Lessons Learned from One-Week Concurrent Engineering Study Approach

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Abstract

The present paper discusses the advantages and disadvantages of the one-week Concurrent Engineering (CE) study approach applied currently in the Concurrent Engineering Faciliry (CEF) at DLR which has been operating since early 2009. Up to now, ca. 20 condensed studies have been performed at the DLR CEF. This paper compares this approach to the more stretched process, applied e. g. at ESA ESTEC's Concurrent Design Facility (CDF). The investigation takes into account the different space systems to be designed, the goals of the studies and the involved personnel, including both internal and external team members. In summary, this paper describes the last three years of CE at DLR, focussing on the mainly applied approach within different feasibility and preliminary design studies.

Keywords

Concurrent Engineering, Systems Engineering, Concurrent Design Facility, Spacecraft Design, Phase A Studies

1 Introduction

The complexity of spacecrafts (S/C) and today's stringent economical requirements and conditions drive the industry, space agencies and research institutions to increasingly apply the methodology of Concurrent Engineering (CE) for system development. CE is an integrated approach of product development following a formalized process with systematic design steps and involves all necessary expert domains as well as the customer, respectively the end user. CE leads to a collaborative and simultaneous work of experts from different areas already in the early phases of a design process. This Systems Engineering (SE) process enables increased quality of the product and reduced cost due to the decrease of later changes, inconsistencies and development time within the product life-cycle.

In the beginning of 2008, the Institute of Space Systems of the German Aerospace Center (DLR) founded in 2007 in Bremen, Germany, started the application of the CE methodology for corresponding spacecraft design activities [Romberg, et al. 2008]. Starting with a training week at the Concurrent Design Facility (CDF) [Bandecchi, et al. 2000] of the European Space Agency (ESA) the DLR team became familiar with the different key elements, which are the:

- Concurrent Engineering process,
- multidisciplinary team arrangement,
- the use of an integrated design model,
- multi-media tools, the software- and hardware infrastructure as well as a
- Concurrent Engineering Facility (CEF) (cf. Figure 1).

Since the new DLR infrastructure had been under construction until the beginning of 2009, a preliminary Design Workshop (DWS) was set-up and evolved within two steps before the fully functional CEF could be used [Romberg, et al 2008]. However, although the DWS infrastructure provided only reduced functionality, the approach of having condensed one-week design studies, instead of more-week studies conducted among others at ESA, was already planned and applied in the very early phases of the DLR CE activities.

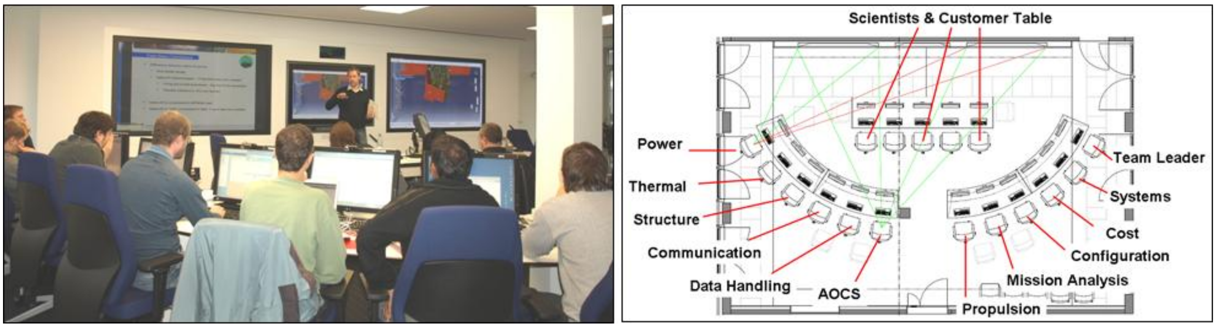

Figure 1: CE Session (left) and an exemplified Set-up of the Main Design Room (right)

Amongst other aspects, one important reason for a squeezed schedule is the fact, that experts who should be on site during a study are spread over all 13 DLR-locations in Germany.

