1. COST ENGINEERING PRINCIPLES AND COST ESTIMATION

1.1 Cost Engineering

1.11 Cost Engineering as Modern Design Paradigm

1.111 Introduction

In the past decades only one principle was guiding launch vehicle design: maximum performance, minimum weight. As long as the performance of rocket engines was mediocre and conventional materials and construction methods prevailed, performance indeed was a critical issue. However, things have changed: Minimizing weight or pushing performance to the maximum possible extent has always been an expensive approach. Present and future priority is on MINIMUM COST. Future launch vehicles are no more national prestige projects but subject of commercial operation and international competition.

"Cost Engineering" is the third level of launch vehicle design and engineering. In the initial launch vehicle history cost were of no concern. This was true, by example, for the SATURN Program, or in Europe for the ELDO-I / Europa I vehicle development. The second step was the "Design-to-Cost"-rule which means to keep to a pre-determined budget. In case of "Cost Engineering" the goal is the minimum cost vehicle design concept. This means that costs have to be taken into account as a design criterion for each technical decision. By example, using less advanced technology and / or existing components will lead to lower development cost (and lower risk !), as well as to lower fabrication costs.

PHASE 1: Launch Vehicle Design without Specific Cost Requirements
Paradigm: Optimization of Performance / Technology
Typical Contract Type: Cost plus Percentage Fee

PHASE 2: Design to Cost, i.e. Design for a given Maximum Development Cost Budget
Paradigm: Performance Achievement
Typical Contact Type: Cost plus Fixed Fee

PHASE 3: Cost Engineering - Design for Minimum Development Cost and / or for Minimum Vehicle and Operations Cost
Typical Contract Type: Cost Plus Incentive Fee

"Cost Engineering" requires not only technical design expertise but also technical judgement and understanding of cost issues and cost drivers. Unfortunately no University provides an education in "Cost Engineering". This goes far beyond cost accounting procedures and spread-sheet organization :

- The first step towards „Cost Engineering" is the understanding of the importance and the serious intention to strive for a cost-optimized vehicle concept and design.
- The second step is the familiarization with cost engineering principles and its potential. This implies the use of a cost data base and a parametric cost model (such as *TRANSCOST*)

It is important - and this is the distinct different to the past methodology - to start cost analysis at the very beginning of a vehicle design process, and NOT after a detailed design has been established. The usual „bottom-up"- cost estimation with detailed costing of each component and each activity is expensive and time consuming. It also may lead to a total cost level that is not acceptable - and the complete process must start again.

1.112 Cost Engineering and Phased Program Planning (PPP)

The standard procedure for the implementation of a space transportation system is the „Phased Program Planning" with the following distinct phases:

PRE-PHASE A:	Definition of the idea, its justification and the potential market
PHASE A:	Conceptual vehicle design and system analysis. First application of Cost Engineering for economic design optimization
PHASE B :	Detailed definition of the system design, establishment of specifications and development plans. Detailed cost estimation (Proposal) - Technology pre-development
PHASE C :	Development of subsystems, systems and complete vehicle integration and verification. Vehicle production setup and first test flight(s) for system qualification
PHASE D :	Production Phase: Continuous production, integration and verification of vehicle elements and complete vehicles
PHASE E :	(Commercial) launch operations
PHASE F :	System phase-out, Abolition activities (if applicable)

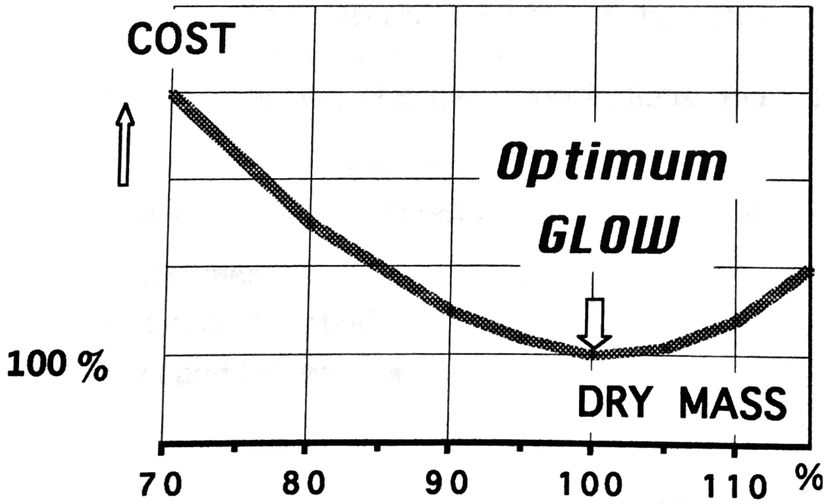
The application of cost engineering is most important in PHASE A since all decisions which have a major impact on costs and economics (and accordingly on the success of the project) are made in this early phase. If this opportunity is missed it will be extremely difficult to „enforce“ cost reductions later (in Phase C or D) when the development cost are growing or competitive cost problems are discovered.

In PHASE B the role of cost engineering is the verification of the detailed cost planning and/or the proposal cost. If there are clear differences then there may be a mistake in cost accounting - or there is a real good reason to deviate from the expected standard cost values.

1.113 Cost Engineering Principles and Applications

For each launch vehicle concept with a given payload requirement there exists an OPTIMUM SIZE (launch mass) resulting from a vehicle dry mass value which provides minimum cost. A low dry mass resulting from wide application of high-tech materials, procedures, subsystems and components will normally lead to high costs - both for development as well as for vehicle production. On the other hand, for a very conventional low-tech vehicle design the dry mass and vehicle size become rather large and heavy (see TRW, 1973, ref.133). This may reduce the development cost but will increase the Cost-per-Flight (CpF). This low-tech approach has been proposed several times in the past but never been realized.

The cost trend which may be understood as CpF (Cost-per-Flight) including development cost amortization vs. dry mass is shown in FIG. 1-01. Both, a higher dry mass and higher GLOW by low-tech approaches lead to cost growth, as well as the application of hi-tech solutions resulting in lower dry mass and lower GLOW.



IG. 1-01: **Basic Cost Trend vs. Vehicle Dry Mass**

This cost engineering approach to define the dry mass value or technology standard which leads to lowest cost and not to minimum weight is NOT in contradiction to the fact that cost models' CERs are normally related to the dry mass. They assume the same technology standard for any vehicle size, and a payload growth with vehicle dry mass increase.

