13 Reasons a Cost Estimate Could Go Wrong During a Concurrent Engineering Study (and How to Avoid Them)

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Abstract: During early phase spacecraft design, the concurrent engineering (CE) approach is proven to be very efficient. But the compressed and iterative nature of CE sessions can make life difficult for a cost estimator due to immature data, many design changes, and an intense workflow, among other issues. This work discusses 13 problem areas that have been encountered or observed mainly during one-week-long, interdisciplinary space system design studies at the German Aerospace Center. It provides practical examples on how to tackle them, e.g. how to deal with rapid data changes, false expectations and a heterogeneous engineering team.

Introduction

Concurrent Engineering (CE) is an efficient Systems Engineering approach which is increasingly applied in early phase spacecraft (S/C) design due to the involvement of all relevant disciplines, including the customer, and is often supported by data models and tools as well as by 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, to 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 rough order of magnitude (ROM) cost or a detailed estimate following an elaborated work breakdown structure (WBS). These and other reasons why cost estimation could go into 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 particularly significant stumbling stones which can be encountered during otherwise very efficient and recommendable Concurrent Engineering activities for space missions and systems in the early phase (here so-called CE studies). We use the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt) Concurrent Engineering (DLR CE) approach as our example.

The potential problems mentioned are not exclusively applicable for CE, nor for the cost domain. As for CE studies 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 a particular approach is applied, but also common rules and practices are followed. Please note that throughout the entire paper, the term CE is exclusively used for Concurrent Engineering and not for Cost Engineering.

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 space missions and systems, the DLR Concurrent Engineering Facility (CEF) has been established as part of the Institute build-up [1]. It is shown in Figure 1.

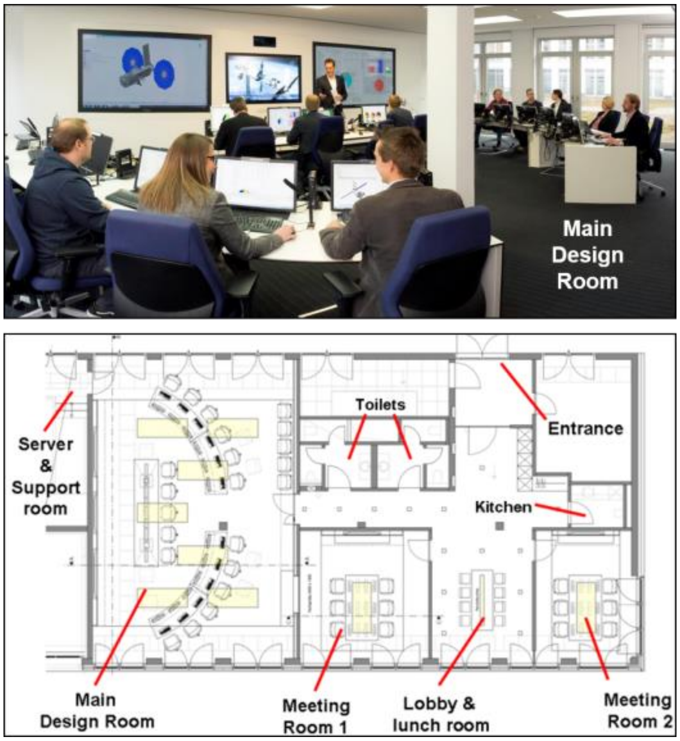


Figure 1: DLR Concurrent Engineering Facility (CEF)

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 structured process, an infrastructure which fosters communication and collaborative 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].

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. ESA also implemented this approach in 1998. It clearly proved the efficiency and high quality for early space system and mission studies. Nowadays, many international organizations apply CE in one way or another as part of their Systems Engineering activities. These organizations include agencies (e.g. NASA, ESA, DLR), system integrators (e.g. Airbus), private or governmental organizations (e.g. Aerospace Corporation, NRO) and universities (e.g. Utah State University, ISU Strasbourg) [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 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 (regarding size and 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,

