TEACHING SPACE MASTER CONCURRENT ENGINEERING

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ABSTRACT

Since 2014 the University of Bremen (Germany) offers the "Master of Space Engineering (SpE)", a master course geared towards international engineering students. For the past years, DLR has supported the program through the compulsory module "Space Systems Engineering and Concurrent Engineering", held at the Concurrent Engineering Facility (CEF) at the Institute of Space Systems. After classical theory lectures on Project Management, Systems Engineering, Concurrent Engineering as well as on the relevant Space Subsystem Domains the students are introduced to CE in practice by performing a four-day simulation of a Phase 0/A CE study. This paper describes the experiences and advantages, as well as the difficulties, of teaching Concurrent Design/Engineering at University within a Space Master course.

ACRONYMS

CE	-	Concurrent Engineering
CEF	-	Concurrent Engineering Facility
DLR	-	German Aerospace Center
MBSE	-	Model Based Systems Engineering
OBDH	-	On Board Data Handling
PBL	-	Project Based Learning
PM	-	Project Management
S/C	-	Spacecraft
SE	-	Systems Engineering
S/S	-	Subsystem
TCS	-	Thermal Control System
VirSat	-	Virtual Satellite

1. INTRODUCTION

1.1 Used Infrastructure for Teaching

The module "Space Systems Engineering and Concurrent Engineering" takes place in the Concurrent Engineering Facility (CEF). This Major Research Facility (in German: "Großforschungsanlage") is used as a system analysis laboratory of the German Aerospace Centre (DLR), operated at the Institute of Space Systems in Bremen. Since the beginning of Concurrent Engineering (CE) activities at DLR in 2008, more than 70 CE studies have been conducted to date in the CEF with international partners from science and industry, in addition to other system design and analysis activities. The successful implementation of CE requires the integration of three main elements: an *infrastructure* that supports the necessary activities and promotes effective communication, a work *process* that encourages effective teamwork, and well-coordinated multidisciplinary *teams*. 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".

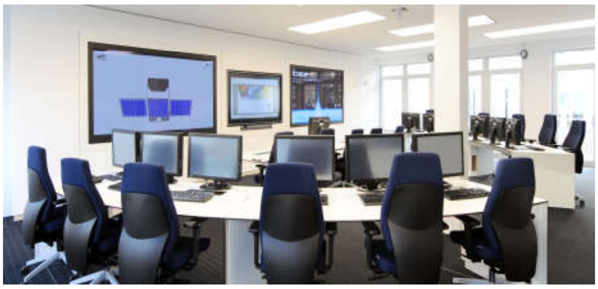

Figure 1: Concurrent Engineering Facility Main Room

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. An overview of world-wide Concurrent Engineering Centres can be found in [1].

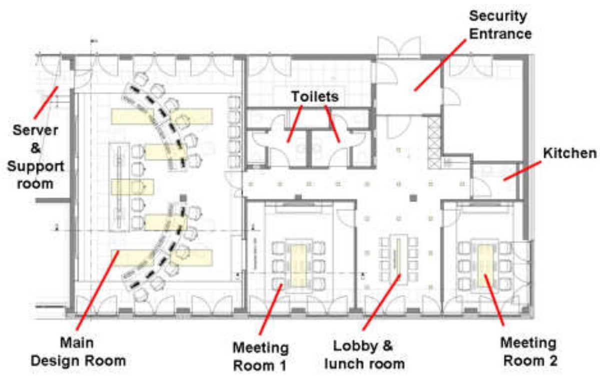

Figure 2: CEF Layout at DLR Bremen

The CEF at DLR Bremen (see Fig. 1) provides 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. DLR Bremen's CEF is divided into 3 design rooms (see Fig. 2): the "Main Design Room", where studies are conducted, and two splinter rooms which are typically used for small-group discussions during the non-moderated time in a study, or to accommodate other parallel working groups or auditors.

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. 3), 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.