Another cost engineering task is to take into account maintainability and refurbishment requirements in case of RLVs already in the early design phase: this means not only to take care of inspection and exchangeability of all components (including propellant tanks !), but also of such operational design features as to overdesign the rocket engines so that they can be operated at 5 to 8 % below the nominal (maximum) thrust level. This improves engine design life and reliability. The higher thrust level seems to increase the development cost in principle, but the downgraded operational thrust level with its inherent increased reliability will reduce the required number of engine qualification firings and thus reduce the overall cost for development and qualification.

A further area of cost engineering is the verification of new technologies: it should be made sure before investing into an expensive technology development program that the new technology is a contribution to *better cost efficiency.* Examples for the contrary are the proposals for tripropellant rocket engines/systems, or inflight air-liquifaction, with the goal of launch mass reduction, but leading to higher costs and greater complexity and risk, instead of cost reduction.

1.12 Cost Estimation and Cost Model Tools

1.121 The Problem of Cost Estimation

Cost estimation for a new project must be based on past experience. Reliable cost data, however, are rare. They are considered confidential in most cases and if published it is normally without detailed definition of the scope. It is even difficult to recover cost data of past projects within a company due to the projects' contractual and administrative complexity including changes, modifications and add-on contracts.

For a serious cost analysis and cost estimation is it essential to clearly distinguish between the key cost areas since they have different characteristics. These are

(1) Development Cost (Non-recurring Cost)
(2) Production or Fabrication Cost, and
(3) Direct and Indirect Operations Cost (including Refurbishment Cost in case of reusable launch vehicles and engines)

It is relatively easy to establish a cost formula or CER (Cost Estimation Relationship) however, this does not mean much without verification by realized projects. The larger the number of reference projects, the better and more credible is a CER.

Cost Models are based in principle on statistical cost data of realized projects. Therefore, it was not possible to establish a realistic Cost Model for launch systems before the year 1970 when the SATURN launch vehicle element costs became available. However, already in 1962 Prof. Eugen Sänger prepared a cost comparison between aeronautical (winged) and ballistic launch systems (ref. 129). He recognized the major and different cost areas like development cost, production cost and ground operations costs. He also recognized that development and production costs depend on the unit mass, but increasing sub-proportionally to the mass. In 1965 Lockheed prepared a „Launch Vehicle Components Cost Study" in 1965 under NASA-Contract. On this basis „A Nonlinear Programming Model for Launch Vehicle Design and Costing" was etablished by B.C.Rush et al (ref. 132).

There presently exist cost models for launch systems of different nature and heritage, using different methodologies: the Aerospace Corp. Launch Vehicle Cost Model (ref. 130) and the NASA MSFC Engineering Cost Model (ref. 27) which are partially or fully classified. A University tool is the TRASIM-Model of the Technical University of Berlin (ref.131). In addition to these transportation-specific models there are cost models with a broader scope, such as the commercial PRICE-H-Model and the USAF - and NASA Cost Model NAFCOM both with confidential data bases. All these models are sub-system-based, i.e. a detailed design of the vehicle is required with definition of the subsystems' mass values.

The *TRANSCOST*-Model in comparison, is a *system-based model* (subsystem data not required, except engine data) and the reference projects for each CER are indicated. TABLE 1-I shows a survey of the actual cost models with their key features which are discussed in the following sub-chapters.

TABLE 1-I : **COMPARISON OF PARAMETRIC COST MODELS**

	PRICE-H	**TRASIM**	**TRANSCOST**
HERITAGE / CERs:	Components, Boxes	Sub-systems	Vehicle Systems and Engines
EMPHASIS :	Manufacturing Cost	Life-Cycle Cost	Vehicle Cost and CpF
TYPE OF COST DATA:	Developm.Cost Manufact. Cost	Developm. Cost Manufact.Cost Operations Cost Life Cycle Cost	Developm.Cost Manufact.Cost Refurbishm.+ Operations Cost Cost per Flight
DATA BASE :	Confidential	Unknown	Ref. Data Visibility
APPLICATIONS:	Commercial, Military and Aerospace Projects	Space Transp. Programs	Launch Vehicle Systems

1.122 The PRICE-H Model

This Model was established by Mark H. Burmeister at the previous RCA-Astro establishment in Princeton, N.J. It was based on and built-up from component level, more specifically from electronics black boxes cost estimates. From this basis it was extended to satellite systems and has then also be used for military systems, aircraft and space systems. It is a more general cost model, not really dedicated to space systems or launch vehicles.

One of the characteristics of the PRICE-H Model is its commercial nature which implies a confidential, unknown cost data base.

The Model uses a number of "Multiplication Factors" :

(A) PLTFM, the basic Platform Value = 1.0 to 2.5
(for launch vehicles between 1.7 and 2.3)

(B) ECMPLX, the Engineering Complexity Factor = 0.2 to 3.1
(combination of design standard and team experience)

(C) MCPLXS, the Manufacturing Complexity Factor.

The basic "Platform Value" has to be selected according to previous similar projects the costs of which are known. The PRICE-H overview table does not provide a dedicated value for launch vehicles, only for "Aerospace" and "Spacecraft" with a range of 1.6 to 2.5. Another way of defining the basic "Platform Value" is by multiplication of a list of "Product Requirements" (200 to 300 points) and "Environmental Conditions" (9 to 10 points for "Unmanned Space").

PRICE-H does NOT provide means for the Ground Segment Cost, Operations Cost, Cost per Flight (CpF) and Life-Cycle Cost (LCC).

1.123 TRASIM, the (Space) Traffic Simulation Model of the University Berlin

The TRASIM-Model has been established specifically for space transportation traffic simulation. It has been conceived at the "Lehrstuhl für Raumfahrttechnik", Technical University Berlin as a FORTRAN computer code in 1989 by B. Johenning using Subsystem CERs from H. Arend, for their project study activities, especially the NEPTUN Heavy Lift Launch Vehicle (HLLV).

The complex TRASIM Simulation Model emphasizes Programmatic Life-Cycle Cost: i.e. an operational model with program duration and number of launches per year is required. Also space infrastructure elements and operations in LEO (Space Station) as well as manned operations are included. The output format is a total cost simulation for each year of the program from development start to the end of operations. Up to 5 different space transportation systems with 8 different mission modes can be included in one computer run. Also nine different transportation nodes between Earth, Moon and Mars can be taken into account.

The vehicle DEVELOPMENT COST are estimated (as MYr) by the sum of 10 subsystem CERs with a multiplication factor for the number of stages (1.06^n), plus a certain management and system integration effort. There is no differentiation for the various types of launch vehicles. Team experience and design status factors are only applied to the rocket engine CER, and material complexity factors are to be used for the structure subsystem elements. None for the equipment CERs.

The number and type of reference projects used to establish the Subsystem-CERs of this fully computerized simulation model is not identified, as well as the basis for the "Material complexity factors".

