STATISTICS AND EVALUATION OF 30+ CONCURRENT ENGINEERING STUDIES AT DLR

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ABSTRACT

As part of the build-up of the German Aerospace Center's (DLR) Institute of Space Systems in 2007, a Concurrent Engineering Facility (CEF) has been set-up to complement the institute's tools and laboratories at its disposal to fulfil its major objective: efficient end-to-end space system design. With initial support by the European Space Agency in 2008, DLR adapted the different elements of such an environment, e.g. the infrastructure itself, the related (systems) engineering processes, the team set-up as well as the data- and multi-media tools, to its own needs.

As of today, more than 30 Concurrent Engineering (CE) studies have been successfully conducted with an average number of about 7 studies per year. Mainly related to the pre-development phases so far, the CE activities include both feasibility analyses for potential future systems and missions as well as for design contributions to already planned projects and missions. Due to the valuable results and further inputs to the respective projects, the intense and fruitful interactions within the team together with the educational aspects for the study participants, an increasing interest in applying the CE approach for internal and external projects can be observed. Since the studies are characterized by e.g. varying study objectives and team members, used data- and design models as well as by process- and planning adaptations, there is a continuous growth of lessons learned from each previous activity.

This paper outlines the different applications of the facility, including a brief description of all systems, missions and architectures which have been designed and analysed in the CEF within the last 4.5 years. Additionally the evolution and progress of the CE approach at DLR will be examined, on the one hand from the organizational point of view and on the other hand with respect to the content-related aspects like e.g. study elements and objectives. Furthermore it provides and discusses various statistics related to amongst others project-, tool- and planning issues of the "30+" studies up to now. A clear set of initial (internal) definitions, additional complementary activities related to the CEF as well as an outlook for the next years, in terms of studies and process development, complete this paper.

INTRODUCTION

The Concurrent Engineering Facility (CEF) is the system analysis laboratory of the German Aerospace Center, operated at the Institute of Space Systems in Bremen. It is a major research institution and has been inaugurated in January 2009. One year before, a precursor preliminary environment, the so-called "DLR Design Workshop" has been established for training and initial concurrent engineering (CE) activities. Supported by the European Space Agency (ESA) and personnel from JAQAR Concurrent Design Services (J-CDS) the DLR team gained experience with the CE methodology, in the usage of a central data model, with the team organization and interaction as well as for the continuous build-up of a more elaborated facility; the CEF.

In the upcoming sections the different activities which have been conducted in this facility are described and discussed, with a clear focus on the CE studies. At first, the CEF itself is outlined. Afterwards some internal definitions are defined, followed by an overview of the CE studies for the different kind of (space) missions and systems. This leads to a set of statistics which help to discuss the needs, results and DLR approach of Concurrent Design. A discussion of all CE-related elements is provided including various lessons learnt. Finally the paper concludes with the description of the relevant side- and parallel activities of the DLR CE team.

THE FACILITY

The CEF is a set of rooms which provides a fully independent environment for a team working in the early phases of the system development timeline. It contains three design rooms, one for the main activities (e.g. plenary sessions) and two for group discussion and side-activities. As can be seen in Fig. 1, an additional lobby provides sufficient space for in-depth discussion amongst the study team members whereas the service rooms allow the team to act fully independent for a pre-defined time-frame. This self-contained arrangement allows also external customers to rent the laboratory for their purposes.

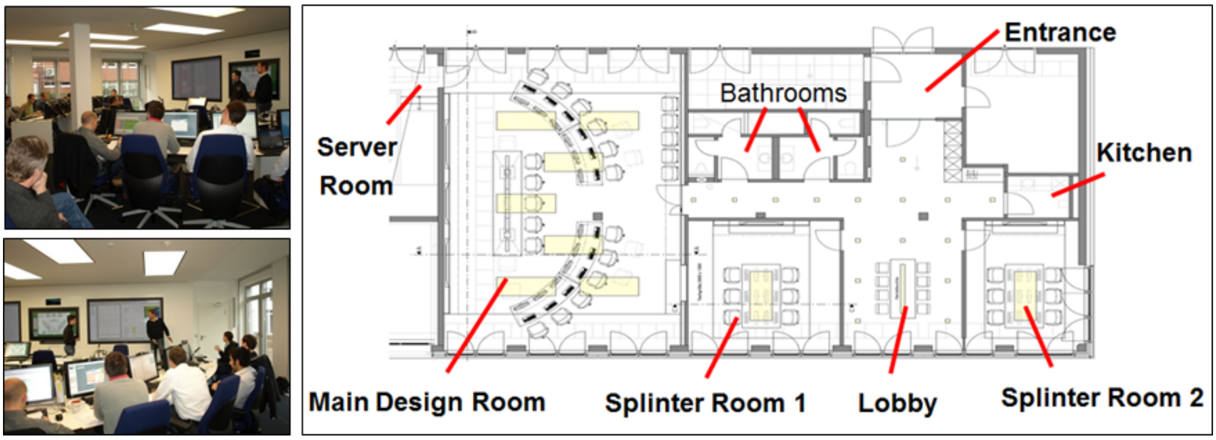

Fig. 1. The DLR CEF

The main design room is equipped with 12 work stations for the system and design team and one central PC for the study team leader. They are connected with the two splinter rooms which contain 4 work stations each. Additionally the multi-media infrastructure, e.g. three screens in the main room plus two Smartboards™ in the other ones as well as a variety of cameras, sound system and a media player is also accessible via the CEF network. Further descriptions can be found in [1] and [2].

