SPECIAL CHARACTERISTICS OF CONCURRENT ENGINEERING STUDIES DEALING WITH CUBESAT MISSIONS AND THEIR IMPACT ON THE CE PROCESS

- SECESA 2016 -

5-7 October 2016

Universidad Politécnica de Madrid (UPM)
Spain

Stephan Siegfried Jahnke[(1)], Antonio Martelo[(1)]

[(1)] German Aerospace Center (DLR), Institute of Space Systems
Robert-Hooke-Str. 7, 28359 Bremen, Germany
Email: stephan.jahnke@dlr.de
Email: antonio.martelo@dlr.de

ABSTRACT

The continuously growing commercial and scientific relevance of nanosatellite missions, especially Cubesats, is clearly discernible in the space community. Due to this, it is important to analyse the special characteristics and demands of early phase studies for such missions to consider them in the Concurrent Engineering Facility (CEF), DLR Bremen's system analysis laboratory. Within such studies, various differences have been observed which make it necessary to adapt the established CE process for study preparation, conduction and post-processing to meet the specific demands of these well-constrained systems, and thereby create the optimal study results together with the design team.

On the design level, the major differences can mainly be traced to two closely connected peculiarities of CubeSat design. First, the targeted system is strictly limited in size, mass and form factor by the associated standard. Because of this, and the growing acceptance of Cubesats, a wide set of highly integrated COTS components and complete subsystems exists on the market with detailed datasheets, and even 3D models freely available on the internet. Secondly, this pool of applicable hardware increases the level of detail the study team has to deal with in a CE study, sometimes even down to connector and harness layout.

In a nutshell, the process of CE studies has to be adapted for these small systems towards a later-phase like level of detail, while preserving the creative and efficient way of solution finding traditionally associated with the CE process, including known benefits such as time and cost savings, and design quality improvement. Based on conducted CE studies for CubeSat missions, this paper points to some of the most noticeable and important lessons learnt and derives suggestions for possible process adaptations.

One of a CE study's team leader's main tasks is to make sure the design process is followed in the most efficient way possible. However, different activities or designs require at times a different approach and ad hoc modifications to the traditional CE process. Starting with the findings from the Cubesat experience, it becomes more and more obvious that the proven process and work approach has to be adapted not only depending on the type of activity conducted in the CEF but also on the design team's background and composition. To exemplify this, the differences for "regular" and CubeSat studies, plus less strictly defined moderated workshops, are analysed in this paper with a special focus on the most promising particular respective communication and guidance styles of the team leaders, as experienced in the CEF.

INTRODUCTION

The origin of the Cubesat community lies basically in the academic environment of universities which aimed for a cheap, fast and easy way to bring their in-house developed hardware into space. The solution was to create a standard for pico- and nanosatellites (with a mass of < 10kg) including suiting dispensers which increased the acceptance of these miniature systems and thereby guaranteed piggy-back launch opportunities on a regular basis. Since the development of this Cubesat Standard by California Polytechnic State University and Stanford University in 1999, it has successfully been established and the application fields are way beyond basic technology demonstration or student hands-on training. Since 2013, over 50 % of the Cubesats are developed within commercial projects. [1], [2] Several New-Space start-ups base their business case on these platforms, from the provision of suitable components, subsystems or turnkey-missions to Cubesat based services (Planet Labs, Inc. as prominent example with an envisaged constellation of 150 Cubesats for earth observation services [3]). One reason for this is the fast development time as well as a shorter time-to-orbit compared to "regular" satellites and by this a facilitated access to space and a faster investment return for the company. To also streamline the systems development process, the design team should rethink the classical sequential or centralized design approach. The application of the Concurrent Engineering (CE) process for Cubesats is a promising way to optimize the development time and to produce a consistent design already in a very early project phase. The interesting question is, whether the well developed and documented process by CE centers, e.g. the Concurrent Engineering Facility (CEF) at DLR Bremen, used so far for mainly bigger less restricted and standardised systems can be used without any modification or if it has to be tuned and optimized to suit the special characteristics of Cubesat systems and their design. Following this main topic of the paper, it leads to more generic questions: to what extend and how does the CE process change dependent on the different types of activities (e.g. inside the CEF)? And how can the study team leader use the process to guide the study team to an optimal design? The described discoveries are partly obtained from subjective observation of the involved CE core team members from a small example set of activities and are not meant to be complete or to be identical for any possible mission scenario or team compilation. Nevertheless, this work can be used as a promising starting point and inspiration for further investigations on this topic.

