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Statistics and Evaluation of 60+ Concurrent Engineering Studies at DLR

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Abstract

Since 2007, the German Aerospace Center's (DLR) Institute of Space Systems in Bremen has operated the Concurrent Engineering Facility (CEF), a system analysis laboratory specialised in performing early stage design in the most efficient and consistent way possible, through the implementation of the Concurrent Engineering (CE) process. Working within a guided procedure, the simultaneous access of multidisciplinary groups of experts to a shared database, and the direct verbal and medial communication between all the experts, are the defining characteristics of Concurrent Engineering studies. As of today over 60 studies have been conducted in the CEF (with an average of about 7 per year), all the while maturing the CE process and adapting it to combine the system and domain expertise of DLR and its specific conditions. Although mostly focused on satellite design, exploration missions and space transport systems, the CEF has enabled the study of different kinds of developments such as life support systems, or space-based and terrestrial infrastructures. CE activities include both feasibility analyses for potential future systems and missions, as well as design contributions to already planned projects and missions. Due to the valuable results and further inputs to all projects, as well as 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 an analysis of the CE studies conducted, and of the systems which have been designed in the CEF since its conception. Furthermore, it provides and discusses various statistics related to the studies conducted up until now, and touch upon major lessons learnt. Additional complementary activities related to the CEF, as well as an outlook for future activities, complete this paper.

Keywords: Concurrent Engineering, Systems Engineering

Acronyms/Abbreviations
Concurrent Engineering (CE)
Concurrent Engineering Centre (CEC)
Concurrent Engineering Facility (CEF)
German Aerospace Center (DLR)
Model Based System Engineering (MBSE)

1. Introduction

The Concurrent Engineering Facility (CEF) is the system analysis laboratory of the German Aerospace Center (DLR), operated at the Institute of Space Systems in Bremen. Since the commencement of Concurrent Engineering (CE) activities at DLR in 2008, over 60 CE studies have been conducted to date in the CEF, in addition to other system design and analysis activities.

In the upcoming sections, the different undertakings conducted in the facility are discussed, with a focus on the CE studies as the main activities for the centre. In addition to a brief summary of the theoretical framework of CE, and introducing the CEF and how CE is practised in DLR, the paper covers the studies that have been conducted, review some relevant statistical data related to the studies and operations of the CEF, describe some experiences and lessons learnt during the different studies, and finally cover other activities carried out in the facility as well as the outlook for CE relevant activities as seen today at DLR.

1.1 Theoretical framework

Concurrent Engineering is a process focussed on optimising engineering design cycles, which complements and partially replaces the traditional sequential design-flow by integrating multidisciplinary teams that work collectively and in parallel, at the same site, with the objective of performing the design in the most efficient and consistent way as possible, right from the beginning (see Fig. 1).

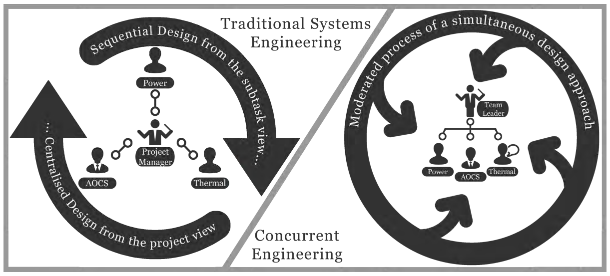

Fig. 1. Sequential vs Concurrent Engineering

Working within a guided process, the concurrent access of all experts to a shared database, and the direct verbal and medial communication between all subsystem experts, are the defining characteristics of CE studies.

Effective implementation of CE can benefit organisations in a number of ways, including greater customer satisfaction, reduced costs, increased quality and reduced design rework and development time (see Table 1).

Table 1. Reported benefits of Concurrent Engineering [1]

Development time	**30 – 50% less**
Engineering changes	**60 – 95% less**
Scrap and rework	**75% reduction**
Defects	**30 – 85% fewer**
Time to market	**20 – 90% less**
Field failure rate	**60% less**
Service life	**100% increase**
Overall quality	**100 – 600% higher**
White-collar productivity	**20 – 110% higher**
Return on assets	**20 – 120% higher**

1.2 Concurrent Engineering Centres

The successful implementation of CE requires the integration of three main elements: a work process that encourages effective teamwork, well-coordinated multidisciplinary teams, and an infrastructure that supports the necessary activities and promotes effective communication.

The infrastructure component can be found in the aerospace industry under the common denomination of “Concurrent Engineering Centre”, although other conventional denominations include “Concurrent Design Centre”, or “Concurrent Engineering Facility”. While different organisations arrange their infrastructure according to their needs, they commonly provide an integrated environment for the team to work together, as well as tools that facilitate the design process and provide a framework for the exchange of information between team members.

A non-exhaustive map of CEC’s around the world is shown in Fig. 2.