CONCURRENT ENGINEERING AT DLR

The general approach of Concurrent Engineering at DLR is to perform efficient design and analysis activities for space missions within the different phases of a project lifecycle, following the established systems engineering rules with an increased effort of communication amongst the entire team of stakeholders, and supported by an infrastructure for co-located and simultaneous design work.

The CE process has been applied for various institute- and DLR internal studies, cooperative activities with industry and academia as well as for purely external studies, only supported by a DLR team leader for the organization and moderation of such an activity. Similar to the ESA approach [3] the process consists of an initiation- and preparation phase, a study phase (where all relevant disciplines come together) as well as a post-processing phase. The study phase at DLR is usually compressed into one working week with daily plenary and working sessions but is flexible to the customer needs as described in the following sections.

The involved number of different disciplines (excluding team leader) is in principle limited to 12, which usually consists of 50% rather system- and 50% subsystem domains. Due to the various mission types (with different targets and architectures) and systems (with different elements) which have been analysed in the CEF so far, the relevant domains for the activity change from study to study which requires a certain flexibility of the team accommodation in the facility. The teams change from study to study. The team leader as well as one systems engineer is usually provided by the facility operating department System Analysis of Space Segments (SARA), which can be considered as the CEF core team. Depending on the project and customer, the initiator of the study brings its own systems-, programmatic- (e.g. risk, cost), subsystem domains and payload engineers. As discussed during the preparation phase the study team is filled up with experts from the Bremen Institute, other DLR sites (e.g. operation engineers from the German Space Operation Center (GSOC) in Munich, structural engineers from DLR Braunschweig) or external consultants, depending on the availability of personnel and budget.

During the initial CE training phase the DLR core team received from the ESA Concurrent Design Facility (CDF) the basic set of IDM work books which has been a core element for data storage and exchange during the first years of the DLR CE activities.

OVERVIEW OF THE COMPLETED CE STUDIES

Including the 4 studies performed in the pre-cursor Design Workshop, but excluding the initial DLR design session at ESA ESTEC in February 2008, 33 CE studies have been conducted in the last 4.5 years from the beginning of 2008 until mid-2012. Table 1 below gives an overview of all studies within this time frame. In order to distinguish between the internal definition of a "CE-study" and other activities, the main requirements for this term are stated in the following.

The CE-study shall:

i. have at least 3 collaborative plenary sessions with working sessions in between
ii. start an introducing presentation session in order to achieve common understanding of the problem based on the definition of study scope prepared prior to the study
iii. finish with a final presentation session to cross-check the latest results, preparing also for the report.
iv. consist of following groups of participants: a customer (team), the systems team (including team leader) and the Design team
v. use a data model for capturing the latest design parameter

A detailed description, e.g. which discipline belongs to which group of participants, can be found in [4]. In contrast to the rather stretched approach of ESA [3], DLR favours the more compressed workshop-like approach with full dedication of the team members to the on-going study [5]

Table 1. List of conducted CE studies at DLR Bremen until 09/2012

No.	Study Topic / Project [Mission and/or System]	Area	Year	Calender Week	Design/Data Model used	Customer/ Initiator
0	Lunar Exploration Lander	Ex	2008	9	IDM-WB	DLR
1	AsteroidFinder/SSB - I	LEO	2008	16	IDM-WB	DLR
2	AsteroidFinder/SSB - II	LEO	2008	26	IDM-WB	DLR
3	LAPIS	Ex	2008	36	IDM-WB	DLR
4	Kickstage	LV	2008	42-44	IDM-WB	DLR
5	AMSAT Pre-design	Ex	2009	5	IDM-WB	DLR
6	MASCOT	Ex	2009	12/13	IDM-WB	DLR
7	MASCOT-XS	Ex	2009	29/30	IDM-WB	DLR
8	AMSAT-Moon	Ex	2009	39	IDM-WB	cooperation
9	Venus-II - 3 stages	LV	2009	45/46	IDM-WB-modf.	external
10	AMSAT-Mars	Ex	2009	47	IDM-WB	cooperation
11	CarbonSat	LEO	2009	49/50	IDM-WB	external
12	MASCOT-DK	Ex	2010	2	IDM-WB	DLR
13	Venus-II - 4 stages	LV	2010	6/7/8	IDM-WB-modf.	external
14	Compass-II	LEO	2010	12	(v)Sys-ed	cooperation
15	MallCom	GEO	2010	18	IDM-WB	external
16	AHAB	LEO	2010	25/26	IDM-WB	cooperation
17	CLAVIS	LEO	2010	41	internal	DLR
18	SolmeX	Ex	2010	44	IDM-WB	cooperation
19	MASCOT-4-PhB	Ex	2011	9	internal	DLR
20	TRIP	Ex	2011	18	IDM-WB	DLR
21	FLaSH	Hab	2011	35	internal	DLR
22	TiNet	Ex	2011	42	IDM-WB	DLR
23	CS-Solmin	LEO	2011	43	IDM-WB	cooperation
24	CS-Moon	Ex	2011	44	IDM-WB	DLR
25	CS-LifeSat	LEO	2011	49	IDM-WB	DLR
26	AEGIS	LEO	2011	50	VirSat	cooperation
27	CERMIT	Ex	2012	6	IDM-WB-modf.	DLR
28	CS-PicoSAR	LEO	2012	12	IDM-WB	DLR
29	ASDR-I	LEO	2012	17	VirSat	cooperation
30	Vertical Farming	Hab	2012	18	internal	DLR
31	ASDR-II	LEO	2012	19	VirSat	cooperation
32	PELADIS	DW	2012	24	VirSat	external
33	GOS-FLdc	LEO	2012	39	internal	DLR

