	21.1 kg	34.1	65.9	0.0	0.0	0.0
Telecommunications:	31.0 kg	22.2	77.8	0.0	0.0	0.0
Antennas:	9.1 kg	11.0	17.6	71.4	0.0	0.0
Command & Data Handling:	50.3 kg	24.6	75.4	0.0	0.0	0.0
Power*: Solar ___ RTG ✓	35.5 kg	64.8	0.0	0.0	35.2	0.0
Aerodeceleration:	-0- kg					
Landing Radar/Altimeter:	-0- kg					
SCIENCE						
Imaging Mass:	-0- kg					
Imaging Resolution:	-0- PPL	Vidicon ___	CCD ___	Fax ___		
Particle & Field:	-0- kg					
Remote Sensing:	-0- kg					
Direct Sensing:	-0- kg					

*For RTG Power Systems, do not include mass of RTG units

LABOR & COST PREDICTION RUN -- Ø8-APR-82

Program: Outer Planet Probe Project — First Launch: April 1992 — Fiscal Year 1982 $M

DEVELOPMENT PROJECT

Element 1: Probes
3 Flight Unit(s)

Category	MASS kgs	DLH khrs	RLH khrs	NRLH khrs	COST $M	INHERITANCE CLASS (%) BB	ER	MIN	MaM	DLHI khrs	NRLHI khrs	COSTI $M
STRUCTURE & DEVICES	58.4	144.8	72.6	72.2	8.2Ø	Ø.Ø	1ØØ.Ø	Ø.Ø	Ø.Ø	87.1	14.4	4.93
THERMAL, CABLING & PYRO	23.9	115.3	58.8	56.5	6.44	Ø.Ø	1ØØ.Ø	Ø.Ø	Ø.Ø	7Ø.1	11.3	3.91
TELECOMMUNICATIONS	12.9	215.1	116.1	98.9	11.82	Ø.Ø	65.Ø	35.Ø	Ø.Ø	155.Ø	38.8	8.51
COMMAND & DATA HANDLING	15.6	171.1	61.8	1Ø9.3	8.59	Ø.Ø	65.Ø	35.Ø	Ø.Ø	1Ø4.7	42.9	5.26
SOLAR/BATTERY POWER	13.4	75.8	25.7	5Ø.1	4.Ø7	Ø.Ø	1ØØ.Ø	Ø.Ø	Ø.Ø	35.7	1Ø.Ø	1.92
AERODECELERATION MODULE	91.9	311.7	94.8	216.9	18.Ø9	Ø.Ø	65.Ø	35.Ø	Ø.Ø	18Ø.Ø	85.1	1Ø.44
REMOTE SENSING INST	5.9	215.1	96.Ø	119.1	12.35	Ø.Ø	1ØØ.Ø	Ø.Ø	Ø.Ø	119.9	23.8	6.88
DIRECT SENSE/SAMPLE INST	21.4	842.4	311.Ø	531.4	45.59	Ø.Ø	62.8	37.2	Ø.Ø	526.Ø	215.Ø	28.46
TOTAL HARDWARE	244.4	2Ø91.2	836.9	1254.3	115.14					1278.3	441.4	7Ø.32
(Percent Cost Reduction												38.9%)

Element 2: Probe Carriers
3 Flight Unit(s)

Category	MASS kgs	DLH khrs	RLH khrs	NRLH khrs	COST $M	INHERITANCE CLASS (%) BB	ER	MIN	MaM	DLHI khrs	NRLHI khrs	COSTI $M
STRUCTURE & DEVICES	183.6	396.7	17Ø.4	226.3	22.46	8.2	1.Ø	Ø.Ø	9Ø.8	356.Ø	195.6	2Ø.73
THERMAL, CABLING & PYRO	52.6	167.3	95.Ø	72.3	9.34	Ø.Ø	Ø.Ø	Ø.Ø	1ØØ.Ø	163.7	68.7	9.14
PROPULSION	16.2	25Ø.8	34.5	216.4	15.68	87.Ø	1.8	Ø.Ø	11.2	58.3	23.8	3.64
ATT & ART CONTROL	21.1	36Ø.Ø	122.3	237.7	21.Ø1	34.1	65.9	Ø.Ø	Ø.Ø	153.6	31.3	8.97
TELECOMMUNICATIONS	31.Ø	584.9	329.2	255.7	32.14	22.2	77.8	Ø.Ø	Ø.Ø	369.Ø	39.8	2Ø.27
ANTENNAS	9.1	194.4	91.2	1Ø3.2	11.Ø1	11.Ø	17.6	71.4	Ø.Ø	15Ø.1	58.9	8.5Ø
COMMAND & DATA HANDLING	53.3	94Ø.1	4Ø9.7	53Ø.4	47.22	24.6	75.4	Ø.Ø	Ø.Ø	489.6	65.Ø	24.6Ø
RTG POWER (W/O RTG'S)	35.5	38Ø.1	249.Ø	131.Ø	18.84	64.8	Ø.Ø	Ø.Ø	35.2	292.9	43.8	14.52
TOTAL HARDWARE	399.4	3274.2	15Ø1.2	1773.Ø	177.71					2Ø43.2	542.Ø	11Ø.36
(Percent Cost Reduction												37.9%)
SYSTEM SUPRT & GRND EQPT		1655.9			88.16					1Ø34.4		55.Ø7
LAUNCH+3ØDAYS & GRND S/W		526.2			29.72					325.8		18.4Ø
SCIENCE DATA DEVELOPMENT		83.6			6.98					51.Ø		4.26
PROGRAM MANAGEMENT/MA&E		573.7			29.24					361.4		18.42
TOTAL DEVELOPMENT		82Ø4.8			446.95					5Ø94.1		276.84
(Percent Cost Reduction												38.1%)

Figure 7. Cost Model Output for Outer Planet Probe Project

cost estimate for this project. "Science Development" refers only to the probe science since the carrier spacecraft has no science hardware. "Probe System" and "Carrier System" each include a portion of the System Support category prorated on the basis of total hardware cost. With contingency, the total development cost is estimated at $353 Million.

Table 13. Cost Summary for Outer Planet Probe Development Project

	FY1982 $M
Program Management/MA&E	18.4
Science Development	39.6
Probe System	56.4
Carrier System	144.0
RTG's	30.0
Launch + 30 Days Operations	18.4
Subtotal	306.8
APA/Reserve (@ 15%)	46.0
Total	352.9

6. Conclusions and Further Development

This report has discussed the effort involved in updating and revising the SAI Planetary Program Cost Model. The Model was updated to include data from the most recent U.S. planetary missions. It was functionally revised to increase its flexibility in application to the broader scope of mission/program scenarios under consideration in NASA's long-range plans. The Model can be directly applied to cost such diverse systems as inertial or spin stabilized spacecraft, atmospheric entry probes and highly autonomous soft landers, and therefore can more readily extrapolate to systems such as surface penetrators and rovers.

A detailed error analysis of the Model against the historical database indicated that, on average, it had captured the information in the database with an error of less than 10%. In its basic form, the Model was found to be highly sensitive to the number of hardware flight units and an adjustment procedure was developed to reduce this sensitivity. This procedure, however, raises the average error of the Model against the database to just less than 20%. Based on this result, application of 20% contingency is recommended for cost forecasts of project definitions which generally fall within the scope of those in the Model's database. For project definitions that are significantly different from those in the database, it must be left to the user to assess the Model's validity in generating a cost estimate and to apply an appropriate contingnecy to the estimate.

In addition to continuing collection and analysis of cost data from on-going projects, three major development efforts have been identified to complete the Model and further enhance its capabilities.

The first task is to complete the model revision effort by developing new algorithms for estimating costs of mission operations and data analysis. Although historical costs will be used as guidelines, these new algorithms must take into account the expected effects of planned cost reducing procedures such as the multi-mission end-to-end information system and reduced cruise phase activity.

The second effort would involve updating the inheritance algorithm with a more systematic determination of the numerical weighting factors used in the algorithm. The factors currently in use represent best estimates of appropriate values. The update will be accomplished by analyzing cost data from past projects which are known to have benefitted from hardware design heritage.

The final task, related to capabilities enhancement, would be to develop a new, analytical model to transform a point cost estimate into annual funding levels. Such a model should account separately for the different phases of a project, e.g. hardware development versus flight operations. It must also be capable of dealing with the wide variety of project implementation scenarios, which can range from relatively simple Pioneer-class projects to highly complex Viking-class projects.

References

1. Pekar, P., A. Friedlander and D. Roberts, "Manpower/Cost Estimation Model for Automated Planetary Projects", Science Applications, Inc., September 1973.

2. Kitchen, L. D., "Manpower/Cost Estimation Model for Automated Planetary Programs - 2", Report No. SAI 1-120-399-C2, Science Applications, Inc., April 1976.

3. Jet Propulsion Laboratory, "Galileo Project Management Report", JPL 1625-92, October 1980.

4. Jet Propulsion Laboratory, "Venus Orbital Imaging Radar: Cost Review", JPL 720-18, June 1978.

5. Jet Propulsion Laboratory, "Comet Rendezvous Development Project: OSS Program Review", JPL 720-32, April 1979.

APPENDIX A

DETAILED COST DATABASE

Appendix A

Detailed Cost Database

Due to the proprietary nature of the data, this appendix is not included in copies of this report intended for distribution external to the National Aeronautics and Space Administration.

APPENDIX B

DETAILED DESCRIPTION OF COST MODEL ALGORITHMS

Appendix B

Detailed Description of Cost Model Algorithms

The individual algorithms which comprise the SAI Planetary Program Cost Model are presented in this appendix in both graphical and functional forms. The function plots also exhibit the data from which the functions were fitted. Statistics associated with the curve fitting process are also shown.

For the hardware-related cost categories, the total labor (DLH) function is presented with the respective recurring labor (RLH) function on the facing page. Labor to cost conversion factors are shown for the total labor functions only.

The test statistics associated with the fitted functions include the correlation coefficient, the t statistics of the estimated coefficients, and the mean percentage error and mean absolute percentage error as defined in Section 3.3 of the report.

The axes of the function plots are not labeled because of the proprietary nature of the sample data. Note, however, that the scaling of each recurring labor plot is the same as its respective total labor plot.

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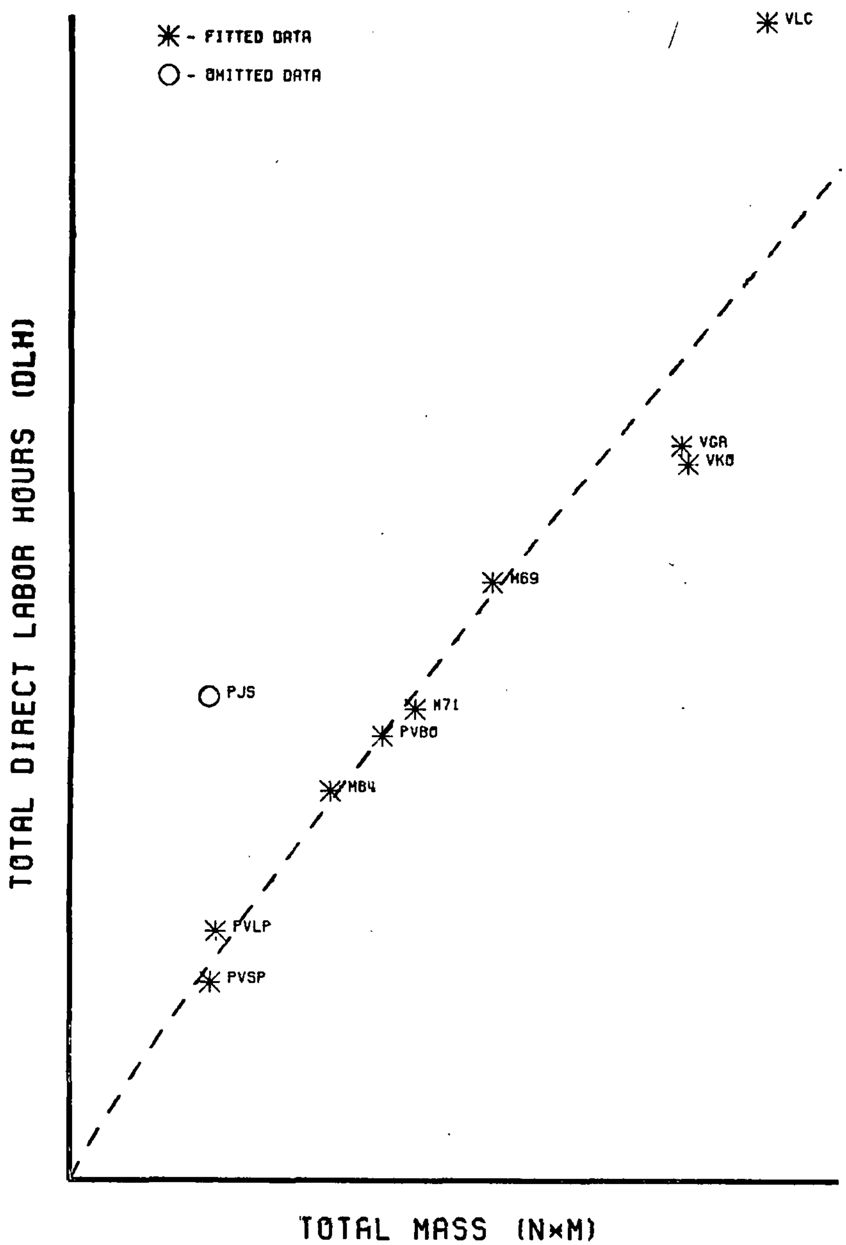
Index to Algorithms

STRUCTURE & DEVICES



TOTAL DIRECT LABOR FUNCTION

$$DLH = 1.629 \times (N \times M)^{0.9046}$$

STATISTICS

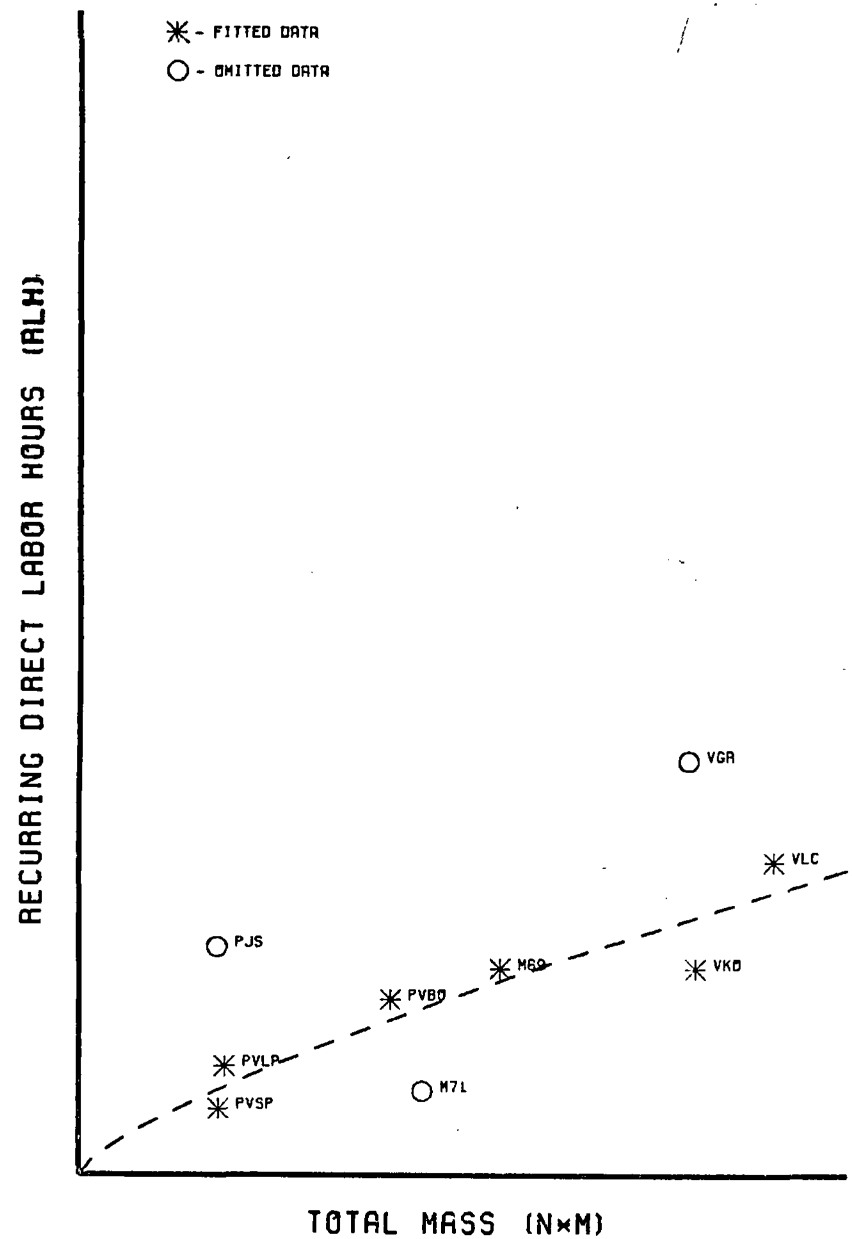
SAMPLE SIZE	9
CORRELATION COEFFICIENT	0.978
T STATISTIC (1.629)	1.16
T STATISTIC (0.9046)	12.40
MEAN PERCENT ERROR	-0.6
MEAN ABSOLUTE PERCENT ERROR	8.4

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.45/HR

LABOR COST TO TOTAL COST : 3.303

STRUCTURE & DEVICES



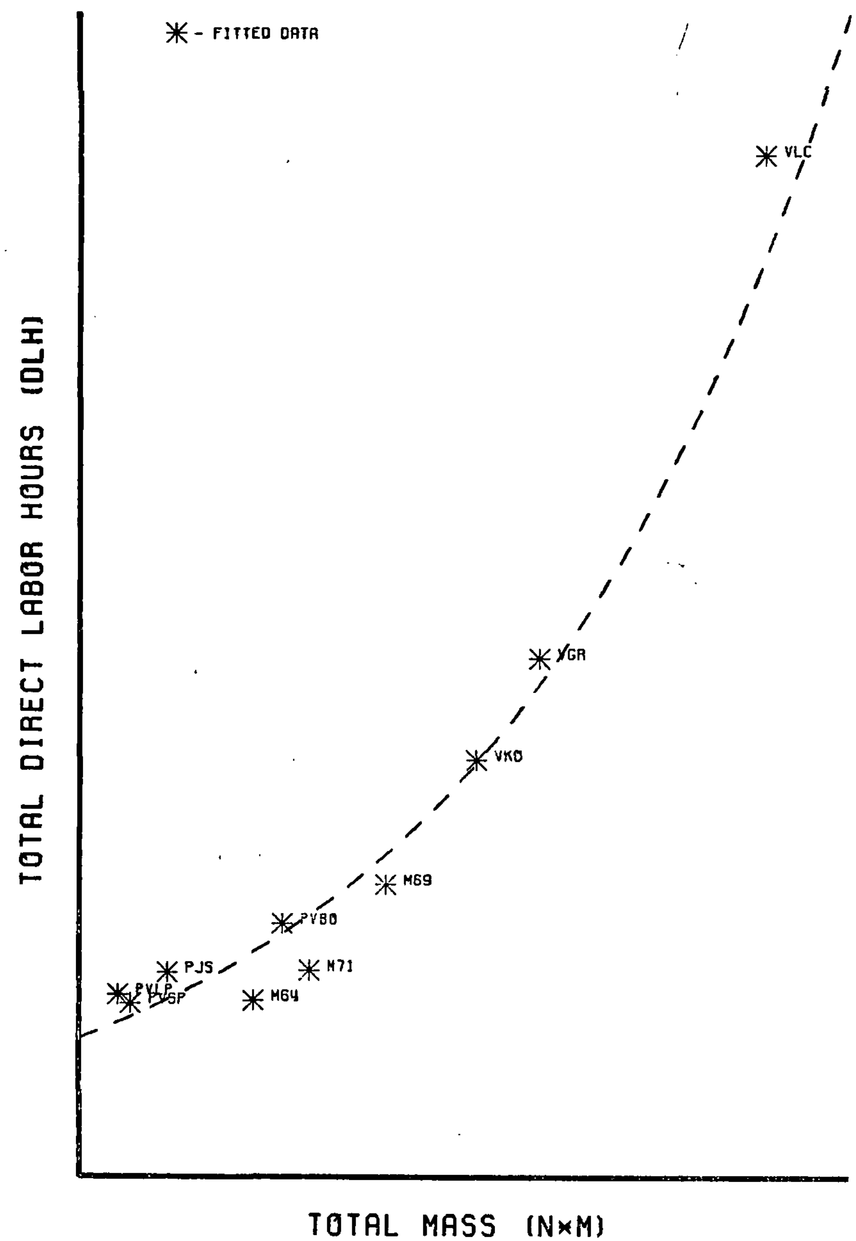
RECURRING DIRECT LABOR FUNCTION

$RLH = 1.399 \times (N \times M)^{0.7445}$

STATISTICS

SAMPLE SIZE	6
CORRELATION COEFFICIENT	0.935
T STATISTIC (1.399)	0.42
T STATISTIC (0.7445)	5.28
MEAN PERCENT ERROR	-1.7
MEAN ABSOLUTE PERCENT ERROR	16.8

