13 Reasons a Cost Estimate during a Concurrent Engineering Study could go wrong (and how to avoid them to come true)

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ABSTRACT

During early phase spacecraft design, the concurrent engineering (CE) approach is proven to be very efficient. But the condensed and iterative nature of CE sessions can also make life hard for a cost estimator. This work discusses 13 problem areas experienced or observed mainly during one-week, inter-disciplinary space system design studies and provides practical examples on how to tackle them, e.g. how to handle rapid data changes, wrong expectations and a diverse engineering team.

Key words: Communication, Early Cost, International, Space, Concurrent Engineering

ACRONYMS

CAD	*Computer-aided Design*
CE	*Concurrent Engineering*
CEF	*Concurrent Engineering Facility*
CER	*Cost Estimation Relationship*
DMM	*Design Maturity Margin*
MBSE	*Model-based System Engineering*
P/L	*Payload*
ROM	*Rough order of Magnitude*
SSCM	*Small Satellite Cost Model*
S/C	*Spacecraft*
S/S	*Subsystem*
WBS	*Work Breakdown Structure*

INTRODUCTION

Concurrent Engineering (CE) is an efficient Systems Engineering (SE) approach which is increasingly applied in early phase spacecraft design due to the involvement of all relevant disciplines, including the customer, often supported by data models and tools as well as a communication fostering infrastructure.

During several moderated sessions, the latest results and problems are shared with the entire team which supports the convergence towards a common solution. This exchanged information is a key input for the cost estimator and provides guidance on what to further discuss, research, or how cost models should be used or adapted. But the data is constantly changing due to the iterative approach. Moreover, the space sector is not famous for public data, making research and comparisons often difficult. With predominantly technical people in the room the cost estimate may also be perceived disconnected.
Based on the study context, managers expect either ROM cost or a detailed WBS-like breakdown. These and other reasons why cost estimation could go in the wrong direction are discussed within the paper, based on experience and observations related to systems, concurrent and cost engineering. It includes real-world examples, ideas for solutions and some anecdotes which shall round off this lesson learnt compilation.

This paper has been prepared to discuss and raise awareness about stumbling stones which can be encountered particularly significant during otherwise very efficient and recommendable Concurrent Engineering (here so-called “CE-studies”) activities for space missions and system in the early phase, using the DLR CE-approach as an example.

The potential problems arising are not exclusively for CE nor for the cost domain. As for CE in general, the approach for Cost Engineering in such an environment varies amongst different institutions. This relates to tools, data available, time available and likely even the objectives and expected outcomes.
This work is based on experiences and observations gathered during several DLR CE-studies during which one particular approach is applied but also common rules and practices are followed.

CONCURRENT ENGINEERING AT DLR

The German Aerospace Center (DLR) is the national aeronautics and space research center. It performs extensive research and development (R&D) activities related to aeronautics, space, energy, transport, security and digitalization. Furthermore DLR contains the German Space Administration, acting on behalf of the Federal Government, which is responsible for the implementation of Germany's Space Program, on national and international level. In 2007 the Institute of Space Systems was inaugurated within the Space R&D branch, with the objective to perform analysis, design, development, testing, integration and management of space systems, including e.g. satellites, probes, habitats and launch vehicles.
In order to conduct efficient feasibility and preliminary design studies for internal and external missions and systems, the DLR Concurrent Engineering Facility (CEF), which is shown in Figure 1 below, has been established as part of the Institute build-up [1].

According to a definition from the European Space Agency (ESA), Concurrent Engineering is a

> "..*systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle*" [2]

The major elements of CE as it is applied in the space sector are a guided and structure process, an infrastructure which fosters communication, collaborative and concurrent working, a central data model to enable instant and simultaneous data exchange, as well as a team representing all relevant disciplines, including the customer [3].

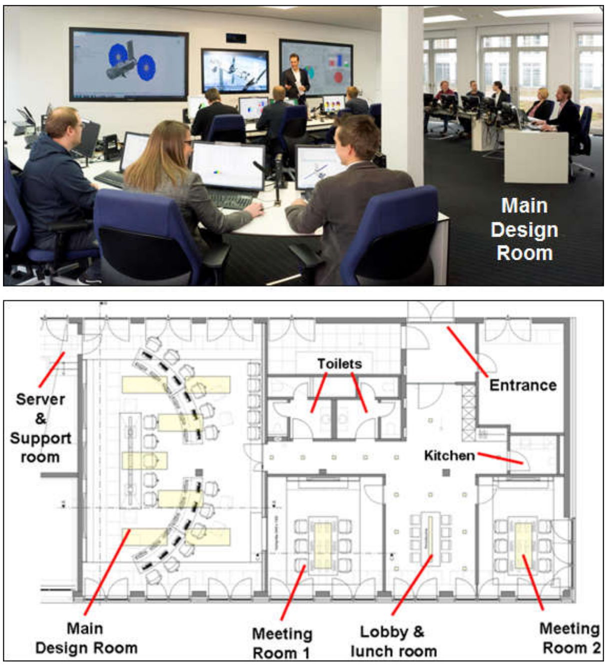

Figure 1: DLR Concurrent Engineering Facility

CE in Space has been applied already in the U.S. for more than 20 years, initially by the Aerospace Corporation and NASA's Team-X, and also at ESA since 1998. It clearly proved the efficiency and high quality for early space system and mission studies. Nowadays many international organizations apply this approach as part of their Systems Engineering activities in one way or another. These organizations include agencies (e.g. NASA, ESA, JAXA, CNES, ASI, DLR), system integrators (e.g. Airbus, TAS, OHB), private or governmental organizations (e.g. Aerospace, Ball, NRO) and universities (e.g. MIT Boston, Utah State University, Skoltech Moscow, ISU Strasbourg, EPFL Lausanne, UPM Madrid, UNSW Canberra) [3]. More details on the general CE-approach and existing facilities can be found for example in [1], [2] and [3].