As can be seen in Table 1 some study names appear multiple times. In order to achieve a better understanding of the study content and major objectives, the projects (which are related to one or more studies) are briefly described in the following. Out of 33, 17 CE studies can be considered as “multiple” and 16 as “single”.

AsteroidFinder (*2 studies*)
As an outcome of a Phase 0 study, the AsteroidFinder payload has been selected as first payload on the compact satellite to be developed in the new DLR Institute of Space Systems, based on heritages from the former DLR missions BIRD and TET. Whereas the first study mainly dealt with the payload accommodation options, the second study finalized the option selection and prepared a preliminary design of the service segment.

MASCOT (*4 studies*)
Originally planned as a proposal for an ESA Marco Polo mission contribution, the Asteroid landing module MASCOT (Mobile Asteroid Surface Scout) has become a selected payload for the JAXA’s Hayabusa-II mission. Whereas the first study was investigating three different large-scaled options, the second study considered a small landing package with a reduced set of instruments. Together with the CNES CE Center (CIC) the system has been elaborated in the third study and prepared for further Phase B activities in the fourth one.

AMSAT (*3 studies*)
Based on the hexagonal AMSAT P5 satellite, the radio amateur society “AMSAT”, together with DLR, investigated two options of how to send a highly cost-efficient spacecraft to another celestial body. Therefore three system and mission design studies have been conducted with Moon and Mars as different targets, an internal, preparatory one and two in collaboration with AMSAT, a DLR service segment design team as well as DLR representatives for additional scientific payloads.

Compact Satellite (CS) (*4 studies*)
Having its origin in the AsteroidFinder design, the compact class satellite bus has been developed at DLR until Phase B. In order to investigate future alternative payload options, several scientific mission proposals have been studied together with the related team of researchers as well as with the DLR compact satellite project team. Within 6 months, 4 independent studies to be compared have been conducted with the goal, to identify a favoured option for the succeeding payload of the CS; including an orbiter for solar observations (No. 23 in Table 1), an exploration mission to the Moon (No. 24), a biological experiment platform in LEO (No. 25) and an Earth orbiter, carrying a radar instrument for SAR measurements (No. 28).

VENUS-II (*2 studies*)
With the DLR agency as a main customer, an EADS Astrium and DLR Bremen consortium investigated two different ways of how to elaborate on the performance of the VEGA launch vehicle upper stage. Two different launcher options, 3 stages and 4 stages, with pre-defined booster stages were baseline for the design of e.g. different tank configuration optimization and engine selections of the upper stage in order to evaluate the increase of payload mass for different options.

ASDR (*2 studies*)
Together with an external partner, DLR has analysed the architecture for heavy space debris removal as well as one dedicated scenario and the corresponding system design.

Two CubeSat (**Compass-II, CLAVIS**), one being an University satellite, and the other one being an DLR internal standard bus (with both designs in phase B) have been detailed in the CEF with the respective project teams. The main objective was finalizing the payload interfaces and accommodation options, having in mind the highest possible degree of standardization for future payloads.

Furthermore, two studies related to habitats have been conducted. **FLaSH** is the design of a ground based laboratory to test new and innovative habitat technologies in order to gain e.g. a closed-loop life support system and positive working- and living environment for long-duration missions. During the **Vertical Farming** study which has been a follow-on activity of the DLR Advanced Study Group (ASG) [6] analysis of an Antarctic Greenhouse Module, dealt with the determination of the technical and economic feasibility of a Vertical Farm as well as their preliminary design.

MallCom, a GEO-stationary satellite which should serve the Balearic Island, as well as the **AEGIS** satellite for Galaxy observations have been designed by external design teams together with a DLR systems engineer for both the technical outcome as well as team educational aspects.

An additional cooperative activity has been the **SolmeX** study [7] which had the objective to design the service segment(s) for a solar magnetism explorer to be proposed to ESA as M-class mission.

Three CE activities starting on Phase 0 level have been mission definition studies for a ball-shaped lunar landing (respectively impacting) instrument package for seismic measurements plus a required transfer vehicle (**LAPIS**), the design of an experimental cryogenic upper stage for a semi-reusable launcher (**Kickstage** study) and for the mission- and later also for the system design of an atmospheric high altitude probe (**AHAP**) which shall perform in-situ measurements in the lower thermosphere.