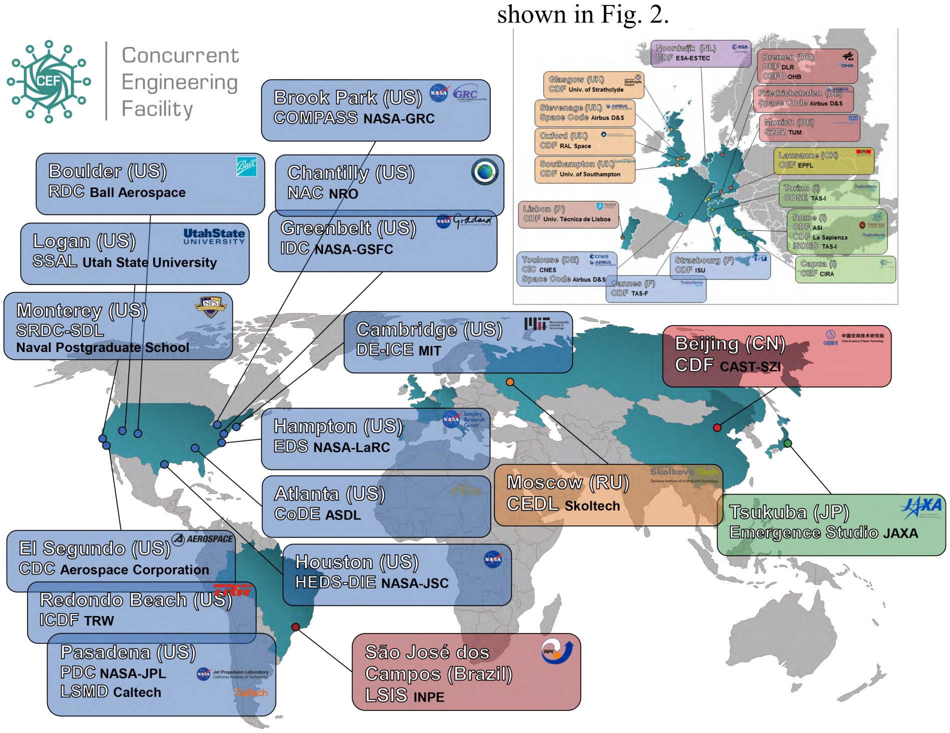

Fig. 2. Concurrent Engineering Centres

The following section of this paper will focus on one such CEC —the Concurrent Engineering Facility at DLR Bremen— and the work carried out there.

2. The Concurrent Engineering Facility

The CEF (see Fig. 3) is DLR's systems analysis laboratory where CE studies are conducted, providing the necessary environment and tools to implement the CE-process. The CEF facilitates simultaneous access to a common set of data, as well as direct verbal and medial communication among the different domains during the design process, through the intelligent use of modern tools and communication technologies.

Fig. 3. Concurrent Engineering Facility Main Room

As previously mentioned in subsection 1.2, CE requires a supporting infrastructure, an efficient work process, and the coordination of experts to produce optimal results. These three aspects are addressed in this section.

2.1 Infrastructure

DLR Bremen's CEF is divided into 3 design rooms (see Fig. 4): the "Main Design Room", where studies are conducted, and two splinter rooms which are typically used for small-group discussions during non-moderated time in a study, or to accommodate other parallel working groups or auditors.

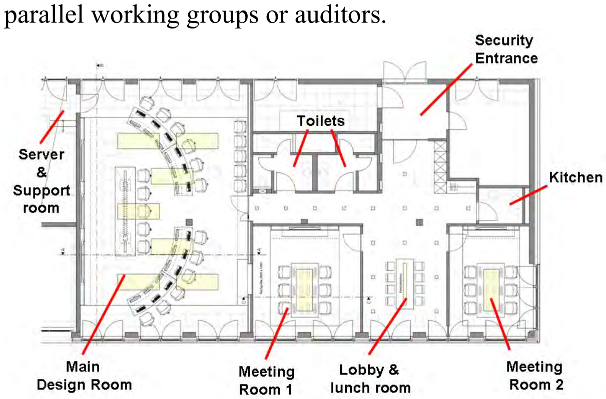

Fig. 4. CEF Layout

The layout of the main design room provides up to 12 workstations (which normally accommodate one domain each, although more are possible), arranged on a broken semi-circle seating arrangement surrounding the front desk (see a study set-up example in Fig. 5), which is reserved for the customer, the Team Leader and the co-Team Leader, and which can seat up to two additional attendants (e.g. a second customer, a guest, or an external specialist). Extra seating at the back of the room is available for guests auditing a study, or for additional participants.