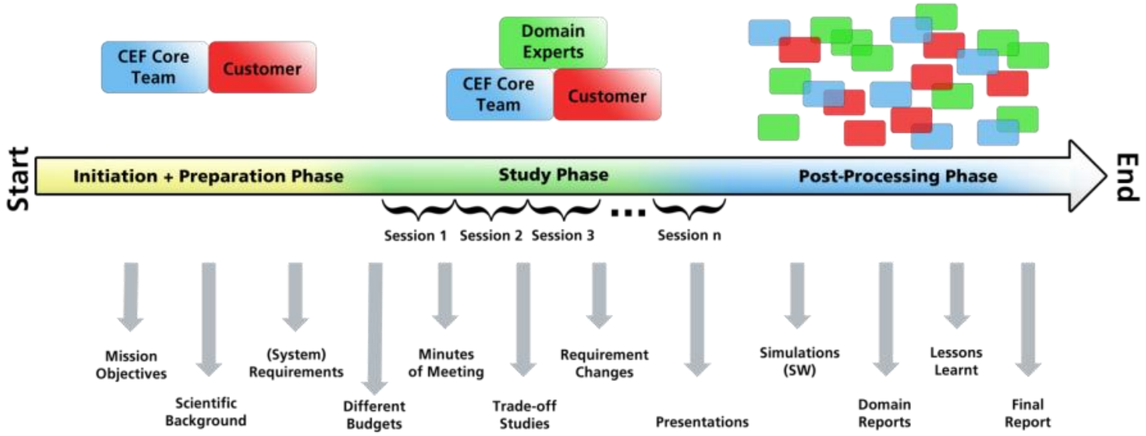


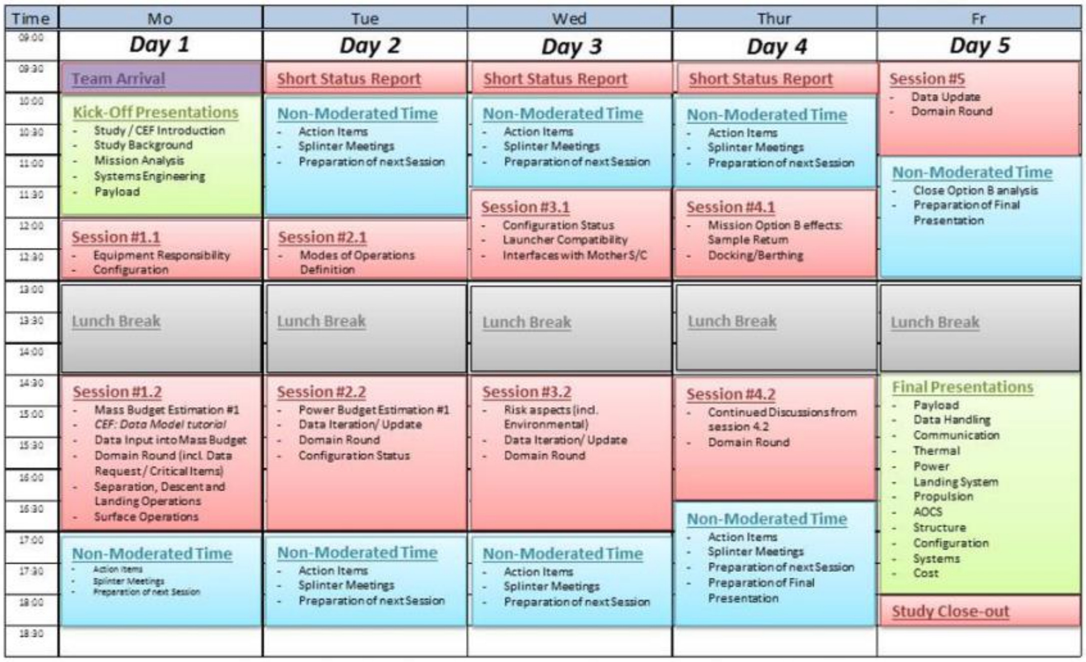
Figure 2: DLR Concurrent Engineering study, overall timeline

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. Figure 3 presents a typical schedule for the actual one-week study phase. In this phase, there is a mixture of moderated (indicated in red) and non-moderated sessions (blue), in which either general and system-relevant or more specific trades and tasks are carried out.

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 compresses all 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



Time	Mo	Tue	Wed	Thur	Fr
09:00	***Day 1***	***Day 2***	***Day 3***	***Day 4***	***Day 5***
09:30	Team Arrival	Short Status Report	Short Status Report	Short Status Report	Session #5 - Data Update - Domain Round
10:00	Kick-Off Presentations - Study / CEF Introduction - Study Background - Mission Analysis - Systems Engineering - Payload	Non-Moderated Time - Action Items - Splinter Meetings - Preparation of next Session	Non-Moderated Time - Action Items - Splinter Meetings - Preparation of next Session	Non-Moderated Time - Action Items - Splinter Meetings - Preparation of next Session	
10:30					Non-Moderated Time - Close Option B analysis - Preparation of Final Presentation
11:00					
11:30			Session #3.1 - Configuration Status - Launcher Compatibility - Interfaces with Mother S/C	Session #4.1 - Mission Option B effects: Sample Return - Docking/Berthing	
12:00	Session #1.1 - Equipment Responsibility - Configuration	Session #2.1 - Modes of Operations Definition			
12:30					
13:00	Lunch Break	Lunch Break	Lunch Break	Lunch Break	Lunch Break
13:30					
14:00					
14:30	Session #1.2 - Mass Budget Estimation #1 - *CEF: Data Model tutorial* - Data Input into Mass Budget - Domain Round (incl. Data Request/ Critical Items) - Separation, Descent and Landing Operations - Surface Operations	Session #2.2 - Power Budget Estimation #1 - Data Iteration/ Update - Domain Round - Configuration Status	Session #3.2 - Risk aspects (incl. Environmental) - Data Iteration/ Update - Domain Round	Session #4.2 - Continued Discussions from session 4.2 - Domain Round	Final Presentations - Payload - Data Handling - Communication - Thermal - Power - Landing System - Propulsion - AOCS - Structure - Configuration - Systems - Cost
15:00					
15:30					
16:00					
16:30				Non-Moderated Time - Action Items - Splinter Meetings - Preparation of next Session - Preparation of Final Presentation	
17:00	Non-Moderated Time - Action Items - Splinter Meetings - Preparation of next Session	Non-Moderated Time - Action Items - Splinter Meetings - Preparation of next Session	Non-Moderated Time - Action Items - Splinter Meetings - Preparation of next Session		
17:30					
18:00					Study Close-out
18:30					

Figure 3: DLR Concurrent Engineering study phase schedule example (one-week approach)

customer, Science/Payload Engineering, Systems Engineering, Mission Analysis, subject matter expertise for Structure, Thermal, Power, Command and Data Handling, Telecommunication and Telecommand, Attitude and Orbit control, Propulsion, Accommodation, Mission Operations, Risk/Product Assurance and also Cost Engineering/Analysis.