Two additional studies with Asteroids as scientific targets have been performed internally, one focussing on the system design of a spacecraft visiting Jupiter Trojans (**TRIP**) [8] and the other one with the main objective to establish a scenario for a crewed (manned) European Near-Earth Object (NEO) mission (**CERMIT**).

Based on the DLR Institute of Space System in-house developments for a compact satellite as well as a standardized CubeSat, a compact version of climate (*here*: CO_2 and CH_4) observing "**CarbonSat**" has been designed as well as a particular option of a solar sail demonstrator platform called Gossamer (**GOS-FLdc**).

TiNet was focussing on the design of Titan entry and landing systems (for lakes and surfaces) with modular payload packages to be deployed as a geophysical network over the Saturn Moon, as well as the related descent scenario for these modules. The transfer was based on the ESA Cassini-Mission.

The most exotic CE study was **PELADIS** which dealt with the design of underwater modules for sulphide ore sensing and depressing as well as the scenario of their deployment, deep water terrain-following and recovery.

SOME STUDY STATISTICS…

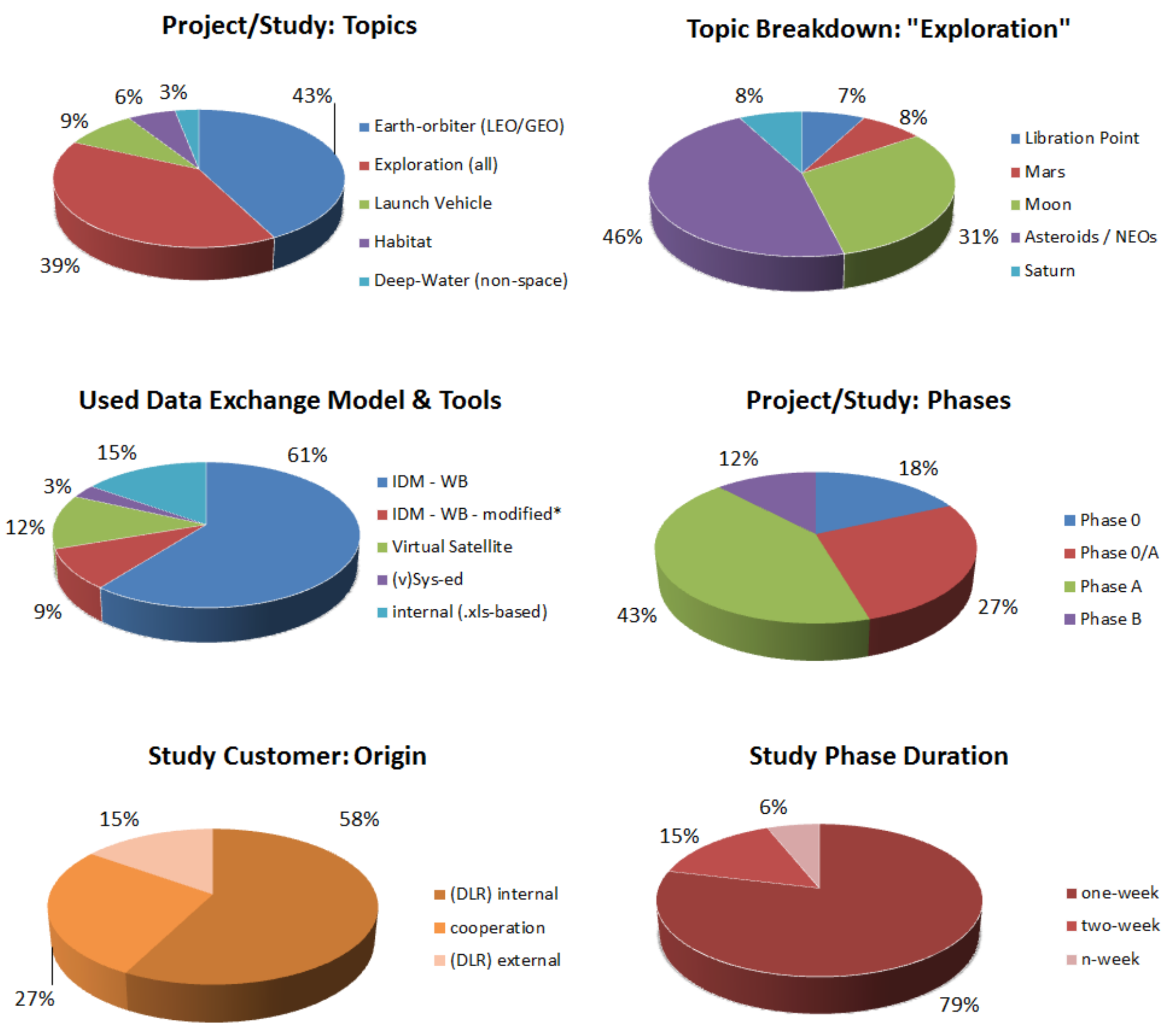

Fig. 2. Study statistic diagrams (in per cent)

Based amongst others on the information given in Table 1, Fig. 2 shows six different pie charts which depict the different topics of the studies, the related project phase and the origin of the customer, the study duration and how often which kind of data model has been used. They shall provide a set of facts to show for instance the current thematic focus of the DLR Space System Institute as well as important organizational aspects related to the CEF. The detailed descriptions, justifications and lessons learnt are discussed in the following section.