In the following the advantages and disadvantages of a *one-week study approach* are discussed, also providing a comparison to the more stretched approaches applied e. g. at ESA ESTEC. It takes into account the different space systems to be designed, the goals of each study and the involved personnel, including both internal and external team members. In summary the last three years of CE activities at DLR are described, focussing on the mainly applied approach within different feasibility and preliminary design studies.

2 The Concurrent Engineering Process

2.1 General Process Description

According to the preferred definition by [Bandecchi, et al. 2000], "*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 manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle.*" Although this definition does not include any limitations with respect to a certain phase of the product life-cycle, the main CE applications in space systems engineering take place within the pre-development phases 0 and A.

Throughout the major space agencies, research and industrial entities, the general characteristics of the CE methodology, besides the already described key elements in chapter 1, are the alternating plenary CE- and post-processing sessions in which the engineers design their subsystems (S/S) in real time, simultaneously during the plenary CE session and on their own or in reduced-groups during the post-processing session. The high amount of parallel work and the iterative nature of the process, ESA appropriately describe with the "Spiral Model" [Henderson, Caldwell 2008], significantly reduces development time, whereas the interdisciplinary and system level awareness of design decisions and their impacts to other domains lead to a decreasing failure potential and hence also cost. The gain in expertise of other fields, by listening and intensively discussing with other domain engineers is an additional value for the different experts.

Generally there is no rule how to make use of the Concurrent Engineering methodology. ESA prefers a longer approach having bi-weekly design sessions over three to six weeks [Bandecchi 2001] whereas DLR favours the squeezed one-week approach.

2.2 DLR Study Phases

Generally, the overall CE process applied at DLR is divided in four different sequential phases: an initiation phase, a preparation phase, the actual study phase, where the entire team comes together and a completing post-processing phase which all can be seen in Figure 2.

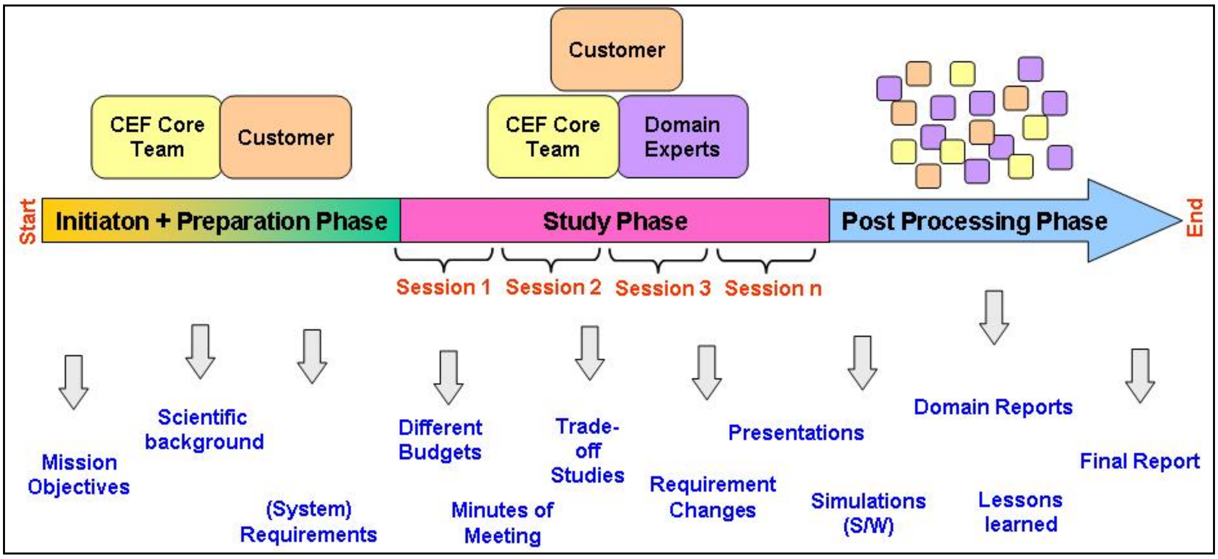

Figure 2: Concurrent Engineering Process Phases and their Outcomes [Schubert, et al. 2010]

Where the initiation and preparation phases involve primarily the system-related team members and the customer, defining the mission and system objectives as well as the expected products and services, the study phase is the timeframe where the collaborative design iterations take place.