At the end of the preparation phase, the CE study organizers distribute a study scope document to the entire team to create a common foundation. 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 work starts immediately with discussing the impact of the top-level requirements for the mission and system design, and with initial definitions of the product tree, preliminary subsystem (S/S) sizing and operational modes. That is when the fun part for all participants including the cost estimators begins.

Cost Estimation in a Concurrent Engineering Environment

In not so serious terms, one has to imagine to have a counter on the desk with 32 to 40 hours counting backwards, approximately 20 people in one single room (thereof at least 15 purely technical experts), a challenging mission statement displayed on the screen, and the only one who is interested in things like fiscal year or full accounting cost is the cost estimator. This is cost engineering within a CE environment in a nutshell.

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

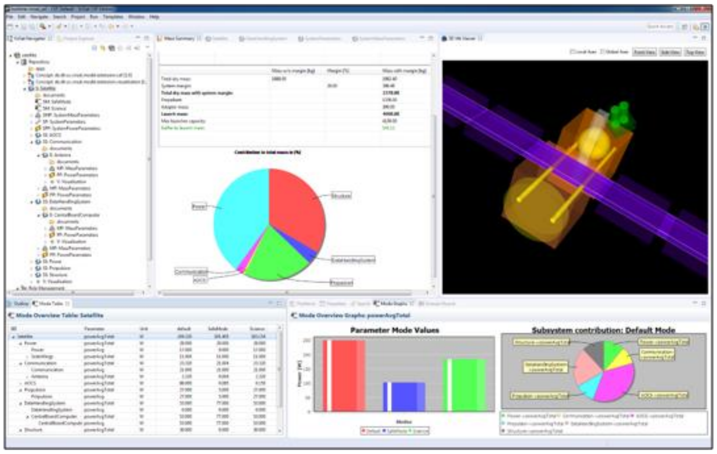


Figure 4: DLR Virtual Satellite data model

- 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 cross-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 at all.

Methods and tools used in the CEF cover amongst others the Small Satellite Cost Model (SSCM) 2014, TransCost, internal Excel tools based on Cost Estimation Relationships (CERs), WBSs and/or the T1 Equivalent Units approach [6], and formerly also the Unmanned Space Vehicle Cost Model. Central data models used at DLR include mainly the Virtual Satellite (VirSat) shown in Figure 4, but also the ESA Open Concurrent Design Tool and the former ESA Integrated Design Model workbooks as complementary and optional models [7].

13 Reasons Why…

In the following, the selected 13 reasons why a cost estimate during a Concurrent Engineering study could go wrong are discussed. For sure, there are plenty of others which could lead to tough work or even wrong results, but these are most prominent reasons 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, Principal Investigators or entire science teams. 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. That is why 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.

However, often it is expected to provide already a bottom-up estimate on work package level, showing even labor cost, material cost, facility and operational cost (see also problem area #11). Other customers rather want to see a split between non-recurring development and recurring production 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. Almost all study customers would like 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 afterwards.

The expected level of detail is often not consistent with the time available to provide the results, nor with what the estimator believes should and could be done at this early stage. Moreover, it might not be understood that even the cost estimation tools available can barely be applied to all of the missions to be studied, 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 for example within the *NASA Cost Estimating Handbook* [8] and shown in Figure 5, could be tailored. It has to be agreed on what the most relevant and possible cost breakdown might be. For instance, if and how production and

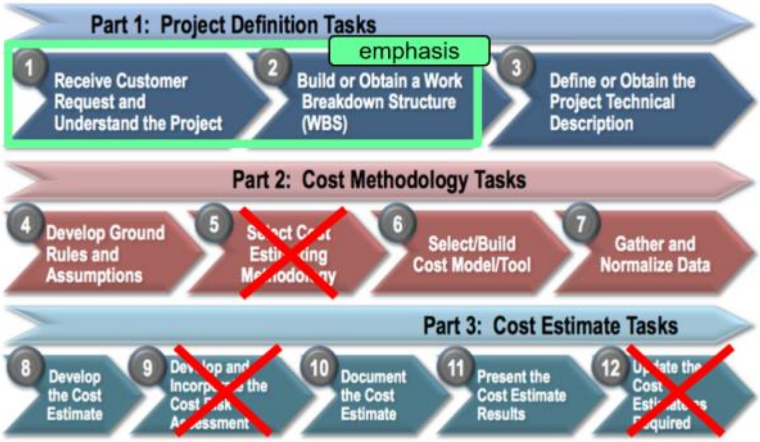


Figure 5: Random example of tailoring the NASA cost estimating process, adapted from [8]

development cost, systems and subsystem engineering, labor and material cost, investments and facilities are broken down. Moreover, it shall be clarified, if the focus is set on space segment cost or e.g. operations cost. 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 planned for implementation may significantly affect the labor rate or productivity assumptions to be considered. This is true for parametric and other estimation methodologies.

