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esa

Successful Cost Estimation with T1 Equivalents

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ESA Cost Engineering Section

- About 10 Cost Engineers
- Cost database CEDRE
    - ESA projects data, mainly satellites
    - Archive of original costs
    - Costs are linked to technical and programmatic information
- Normalization of cost data is part of CER development / tool calibration
- Use of many different cost estimating tools
    - RACE
    - ESA Standard CERs
    - SPICE
    - Precursor Models developed for special applications
    - True Planning
- Preparation of cost estimates is a standard process
    - in support of various studies
    - for all major spacecraft procurements
    - independent and unbiased, to be prepared before receiving industrial proposals

ESA Cost Engineering mainly has to estimate development projects. Often these are first-of-the-kind missions, which by nature are difficult to estimate.

Lessons learned from estimating of development costs

The scope of development effort is different from project to project. Scopes depend on heritage and company experience, often evaluated from

- Requirements
- TRLs
- Qualification levels
- Model philosophy
- Engineering effort

- Different scopes let to poor correlation of historical data
- Scope needs to be normalized through appropriated parameters
  - CERs tend to be complex

Disadvantages of complex CERs:

- Often sophisticated mathematical formulas
- Less transparent, difficult or even impossible to draw diagrams of the CER
- Unexpected levers on costs
- Uncertainty beyond the boundaries of historical data
- Programmatic parameters are often difficult to handle
  - Availability of inputs
  - Barely to measure, subjective determination of values

History of the method with T1 Equivalent Units

The method is old.

It has been reported

- 1976 in a doctoral thesis of Ralph Jaeger
- 1994 in SSCAG, Rules of Thumb provided by Claus Meisl

Also 1992 in Space Economics 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.)"*

- I (the author of this presentation) personally hesitated for about 20 years to use this method, because it looked too simple and therefore seemed not to be reliable!

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

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

SPICE

SPICE (Standard Parametric Information for Cost Engineering)

- ESA own developed tool
- General parametric cost model, applicable for any space system or launcher
- Simple formulas running on EXCEL
- Designed for parameters which are obtainable from historical data and available in early study phases
- Ability to check the balance between NRC and RC (or T1)

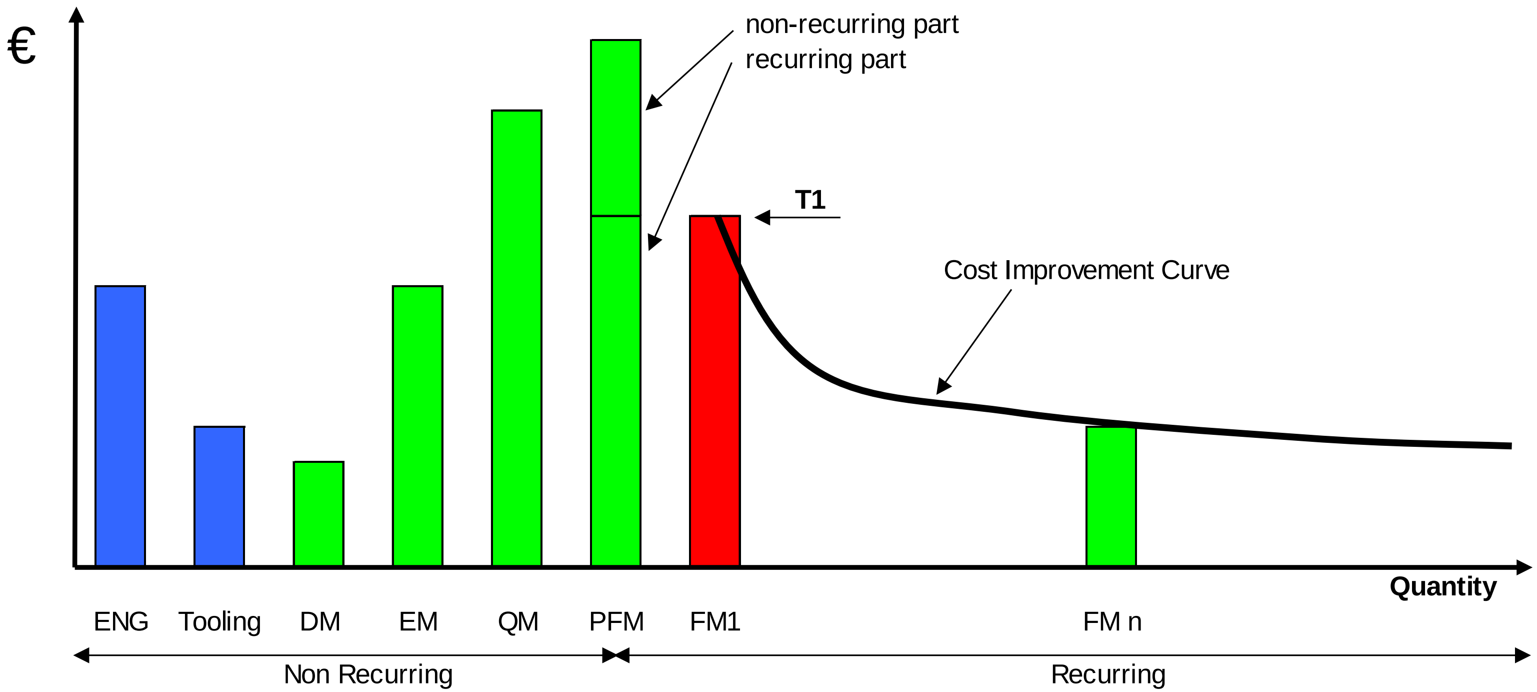
SPICE utilizes the Equivalent Unit Calculation at equipment level:

Development Cost = T1 * EU

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

- Various estimating methods are possible for T1:
    - Calculation from Mass and Manufacturing Complexity (preferred method)
    - CER
    - T1 of standard equipment selected from database
- Constraints to be considered for estimation of T1:
    - Clear rules between NRC and RC (Clear definition of T1)
    - Consistent Learning Curve
- Estimating error in T1 reproduces an error in development!