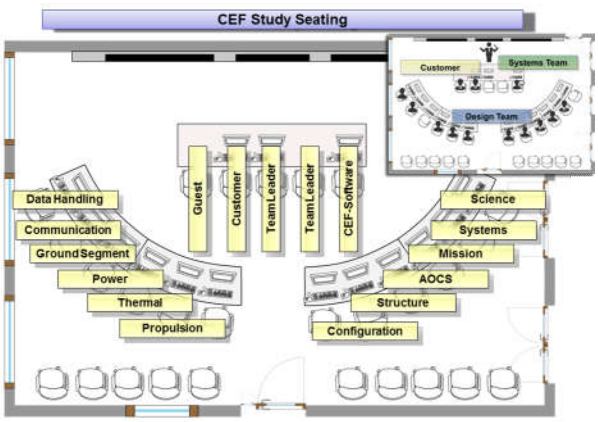

Figure 3: CEF Main Design Room (set-up example)

1.2 Procedure and Software

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 possible, right from the beginning (see Fig. 4).

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 the CE approach. Effective implementation of CE can benefit organisations in several ways, including greater customer satisfaction, reduced costs, increased quality, and reduced design rework and development.

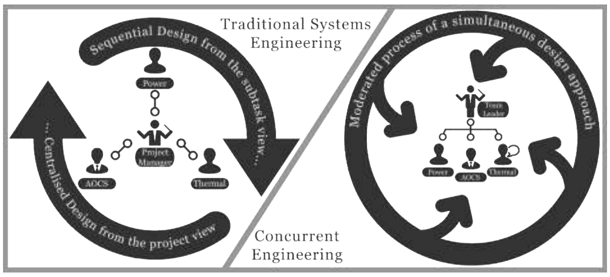

Figure 4: Sequential vs Concurrent Engineering

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" (VirSat), a software application developed by DLR to support spacecraft systems engineering [2].

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.

The DLR in-house S/W VirSat aims to provide an integrated design environment for engineers and to support the design process over the full development life cycle. The development 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, VirSat provides an intuitive user interface. 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. Further descriptions and information for the CEF and VirSat can be found in [3,4].

2. TEACHING CONTENT

2.1 Basic Engineering Theory

Within this one-week educational block event offered now twice a year for space master students, the first one and a half days are dedicated to a series of classical lectures covering:

- Space Project Management, including:

  - ECSS Standards and its structure
  - Project Management Process
  - Project Planning (Project Phases and Reviews, Project Goals, Project Structures, Cost Estimation, Time Management
- Configuration and Information Management
- Risk Management (Process, Identification, and Evaluation, Steering, Documentation)
- Space Systems Engineering, including:
  - V-Model
  - Project Phases
  - Requirements
  - Verification / Validation,
  - Mission Analysis
  - Mission Objectives
  - Mission Architecture (from Launch to Disposal)
  - Space System Design
  - Subsystems Overview
  - Space Applications
- Introduction to all CE-relevant Subsystems (e. g. Power, Structure, Configuration, OBDH, Communications, Mission Analysis, Operations, Launcher Aspects, TCS, Cost, Risk, and Systems

2.2 Theory of Concurrent Engineering (CE)

This part of the course covers the basics of the CE-process, as practised in DLR. The applied process follows the so-called "IPSP approach" (Initiation & Preparation, Study, and Processing). It is divided into three main steps (see Fig. 5) 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.

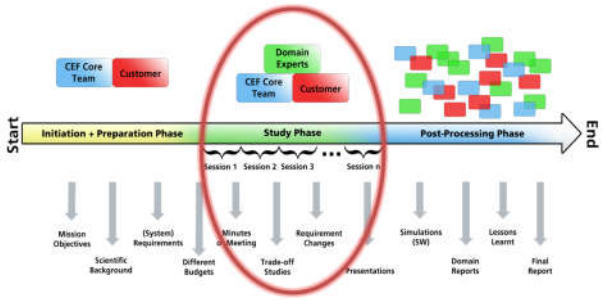

Figure 5: Phases – Overview ("IPSP" – Approach)

This process has been applied within DLR internal studies and for cooperative activities with industry and academia, as well as for purely external studies that were only supported by a DLR team leader for the organization and moderation of the activity. The steps for a CE study are as follows:

1a. *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.

1b. *Preparation Phase* (starts weeks before using the CEF): preparations are both organisational (definition of team members, study schedule, agenda for the 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.