During one study there was an engineer who considered the involvement of Greek institutions for building a formation of CubeSats. Although the currency for most countries in Europe is euro (€), labor rates can be completely different when comparing e.g. northern with southern European countries. In this study case it was required to decide which work packages (or S/S) should be assessed with a labor rate of 200,000 € per work-year and which ones with 100,000 €.

Prior to the study, even if not a single detail is available for the technical baseline, a cost-internal stakeholder analysis should be performed. It needs to cover all aspects related to the different team members and maybe their different attitude in terms of supporting a cost estimate. It also shall identify how different international contributions for the mission could affect the estimation process, and what elements (e.g. labor) might need adjustments. This exercise last only minutes but it 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 a poor data set, is often 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 that are not transparent to 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 [9], which covers the S/C bus cost (which is the full satellite without the payload), 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 even to invest in extensive internal developments.

However, sometimes the space mission to be designed and analyzed is so 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 freely available CERs, a parametric tool, or 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 are captured in US dollar ($), and might force the estimator to convert the results into the required currency. Then the question still remains which inflation scheme should be applied, the NASA inflation index, European annual average inflation or a national one. 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 combing cost references from different other missions where some elements are similar in one, and some elements are similar in another mission (or system). Ultimately, the decision has to be made whether the available support tools are fully or partly applicable, whether 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 one 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 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. in k€/kg). However, due to lack of time, data clarity, understanding or precision, both the estimator and the customer could simply have wrong interpretations of such a factor, which was identified or given.

Specific costs are often not equipped with a fiscal year, which should be carefully considered if the developed/found value is old. But even more important are the correct contextual assumptions for the mass and cost contributors. 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 50,000 k€ for the S/C itself and 100,000 k€ for the entire project lifecycle (incl. launch and operations). If 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 used for the service segment (bus) only, but sometimes for the full satellite including the payload (P/L).

Specific cost options [k€/kg] (FY 2020)		S/C bus cost [k€]	Project cost [k€]
		50000	100000
S/C dry mass [kg]	250	200	400
S/C launch mass [kg]	350	143	286

Table 1: Different interpretations of specific cost in k€/kg

The estimator needs to make sure what values shall be taken, and explain this in front of the entire study team. And if someone else is arguing during the study that the specific cost number from another source is different, first it has to be agreed on the correct interpretation of this initial -quick-look reference number.

Use of margins and contingencies (#5)

In the early design phase, 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, for instance the *Concurrent Design Facility Studies Standard Margin Philosophy Description* compiled by the European Space Agency [12].

Options: =>	Option (1)		Option (2)	Option (3)
Cost Item	mass [kg]	Design Maturity Margin (DMM)	mass + DMM [kg]	mass + 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

Table 2: Satellite mass budget example on subsystem level, showing 3 options for mass values to be used as potential inputs for parametric cost estimation tools

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 this team is not necessarily used to work together. This means that the systems engineer and team leader have to make sure that everyone has the same understanding related to the application of contingencies and margins. This is 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 must be clear exactly what values are to be taken. When using for instance mass-based CERs, there are in principal three major options.

Table 2 presents a mass budget on subsystem level for a small satellite, where the masses are the sum of the respective equipment, with and without margins. Out of these three options listed in the following, it has to be decided which mass values 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 including design maturity margins (DMM), displayed in the 4th column from the left,
3) S/S mass including DMM, plus the system margin portion on top, i.e. the values from the 4th column and additionally 20% extra for each S/S.

Usually, the tools and CERs are primarily based on actual data. Furthermore, mass growth is a typical phenomenon in space system development which eats up contingencies and margins throughout the phases. Hence, it is recommended to use option (3) if nothing else is explicitly requested, which is the S/S mass including DMM and the system margin portion on top. Alternatively, option (2) could be used, but the additional uncertainty shall be clearly reflected in the cost-risk analysis or at least within the documentation of the 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. Looking at our example, this means that the Thermal S/S mass to be taken for the CER or tool is not 10 kg, nor 12 kg, but 14.4 kg. Please see also reason #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 parameters should be clear, documented and agreed on. During the rapid and iterative estimation loops within the CE environment these details may be easily overlooked.

Heritage & Complexity (#6)

As for any other study or project, the cost estimation has to consider 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 needed 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 whether they design something new or just a derivation of an existing system. But for the cost estimator the question remains, how strong this would affect the results. Some CERs and tools account for one or 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 whether the data, tools, models or CERs account for this already, or if these factors have to be applied on top of the given outcomes. The key assumptions in the *SSCM 2014 User's Manual* [9] 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. Alternatively, a certain percentage, a linear or an exponential factor could be used as done for several CERs. However, this has to be selected and defined with care. These factors can vary from only a few additional percentages to doubling or tripling of cost when comparing an average heritage (e.g. 50%) to a completely new development. The same is true for similarly subjective assessments of complexity.