With initial support of the ESA Concurrent Design Facility (CDF) team, the DLR CEF adapted the Concurrent Engineering process and all related elements such as the actual infrastructure, required data models and software tools and also the team (wrt. size, compilation) to their own needs. With currently more than 70 studies completed, the CE-process is already well established but also continuously improving due to the on-going challenges of new customers, study topics, support technologies or team members.

Whereas the overall study timeline including initiation, preparation and also post-processing phases can last several weeks, the actual CE-study phase at DLR typically lasts one full week [4]. Figure 2 shows the overall timeline including the different parties involved and information products generated, and Figure 3 presents a typical schedule for the actual 1-week study phase. During this phase a mixture of moderated (indicated in red) and non-moderated sessions (blue) take place, in which either general and system-relevant, or more specific trades and tasks are perform respectively.

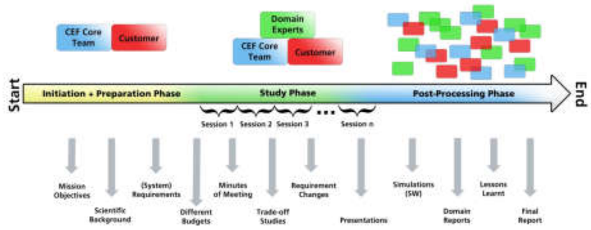

Figure 2: DLR CE-study overall timeline

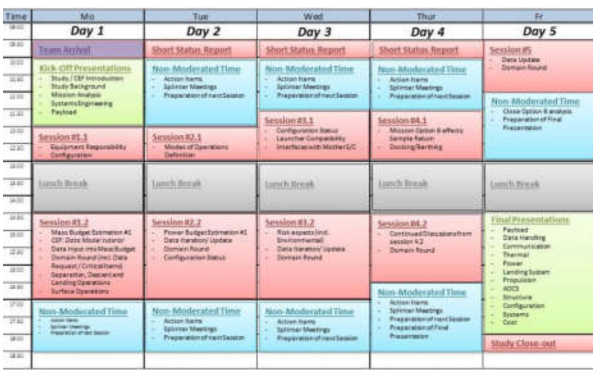

Figure 3: DLR-CE study phase schedule (1 week)

As a different example, ESA organizes their sessions over several weeks with only one or two moderated sessions per week [2], while Team-X at NASA Jet Propulsion Laboratory (JPL) also compresses the study sessions into less than one week, as indicated amongst others in [5].
A common set of domains and their representatives covers the moderator, the customer, Science/Payload Engineering, Systems Engineering, Mission Analysis, subject matter expertise for Structure, Thermal, Power, C&DH, TT&C, AOCS and Propulsion, 3D-Accommodation/Configuration engineering, Mission Operations, Risk/Product Assurance and also a Cost Engineering/Analysis.

In summary, at DLR, during the preparation phase, the CE-study organizers distribute a study scope document to the entire team for preparation. In the beginning of the actual study week, when everybody comes together in the CEF, the key information is presented again to the team. Afterwards, the discussions and work starts immediately for instance with initial discussions on the impact of the top-level requirements towards the mission and system design, with initial definitions of the product tree, preliminary subsystem sizing and operational modes. That is when the fun part for all participants including the cost estimators begins…

COST ESTIMATION IN CE ENVIRONMENT

In not so serious terms, try to imagine you have a counter with 32 hours (i.e. 4 labour days with 8 hours working time each) counting backwards on your desk (which is not your daily one), approximately 20 people around you (thereof at least 15 technical experts) in one single room, a challenging mission statement displayed on the screen, and you are the only one person who is interested in things like fiscal year or full accounting cost. If you manage to do so, you have understood cost engineering within a CE environment in a nutshell.

In more serious terms, depending of course on the level of preparation, time or the experience and approach of the cost estimator, a typical set of activities during such kind of CE-study looks like this:

- Gather project-related data to establish technical and programmatic baseline,
- identify similar missions (if data available) and derive analogy-based specific ROM cost values as starting point,
- check what methods and tools should be further used and discuss this with project manager and customer,
- use available data, perform estimates, iterate as the data becomes more mature,
- support the technical team and managers with cost expertise during system trades,
- compare and x-check estimates amongst different methodologies and tools, if possible, and
- identify and present what cost have been elaborated in detail and which are estimated with more simple rules of thumbs, or even have not been included.

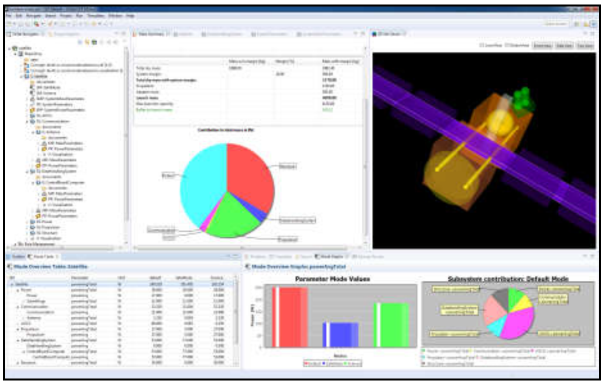

Figure 4: GUI of DLR 'Virtual Satellite' data model

Methods and tools used in the CEF cover amongst others parametric estimations using the *Small Satellite Cost Model 2014 (SSCM14), SEER-Space, TransCost, SMAD*-CERs, own Excel tools, the T1 Equivalent Units approach [6] and formerly also the *USCM*.
Central data models used at DLR include mainly the Virtual Satellite (VirSat), shown in Figure 4 but also the *ESA Open Concurrent Design Tool (OCDT)* and the former *Integrated Design Model (IDM)* workbooks as complementary and optional models [7].