T1 Equivalents



- All NRC elements are estimated as equivalents of T1
- Mgmt and PA (level of effort costs) are per ratio included in all cost elements
- T1 is the “theoretical” cost of only one FM to produce
    - ➢ CIC (Cost Improvement Curve) to be established accordingly!
- PFM is a special case to be split into NRC and RC

T1 Equivalents at Equipment Level

T1 Equivalents

Satellite Equipment Level	Unit Mass [kg]	Complexities		Hardware & Test Factors				ΣEU	Cost		Assumptions		
		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			

Shown cost figures and factors are examples only

Equipment Level (Equipment level contractor's cost)

- HW & Test Factors consider HW quantities and tests
- Number and kind of models depend on TRL and programmatic assumptions
- Scope of design effort judged from TRL and heritage, often provided from experts

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 modeled as FM = 1 plus QM = 0 … 0.5)

FM = Flight Model

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

System and Subsystem Level Tasks

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			

Definitions:

- All equipment mass sums up to the total hardware included in the system.
- All equipment cost reflects the costs to equipment subcontractors.
- In-house equipment manufactured by the Prime or S/S-Contractor should include all costs as for an equipment subcontractor.
- System and subsystem level tasks are overarching activities for functional and physical integration of equipment to a system, including system's engineering.

➢ The workshare between Prime and responsible Subsystem Contractors is different from project to project. It depends on individual planning of work. No metrics is applicable!

➢ Therefore only system plus subsystem level costs together provide an appropriated ratio to the sum of equipment level costs.

T1 Factors at System Level

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

- System and subsystem level costs are (preliminary) joint together
- Project Office factors
  - depend on the scope of system and subsystem engineering
  - depend on number of subcontractors involved
  - increase by 20 to 25%, if Phase B2 is included
- AIT models and factors reflect the model and test philosophy at system level
- Presently for an estimate the factors are selected from analogous historical references
  - Reference tables still need to be developed
  - Traditional cost-to-cost relationships (% on HW+SW) and other parametric means are still used for cross-check of results

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					

Remember: T1 used in this method is the recurring production of the first unit at equipment level.

The recurring cost of a first complete system can be easily estimated with factors on the sum of T1 at equipment level:

- Project Office factor between 0.2 and 0.3, depending on the amount of CCNs. For advanced lot production this factor is even below 0.2.
- AIT factor around 0.08, including acceptance testing instead of qualification testing.

Additional recurring flight systems to be estimated by the learning curve.

Calibration

Split of historical costs in NRC and RC is mandatory.

ECOS (ESA costing SW for industrial proposals) asks for FM cost, what is recurring:

- FM + fraction of PO = Flight Unit Cost = T1
- Cost normalization: T1 = FM * 1.15 (PO considered as 15% of FM)

➢ With well received ECOS files it is possible to calculate T1 Equivalents immediately!

However:

- Often contractors don't provide necessary cost details at equipment level.
- Often reported FM cost are incomplete or from bad quality. They don't represent the complete MAIT of FM.

→ FM remains unknown!

➢ In case of missing FM the T1 needs to be guessed, also supported by parametric means.

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

Main Problem: Different Accounting Rules

Different contractors often apply different rules for breakdown of costs.

Example:
In case A the prime contractor claims a workshare of 10% in addition to the subcontractor quotation. This could be the procurement overhead, what normally is part of system level activities (see case B). But also it could be a workshare, i.e. engineering, manufacturing, etc.

- Different accounting rules let cost data scatter!
  - Scattering at equipment level
  - Mismatch between costs at system and equipment level

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

It is essential to normalize costs to a standard breakdown!

- Clear rules for all contractors would be desirable for a good understanding of all cost data.

Lessons learned from estimation with T1 Equivalents

- Jaeger and Meisl used EU factors at system level only. Estimates on subsystem, equipment or component level are more accurate, and determination of factors is more precise.

- Rigorous calibration with equipment data proved the applicability of the method at lower product tree levels.
  - Linear factors result in acceptable bandwidths
  - The method was found to be as good as for other estimating tools
  - The transparency of costs provides a "good feeling" to the estimator:
    - Linear factors directly show cost levers
    - Factors provide the link between historical data and estimates
- Also for system and subsystem level activities the method seems to be promising.
- However, it is mandatory to follow rules for cost breakdown and accounting (what is necessary for any other parametric method too).

- T1 Equivalents are simple to understand also by third persons. They allow fruitful discussions on costs.

- At ESA the method is in use since 7 years. It has been successfully applied for estimates on various satellites, launchers, probes, landers, human space and others.