EVALUATION AND LESSONS LEARNT

This section will describe the experiences gained during the different studies and the general CEF evolution, discussion the presented statistics, giving some insights regarding advantages and disadvantages of the Concurrent Engineering approach and programmatic inclusion at the DLR Institute of Space Systems. It provides a compilation of lessons learnt with recommendations of how one could improve the application of the CE methodology internally as well as in general.

The Infrastructure

The CE lab, as it has been built-up from the beginning, is a modern environment which generally attracts and motivates people to spend time working there during the studies. However, since it is not the daily working place of the team members it cost some effort to get used to the place and to make best use of it. Since the CEF is a major research institution which allows to be used by external entities, the server network is kept disconnected from the DLR one due to IT security reasons. This reduces the flexibility for data transfer (i.e. the free use of USB sticks by the participants) and even more important: the parallel access for internal users to both the daily DLR working server and the CEF server.

Additionally, the intention was and still is, to keep the working atmosphere as informal as possible in order to concentrate on the design and reduce interpersonal distances. Hence, the facility contains only 12 work stations which are placed close to each other on 2 quarter-round tables, equipped with 6 seats each. This allows quick communication amongst the participants but reduces space for additional references and tools on the table such as notepads, individual laptop, books and personnel belongings (e.g. coffee mug). It has been observed that any additional (shelf) space in the room is used by the team in order to create their own cosy atmosphere. Mobile tables for instance could enhance the efficiency. They could serve as an additional shelf behind the seats or as central units for rapid group discussions between the sessions.

The set-up with three screens has been very useful to share different information (e.g. requirements list, configuration status and mission trajectory) at the same time. However, the fact that the individual screens are mounted on a movable arm which allows to turn, lift and tilt them, shows that not all requirements of an “ideal” set-up can be satisfied because the flexible screen positioning allows easier interactions with the neighbours but could also lead to a (visible) interruption during the plenary sessions when they are lifted up because a domain engineer would like to work with his own laptop at the same time.

Although ideally all team members work co-.located in the facility, there is often the need to have video- or teleconferences during plenary sessions (e.g. if one team member is only available from remote) or during the off-line work when additional experts for special problems have to be consulted. The facility is equipped with a powerful videoconference system but lacks the ability of pure teleconferencing in the splinter rooms as well as in the main rooms. System independent telecommunication units, possibly installed on some of the desirable mobile shelves, would be an improvement compared to an ordinary telephone handset without a proper microphone.

Study Requests and Topics

So far, almost 60% of the studies have been requested by DLR internal departments with randomly all projects being linked to the Institute of Space System, as can be seen in Figure 2. The customers were usually the department heads if the project status was still in the intended stage (Phase 0; or Phase A without clarified funding at that time) or the respective project managers, especially when the status was more mature. Both, satellite design activities, as well as exploration missions have been 40% of the CEF occupancy rate for CE studies, with requests mainly made by the exploration system- and the satellite system department as well as by the SARA department systems which operates the facility. This is due to the fact that these three departments are the ones with the strongest system focus, whereas the others (for navigation-, avionic- or propulsion systems) are focussed rather on technology development than on system studies or even spacecraft development and integration.

Three studies (9%) have been initiated by the second system analysis department which focussed on space transportation, internally as well as with external entities as a customer. These, together with the habitat studies initiated by the CEF operating system analysis group represented the biggest challenges for applying the elements of Concurrent Design. Even if the iterative nature of such a methodology can be used for any project, the models, software, disciplines and duration of specific design task were quite different. As described in the other sub-sections, there had to be some adoptions in order to run the process smoothly. On the other hand, the experience gained during such activities, where for instance the team leaders were faced a topic in which they have less experience, this helped to achieve even a broader view on system complexity and led to additional lessons learnt for all relevant elements such as the mentioned models and team set-up.

The CEF is an environment where interdisciplinary engineers can work together in a way that results are produced and presented on-line. This increases the system awareness of all other involved parties. This is not only limited for internal use but could add even more value if entities work together which might follow different working standards, scientific a approaches as well as (inter)national interests. That's why one forth (27%) of the CE studies have been based on cooperation, mainly for national and international proposal or to combine and streamline the expertise and work already done by academia and industry for joint space projects.

Objectives and Phases

The project phases in which the studies have been performed were the main driver for the set of study objectives since they were related to the upcoming events (e.g. reviews) in the schedule or to the treatments of former shortcomings. Also the discussed variety of projects leads to many different study objectives which have been defined prior to the CE studies by the customer and the systems team. The most common, especially for phase phase 0 and 0/A activities are:

- To establish a feasible mission scenario
- To define system design options
- To define system budgets for mass, power, data and temperature parameters
- To achieve a preliminary configuration with the accommodation of payload and subsystem components
- To provide an initial estimate of costs and risks of the system/mission

It has to be remarked that the definition of phases here is partly perceived, especially for projects without a project plan at the time of the study. Almost one third (i.e. 27%) started with the mission definition and entered the feasibility analysis phase during the sessions, that's why they are stated as Phase 0/A studies in Figure 2. On the other hand this "uncertainty" is an additional indicator for the rapid design maturity evolution during CE studies in a very short time frame.