CUBESAT DESIGN CHARACTERISTICS

The most important difference between satellites following the Cubesat standard and other small or big satellites is the limitation in outer dimensions (form-factor) and mass. The standardisation of these parameters allows for a simplified and more modular sub-system and overall design. A quick internet search on Cubesat components performed in the course of this paper already returns a vast number of results for manufacturers and suppliers of highly integrated sub-systems which often are well documented by datasheets and even include 3D models for direct integration into the overall system configuration. The two pie-charts on the left in Fig. 1 visualise the results of the supplier survey. From the 34 found suppliers of Cubesat related hardware, 62 % do publish detailed specifications and datasheets on their website. The CAD model availability (15 % fully available plus 12 % partly) is reduced but still high compared to other satellite systems, where it is hard to obtain a CAD model before actual procurement. Even though this shows some potential for improvement, most often the information included inside the associated data sheet allows to create simplified blocks with the major dimensions to include into the configuration as placeholders. The offered subsystems cover the complete range of standard satellite domains (c.f. Fig. 1, right) with a strong focus on electronics and PCB-based systems of any kind. It is also noticeable, that there are no components offered for TCS. This can be explained by the fact, that this sub-system normally plays a subordinated role for Cubesats in Low Earth Orbit (LEO), as it is a highly integrated and therefore dense system with insufficient capabilities for an active TCS design, which would need dedicated components. Exceptions may exist for special cases (e.g. deep space missions).

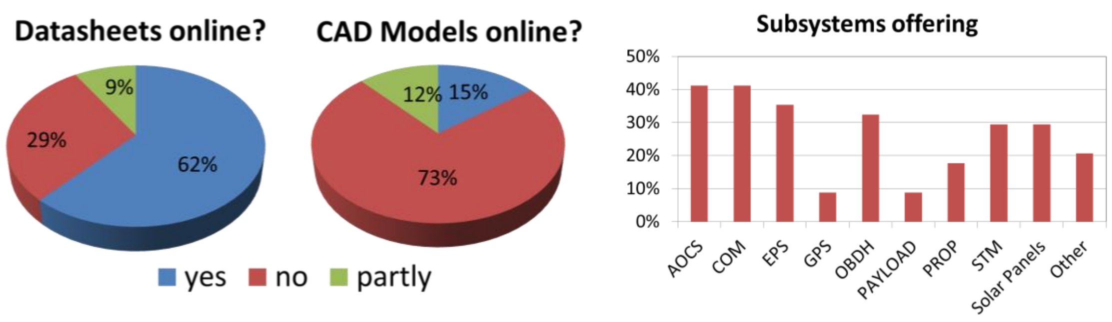

Fig. 1: Results of internet search on Cubesat components w.r.t availability of associated data (left) and offered types of sub-systems (right).

From this steady-growing database of components, the engineer can select those solutions which suit his needs and technical requirements the best, and can be sure that they physically fit inside the allowed cross-section envelope. Several single subsystems subsequently can be easily combined to stacks. Most suppliers use a common bus architecture and PCB layout (i.e. PC-104) so that mechanical and electrical interfaces are compatible. From the integration point of view two main characteristics of the available sub-systems (next to technical performance) are the assembly height and the mass. Together with the fix PCB area this allows for simple and quick mass and volume budgets to be created and optimized against the Cubesat standard constraints. Depending on the aim and complexity of the Cubesat mission, the complete satellite bus can be built from existing sub-systems building-blocks with a relatively moderate workload. The payload often may be the only part of the satellite which has to be developed and adapted for a Cubesat mission. [4]

The original single Cubesat (1U) is well suited for first assessments and hands-on education as even with its very limited available volume fully functional satellite systems can be integrated, due to the miniaturization of electronics. For more challenging and complex missions, multiple cubes can be arranged to double (2U), thrice (3U) or even 12-times (12U) the volume. The advantages and characteristics mentioned before are unaffected by the increased satellite size and mass, as long as it still follows the standard and uses associated components and sub-systems. Cubesats are normally not the primary payload of a launcher and thus, the Cubesat design should be robust enough to cope with a wide range of orbits to not miss available launch opportunity as piggy-back. Also the payload should be designed to be functional in a wide range of orbits to not be too restrictive.

