Phase 0 Space Mission Estimates

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BIOGRAPHY

Michel van Pelt is Cost Engineer and Concurrent Design Team Leader at the European Space Agency, involved in a variety of launcher, satellite and space probe projects. He has a Master degree in Aerospace Engineering from Delft University of Technology in The Netherlands, and has been working at ESA ESTEC since 1998, preparing cost models, cost estimates and analyses of financial proposals. Michel regularly works in ESTEC's Concurrent Design Facility as Cost Engineer as well as Team Leader (most recently for the SPICA next-generation IR space telescope, involving also the Japanese space agency), and furthermore supports ESA with various outreach activities.

He is also author of several popular science books, of which 'Dream Missions; Space Colonies, Nuclear Spacecraft and Other Possibilities' is the most recent.

INTRODUCTION

How to prepare very early estimates for future space missions, within little time and using even less inputs? Based on experience with preparing estimates for the very first Principal Investigator proposals for new ESA Science missions (ranging from small missions such as space telescopes based on standard LEO platforms to Medium-class missions like Plato), this paper provides rules-of-thumb, observed high-level cost drivers and trends, checklists, potential pitfalls and general lessons learned. The aim is to explain why early estimates are important, that it is in fact possible to prepare them with a reasonable level of accuracy, how such estimates can be used for early selections and trades, and to enable others to build their own "Phase 0" cost models using the suggestions and relationships shared in this paper.

THE NEED FOR PHASE 0 ESTIMATES

The European Space Agency frequently issues 'Calls for Ideas' for new space missions, which often result in several tens of acceptable proposals. At least in the domains of Science and Earth Observation, these proposals often describe in fair detail the scientific 'raison d'être' but the spacecraft design in only relatively sketchy terms. Sometimes even a subsystem level mass breakdown is missing, let alone a detailed equipment description, comprehensive schedule and development model philosophy. In other words, the typical inputs for a detailed and accurate mission level cost estimate are often mostly missing.

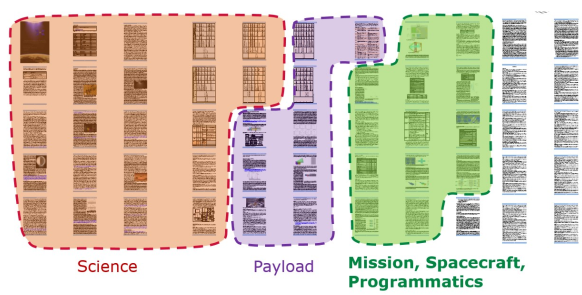

Figure 1: Typical "Call" proposal contents

On the other hand, the first selection of reasonably viable ideas is usually for an important part depending on whether such ideas stand a chance of remaining within a certain budget envelope. This cost constraint is typically expressed in the agency's "call". Ideas for which the cost are clearly well above this constraint (for instance because the launch price is already eating up most of the available budget) can be discarded quickly. This may also be true for concepts that are certainly far below the cost cap, often because they are of such low complexity that they do not offer the amount of science return the "call" is asking for (for instance a nanosat project being proposed for a "call" targeting small satellites).

After this first pre-selection there typically remain still a few tens of proposals for which early estimates are essential to judge whether the required mission budget stands a reasonable chance to remain within the expressed cost cap, and/or what the impact of options, down-scopes, inter-agency partnerships etc. may be. Typically, estimates for such large numbers of proposals need to be prepared within no more than a few weeks, in time for the final selection review.

In short, for such "calls for ideas" the amount of technical and programmatic information, nor the preparation time, allow for detailed cost estimates using tools typically developed for use in later phases of development. Nevertheless the estimates need to be accurate enough to allow selection on cost criteria, and provide sufficient breakdown to be able to compare concepts that may have similar total cost but not necessarily the same cost breakdown and cost risk (for instance a mission using a low-cost platform but high-cost launch versus a mission envisioning a newly developed, high-cost platform with a low-cost shared launch).