The phase 0 and 0/A studies were the most easy to plan since the CE approach could be kept for almost all activities, either for exploration or Earth orbiting missions. These studies started with an idea, some references and a basic set of about 10-20 system requirements, whereas Phase A studies had already an extended list of subsystem requirements and much more precise objectives as there were:

- To increase the performance for a upper stage
- To trade and select system option(s)
- To prepare a test planning scenario for the project
- To evaluate the technical and management risk and the cost of the projects

Without additional preparation and handled as usual Phase 0-A studies, there were four (one-week) studies taking place in the CEF with projects already in Phase B. Here it was much easier to define splinter-meetings and action items prior to the co-located activity but there was a different share of time for plenary and off-line work. Some of the main study objectives (*here*: partly generalized) were:

- To design a new system option and to compare it with the default one
- To investigate design flexibility for programmatic uncertainties
- To increase design consistency of the service segment
- To define the physical payload interfaces
- To define the provided payload performance parameters
- To revise the design by changing to more low cost components

The majority of these four studies was conducted with a shorter preparation time because there were mainly unexpected needs for technical revisions appearing, or objectives related to investigate design scalability for reacting on management issues. In order to handle these cases in the future more efficient, DLR intends to research more in the direction of CE across the phases in order to forecast such situations better and include the CE approach already in the project plans with clear session focusses in the future project plans.

Time Planning

Due to the limited availability of experts at one DLR site and the increased project focus, the preferred schedule for a CE study includes one week with all involved disciplines in the facility (study phase), a 2-3 months initiation and preparation phase as well as a 1-2 week post-processing phase. Since there is also only a small core team for team leading and data model preparation, no parallel use of the CEF is possible at this stage [5]. On the one hand this eliminates any effort for switching amongst study-related facility set-ups back and forth but reduces the flexibility of reacting on the project needs and team member (un-)availability.

As particularly presented in Fig. 3, the use (and "macro-time-planning") of the CEF is mainly driven by the project needs and not homogeneously distributed. This results in an unbalanced workload of the CEF core team which requires a certain time margins in other research or teaching activities which have to be fulfilled by the DLR engineers.

The 2011 example is an extreme case with 3 studies in 3 weeks during autumn, which carried on the one hand the risk of CEF hard- and software failures and on the other hand of team leader unavailability who are members of a small core team. This was only possible because 3 consequent studies (black framed in week 44, 45, 49) have been performed with the same design team, i.e. the "CS-Compact Satellite" team, and varying payload responsible only. The fact, that only one-week studies have been conducted in this year has been unintended.

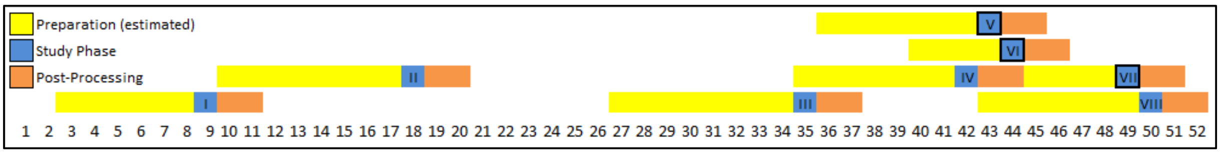

Fig. 3. Example CE Study timeline of the year 2011

Study phase related time planning ("micro-planning") is also a challenge. Due to the matrix organization of the Institute, the people are working on more than project which collides with the fact that necessary domains provided by other Institutes prefer a time-slot with full dedication on the project (as done for the one-week approach) to reduce travel and lodging costs. A careful personnel planning has to be done during the preparation phase by the project leaders / customers, supported by the CE study team lead.

Once the team is set, the daily planning has to be worked out, i.e. which topics shall be concentrated on and in which order. Especially for external customers who do not have much experience with the CE methodology, the multiple-week approach with longer off-line work phases seems to be favourable since it offers more time for contractual and technical decision gates. The more uncertainties there are in the project from the technical and personnel view, the longer the preparation phase and the longer the duration of the study phase.

A clear definition of session slots over the year (e.g. 3-5 available plenary sessions a week), which could be booked for certain studies, could provide more transparency to internal team members for their project work planning and also to external customers for the CEF contract periods, but reduce flexibility for emerging re-design activities and if there are changes in personnel.