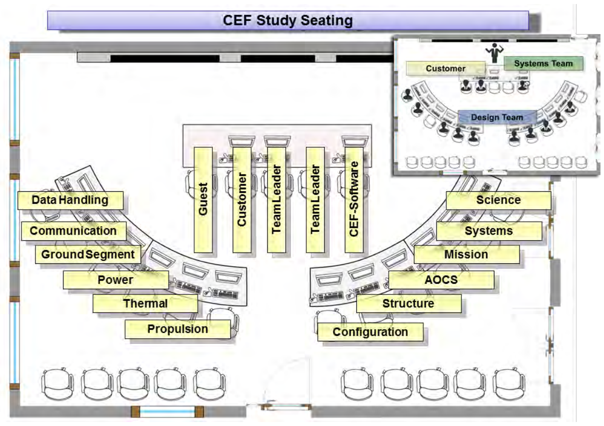

Fig. 5. Main Design Room (set-up example)

In addition to the workspace and multimedia-infrastructure, the CEF incorporates a set of software tools at the disposal of the CE study participants (e.g. CATIA, STK), a critical one being Virtual Satellite, a software application developed by DLR to support spacecraft systems engineering.

The CE methodology requires access to a shared pool of information and a distributed software methodology (*i.e.* simultaneously accessible and editable), so the use of a centralised model which can be accessed simultaneously by all the technical team members, and monitored by the systems engineer, makes a Model Based System Engineering (MBSE) approach ideally suited to the task.

Virtual Satellite aims to provide an integrated design environment for engineers and to support the design process over the full development life cycle, but the development until now has been focused on the feasibility studies typically carried out in Concurrent Engineering Facilities. The core element of the Virtual Satellite software is an underlying data model that represents aspects of satellite design, offering the necessary flexibility and extensibility.

To facilitate use, and reduce learning time for new CE study participants, Virtual Satellite provides an intuitive user interface (see Fig. 6). This is particularly important for DLR, as CE study participants are selected depending on the particular activity, and this heavy rotation requires new participants to learn how to use the tool as fast as possible and with ease.

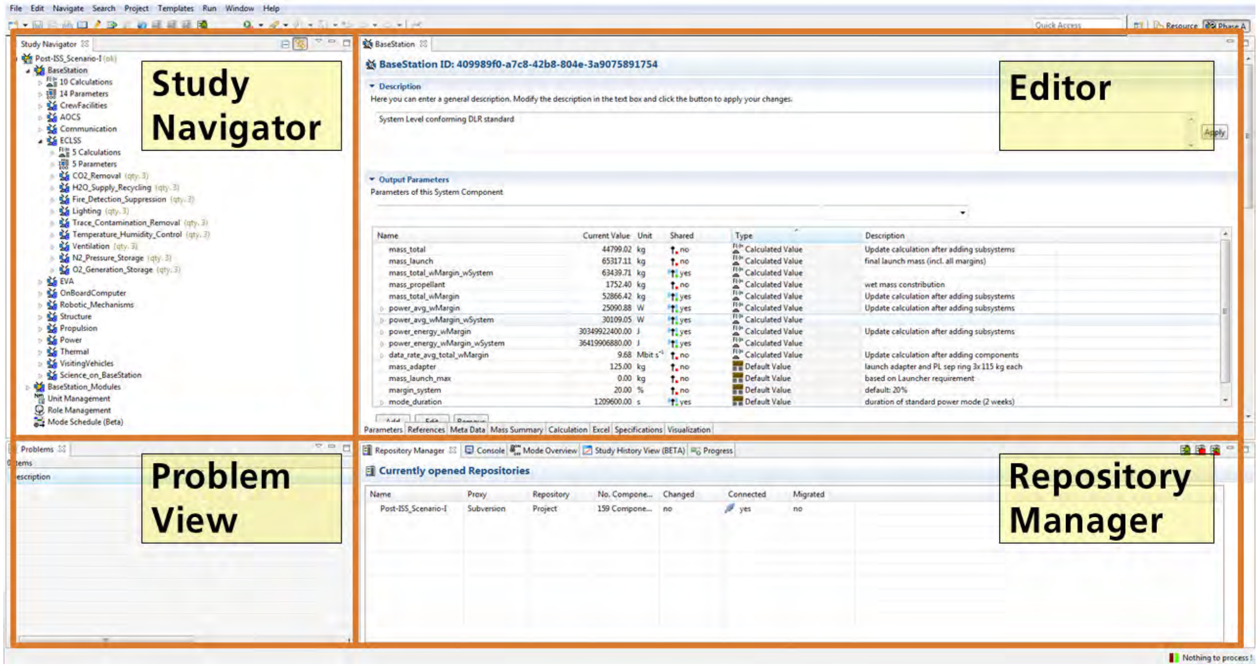

Fig. 6. Virtual Satellite User Interface

Further descriptions and information for the CEF and Virtual Satellite can be found in [2], [3], [4].

2.2 DLR's CE-process

The CE-process, as practised in DLR, follows the so-called "IPSP approach" (Initiation, Preparation, Study and Processing).

The IPSP approach (see Fig. 7) is a four step process that covers the whole development life cycle for a CE study, all the way from the moment the initial mission objectives are defined and the CEF facility is booked, down to the moment the final report is submitted.

