Successful Cost Estimation with T1 Equivalents

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Abstract

The parametric estimation of development costs is difficult, and many cost models and CERs are barely predictable, because of sophisticated methods. Due to complex mathematical formulas of the models the estimators often have not the “good feeling” on the results. This paper shows a more simple and transparent method, which utilizes linear factors on T1 (the recurring first unit). The successful applicability of T1-equivalents could be demonstrated with the ESA internal cost model SPICE. SPICE (Standard Parametric Information for Cost Engineering) is a general model, which has been applied for various space program and launcher cost estimates since many years.

Also the paper addresses tailoring of T1-equivalents to the different levels of a cost breakdown structure. This includes data structuring and the problem of missing industrial standards.

Biography of Georg Reinbold

Georg Reinbold is Senior Cost Engineer at ESA, the European Space Agency.

Georg began his career in the aerospace industry at former Astrium in Bremen in the year 1989. In the Project Control Division he was responsible for integration of overall cost of the Columbus program. He was part of a small team, which developed new and computerized project control methods for this important program, including Cost Reporting, EAC Procedure, WBS Management and Performance Measurement.

In 1990 he was trained on PRICE-H in Mount Laurel. Over the years many other training courses followed, including all other PRICE tools, FAST-E, SEER-H and ACES. From 1993 onwards Georg was fully assigned to parametric cost estimation. He supported large projects such as Ariane 4 production, Ariane 5 development and production , ATV and Columbus, as well as many studies on future spacecrafts, space stations, lunar and planetary landers, launchers and reusable launchers. In the year 2001 he developed the LCCM-2 parametric cost model based on EXCEL, which was capable to replace the PRICE-H tool.

Georg was 20 years with Astrium in Bremen, before he joint to ESA as senior cost engineer. At ESA he developed a parametric tool named SPICE. His major involvement is presently the Ariane 6 development.

Georg has more than 25 years of experience in parametric cost estimation. He is member of ICEAA, the German ISPA and SSCAG. In the year 2000 he was honoured by the international ISPA as the Parametrician of the Year.

ESA Cost Engineering Section

The ESA Cost Engineering Section (TEC-SYC) belongs to ESTEC in Noordwijk and is organized in the technical directorate. About 10 cost engineers are supporting all ESA directorates. The preparation of cost estimates is a standard process. The team is regularly involved in system studies executed in the Concurrent Design Facility (CDF). More important are independent estimates for actual spacecraft procurements. In order to be unbiased and independent these estimates have to be deliver before receiving the proposals from industry. Mainly this concerns development programs of new satellites, which are often a first its kind mission. By nature those estimates are difficult.

Also the cost engineering section maintains a cost database. The database includes costs and technical information collected from all available ESA programs, mainly from satellites but also from human space and launchers. The original costs are archived as it was reported. The subsequent normalization is part of CER development and tool calibration.

There are many cost estimating tools in use:

- RACE for rapid estimation of satellites
- ESA Standard CERs for subsystems and equipment
- SPICE as a general tool (similar to PRICE-H) applicable for all types of spacecrafts and launchers
- Several Precursor Models for special applications, i.e. for scientific large payloads
- POCOMO for estimation of project office costs
- TruePlanning and PRICE-H

Except for TruePlanning all tools are own in-house developments. Also it is to mention, that the Precursor Models generate input parameters from various technical data for the commercial PRICE-H model, which runs in the background.

Some of the tools are less transparent, especially the commercial tools are black boxes. Here the estimator has no other chance than to rely on the results. This paper shows a rather simple method which provides a good feeling on the results. The method is part of the in-house developed SPICE tool.

Lessons learned from estimating of development costs

Estimation of production costs is rather simple compared to the estimation of development costs. While the scope of production effort is clearly defined by the quantities, the scope of development effort is much more difficult to determine. It depends on heritage, company experience and availability of resources and special facilities. Thus the scope of development is different from project to project. It is subject of evaluation from:

- Amount of requirements
- TRLs achieved at begin of development
- Required qualification levels (full qualification, delta qualification or analytical qualification)

- Number of models to be built for tests and qualification
- Engineering effort for preliminary and detailed design

The different scopes of development are the reason why data points do largely scatter for simple CERs. However, CERs can be improved through introduction of appropriated programmatic parameters. But this makes the CERs complex.

With complex CERs the cost estimator loses the good feeling, especially if the CER was developed by colleagues, which then have the better background knowledge. Complex CERs often include sophisticated mathematical formulas, which are less transparent and impossible even to draw as 3d-diagram. Also some constellations in setting of multiple parameters may provide surprising results, either due unexpected levers on costs, or due setting of parameters outside the boundaries of historical data.