THERMAL CONTROL, CABLING & PYROTECHNICS



TOTAL DIRECT LABOR FUNCTION

$$DLH = EXP(4.27 + 0.0061 \times N \times M)$$

STATISTICS

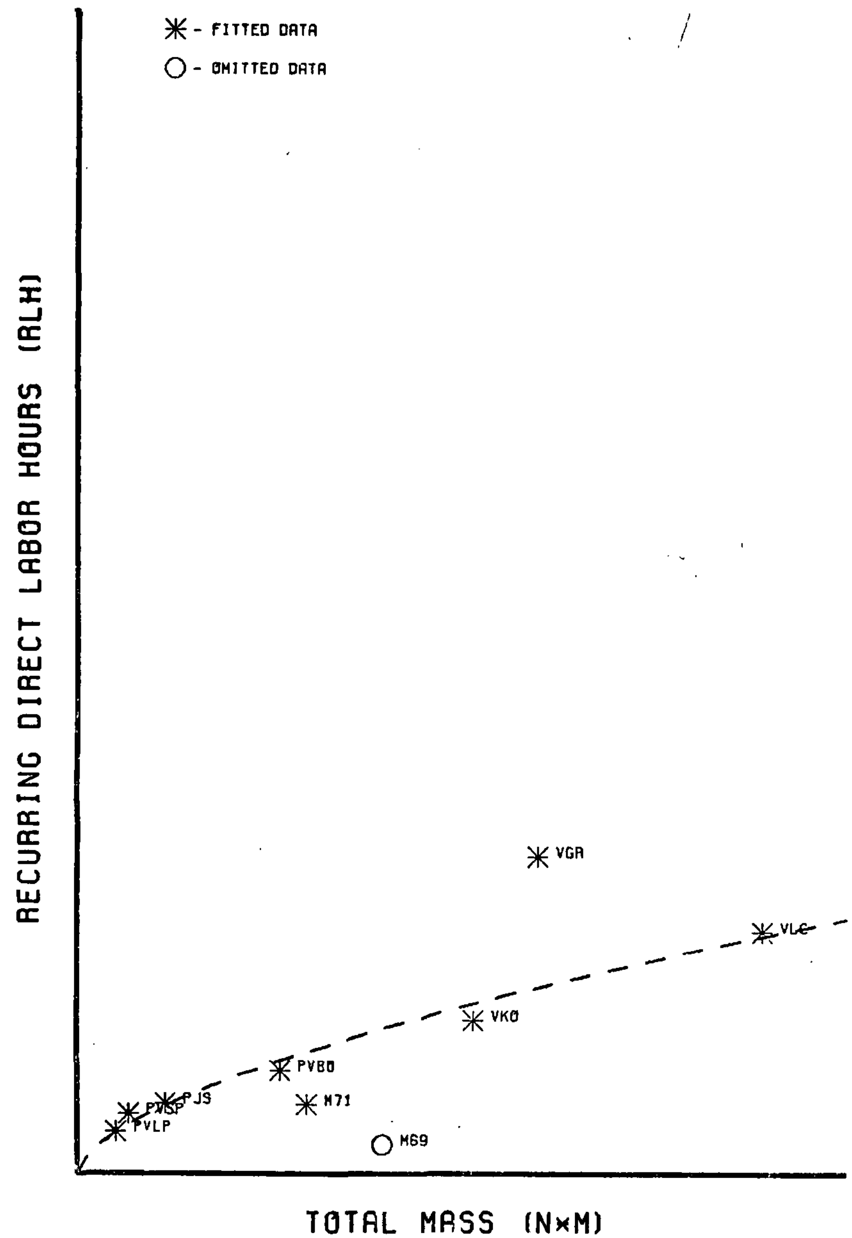
SAMPLE SIZE	10
CORRELATION COEFFICIENT	0.968
T STATISTIC (4.27)	51.48
T STATISTIC (0.0061)	10.88
MEAN PERCENT ERROR	-1.0
MEAN ABSOLUTE PERCENT ERROR	15.6

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.26/HR

LABOR COST TO TOTAL COST : 3.317

THERMAL CONTRØL, CABLING & PYRØTECHNICS



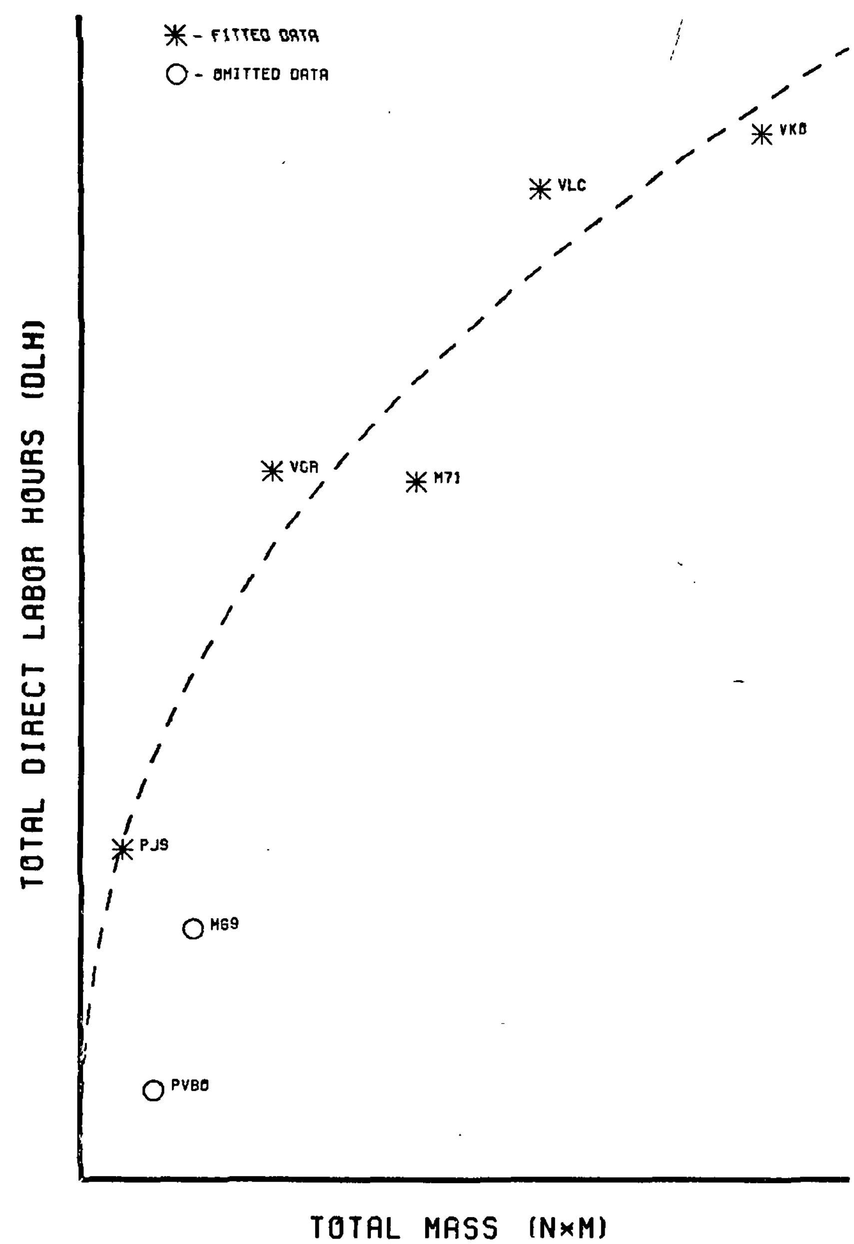
RECURRING DIRECT LABØR FUNCTIØN

$RLH = 3.731 \times (N \times M)^{0.6082}$

STATISTICS

SAMPLE SIZE	8
CØRRELATIØN COEFFICIENT	0.902
T STATISTIC (3.731)	2.46
T STATISTIC (0.6082)	5.11
MEAN PERCENT ERRØR	-4.4
MEAN ABSØLUTE PERCENT ERRØR	20.3

PROPULSION



TOTAL DIRECT LABOR FUNCTION

$$DLH = 56.188 * (N \times M)^{0.4166}$$

STATISTICS

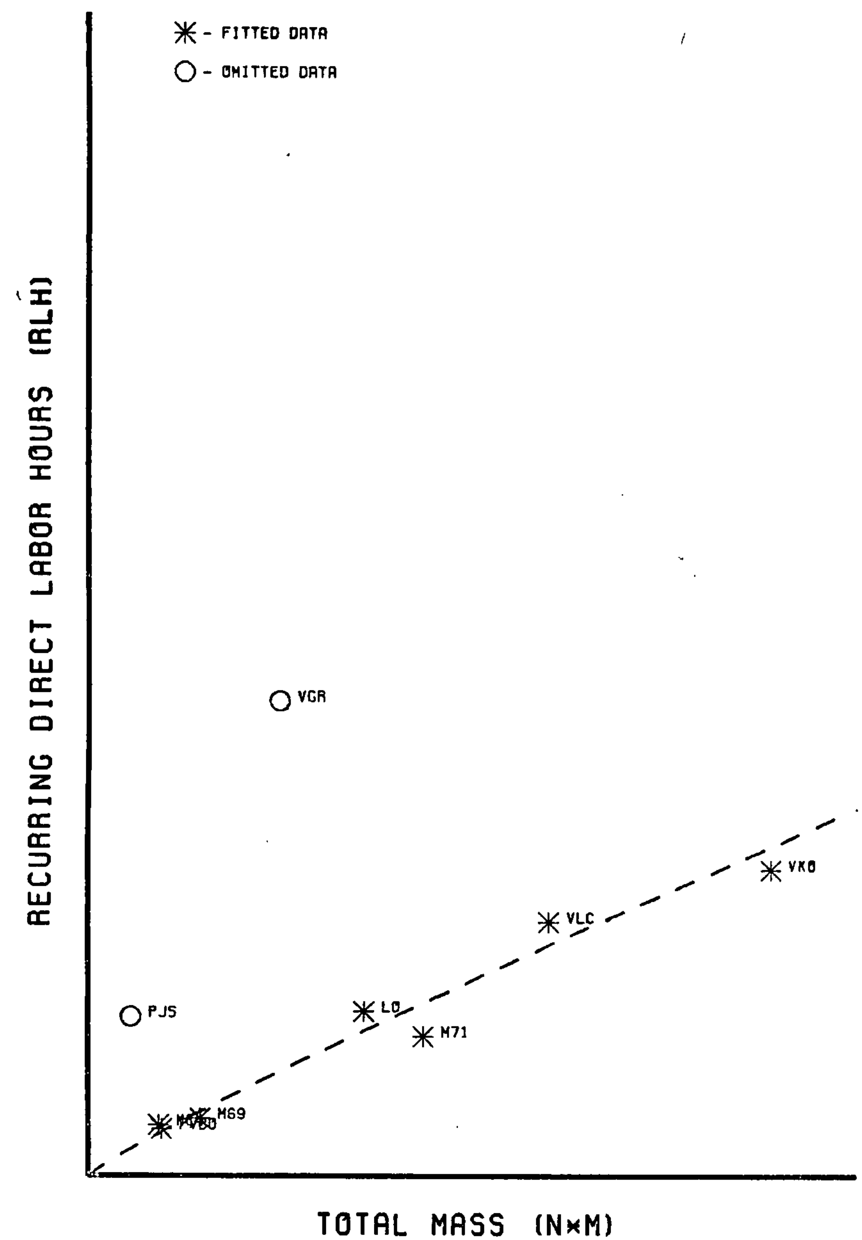
SAMPLE SIZE	5
CORRELATION COEFFICIENT	0.977
T STATISTIC (56.188)	15.49
T STATISTIC (0.4166)	7.90
MEAN PERCENT ERROR	-0.4
MEAN ABSOLUTE PERCENT ERROR	7.7

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.54/HR

LABOR COST TO TOTAL COST : 3.616

PROPULSION



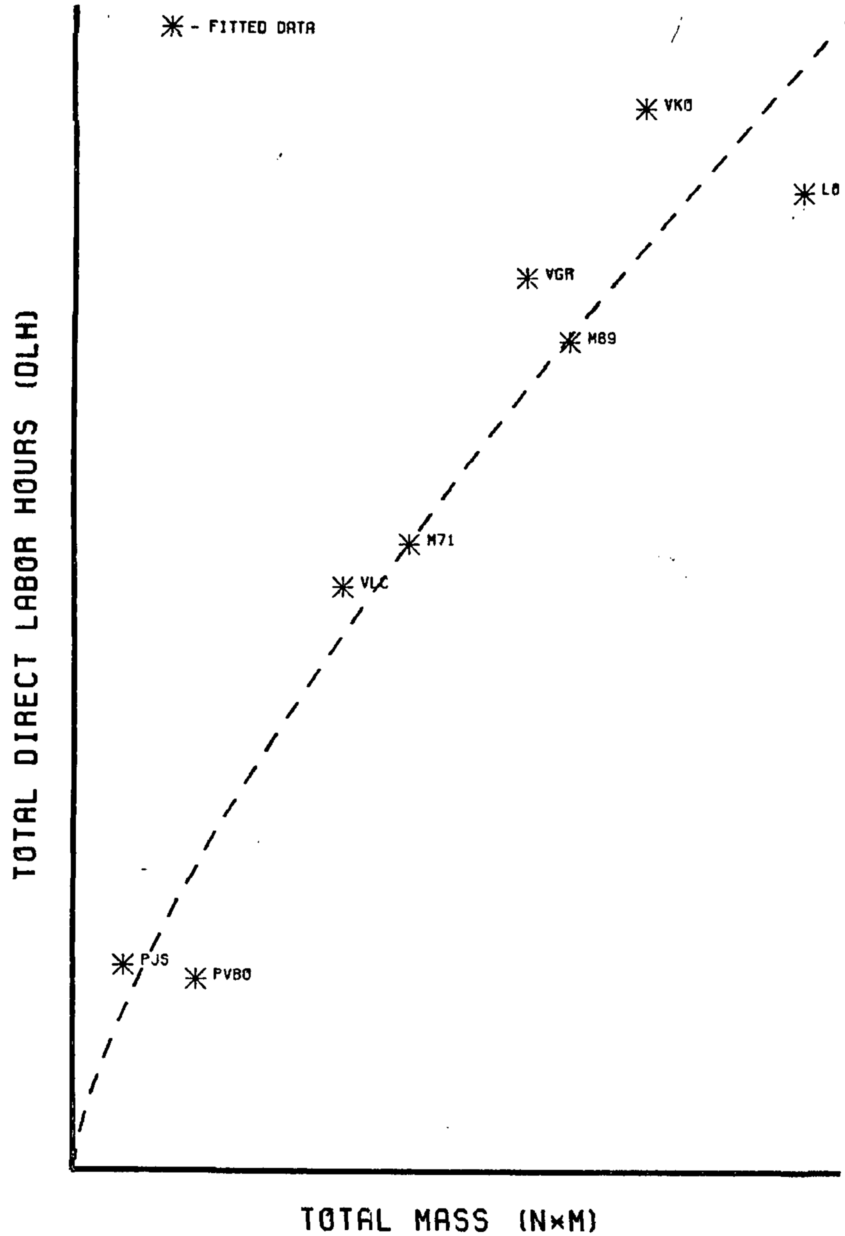
RECURRING DIRECT LABOR FUNCTION

$RLH = 1.0 \times (N \times M)^{0.9011}$

STATISTICS

SAMPLE SIZE ———————— 7
CORRELATION COEFFICIENT ——— 0.988
T STATISTIC (0.9011) ———— 93.35
MEAN PERCENT ERROR ————— -0.2
MEAN ABSOLUTE PERCENT ERROR — 11.2

ATTITUDE & ARTICULATION CONTROL



TOTAL DIRECT LABOR FUNCTION

$$DLH = 21.328 \times (N \times M)^{0.7230}$$

STATISTICS

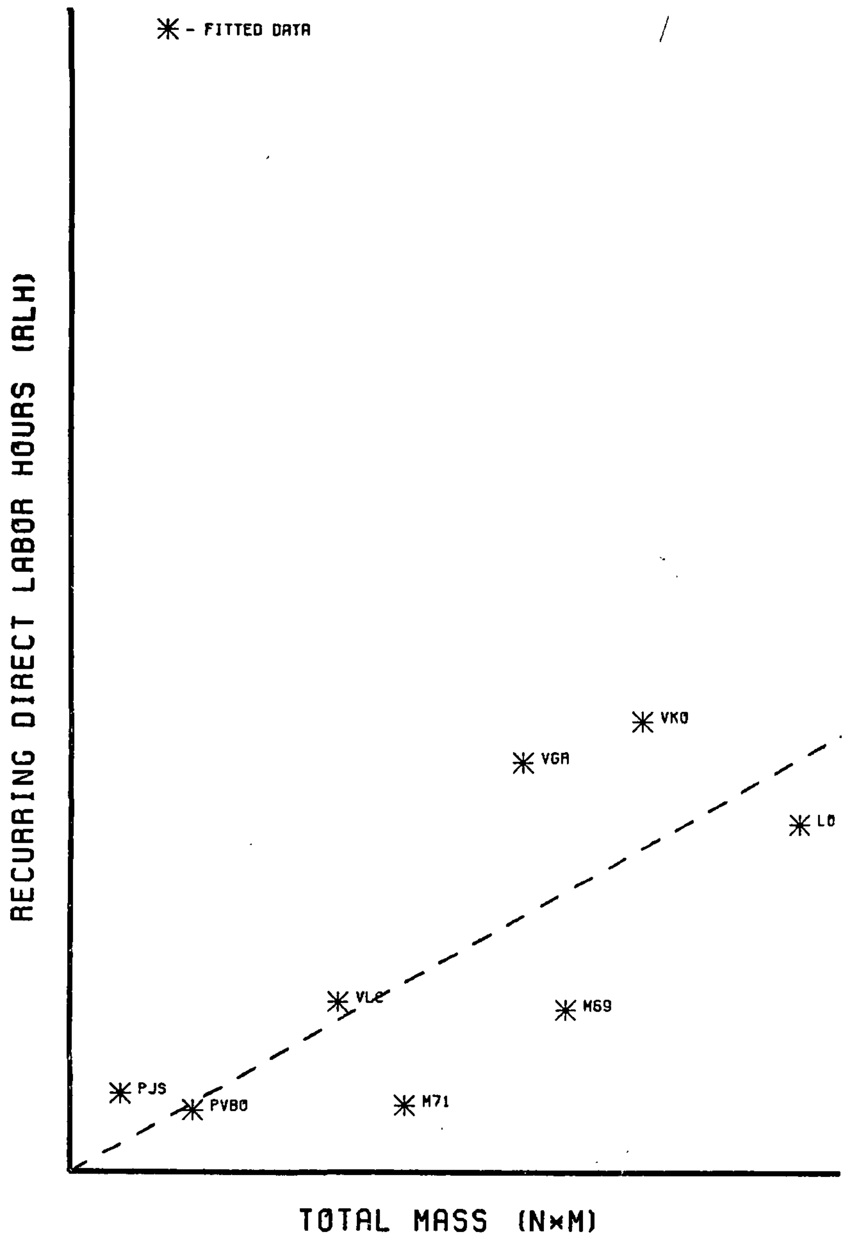
SAMPLE SIZE	8
CORRELATION COEFFICIENT	0.947
T STATISTIC (21.328)	7.17
T STATISTIC (0.7230)	7.24
MEAN PERCENT ERROR	-2.3
MEAN ABSOLUTE PERCENT ERROR	16.1