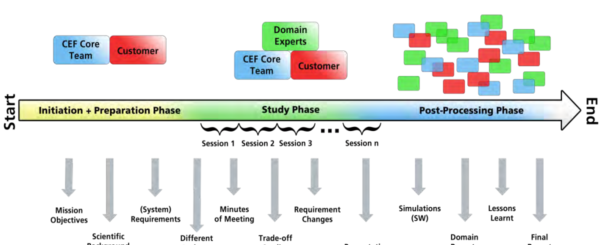

Fig. 7. Phases – Overview ("IPSP" – Approach)

This process has been applied within DLR internal studies and for cooperative activities with industry and academia, as well as for purely external studies which were only supported by a DLR Team Leader for the organization and moderation of the activity.

Succinctly put, the steps followed are:

1. Initiation Phase (starts months before using the CEF): the customer and CEF personnel define study objectives (i.e. expected results), identify required disciplines (i.e. Domain Experts) and outline time planning.
2. Preparation Phase (starts weeks before using the CEF): preparations are both organisational (definition of team members, study schedule, agenda for first session, and funding of participants and facility), and technical (definition of initial baseline consisting of mission objectives, mission and system requirements, identification of up to three possible system concepts, and initial mission analysis), and are mostly conducted by DLR's CEF personnel, with support of the customer.
   Decisions are made in agreement with the customer, and the phase ends with a final definition of these two aspects, and the invitation of the Study Team components.
3. Study Phase (1-2 weeks in the facility): at the study phase the whole team comes together in the CEF to undertake the system design. At DLR this is usually compressed into one working week with daily plenary and working sessions, but it is flexible to the customer needs and can depend on the complexities of each project.
   The mandatory steps of a CEF study include:
   - Kick-Off with presentations of the study key elements (goals, requirements).
   - Start with a first configuration approach and estimation of budgets (mass, power, volume, modes …) on subsystem level.
   - Perform iterations on subsystem and equipment level in several sessions (2 - 4 hours each),

trading between several options as deemed necessary.
- In between sessions, non-moderated work: subsystem design in splinter groups or individually, as appropriate.
- At the end of the study, final Presentation of all disciplines / subsystems.

4. Post-processing Phase (after the study): as the final phase of any study, the study products are compiled:
   - Collecting Results (each S/S provides input to book captain)
   - Evaluation and documentation of results
   - Transfer open issues to further project work
   - Implementation of lessons learnt into the CE-process

2.3 The team and study participants

Although there is no fixed structure or list of roles that can cover every imaginable study, there are several positions that are compulsory to the CE process.

The “Technical Team” is composed by the participants that provide the technical foundation for the study and who, as the name suggests, perform the actual design of the system/subsystem. Specifically, the Technical Team is formed by a Systems Engineer and the necessary Domain Experts (experts in fields of knowledge necessary for the specific CE study, who are responsible for the definition and technical decisions made in their domain). Domain Experts can come from inside DLR (be it the DLR Institute of Space Systems or any other DLR Institute providing special expertise) or be “Externals” – partners from German or international academic institutions or industry.

In addition to the Technical Team, studies also require three essential roles: the “customer”, the “Team Leader” and the “co-Team Leader”. The Team Leader and co-Team Leader are responsible for the smooth running of the studies, from preliminary set- up to the distribution of the study final documentation. This includes moderating the team throughout discussions, being responsible for the introductory and overall mission and system description part, as well of the study conclusions.

The customer is a key figure, as being the designated responsible from within a client that promotes a study, he must define the mission and study objectives, and approve the requirements defined by the Team Leader during preparation. He will also have final authority throughout the design process when decisions have to be made which are not necessarily technical in nature (e.g. if de-scoping of requirements proves to be necessary, or if multiple options for the design are possible with none of them presenting a significant advantage).

3. Overview of completed studies

60 CE studies have been conducted since the start of CE activities at DLR Bremen, until the end of 2016. Table 2 below provides an overview of these studies.

Table 2. Conducted CE studies

Year	#	Name
2008	1	AsteroidFinder/SSB - I
2008	2	AsteroidFinder/SSB - II+III
2008	3	LAPIS - Lander Package Impacting a Seismometer
2008	4	Kickstage - Cryogenic Kickstage
2009	5	AMSAT Pre-design
2009	6	MASCOT - Marco Polo Surface Scout
2009	7	MASCOT-XS - Marco Polo Surface Scout Xtra Small
2009	8	AMSAT-Moon
2009	9	Venus II (3 Stages)
2009	10	AMSAT-Mars
2009	11	CarbonSat
2010	12	MASCOT-DK - Mobile Asteroid Surface Scout (Design Consolidation)
2010	13	Venus-II (4 stages) - Venus II Upper Stage Part 2
2010	14	Compass-II
2010	15	MallCom - Yacht Teccon MallCom
2010	16	AHAB - Atmospheric High Altitude Probe
2010	17	CLAVIS
2010	18	SolMex - Solar Magnetism Explorer
2011	19	MASCOT-4-PhB - Mobile Asteroid Surface Scout (for Phase B)
2011	20	TRIP - Trojan Investigation Probe
2011	21	FLaSH - Facility of Laboratories for Sustainable Habitation
2011	22	TiNet - Titan Network
2011	23	CS-Solmin - Compact Satellite: Solar Magnetism Investigator
2011	24	CS-Moon - Compact Satellite: Moon
2011	25	CS-LifeSat - Compact Satellite: LifeSat
2011	26	AEGIS - Advanced European Galaxy Imager & Spectrograph
2012	27	CERMIT - Crewed European Exploration Mission Trail
2012	28	CS-PicoSAR - Passive Interferometric Ocean Currents Observation Synthetic Aperture Radar
2012	29	ASDR-I - Active Space Debris Removal