Such adjustments, either manually or as a part of a tool, should be factored in at the very end of the study, when most technical data are available. During the CE study itself the team or at least systems engineer will usually strive for highest possible heritage and lowest complexity. As an estimator, 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, but self-explaining issue, probably partly also a self-made problem of the DLR CE approach or institutions with similarly dense study timelines. Although this approach is very efficient, the absolute time for analysis and potential re-work is short. First, within one week plus maybe some days before and afterwards, one cannot perform the complete cost estimation process as stated e.g. within the *NASA Cost Estimating 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, which are used as input for the cost analyses, and hence the estimator is rather busy during later design iterations.

Therefore, it is imperative to use a tool, calculation, CER, or a model template the estimator is 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 estimation. This is the case for example during 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 the estimator is lacking both, due to the technical immaturity of the present mission/system at that stage, and also due to low (or no) comparability to former missions or simply lack of access to previous mission data. Unfortunately, in Europe there is no public database available such as CADRe or ONCE [14] in the United States.

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 related 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. If there are technological or operational differences apparent between the CERs used and the spacecraft to be designed for instance, effort shall be made to replace or adjust the cost of particular subsystems which differ most. This can be done 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. We look at following example: There is a requirement for a small satellite mission with a maximum launch mass of 300 kg. At the end of study day one, with an initial version of the product tree available, the preliminary mass budget indicates a launch mass of 225 kg. However, not every engineer adds the relevant data into the data model already in the beginning, so maybe the structural mass is still missing entirely, the harness mass is not yet considered, and the propellant mass is completely unknown. In the course of the second day, subject matter experts close some design gaps, discuss and re-iterate with comfortable contingencies. This results in a total launch mass of 410 kg. During day 3, the team identifies that the P/L and the S/C bus both included an optical bench and Star Trackers within their budgets, that the operational modes are not fully consistent, and that there is no need for an X-band system anymore. This leads to an updated launch mass of 340 kg. Day 4 is typically the day reserved for refinements. The amount of data needed as input for an e.g. parametric cost

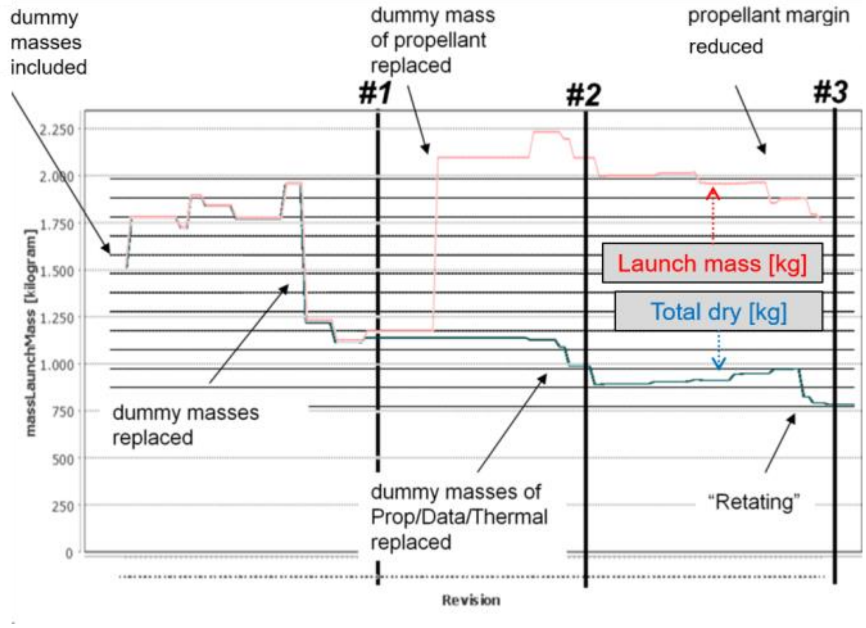


Figure 6: Example of mass variations over time during a Concurrent Engineering study, taken out of the data model history

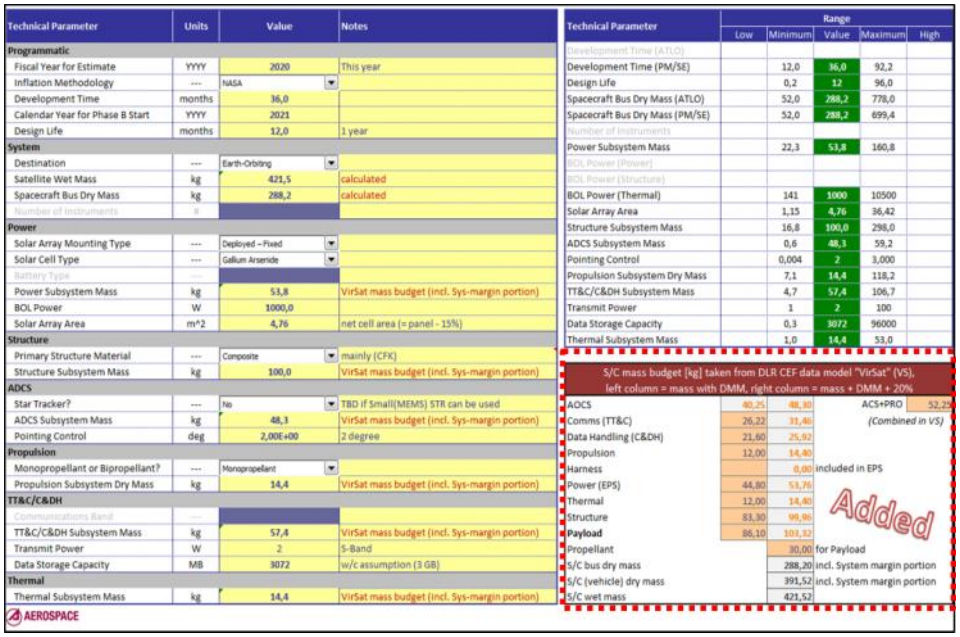
estimation model is mostly complete, and – in our example – the total launch mass deceased to 290 kg, which is compliant to the requirement.