Based among others on the experience of ESA Concurrent Design studies, this phase is basically covered by two presentation sessions, one for introductions in the beginning and one for the conclusions on subsystem as well as on system level at the end. Furthermore, the study phase contains up to four plenary concurrent design sessions, lasting two to four hours and offline-work in between for particular domain-specific analyses and reduced working groups.

3 The One-week Approach

3.1 Background

Within the last three years at DLR CE facility, 20 studies covering a variety of space systems have been performed. 13 of the studies had durations of one week, covering the design activities of compact class-, nano-, cube- and geostationary satellites as well as different kind of lunar and Martian probes.

In comparison, all three conducted launch vehicle studies within the CEF lasted two or more weeks, not because of team member availability issues but rather the higher expected sequential information flow during the design iterations.

Here, the exchange of information and data from one domain to the other was identified as more step-wise than during satellite design processes. The launcher performance analyses, which have been the major drivers for the studies, required information of the different stages, in particular the upper stage design, which again required the selection and arrangement of the units within the stage.

Two other preliminary design studies of low Earth satellites which had been scheduled over two weeks as well, did not have to consider organisational constraints like travels and team member accommodation since the involved disciplines and the customer came from institutions close to DLR Bremen.

There was only one study about an Asteroid landing module with an international set of experts scheduled over two weeks where three very different system options had been investigated.

3.2 Study Organisation

The so-called “Study Phase” is not the only part of an entire CE study, but the main one. Although a lot of managerial and technical preparations take place beforehand, the actual design iterations including all subsystems are performed within this dedicated time-frame.

In order to provide a general overview, Figure 3 shows the different sessions of the study phase, typically scheduled within one week:

DLR CE - Study Schedule (1 week example)

	Monday	Tuesday	Wednesday	Thursday	Friday
morning	*Team Arrival* Kick-off Presentations	*Post-processing*	CE Session #2	CE Session #3	CE Session #4
	Lunch / Break				
afternoon	CE Session #1	*Post-processing*	*Post-processing*	*Post-processing*	Final Presentations *Team Departure*

Figure 3: Exemplified Schedule for a DLR one-week CE study

According to the above displayed study schedule the typical order, respectively focus of technically related issues to be handled for a satellite design study per Concurrent Engineering session is as follows:

- ***Session #1*** is the first session in which the domain engineers are requested to provide an initial estimation of their design, mainly focussing on the overall subsystem mass and a preliminary set of components to be required. Furthermore this session is dedicated to the definition of clear subsystem boundaries in order to eliminate uncertain equipment responsibilities, e.g. who has to consider the solar array framework (power vs. structure).
- ***Session #2*** is characterized by the definition of the S/C operational sequences (i.e. modes of operation) and the subsystem trades being performed during “splinter-discussions” of the previous full day post-processing time. The modes will lead to a more elaborated power design by defining the required energy demand per subsystem component (and mission sequence) during and after this session.
- ***Session #3*** focuses on finalizing the preliminary power and thermal design. The different S/S inputs with respect to the energy demand per units allowthe power engineer to e.g. define the bus voltage, design the solar arrays and/or battery. This strongly influences the thermal design with respect to heat dissipation. Additionally the domain engineers have to finalize their assumptions for the temperature ranges in order to identify the thermal critical items.
- ***Session #4*** is the last session within a typical one-week study and ensures a last update of design changes which occurred after session #3. Typically the accommodation of the different components will be detailed for both, inner parts like propulsion tanks (if any) and the electrical equipment as well as for sensors, thrusters and radiators placed or looking outside the spacecraft. This leads also to a review of the current structure which then updates the mass budget.

Of course, the list above is by far not completed but describes the basic pillars of such a one-week study performed at DLR. The different design tasks per domain, system trades, joint discussion about the configuration status, the subsystem roundtables where all subsystems are forced to provide a quick, informal overview about their current design (parameter- and configuration-wise) as well as to request missing information and data from the colleagues, take place in every session.