2. *Study Phase* (1-2 weeks in the facility): in this 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. *This phase is run during the practical part of the teaching event* (see in Fig. 5 the red ellipse in the middle as well as section 2.3 below). The mandatory steps of this core phase include:

- Kick-Off with presentations of the study key elements (goals, requirements),
- start with a first configuration approach and estimation of budgets (e. g. 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 with subsystem design in splinter groups or individually, as appropriate,
- final presentation of all disciplines / subsystems at end of the study week.

3. *Post-processing Phase*: all the achieved results and study products are compiled. This phase includes:

- 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 Practical Part of Teaching

The 15-20 students are grouped in pairs, and assigned to one of the conventional domains like e. g. Power, Structure, Configuration, Communications, or Mission Analysis. Typically the role of Systems Engineer, and the domains of Cost and Risk, are assigned to a single student since our experience indicates that the work to be done is neither easily distributed nor sufficient for two students. The Customer is represented by the main lecturer, and the team leading, i. e. the moderation of the process, is performed by supporting lecturers from the CEF core team of the institute.

At the beginning of the study -on the latter half of the second day- the students are introduced to the practical activity with a succinct study-scope. This ca. 10 page document is based on the standard study-scope document format used in real CE studies in the CEF. The study scope includes the main goal, some other relevant information, and around 10-15 top-level requirements.

As an example, the following study goal was provided to the students one year (see additional Fig. 6):

- **Design of a 3U–Cubesat with a camera for plastic island detection/tracking in oceans**

Figure 6: Plastic islands in the ocean
(source: Berliner Zeitung, Photo: AFP)

Since the course is formulated following a Project-Based Learning approach, the study scope includes intentionally, by design, several *insufficient, poorly worded, contradicting, and/or unnecessary requirements*. Not having been made aware of this, students find themselves in the (unfortunately) common real-life situation where poorly defined requirements can create a myriad of problems to the engineers that have to work with them.

Students need to first realise that there are so called "bad" requirements (without interference from the lecturers), then identify all of them, and finally negotiate with the customer whatever changes are necessary for them to be able to come up with a feasible design. This exercise has proven to be a good way for students to better understand the importance of the proper definition or requirements. They learn in reality, that regardless of whether the project is driven by industry or by scientific institutions, insufficient preparatory work and imprecise, unnecessary or even mutually exclusive requirements will always have a big impact on the project execution, and lead to long design discussions (especially in a CE environment).

As an example of bad requirements provided to students, consider:

- *RQ-xy1: "As much scientific data as possible must be achieved within 1U of the CubeSat"*

Since each domain must identify those requirements that are relevant to them, in the case of the example above the students in charge of the payload domain would have to first identify this as a requirement that they must abide by and, after understanding the implications, they would need to discuss the requirement with the customer.

It does not need to be explained in more detail here that a subsequent discussion will lead to identifying this as an inappropriate requirement, and for it to be deleted. Then, under the guidance of the payload domain, the students are asked to formulate a meaningful requirement for the payload that enables the further design of the spacecraft.

Another trivial example of a bad requirement provided to students which looks very clear at first glance would be:

- *RQ-xy2: "The CubeSat shall have a mass of 2 kg"*

But in this case, after discussion it becomes clear that this is also impossible to achieve in practice. Here, the requirement would be violated if the mass was exceeded or undershot by a single gram. This, and many other examples, make it clear to students *in practice* that a requirement must meet certain criteria. It becomes clear to everyone that a successful design is only possible if there exists a clean set of quantifiable, unambiguous, unique and verifiable requirements.

After further concurrent analyses and correction of the initial deliberately incomplete specification given in the study scope, the iterative design based on the CE-process described above is performed for the rest of the week. In the following typical example results of a corresponding training course are summarised.

3. RESULTS

At noon of the last day (Friday) the process is concluded, with the expectation of having a common mission and a 3U cubesat Phase A design including the data and configuration of all relevant subsystems, including:

- main budgets (Mass, Power, Data-Links) for different ops modes
- VirSat data model (S/S – level)
- Mission Analysis Concept (STK)
- Operation Concept
- CAD – model of S/C (S/S and component level, Catia 5.0)
- Risk Analysis
- Cost Estimation
- EOL - Concept

In order to maintain the mission realistic, but within a level of complexity that is achievable for the students, the required operational mission duration is limited to one month. This way, thermal and radiation analyses can be considered unnecessary for this activity, and students can therefore focus of the other domains which they are more familiar with.