A major issue concerns the determination of input values. Programmatic aspects are barely to measure, and selection of parameter values are often highly subjective and depend on the estimator's skill. Also parameter values need to be available and obtainable from normal project documentation. They should be known for estimates also in early study phases, and if not, it should be possible to guess them with sufficient accuracy.

Is there any method to avoid complex CERs? The estimation with T1-equivalents could be a rather simple approach to development cost.

History of the method with T1 Equivalent Units

Jaeger, 1976:	
HELIOS Satellite	
Structure Model	0.1
Thermal Model	0.2
Engineering Model	0.5
Prototype	1.5
Design & Development and Redesign	2.0
Flight Units	2.0
Spares	0.2
Total EU	**6.5**
Total Project Cost = Flight Unit Cost x 6.5	

The method of T1 Equivalent Units is old. I detected it in a doctoral thesis of Ralph Jaeger, issued 1976, who applied it for cost breakdown of the HELIOS satellite. Jaeger questioned the stability of the factors for future estimates. He could not prove it due to a lag of historical data.

Also the method was reported 1994 in SSCAG, in the rules of thumb provided by Claus Meisl.

Meisl, 1994:

Spacecraft development costs are one-and-a-half to seven times first unit cost depending on amount of new design and level of technology used. Development cost includes design, testing and qualification, but excludes protoflight hardware and support.

Dev $(M) = 1st Unit Cost x Factor

	Factor	
	Simple S/C	Complex S/C
All new design	5 to 7	4 max
50% new design	4	3
90% off the shelf	1.2	1.4

Finally I found it in a book named Space Economics, published 1992 by AIAA, where H.C. Mandell mentioned an **Equivalent Units Calculation**:

> *"In this method every prototype article is assigned as an equivalent quantity of flight units , and an equivalent is also estimated for design and development activity, taking into account difficulty, inheritance, etc."*

The method looked simple, too simple for a reliable costing tool, I thought many years ago. However, after 20 years of experience in estimating development costs I remembered this simple approach. First of all I discovered that Meisl was right: Development costs of satellites are within the range of his rules of thumb. Secondly the factors are linear. While Meisl and Jaeger estimated at total system level, the linearity of factors should allow to apply them at subsystem and equipment level too! That would increase the overall estimating accuracy. That was my idea for a new costing approach.

SPICE

At ESA I got the opportunity to develop a new cost model. We called it SPICE – Standard Parametric Information for Cost Engineering. SPICE is a general cost model. It allows to model individual product trees, thus it is applicable for any space system or launcher. It is rather a method providing ground rules and simple formulas for cost modelling in EXCEL. The parameters are easy to obtain from historical data, or to be determined from tables.

SPICE utilizes the Equivalent Unit Calculation at equipment level:

Development Cost = T1 * EU

(T1 = Theoretical First Unit, EU = Sum of Equivalent Units)

The EU-factor provides a good measurement for the ratio between recurring and non-recurring costs. It can be used for benchmarking to other projects too. The EU-factor is estimated from the sum of detailed T1-equivalents.

EU = DD + DM + EM + QM + FM

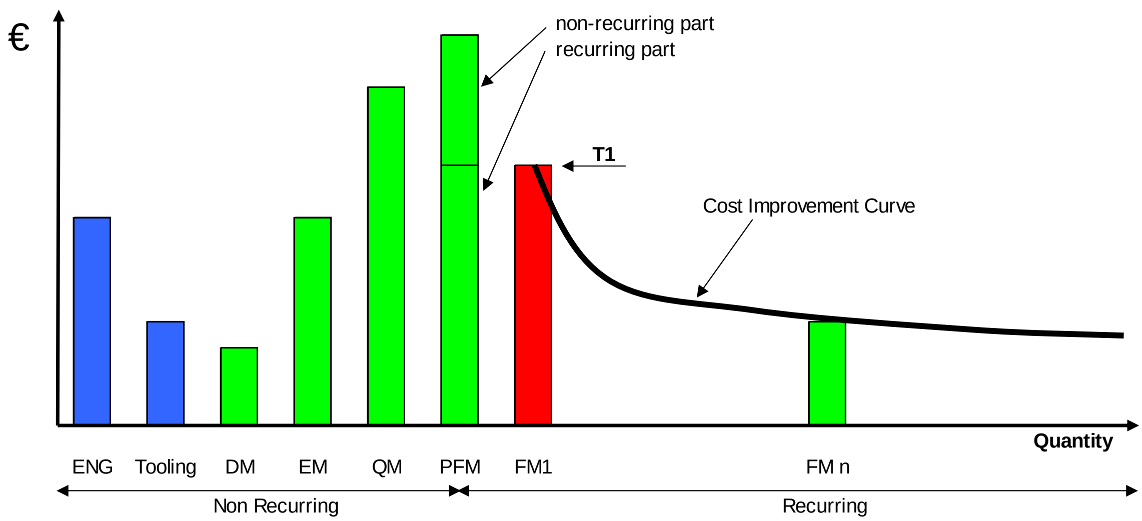
(DD = Design & Development Engineering, DM, EM, QM, FM = Hardware Models and Tests)