CUBESAT CE STUDIES

The necessity to adapt the CE process with respect to the Cubesats peculiarities is also emphasized by the fact that there are aspirations to introduce an altered systems engineering approach especially for Cubesats, based on the guidelines of NASA's Systems Engineering Handbook, as stated in [5]. Thus, the continuation of this approach towards CE studies is a logical consequence. NASA's concurrent engineering team (Team X) already reacted and founded a special task-force (named Team Xc) to meet the increasing demand for a rapid small sat – in particular Cubesat – concept generation and preliminary design studies [6].

Following the conventional process, each CE study activity, as they are conducted at DLR Bremen's CEF (c.f. [7] for further descriptions), can be divided into 3 phases: 1) Initiation and Preparation, 2) Study and 3) Post-Processing ("IPSP" approach). This paper focusses on the former two phases, for which specialities and differences of a Cubesat study can be derived from experience during the CE sessions and explained by the Cubesat characteristics described above.

Preparation Phase

The preparation of a CE study in general is an important part of the overall process and creates the basis for successful and smooth study conduction. The CE-team at DLR Bremen has a step-by-step checklist for this first phase. It describes all necessary tasks to be completed before the beginning of the actual study and includes organisational aspects as e.g. time and personal planning, as well as requirement iterations, study scope definition and preliminary design tasks for mission analysis and system configuration [8]. While this proven preparation list is considered as applicable also for a Cubesat study, some of the tasks should be given special attention and performed differently than for other systems to react to the described special characteristics.

First point to mention is the selection of the appropriate team-size and personal. For most of the Cubesat use-cases (except for those where bus technology shall be developed and demonstrated) it can be safe to assume that there are suiting commercial-off-the-shelf (COTS) subsystems available for the basic satellite systems and ready to be used within the study. This means, that the task during the CE sessions of the single domain expert is shifted from actual design of the sub-system and estimation of key-parameters towards the selection of the most suiting existing solution from e.g. a database and interface cross-check to other sub-systems. Conducted studies show that, due to this fact and in contrast to conventional studies, it can be possible for experienced engineers to overtake several domains in parallel while still being able to handle the work-load within a CE study and thereby reduce the team-size and the personnel costs. Looking at the major sub-systems of a satellite, suitable bundles can be created for closely related domains as e.g. Power / Communication / On-board-data handling, Attitude & Orbit Control / Propulsion or Structure / Mechanisms & Configuration. As stated and explained above, Thermal Control can often be excluded from the list of domains. The importance of a system engineer and a customer monitoring the system conformity and requirements is unaffectedly high. As a reference, two exemplary study seating orders from actually conducted studies inside DLR's CEF for a regular and a Cubesat study are compared in Fig. 2 which also indicates the potential savings in personnel cost (approx. 30%).

Mission analysis can be done prior to the study for a range of applicable orbits providing the worst-case values for e.g. eclipse times and downlink-rates to suit the piggy-back launch design approach. Following this, the study team can start their component selection directly without any delay based on these values. Nevertheless, the Mission Analysis expert should at least be accessible for possible inquires or major changes in orbit requirements. Depending on the complexity of the payload, the responsible scientists / experts should be participating.

The payload in most missions is, in contrast to e.g. the avionics, no COTS system. It has been observed that, unlike other satellite missions, where the satellite is built around the payload, it might have to be adapted in ranges to be in line with the Cubesat standard and the overall system design.