1.124 The NASCOM-Model

The NASCOM-Model widely used in the USA has a database which according to ref.144 contains technical and programmatic data at component, subsystem and space system level for 100 unmanned spacecraft, 8 unmanned spacecraft, 11 launch vehicle stages, and 3 rocket engines, contained in the NAFCOM cost model. The largest data collection is, however, in the instrumentation area: it comprises 366 scientific instruments

An interesting feature of the NASCOM Model is the productivity improvement vs. time which is taken into account in some CERs. However, there is also a different cost trend in the area of avionics (and software) due to the increasing functional requirements and capabilities.

1.125 The *TRANSCOST* - Model (see also Chapter 1.2)

The *TRANSCOST*-Model has been established as a launch vehicle-dedicated system model in 1971 by D. E. Koelle (as an outgrowth of his dissertation), improved and extended in several steps to the actual version 7.2 as of April 2007. The Model is used not only in Europe and the USA but also in Russia, China, Japan and India. More than 360 copies of the *TRANSCOST*-Versions 6 and 7 have been ordered by the major Space Agencies, Aerospace Companies and Institutions worldwide. It is probably the most widely used cost model in the space transportation area.

The major differences of the *TRANSCOST*-Model compared to the previously described cost models are as follows:

(1) It is based on a comprehensive and continuously updated vehicle and engine cost data collection from a period of over 47 years (1960 to 2006).
The reference projects used for each CER are shown, providing for a unique basic cost data visibility.

(2) It represents not only a means for cost estimation but has been conceived as a tool for Cost Engineering. It is dedicated to launch vehicle development, manufacturing and operations cost and conceived such that it allows to perform a <u>cost-optimized vehicle design</u>, both for ELVs and RLVs.

1.13 Applications of Cost Engineering

Cost Engineering is the paradigm for modern launch vehicle optimization with the goal of minimum development and operations costs. This is different to the past paradigm of performance-optimized vehicles (maximum payload or minimum launch mass), a paradigm which may lead to expensive and non-competitive solutions.

Specifically, cost engineering tasks and applications comprise the following options to arrive at an economic launch vehicle design :

(1) Selection of the most economic VEHICLE CONCEPT for a given payload in the early design phase from a number of alternatives; emphasis can be given to minimum development cost, and/ or minimum Cost-per-Flight (CpF), or Life-Cycle Cost (LCC).

(2) Definition of the economically optimum VEHICLE PAYLOAD CAPABILITY in case of a given program scope or life cycle, related is the number of annual launches (LpA).

(3) Determination of the optimum launch VEHICLE SIZE (launch mass or GLOW) by a trade-off between the application of conventional and advanced technology. The use of conventional technology in some areas increases the launch mass but can reduce the development and fabrication costs. Advanced technologies should only be used if qualified and if cost-effective.

(4) Determination of the optimum ROCKET ENGINE(s) thrust level and qualification program (no. of test firings) for minimum development cost of rocket engines. A 5 % overdesign of the engine(s) , resp. operation at 95 % thrust level can reduce the number of qualification firings for a required reliability level and thus reduce the total development and qualification costs.

(5) Evaluation of existing subsystem/ components/ engines for a new vehicle - instead of a new development from scratch - even if they are oversized or required modifications

(6) Cost-per-Flight Definition for any vehicle concept and analysis of the impact of annual launch rate - a most important criterion with respect to the direct and indirect operations costs.

(7) Cost-per-Seat Definition for Space Tourism Launch Vehicles with the major impact of passenger capacity and flight frequency vs. market size, required for any business plan.

(8) Definition of the optimum total number of flights for a reusable launch vehicle, taking into account vehicle cost amortization and refurbishment cost which are increasing with the growing number of reflights.

These are only examples; a number of additional applications can be conceived such as mentioned before (impact of schedule and/ or project organization and management, cost impact of launch rate variations, etc.) . Examples for cost engineering analyses using the *TRANSCOST* - Model are presented in Chapter 6.

1.14 List of Abbreviations (Glossary)

ABM Apogee Boost Motor (or Module)
AFB Air Force Base (US)
AMLS Advanced Manned Launch Sytem
ATE Advanced Technology Engine (ESA Study)
AU European Accounting Unit
BAU „Business as Usual" (=Governmental Contract)
BoM (BoL) Begin of Mission (Begin of Life)
CCC Carbon-Carbon-Composite
CER Cost Estimating Relationsship
CES Crew Escape SYSTEM
CEV Crew Excursion Vehicle
CFRP Carbon-fibre Reinforced Plastic
CL Confidence Level
CLV Crew Launch Vehicle (ARES)
CRV Crew Return Vehicle (ORION)
CpF Cost-per-Flight
CNES Centre Nationale d'Etudes Spatiales (= French Space Agency)
COMSTAC Commercial Space Transportation Advisory Committee
COTS Commercial-Off-The-Shelf (elements)
COTS Commercial Space Transp.Services
CRV Crew Return Vehicle
CSTS Commercial Space Transp. Study
CTC Cost-to-Completion
CTV Crew Transfer Vehicle
CZ Chiang Zhen = Long March (Launch Vehicle, China)
DDT&E Design, Development, Testing and Evaluation
DLR Deutsches Zentrum für Luft- und Raumfahrt (= German Aerospace Center)
DOC Direct Operations Cost
DOD Department of Defense (USA)
ECU European Currency Unit
EDS Earth Departure Stage
ELDO European Launcher Development Organization
ELV Expendable Launch Vehicle
EPS Expendable Perigee Stage
ESA European Space Agency
ETO Earth-to-Orbit
Euro European Currency Unit (previously: AU and ECU)
FESTIP Future European Space Transportation Investigation Program
FFP Firm Fixed Price (Contract)
FSSC Festip Space System Concept
F/ W Thrust-to-Weight Ratio
FY Fiscal Year
GEO Geostationary Earth Orbit
Gg Gigagram (= 1000 metric tons)
GLOW Gross Lift-Off Weight
GNC Guidance,Navigation &Control
GSLV Geosynchronous Satellite Launch Vehicle (ISRO)
GTO Geostationary Transfer Orbit
HMS Health Monitoring System
HRST Highly Reusable Space Transportation (System)
HTO(L)Horizontal Take-off (and Landing)
IOC Indirect Operations Cost
IOC Initial Operational Capability
Isp Specific Impulse
IRR Internal Rate of Return
ISAS Institute of Space and Astronautical Science (Japan