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.63/HR

LABOR COST TO TOTAL COST : 3.347

ATTITUDE & ARTICULATION CONTROL



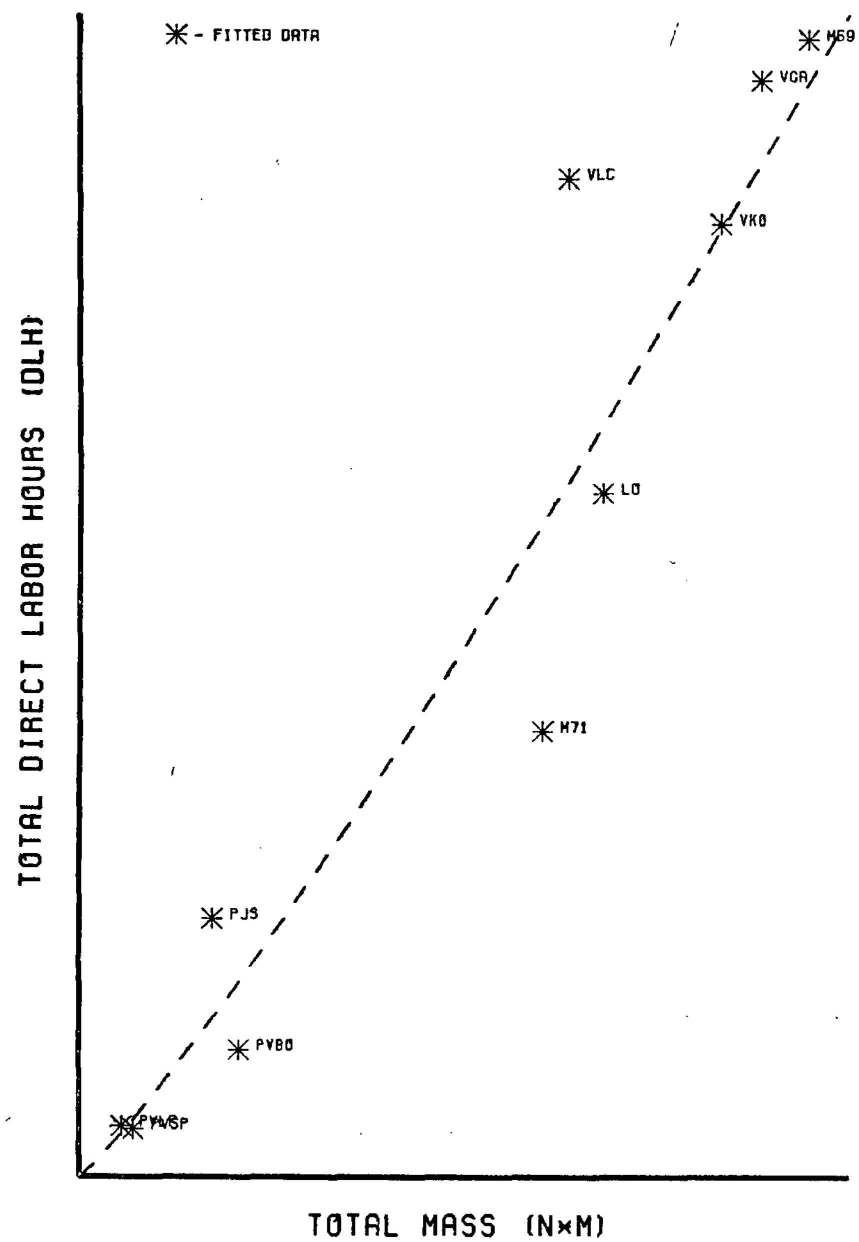
RECURRING DIRECT LABOR FUNCTION

RLH = 1.9317 × (N×M)

STATISTICS

SAMPLE SIZE ————————	8
CORRELATION COEFFICIENT ———	0.760
T STATISTIC (1.9317) ————	6.68
MEAN PERCENT ERROR —————	-18.7
MEAN ABSOLUTE PERCENT ERROR ——	53.6

TELECOMMUNICATIONS



TOTAL DIRECT LABOR FUNCTION

$DLH = 4.471 \times (N \times M)^{1.1306}$

STATISTICS

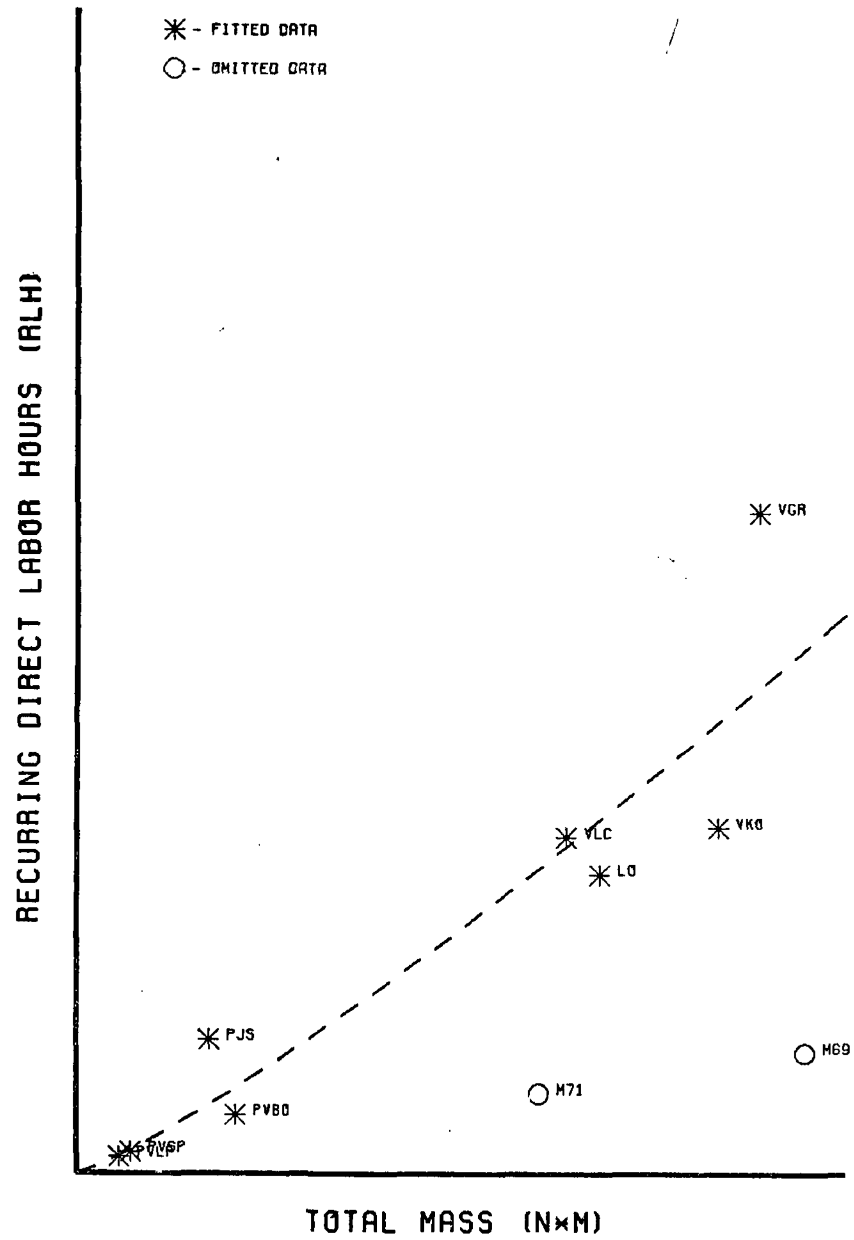
SAMPLE SIZE	10
CORRELATION COEFFICIENT	0.972
T STATISTIC (4.471)	4.04
T STATISTIC (1.1306)	11.80
MEAN PERCENT ERROR	-3.9
MEAN ABSOLUTE PERCENT ERROR	22.6

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $ 9.99/HR

LABOR COST TO TOTAL COST : 3.352

TELECOMMUNICATIONS



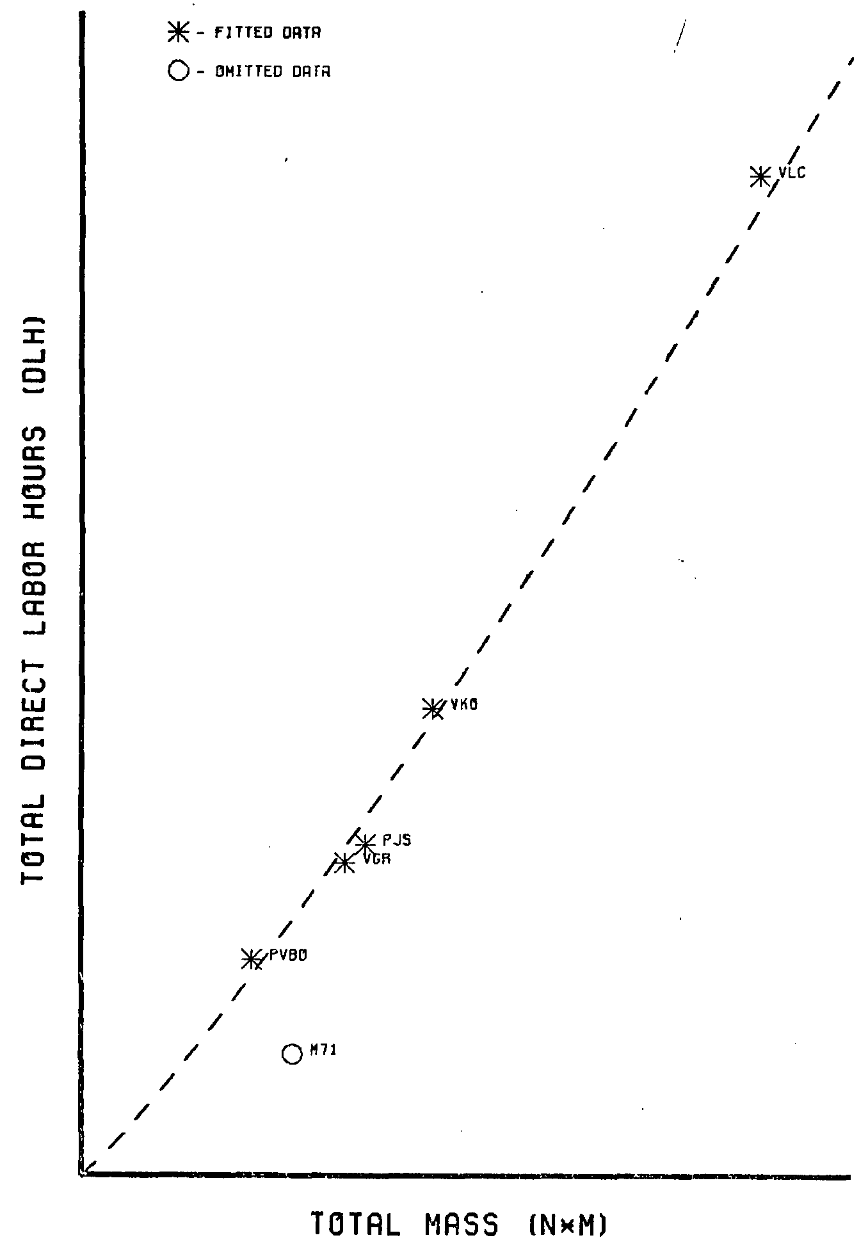
RECURRING DIRECT LABOR FUNCTION

$RLH = 1.626 * (N*M)^{1.1885}$

STATISTICS

SAMPLE SIZE	8
CORRELATION COEFFICIENT	0.970
T STATISTIC (1.626)	1.08
T STATISTIC (1.1885)	9.74
MEAN PERCENT ERROR	-4.6
MEAN ABSOLUTE PERCENT ERROR	23.9

ANTENNAS



TOTAL DIRECT LABOR FUNCTION

$DLH = 6.093 * (N*M)^{1.1348}$

STATISTICS

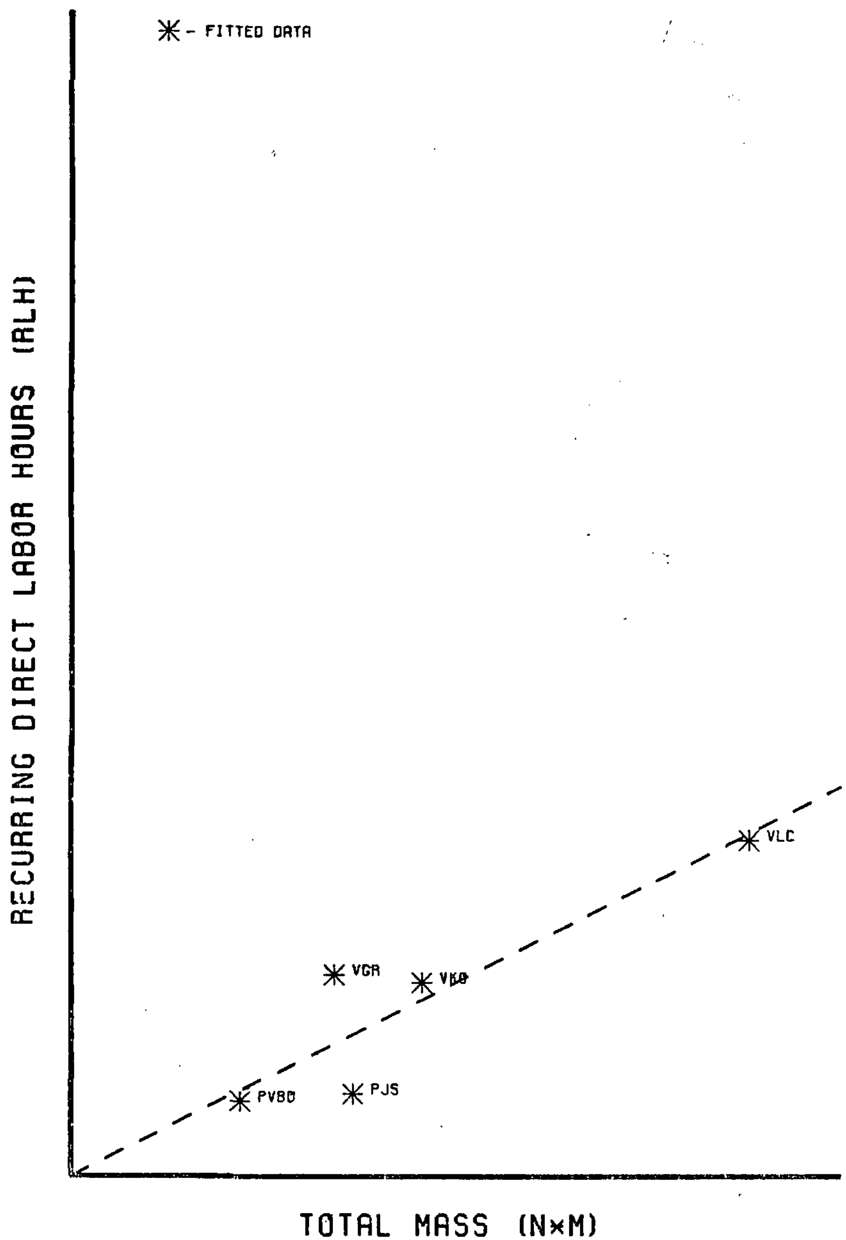
SAMPLE SIZE —————————— 5
CORRELATION COEFFICIENT ——— 0.994
T STATISTIC (6.093) —————— 9.91
T STATISTIC (1.1348) ————— 15.80
MEAN PERCENT ERROR —————— -0.2
MEAN ABSOLUTE PERCENT ERROR —— 5.2

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $ 9.96/HR

LABOR COST TO TOTAL COST : 3.466

ANTENNAS



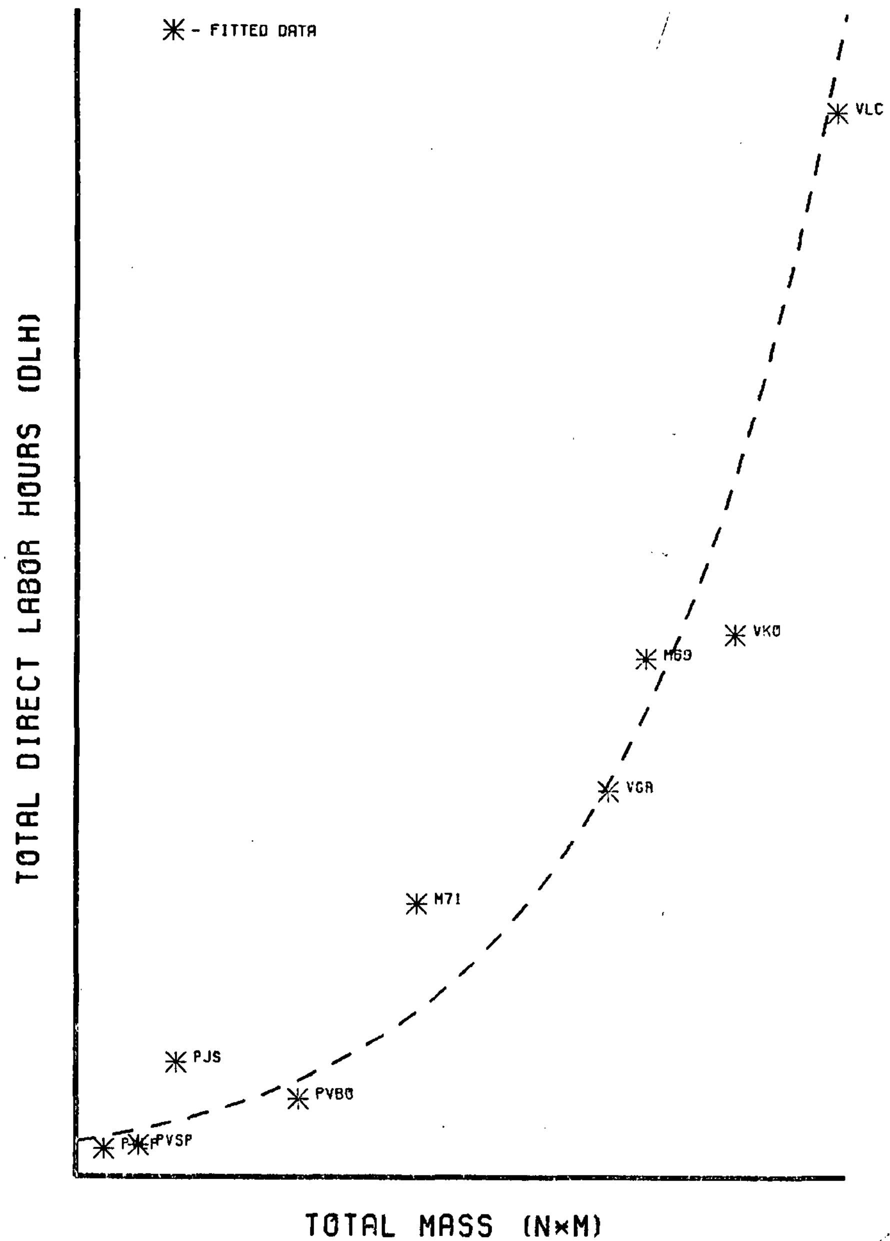
RECURRING DIRECT LABOR FUNCTION

RLH = 3.339 × (N×M)