Data Model

In the beginning, a lean version of the Excel work books of the ESA Integrated Design Models has been used. Once got used to, the team learned how to beneficially apply the structure of input-, output-, presentation and summary sheets which are linked to a central data exchange. During the first months, several additional calculation sheets have been generated by the CEF core team supported by domain experts, for e.g. power- and data budgets, solar array design or structural analyses. Since the IDM-WBs lack flexibility in creating new parameters, history tracking of parameters, versioning of iterations, system independency and cell link transparency, as partly described in [9], parallel testing of model alternatives and internal developments have been performed. The TU Munich "virtual System Editor ((v)Sys-ed)" and the DLR internal development "Virtual Satellite (VirSat)" have been tested, whereas the latter one, which allows the exclusive adoption to the needs of the DLR CEF, has become the preferred model to be used for CE studies.

However, due to clear advantages of Excel, like well-known usage, customizable tables, the WBs have been used for more than 60% in the initial- (*here*: version 6.14) and additional 9 % (i.e. 3 times) in a modified version. There, the data exchange- and simultaneous utilization capability has been used but parameter- and discipline names had to be changed within the WBs. Furthermore additional option comparison, summary and calculation sheets have been added. Unfortunately the file names of the work book had to stay the same (e.g. “propulsion” instead of the required discipline name “engine”) in order to keep the useful exchange functionality.

For an AsteroidFinder-Phase B-Session (see section “additional activities”) session, the Concurrent Design Platform (CDP) developed by J-CDS has been used. Five times (=15%) the parameter set of the projects to be served in the facility had reached already such a level of maturity which led to the decision that none of these tools allowing multiple access by separate work books or clients have been used. The effort to press the available data into the CE models has been considered as too high and the rate of parameter updates as too less. For the “FLaSH” habitat study, which dealt with a complete different set of disciplines, parameters and their flow, a new model has been developed during the preparation phase

Since the DLR CEF follows a service-oriented approach, all available models (besides (v)Sys-ed and most likely the FLaSH-related model [10]) can be offered to the customer and will be determined during the initiation phase. In the future, DLR will also use the Open Concurrent Design Tool (OCDT) developed by ESA and industry of the member states in order to work more closely amongst the different European Design Centres. But for internal use, the Virtual Satellite will be the baseline and equipped with additional supporting S/W features in the near future. The lessons learnt from these projects could help to improve the usage of both tools and others.

Teaming

The most important factor during CE activities is the team and the communication amongst the members. Usually, the team leader is provided by the SARA department. The systems engineer and several subsystem responsible are brought in by the project. Especially for early design studies, there is no personnel available in the project team to cover every domain. Then the team will be filled up by members of SARA, depending on their expertise, as well as from other departments or even institutes, depending on the future planning regarding work distribution and also the availability.

One major outcome of the 4.5 years CE experience is that it is highly desirable to have another systems engineer from the CEF operating team as well in order to link the technical expertise of the project systems engineer and the team leader of the study. He furthermore supports the engineers with the use of the data model and could act as back-up-team leader in case of his or her unavailability.

In general it is very helpful if not everybody of the design team is a “newcomer” in the CEF since it takes some effort to get used to the environment and infrastructure as described above. A mixture of about 50% people with and without experience has been observed as manageable. Due to the matrix structure for projects in DLR there might be the same people serving the same disciplines in different projects which result in multiple CEF appearances of personnel even if the study team is completely provided by the project team and no additional, typical CE familiar people (e.g. from SARA) have to join.

One of the biggest challenges when dealing with the people is to keep an equal work load amongst the disciplines. It is the task of the team leader to organize the group discussions and this includes identifying which domain has more to do than another one at that time. In this case, the tasks should be shared even if one enters another area where the person is not an expert.

This is also a reason for the DLR approach to keep the amount of team members to a minimum level (*here:* 12 domains + team leader(s), customer(s) and ad-hoc experts), which still has to cover all the relevant design aspects. A classical team set-up for satellite design studies are:

- Systems team (~5 people) consisting of
  - 1 team leader, 2 systems engineers, 1 mission analyst, 1 cost (and risk) analyst,
- Design team (10 people), i.e. 1 person each per following disciplines:
  - Payload/Instrument, Attitude and Orbit Control, Thermal, Power, Propulsion, Data Handling, Communication, Structure, mechanisms, Configuration

For launcher-related studies this set-up has been changed for instance to more nested “disciplines”, based on the expertise and the roles of the participating entities, as there were

- System (entire launcher)
- Trajectory (entire launcher)
- Structure (upper stage)
- Engines (as part of the upper stage)
- Tanks (as part of the upper stage)

This led to changes in the data model and also in the work flow since the engine had to be selected for the structure of the upper stage which in turn had to be accommodated (parameter-wise) on the booster stage options for finding the most efficient launch vehicle configuration.

Another observation has been done during the Architecture studies (e.g. TRIP) where the domains were working on a much higher level defining system options. There, the subsystem responsible persons had to be grouped in order to identify suitable system options for the analyses scenario, as can be followed in [8].