13 REASONS WHY…

In the following, the 13 selected reasons (or problem areas) why a cost estimate during a Concurrent Engineering Study could go wrong are discussed. For sure, there are plenty of others ones who could lead to tough work or even wrong results, but these are most prominent ones according to the author's experience.
Moreover, most of them are intertwined and also not exclusively applicable during CE-studies but also in any other cost estimation activity, some are even very obvious, but these selected reasons may increase the level of impact when they come true.

For each of the aspects, there are some ideas, lessons learnt or recommendations provided on how problems could be reduced or even avoided.

Wrong Expectations (#1)

Customers in a CE-study at DLR come from totally different areas. They could be project managers, department/group/directorate heads in charge of a space program, or Principal Investigators and science teams, both internal and external. Depending on the type and number of stakeholders, their background and interests as well as their expectations with respect to the cost estimation results may extremely vary from study to study but also amongst the estimator and the customer within one particular study.

The CE-approach is very suitable for early design activities, hence these multi-disciplinary studies take place most often in Phase 0 or A of a project.
This results in a certain granularity of the estimate, with cost usually presented on segment or subsystem level.

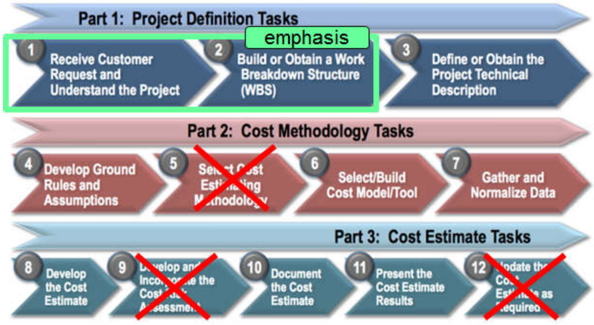

Figure 5: Random example of tailoring the NASA cost estimating process, adapted from [8]

However, often it is expected to provide a bottom-up estimate on work package level showing also labour cost, material cost or facility and operational cost (see also problem area #11). Other customers rather want to see a split between development (NRE) and production (RE) cost.

Most of them expect the results (without knowing them in advance of course) to meet their available budget, which is often fix and constant per year, within the available time. Basically all customers want to get a single, final number at the end of week which they can take home and which is rarely considered a subject for further correction or increase.
The level of detail which is expected is often not in-line with the time available to provide the results, nor is it in-line with what you think should and could be done at this early stage. Moreover, it might not be understood that even the tools which are at hand can barely be applied to all of the missions, particularly for new designs.

To avoid bad surprises at the end, the cost estimator needs to iterate with the study leader and customer the expectations already during the preparation phase, i.e. prior to the first study session. Part of such discussion should be how the standard cost estimation process, as described e.g. in [8] and shown in Figure 5, can be tailored and what the possible and most relevant cost breakdown might be, for instance if rather production and development cost need to be distinguished, System and S/S effort, labour and materials, investments and facilities, or if the space segment cost is more interesting than the operations cost, or vice versa. These discussions support the decision which methods and tools could be an option for the estimator, and the identification on how the final format for the representation of the cost can be set up in a most suitable way.

International and multi-disciplinary Team (#2)

The CE-study team is not only multi-disciplinary but also very international, particular in European entities such as ESA or DLR. Various nationalities are working together in one room, which brings in different cultures, different ways of thinking, working and communication, as well as different languages and levels of English. This is a very powerful basis to boost creativity and it also provides a vast range of knowledge due to the different educational backgrounds and maybe previous international company experiences. On the other hand, for a one-week CE-study this compiled team has to be harmonized somehow, which is a challenge for all domains and subject matter experts (and not only cost).

In addition to the team working on the design within the CEF, if the CE-study is part of a bid preparation, the potential industry consortium which is planned for implementation may significantly affect the labour rate or productivity assumptions which have to be taken into account. This is true for parametric and other estimation methodologies.

During one study there was for instance an external systems engineer from Greece who considered the involvement of Greek institutions for building a set of CubeSats. Although the currency might be the same (here: EURO), the labour rates can be completely different when comparing e.g. northern with southern European countries. I this study case it was required to decide which work packages (or Subsystems) should be assessed with a rate of around 200 k€ per work-year and which ones with around 100 k€.

Prior to the study, even if not a single detail is available for the technical baseline, a cost-internal stakeholder analysis should be performed, which covers all aspects for dealing with the different team members and maybe their different attitude in terms of supporting a cost estimate, and also how different international contributions for the mission could affect the estimation process and what elements (e.g. labour) might need adjustments. This exercise last only minutes but can save a lot of time, hassle and last minute corrections during the study sessions.

Tools not available or applicable (#3)

Concurrent Engineering follows an iterative approach, which requires rapid assessments and analyses, quick engineering tools, intensive communication, the ability to think out of the box but also a systematic way of performing the tasks as much in parallel as it could be. But space missions are often characterized by unique designs. Space system cost and also technical data is barely available, especially if the own company does not have a large record of building space systems itself. The time do develop dedicated CERs, maybe even based on the poor data set, is simply not given during a CE-study (see also #7 and #8) therefore the remaining solution is typically to use an already established tool which supports the estimate with historical, underlying data and CERs gathered and developed by others, and which are not visible for the end user.

There are some tools out there which are accessible for everyone on no cost. In many cases they cover a special mission or system type, for example the Small Satellite Cost Model (SSCM) [9], which covers the S/C bus cost, roughly in the 100-1000 kg range.

More detailed or more powerful tools can be in-house developments (such as several NASA ones) or commercially available. Unfortunately, not all institutions are able to afford commercial tools or to invest in internal developments.

However, sometimes the space mission to be designed and analyzed is so fancy or special that even no tool is applicable. This leads to a lot of 'modelling' during the dense set of CE-sessions by the cost estimator, which is already challenging. By using as a starting point for instance the mentioned freely available CERs and tools (e.g. *SSCM, USCM, NASA PCEC*) or analogy-based, specific ROM cost factors from former missions for the basis of estimate (BoE), still a lot of adjustments have to be made. Most cost data is captured in US$ for instance and might force the estimator to adjust the results to the required currency, such as € in Europe.