STATISTICS

SAMPLE SIZE	5
CORRELATION COEFFICIENT	0.898
T STATISTIC (3.339)	9.41
MEAN PERCENT ERROR	-9.2
MEAN ABSOLUTE PERCENT ERROR	26.3

COMMAND & DATA HANDLING



TOTAL DIRECT LABOR FUNCTION

DLH = EXP (4.26 + 0.0241 * N×M)

STATISTICS

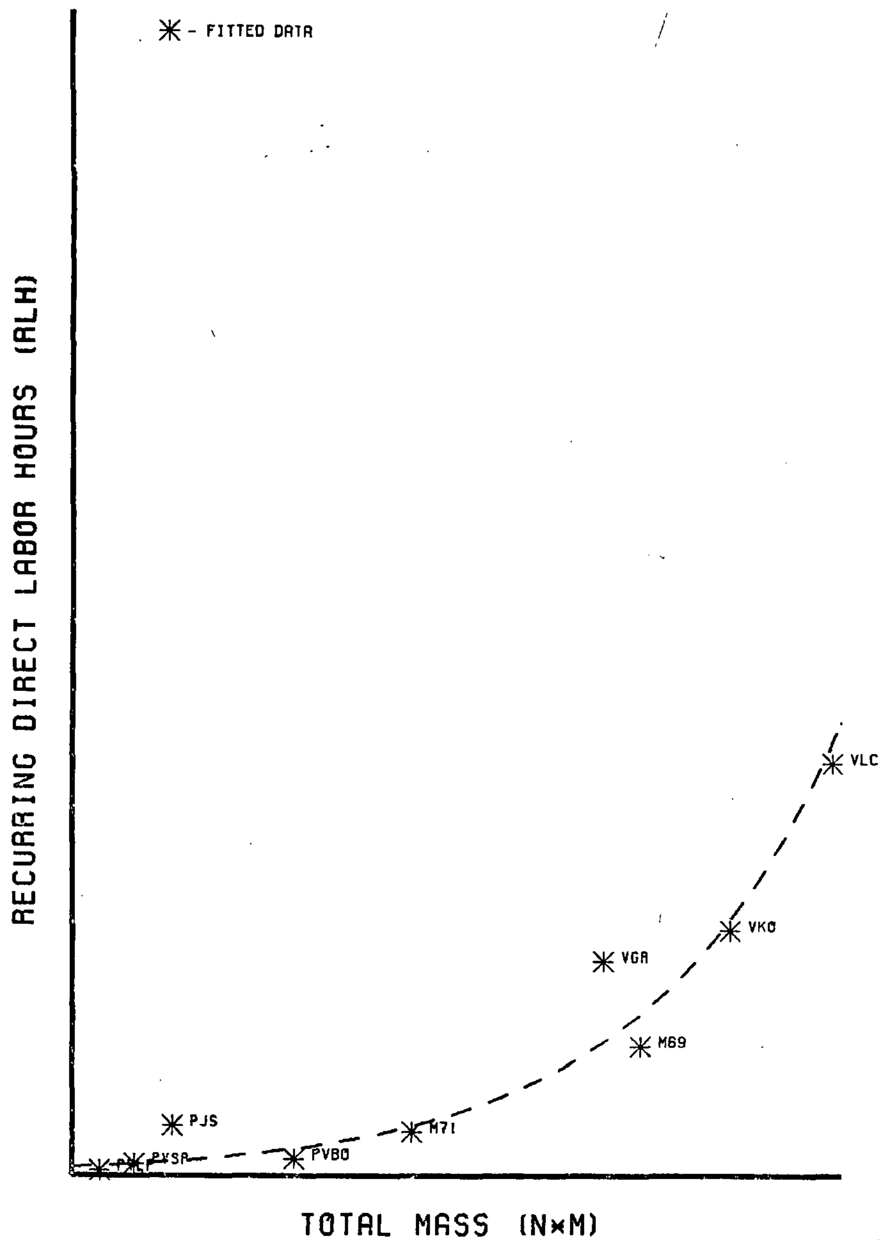
SAMPLE SIZE	9
CORRELATION COEFFICIENT	0.956
T STATISTIC (4.26)	18.00
T STATISTIC (0.0241)	8.59
MEAN PERCENT ERROR	-6.1
MEAN ABSOLUTE PERCENT ERROR	28.5

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $ 9.68/HR

LABOR COST TO TOTAL COST : 3.163

COMMAND & DATA HANDLING



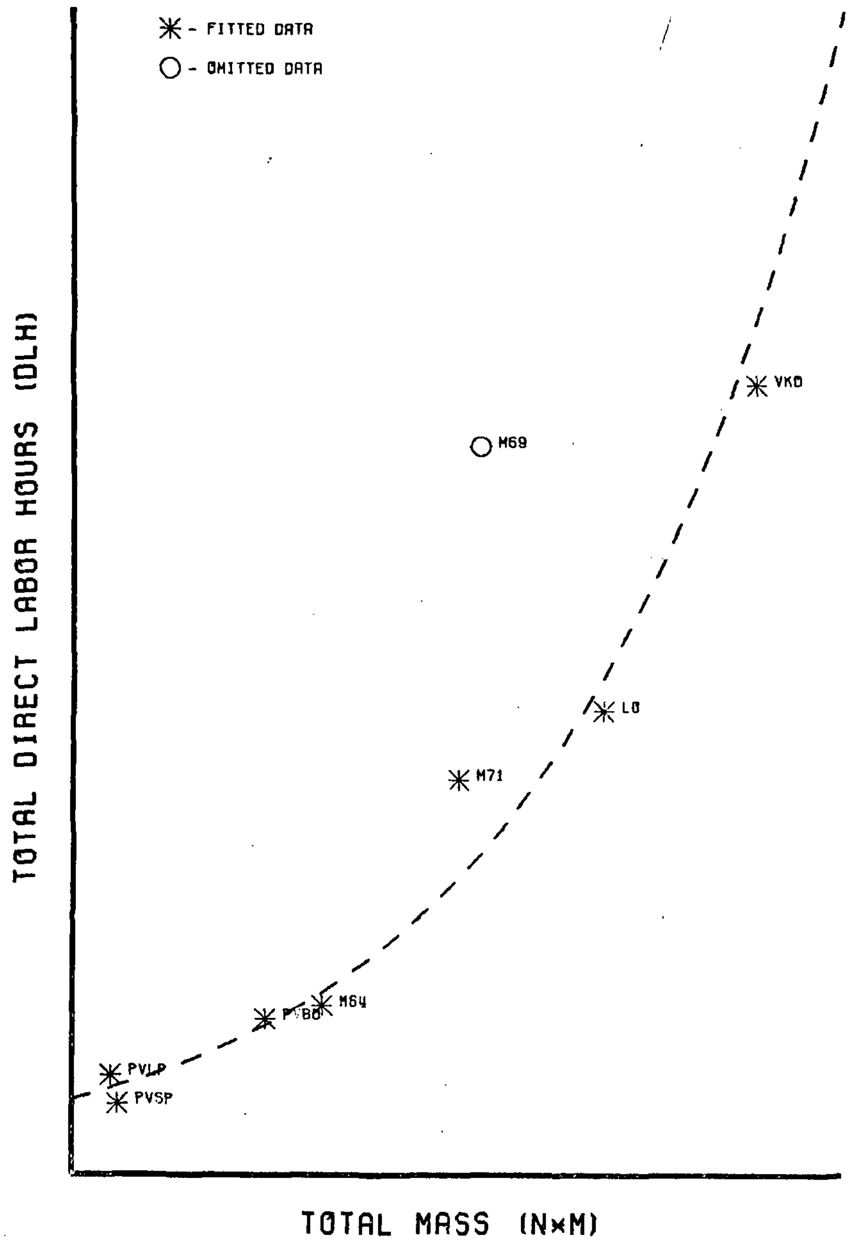
RECURRING DIRECT LABOR FUNCTION

RLH = EXP(2.868 + 0.02726 × N×M)

STATISTICS

SAMPLE SIZE	9
CORRELATION COEFFICIENT	0.930
T STATISTIC (2.868)	8.34
T STATISTIC (0.02726)	6.67
MEAN PERCENT ERROR	-12.4
MEAN ABSOLUTE PERCENT ERROR	36.5

SOLAR/BATTERY POWER



TOTAL DIRECT LABOR FUNCTION

DLH = EXP (3.963 + 0.00911 × N×M)

STATISTICS

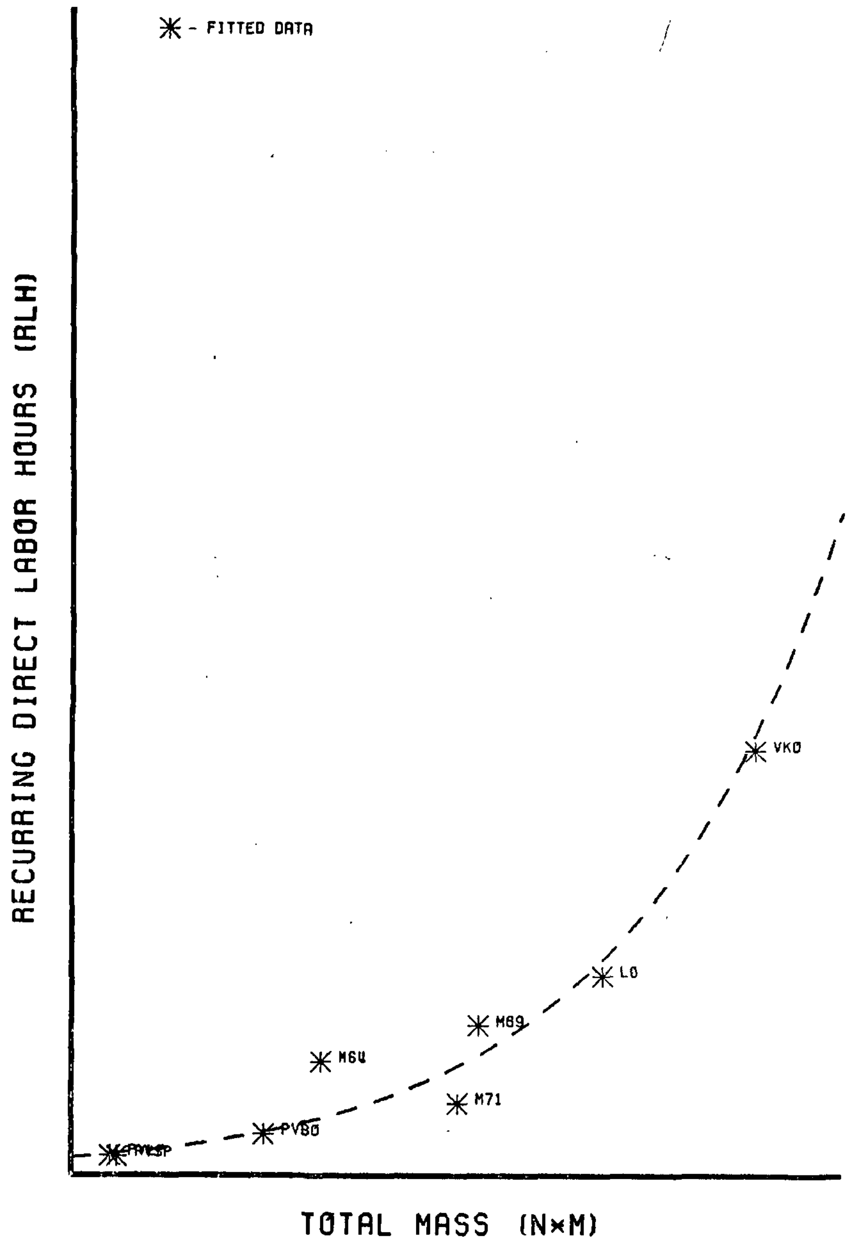
SAMPLE SIZE	7
CORRELATION COEFFICIENT	0.982
T STATISTIC (3.963)	34.34
T STATISTIC (0.00911)	11.61
MEAN PERCENT ERROR	-1.1
MEAN ABSOLUTE PERCENT ERROR	12.7

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.41/HR

LABOR COST TO TOTAL COST : 3.148

SØLAR/BATTERY PØWER



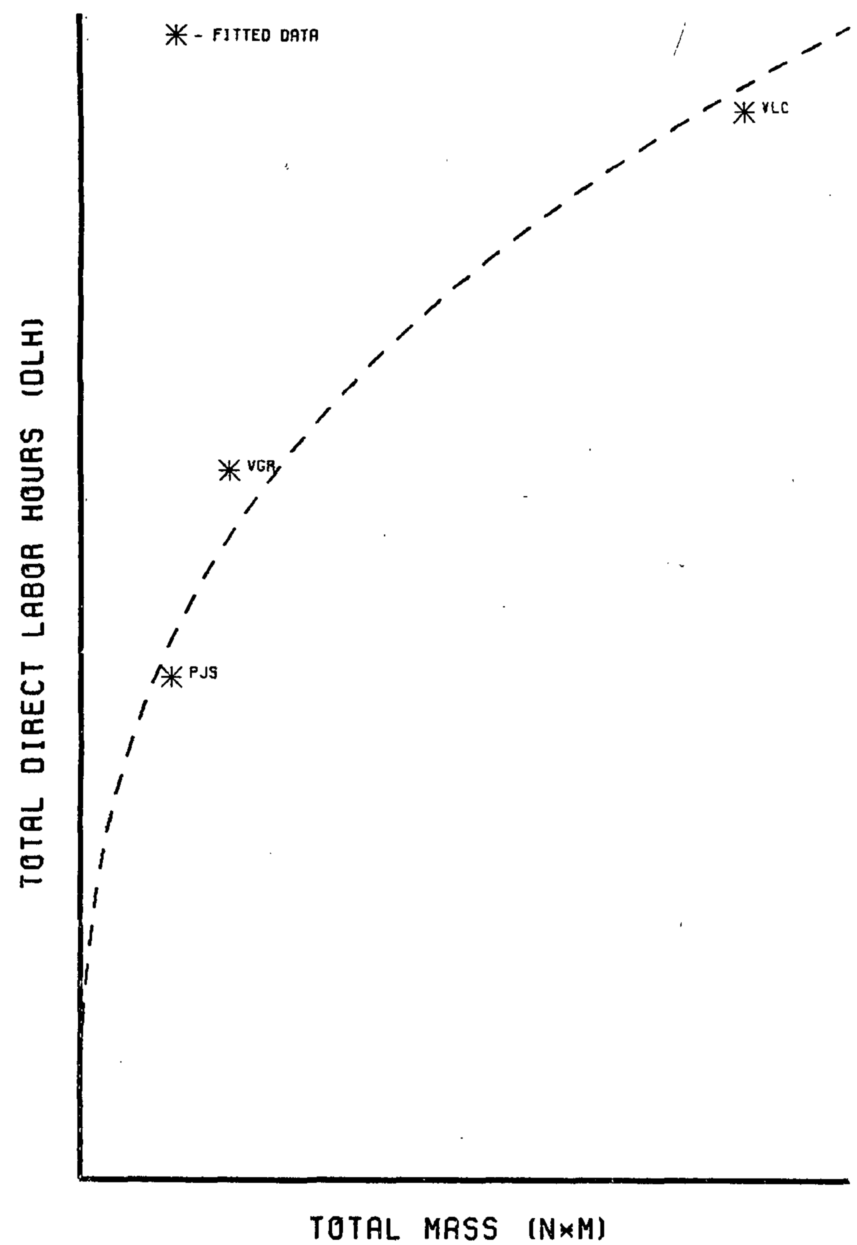
RECURRING DIRECT LABØR FUNCTIØN

RLH = EXP (2.518 + 0.01204 × N×M)

STATISTICS

SAMPLE SIZE ———————————— 8
CØRRELATIØN CØEFFICIENT ——— 0.958
T STATISTIC (2.518) ————— 11.45
T STATISTIC (0.01204) ———— 8.13
MEAN PERCENT ERRØR —————— -4.2
MEAN ABSØLUTE PERCENT ERRØR —— 21.3

RTG POWER



TOTAL DIRECT LABOR FUNCTION

$$DLH = 65.30 \times (N \times M)^{0.3554}$$

STATISTICS

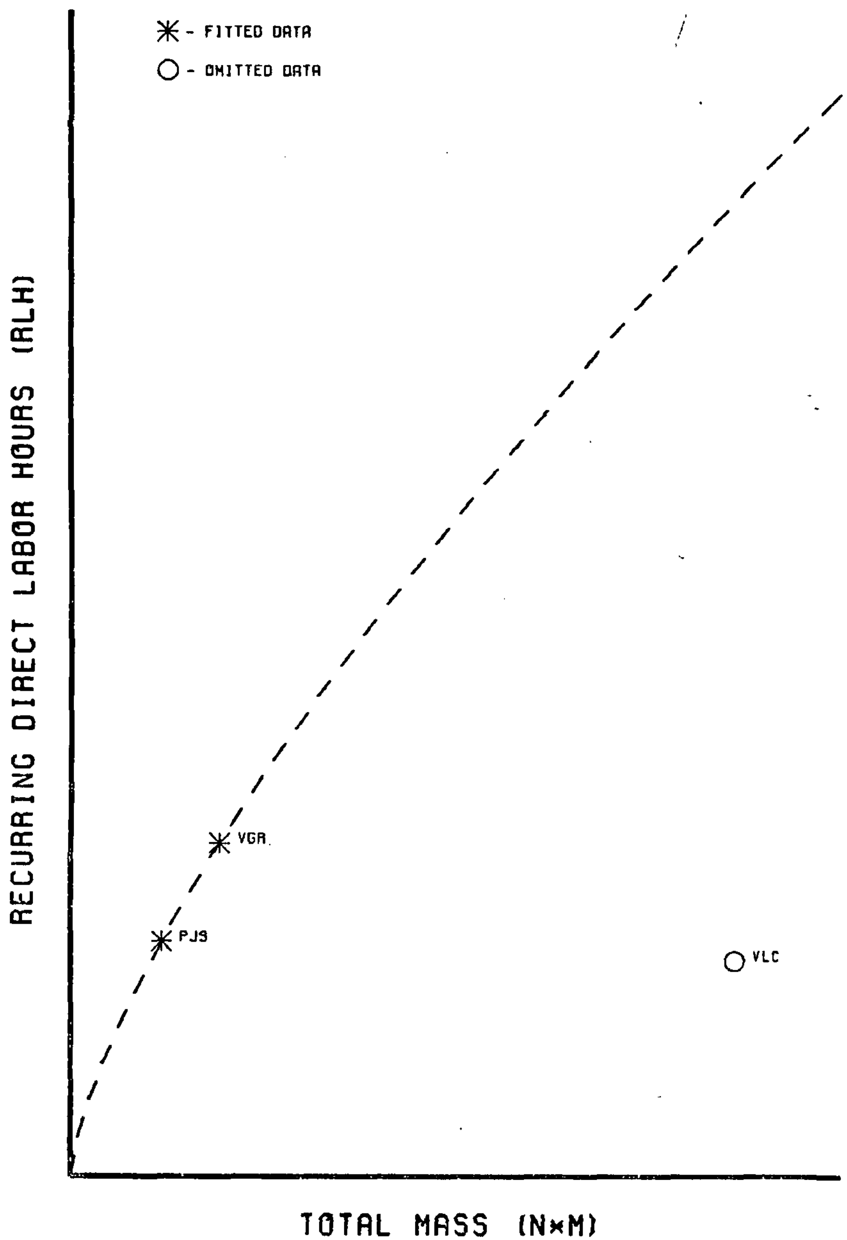
SAMPLE SIZE ——————————— 3
CORRELATION COEFFICIENT ——— 0.973
T-STATISTIC (65.30) ————— 11.06
T STATISTIC (0.3554) ———— 4.21
MEAN PERCENT ERROR —————— -0.1
MEAN ABSOLUTE PERCENT ERROR -- 6.3