ADDITIONAL STUDIES

Besides the classical CE-studies described and discussed within the past chapters, several other design and analysis activities took place and will be explained in the following. The major ones, which can be somehow considered as CE studies as well, but did not meet all of the requirements as defined in the third section of this paper, are listed below:

- AsteroidFinder CE-Sessions for Phase B design [11] in
- SpaceLiner Interior Workshop
- Micro-Studies, e.g.:
    - SWON (Swarm Architecture Micro-Study)
    - FireSat (VirSat Validation and Test study)
- Multi-level parking structure of a DLR site

These studies and workshops were held in one, two or three days with either full-time plenary sessions or similar to CE-studies, with off-line sessions in between. The moderation of the parking structure workshop for instance was done by a construction manager assisted by a CE experienced SARA member. The main objective was to identify possible places for a multi-level car park, considering the traffic routes during peak/rush hours, the gained parking places, the design and different regulations from the local authorities. Domain specific tools have been installed in the CEF in order to visualize the decisions. There was no need for a special data exchange but the key facts have been documented in the proceedings.

The Interior workshop for the SpaceLiner concept was driven by the human aspects of an airplane which launches like a rocket. This included the need for safety cabins, entry and escape procedures and flight entertainment aspects.

During these studies it became again obvious that communication amongst the participants is what counts and that information has to be properly documented and exchanged, especially when totally different minds (*here:* designers, lawyers, engineers) work jointly on one project.

COMPLEMENTARY CEF RESEARCH ACTIVITIES

In addition to the conduction of classical CE studies, micro-Studies, workshops and test- & training activities the DLR core team is constantly involved in further so-called “CEF-enhancement” activities which are referring to both the infrastructure and process-related issues.

The major fields of research and driving internal projects are:

- The DLR Advanced Study Group, as a pre-cursor think tank for Phase 0 [6]
- Elaboration of the social-cognitive awareness of the team leaders together with the University of Luxembourg, e.g. for Critical Instance Interaction (CII) [12].
- Investigations of how to apply CE for Phase B and higher phases [13]
- The support and integrated architecture definition of
    - CE models, software and their features, e.g. Virtual Satellite [14].
    - A knowledge management (KM) system [15]
    - Databases for components, parameters as well as for simulation models (e.g. SimMoLib [16]),
- System-of-System handling in the CE environment (as part of an ESA project)

All these activities and parallel projects intend to provide an even more integrated and sustainable working environment and also a more efficient process regarding not only the technical but also the interpersonal issues.

CONCLUSIONS

As described within this paper, 33 Concurrent Engineering Studies and many additional workshops, design sessions for space and also other sectors have been performed. There are “one-time” activities such as mission definition or feasibility studies for e.g. proposals, cooperation activities or as part of general DLR space system analyses tasks, as well as multiple recurring systems (as for MASCOT or the CS studies) to be developed with the aid of the CE methodology with different objectives related to the project phases.

The main interesting outcomes of the observations, daily challenges and lessons learnt are summarized in the following:

- The team members (and potential back-ups) covering all relevant disciplines and their availability have to be defined as one of the first tasks during the preparation phase.
- The availability of the facility by the operators on the one side and the request for performing studies by the customers has to be forecasted carefully.
- Since it is easier to work in the CEF environment with knowledge already about the use of a data exchange model, these tools (which preferably will be used from the very beginning) shall allow also the distributed utilization with simultaneous access.
- A flexible model or data sets (e.g. via parameter libraries and classes) help to serve other technical complex systems as the current ones do already for satellite design.
- The social-cognitive factors are very important in order to understand the attitude, preferences and confidence of the individuals working together, especially for the team leader in order to guide the team through the design steps most efficiently.
- Capturing and re-using knowledge is one key to success for an increased time- and cost efficiency in consequent studies.

Key points of the CEF evolution have been:

- the recent implementation of the DLR customized data exchange model “VirSat” from the ***technical*** side, since it considers the needs for flexible use and supports links to other tools,
- the successful studies and derived lessons learnt with external customers funding the activities, from a ***management*** perspective, since the external views and expectations have again improved the structured approach of how to organize and prepare a CE study,
- the SolmeX study in which all participants have been observed by a team of the University of Luxembourg with respect to ***personnel*** (since they generated more than 200h of video plus additional audio data for analysing and increased again the awareness for social aspects).

OUTLOCK

The success of the already performed studies has been widely noticed in DLR and in the industry. Furthermore the visibility of the CEF has been increased, especially in the national space program related entities. However, the “complementary research activities” have to be performed within internal projects as well as together with ESA and partner states.

The CE methodology has a high potential to be applied in more space projects and across different stages but this requires upfront definitions of how to be implemented in the different project plans.

The DLR focus will continue to be on internal project support and feasibility analyses but needs a more distributed planning over the year. Different tools and libraries will be constantly supported in their developments in order to achieve models and software tailored to the needs of co-located and distributed teams in international organizations.

The goal is to have an increased number of personnel for the CE related tasks available and to create or acquire more subsystem related knowledge besides the team leading and systems engineering expertise of the CEF core team (i.e. SARA).

If implemented in some DLR project plans, the CE team will also continue evaluating the different approaches of one- or two week- and more stretched studies.

Finally the lessons learnt of the 30+ studies conducted so far plus all of the additional activities have to be carefully and properly taken into account, which is still an on-going process.

ABBREVIATIONS

Ex	Exploration
GEO	Geostationary Earth Orbit
LEO	Low Earth Orbit
LV	Launch Vehicle
NEO	Near-Earth Object
TU	Technical University

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