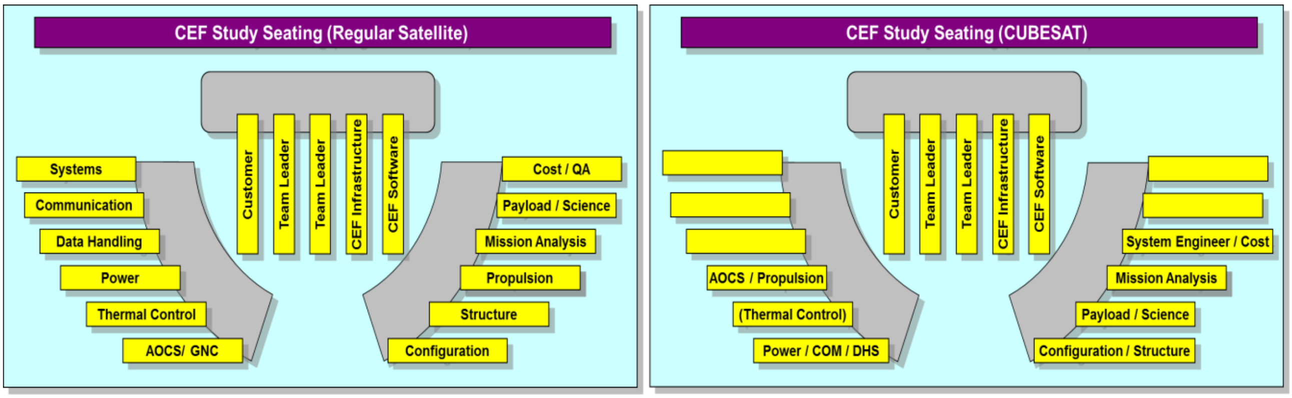

Fig. 2: Comparison of exemplary personal and seating inside DLR's CEF for a regular and a Cubesat study.

Just as for other study types, the accommodation and overall configuration is a very important task with some special characteristics. Even though, it is good practice for every CE study to prepare an initial 3D model of the to be designed system, this model normally undergoes major changes throughout the study which often leads to a huge work-load for this domain especially in the last few days of the study when the design and the sub-components are finally defined. For a Cubesat, once the appropriate size (i.e. number of units/cubes) is selected, the outer envelope and the structure are untouched and only subject to minor modifications. This either allows to shift a lot of work to the preparation phase, or – as another extreme – to no initial configuration at all (e.g. if the Cubesat size or body-mounted vs. deployable solar panels is still under discussion) and selecting from existing or ready-prepared Cubesat structures on the first days of the study. Nevertheless, the Configuration engineer should prepare or at least have access to a set of CAD models for all applicable subsystems from which he can easily select the suiting components to facilitate his work during the study to reduce the time needed to create 3D parts from scratch.

The considerations so far show the importance of easily accessible information and data for Cubesat components and together with the internet research on Cubesat manufacturers lead to the idea to provide a database for the available COTS Cubesat components inside the CE facility. The database functionality and content is still to be defined and developed, but there are existing concepts for internet search engines (like e.g. www.satsearch.co or space-point database) which could be used for starters. During the study the data model can be fed with actual and accurate information for mass, power consumption and even hardware cost from the data sheets. This creates a consistent and complete system design with a Phase-B-like level of detail. MBSE approaches and a suitable data model for later phases, which facilitate to directly reuse the data model throughout the later phases, are considered as especially helpful for this reason as they allow a smooth transition to an up-following project phase. The creation of a more specific Cubesat data model template or reference model (as currently performed by INCOSE Space System Working Group [9]) with additional cross checks against the Cubesat standard, maybe also directly linked to a component database, to be re-used for several studies, can be considered as promising feature. As part of the preparation, this generic and abstract Cubesat model could already be implemented and adapted towards the specific Cubesat mission, to have a working model at the beginning of the study.

Study Phase

The actual conduction of the Concurrent Engineering Study at the facility in principle follows the proven process for conventional CE studies and the associated schedule, which consists of presentations for common understanding, moderated sessions and unmoderated time for actual work on the model, calculations and budgets. The biggest difference observed within the conducted Cubesat study is the fact that discussions during these sessions and splinter meetings tend to go into a quite deep level of detail, which normally would not be appropriate for a typical Phase 0/A study, but rather reminds more on a project in Phase B.

This is closely related to the Cubesat characteristics described above. Since most of the equipment can be selected from a set of existing and often even flight-proven COTS components, all information for these design details are available and play an important role for the consistent and functional final product. An example shall be used for clarification.

For some sub-systems the analysis even goes down to the connector position or pinout of sub-system PCBs, a totally unusual topic for a feasibility study inside the CEF which normally should be supressed by the team leader. But for the Cubesat it can become a crucial point and a show-stopper for the complete design, if the selected sub-systems cannot be directly connected inside a common stack. For regular satellites, adapter cables or boards might be a solution for such issues. For Cubesats, this would mean that additional (customized) adapter boards have to be included between the COTS boards inside the electronic stack, which increases the height and in return might violate the restricted height of the selected Cubesat envelope.