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $ 9.51/HR

LABOR COST TO TOTAL COST : 3.177

RTG POWER



RECURRING DIRECT LABOR FUNCTION

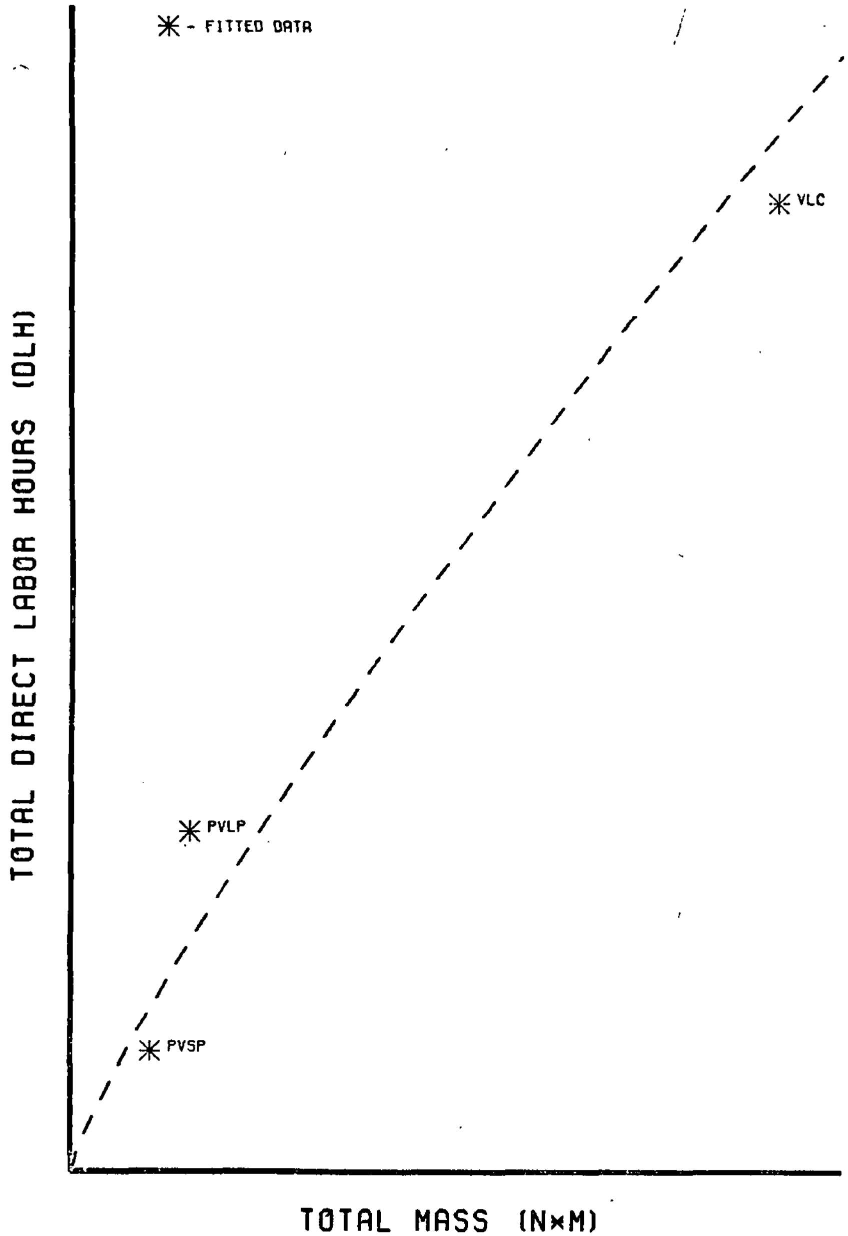
$RLH = 7.88 \times (N \times M)^{0.715}$

STATISTICS

SAMPLE SIZE —————————— 2
CORRELATION COEFFICIENT ——— 1.0
T STATISTIC (7.88) —————— *
T STATISTIC (0.715) ————— *
MEAN PERCENT ERROR —————— 0.0
MEAN ABSOLUTE PERCENT ERROR — 0.0

* T statistics are indeterminate

AERODECLERATION MODULE



TOTAL DIRECT LABOR FUNCTION

$DLH = 3.481 \times (N \times M)^{0.8416}$

STATISTICS

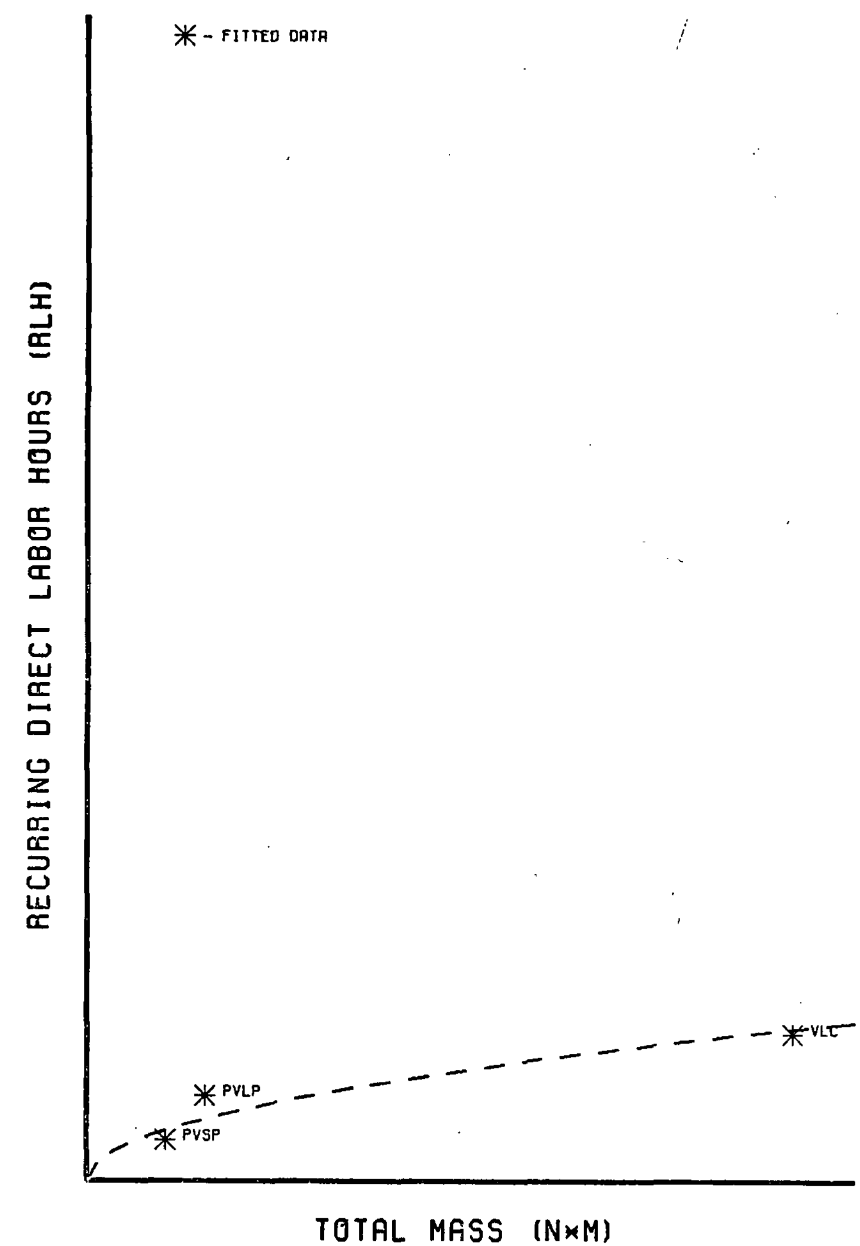
SAMPLE SIZE	3
CORRELATION COEFFICIENT	0.941
T STATISTIC (3.481)	0.79
T STATISTIC (0.8416)	2.78
MEAN PERCENT ERROR	-4.3
MEAN ABSOLUTE PERCENT ERROR	25.3

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.73/HR

LABOR COST TO TOTAL COST : 3.296

AERODECELERATION MODULE



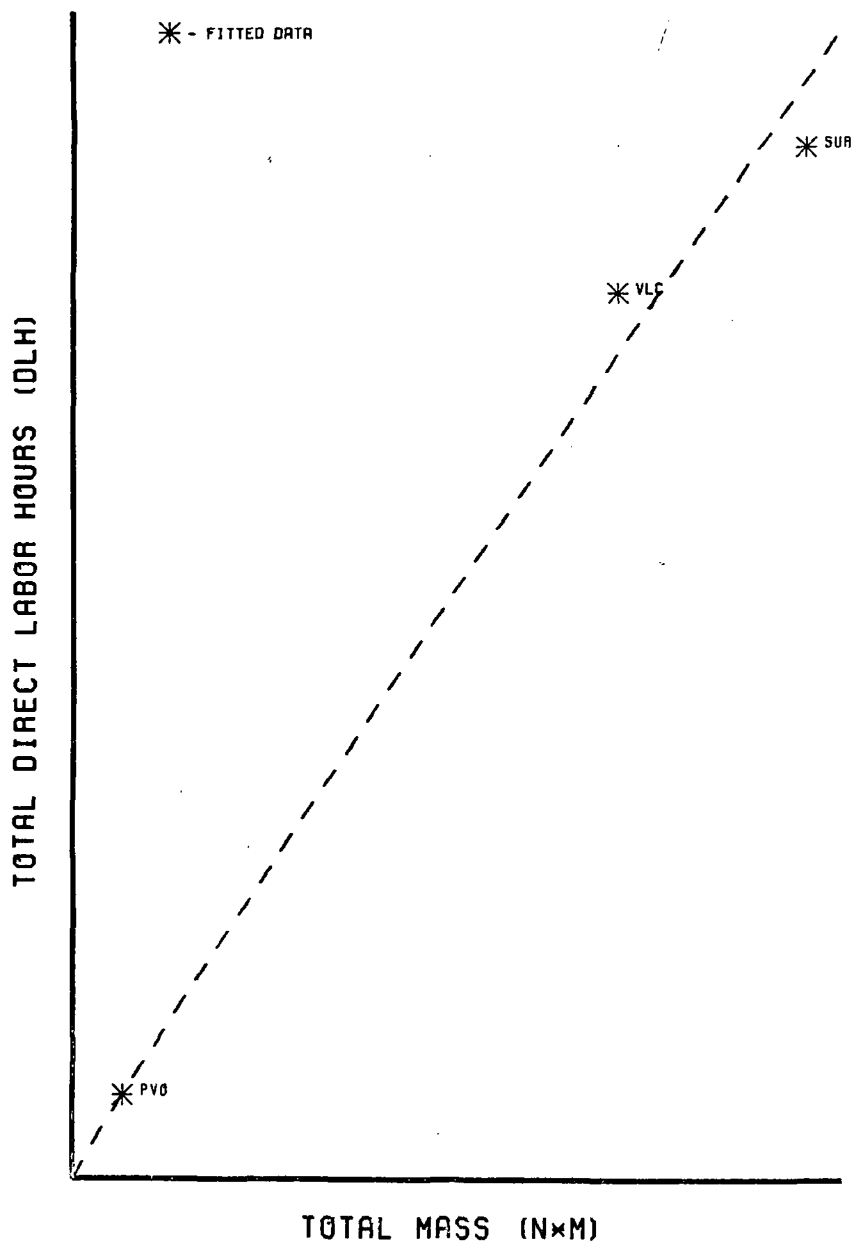
RECURRING DIRECT LABOR FUNCTION

RLH = 4.662 * SQRT (N*M)

STATISTICS

SAMPLE SIZE	3
CORRELATION COEFFICIENT	0.943
T STATISTIC (4.662)	9.74
MEAN PERCENT ERROR	-0.8
MEAN ABSOLUTE PERCENT ERROR	18.2

LANDING RADAR/ALTIMETER



TOTAL DIRECT LABOR FUNCTION

$DLH = 11.409 \times (N \times M)^{0.9579}$

STATISTICS

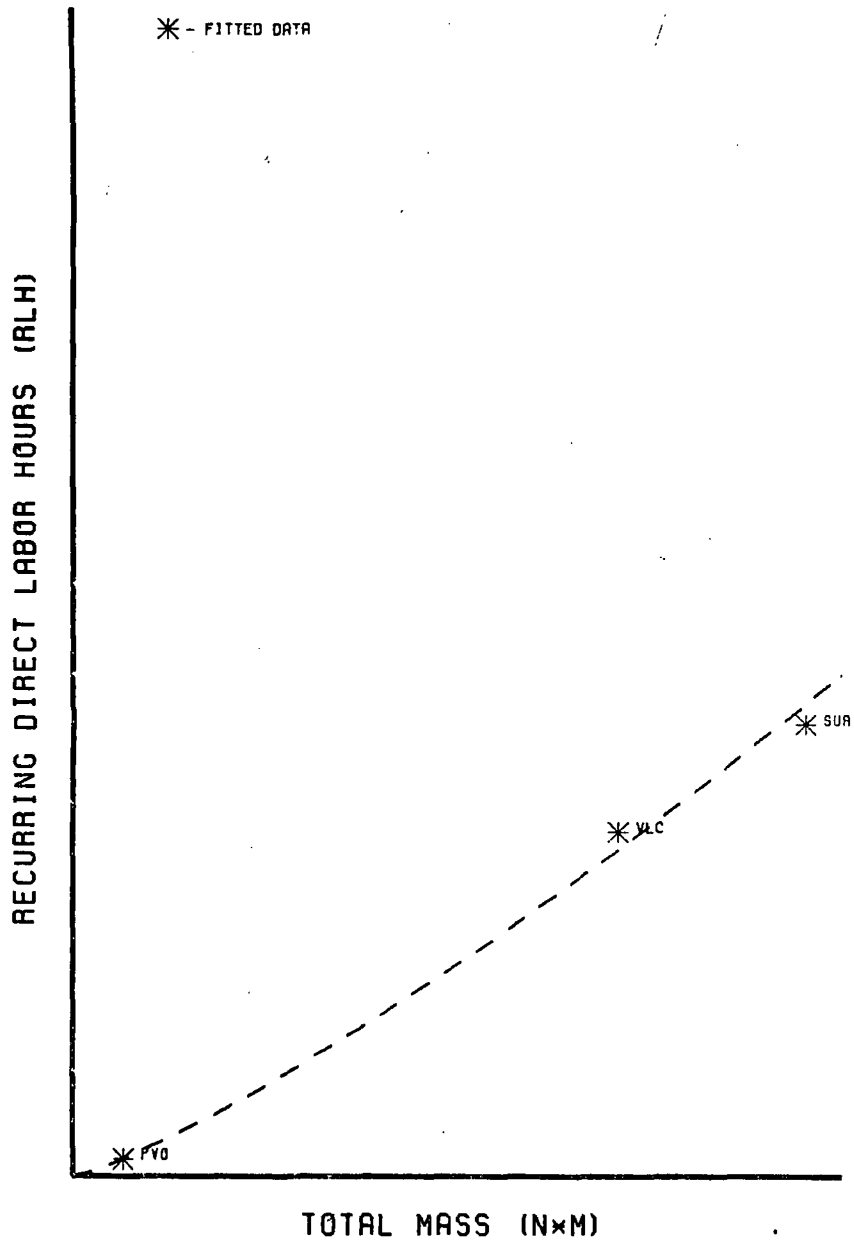
SAMPLE SIZE ---------------------- 3
CORRELATION COEFFICIENT ------ 0.999
T STATISTIC (11.409) --------- 13.19
T STATISTIC (0.9579) --------- 21.51
MEAN PERCENT ERROR ----------- -0.2
MEAN ABSOLUTE PERCENT ERROR -- 4.6

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.08/HR

LABOR COST TO TOTAL COST : 3.158

LANDING RADAR/ALTIMETER



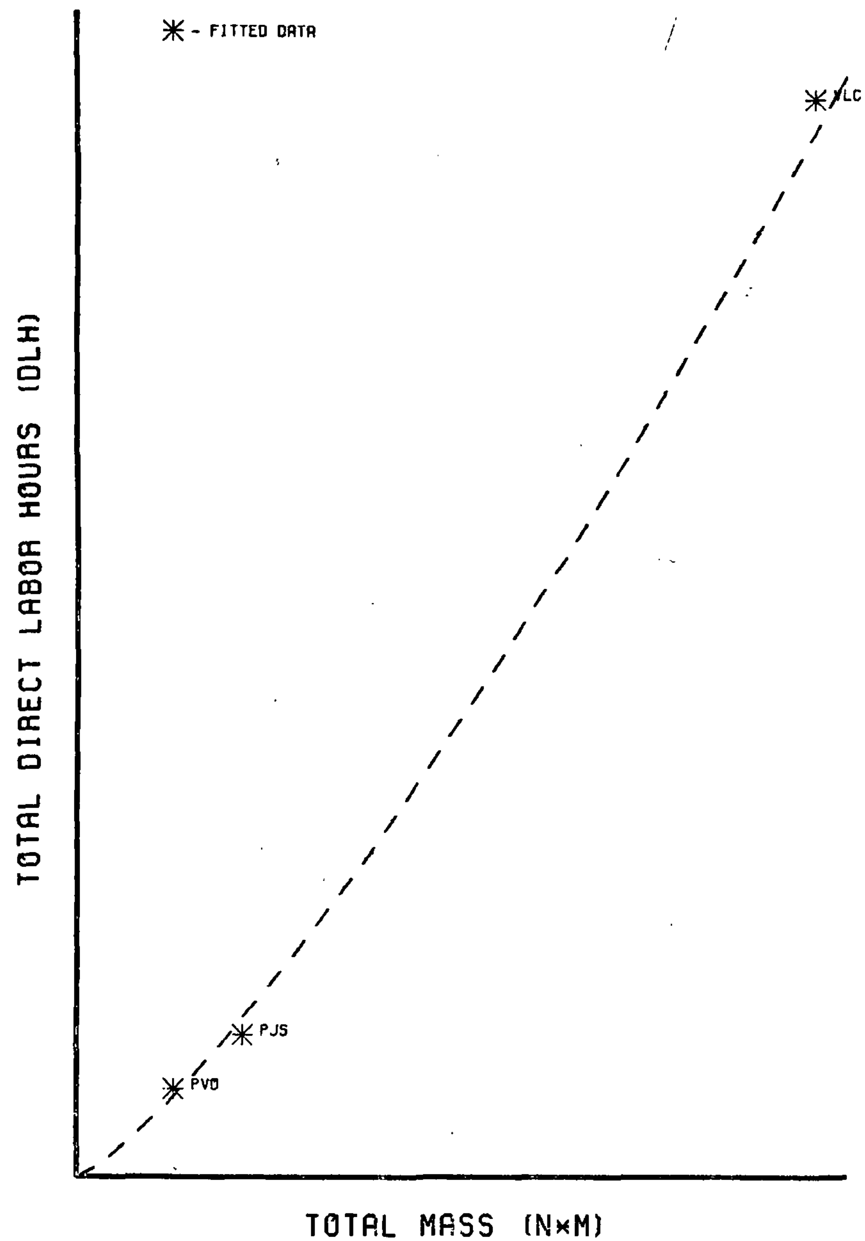
RECURRING DIRECT LABOR FUNCTION

$RLH = 1.223 \times (N \times M)^{1.2367}$

STATISTICS

SAMPLE SIZE	3
CORRELATION COEFFICIENT	0.999
T STATISTIC (1.223)	1.54
T STATISTIC (1.2367)	39.19
MEAN PERCENT ERROR	0.0
MEAN ABSOLUTE PERCENT ERROR	3.2