ISRO Indian Space Research Organisation
ISRU In-Situ Resources (Utilization)
ISS International Space Station
JAXA Japanese Aerospace Exploration Agency
kN kilo-Newton (1 kN = 224.8 lbf)
KSC Kennedy Space Center (NASA)
LACE Liquid Air Collection and Enrichment
LaRC NASA Langley Research Center
LCC Life-Cycle Cost
L/ D Lift-to-Drag Ratio
LEO Low Earth Orbit
LF Learning Factor
LFBB Liquid (Prop.) Fly-back Booster
LH_2 Liquid Hydrogen
LLO Low Lunar Orbit
LLV Lunar Lander Vehicle
LOC Loss of Crew
LOM Loss of Mission
LOX Liquid Oxygen
LpA Launches per Annum (launch frequency)
LSAM Lunar Surface Access Module
LTV Lunar Transfer Vehicle (LEO-LLO-LEO)
Mg Megagram (= metric ton = 1000 kg = 10^6 gram)
MTBO Mean Time Between Overhaul
MTBF Mean Time Betwen Failure
MYr Man-Year (cf. TABLE 1-I)
NAFCOM NASA-Air Force Cost Model
NAL National Aerospace Laboratory (Japan) - until 2003
NASA National Aeronautics and Space Agency (USA)
NASDA National Space Development Agency (Japan) - until 2003
NASP National Aerospace Plane (USA)
NMF Net Mass Fraction
NMF* Net Mass Fraction excl. engines
NPV Net Present Value
Ns/ kg Newton-sec per kilogramm (I_{sp})
NRC Non-recurring (= development) cost
OAM Orbit Adjust Module
OMB Office of Management and Budget
OMS Orbital Maneuvering System
ORU Orbital Replacement Unit
OTV Orbit Transfer Vehicle
PPP Phased Program Planning
PSLV Polar Satellite LaunchVehicle (ISRO)
RBCC Rocket-based Combined Cycle
RCS Reaction Control System
RLV Reusable Launch Vehicles
ROI Return on Investment
RPS Reusable Perigee Stage
RSC Refurbishment and Spares' Cost
RSRB Reusable Solid Booster
SL Sea Level
SRB Solid-propellant Rocket Booster
SOC Space Operations Center (LEO)
SpTC Specific Transportation Cost
SRM Solid-propellant Motor
SSME Space Shuttle Main Engine
SSPS Space Solar Power Station
SSTO Single-Stage -to-Orbit (Vehicle)
STA Structural Test Vehicle
STS Space Transportation System
TCS TransCostSystems
TFU Theoretical First Unit (of a production program)
TPS Thermal Protection System
TR Technical Report
TRL Technology Readiness Level
TSTO Two-Stage-to-Orbit (Launch Veh.)
TQF Technical Quality Factor (p.21)
USAF US Air Force
VAB Vehicle Assembly Building
VEB Vehicle Equipment Bay
VHM Vehicle Health Monitoring
VRC Vehicle Recurring Cost (= Unit Production Cost)
VTHL Vertical Taket-off, Horizontal Landing
VTOL Vertical Take-off and Landing
WTS Winged Two-stage System

1.2 The *TRANSCOST*-Model

1.21 Model History and Background

The *TRANSCOST* -Model for Space Transportation Systems Cost Estimation and Economic Optimization is based on the author's dissertation, prepared in the period 1965 to 1970, entitled „Statistic-Analytical Cost Models for the Development and Fabrication of Space Systems", Technical University of Munich, Germany, July 1971. This work was first published in the Journal „RAUMFAHRTFORSCHUNG in German, (ref.1), then as ESA Report TT-4 (1973) in English, and also in Russian in the Journal „Woprosi Raketnoi Techniki, No.12/1972. A Chinese translation of Version 6.1 was prepared in 1997 by CAST, the Chinese Academy of Space Technology, Beijing (400 copies).

Wernher von Braun in his letter from NASA Headquarters in Washington, dated Jan.10, 1972, congratulated the author „on a very thoughtful, thorough, and concise piece of work". Mr.Larry M. Mead, V.P. Grumman Corp., cited it as „the most comprehensive analysis of past programs that I have seen" (letter dated Oct. 27, 1972).

FIG.1-02: **The author of the Handbook** (at that time Director, Advanced Space Systems and Technology at the Space Division of MBB - Messerschmitt-Bölkow-Blohm GmbH) **meets Dr.Wernher von Braun in Ottobrunn**

The second major step towards the present *TRANSCOST*-Model are the analyses performed in the period 1974 to 1978 and published in refs. 3 and 4, dealing for the first time with modelling of *Operations Cost* which are of major importance for future *reusable* launch vehicles.

The long-term history and growth of the *TRANSCOST* - Model is illustrated best by a survey of the various editions:

1971	**Version**	**1.0**	
1980	**Version**	**2.0**	
1982	**Version**	**3.0**	(41 pages)
1983	Version	3.1	
1988	**Version**	**4.0**	(60 pages)
1991	**Version**	**5.0**	(83 pages)
1993	Version	5.1	
1995	**Version**	**6.0**	(143 pages)
1997	Version	6.1	
1998	Version	6.2	
2000	**Version**	**7.0**	**incorporated in the Handbook** (227 pages)
2003	Version	7.1	Handbook Rev.1 (264 pages)
2007	Version	7.2	Handbook Rev. 2 (276 pages)

1.22 Specific Features of the TRANSCOST-Model

Cost estimation on system level by an analytical cost model is an important design tool for the definition of a cost-effective, economic space transportation system. As shown in FIG. 1-03 the „TOP-DOWN" cost estimation represents the first phase