However, during the final presentation session on day 5, one engineer figures out that the redundancy scheme for the avionics is not compliant to the failure-tolerance requirement for this mission. Now the mass increases up to 320 kg again, which won't be a show stopper at this stage, but shall indicate that there is always changes to be expected. Another example of these changes is presented in Figure 6. In order to constantly build up and update the cost estimate, by e.g. using amongst others the SSCM for this S/C size, the available cost model needs to be updated easily without mixing up numbers or forgetting something.

As for many other 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 2014, where an input sheet has been modified accordingly. On the left side is the original input area for the tool, while on the top right the technical parameter values are checked to see whether they are in the permissible 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.

In Figure 7, the S/S masses are converted to masses including design maturity margins plus the system margin portion (as discussed in #5), and then linked to the actual input area. Moreover, the system masses (dry, wet, launch) are organized in such a way that a quick comparison with the actual system mass budget is easily possible to identify gaps or overlaps.

It would be even better, however, if such an 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.



Technical Parameter	Units	Value	Notes
Programmatic			
Fiscal Year for Estimate	YYYY	2020	This year
Inflation Methodology	---	NASA ▾	
Development Time	months	36,0	
Calendar Year for Phase B Start	YYYY	2021	
Design Life	months	12,0	1 year
System			
Destination	---	Earth-Orbiting ▾	
Satellite Wet Mass	kg	421,5	calculated
Spacecraft Bus Dry Mass	kg	288,2	calculated
Number of Instruments	#		
Power			
Solar Array Mounting Type	---	Deployed – Fixed ▾	
Solar Cell Type	---	Gallium Arsenide ▾	
Battery Type	---		
Power Subsystem Mass	kg	53,8	VirSat mass budget (incl. Sys-margin portion)
BOL Power	W	1000,0	
Solar Array Area	m^2	4,76	net cell area (= panel - 15%)
Structure			
Primary Structure Material	---	Composite ▾	mainly (CFK)
Structure Subsystem Mass	kg	100,0	VirSat mass budget (incl. Sys-margin portion)
ADCS			
Star Tracker?	---	No ▾	TBD if Small(MEMS) STR can be used
ADCS Subsystem Mass	kg	48,3	VirSat mass budget (incl. Sys-margin portion)
Pointing Control	deg	2,00E+00	2 degree
Propulsion			
Monopropellant or Bipropellant?	---	Monopropellant ▾	
Propulsion Subsystem Dry Mass	kg	14,4	VirSat mass budget (incl. Sys-margin portion)
TT&C/C&DH			
Communications Band	---		
TT&C/C&DH Subsystem Mass	kg	57,4	VirSat mass budget (incl. Sys-margin portion)
Transmit Power	W	2	S-Band
Data Storage Capacity	MB	3072	w/c assumption (3 GB)
Thermal			
Thermal Subsystem Mass	kg	14,4	VirSat mass budget (incl. Sys-margin portion)

Technical Parameter	Range				
	Low	Minimum	Value	Maximum	High
Development Time (ATLO)					
Development Time (PM/SE)		12,0	36,0	92,2	
Design Life		0,2	12	96,0	
Spacecraft Bus Dry Mass (ATLO)		52,0	288,2	778,0	
Spacecraft Bus Dry Mass (PM/SE)		52,0	288,2	699,4	
Number of Instruments					
Power Subsystem Mass		22,3	53,8	160,8	
BOL Power (Power)					
BOL Power (Structure)					
BOL Power (Thermal)		141	1000	10500	
Solar Array Area		1,15	4,76	36,42	
Structure Subsystem Mass		16,8	100,0	298,0	
ADCS Subsystem Mass		0,6	48,3	59,2	
Pointing Control		0,004	2	3,000	
Propulsion Subsystem Dry Mass		7,1	14,4	118,2	
TT&C/C&DH Subsystem Mass		4,7	57,4	106,7	
Transmit Power		1	2	100	
Data Storage Capacity		0,3	3072	96000	
Thermal Subsystem Mass		1,0	14,4	53,0	

S/C mass budget [kg] taken from DLR CEF data model "VirSat" (VS),
left column = mass with DMM, right column = mass + DMM + 20%

AOCS	40,25	48,30	ACS+PRO	52,25
Comms (TT&C)	26,22	31,46	*(Combined in VS)*	
Data Handling (C&DH)	21,60	25,92		
Propulsion	12,00	14,40		
Harness		0,00	included in EPS	
Power (EPS)	44,80	53,76		
Thermal	12,00	14,40		
Structure	83,30	99,96		
Payload	86,10	103,32		
Propellant		30,00	for Payload	
S/C bus dry mass		288,20	incl. System margin portion	
S/C (vehicle) dry mass		391,52	incl. System margin portion	
S/C wet mass		421,52		

Figure 7: Screenshot of an adapted SSCM 2014 [9] input sheet

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 but only positive: a bit of consistency is better than no consistency, thus we are talking about a luxury problem. But the cost domain is typically not included in these data models. This is also true in many cases for some domains, which use powerful commercial software, such as computer-aided design (CAD) or orbital simulations tools. There are attempts to interface these tools to the central data model but this is still not very common.