LINE-SCAN IMAGING



TOTAL DIRECT LABOR FUNCTION

$DLH = 10.069 * (N*M)^{1.2570}$

STATISTICS

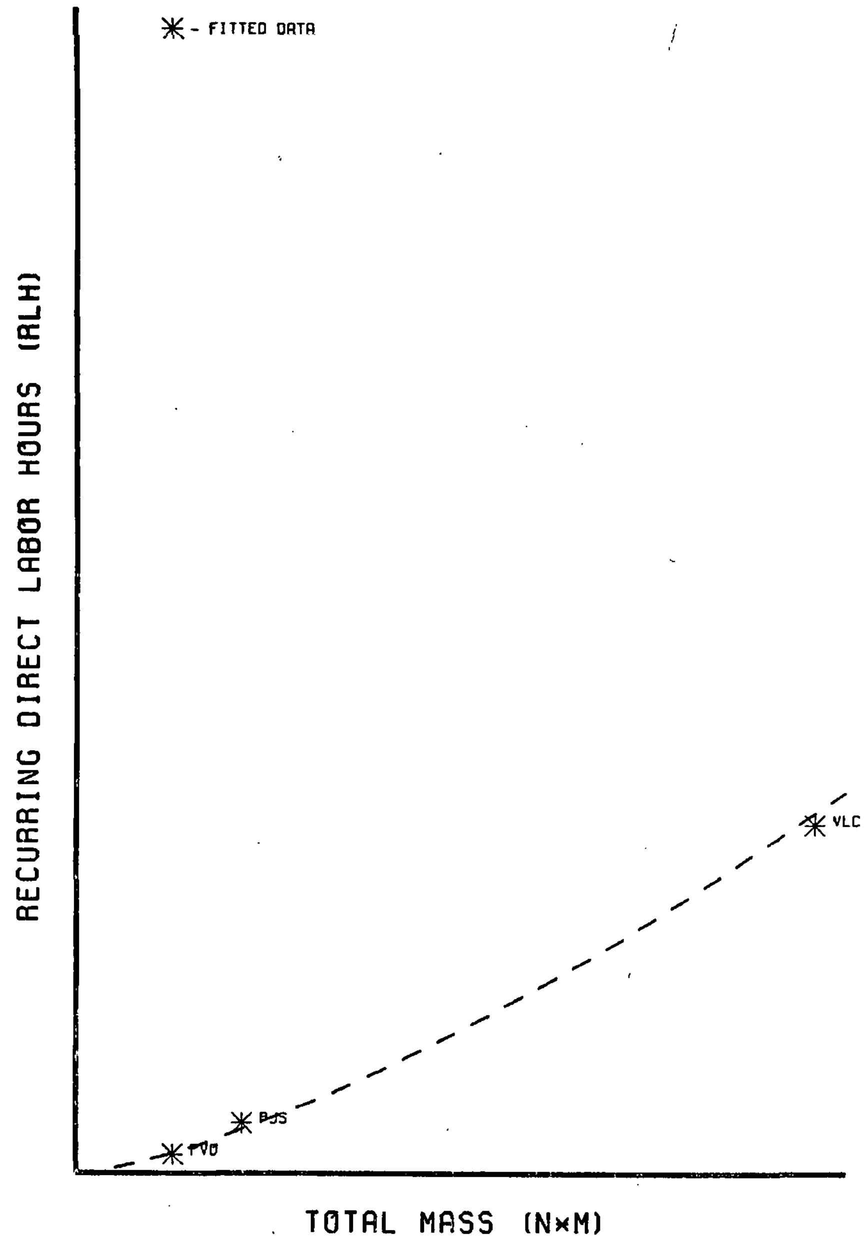
SAMPLE SIZE	3
CORRELATION COEFFICIENT	0.997
T STATISTIC (10.069)	8.97
T STATISTIC (1.2570)	12.78
MEAN PERCENT ERROR	-0.4
MEAN ABSOLUTE PERCENT ERROR	7.8

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.57/HR

LABOR COST TO TOTAL COST : 3.604

LINE-SCAN IMAGING



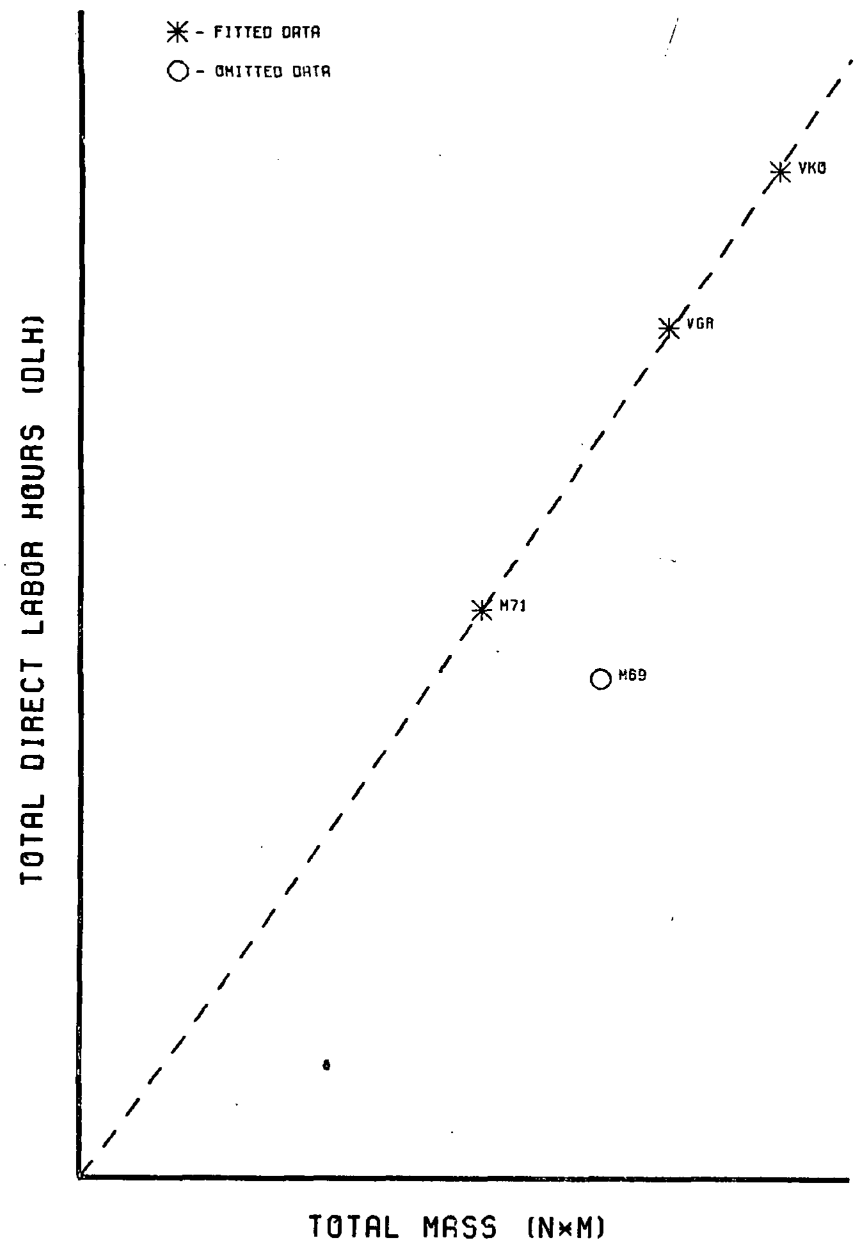
RECURRING DIRECT LABOR FUNCTION

$RLH = 1.989 * (N \times M)^{1.4089}$

STATISTICS

SAMPLE SIZE	3
CORRELATION COEFFICIENT	0.997
T STATISTIC (1.989)	2.44
T STATISTIC (1.4089)	13.09
MEAN PERCENT ERROR	-0.4
MEAN ABSOLUTE PERCENT ERROR	8.4

VIDICON IMAGING



TOTAL DIRECT LABOR FUNCTION

$DLH = 4.463 \times (N \times M)^{1.0369}$

STATISTICS

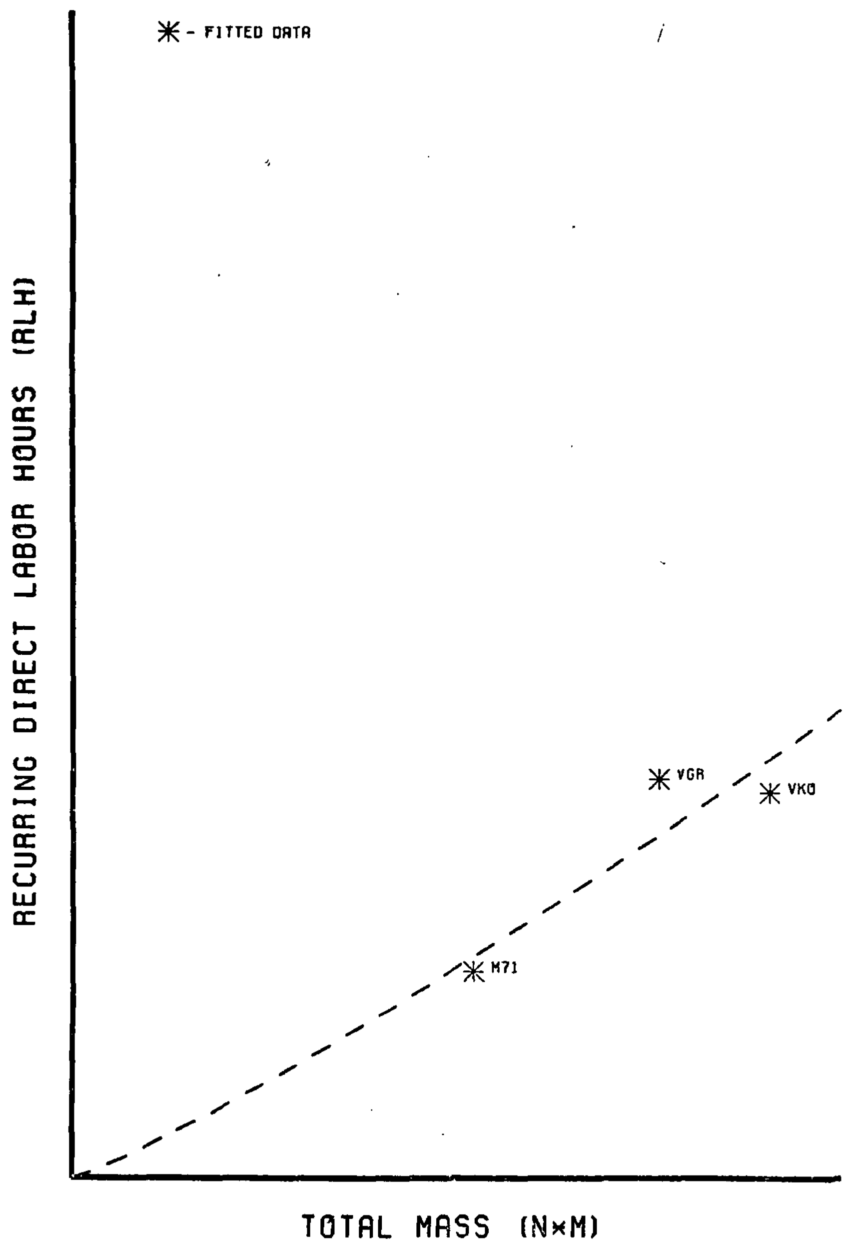
SAMPLE SIZE ———————— 3
CORRELATION COEFFICIENT ——— 0.999
T STATISTIC (4.463) ————— 15.04
T STATISTIC (1.0369) ———— 44.51
MEAN PERCENT ERROR ————— 0.0
MEAN ABSOLUTE PERCENT ERROR —— 0.5

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $ 9.52/HR

LABOR COST TO TOTAL COST : 3.586

VIDICON IMAGING



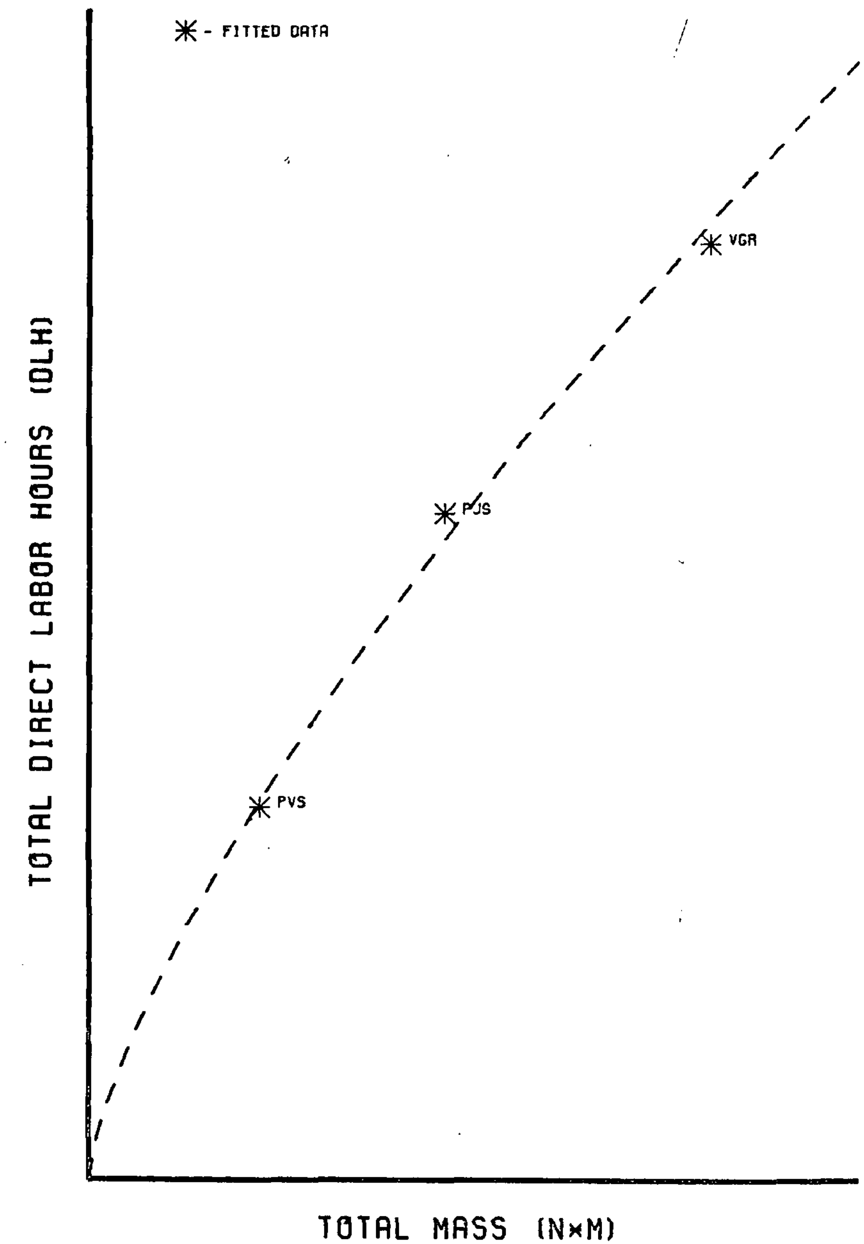
RECURRING DIRECT LABOR FUNCTION

$RLH = 1.0 \times (N \times M)^{1.152}$

STATISTICS

SAMPLE SIZE	3
CORRELATION COEFFICIENT	0.934
T STATISTIC (1.152)	64.22
MEAN PERCENT ERROR	-0.7
MEAN ABSOLUTE PERCENT ERROR	10.1

PARTICLE & FIELD INSTRUMENTS



TOTAL DIRECT LABOR FUNCTION

$DLH = 25.948 * (N*M)^{0.7215}$

STATISTICS

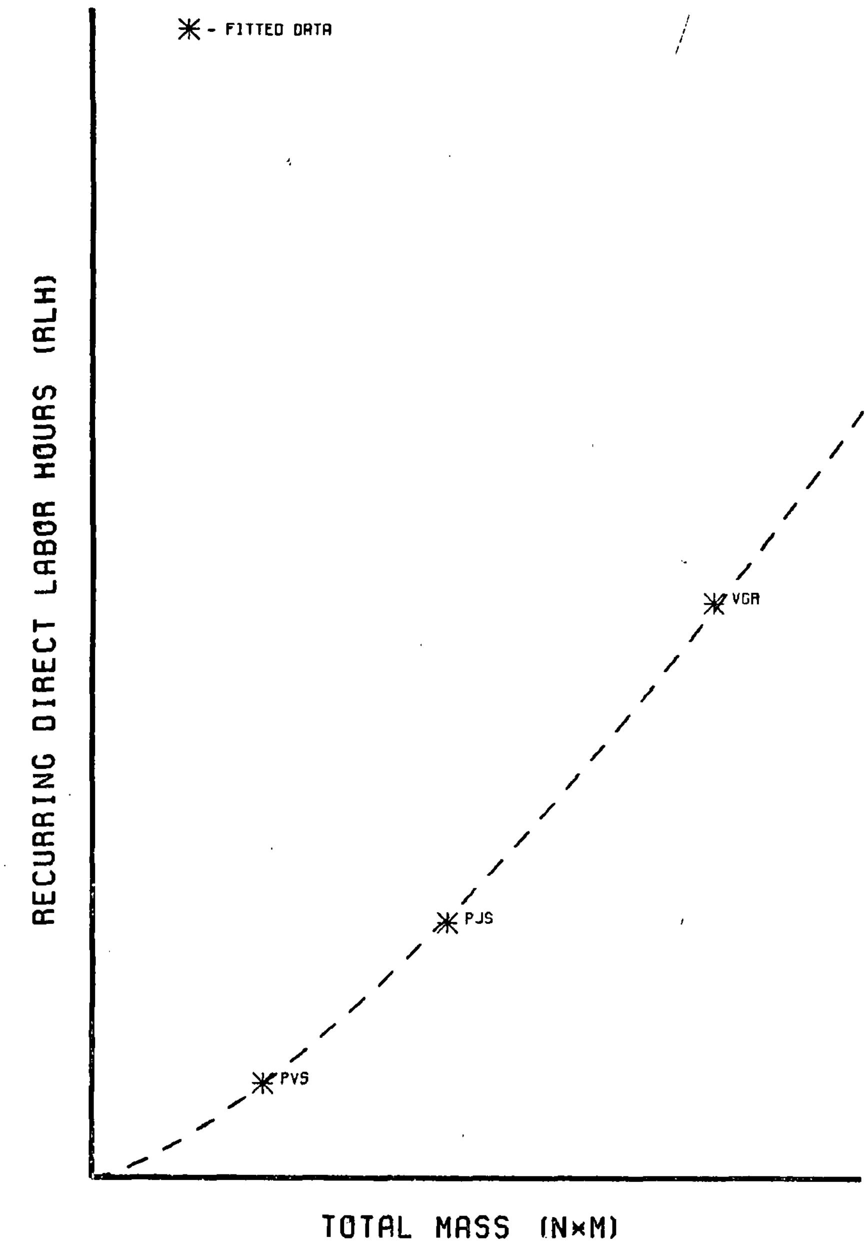
SAMPLE SIZE ---------------- 3
CORRELATION COEFFICIENT ------ 0.997
T STATISTIC (25.948) --------- 16.38
T STATISTIC (0.7215) --------- 13.83
MEAN PERCENT ERROR ----------- 0.0
MEAN ABSOLUTE PERCENT ERROR -- 2.6