From this example it becomes clear that therefore all these discussions about small details have to be allowed, encouraged and supported by the study's team leaders and to be considered as additional time-slots inside the study schedule. Experience shows that discussions, which involve basically the complete design team and therefore needs to be performed inside the plenum tends to eat up the time originally dedicated to unmoderated sessions and therefore should be considered as especially important for Cubesats.

Linked to this problematic, one proposed useful tool for this purpose, along with the classical budgets for system mass and power consumption, is to track the overall height – and due to the fix form-factor of Cubesat boards also volume – of the electronic stack; preferably in combination with CAD-walkthroughs for a better visualization and basis of discussion, this allows for rather easy but significant information about "fill ratio" and thereby the available volume for additional boards inside the Cubesat to verify the design. An exemplarily created Cubesat design is shown in Fig. 3. The included components of the stack are divided into different categories, depending on the amount of information available on the selected equipment. Red represents components, which are considered as black-boxes of any type. This category might be applicable for payloads, which are not yet completely defined, might have to be customized or could still be adaptable in height. Blue symbolizes dummy boards, which either are not available as detailed 3D model from the distributor or will have to be customized, but are likely to follow the PC104 standard. Finally, detailed available COTS component models are included in green. A negative budget for available volume at the end of the study is tantamount with an unfeasible design. A corresponding calculation could be integrated into the data model without too much effort.

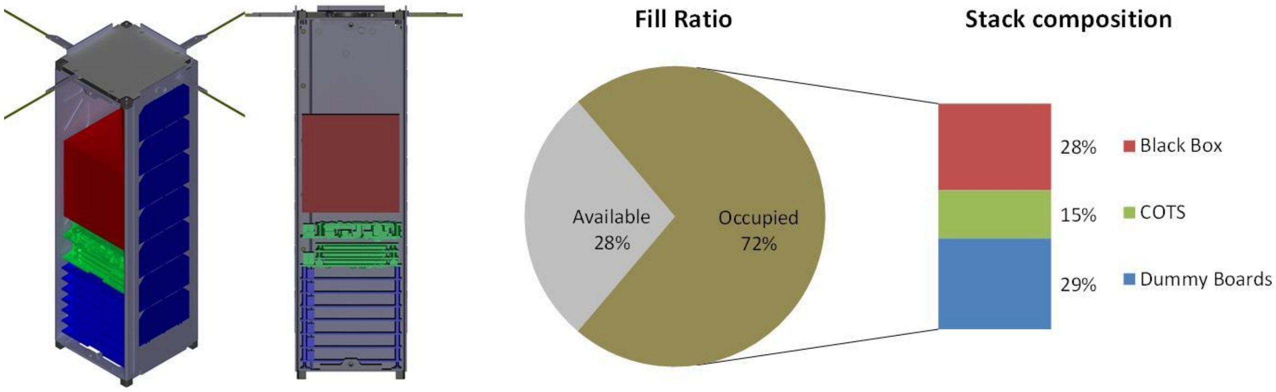

Fig. 3: Fill-ratio and stack composition analysis of an exemplary Cubesat for design consistency check.

On the other hand, once the COTS components are selected and verified, the Cubesat can become accurately designed quite fast without much iteration needed. Thus, the time dedicated to perform moderated domain rounds where each sub-system expert inserts and updates information into the data model can be reduced. This characteristic can be seen in Fig. 4 which shows the evolution of the system total mass of a 3U Cubesat and a regular study (in this case Post ISS Free Flyer) as extracted from the Virtual Satellite data model. This parameter has been selected as a reference because it shows best at which point of the design process there had been changes in the list of components. Two coherent tendencies for Cubesat studies can be observed from this comparison. First thing to notice is the variance in absolute number of revisions, which, contemplated separately, could be explained by the different complexity of the two systems. Together with the second characteristic, which is the reduced number of changes in the mass parameter value throughout these revisions for a Cubesat, the graphs lead to the different conclusion, that for this particular Cubesat study, the study team had a very clear idea which components need to be accommodated to obtain a functional design. In total there were only two points during the design where the mass changed significantly. The long period of a constant mass in the mid-part of the study can be translated to the fact that even though the work continued and discussions were ongoing, the overall system's component list has been untouched. This can be traced to the behavioural pattern of the domain experts (which can also be observed for regular studies) that once COTS equipment has been selected, it tends to be unchanged. In conclusion, as a Cubesat mainly consists of COTS sub-systems, there are less design changes. In contrast to that, the much more conceptual and unrestricted Post ISS study [10], where experts had to use their experience and partly best-engineering-guesses for their sub-system mass, shows a much more dynamic evolution of the system's total mass.