2012	30	Vertical Farming
2012	31	ASDR-II - Active Space Debris Removal
2012	32	PELADIS - PELAgic DIScoverer
2012	33	GOS-FLdc - Gossamer-1 Frog-leg decentralized (FLdc) deployment
2013	34	C.R.O.P. container
2013	35	Main Belt Comet (MBC)
2013	36	AngelA-I - A New Generation Launcher-I
2013	37	EnvisaR - Envisat Removal
2013	38	Robex - Robex Active Seismic Network
2013	39	KT - Kennedy-Thorndike
2013	40	ADR-S - Active Debree Removal Service
2013	41	Shefex-III - Sharp Edge Flight Experiment – III
2013	42	AngelA-II - A New Generation Launcher-II
2014	43	HYPMOCES - Hypersonic Morphing for a Cabin Escape System
2014	44	ROBEX-ALUNIR - A large LUNar mIssion for Robex
2014	45	AngelA-III - A New Generation Launcher-III
2014	46	GHM - Green House Module
2014	47	IoTA - Interorbital Tug Assessment
2014	48	Post-ISS Nutzlasten
2015	49	OOS-RAV - On Orbit Servicing – Robotic Arm Verification
2015	50	Post-ISS Scenario I
2015	51	TROJAN Lander
2015	52	EDEN ISS
2015	53	AIM Mascot 2 - Asteroid Impact Mission / Mobile Asteroid Surface Scout 2
2015	54	VF 2.0 - Vertical Farm 2.0
2015	55	Post-ISS Scenario II
2016	56	AIM PALS - Asteroid Impact Mission - Payload of Advanced Little Satellites
2016	57	S2TEP - Small Satellite Technology Platform
2016	58	DEMOCRITOS - DEMOnstrators for Conversion, Reactor, Radiator and Thrusters for Electric Propulsion Systems
2016	59	Refex - Reusability Flight Experiment
2016	60	GoSolAr - Reusability Flight Experiment

From the 60 studies, 35 of them have been stand-alone activities, while the remaining 25 have been part of 9 multi-study projects. A listing of these projects can be found below in table 3.

Table 3. List of multi-study projects

AsteroidFinder	2 studies
MASCOT	4 studies
AMSAT	3 studies
Compact Satellite (CS)	4 studies
VENUS-II	2 studies
ASDR	2 studies
ANGELA	3 studies
SHEFEX	3 studies
Post-ISS	3 studies

In the following subsections, these multi-study projects will be briefly described. Although the first five have been described in previous work [5], for the sake of completion they will be included here. As the descriptions are re-used, albeit in a modified form, these six subsections shall be referenced.

3.1 AsteroidFinder [5]

As an outcome of a Phase 0 study, the AsteroidFinder payload was selected as the first payload for the compact satellite concept developed in at DLR's 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.

3.2 MASCOT [5]

Originally planned as a proposal for an ESA *Marco Polo* mission contribution, the Asteroid landing module, MASCOT (Mobile Asteroid Surface Scout) became a selected payload for the JAXA's *Hayabusa-II* mission.

Whereas the first study investigated 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 was elaborated in the third study and prepared for further Phase B activities in the fourth one.

3.3 AMSAT [5]

Based on the hexagonal AMSAT P5 satellite, the radio amateur society "AMSAT", together with DLR, investigated two options on how to send a highly cost-efficient spacecraft to another celestial body.

Three system and mission design studies were conducted with Moon and Mars as different targets, an internal preparatory one, and two in collaboration with AMSAT, and DLR service segment design team as well as DLR representatives for additional scientific payloads.

3.4 Compact Satellite (CS) [5]

Having its origin in the *AsteroidFinder* design, the compact class satellite bus was developed at DLR until

Phase B. In order to investigate future alternative payload options, several scientific mission proposals were 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 were conducted with the goal of identifying 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).

3.5 VENUS-II [5]

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.

3.6 ASDR [5]

Together with an external partner, DLR analysed the architecture for heavy space debris removal as well as one dedicated scenario and the corresponding system design.

3.6 ANGELA

In the first study, different configurations of a two stage launcher with boosters, a so called P-HH configuration were analysed. The structural concepts of the first and second stage as well as the number of boosters were varied and, in addition, a number of technical trade-offs were examined. Each configuration was optimized for given payload performances, and a reference design minimizing the recurrent cost was selected.

In the second study, different configurations of a tree stage launcher, a so called PPH configuration, similar to the Ariane 6 configuration studied by ESA in 2013 and 2014 were examined.