This paper is not dealing with estimation of T1 or recurring costs. For standard equipment T1 is often known and can directly picked up from the database, or it can be estimated from CERs. The preferred solution in SPICE is to estimate T1 from mass and manufacturing complexity, similar to PRICE-H.

Important constrains are related to T1. Its estimation needs to be based on consistent rules, otherwise a set of uniform EU factors cannot be applied! This concerns clear rules between recurring and non-recurring (T1 is recurring), and a consistent learning curve.

It is to mention that an estimating error in T1 automatically reproduces an error in development cost!

T1 Equivalents



The diagram above shows how it works. T1 (or FM1) is in the centre of the estimate. All non-recurring cost elements are estimated as equivalents of T1, also engineering and tooling. Since T1 includes management and product assurance, management and product assurance is included in all other cost elements too.

As a ground rule the qualification effort of a proto-flight model is shared to non-recurring, while the remaining manufacturing effort is shared to recurring. This way to separate costs stems from NAFCOM.

In this method T1 is defined as "theoretical cost of only one unit to produce". The cost improvement curve has to consider this definition, especially if production costs are used for tool calibration. For example historical costs of production lots have to be normalized along the learning curve (LC) back to T1. An uncontrolled change of the learning curve would lead to changed T1, and thus would damage the whole model! The once established T1-equivalents would become obsolete. Therefore the LC should be consistent. In SPICE a 90% Crawford LC has been found appropriated for satellites. For launchers it is a 93% LC on quantity in combination with a 89% LC on rate per year.

T1 Equivalents at Equipment Level

T1 Equivalents

Satellite Equipment Level	Unit	Complexities		Hardware & Test Factors				ΣEU	Cost		Assumptions		
	Mass [kg]	MX	DD	DM	EM	QM	FM		T1 [k€]	Total [k€]	TRL	Design	Remark
Structure	61.0	7.13	1.5			1.3	1	3.8	897	3409	5	new design	
OBC	10.0	9.24			0.7		1	1.7	1410	2397	9	existing	
Star Tracker			0.2		0.7	0.1	2	3.0	330	959	8	minor modification	T1 from database
PCDU	17.6	8.35	0.5	0.2	0.7	0.3	2	3.7	999	3603	7	modification	
etc	...	...	...	...	...	...	...	...	...	...			
Total Hardware Phase C/D								**2.1**	**14000**	**30000**			

The above table provides an example on how the estimate can be organized in EXCEL. It shows the equipment level costs, meaning the costs are estimated as for equipment level contractors. The T1-equivalent units are in red colour.

Shown cost figures and factors are examples only

Typical T1-equivalents used are listed below:

DD = Design & Development Engineering

DM = Development Model, in-house models, breadboards, also incl. tooling
DM factor depends on kind of model, tooling, etc.

EM = Engineering Model
EM is often below flight standard (i.e. without hi-rel parts)
EM = 0.5 … 1.1, depending on flight representativeness

QM = Qualification Model, also Structure Thermal Model (STM)
QM = 1.1 … 1.3
(much higher values for rocket engines or other complex items)
In case of PFM the qualification effort is shared to QM
(PFM to be modeled as FM = 1 plus QM = 0 … 0.5)

FM = Flight Model

The numbers and kind of models are stored in the historical database. For estimates this information might not always given as input, but it can be obtained from TRL and other assumptions, also from discussions with engineers. The factors per model include quantity, degree of flight model representativeness and amount of tests. The estimator may select the factors from calibrated references, or guess them from own experience.

A bit more uncertain is the selection of T1-eqivalents for DD (Design & Development Engineering). A preliminary reference table is supporting it.