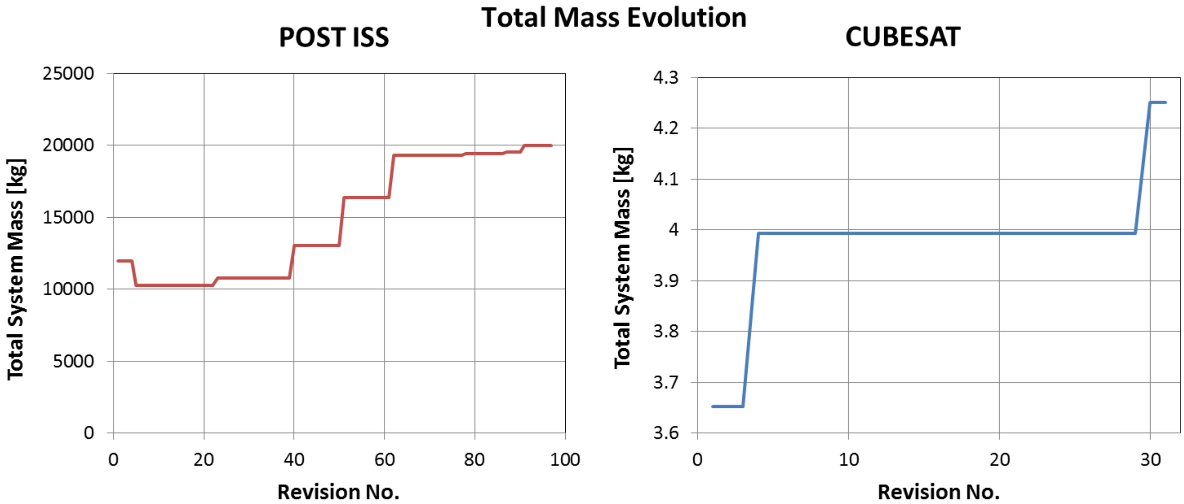

Fig. 4: Evolution of the system total mass over revision number of the data model for a Cubesat and a regular study example (here Post ISS, [10]).

Even though the described peculiarities of a Cubesat study may be similar for several studies and therefore, may be a good guideline to adapt the schedule and major point of discussions accordingly from the start, the team leader has to follow the discussions carefully and be ready to react and modify the planned activities ad-hoc if it turns out that specific, unforeseen, topics for this particular system design are mandatory but also guide the study team to follow the CE process to the maximum extent to make use of the proven advantages. Nevertheless, sometimes it might also be necessary to tweak the CE process to a more workshop-like approach, which – as understood at DLR CEF – is a more open activity than an actual CE study.

CE PROCESS ADAPTATIONS FOR DIFFERENT CE ACTIVITIES

Although the main use of the CEF is to perform CE studies, the general CE process as applied in DLR has been proven to be flexible enough to benefit other activities with minor adaptations. Activities frequently performed are workshops; in particular, workshops oriented to define requirements, and analyse and discuss issues regarding the initiation of a project or study (pre-phase 0). These workshops typically last two or three days, with a similar organizational structure to regular studies, but focusing much more on group discussions and for the most part not needing to perform specific work at subsystem level (e.g. calculations, design of systems, detailed configuration …).

In 2016 DLR performed a study preparation workshop and a study for a project under the name of S2TEP (Small Satellite Technology Experimental Platform), which we will use as a case example for the purposes of this paper. Observing the agenda for the two (see Fig. 5), it can be seen how the definition of the study schedule follows a similar arrangement both for studies and workshops. The main differences that can be discerned are that the total duration of a workshop is less, both in days and hours per day, and that the moderated sessions for the workshop are sizably larger than those of the CE-study.