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.62/HR

LABOR COST TO TOTAL COST : 3.395

PARTICLE & FIELD INSTRUMENTS



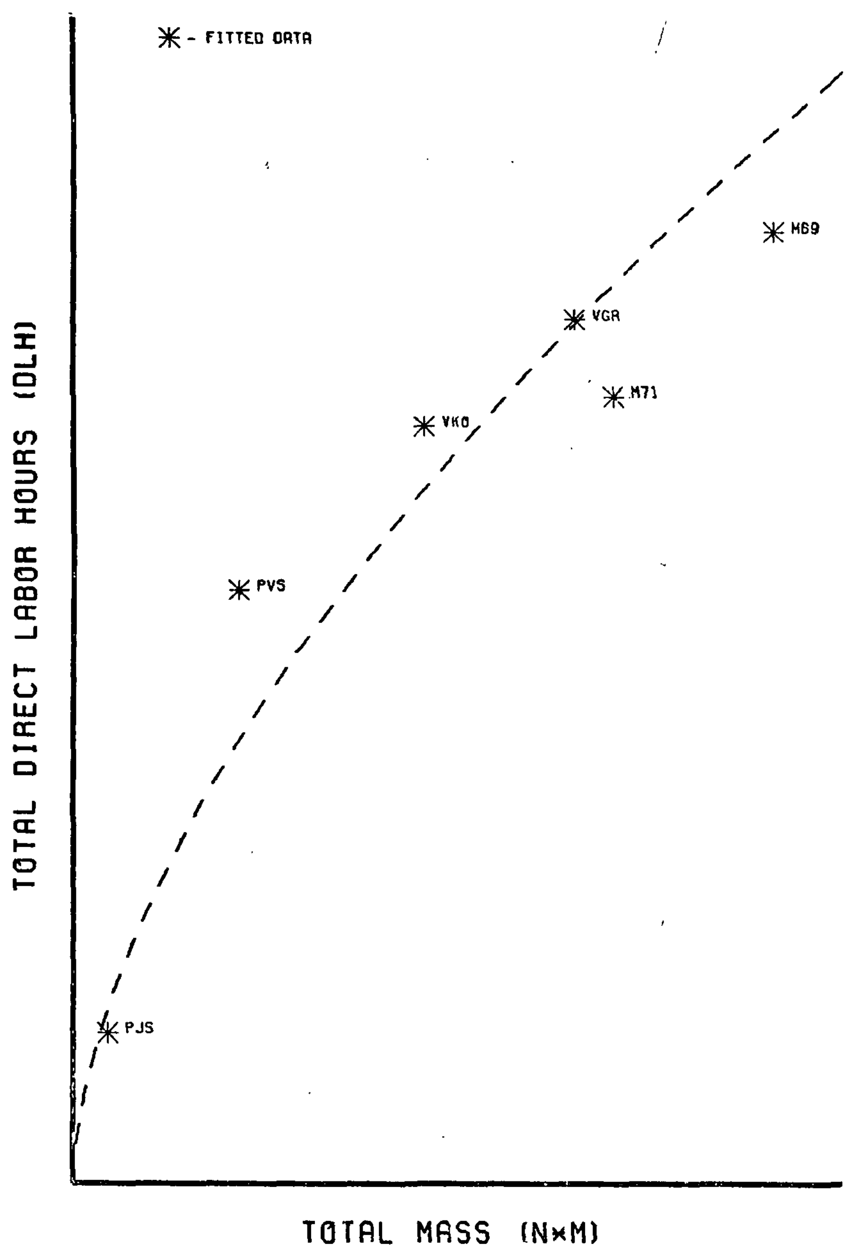
RECURRING DIRECT LABOR FUNCTION

$$RLH = 0.790 \times (N \times M)^{1.3976}$$

STATISTICS

SAMPLE SIZE	3
CORRELATION COEFFICIENT	0.999
T STATISTIC (0.790)	-2.16
T STATISTIC (1.3976)	48.74
MEAN PERCENT ERROR	0.0
MEAN ABSOLUTE PERCENT ERROR	1.4

REMOTE SENSING INSTRUMENTS



TOTAL DIRECT LABOR FUNCTION

$DLH = 38.016 * (N*M)^{0.5990}$

STATISTICS

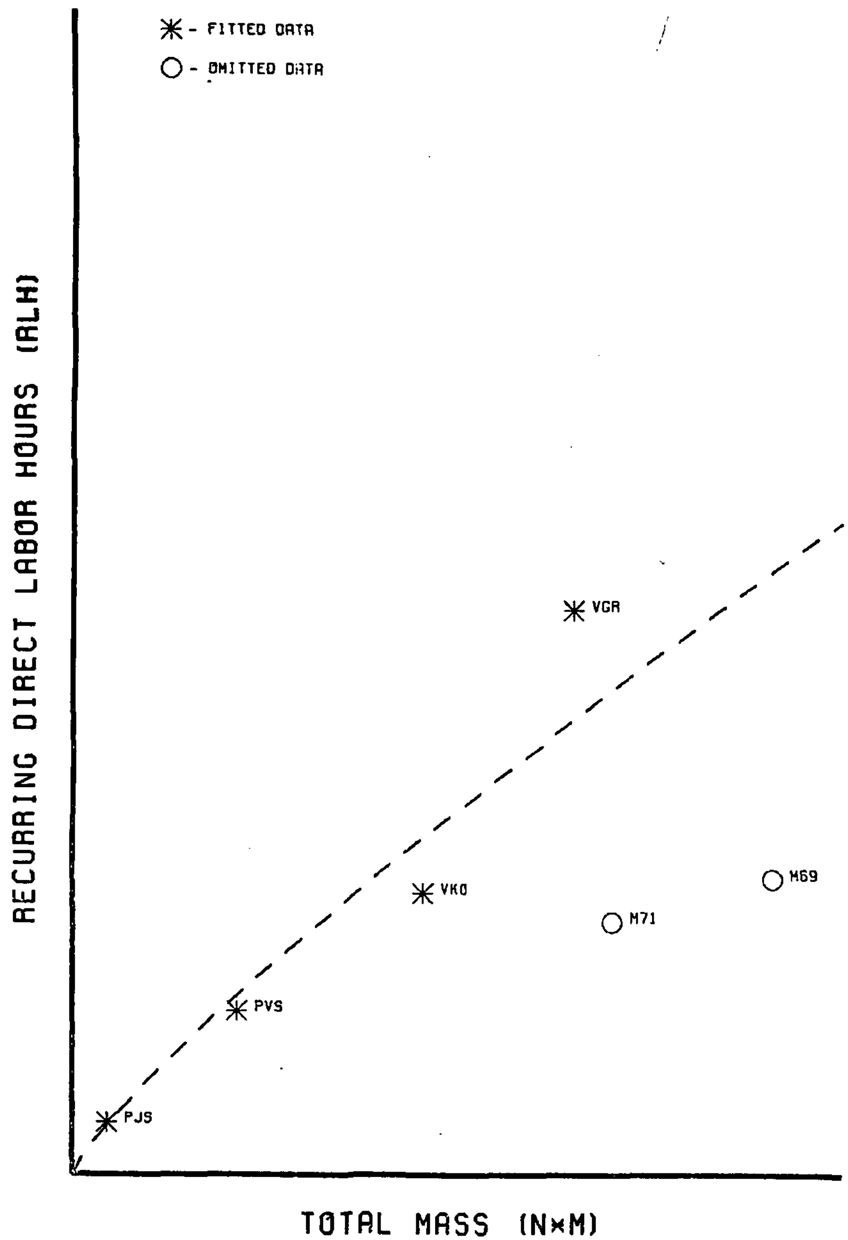
SAMPLE SIZE	6
CORRELATION COEFFICIENT	0.970
T STATISTIC (38.016)	12.46
T STATISTIC (0.5990)	7.94
MEAN PERCENT ERROR	-1.2
MEAN ABSOLUTE PERCENT ERROR	12.5

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.65/HR

LABOR COST TO TOTAL COST : 3.286

REMOTE SENSING INSTRUMENTS



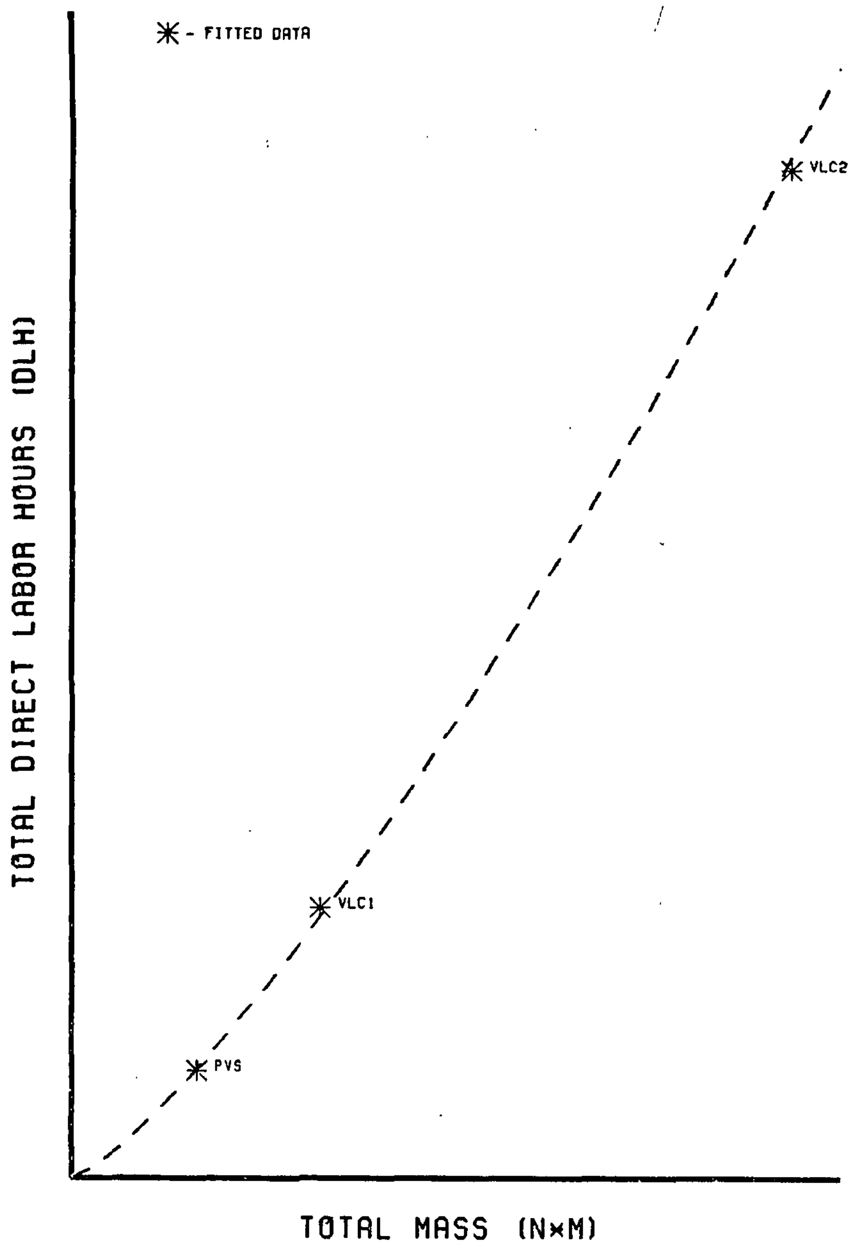
RECURRING DIRECT LABOR FUNCTION

$$RLH = 7.074 \times (N{*}M)^{0.8393}$$

STATISTICS

SAMPLE SIZE	4
CORRELATION COEFFICIENT	0.985
T STATISTIC (7.074)	5.36
T STATISTIC (0.8393)	7.99
MEAN PERCENT ERROR	-1.1
MEAN ABSOLUTE PERCENT ERROR	14.0

DIRECT SENSING & SAMPLING INSTRUMENTS



TOTAL DIRECT LABOR FUNCTION

$DLH = 6.173 \times (N \times M)^{1.2737}$

STATISTICS

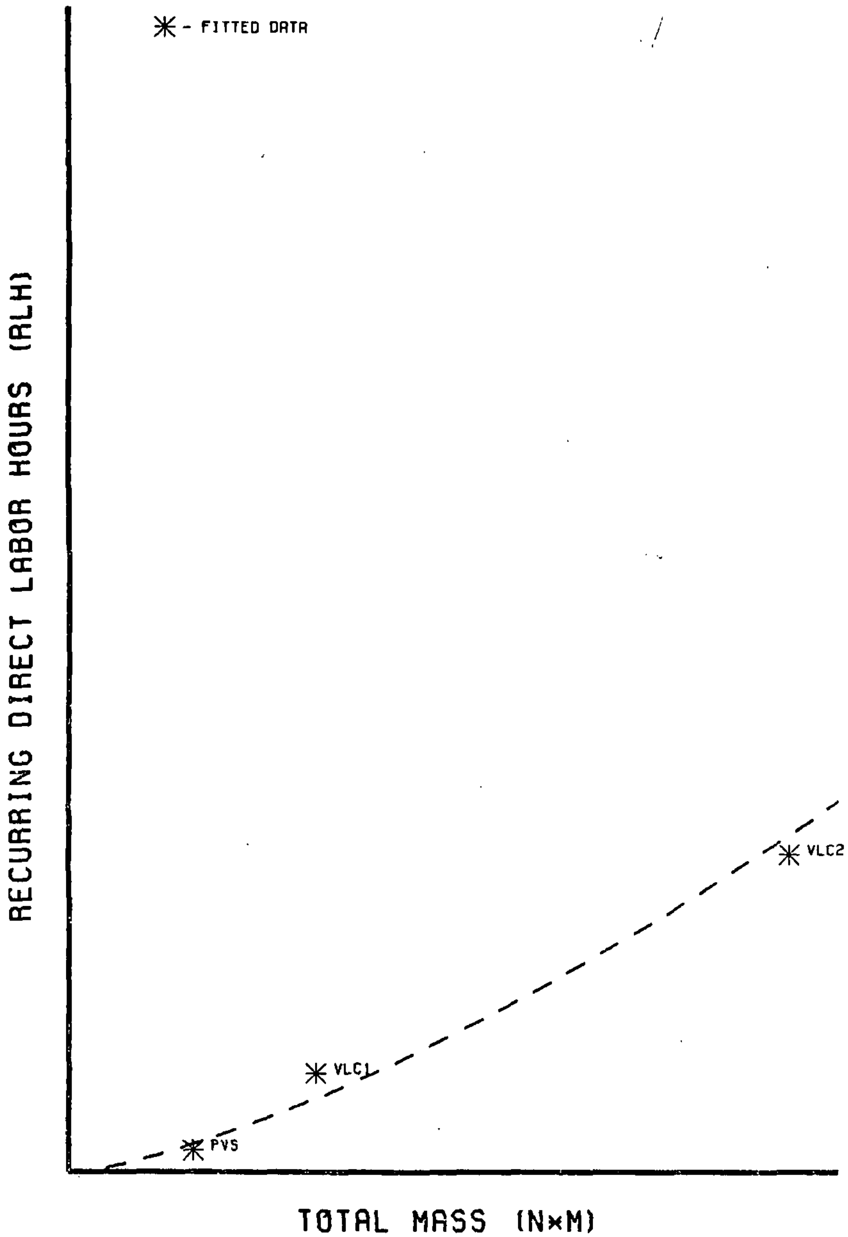
SAMPLE SIZE ———————————— 3
CORRELATION COEFFICIENT ——— 0.999
T STATISTIC (6.173) ———————— 13.44
T STATISTIC (1.2737) ——————— 37.64
MEAN PERCENT ERROR ————————— 0.0
MEAN ABSOLUTE PERCENT ERROR —— 2.3

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $ 9.55/HR

LABOR COST TO TOTAL COST : 3.454

DIRECT SENSING & SAMPLING INSTRUMENTS



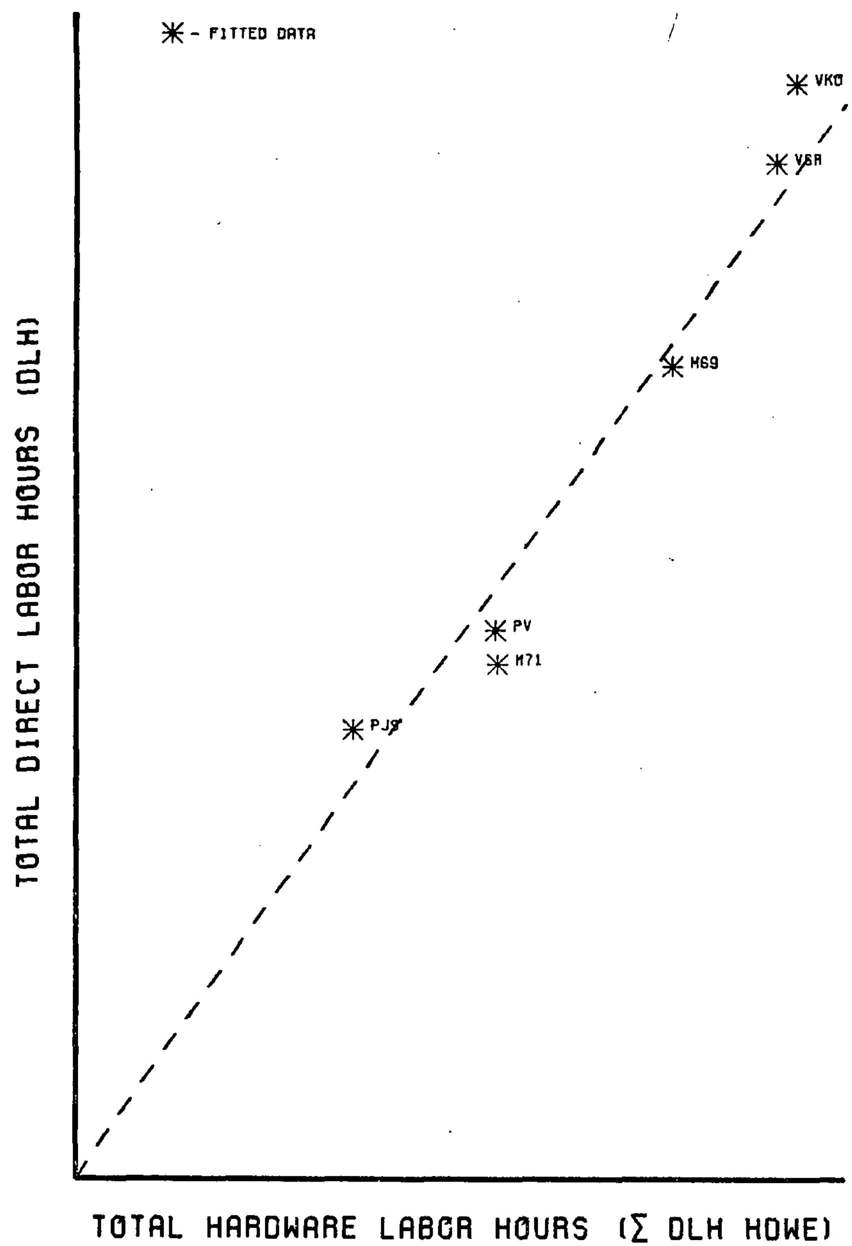
RECURRING DIRECT LABOR FUNCTION

$RLH = 1.0 \times (N \times M)^{1.4197}$

STATISTICS

SAMPLE SIZE	3
CORRELATION COEFFICIENT	0.978
T STATISTIC (1.4197)	35.07
MEAN PERCENT ERROR	-3.6
MEAN ABSOLUTE PERCENT ERROR	20.5