MISSION COST BREAKDOWN

In preparing the required phase 0 estimates, it is important to first establish what the cost cap and hence the cost estimate are required to cover. In the case of ESA's Science and Earth Observation "call for ideas" the budget often covers the entire mission from implementation on: Phase B2, C/D, E1, E and G (disposal). A typical Agency cost breakdown for a science mission, excluding the payload instruments provided and paid for by scientific consortia, is shown in the figure below:

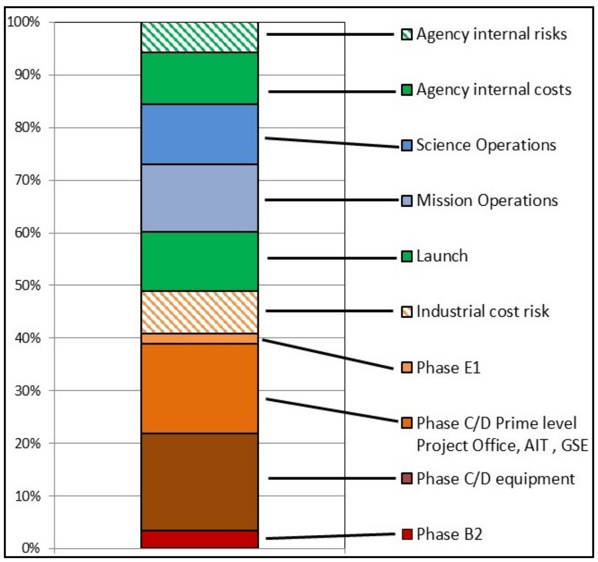

Figure 2: Typical space mission cost breakdown

This breakdown gives an idea of the relative size and therefore importance of each cost contribution, indicating that the Phase C/D costs are obviously far more driving for the total mission budget than the relatively small Phase B2 and Industrial Phase E1 cost. Clear is also that the launch price, typically a fixed amount once a certain launcher is selected, forms a major part of the budget.

Important is also a healthy risk margin, both at Industrial cost level (to account for Class B Contract Change Notices, delays etc.) as well as Agency level (to account for Class B Contract Change Notices, internal project team cost increases due to delays, additional technology development costs, unknown risks affecting the project and such). Also the fact that the various estimates have a relatively high uncertainty due to their relatively rough nature needs to be covered by these margins. At the early stage of mission definition the discussed estimates are concerned with, these risk margins inevitably need to be relatively high.

The following sections each address the major cost areas of Figure 2 in the typical order in which the can be estimated, providing (within the constraints of the confidentiality of the cost information) rules of thumb and suggestions.

Industrial Phase C/D

Unless a fully off-the-shelf platform is used, for early Industrial Phase C/D cost estimates it is recommended to prepare a subsystem level cost breakdown for what concerns the hardware and onboard software, and to split the cost for the Prime contractor (being responsible for the spacecraft at system level) to the level of Project Office (encompassing Management & Control, Product Assurance and Engineering), AIT/V (Assembly, Integration, Test/Verification) and GSE (Ground Support Equipment).

A fast and potentially reasonably accurate method is 'benchmarking', whereby reference spacecraft projects with known proposal, contract and/or Cost at Completion prices are used as reference. Subsystems on the newly proposed project that are similar to those of the reference project(s) can then be expected to involve similar cost, so that only more elaborate analysis is needed for the less similar subsystems. For those cases other 'benchmarks', now at subsystem level, may be used.

Figure 3: Benchmarking

For example, an estimate for a relatively simple Mars orbiter might be based on known costs for an Earth observation platform, with the cost for the propulsion and communications subsystems replaced with known costs for another interplanetary mission of similar size but higher overall complexity (that mission may for instance involve more elaborate GNC, Power, Structure and Thermal subsystems, rendering the whole spacecraft less useful for benchmarking purposes than the simpler Earth observation platform).

In such cases the Prime level Project Office, AIT/V and GSE costs may be estimated as a percentage of the sum of the subsystems costs. This percentage can be derived from the benchmark project(s), then applied to the subsystems cost estimate for the new project (which incorporates the delta costs for the different subsystems).

Note that it is imperative that the benchmark cost data is escalated to the Economic Conditions (currency year) in which the new cost estimates are required to be expressed; using data on a project of 10 years ago without this adjustment can easily result in a straight-off error of 20% in the total estimate (based on an escalation of 2% per year => $102\%^{\wedge 10} = 122\%$).