In the third study, the reference design of the first ANGELA CE study was further optimized by studying additional technical trade-offs. The staging characteristics were optimized, especially the interest to have two versions of the launcher with 2 and 4 boosters or three versions of the launcher with 2, 4 and 6 boosters was examined.

3.6 SHEFEX

SHEFEX is to be a cost-effective re-entry platform for experiments in a hypersonic regime. The main objective of the mission is the acquisition of data for flight condition, the vehicle condition and the experiments during re-entry.

3.6 Post-ISS

Currently, DLR investigates possible new designs and configurations for a platform that could continue astronautic spaceflight in LEO after ISS is decommissioned. The studies conducted up to date have all covered different aspects of the potential design.

4. Statistics of 60 CE studies

Based on records of the conducted studies, an analysis of the information provides some further insights into the activities performed in the CEF.

As evidenced by the distribution of studies per category in combination with a breakdown of the targets of the missions studied in the CEF (see Fig. 8), it is evident that albeit the wide variety of different systems that have been designed (including launchers, satellites, landers or greenhouses), spacecraft and orbital systems are the main systems benefiting from the use of the CEF. This is not surprising, considering distribution of the projects carried out in the Institute of Space Systems, but it is interesting to note how balanced the different topics are.

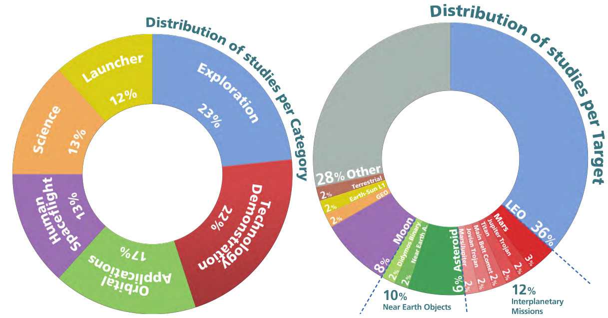

Fig. 8. Studies per category and target

Another interesting aspect of the CEF is the comparison of the distribution of studies according to the customers and type of activity (see Fig. 9).

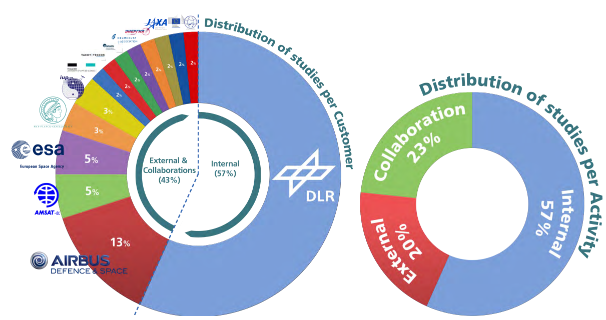

Fig. 9. Studies per customer and activity

Although the majority of activities are initiated internally in DLR, it is important to note how over 40% of the activities conducted in the CEF are collaborations with other institutions, or directly third-party promoted studies. This is particularly noteworthy when looking at the affiliation of the people participating in the studies (see Fig. 10), as it evidences that the CEF is not strictly an internal tool manned by DLR personnel, but rather a space of collaboration between experts from different fields, as well as different organisations.

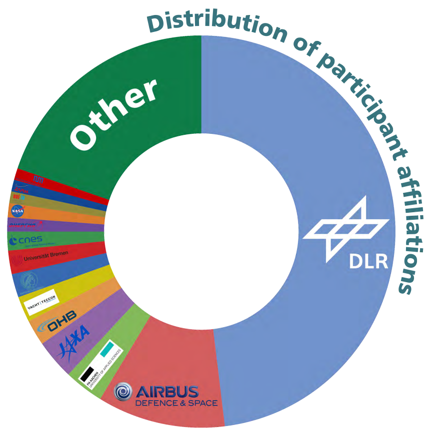

Fig. 10. Affiliations of CE study participants

Another final aspect to consider is the variety of nationalities that have worked in the different CE studies (see Fig. 11). DLR being a German entity, it stands to reason that the majority of the participants would majoritarily be of German nationality, but it is still interesting to see how almost 40% of the participants come from other countries, and even more so when considering that over 12% are non-Europeans.

Fig. 11. Nationalities of CE study participants

Table 4. Other figures of interest

Maximum number of participants in a study	30
Average number of participants in a study	18
Average number of new participants in a study	8
Number of distinct participants in CE studies	530
Number of participants that only participated in 1 CE study	346

As table 4 above indicates, it is noteworthy to point out that over 40% of the participants in any study are typically new to the process and the CEF. This is also highlighted as 530 different people have participated in the 60 CE studies carried out, and 346 of them only once.

5. Lessons learnt

The experience gained during the different studies and the general CEF evolution have provided a number of insights into different advantages and disadvantages of the CE approach as implemented in DLR Bremen. Throughout this section, a compilation of lessons learnt and recommendations deemed to be useful are outlined.