3.3 Technical, Content-related Implications

For the squeezed CE study approach the systems team has to prepare the technical way forward, i.e. the sequence of the major design issues to be resolved, comparably detailed. Starting fully from scratch is not useful since the time is limited to a couple of days in total. The selection, elimination and preliminary definition of one or more system design options has to be done during the preparation phase, as for any other CE study approach as well. In addition to that and taking into account the typical design steps for each session described in section 3.2, the team has to walk through a rough pre-defined set of design sequences.

Since the engineering activities (e.g. definition of S/S equipment, acquisition of input data, calculations / analyses / simulations and provision of output data) per discipline are executed rather sequentially, other domains have to "wait" until they receive their required input. This is the case especially for the cost and configuration domain.

The cost domain wants to know for instance the technologies applied and components used within the subsystems when using cost models like the Small Satellite Cost Model 2007 (SSCM07) [Mahr 2007] as well as the related power demand and different subsystem masses when using the Cost Estimation Relationships (CERs). Both kinds of information are not available in the beginning and become credible close to the end of each study. This increases the work load during the last CE- and off-line sessions and reduces it during the first days. However, the cost domain has to acquire the desired information walking to the different experts and asking for their assumptions and design progress several times. Since everybody has a long list of own tasks to be resolved, from experience the provision of new information to the cost engineer will be neglected. The configuration domain is able to design the basic envelope and structure according to the system requirements and preparatory work on system level already in the beginning but for the detailed placement and mounting of components or the derivation of values for the e.g. center of gravity, more information is required from the subsystems.

The data model, e.g. the ESA Integrated Design Model (IDM) [Henderson, Caldwell 2007] allows the exchange of parameters including dimensions in x-, y-, and z-axis but does not reflect the actual or preferred position of the components. Due to this the configuration engineer has to rely on verbal information and notes regarding the correct placement, either handwritten or using 2D-drawing tools / software. Figure 4 shows an exemplified basic set of information provided to the configuration engineer by other domains during the CE study:

Unit Name	Quantity	Dim1 Length	Dim2 Width or D	Dim3 Height
Click on button above to **insert new unit**				
Computer and Mass Memory (hot redudant)	2	0,2	0,1	0,0
Computer and Mass Memory (cold redudant)	2	0,2	0,1	0,0
Middleware Switch (primary)	1	0,2	0,1	0,0
Middleware Switch (cold redudant)	1	0,2	0,1	0,0
Analog-digital converter board (primary)	1	0,2	0,1	0,0
Analog-digital converter board (cold redudant)	1	0,2	0,1	0,0
Backplane	1	0,5	0,2	0,0

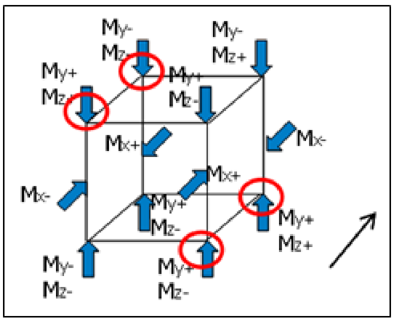

Figure 4: Information provided to the configuration engineer by other domains: The left part is a snapshot of the ESA IDM showing the dimensions of an Equipment Summary Sheet from the Data Handling domain; the right part illustrates an example for recommended placement of reaction control engines

Tracking the validity of such information (same problem as for the cost domain) stays critical and leads to requests for updates on a daily basis. This is one big field where the use of Knowledge Management tools like digital note pads capturing e.g. sketches electronically would be beneficial.

However, the systems team, namely the team leader, systems engineers and their assistants, who are in charge of the daily planning from the technical and organisational point of view, have to keep a certain degree of flexibility. Too formal organisation of the sessions will lead to a significant decrease of creativity. The major implications for the organisational aspects will be described within the following chapter.

3.4 Management and Organisational Implications

For short studies, the time planning has to be executed more carefully. It has to be counted in hours rather than in days as it is the case for longer studies and this increases organisational sensitivity. On the on hand, having the team together for one or two times three hours each, it does not matter if the plenary session takes place either in the morning (as mainly the case within the example in Figure 3) or in the afternoon. On the other hand, for such squeezed approach one has to consider departure and arrival times in the beginning and the end of the study as well as on a daily basis. It has to be ensured, that there is sufficient preparation time.