A schematic of this 'benchmarking' logic is shown in the figure below:

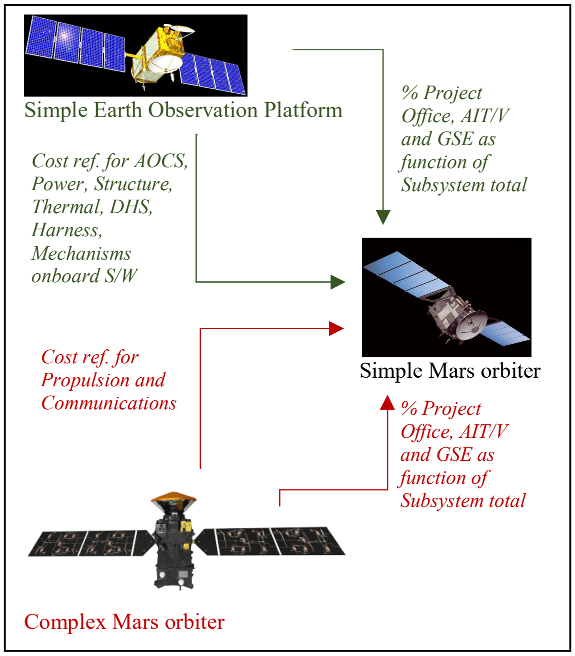

Figure 4: 'Benchmark'-based Phase C/D estimate

It is also important to note that the nature of the cost information for selected benchmark needs to be understood and adjusted for; does the reference data concern proposal/contract cost or Cost at Completion? In the latter case the cost data at most levels includes cost increases due to Contract Change Notices, schedule delays and various unexpected events, which for a new Phase 0 estimate need to be removed and considered as input for the cost risk margins. If this is not properly done, all the cost increases in the benchmark project are taken into account to set the cost for the new project, on which margin is subsequently added, as shown in the figure below. The result is then effectively an overload of margin built into the new estimate, an important part of which hidden in the basic cost estimates.

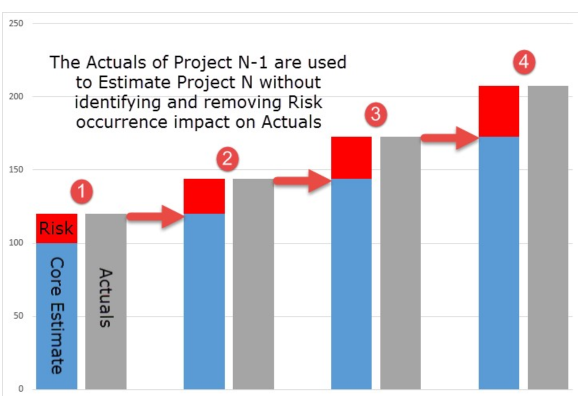

Figure 5: Incremental cost increase due to blind benchmarking based on CaC data.

Apart from, or in combination with, benchmark references, system and subsystem level cost models that rely on limited input can be used to estimate Phase C/D costs to a reasonable level of certainty. Publicly available Cost Estimation Relationships (CERs) can be found in the chapter on cost estimating in the famous system engineering book 'Space Mission Analysis and Design' [1].

The Cost Engineering section of ESA has developed a specific tool called RACE (for 'Rapid Advanced Cost Estimates') [2], which enables fast cost estimates of all typical spacecraft platform subsystems as well as the Prime contractor activities based on the platform dry mass and relative complexity.

An example is shown in figure 6 below, where a relationship is depicted for the cost for a certain subsystem as a function of the platform dry mass. For a "typical" spacecraft a trend line can be found that fits many cases. Other cases however do not fit this line, being significantly less or more expensive than could be expected from the "typical spacecraft" trend line/CER. Normally clear technical explanations exist for these "outliers", which can be expressed in a lower or higher complexity as a function of performance, TRL, capability and such. An example of the parameters taken into account in RACE for the propulsion subsystem is shown in Figure 7.

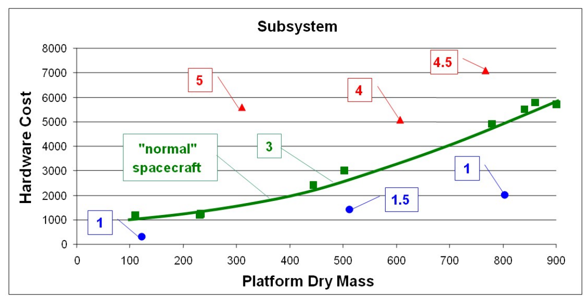

Figure 6: Subsystem cost as function of Platform dry mass and relative complexity