The question remains which inflation scheme should be applied, the NASA inflation index, European annual average inflation or the national one (German, in the DLR case)? Compared to the overall uncertainties, especially for the very specific space missions such aspects could potentially be neglected.
Furthermore the desired cost breakdown is not fully possible, or the tools/CERs do not capture the latest technologies, or some parameters are out of range.

The lack of full applicability could be compensated by following an amalgamation approach as described in [10] and substitute e.g. certain parametric estimates with dedicated analogy or bottom-up estimates on S/S or unit level, or by performing 'benchmarking' [11] and taking and combing cost references from different other missions where some elements are similar in one, and some elements are similar in another mission (or system). In the end the decision has to be made if the available support tools are fully or partly applicable, if they can be made applicable or not. If the latter is the case, then do not use it.

Specific / ROM cost (#4)

CE-studies could be hectic events from time to time. The fact that you can hardly compensate with working over-hours, given the short and intense study phase, may lead to too quick and hence too dirty assessments. For example, in order to have an initial feeling (and subsequently a first response to the customer or the study team) on the overall cost, the cost estimator could do a quick ROM cost assessment using a simple analogy estimate or specific cost factors from literature, such as cost per S/C mass (e.g. k€/kg).
However, due to lack of time, data clarity, understanding or precision, you could simply have a wrong interpretation of the factor which you identified or have been given.

Specific costs are often not equipped with a Fiscal Year, which should be carefully considered if the developed/found value is old. More important are the correct assumptions for the mass and cost contributors.

Table 1: Specific cost interpretation options

Specific cost options [k€/kg], (FY 2020)		*S/C bus cost [k€]*	*Project cost [k€]*
		50,000	*100,000*
S/C dry mass [kg]	*250*	**200**	**400**
S/C launch mass [kg]	*350*	**143**	**286**

If they are unclear, following situation could occur: Imagine a mission with a S/C dry mass of 250 kg and launch mass of 350 kg, with a cost of 50 M€ for the S/C itself and 100 M€ for the entire project lifecycle (incl. launch and operations), stated in FY2020, constant year million euros. In case it is not completely clear what the specific cost value in k€/kg is referring to, this can lead to significant differences up to a factor of 2.8 in our example (i.e. 400/143), as can be seen in Table 1. Additionally, the term S/C is sometimes uses for the service segment (bus) only, but sometimes including payload. So make sure what values to take and at least equally important, that this is something to be explained in front of the entire study team. And if someone else is arguing during the study that she/he has other values in mind, first the correct interpretation of this 'initial-quick-look reference' number has to be agreed on.

Use of margins and contingencies (#5)

During early stage design, there is still a lot of uncertainty carried along and therefore, a proper margin and contingency philosophy has to be applied.
There are several standards and guidelines, e.g. [12], on how to apply them on technical as well as on cost-related parameter.
In CE-studies there is an interdisciplinary and multi-cultural team (as for most projects in general) which has been called in to support the present study and is not necessarily used to work together. This means the systems engineer and team leader have to make sure that everyone has the same understanding and basis for the application of contingencies and margins to avoid double-counting or forgetting them, or piling them up in an unfortunate way, as shown e.g. in [13].
Furthermore, for using the technical parameters and requirements as input for parametric cost models it has to be clear what values to take exactly. When using for instance mass-based CERs there is in principal three major options.

Table 2 shows a mass budget on subsystem level for a small satellite, where the S/S masses are the sum of their actual equipment, with and without margins applied based on the ESA CDF margin philosophy [12]. From these options, listed in the following, it has to be decided which value should be used:
(1) S/S mass (as sum of the equipment masses) without any margin, i.e. best guess only, shown in the 2nd column from the left,
(2) S/S mass with design maturity margins (DMM), displayed in the 4th column from the left,

(3) S/S mass with DMM and the system margin portion on top, i.e. the values from the 4th column plus in this case 20% on each S/S.

Table 2: Mass Budget example (S/S view) of a Satellite, incl. 3 potential options for mass values to be used in parametric cost estimation tools

Options >>	(1)		(2)	(3)
Cost Ttem	m [kg]	DMM (avg.)	m + DMM [kg]	m + DMM + SM [kg]
Payload	85	10%	86,10	103,32
S/C Bus S/S total	206	17%	240,17	288,20
Structure	70	19%	83,30	99,96
Thermal	10	20%	12,00	14,40
Power (EPS)	40	12%	44,80	53,76
AOCS/GNC	35	15%	40,25	48,30
Propulsion	10	20%	12,00	14,40
TT&C	23	14%	26,22	31,46
C&DH	18	20%	21,60	25,92
Total dry	291		326,27	n/a
Systemmargin (SM)		20%	65,25	
Total dry + SM			391,52	391,52
Propellant			30,00	30,00
Total wet			421,52	421,52
Launch Adapter			5,00	5,00
Total launch			426,52	426,52

Since the tools and CERs are primarily based on actual data, and due to the tendency of mass growth and eating up margins during the development process, it is recommended to use in the above case option (3), i.e. the S/S mass including DMM and the system margin portion on top, or – if not possible or desired – to use option (2) and clearly reflect the additional uncertainty in the cost-risk analysis or at least within the documentation of results.

Depending on the data model used for the CE-study (or project in general) the S/S mass values may need to be recalculated at some stage, e.g. with factor 1.2 in our case. This means that the Thermal S/S mass to be taken for the CER/Model is not 10kg, nor 12 kg but 14.4 kg. Please see also problem area #9 (rapid data changes) for further discussions on data model value utilization.

During the tool selection process which should take place prior to the actual study phase, the use and application of technical margins not only for mass but also for other parameter should be clear, documented and preferably also agreed on. During the rapid and iterative estimation loops within the CE-environment these details may be overlooked.