The team has to be on schedule. A short-termed postponement of plenary sessions for one or two hours is almost impossible and would lead to significant changes in the overall study schedule. If there are external parties involved, cooperation partners, subcontractors or important guests, these actions have to be implemented in the planning as soon as possible. Especially during the preparation phase the organisational part is vital. In any case, the mission- and system objectives as well as the system level requirements have to be set.

If possible, the majority of group discussions (splinter-meetings) should be defined and assigned to both, the different domains and dates, respectively post-processing sessions. Many activities will run in parallel during a one-week study and the personnel resources have to be shared precisely. The main aspects hereby considered are:

- The order of events, i.e. which discussion shall be held at which time,
- Customer and systems team member involvement,
- Technical preparations (e.g. figure of merit definition for S/S trades)
- Room sharing (i.e. video conferences in main room; normal meetings in support rooms)

One major advantage is that one week is comparably easy to block for the participants. Similar to holidays or a business trip people can reserve the week for the CE study. They do not have to know in advance the availability spread over several weeks. Being involved in many projects at the same time the probability is high that changing demands and appearing meetings, trips or tasks lead to unavailability of the participants for certain sessions.

Furthermore, if an engineer can not participate e.g. one day within the squeezed study duration, and if a back-up person is organized in advance and preferably attends the session before he takes the responsibility, the handover is much more effective since the time a new person has to remember the contents discussed from the previous session is most likely just one day.

Of course there is also the risk if the main person for the job does not appear due to e.g. sickness; the preparation time for the back-up person is almost zero. The need for a back-up person is very important for the Team Leader position. During the first studies DLR experienced that dual leadership improves the system team performance due to both, efficient work share and the opportunity to change tasks, e.g. moderation, on the fly at any time.

Since the study team of DLR's CEF is not a permanent but a varying one, a certain amount of participants might not have experience with the process and especially not with the utilized design model, e.g. the ESA IDM. In order to avoid wasted time due to workbook handling issues (or errors) on subsystem side, or related repairs on system side a tutorial should be organized prior to the study, if the majority of attendees are unfamiliar with the model. In addition, a short model handling introduction takes place at the end of the kick-off session within every DLR CE study.

4 Comparison between Long and Squeezed Processes

Some of the avantages of the one-week approach are the team member's focus on the design and the increased identification with their respective tasks. The team building aspect is more in the foreground; it has been observed that people start acting more informal due to the close and intensive interaction and hence concentrate more efficient on the technical solutions than on interpersonal barriers.

Furthermore, the lack of information is reduced because the disturbances due to other project involvements are limited or even excluded. The team can be easier coordinated since there is CE study work every day which keeps the people in or at least close to the facility. This allows a better organization of splinter discussions and intermediate announcements.

Nevertheless, the short duration with high frequent design iterations also provides risks and disadvantages. Due to the limited amount of time, only a reduced number of options – at least on system side – can be investigated. This increases the preparation work on a system level during the phases prior to the study and could constrain creativity on the subsystem level during the study phase. Additionally, and in contrast to the typical ESA approach for pre-phase A studies having design sessions distributed over three to six weeks, the DLR approach reduces the ability of the team member for other project work [Schumann, et al. 2008] which on the other hand increases the focus on the ongoing CE study. Furthermore it does not allow parallel studies because the infrastructure and also the majority of the personnel are fully occupied. On the contrary, this facilitates the establishment of the dual lead with full focus on one study.