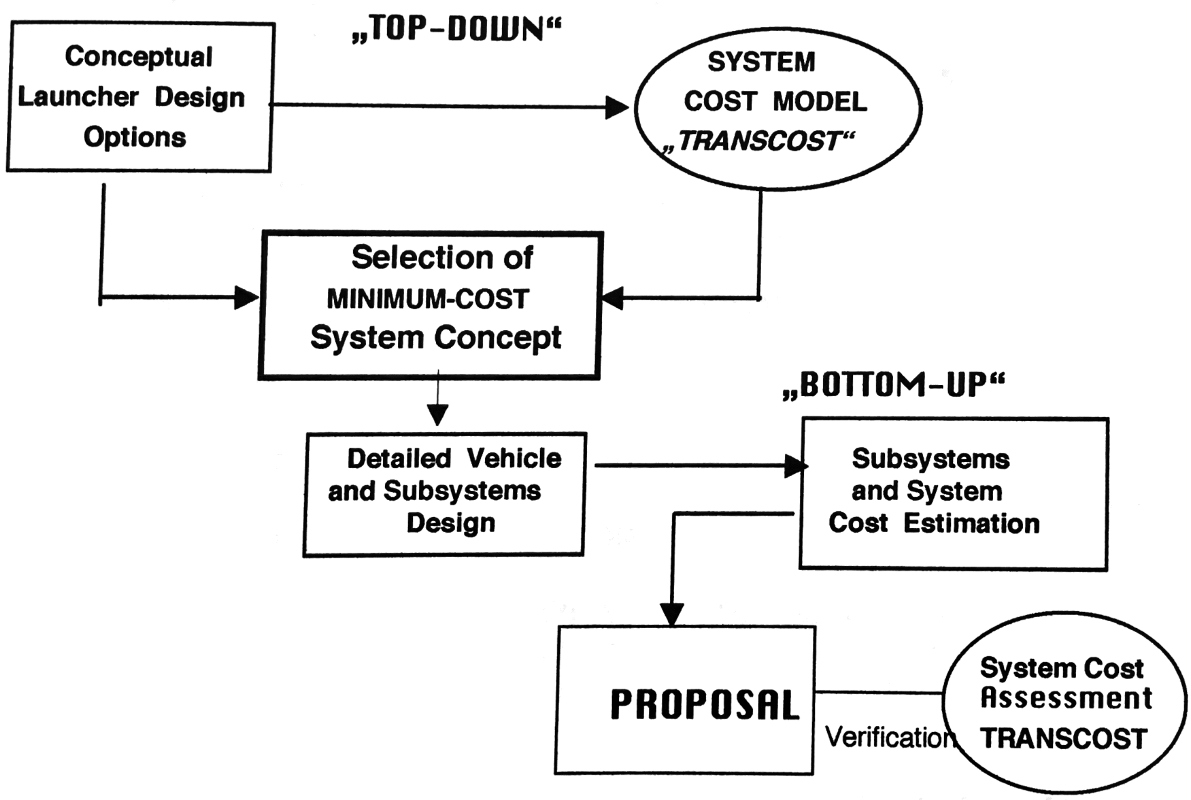


FIG.1-02: **The Dual Role of Cost Estimation: For Vehicle Concept Selection and for Check of the Bottom-up Cost Accounting**

of a design cycle, not replacing the detailed subsystem costing or „BOTTOM-UP" cost analysis. For this purpose, however, the different vehicle subsystems have to be selected and defined which requires a large amount of engineering analysis. The analytical TOP-DOWN analysis with system-level CERs (Cost Estimation Relationsships), as provided by the TRANSCOST-Model allows to avoid the detailed and costly subsystem engineering process for a non-optimum vehicle. This work should only be performed after the cost-optimum vehicle concept has been found as the <u>second design phase</u>. This work dedicated to the subsystems' definition serves as basis for a detailed vehicle cost proposal, the „BOTTOM-UP" cost estimate. After that, the result of the analytical cost estimate can also be used for verification of the detailed estimate, and vice versa.

The *TRANSCOST*-Model with its system-oriented CERs has been conceived as a cost-engineering tool for the definition of a cost-optimum launch vehicle configuration. The Model specific features are summarized as follows :

The *TRANSCOST* - Model

- ❑ has been established for the initial conceptual design phase of space transportation systems and engines,
- ❑ is a SYSTEM - Model which does n o t try to go further into subsystems (except the engines proper), since this is not considered appropriate or feasible in the initial vehicle design phase,
- ❑ is a „transparent model" with graphical display of the reference data points - instead of a classified computer data base,
- ❑ is based on a comprehensive data base gathered over a period of some 47 years (1960 to 2006) from US, European and Japanese space vehicles and engine projects;
- ❑ has been conceived such that it cannot only be used for the design of conventional vehicles but also for advanced (reusable) space transportation concepts;
- ❑ uses the „Man-Year" (MYr) as costing unit, in order to get firm cost data which are valid internationally and independent from annual changes due to inflation and other factors, such as currency conversion rate fluctations;
- ❑ has a reference projects' cost data range of +/- 15 to 20 % which is considered to be the best possible accuracy for historic cost data regression.

The cost values derived by the *TRANSCOST*-CERs, are based on effective industrial development and production. They must be considered, therefore, as PRICES including the normal profit margin of 5 to 12 %. Special incentive fees, however, would have to be considered in addition.

The accuracy of cost estimates or predictions derived with the *TRANSCOST* - Model depend completely on the carefulness and the technical judgement capability of the user. Taking into account the CER data and all the other cost impact factors described in this Model the cost prediction should be very realistic.

1.23 Cost Model Structure and Elements

The *TRANSCOST*- Model is organized in three interconnected submodels, taking into account the three different cost areas in the space transportation business:

- -- the Development Cost Submodel,
- -- the Vehicle Cost Submodel (Production, Integration and Verification)
- -- the Ground and Flight Operations Submodel.

The advantage of this model structure is the possibility of making a cost assessment in all these three areas separately and/ or combine them as well, depending on the specific case of application.

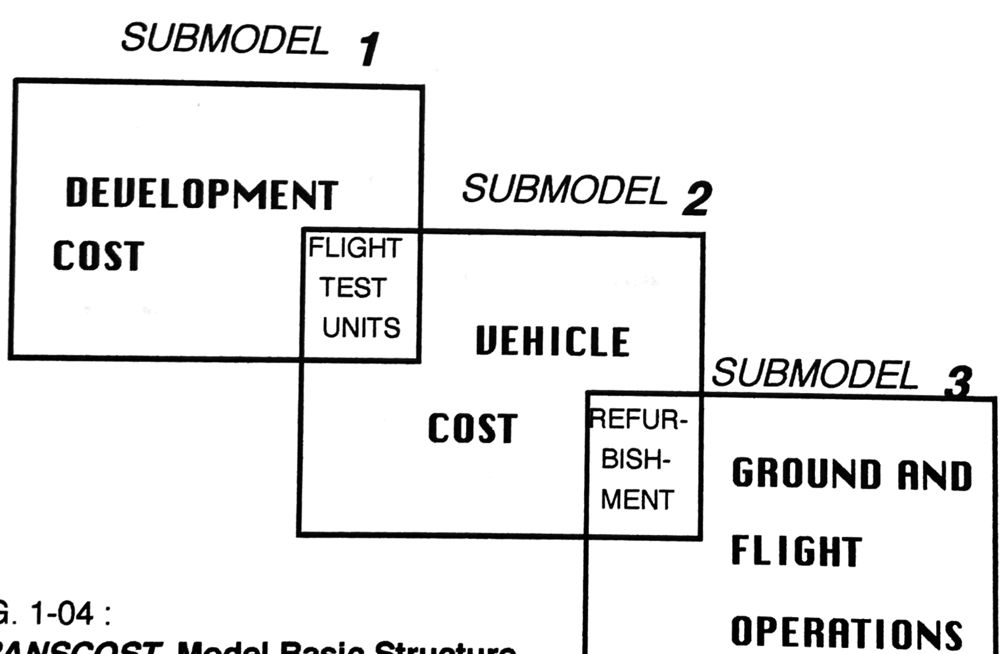


FIG. 1-04 :
***TRANSCOST* Model Basic Structure**

The subdivision into the three submodels as illustrated in FIG.1-04 has been proven to provide the flexibility required for the different applications mentioned in the previous chapter. The next level of model organization for Submodels 1 and 2 are the different technical systems with similar characteristics. For the **Development Cost Submodel** these groups have been extended from 10 in the last TRANSCOST Model Version to now 13 different engine and vehicle species :