SYSTEM SUPPORT & GROUND EQUIPMENT



TOTAL DIRECT LABOR FUNCTION

$$DLH = 0.3627 \times (\Sigma\ DLH\ HOWE)^{0.9812}$$

STATISTICS

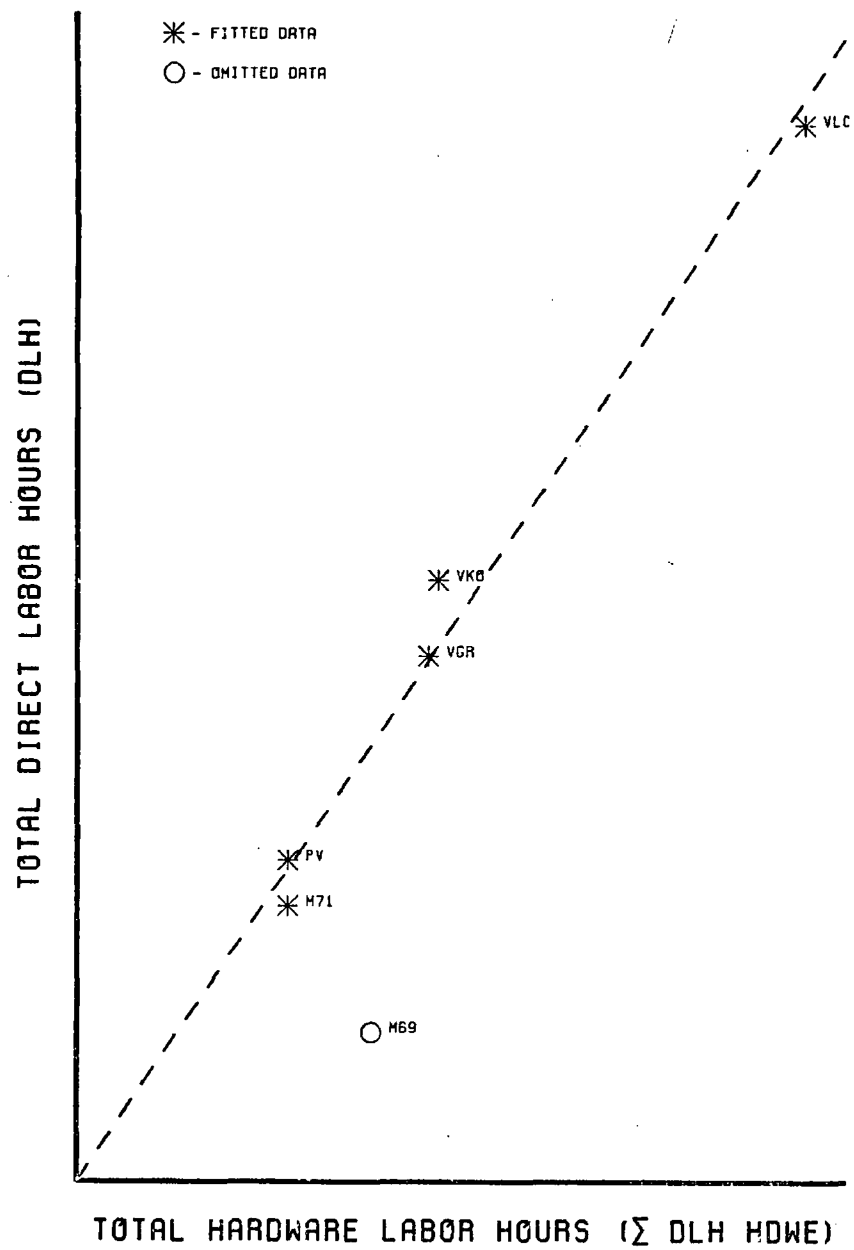
SAMPLE SIZE	6
CORRELATION COEFFICIENT	0.963
T STATISTIC (0.3627)	-0.89
T STATISTIC (0.9812)	7.12
MEAN PERCENT ERROR	-0.5
MEAN ABSOLUTE PERCENT ERROR	8.4

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $10.55/HR

LABOR COST TO TOTAL COST : 3.076

LAUNCH + 30 DAYS ØPS & GRØUND SØFTWARE



TØTAL DIRECT LABØR FUNCTIØN

DLH = 0.09808 × (Σ DLH HDWE)

STATISTICS

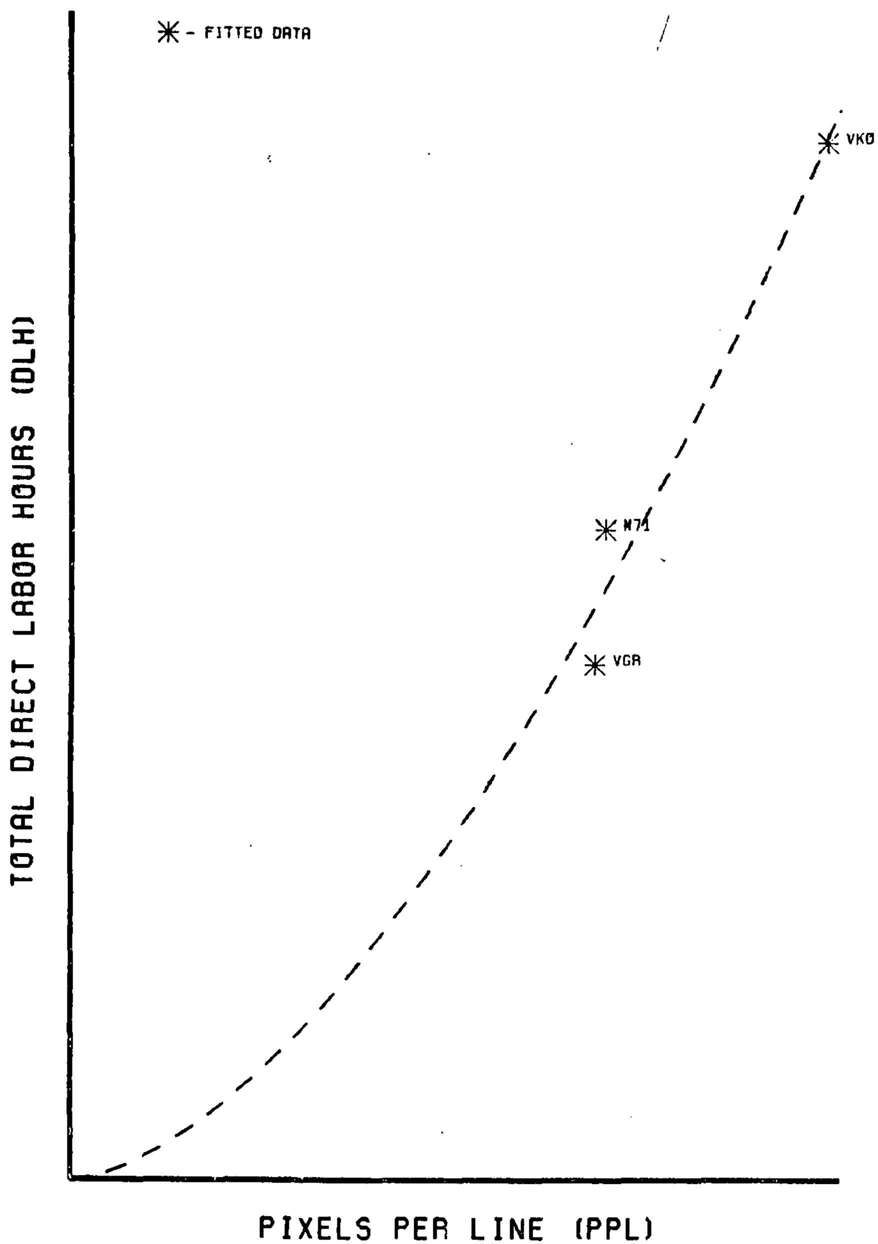
SAMPLE SIZE ------------------ 5
CORRELATIØN CØEFFICIENT ------ 0.992
T STATISTIC (0.09808) -------- 34.53
MEAN PERCENT ERROR ----------- -0.4
MEAN ABSØLUTE PERCENT ERROR -- 6.1

CØNVERSIØN FACTØRS

LABØR HOURS TØ LABØR CØST: $10.71/HR

LABØR CØST TØ TØTAL CØST : 3.214

IMAGE DATA DEVELOPMENT



TOTAL DIRECT LABOR FUNCTION

$DLH = 0.00124 * PPL^{1.6290}$

STATISTICS

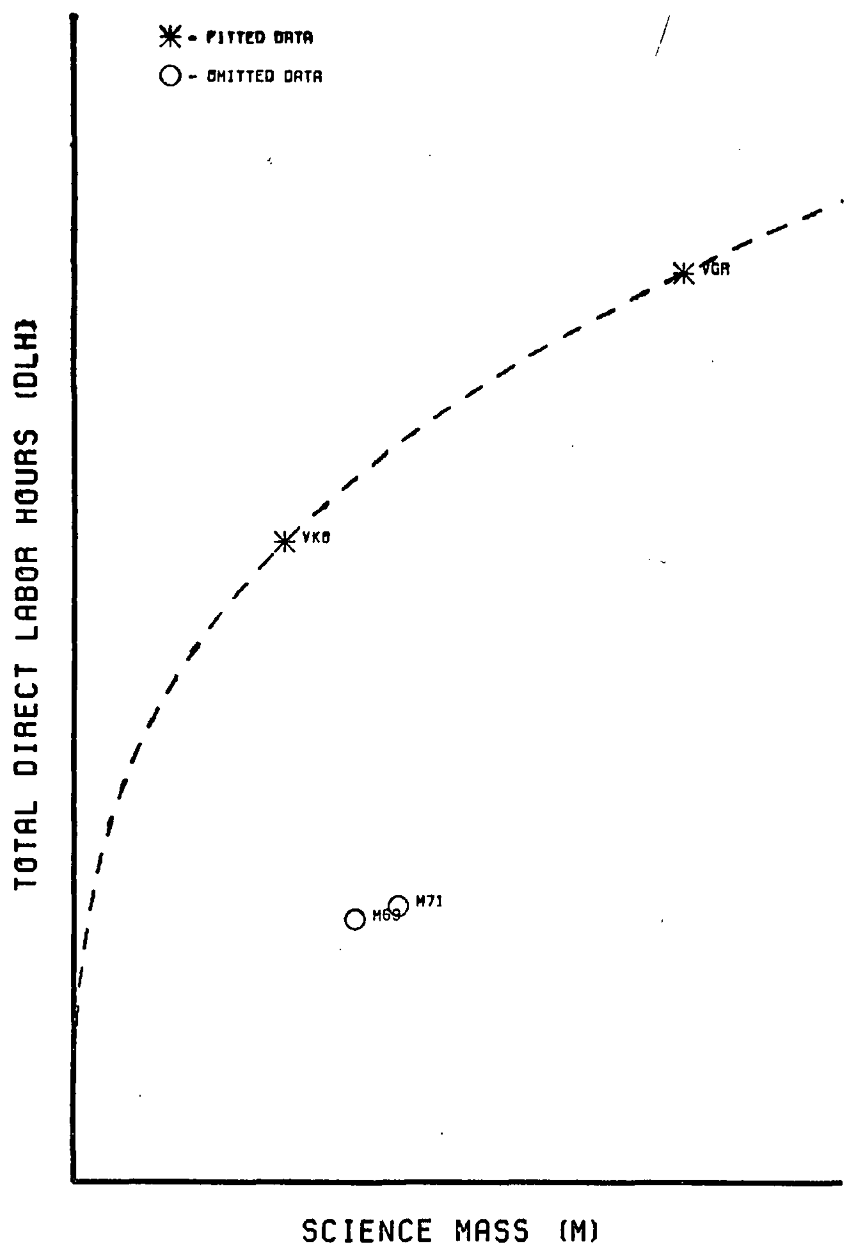
SAMPLE SIZE ———————— 3
CORRELATION COEFFICIENT ——— 0.950
T STATISTIC (0.00124) ———— -1.91
T STATISTIC (1.6290) ————— 3.17
MEAN PERCENT ERROR —————— -0.4
MEAN ABSOLUTE PERCENT ERROR — 7.3

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $11.46/HR

LABOR COST TO TOTAL COST : 3.130

SCIENCE DATA DEVELOPMENT



TOTAL DIRECT LABOR FUNCTION

$DLH = 27.836 \times M^{0.3289}$

STATISTICS

SAMPLE SIZE	2
CORRELATION COEFFICIENT	1.0
T STATISTIC (27.836)	*
T STATISTIC (0.3289)	*
MEAN PERCENT ERROR	0.0
MEAN ABSOLUTE PERCENT ERROR	0.0

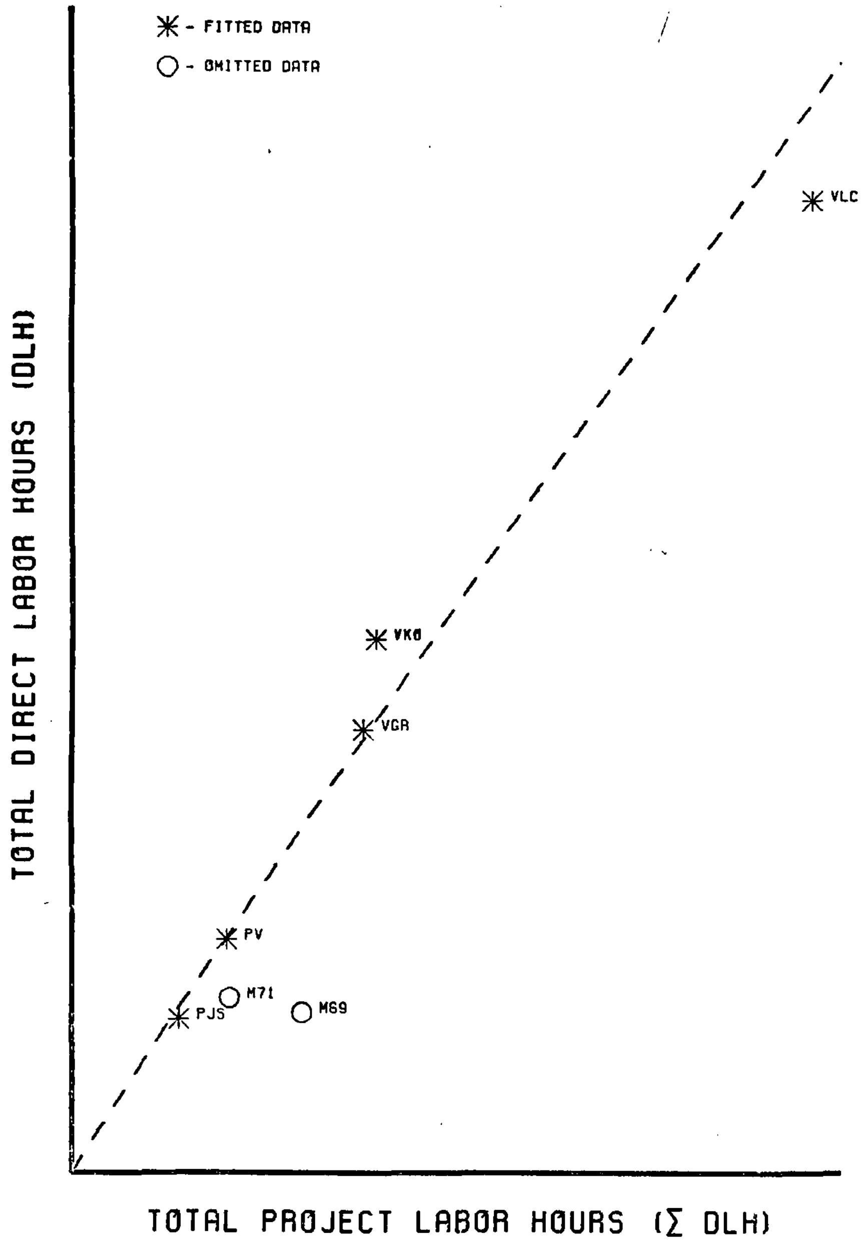
* T statistics are indeterminate

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $12.76/HR

LABOR COST TO TOTAL COST : 3.987

PROGRAM MANAGEMENT/MA&E



TOTAL DIRECT LABOR FUNCTION

$$DLH = 0.10097 \times (\Sigma\ DLH)^{0.9670}$$

STATISTICS

SAMPLE SIZE ---------------------- 5
CORRELATION COEFFICIENT ------ 0.990
T STATISTIC (0.10097) --------- -3.19
T STATISTIC (0.9670) ---------- 11.23
MEAN PERCENT ERROR ----------- -0.4
MEAN ABSOLUTE PERCENT ERROR -- 7.2

CONVERSION FACTORS

LABOR HOURS TO LABOR COST: $11.57/HR

LABOR COST TO TOTAL COST : 2.685

APPENDIX C

INHERITANCE MODEL

Appendix C

Inheritance Model

The following pages define the inheritance classes and associated cost reduction algorithm used with the SAI Planetary Program Cost Model. Although the definitions refer to "cost", in practice the inheritance algorithm is applied individually to the subsystem labor hour estimates prior to conversion from hours to cost.

The underlying assumption upon which this inheritance model is founded is that heritage in design philosophy and/or physical hardware affects only the non-recurring portion of cost. Thus, at the highest extreme of heritage, a project which uses unaltered residual hardware from a previous project still incurs a transfer cost exactly equal to the recurring cost of the hardware item. At intermediate levels of heritage, a fixed percentage of the non-recurring cost is incurred depending on the inheritance class.

The inheritance class definitions were determined by mutual consent of cognizant personnel at NASA, JPL, and SAI. The inheritance class weighting factors were not derived by analytical techniques but were also developed by consensus agreement.

SAI PLANETARY PROGRAM COST MODEL
INHERITANCE CLASS DEFINITIONS

- Class One: Off-the-Shelf/Block Buy.

  The subsystem is taken off of the shelf in working condition or ordered while the normal production line is operating as an additional unit.

  - Inheritance = 100% of non-recurring cost (NRC)
  - Cost = recurring cost (RC)

- Class Two: Exact Repeat of Subsystem.

  The exact repeat of previous subsystem but to be used in slightly different spacecraft or after line has closed down. Only design work is needed.

  - Inheritance = 80% of NRC
  - Cost = 20% of NRC + 100% of RC

- Class Three: Minor Modifications of Subsystem.

  A previous design is required but it requires minor modifications. Thus, the spacecraft will still incur all the design cost and most of the test and development cost in ensuring compatibility of the old design and the new minor mods with the new use of the subsystem.

  - Inheritance = 25% NRC
  - Cost = 75% of NRC + 100% of RC

- Class Four: Major Modifications of Subsystem.

  A previous design is required but major modifications have to be made to the design. This gets very close to a new subsystem since even new subsystems rely on previous design and experience. Some savings in development is possible.

  - Inheritance = 5% NRC
  - Cost = 95% of NRC + 100% RC

- Class Five: New Subsystem.

  The subsystem is basically new design.

  - Inheritance = 0% NRC
  - Cost = 100% NRC + 100% RC

Cost Reduction Algorithm by Inheritance Classes

Let X_1 = Percent of Subsystem Off-the-Shelf
X_2 = Percent of Subsystem Exact Repeat
X_3 = Percent of Subsystem Minor Mod
X_4 = Percent of Subsystem Major Mod
X_5 = Percent of Subsystem New Design

Thus $X_1 + X_2 + X_3 + X_4 + X_5$ = 100% of Subsystem Mass

NRC = Non-recurring cost estimate (without inheritance)
RC = Recurring cost estimate
TC = Total cost estimate (including inheritance effects)
Z = Percent cost reduction

If $Z = 1.0X_1 + 0.8X_2 + 0.25X_3 + 0.05X_4 + 0.0X_5$

Then TC = (100% - Z) NRC + RC

APPENDIX D

DETAILED ERROR ANALYSIS

Appendix D

Detailed Error Analysis

Due to the proprietary nature of the data, this appendix is not included in copies of this report intended for distribution external to the National Aeronautics and Space Administration.