Heritage & Complexity (#6)

As for any other study or project, the cost estimation has to take into account factors for heritage and complexity adjustments. Particularly for parametric estimates which are based primarily on CERs with mass as independent variable, the results would not capture how much of the design and test effort and models could be saved (or are needed in addition) due to heritage, nor how complex either the design, assembly and integration or control of the space system could be. In an early phase CE-study, the team has likely an understanding if they design something new or a derivation of an existing system, and if this is a rather simple or complex solution, but for the cost estimate the question remains, how strong this would affect the results. Some CERs and some tools account for one of both factors already; some do not consider them at all. Moreover, there are big differences on how heritage and complexity are addressed within these tools.

The estimator has to make sure if the tools (or CERs, sophisticated models), or the approach and data for an analogy estimate account for this already, or if these factors have to be applied on top of the given outcomes. The key assumptions for the SSCM14 for example state an ‘average’ amount of heritage and an ‘average’ level of technological complexity, stressing the fact that a proper cost-risk assessment is required [9]. Alternatively, a certain percentage, linear or exponential factor could be used, as done within/by several CERs, but this has to be selected and defined with care, since these factors, e.g. for heritage, can vary from less than 1.3 to more than 2.5 when comparing an ‘average’ heritage (e.g. 50%) to a completely new development. Same is true for the similarly subjective complexity assessment.

However, this adjustment, either manually or as a part of an e.g. parametric tool, should be factored in at the very end of the study, when most technical data is available. During the CE-study itself, in most cases, the team or at least systems engineer will strive for highest possible heritage and lowest complexity. Keep an eye on it, try to support the discussions and trades along the way, but work this out in detail as late as possible.

If possible, this exercise should be done on S/S-level to reflect a potential high or low re-use and complexity per S/S of the space system, compared to others.

Lack of time (#7)

This is a major, self-explaining issue, partly also a self-made one for the DLR CE-approach and institutions with similarly dense study timelines. Although this approach is clearly very efficient, the absolute time for analysis and potential re-work is short.

First, within one week plus maybe some days before and afterwards including preparation and conclusion respectively, one cannot perform the complete cost estimation process as stated e.g. in the NASA cost estimation handbook [8] in full detail, simply due to the lack of resources and the early stage of most studies.

The lack of time is a central reason for potential cost estimation errors or incompletion. It is critical for all domains, but the cost domain is heavily dependent on the outputs from others, to be used as input for own analyses, and hence is rather busy at the later stage during the design iterations.

Therefore it is imperative to use a tool, calculation CER, or template you are really familiar with; there won’t be much time for experimenting. Implementing a proper process and adapting the tools for it, standardizing them and connecting them to a data base could turn the problem into an opportunity and enable a very efficient design process and cost estimate, as it is the case e.g. for NASA team-X studies where "costing at the speed of light" [5] is commonly performed.

Lack of data (#8)

Cost estimation relies heavily on data. This includes technical data to establish the technical baseline for an estimate, as well as cost data from previous missions, designs or equipment selected. Often you lack both, due to the lack of technical maturity of the present mission/system, especially in the beginning of the study, and also due to the lack of comparability to former missions or simply lack of access to previous data. Unfortunately, in Europe for instance, there is no such databases available as CADRe or ONCE [14] in the U.S.

This is again one of the reasons why parametric tools with a few technical input parameters are essential and of great help during this early stage of mission design. CERs and the tools making use of them (if available and applicable) contain already a large set of data points which do not have to be researched again.

In case there is technological or operational differences apparent between the CERs used and the spacecraft for instance, effort shall be made to replace or adjust the cost of particular subsystems which differ most by using e.g. 'benchmarks' from other subsystems of more suitable space missions where cost may be known, as also proposed in [11] (see also #3).

At least the unknowns have to be known, and clearly documented in any case.

Rapid data changes (#9)

Concurrent Engineering and its highly iterative nature involving every discipline early on in the project is a big advantage. However, the rapid evolution of data leads to a couple of challenges.

During one week, the total launch mass may change dramatically after each session. Assuming a requirement for a small sat mission with maximum of 300 kg launch mass, at the end of day one, with an initial version of the product tree, the mass budget will tell you 225 kg. However, not everyone adds the relevant data into the data model in the beginning, so one may assume that the structural mass is missing entirely, harness is not yet considered, and propellant is fully unknown. In the course of the 2nd day, subject matter experts close the gaps, discuss and re-iterate with comfortable contingencies which leads to a total launch mass of 410 kg. During the 3rd day the team identifies that P/L and the S/C bus both included an optical bench and Star Tracker into the budgets, the operational modes are pre-defined as such that the data downlink and the science measurements do not take place at the same time, and that we do not need an X-band system anymore. This leads to an updated launch mass of 340 kg. The 4th day is the day of refinement; the amount of data needed as input for an e.g. parametric model is also complete, and the total launch mass is now 290 and hence closely complies with the requirement.

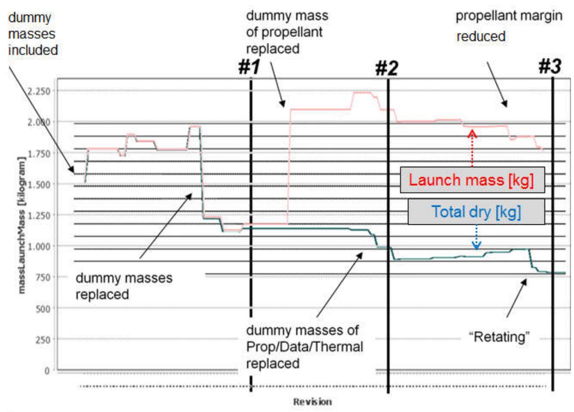

Figure 6: Example of mass variations over time during different revisions/iterations of a CE-study, taken out of the data model history, incl. explanations

However, on the last day, someone figures out that the redundancy scheme for the avionics is not in-line with the single-failure-tolerant requirement for this e.g. (hopefully under) 50-60 M€ mission and now the mass increases, including margins, up to 320 again, which will likely not be a show stopper at this stage. An example of these changes, with other values, is shown in Figure 6. In order to constantly build up and update the cost estimate, e.g. using amongst others the Small Satellite Cost Model for this mass range, and to continue supporting properly some design trades taking into account the cost increase/decrease effects, the cost model has to be able to be updated easily without mixing up numbers or forgetting something.