The non-moderated time in studies are more important since domain experts have a greater need for splinter discussions that do not require the whole group, and because the work is more specific (e.g. calculations, re-designs, and searching for specialised information are all actions that recursively happen in the non-moderated time of a study). In workshops, the emphasis is on the group discussions, where the constraints that will affect the different subsystems have to be agreed upon by the experts. This makes the structure of a workshop less rigid than that of a study, and requires the moderation to be more lenient and adaptable to the discussion than in studies.

Another important difference between a study and a workshop in the CEF is that since for the most part no specific values for physical parameters are determined in these workshops (except as a requirement of a maximum or minimum value, or possibly a range for a particular parameter, e.g. mass, orbit inclination, etc.), the use of tools is rare. In particular Virtual Satellite [11], DLR's proprietary Model Based Systems Engineering (MBSE) based integrated design environment, has never been used or considered necessary at this stage, as it is focused on defining requirements and actions to be performed for a posterior study.

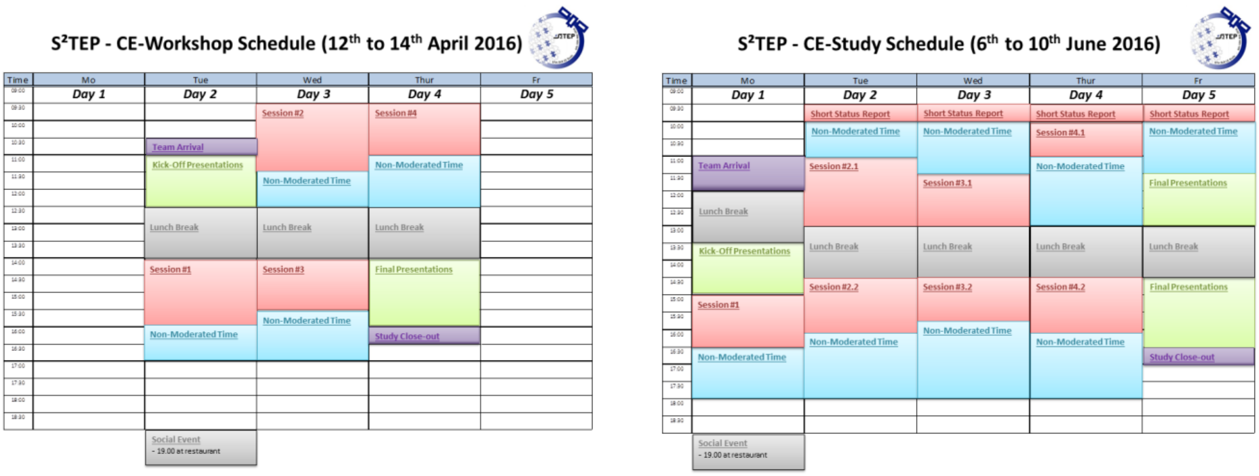

Fig. 5: CE-Workshop Schedule vs CE-Study Schedule

A different type of activity which has also been performed at DLR Bremen benefiting from a CE based approach is Concurrent Evaluation; industry proposals on federal tenders are evaluated by assessing ideas for spacecraft or missions, with a main focus on the mission architecture design.

The process for this activity starts with the initial identification of scenarios, which are established in brainstorming sessions by the experts. Later, an iterative process of evaluation is performed to analyse the different scenarios one by one, and based on the demands of the payloads and environment, the experts assess the domain specific tasks for each mission scenario and define requirements at system and subsystem level.

An interesting adjustment in this type of activity, is the use of an adapted excel-based Integrated Design Model (IDM), which does not focus on physical parameters (such as mass, or power) as is the case in CE studies, but rather on abstract parameters (e.g. technical feasibility, socio-political impact, risk, cost-drivers…).

These adaptations have been proven to provide an increased and consistent level of understanding of all participants, a streamlined, fast-executable process for evaluation, and improved results compared to the classical approach to the evaluation of proposals.