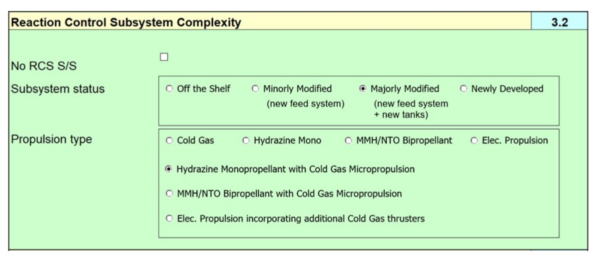

Figure 7: Example of complexity driving parameters

When using such relationships for estimating, with the Platform Dry Mass (estimate) as input, a first idea of the subsystem's total hardware cost can be obtained. Adjustments are subsequently made by use of a complexity relationship, which effectively raises or lowers the cost predicted by the 'typical spacecraft' CER according to the relative complexity of the project w.r.t. this. In RACE, the complexity is set as a value between 1 and 5, whereby 'Complexity 3' represents the 'typical spacecraft', with a subsystem based on existing and modified equipment (and hence multiplies the basic CER result by 100%). 'Complexity 1' represents the least complex and fully off-the-shelf version of the subsystem in question (for instance multiplying the basic CER result by 30%), and 'Complexity 5' the observed most complex, newly developed option for said subsystem (with a multiplication factor of for instance 250%).

After having obtained estimates for all subsystems, estimates for the Prime level Project Office, AIT/V and GSE cost can be added according to the percentage logic explained before. In RACE these percentages are themselves subject of complexity factor adjustments, with for instance lower results for spacecraft with simple payload interfaces and lacking a propulsion subsystem, or higher estimates for projects with many contractor layers.

It is important to note that it has been found that Planetary Protection cost impacts can be significant, when applicable, especially for Class IVa and IVb missions (applicable to mission landing on planets and moons that may harbour (traces of past) life, respectively sample return from such bodies). These can be covered by percentage cost increases on Phase C/D equipment, Prime level Project Office and especially Prime level AIT cost. Data available in ESA suggests for Class III missions a 3% addition to equipment and Project Office cost and a 10% increase in AIT, and for Class IVa 10% addition to equipment and Project Office cost and a 70% (!) increase in AIT cost.

Industrial Phase B2

Analysis of ESA space missions cost data indicates that for early estimates, the Industrial Phase B2 costs can quickly and with reasonable accuracy be estimated as a percentage of the Industrial Phase C/D cost estimate total. 10 to 15% of the Industrial Phase C/D cost for the first, non-recurring spacecraft is suggested (with Phase B2 costs being zero for any recurring spacecraft).

Industrial Phase E1

Project cost date for ESA space missions suggest that the cost for the Industrial support to Phase E1 (transportation, support to Launch and Early Operations Phase - LEOP) can be estimated as fixed amounts depending primarily on the type and size/complexity of the spacecraft. For instance, where the Phase E1 cost for an S-class (Small) science mission may be typically *X* M€, the cost for an M-class (Medium) mission can be *2X* M€. Such relatively crude cost categories are typically sufficient to obtain a reasonably accurate early estimate for use in an early phase.

Launch

The launch price typically represents a significant part of the mission budget, but also one that is often fairly accurately known at the start of a project. Within a space agency or company launch prices for existing launchers can typically be obtained from launch contracts for missions in more advanced stages of development, and/or from price information available in the public domain (such as the 'Annual Compendium of Commercial Space Transportation' yearly issued by the Federal Aviation Administration [3]).

However, it is important to keep in mind that launch prices may increase significantly over several years, especially for launchers still under development at the time the mission budget estimate is prepared. Also important is to ascertain what the launch price includes; often it includes only all normal launcher-spacecraft integration activities at the launch site apart from the final preparation of the spacecraft (which is a Phase E1 activity and hence cost for the Prime level Industry). However, some spacecraft come with special requirements like long launch preparation times, late-access for loading liquid helium for cryogenically cooled space telescopes etc., which make the launch preparations more extensive and complex than for the commercial satellites for which the baseline launch prices are established. Unless the launch price is well established, it may therefore be important to assign significant margin to the launch cost estimate.

The cost of insurance against spacecraft loss during launch and early operations may be applicable (but typically not for ESA missions); this typically involves in the order of 10% of the cost for rebuilding the spacecraft (i.e. recurring cost), with a new launch being provided by the responsible launch company at zero cost [4].