As for many problems, preparation is also the key here. The cost estimator needs a good understanding of the potential cost drivers already prior to the study, make first and robust assumptions for the technical baseline, and perform initial sensitivity analyses. Furthermore, the selected tools should be usable for such a series of iterations. As an example, Figure 7 shows the SSCM 14, where an input sheet has been modified to do so. On the left, there is the original tool input section whereas on the top right the technical parameter values are checked if they are in the applicable range or not. Manually added there is a box on the lower right side, in which the mass budget on S/S level can directly be taken from the CEF data model.

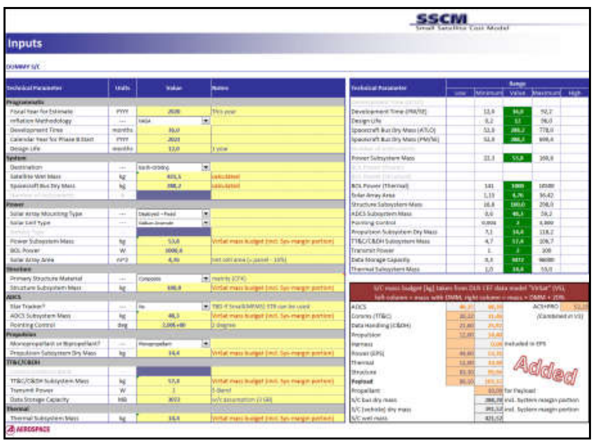

Figure 7: Screenshot of an adapted SSCM14 input sheet

The S/S masses are converted to mass with DMM and system margin portion (as discussed in #5) and then linked to the left input table. Moreover, the system masses (dry, wet, launch) are organized as such that a quick comparison with the actual mass budget can be made easily to identify gaps or overlapping.

It would be even better, however, if such adaptation effort would not be necessary, but unfortunately most cost tools or calculations are difficult or inconvenient to connect to the central, multi-accessible data model, and vice versa. This brings us to the next reason why a cost estimate in a CE environment could go wrong:

Disconnection to central data model (#10)

Using a central data model, which acts as a single source of truth is great. It can be used in any project, but a CE-study is a good event for which the data model could be initiated or initially be prepared for. In principle there is nothing negative only positive: a bit of consistency is better than no consistency, thus we are talking about a luxury problem. The cost domain is not really included in the data model. This is also true in many cases for domains which use powerful commercial software, such as CAD-tools (e.g. CATIA) or orbital simulations tools (e.g. STK – System Toolkit). There are attempts to interface these tools to the central data model but this is not very common yet.

For the cost estimator this means that an effort could be made to somehow link her/his estimation templates (e.g. spreadsheets), CERs, or own database to such a model, if confidentiality or other non-technical aspects allow for this. Since rapid data changes occur (see #9), it is mandatory to make robust, well forecasted assumptions for premature technical input data, keep an eye on the data model results, and organize the relevant model outputs which are of interest for the cost estimation as good and efficient as possible. Cost engineering as part of Model-based Systems Engineering (MBSE) is definitely an underestimated topic which provides a lot of material for further research.

Figure 4 presented earlier displayed the GUI for the *Virtual Satellite* central data model used DLR. It is an *eclipse*-based, open source tool enabling multiple-access (with role management), using *Subversion* (SVN) for version control. It includes features such as a product tree, prepared mass budgets, power budgets and modes, a preliminary distributed CAD functionality, functional diagrams, a calculation mask and an Excel interface, but no dedicated cost estimation feature. This is just one example indicating that the concept of cost estimation has not yet fully arrived in the MBSE world.

DLR is working on this topic and welcomes any other activities going into the same direction which seems to be the case looking at the presentation list of the ICEAA 2020 workshop [15].

Bottom-up estimates during a CE-Study (#11)

CE-Studies are most suitable for Phase 0/A studies, as mentioned already. This means that the primary cost estimation methodologies are parametric or base on analogies.
However, similar space missions or systems are barely available, either because something comparable has never been designed or the data is simply not available, which makes analogy assessment sometimes difficult. The parametric approach on the other hand is not well understood by many engineers and sometimes not even accepted (see also #1 and #13). This is particularly true if a tool or CER is used which does not really reflect the way of computing cost for a certain type of mission or for a certain institution or culture. Hence a lot of effort is spend to defend the methodology selection and respective results (with or without adjustment to account for the "differences"), instead of detailing and improving the estimate itself.

Besides the managers or customers who want a super-detailed WBS-based cost estimate already in a Phase 0 study although it is still not even clear if for instance a Propulsion system is needed or not (again, see #1), many engineers tend to feel more comfortable discussing materials and labour cost than to trust a number which is spit out of a parametric tool. The power of parametrics, especially for trade studies where you could easily assess the impact of using e.g. Star Trackers or not, or to what extend the pointing accuracy affects the cost, is not always understood. Sitting face-to-face within an office may lead to a discussion on eye-level but with 15 people next to you who are not familiar with such things as CERs, this is challenging.

Consequently, during many CE-studies a preliminary bottom-up estimate has been made. The advantage is that the estimate makes use of the engineer's experience in terms of materials and labour cost. However, the former may not be properly linked to the model philosophies, test and ground equipment. Especially the spacecraft operation is often drastically under or overestimated, which is due to the short time available and the pressure to continue iterating rather on the technical numbers. In summary, within a CE-environment following a more condensed approach of days instead of weeks, the disadvantage of bottom-up estimates in early phases becomes very apparent.