For the cost estimator this means that an effort could be made to somehow link the estimation templates (e.g. spreadsheets), CERs, or own databases to such a model, if confidentiality or other non-technical aspects allow it. Since rapid data changes occur (see #9), it is mandatory to make robust, well forecasted assumptions for premature technical input data. One needs to 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 issue, which provides a lot of opportunities for further research.

Figure 4 showed the Virtual Satellite central data model used at DLR. It is an eclipse-based and open source tool enabling multiple-access (with dedicated role management). It uses Subversion 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, which indicates that the concept of cost estimation has still not 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 by looking for instance into 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 based 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 assessments 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 when 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. As a result, much effort is spent defending the methodology selection and respective results, instead of improving the estimate itself.

Besides the managers or customers who want a super-detailed 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 labor cost than to trust a number which is spit out of a parametric tool. Unfortunately, the power of parametric estimation is not always understood. During trade studies, where the estimator could easily assess with their CERs the financial impact of using e.g. a Star Tracker or not, or the pointing accuracy cost sensitivity, many engineers do not trust this statistics-based approach.

Consequently, during many CE studies, a preliminary bottom-up estimate shall and has been made. The advantage is that the estimate makes use of the engineer’s experience in terms of materials and labor 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 parameters. As a result, within a CE environment which follows more condensed approach of days instead of weeks, the disadvantage of bottom-up estimates in early phases becomes very apparent.

One lesson 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 whether or not the domain experts should be confronted with these historical and average values upfront, to get an idea on the ballpark values for their more detailed cost contributions. 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 attitude and set of assumptions amongst all contributors, which include the subject matter experts, and maybe their superiors. It makes a huge difference if someone tends to provide a very conservative number to already claim a certain work package budget and to prepare for upcoming negotiations, or if someone does rather the opposite and estimates rather at the lower end, 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 and approach need to be clear to everyone (see also #1).

Optimizing in the wrong place (#12)

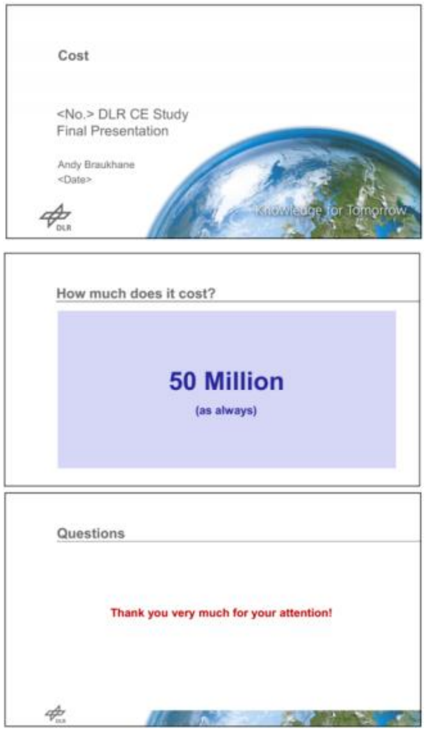
A space mission consists of different segments, such as the space system (including bus and payload), the launch vehicle, and the ground segment including operations. Most CERs and tools are available for the space system, some with, some without payload. Moreover, the majority of CE study team members each represent one 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 are also holistic tools out there, such as the parametric QuickCost tool [16]. The S/C bus and P/L cost in version 6 of this tool are estimated using CERs. Launch cost are entered directly (if desired) while all other NASA WBS elements are covered by adding various and suggested percentages to the sum of the S/C bus and P/L costs. Using the average values shown in [16], the space segment is dominating the total project cost with approx. 60-80%, depending on the launch cost. However, especially for long-duration science and exploration missions, the operations cost can increase significantly. But this can also be the case for more regular Earth Observation missions if standard components are used, or 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 associated to other parts as well. Focus should be set on the cost drivers. Discussions on 100 k$ level should be saved for later, and a rough mission cost breakdown has to be prepared, based on the most suitable references and most driving requirements. For the most likely used CERs, the sensitivity and slopes need to be known in order to know better on which updated values to focus, and where the estimate can survive with rougher assumptions (since the cost differences may not be significant).

Lack of acceptance or perceived relevance (#13)

As indicated already, the non-technical participants of early space mission studies are the absolute minority. Focus is often set on the science case and technical feasibility. However, without an initial assessment on the cost, no statement regarding a potential implementation of this mission can be made. Only studies of commercial systems (e.g. for a new communication satellite) might be different, since they do not only include the cost but also business model considerations. On the other hand, commercial systems usually do not require a pre-Phase A analysis, since there is very likely a reference S/C platform available within the industry, and the mission-related aspects are comparably simple.