5.1 Infrastructure

For IT security reasons, the CEF hosts its own servers which are kept disconnected from DLR's common network. This is a requirement from the central IT of DLR, since CE studies are commonly joined by external entities and personnel. These necessary constraints reduce the level of flexibility of the facility, especially for DLR personnel who cannot access any information that is normally stored in the common server. This can cause delays and inconveniences or DLR participants trying to access large amounts of data or run program instances on the common server, as it must be done through a VPN connection with a private laptop, as it cannot be done on the CEF workstations.

Other organisations might not have this issue, but the need for such a high level of security should be carefully considered. Not only does it require a second physical network, but also limits other potential solutions for the interconnection of certain elements in the facility. For example, at present, a commonly used solution to streaming between a computer and mobile device to screens is the use of wireless devices such as Clickshare or Airtame. Since the signal of such devices can be intercepted and hacked, it will limit their use for entities where sensitive information will need to be shared via display. Since these are lower cost solutions than traditional cable-based systems and are also easier to replace, the trade-off between security and complexity/cost should be considered.

Another element of the design and use of the CEF was the intention to reduce interpersonal distances as a way of facilitating communication within the group. In addition to encouraging participants to feel comfortable and striving to keep the work environment as informal and friendly as possible, the layout of the tables itself is meant to keep the experts close together to allow easier interaction with the neighbours. This restriction on desk-area, however, can become a problem when most participants require their personal laptops, reference books, etc. This has been resolved in the CEF through the use of mobile tables that can serve as shelf-areas, or easy access work areas within studies.

A common occurrence is that many participants prefer to use their own laptops and software during the study. This does not impact the workflow negatively, and the CEF provides connections via VGA to facilitate displaying content or presentations from a laptop directly on the CEF front screens. In any case, it should be noted that any facility should consider the need of being fully or partially equipped with workstations depending on their own operation, since a "lean" facility without workstations where participants would bring their own laptops could suffice depending on the organisation's needs.

5.2 Time planning

Due to the common participation of external experts —and DLR experts from multiple sites— in most CE studies, the preferred schedule for a CE study is set to one week where all the participants remain in the facility. The advantages of this approach are the increased project focus, the fast time to completion for the design, and the reduction of costs (in particular travel costs for non-local participants) compared to other approaches where study days are spaced out in a few weeks. The disadvantages are the need for the experts to disengage from any other parallel activities/projects they might be involved with for the duration of the study, and a reduced amount of time to run simulations or calculations compared to other approaches.

An important time planning element from the organisational point of view is the fact that the CEF is a horizontal service that is dependent of the needs of different projects. Because of this, it is difficult to spread out studies, and rather the CEF must be flexible to accommodate projects to the best of our ability. This typically results in an unbalanced workload, with periods of time with no activities, and periods with multiple studies in small amount of time. This factor is even more pronounced in DLR, since many times we depend on external customers and organisations which can complicate the planning even more. This instability also can impact the acquisition of participants, as experts might be unavailable or unwilling to participate in multiple studies within a short period of time. Also, when a third party is involved in a study, it might be necessary to connect via video-link to their companies to include experts remotely to the conversation or to ask them questions. This can be a challenge when these experts are in other continents, due to time differences. This can become particularly critical and difficult to manage from a time planning perspective when the study requires to connect to multiple time-zones simultaneously (e.g. to Japan and to U.S. at the same time).

5.3 Data model

As previously mentioned in section 2.1, Virtual Satellite is the software used in the CEF for the integrated design of systems. Being an in-house development, the software has evolved with the input of the CEF team, and therefore has changed to accommodate the needs of DLR's CE process. Before the development of Virtual Satellite, a lean version of the Excel work books of ESA's Integrated Design Model (IDM) was used. Excel-based solutions are common in many CEC's, as it is a well-known tool, and provides easy customizable tables. This is also one of the reasons that the current tool used by ESA (OCDT – the Open Concurrent Design Tool), a new development fully implemented in 2016, is also EXCEL based.

For the CEF, however, due to the high rotation of participants mentioned in section 4 (almost half of the participants in any study are new to the CEF, on average), require the use of the tool to be as easy as possible. Because of this, major emphasis has been made on producing an intuitive interface, as well as to streamline the way that it is introduced during the CE sessions. The typical process followed in-study is to do 2 or 3 brief presentations of the functionality of the tool as it is necessary. Due to the organisation of CE studies, typically the first parameter that can be estimated and input into the model is the mass, so the first presentation of Virtual Satellite covers the basics of the tool (e.g. the layout, views of other subsystems, input of values and creation of new parameters, etc.) and covers examples with the mass parameter. Later in the study, when power modes are considered, a second presentation is made of how to include values for the different modes, for example. The combination of both an easy to use tool and a need-of-use approach to the presentations has worked well and facilitated the workflow and rapid learning of first time CE study participants.

An organisation with a high participant rotation will need to put extra-effort to facilitate the use of their tools (EXCEL-based or not), but will benefit from the potential collaborations and the participation of external experts, while an organisation that keeps their activities internal can reduce the amount of work dedicated to their tool and grow it organically within studies or in post-processing.