One lessons learnt is to have – based e.g. on parametric studies – a rough cost distribution per S/S at hand, and a preliminary assessment of how much additional effort is needed for system wraps such as management or product assurance. It could be decided on a case by case basis if the domain experts should be confronted with these historical and average values to get an idea on the ballpark values for their more detailed cost contributions, or not. If specific cost factors (e.g. in k€/kg) are available and well understood (see #4), they are helpful for sanity checks, too.

Moreover, for a bottom-up estimate there has to be a common approach and set of assumptions amongst all contributors, which include the subject matter experts, and maybe their superiors. It makes a huge differences if someone tends to provide a very conservative number to already claim a certain budget and to prepare future negotiations, or if someone does rather the opposite and estimates at the lower end and with realistic cost distributions over time, to ensure that the project is more likely to be funded. If bottom-up estimates are really necessary or desired, the cost breakdown needs to be clear to everyone (see also #1).

Optimizing in the wrong place (#12)

A space mission consists of different segment, such as the space system (including bus and payload), the launch vehicle and the ground segment including operations.
Most CERs and tools are available for the space system, some with, some without payload. Moreover, the majority of CE-study team members represent S/C subsystems. This might support a more detailed cost estimate on S/C bus level, no matter which estimation methodology is applied, compared to the other segments. There is also holistic tools out there, such as the parametric QuickCost tool developed by Hamaker. The S/C bus and payload cost in version 6 of this tool [16] are estimated using CERs, launch cost are entered directly (if desired) while all other NASA WBS elements are covered by adding different percentages on the sum of the S/C bus and P/L cost. Using the average values as shown in [16], the space segment is dominating the total project cost with approx. 60-80% in this 'average' case, depending on the launch cost.
However, especially for long-duration science and exploration missions, the operations cost can significantly increase. But this can also be the case for more regular Earth Observation missions if standard components are used, low complexity and a strong heritage approach is followed.

The key message is that while detailing one part of the project life-cycle cost it could be easily underestimated that there is significant cost, or uncertainties or both associated to other parts, too.

Focus should be set on the cost drivers, discussions on 100 k$ could be saved for later, and a rough mission cost breakdown has to be prepared based on the most suitable references and most driving requirements which could be found. With respect to CERs potentially used, the sensitivity and slopes need to be known in order to know better on what updated values to focus and where the estimate can "survive" with a more rough assumptions (since the cost differences may not be significant).

Lack of acceptance or perceived relevance (#13)

As indicated already a few times, the non-technical participants of early space mission studies are the absolute minority. Focus is set on the science case and technical feasibility, what is understandable. However, without an initial assessment on the cost, no statement regarding a potential implementation of this mission can be made.

Note that studies regarding commercial systems, e.g. for a new geostationary communication satellite, are of course an exception, since they do not only include the cost but also business model considerations. On the other hand, commercial missions usually do not require pre-Phase A analysis, since there is likely a reference platform and the mission-related aspects are comparably simple.

Models and design processes amongst engineers are understood, even if one does not exactly knows how to design another subsystem for example. An electrical engineer developing a power system has an idea of the steps necessary to come up with an on-board computer sizing, and should also be able to properly assess the risk and potential mitigation strategies. She/he also might have some cost numbers at hand and can provide an estimate of the required labour throughout the development (with a very big uncertainty for fancy missions analyzed in a very early phase), but if things like confidence levels or fiscal year enter the game, engineers often cannot or do not want to understand why this is even important, or do not even pay attention until the final magic number is shown.

Additionally, the cost estimate presented is subject to intensive discussion (much more than the maximum power demand during an orbit raising maneuver), and there is sometimes the tendency – rather from management than subject matter expert side – to quickly re-assess the cost on a napkin with the aim to show that the estimate is too high.

Having in mind that most of the described problem areas in this paper are also applicable to the other team members, there simply might not be the time left to talk extensively to them for proper cost and cost-risk assessments, since they need (or want) to focus on their design tasks.

However, as for many other things, it is important to properly explain all assumptions, processes and steps to make them transparent. Since it is one of the strengths of the CE-methodology, educating others to make aware that a decision made by someone affects the design of someone else is imperative.

In the course of a mission selection campaign at DLR, several 3-day CE-studies have been conducted, with the aim to investigate missions and science cases to be realized with a small satellite. In the final presentation session, cost is usually one of the last talks (maybe this should be changed one day). Maybe due to the above discussed aspects or the fact that long days were behind the team, almost no one paid attention. For one of the later designed missions, a lessons learnt was to shock them a bit, with extreme simplified (i.e. very easy to digest) content and the maximum possible cost which had been assessed.