The condensed one-week study, with collaborative design sessions on a daily basis, limits the utilization of sophisticated domain specific tools with time-consuming analyses. It requires rapid design tools, e.g. calculation spreadsheets and simplified simulation models which furthermore allow a quick data exchange via the Integrated Design Model (IDM). Table 1 provides an overview about the main characteristics discussed for both, the squeezed and longer processes:

Table 1: Comparison between the one-week and the longer process

One-week Approach	**Long(er) Approach(es)**
Short-termed results	Allows parallel work and use of the facility
Increased project focus by the study team members; less "frictional losses"	Increased amount of time for "offline-work", i.e. analyses, simulations, drawings, trades & reviews
Reduced travel time for external participants, if full-week availability can be ensured	Increased redundancy in terms of organisation: allows more time for fixing e.g. IT-issues in the Lab
Strong team building	Enables cost and risk estimation as more parallel work, when acquiring data after each design session
Less parallel work of team members	More sessions possible
Facilitates dual study lead and the availability of back-up personnel	Increases preparation time for back-up personnel

5 Lessons Learned and Recommendations

For further application of the squeezed one-week approach or any other similar short CE studies within DLR or other organisations the following set of recommendations and lessons learned, described within this paper, should be taking into account:

- Define focus / main topics for each CE session prior to every study
- Identify also potential group discussions and domains to be present in advance
- Organize tutorial session(s) for the model and/or domain specific tool utilization if a high amount of participants are not familiar with this elements
- Prepare configuration (i.e. CAD) files as much as possible or split into part- and assembly designers during the study phase
- Start with the definition of subsystem equipment already in the first session (also for Phase 0 studies); force the team to provide first estimations wherever possible
- Make use of the team building aspect: reduce informal borders and let the participants feel comfortable and as an important part of the group

6 Conclusions

Based on the experiences gained at DLR, the paper describes the lessons learned which have been experienced with respect to the condensed one-week approach as well as their implementation into the applied CE process. Recommendations regarding the

- organizational and technical preparations,
- the impact for post-processing activities,
- tool and model utilization,
- as well as the social aspects of the multidisciplinary team building

have been derived and shall support the future application. The implications for organisational and technical issues were described and examples for advantageous and critical issues, on system as well as on domain-level were given.

Additionally a comparison has been performed between the one-week and the other study approaches being applied internally as well as within the major international space entities considering the Concurrent Engineering methodology. Similar short studies have been conducted for instance at NASA's Team X of the Jet Propulsion Laboratory (JPL), at the Goddard Space Flight Center (GSFC) [Avnet, Weigel 2010] or at the Concept Design Center (CDC) of The Aerospace Cooperation [Aguilar, et al. 1998]. As experienced at DLR, the CDC team also has considered a short number of sessions (e.g. two or three) as reasonable for pre-development studies, whereas the permanent design team of JPL is more open for longer studies [Smith 1997], especially when the mission complexity increases.

As stated already in the Introduction there is no rule how to apply and organize Concurrent Engineering session, but there might be different approaches which meet certain requirements more effectively, depending on the organisation and its objectives.

As for CE in general, the one-week approach is an effective means for qualitatively improved spacecraft design, reducing cost and time while increasing performance of the development team. Compared to longer approaches it has its advantages (e.g. increased project focus) as well as disadvantages (criticality of time).

Initially established due to constraints regarding availability of personnel, this approach turned out to be the most effective way to proceed for Phase 0/A studies at the DLR Institute of Space Systems so far.

7 Outlook

Within the frame of the AsteroidFinder project, the CE methodology has already been applied also for Phase B spacecraft development [Findlay, et al. 2010]. Since subsystem design becomes more detailed and simulations take much longer during later project phases, combined one to three days CE sessions took place once every four to six weeks. This approach will be further investigated and compared to some attempts for Phase B applications still following the one-week approach as done so far for the Asteroid landing module MASCOT (Mobile Asteroid Surface Scout), focussing on certain subsystem design aspects and their integration on system level. In addition, an academic CE study will be held with CE sessions only once a week. This allows an even detailed comparison between different squeezed and stretched approaches for Concurrent Engineering activities related to spacecraft design in the near-term future.

Together with the University of Luxembourg, the DLR Institute of Space Systems is currently also analyzing the interpersonal behaviour and team interactions using video and audio recordings of a one-week CE study for SolmeX [Maiwald, et al. 2010], a solar exploration mission investigated together with the Max Planck Institute for Solar System Research. This analysis includes interviews, external feedback and team member reflections. It shall provide additional data about the social aspects occurring during collaborative design studies.

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