Scope of Design Effort	DD
Off-the-shelf, existing	0
Minor modification	0.1 – 0.2
Modification	0.5
Major modification	1
New design	1.5 – 2.0
New development	2 – 3

Shown cost figures and factors are examples only

It is to mention that similar T1-equivalents can be used across most product families without special adjustment per family. But for solid rocket motors and liquid rocket engines the factors are much higher, probably due to the nature of hot firing tests and multiple design cycles.

T1 Factors at System Level

In this method all hardware belonging to a spacecraft is defined as equipment. Software counts in addition. System and subsystem level tasks are necessary for higher level engineering and integration. Satellite projects are normally organized for direct procurement of equipment by the prime contractor, without involvement of subsystem contractors. However, human space and some other programs often are established on more heavy organizations with responsibilities given to subsystem contractors too.

The fictive example below shows a WBS, where a subsystem contractor is responsible for the Propulsion subsystem.

WBS	Equipment (HW)	System & Subsystem Level PO	System & Subsystem Level AIT
PO			
Mgmt		x	
PA		x	
Eng		x	
Mechanical Eng			
Thermal Eng			
Electrical Eng			
etc			
AIT			x
Structure	x		
Mechanisms	x		
Power Subsystem			
Solar Array	x		
Batteries	x		
PCDU	x		
Harness	x		
Propulsion			
Lead Tasks		x	
AIT			x
Propellant Tanks	x		
Main Engine	x		
Thrusters	x		
Propulsion Equipment	x		
Avionic			
DMS	x		
RTU	x		
etc			

In order to achieve a good correlation of factors, system and subsystem level tasks are added together. This is a valid approach under the assumption that prime and subsystem contractors are sharing the work. However, slightly overlapping of tasks and additional supervisory activities of the prime are normal and should be considered with the factorization.

Satellite Development	Reference T1 [k€]	Factor	Cost [k€]	% of HW + SW	Remark
Satellite Equipment Level (HW)	**14000**	**2.1**	**30000**		**Reference**: Sum of all equipment level costs
Software			**1000**		not depending on HW cost
System & Subsystem Level:					
Project Office	14000	1.5	21000	68	includes systems engineering
AIT				18	
PFM (Protoflight Model)	14000	0.25	3500		factor on ∑ of Equipment T1
STM (Structure Thermal Model)	1200	0.15	180		factor on ∑ of Structures T1
ATB (Avionics Test Bench)	7000	0.25	1750		factor on ∑ of Avionics T1
GSE	14000	0.20	2800	9	
Subtotal	**14000**	**2.09**	**29230**	94	
Total Phase C/D	**14000**	**4.3**	**60230**		Total factor on ∑ of Equipment T1

Shown cost figures and factors are examples only

The table above shows the estimation of costs at system level and how it can be organized in EXCEL. The main reference for factors is the sum of all T1 costs from equipment level. This represents the recurring value of all spacecraft's hardware, however without integration to the system.

The Project Office tasks, which include Management, Product Assurance and Systems Engineering, are estimated by a factor on the T1 reference. This factor depends on

- Scope of system and subsystem engineering
- Number of subcontractors involved
- Schedule (normally phase C/D, but if phase B2 is included, the factors increase by 20% to 25%)

The kind of AIT models reflects the model philosophy at system and eventual subsystem level. In the example the PFM factor is put on the sum of equipment T1 (as it is the case for the PO factor). This makes sense, because all hardware needs to be integrated to the final flight model and tested. Other models at system level are normally partial models only. In the example the STM (structure and thermal model) is representing the integration and test of structures, mechanical parts and mass dummies. The ATB (Avionics Test Bench) represents the integration and test of engineering models (electrical representative models) connected to EGSE and simulators. For both models the T1 references could be summed up from the equipment level due selection of what belongs to structures and what to avionics.

Although this method seems to be promising, it is still recommended to cross-checked the results with other methods. In the above table the column “% of HW and SW” refers to the traditional cost-to-cost relationship. A further cross-check can be done with the team-size-and-time method.

Presently all factors are to select from appropriated historical projects. A reference table for a common use of average factors is still under investigation.