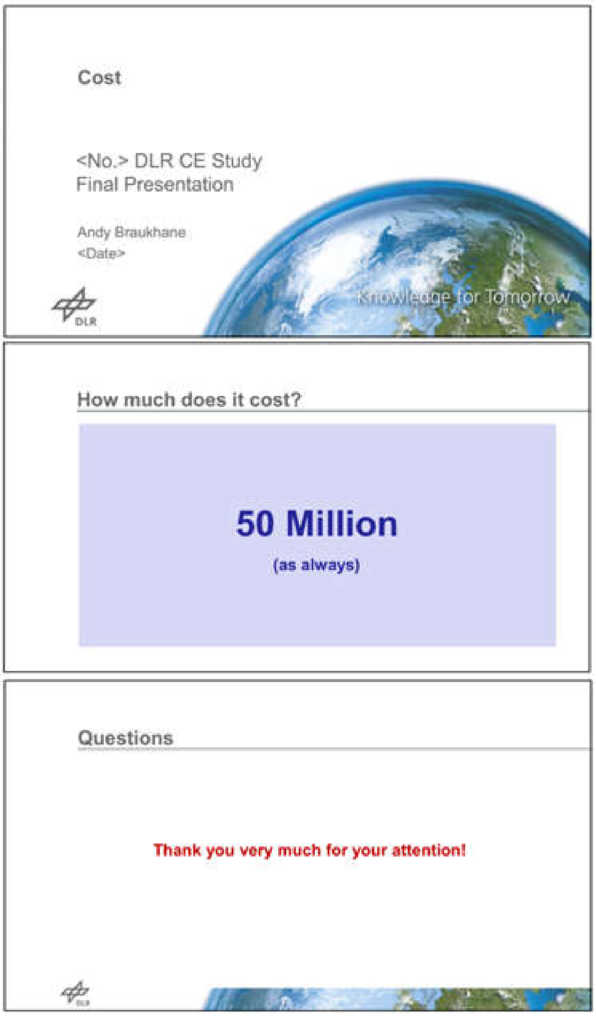

Figure 8: Set of concluding cost slides presented at the end of a recent DLR CE-study, which raised a lot of attention before the actual content was shown

Figure 8 shows the three slides which were presented as a first shot, before the joke was confessed and the proper presentation was held. As a result, everyone was awake, was paying attention and well understood how the numbers were identified, adjusted and how they could be compared with the other missions.

SUMMARY & CONCLUSION

Concurrent Engineering is a very efficient approach well suitable for early phase studies in the space domain. It reduces time, cost and risks while increasing quality and mutual understanding. However, it is not perfect and also has some dark sides as discussed in [17], depending on the implementation and application.

The presented work discusses 13 problem areas and reasons why a cost estimate which is performed in a CE-environment could go wrong, with a focus on the DLR approach to Concurrent Engineering.

As stated, these reasons are not exclusively limited to the cost domain or even CE, but partly also for early phase projects and collaborative efforts in general, and they are also not self-standing but closely linked to each other. Moreover the list is not exhaustive at all.

Mutual influences

As indicated within the previous subchapters, most of these reasons are linked, mutually influenced and even dependent on each other. Some are more CE-specific; some apply to the cost engineering process basically within all projects. Some are more DLR-specific, some relate to all similar processes.
The mutual influences presented in Figure 9 are an attempt to highlight what are the most dominant reasons which potentially could create or amplify other reasons why cost estimation in a CE-study could go wrong. The more connections, the stronger might be the direct influence on other factors. However, this does not relate to the actual impact on the cost estimate but shall indicate what should be kept in mind first in order to maintain full control over the cost estimate performed during a CE-study.

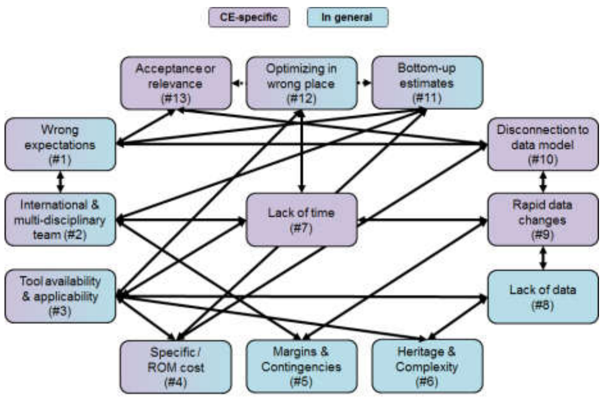

Figure 9: Mutual influences of discussed problem areas

Lessons learnt

Derived from the discussions with respect to the 13 problem areas, a set of general and summarized lessons learnt is compiled in the following. It focused on four main categories, which are: Awareness, Preparation, Communication and Documentation.
These categories are further broken down into 12 plus one 'bonus' recommendations to fight against the 13 problem areas.

Awareness

a) Check who is involved
b) Understand potential problems, prioritize
c) Accept to make compromises, be flexible

Preparation

d) Check all available data, tools, methods
e) Adjust, to be fast
f) Tailor, to be in-line with expectations

Communication

g) Clarify & harmonize inconsistencies, assumptions
h) Explain what you want and can do
i) Educate how you do things, shake team if needed

Documentation

j) Agree on what has been discussed, by consensus
k) Make transparent what you assume and provide
l) Try to connect cost data to common data set/model

One promising approach to address several of the above mentioned aspects is to use a top-level all-in-one tool, such as the "S-chart" used at NASA JPL for rapid, comprehensive mission architecting [18] at Team-X, which is shown here in Figure 10.

It aims to provide a simultaneous view of all major mission considerations, such as the programmatic constraints, technical performances, capabilities and margins, science performances, high-level system descriptions and also cost. This tool, or something along those lines, can be permanently displayed in the CE-environment to keep everyone informed about the latest status. If this is already embedded within a central data model, this would be even better.

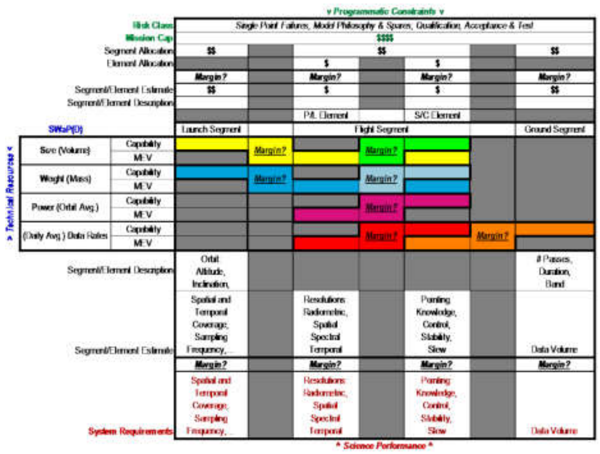

Figure 10: S-chart used at NASA JPL for Rapid Mission Architecting, here on Segment level [18]

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BIOGRAPHY

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