Cost

<No.> DLR CE Study
Final Presentation

Andy Braukhane
<Date>

Knowledge for Tomorrow

DLR

How much does it cost?

50 Million
(as always)

Questions

Thank you very much for your attention!

DLR

Figure 8: Set of concluding cost presentation slides at the end of a study, which raised attention before true content was shown

However, technical models and design processes amongst engineers are understood, even if one does not exactly know how to design another subsystem for example. For example, an electrical engineer developing a power subsystem has an idea of the steps needed to design an on-board computer architecture, and should also be able to properly assess the risk and potential mitigation strategies. The work package leader also might have some cost numbers at hand and can provide an estimate of the required labor throughout the development (with a very big uncertainty for fancy missions analyzed in a very early phase). However, if less technical terms like confidence levels or fiscal years are presented, most engineers often cannot, or do not want to understand why this is even important, or do not pay attention at all until the final magic cost number is shown.

Experience shows, that the cost estimate presented is subject to intensive discussion, much more than the maximum power demand during an orbit raising maneuver. There is also sometimes the tendency, rather from management than engineering side, to quickly re-assess and oversimplify the cost on a napkin, with the aim to show that the estimate is still too high.

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

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

For example, 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. During the final presentation session, cost is usually one of the last talks (maybe this should be changed one day). Probably 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, another lesson learnt was to shock them a bit, with an extreme simplified (i.e. very easy to digest) content and presenting solely the maximum possible cost which had been assessed.

Figure 8 shows the three slides that were presented as a first shot, before the joke was confessed and the actual presentation was given with all the assumptions and the approach. As a result, everyone was awake, paying attention and

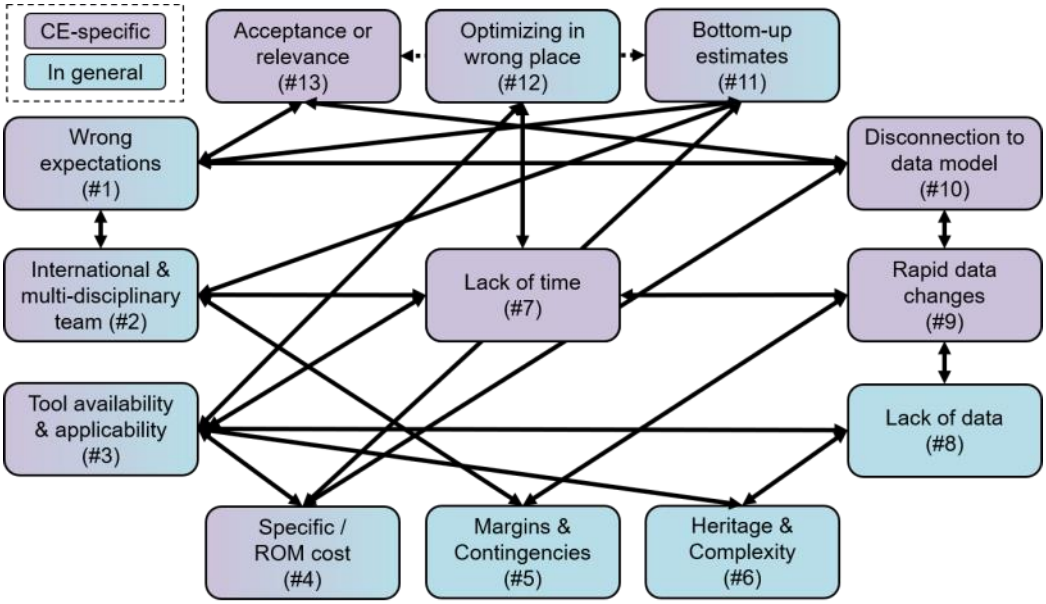


Figure 9: Mutual influences of discussed problem areas

ultimately well understood how the numbers were identified, adjusted and how they could be compared with the other missions.

Summary and 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. The focus was set on the DLR approach to Concurrent Engineering.

As stated, many of these reasons are not exclusively limited to the cost domain or even CE, but also for early phase projects and collaborative efforts in general. They are also not self-standing but closely linked to each other, and 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 only indicate what should be kept in mind first in order to maintain full control over the cost estimate performed during a CE study.

Lessons learnt

Derived from the discussions above, a set of 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 twelve recommendations to fight against the 13 discussed problem areas.

Awareness

- Check who is involved
- Understand potential problems, prioritize
- Accept to make compromises, be flexible

Preparation

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

Communication

- Clarify and harmonize inconsistencies and assumptions
- Explain what the estimator/analyst wants and can do
- Educate how the estimate is done, and shake (or shock) the team if needed

Documentation

- Agree on what has been discussed and decided by consensus
- Make transparent what the estimator/analyst assumes and is able to provide
- 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 [18] used at NASA Jet Propulsion Laboratory for rapid, comprehensive mission architecting at Team-X. The aim is 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. Such chart, or something along those lines, can be permanently displayed in the CE environment to keep everyone informed about the latest status. If it is already embedded within a central data model, this would be even better.

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