Operations

Mission Operations covers the Operations Control Centre facility, hardware, software and personnel (incl. training) and the Ground Stations and Communications Network. Mission Operations are required for any space mission. Science Operations are more specific, and typically only covered by the ESA budget for astronomy and interplanetary missions. Science Operations typically cover observation planning, instrument calibration and payload data processing and analysis.

Both of these Operations often represent a significant part of the total mission budget, especially for missions involving many manoeuvres and/or very long missions.

Although accurate estimates for Mission and Science Operations require extensive analysis of which ground stations are needed when and for how long, type and moment of manoeuvres, specific control expertise needed and the manning of the operations centre (24/7, on-call in weekends, etc.), for early estimates typically relatively simple cost models of the following form suffice for both types of Operations:

*Ops_Cost = [Control Centre development & training cost] + [Ops cost during orbit transfer] * transfer_duration + [Ops cost in full operational phase] * operational_phase_duration*

If the mission does not incorporate a long (interplanetary) transfer to the operational destination, in the order of several months, the middle part of this equation can typically be ignored.

The magnitudes of the cost factors between brackets typically depend on the type and size of the mission; as for the Phase E1 costs, mission categories can be identified with more or less fixed amounts for Control Centre development & training cost, monthly operations costs during transfer and monthly operations cost during the full operational phase. In the ESA science missions domain the more or less established categories are Small, Medium and Large missions. It needs to be noted that for very small, often experimental missions like ESA's series of Proba satellites and especially CubeSats, the cost factors can be much lower than for an ESA S-class (Small) science mission. This is because such missions typically rely on a significantly simplified ground segment, with less, smaller ground stations and an operations team that does not need to be fully dedicated to one mission full time. Moreover, such missions typically do not involve specific Science Operations.

Agency Internal Cost

Space Agency internal cost, accounting for the dedicated project team as well as internal technical support during development and major project reviews, form another block of cost that has an important influence on the overall mission budget.

For Phase 0 estimates, it was found that the estimate for this can take the simple form of a percentage of the Industrial Phase B2/C/D cost including risk margins:

*Agency_Internal_Cost = (Industrial Phase B2 + Phase C/D + Industrial Cost Risk Margin) * X%*

ESA data suggests this percentage can be approximated as a linear function of the total Industrial cost of a mission, as shown in the figure below:

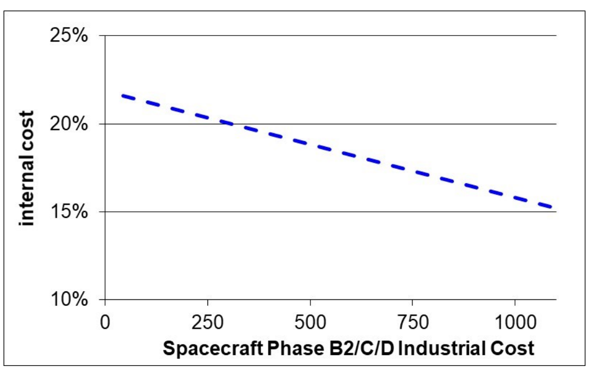

Figure 8: Agency Internal Cost factor as function of Industrial Cost in M€ in today's Economic Conditions

Cost Risk Margins

For the risk margin at Industrial and Agency level there are various approaches. For the Industrial cost, the simplest is to allocate a fixed percentage on the total Industrial Phase B2/C/D/E1 cost estimate; for Phase 0 estimates this percentage is recommended to be around 30%. This percentage could be set according to a look-up table that may take into account risk contributors as described in the following part of this section. An interesting approach is also that developed by the late Steve Book in his paper *How to Make Your Point Estimate Look Like a Cost-Risk Analysis (so it can be used for decisionmaking)* [5].

A more detailed approach can be to break down the Industrial cost risk margin into different contributors, for example:

- Technical Risk
    - Development Status Risk (related to TRL)
    - Programmatic Risk
    - Industrial Procurement Risk (e.g. price increases)
- Maturity Risk
    - Design Maturity Risk (unknown risks)
    - Costing Model Accuracy Risk.