CONCLUSION

The processes used at DLR's CEF and other concurrent design centers are proven by numerous successfully conducted studies for a wide variety of different systems. These processes often need to be adapted ad-hoc by the team leader during a study as not every circumstance or discussion topic can be foreseen during the planning phase. Based on what has been observed from a conducted Cubesat study, which is a system with very characteristic design peculiarities related to the restrictions of the associated standard, the idea arose to analyse the needs of specific activities inside the facility to be optimally prepared for the necessary type of analyses, discussions and design dynamics to minimize the necessary ad-hoc adaptations and to stream-line the design process. For Cubesat studies, a set of recommendations for process adaptations during planning and conduction of the CE study have been given and additional tools and analyses have been proposed to be included inside the data model. The promising application of an MBSE approach using a generic Cubesat reference model together with a to-be-developed database of existing COTS components and sub-systems has been pointed out to implement additional (automated) design checks and achieve the ability to re-use the CE data in later phases of the project, ensuring a smooth transition to activities outside the CEF. To validate the described assumptions for process and method optimizations in future perspective, a larger set of example activities will be required, i.e. additional Cubesat studies with different mission scenarios, to test these assumptions and subjective observations against and by that quantify their benefits for the design process for CE activities.

Workshops, as understood within DLR's CE-core-team, are loosely structured, more open activities, which are conducted without completely following the proven CE process. Therefore, it is important for the team leaders to be optimally prepared. As the data model often is not used within these activities, the major study products are calculations and presentations created during the workshop. The commonality between the Cubesat study and these workshops can be condensed to the importance of open discussions on particular, sometimes quite detailed, topics which might be crucial for the overall mission design.

Finally it can be asserted, that the CE environment is not only restricted to its use for classical CE studies but can be beneficial for a wide set of activities, topics and type of systems if the study leader is aware of their peculiarities and takes them into account during preparation and conduction.

REFERENCES

[1] M. Swartwout, “The first one hundred Cubesats: a statistical look”, Journal of Small Satellites, Vol. 2, pp.213-233, 2013.

[2] M. Swartwout, "CubeSat Database”, (Online) https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database, last cited: July 2016.

[3] Planet Labs, Inc., “Planet Labs Specifications: Spacecraft Operations & Ground Systems”, Version 1.0, June 2015.

[4] K. Woellert, P. Ehrenfreund, A. J. Ricco. H. Hertzfeld, „Cubesats: Cost-effective science and technology platforms for emerging and developing nations“, Advances in Space Research 47, pp. 663-684, October 2010.

[5] S. A. Asundi, N G. Fitz-Coy, „Cubesat mission design based on a systems engineering approach”. Aerospace Conference, 2013 IEEE, pp. 1-9, Big Sky, MT, March 2013.

[6] P. Zarifian, T. Imken, S. E. Matousek, R. C. Moeller, M. W. Bennett, et al., "Team Xc: JPL's collaborative design team for exploring Cubesat, Nanosat, and Smallsat-based mission concepts", 2015 IEEE Aerospace Conference, pp. 1-10, Big Sky, MT, March 2015.

[7] H. Schumann, A. Braukhane, A. Gerndt, J. Grundmann, R. Hempel, et al., “Overview of the new concurrent engineering facility at DLR,” in 3rd International Workshop on System & Concurrent Engineering for Space Applications (SECESA), Rome, October 2008.

[8] A. Braukhane, D. Quantius, V. Maiwald, O. Romberg, „Statistics and evaluation of 30+ Concurrent Engineering studies at DLR“, 5th International Workshop on System & Concurrent Engineering for Space Application (SECESA), Lisbon, October 2012.

[9] D. Kaslow, L. Anderson, S. Asundi, B. Ayres, C. Iwata, et al., “Developing and distributing a Cubesat model-based systems engineering (MBSE) reference model”, 31st Space Symposium, Colorado Springs, April 2015.

[10] O. Romberg, D. Quantius, H. Dittus, S.Baerwalde, W.Seboldt, et al., “Orbital Hub - DLR Vision 2025”, DLR Institute of Space Systems, System Analysis Space Segment, DLR-Brochure, March 2016.

[11] M. Deshmukh, V. Schaus, P. Fischer, D. Quantius, V. Maiwald, et al., “Decision Support Tool for Concurrent Engineering in Space Mission Design.”, Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment, Volume 1 (Part 5), pp. 497-508. Springer - Verlag London. ISPE International Conference on Concurrent Engineering, September 2012.