Fig. 7 shows the results of a CubeSat designed by a group of master students in a one-week training course in the CEF Bremen.

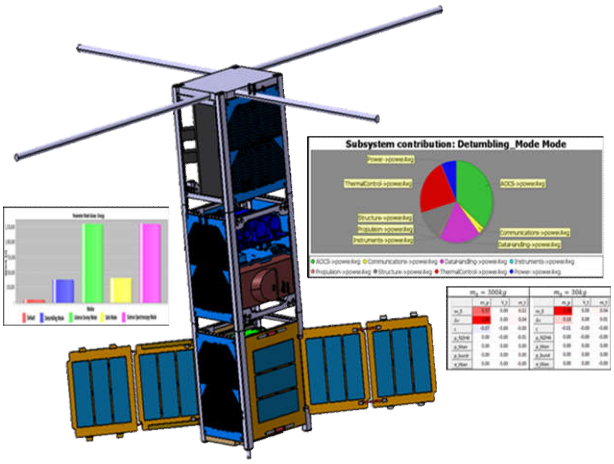

Figure 7: 3U-CubeSat designed by master students

Amongst other tasks, students are also encouraged to come up with a mission name and patch. Sometimes, the students come up with a rather original concept and name for their mission as following example shows:

"**Uni**versity **C**ube**S**at **for** **N**oobs"

The corresponding logo designed by the students can be seen in Fig. 8.
Finally, at last day on a Friday-afternoon, each student has to show his/her results domain-wise within a classical Final Presentation. This is already part of a later oral examination about PM, SE & CE theory.

Figure 8: Logo for the mission „UNICORN"

4. CHALLENGES

Performing a CE activity is an excellent way to perform Project Based Learning with engineering students. It enables them to put into practice the different elements they learn throughout the masters and their earlier studies in an environment which promotes collaboration and accentuates the impact of system and subsystem level decisions on the mission and design. In spite of this, some difficulties are always present.

The first critical issue to mention is the lack of an homogeneous educational background amongst the students. For the practical part of the course the lecturers must consider that the participants come from all over the world and have different educational backgrounds previous to the Master i. e. they come from countries and institutions with different university curriculums, and have degrees in different engineering or scientific fields (in particular wrt space science & technology).

Of course, since all the students have different educational backgrounds, sometimes there is one or more domains with which no student is familiar, which can be an issue. In the lecture part of the course an introduction is provided to all required domains, but of course that is not enough for a completely unfamiliar student to take charge of an unknown domain. This requires an additional preparation and real-time effort on the side of the lecturers, to be able to support the student/s that might find themselves in this situation. This issue can also become compounded with the familiar work-imbalance of the different domains throughout the week (e.g. configuration has low work-volume at the start and a lot at the end of the study, while payload has a high work-load at the beginning and almost nothing at the end), creating some challenges for the lecturers to keep everyone engaged and involved.

Another element to take into account is that in German universities participation is normally voluntary, and only attendance to an exam is mandatory. Since the CE process requires all participants to be involved and engaged, it is important to make the students understand the need for them to be committed to the course, as they are all “links in a chain”.

Some other aspects, which means challenges for the lecturers are the inhomogeneous work load at different times during the week, e. g. domain “configuration” (high at the end of the week and domain “cost” (low at the beginning). The inhomogeneous level of task difficulty is a critical aspect, too.

5. SUMMARY AND CONCLUSIONS

The course “Space Systems & Concurrent Engineering” is a mandatory subject within the Space Engineering Master Module of University Bremen, Germany.

The teaching is performed as a Project Based Learning course in the Concurrent Engineering Facility of DLR, based on a mix of theory in Project Management, Systems Engineering, Concurrent Engineering and, finally, learning by doing by running a “real” CE study.

Beside some challenges described in the present paper the CEF setting is ideal to introduce students to Systems & Concurrent Engineering and to promote a systems view, allowing them to discover the impact of subsystem-level decisions over other subsystems – and even the overall system – in a highly interactive way. It provides a valuable experience of real life situations inclusive impacting design discussions (especially in a CE environment).

The learning outcome is clear, and the activity has been consistently rated as extremely positive by the students. In 2018 the event was even nominated for the renowned "Berninghausen Prize" for excellent teaching.

ACKNOWLEDGEMENT

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