Recurring Production

Shown cost figures and factors are examples only

Satellite Recurring Production	**Reference T1** [k€]	**Factor**	**Cost** [k€]	% of HW + SW	**Remark**
First Recurring Unit:					
Satellite Equipment Level	14000	1.0	14000		no changes
Software			0		no SW update
Project Office	14000	0.30	4200	30	factor typically between 0.2 and 0.3
AIT	14000	0.08	1120	8	factor typically between 0.06 and 1.2
First Recurring Unit	**14000**	**1.4**	**19320**		Total factor on ∑ Equipment T1
Additional units to be calculated by Learning Curve					

The estimation of recurring production of an integrated spacecraft is easy to obtain with this method. The T1 reference is the same as for estimation of development costs; it is the sum of all T1 from equipment costs. The factors to estimate PO and AIT are already known from traditional cost-to cost CERs. For the first recurring unit the PO factor is between 20% and 30%, depending on the amount of engineering changes. This is much less than for development, because recurring production doesn’t need development engineering, except for changes. For advanced lot production the PO factor is even below 20%. AIT includes acceptance testing only. The factor is about 8% in average, what is much below of PFM testing in development.

The resulting cost is for a first recurring unit. Additional units are to calculate by means of the cost improvement curve.

Calibration (how to obtain T1-Equivalents from historical data)

The split of equipment costs in non-recurring and recurring is mandatory. Cost data of ESA projects are normally reported by means of ECOS, especially in case of phase C/D proposals. ECOS, the ESA Costing Software, provides a product tree oriented cost breakdown. Each work packages of the WBS is built from a Product Tree Element plus a Support Function. The main important elements of the Support Function Tree are listed in the table below.

ECOS Support Functions		
PO		Project Office
	MGMT	Management
	PA	Product Assurance
	ENG	Engineering
MAIT		Manufacturing, Assembly, Integration, Test
	DM	Development Model
	EM	Engineering Model
	QM	Qualification Model
	PFM	Proto-flight Model
	FM	Flight Model
GSE		Ground Support Equipment
SW		Software
O&L		Operations & Logistics

The FM (Flight Model) reflects recurring cost. T1 of an equipment can be determined accordingly:

T1 = Flight Unit Cost = FM + fraction of PO

So the calculation of T1 includes a bit of cost normalization. The fraction of PO derived from statistics (PO considered about 15% of FM):

T1 = FM * 1.15

Finally with well received ECOS data the calculation of T1-equivalents is immediately done. (DD-factor = ENG/FM, EM-factor = EM/FM, etc.) In case PFM has been reported instead of FM, a further normalization needs to be done.

However, in some proposals the contractors don't provide sufficient cost details for equipment. Often a lump sum MAIT is reported and FM remains unknown. In such a case T1 needs to be guessed, also with help of parametric means and especially due top-down established T1-equivalents! One can say that would not be a true calibration of data. However, it is a partial calibration!

Main problem: Different Accounting Rules

Different contractors often apply different rules for breakdown of costs. An example is given below for cases A and B. In both cases the overall costs contributing to Equipment X is 110k€. But what is the cost of Equipment X?

WBS	**A**	**B**
System Level		
Procurement Eng.		10
Equipment Level		
Equipment X	**110**	**100**
Subco	100	100
Prime	10	

In case A the prime contractor claims a workshare of 10% in addition to the subcontractor's quotation. This could be the procurement overhead, but also a true workshare, such as engineering, manufacturing, given parts, etc. Without further explanation the true cost of Equipment X remains unknown. In case B the situation is clear: Equipment X costs 100k€, and procurement engineering of the prime counts in addition.

It is obvious that different accounting rules let cost data scatter:

- Scattering of source costs used for CER creation
- Scattering of factors between system level and equipment level

In order to avoid data mismatches it is essential to normalize all costs to a standard WBS. Also clear rules for all contractors would be desirable for a good understanding of all data.

Lessons learned from estimation with T1 Equivalents

Jaeger and Meisl used EU-factors (equivalent units factors) at total system level. Estimates at subsystem, assembly or component level are more accurate. The breakdown reflects the design in more detail. Also the determination of the factors is more precise. The linearity of factors makes the estimation possible at lower levels of the product tree.

Rigorous calibration with equipment data proved the ability of the method. Although factors slightly differ from product family to product family, a uniform use across most families is acceptable. T1 equivalent factors can be applied for lead tasks at system and subsystem levels too. However, this part of the method is still under investigation and improvement.

Linear factors, which resulted from calibration, were mainly in an acceptable bandwidth. The accuracy of the method was found to be as good as with other estimating tools. The costs are more transparent. The factors directly show cost levers. Also the factors directly show the relative difference between historical cost and the estimate. This provides a “good feeling” to the estimator.

T1 Equivalents are simple to understand also by third persons. They are easy to remember from historical data and thus also allows fruitful discussions on costs.

At ESA the method is in use since 7 years. It has been successfully applied for estimates on satellites, probes, planetary landers, launchers, human space and other studies and projects.