		CODE
(1)	SOLID-PROPELLANT ROCKET MOTORS	ES
(2)	LIQUID-PROPELLANT ROCKET ENGINES WITH TURBOPUMPS	EL
(3)	PRESSURE-FED ROCKET ENGINES	EP
(4)	AIRBREATHING TURBO- AND RAMJET-ENGINES	ET
(5)	SOLID-PROPELLANT ROCKET BOOSTERS	VR
(6)	PROPULSION SYSTEMS / MODULES	VP
(7)	EXPENDABLE BALLISTIC ROCKET VEHICLES	VE
(8)	REUSABLE BALLISTIC LAUNCH VEHICLES	VB
(9)	WINGED ORBITAL ROCKET VEHICLES	VW
(10)	HTO FIRST STAGE VEHICLES, ADV.AIRCRAFT	VA
(11)	VTO FIRST STAGE FLY-BACK ROCKET VEHICLES	VF
(12)	CREWED RE-ENTRY CAPSULES	VC
(13)	CREWED SPACE SYSTEMS	VS

The special treatment of engines is required since a vehicle can have different numbers of engines which may be an already existing model, or requiring new development.

For the **Unit Production Cost Model** (Submodel 2) eight specific CERs cover the different engine and vehicle options

		CODE
(1)	SOLID-PROPELLANT ROCKET MOTORS	ES
(2)	LIQUID-PROPELLANT ROCKET ENGINES WITH TURBOPUMPS	EL
(3)	AIRBREATHING TURBO- AND RAMJET-ENGINES	ET
(4)	PROPULSION MODULES	VP
(5)	BALLISTIC ROCKET VEHICLES (EXPENDABLE & REUSABLE)	VE
(6)	HIGH-SPEED AIRCRAFT/ WINGED FIRST STAGES	VA
(7)	WINGED ORBITAL ROCKET VEHICLES	VW
(8)	CREWED SPACE SYSTEMS	VS

For each of these technicial systems in the development and production area a specific CER (= Cost Estimation Relationship) has been derived which is mostly mass-related with the basic form of

$$C = a \cdot M^{x}$$

with C = cost, a = system-specific constant value, M = mass in kg,
x = system-specific cost-to-mass sensitivity factor.

For **Ground and Flight Operations Submodel** the cost organization is according to the type of activities, such as

(1) PRELAUNCH GROUND OPERATIONS
(2) LAUNCH AND MISSION OPERATIONS
(3) GROUND TRANSPORTATION AND RECOVERY
(4) PROPELLANTS, GASES AND MATERIAL
(5) PROGRAM ADMINISTRATION AND SYSTEM MANAGEMENT,
(6) TECHNICAL SYSTEM SUPPORT
(7) LAUNCH SITE AND RANGE COST

In this case CERs can only be applied in some cases; in others manpower assumptions have to be made.

1.24 Data Processing and CER Derivation

The key to a realistic cost model is the careful determination of the CERs. The methodology applied for the *TRANSCOST*-Model is shown in FIG.1-05: the first step is the establishment of a correct and large enough data base. The raw cost data have

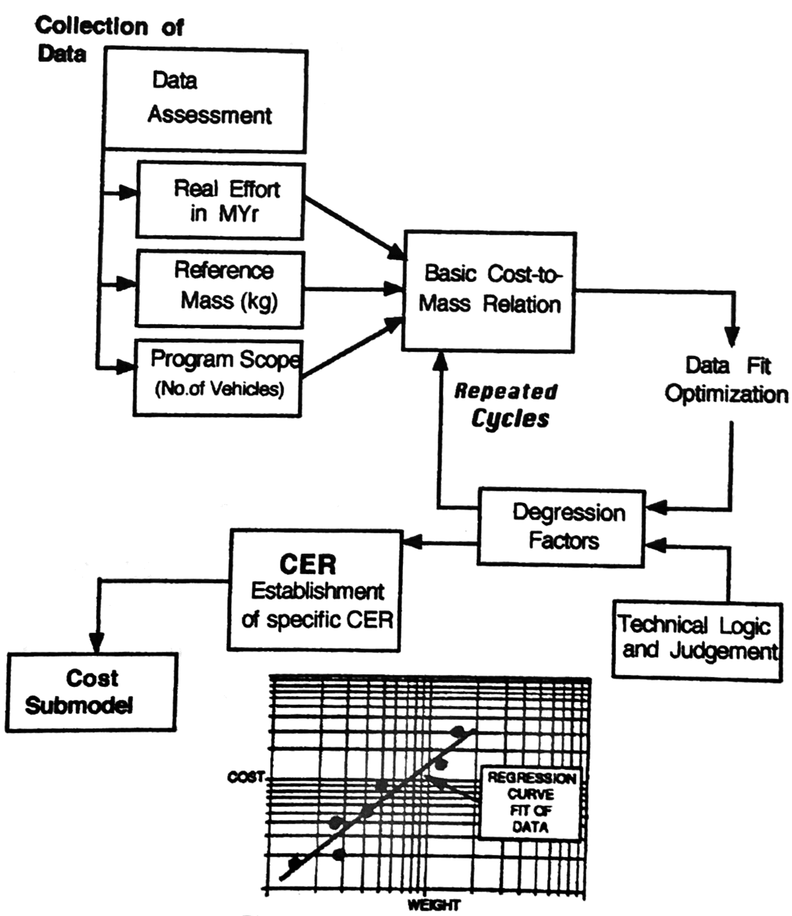


FIG. 1-05: **Cost Model Derivation Process: From Raw Data to a CER**

to be assessed on the validity and the time period covered. Then a conversion of the actual costs to the appropriate MYr-value is required in order to make projects comparable performed at different time periods and in different countries.

From the specific cost-to-mass relationship of a group of similar systems, both key factors, namely a and x can be determined. This is done with help of the EXCEL Program which automatically derives the "best fit" result. This evaluation also must take into account to exclude extreme reference values, if the reasons for extraordinary high or low cost are not known, and to consider the "first-of-a-kind"-projects with increased costs (in average some 25% above the reference level).