5.4 Team formation and communication

The most important factor for the success of any CE study is the team and achieving a high level of communication. This is particularly true in an environment such as the CEF, where interdisciplinarity is required, but additional factors also work against communication.

An important asset of CE is that it enables people with different levels of experience, areas of knowledge and ways of thinking to work together in an environment that encourages new concepts and ideas. This very same aspect can constitute a challenge to communication in many different dimensions. Whereas a professional in one field will consider certain aspects of his area of expertise as common-knowledge, this is not necessarily true. Bridging this gap of miscommunication is important, as only when the whole team is on the same page and fully understands the needs and limitations of the other elements of the design ‒and the impact of those elements on their own‒, can an optimal design be established.

In addition to the potential miscommunication due to the difference of understanding of different disciplines other dimensions have also to be considered, such as the background of the different participants (level of experience, or familiarity with working in a structured environment), potential language barriers, or those derived from intercultural differences. All these elements must be handled by the Team Leader and co-Team Leader during the study, particularly during the moderated sessions, where they must ensure that lines of communication remain open between participants and that everyone is following, and actively participating in, the conversation.

To manage potential miscommunication aspects, a number of actions can be taken:

- Moderation being critical, the Team Leader and co-Team Leader must make sure that everyone in the team feels comfortable and expresses their view, but it sometimes will require them to motivate less communicative participants, or to contain more outgoing ones so the conversation flow involves everyone, while being on point. This can in a certain way be helped by introducing “house rules” at the beginning of the study, such as asking participants to feel free to bring up ideas and concerns, but also to keep in consideration other participants that will want to speak, or not to argue for arguments sake. This definition of boundaries will establish a baseline, and prevent any participant of feeling singled out.
- Another aspect to be taken into consideration by the Team Leader is the gradual introduction of information. As the timeframe in the CEF is so condensed, it is also important to reiterate the main points, decisions made, and actions still pending to ensure that everyone in the team has these considerations present, as CE studies tend to be intense and participants cannot be expected to be focused on everything that happens 100% of the time.
- Besides the Systems Engineer integrated in the Study Team, it is highly desirable to have at least another systems engineer participating in the study. This facilitates the integration of the technical expertise provided by the domains, and reinforces the interfaces and system view throughout the discussions. In the CEF, typically both the Team Leader and co-Team Leader are systems engineers.
- In general, it is helpful if at least half the participants in a study are not participating in a CE study for the first time. This makes it easier for the integration of the team into the CE work process, as it requires less effort to get them used to the environment and infrastructure, and more experienced team members can support newcomers.
- One big challenge is to keep an equal work-load amongst disciplines. CE is particularly efficient in the design of systems whose subsystems can be developed in parallel (e.g. satellites); through communication and iterations of the design, the different aspects rapidly converge into a final design. Unfortunately, no system design can be broken down perfectly parallelizable tasks, which will leave some domains subject to waiting for input from others. It is the Team Leaders task to reduce this as much as possible through correct planning, and identifying the workloads of the different domains as well as tasks that can be shared.

6. Other activities conducted at the CEF

Although mostly focused on satellite design, exploration missions and space transport systems, the CEF has enabled the study of many other types of systems, such as life support systems, and space-based or terrestrial infrastructures. These activities have not only been supported through CE studies, but also through dedicated workshops, concept or requirement definition meetings, and other work formats that could benefit of a “CE-inspired” process.

In addition, the CEF has been used for educational purposes, including Systems Engineering and Concurrent Engineering courses.

7. Outlook

The CE methodology has a high potential to be applied in more space projects and across different stages. Currently, efforts are being done within DLR to evolve Virtual Satellite into a tool capable of extending its use beyond the early phases covered in a CE study (Phase 0, A/B), supporting collaborative engineering in later phases. On the CE team side, processes for an optimal integration of the use of the CEF in later phases are being defined, with the objective of integrating such a methodology with the new software, and testing it in future projects. These activities are in line with the Space 4.0 paradigm currently supported by ESA.

DLR's focus will continue to be on internal project support and feasibility analyses, but will continue to pursue external collaborations and look for new activities and work formats to which a CE methodology might provide added value.

In addition, continuous evaluation of the CEF infrastructure and the CE-process will be undertaken, so as to adapt and evolve them as deemed necessary.

8. Conclusion

60 Concurrent Engineering studies and many additional workshops, design sessions for space and also other sectors have been conducted with the aid of the CE methodology. A good number of lessons have been learnt throughout this experience, some of the most important of which have been addressed in this paper.

As evidenced through statistics derived from the records of these studies, a constant flux of participants new to the CE methodology —many of whom are international and intercultural— participate in the activities carried out in the CEF. This makes the communication aspect, already fundamental to the CE process, especially critical. This has guided the way studies are conducted, as well as the evolution of Virtual Satellite, and will be an important driver in future actions and activities in DLR's CEF.

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