In this example the Development Status Risk can be a percentage on each equipment cost estimate as a function of its current Technical Readiness Level (TRL): the lower the TRL, the higher the percentage of margin. Programmatic Risk could be a percentage of the Prime Project Office cost, and Industrial Procurement Risk a percentage of the combined subcontractor cost (at the level of equipment, software and possibly subsystem contracts). The Design Maturity Risk would cover for uncertainties in the design and project organisation for which the estimate is prepared (as the technical baseline as well as the assumed industrial organisation philosophy may change). The Cost Model Accuracy Risk is to cover for the inaccuracies in the cost estimate methods and relationships: the lower the number of references and the lower the quality of the cost models used, the higher the percentage margin added.

At Agency level the risk margin should cover for:

- Launch price increases
- Mission and Science Operations cost increases
- Agency project team cost increases (due to schedule stretch and/or the need for a larger project team)
- Unknown Industrial risks (Class-A Contract Change Notices, funding issues complicating the project organisation and schedule, etc.).

These could be covered by percentage margins added to the launch price, operations cost and agency internal cost, while the unknown Industrial risk could be covered by a percentage on the total value of the Industrial Phase B1/C/D/E1 cost including Industrial cost risk margin. For the Agency internal risk margin covering the Industrial spacecraft cost and the Agency internal cost (thus not covering the launch and operations, it is recommended to put ≥15% on the on total Industrial Phase B2/C/D/E1 cost including Industrial risk margin + ESA internal project cost.

It is recommended that whatever the more detailed cost risk assessment used, a high-level "sanity check" is made by assessing the suitability of the resulting overall risk margin as a percentage of the total estimate.

ESTIMATE LOGIC SUMMARY

Based on the methodology described above, the suggested cost estimate logic can be summarised as follows:

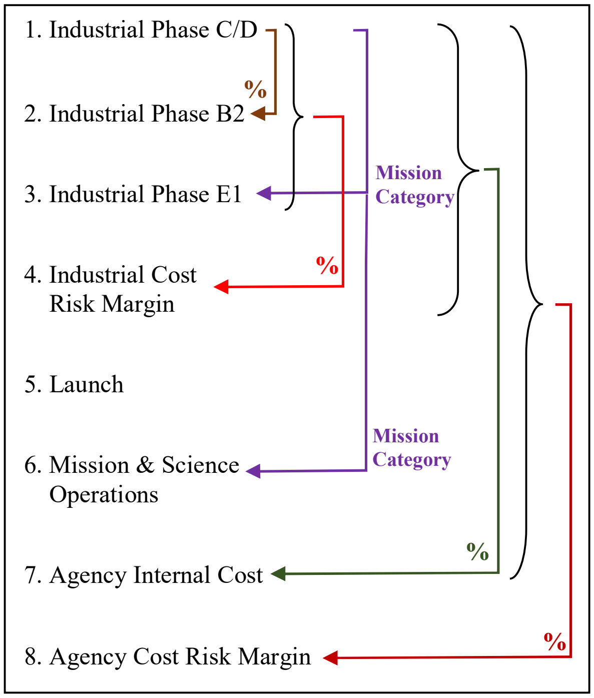

Figure 9: Estimate logic schematic

Provided that the right references are readily available, and a robust logic for the various percentages for Agency Internal Cost and the Risk Margins has been established, this method allows for fast yet sufficiently trustworthy cost estimates with reasonable cost breakdown.

USE BEYOND PHASE 0

The usefulness of relatively rough estimates for very early assessments and trades has been described earlier, but their use can extend beyond this. They can for instance also be used to obtain a rough total mission budget when only a detailed industrial spacecraft cost estimate is provided, by adding estimates for launch, operations and Agency internal cost and risk margin.

Another use is that of consistency check for more detailed estimates in later phases, ensuring that all is covered and that the magnitudes of the various high-level cost contributors are reasonable (such comparisons may also feed back into the cost estimate model, resulting in for instance adjustments in the risk margin percentages applied for subsequent Phase 0 estimates for other projects).

CONCLUSIONS

Phase 0 cost estimating tools developed in ESA Cost Engineering, based on the principles presented in this paper, allow early cost estimates in relatively little time and based on little and relatively rough input information. The estimates can be improved and further detailed as the conceptual definition progresses, as the method allows easy incorporation of more sophisticated tools and methods that require more elaborate inputs.

The method has been implemented in various ESA Science and Earth Observation "calls for ideas", with satisfactory results that have proven to be of reasonable accuracy when compared with the more detailed and accurate cost estimates and proposals of the same projects in later phases. In these phases typically the cost risk margins have decreased (as they have effectively been "eaten up") but the overall budget level remained comparable.

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