For *development CERs*, however, this process is not sufficient to achieve the desired reference data range of + /- 20 to 25 %. It is required to introduce three degression factors for the Development Cost Submodel CERs:

f_1 = **Technical Development Status Factor,** related to the status of other similar projects (First of its kind, etc.),

f_2 = **Technical Quality Factor**, derived specifically for each system from inherent technical parameters, and

f_3 = **Team Experience Factor,** based on the previous team experience with similar projects

For the Vehicle Production Cost Model the „Learning Factor“ has to be taken into account, with

f_4 = **Cost Reduction Factor for series production.**

The definition of the appropriate range of values to be applied are described in chapter 3.2 (Unit Production Cost, Learning Factor p / Production Quantity Impact)

1.25 Cost / Mass Relationship and Mass Margins

Most CERs are based on a reference mass of the system or unit. This does not mean, however, that cost are directly proportional to the mass. The real situation is much more complex and there are cases that lower mass means higher cost, by example the introduction of advanced technology in order to reduce weight, but this can be taken into account by the Technical Quality Factor, as shown in examples later.

Another problem is the underestimation of the vehicle system or unit mass which is the rule for advanced projects in the initial design phase. This has nothing to do with safety design margins or unsufficient calculation accuracy, but with the addition of a large number of secondary items as well as additional requirements coming up in the detailed design phase. Since an underestimation of mass automatically leads to too low cost, it is required to include in each project mass estimate an add-on mass margin of 5 to 20 %, depending on the study phase (see TABLE 1-II).

This shall be illustrated by historic facts: The actual mass increase for the THOR vehicle was 6.3 % between design and delivery, for the SATURN S-IV and S-IVB cryogenic stages 13.7, resp. 12.5 %. The LUNAR LANDER Module even experienced a mass growth during development of not less than 27 % (cf. FIG. 2-57). But this

TABLE 1-II : **Recommended Design Mass Margins**

	Phase A Study	*Phase B Study*
-- FIRST OF ITS KIND	20 - 15 %	15 - 12 %
-- ADVANCED DESIGN	15 - 10 %	10 - 7 %
-- CONVENTIONAL DESIGN	10 - 7 %	8 - 5 %

is no surprise for a „first generation" system. The SPACE SHUTTLE Orbiter exhibited 25% mass growth during development (ref. 93). The Airbus A 380 had a mass growth of some 3 % during development.

Based on past experience it is recommended to use at least the mass margin values shown in TABLE 1-II for space transportation system studies.

This mass margin should not be considered as structural design margin. This structural safety factors are generally between 1.1 to 1.25 for expendable vehicles and 1.4 to 1.8 for reusable launch vehicles (cf. TABLE 2-I).

1.26 The Man-Year (MYr) Cost Definition

A specific feature of the *TRANSCOST*-Model is the application of the Man-Year effort as costing value. This is not (yet) a commonly introduced feature, however, it is the only way for a cost model derived from and to be used for projects of different time periods - between 1960 to the year 2006 - and in different countries with different currencies, different inflation rates and floating conversion rates to the US Dollar.

For illustration of the problem FIG. 1-05 shows the variation of the exchange rate between the European currency unit Euro and the previously used „ Accounting Unit (AU)" or ECU and the US Dollar. Similar fluctuations have taken place in case of the Yen vs. the US$ (between 100 in 1999 and 240 in 1984). It would be very difficult to consider these variations in a Dollar-based cost model.

TABLE 1- II : **Cost History of 1 MYr (ManYear) in the US-, European and Japanese Aerospace Industry**

YEAR	**USA*)** US$	**Europe**)** Euro(ECU /AU)	**Japan***)** MillionYen
1960	26 000	18 000	
1961	27 000	18 900	
1962	28 000	20 000	
1963	29 000	21 000	
1964	30 000	22 000	
1965	31 000	23 200	
1966	32 300	24 400	
1967	33 200	25 700	
1968	34 300	27 400	
1969	36 000	29 100	
1970	38 000	31 000	
1971	40 000	33 050	
1972	44 000	35 900	
1973	50 000	38 700	
1974	55 000	43 600	
1975	59 500	50 000	
1976	66 000	55 100	
1977	72 000	60 500	
1978	79 700	65 150	
1979	86 300#	71 800	
1980	92 200	79 600	
1981	98 770	86 700	
1982	105 300	92 400	
1983	113 000	98 300	
1984	120 800	104 300	14.6
1985	127 400	108 900	15.2
1986	132 400	114 350	15.8
1987	137 700	120 000	16.4
1988	143 500	126 000	17.1
1989	150 000	133 000	17.6
1990	156 200	139 650	18.1
1991	162 500	145 900	18.6
1992	168 200	151 800	19.0
1993	172 900	156 800	19.5
1994	177 200	160 800	20.0
1995	182 000	167 300	20.5
1996	186 900	172 500	21.0
1997	191 600##	177 650	21.5
1998	197 300	181 900	22.0
1999	203 000	186 300	22.6
2000	208 700	190 750	23.2
2001	214 500	195 900	23.8
2002	220 500	201 200	24.4
2003	226 400	207 000	25.0
2004	232 100	212 200	25,6
2005	240 000	217 500	26,3
2006	246 000	222 300	26,9
2007 estimate	252 000	228 500	27,5

Footnotes see next page

*) Established with application of NASA's official annual cost escalation factors
**) Based largely on official ESA annual cost growth values
***) Basis data from „The Aerospace Industry Year Book", Society of Japanese Aerospace Companies
\# = USAF Reference value
\## = NASA 1997 effective average MYr cost from 533 contracts

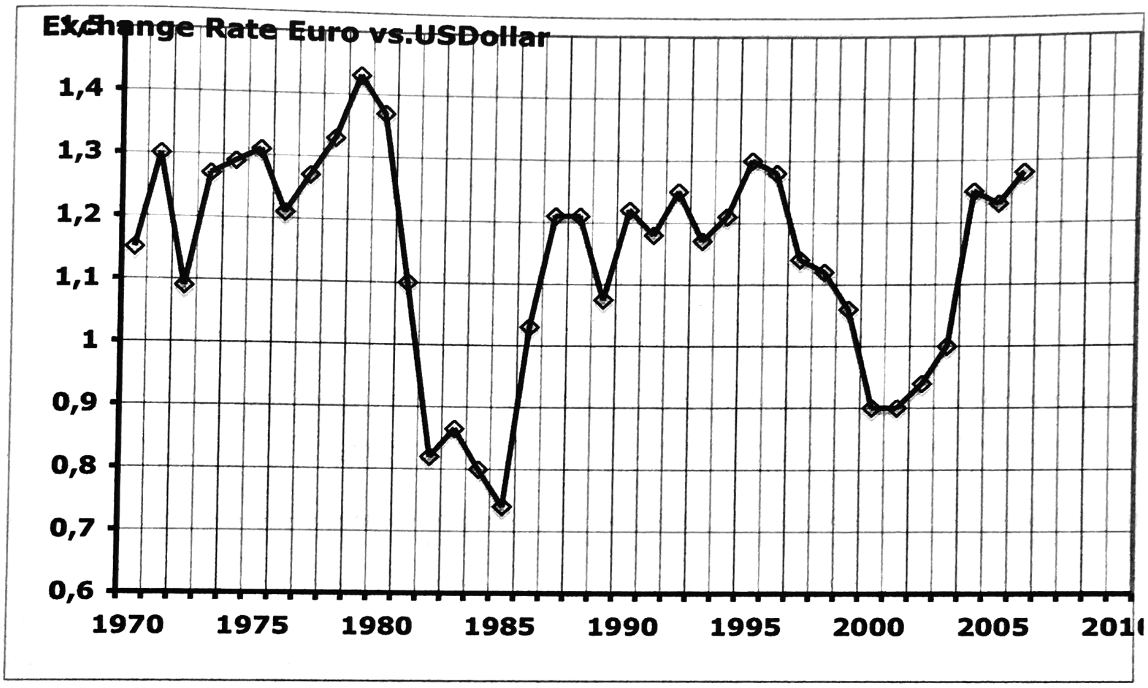


FIG. 1-05: **History of the Currency Exchange Rate EURO** (AU, ECU) **vs. USD**

1.27 Impact of Productivity in different Countries/Regions

1.271 Productivity Improvement vs.Time

Productivity improves with time by better knowledge and the application of more advanced material and processing technologies. By example, a NASA analysis (ref.144) concluded that the APOLLO Hardware nowadays, some 50 years later would require 33% less effort to develop and 22 % less to build. However, this is limited to mechanical systems; in the area of avionics and software the contrary is the case due to the much increased requirements and capabilities. Therefore, since the TRANSCOST-Model is a systems model where the two effects are considered to balance out more or less, productivity improvement vs. time is not being taken into account.

1.272 Productivity Difference in other Countries/ Regions

There seems to be a certain difference in productivity in some areas of the world compared to others which may influence the number of ManYears required for the same task. The data base for the *TRANSCOST*-Model stems mainly from US projects and is, therefore, based on the productivity in the US Aerospace Industry.

If „productivity“ is defined as a combination of annual working hours, education and dedication to work then it should be feasible to establish a „productivity correction factor“ with respect to the productivity in the USA. The following table is an attempt to derive some kind of numerical factor which certainly is subjective with respect to the quality of education and dedication.

It is left to the user to apply such a factor and / or to modify it according to his / her own judgement. It seems, however, that the application of such a „productivity correction factor“ to the MYr effort data does improve the coherence of international reference data.

TABLE 1-IV: **Productivity Model for Different Countries/Regions (f_8) 1980-99**

COUNTRY	(1) Effective Working Hours per year		(2) Relative Education	(3) Relative Dedication	Relative Productivity (Product of items1-3)	MYr Correction Factor f_8
USA (REF.)	1847,	$h^{0.7}$ =1.94	1.00	1.00	194 = 1.00	**1.00 (Ref.)**
Europe (ESA)	1583	174	1.20	1.08	225 = 1.16	**0.86**
France	1611	176	1.30	1.10	252 = 1,30	**0,77**
	1561*	172	1.30	1.10	246 = 1.27	**0.79**
Germany	1568	172	1.30	1.13	252 = 1,30	**0,77**
	1674*	180,5	1.30	1.13	265 = 1.37	**0,73**
Japan	2052	208	1.13	1.18	278 = 1.43	**0.70**
Russia	est. 1600	175	0.75	0.70	92 = 0.47	**2.11**
China	1958	201	0.85	0.85	145 = 0.75	**1.34**

*) Post-2000 values

Effective working hours are defined as total nominal working hours per year, minus vacation, illness (average) and other absence, plus overtime hours.

Most the values in TABLE 1-IV have been valid for the 90ies, with some updates according to OECD data. The MYr correction factor may change with time, both by

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*) Post-2000 values

Effective working hours are defined as total nominal working hours per year, minus vacation, illness (average) and other absence, plus overtime hours.

Most the values in TABLE 1-IV have been valid for the 90ies, with some updates according to OECD data. The MYr correction factor may change with time, both by improvements in engineering education as well as by change of the effective total working hours per year. So in France the total working hours per year have been reduced, while there has a slight increase in Germany in the last years according to OECD data.

1.28 Launch Vehicles' Mass Definitions

The following definitions and designations have been used in this book for the launch vehicle mass values :

M_0 total system mass or launch weight = GLOW, GTOW
M_1 total vehicle mass excluding payload
M_P usable propellant mass for the ascent phase
M_{net} vehicle net mass (M_1 - M_P), equivalent to vehicle mass at main engines' cut-off
M_E rocket engine(s) mass
M_{dry} vehicle dry mass (with engines)
M_S vehicle dry mass without engines
$M_{P/L}$ Payload (with adapter but without fairing or container)

1.29 List of Symbols

C Cost in MYr (man-Years)
C* Specific cost in MYr / Kg
D Launch operations effort
F Fabrication, Integration and verification effort (MYr)
f_0 project system engineering and integration factor verification
f_1 technical development standard correlation factor
f_2 technical quality correlation factor
f_3 team experience correlation factor
f_4 cost reduction factor, resulting from Learning Factor application
f_6 cost growth factor for deviation from the optimum time schedule
f_7 cost growth factor for development by parallel contractors
f_8 productivity correction factor
H development effort for a specific element in MYr
k stage net mass fraction of expendable vehicles = Mnet/ MP
L launch rate (number of launches per year (LpA)
M reference mass (kg)
N number of stages, engines, crew members or qualification firings
n number of *equal* units to build
p Learning factor
Q Vehicle Factor in Mission Control Cost
r number of flights per vehicle or engine(s)
R refurbishment effort in MYr
T mission period (days)
x CER factor for the cost/ mass sensitivity

SUBSCRIPTS:
a crew members (number of)
B administration / amortization charge
C prelaunch operations
D development
e launch and mission operations
F fabrication, assembly and verification
G guidance, control and recovery
m mission
N vehicle stage number
O Operations
P propellants
Q qualification
R reusable
t transportation
V vehicle system