MEANING OF CONCURRENT SPACE ENGINEERING IN PHASE B

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ABSTRACT

Nowadays, Concurrent Engineering (CE) is a well-established process for pre-development phases within the space sector and applied in international agencies, in industry and academia since several years. Recently the high efficiency of a Phase 0/A CE-process could be verified in many studies at the Concurrent Engineering Facility (CEF) of the German Aerospace Center (DLR). The decrease of cost, time and inconsistencies in system design is apparent. This is a result amongst others out of the participation of all domains related to the space mission, the use of a common data model and very frequent iterations in the development process.

The DLR Institute of Space Systems has already gained first experiences of Phase B Concurrent Engineering in the frame of the DLR Compact-Satellite project as well as within two CE studies related to CubeSats. These activities have been executed primarily on an empirical basis. It has been done by addressing the needs of the respective project status and simultaneously working out the desired results with all relevant team members in the DLR CEF.

In order to elaborate a meaningful approach for supporting higher space project development phases applying CE, an intensive discussion of the stakeholder's needs, expected results and possible design processes is required. The actual questions deal with aspects of preliminary and detailed design, with the major differences between Phase A and Phase B activities in view of CE, with tools commonly used by the domain experts and how these could be linked to the CE-process and a central data model. Are generic processes required or rather different, dedicated types of CE activities along the Phase B timeline? Are they similar or not for system design, subsystem issues or associated topics such as verification and validation planning, cost estimation or requirement reviews? Do these activities and their objectives have to be pre-defined and shall they be implemented entirely in the project plan already at a very early stage? Is it advisable to keep margin with respect to the schedule for trouble-shooting tasks like a potential payload/bus interface re-design study?

In the frame of corresponding work a discussion baseline for the long list of aspects related to CE in higher project phases is provided, by mainly introducing the basic characteristics, requirements and constraints of Phase B design and the comparability to earlier and also higher phases. Furthermore, a set of pros and cons are described for scenarios of how, when and where CE could be applied in Phase B. Finally, initial proposals are given for potential adaptions of organizational and process-related aspects such as the definition of a CE activity timeline, including the variation of design iteration cycles, the team set-up for dedicated sessions and how the H/W and S/W infrastructure could be prepared. Achieving a common understanding of these issues is an important step for more sustainable and efficient space product development applying the methodologies of CE also in Phase B and beyond.

INTRODUCTION

This work summarizes the work performed so far by the German Aerospace Center (DLR) - Institute of Space Systems with respect to the application of the Concurrent Engineering (CE) methodology to higher project phases, in particular Phase B.

At first an introduction of the different project phases, defined by the European Cooperation for Space Standardization (ECSS) and of the CE approach, applied generally and at DLR is given, followed by the description of a few CE-related activities performed so far. Furthermore, the value of applying CE in Phase B is discussed, and it will be looked at the actual tasks in such a phase. The explicit differences of early- and later design phases, in general and in the context of

Concurrent Engineering are addressed and lead to the question of how to adapt the CE-process for more detailed (Phase B) activities. Some initial assessments and recommendations are made which shall provide a baseline for potentially more effective development of space systems in higher project phases. This later on has to be discussed within the space- and concurrent engineering communities.

Phase Overview

Based on the ECSS definition the product life-cycle is divided into several phases, addressing the design, utilization and disposal phase. Furthermore the standard [1] defines a set of reviews to be performed after or within certain phases, as summarized in Table 1:

Table 1. ECSS Phases [1] including assessed Technology Readiness Level (TRL) [2]

Phase	Definition	Includes Reviews	Ends with Review	TRL to be reached
0	Mission Analysis		MDR	1-2
A	Feasibility		PRR	2-3
B	Preliminary Design/Definition	SRR	PDR	4-5
C	Detailed Design/Definition		CDR	6-8
D	Production		QR	
E	Acceptance (E1); Utilization (E2)	AR; ORR,FRR,LRR	FQR; EOLR	9
F	Disposal			

Concurrent Engineering

One effective methodology to perform rapid mission analyses and system design is Concurrent Engineering. Having all relevant disciplines involved in the design process already from the very beginning and use common data and design models to document and share parameter as well as decisions, this leads to a more consistent design in less time and finally with less cost.

Nowadays Concurrent Engineering primarily focuses on Phase 0/A activities, since the added-value is very obvious and the iterative nature especially of the early mission and space system design requires intensive communication and iterations amongst the different disciplines.

CE ACTIVITIES AT DLR

One programmatic goal of the CEF is amongst others to integrate expert-know how by connecting not only the Institute departments but any expertise distributed in DLR’s 13 sites. This should support the system analyses processes and add value to the system design processes.

Early Design Studies

As summarized in [3], [4] and [5] the use of the CEF and its related processes is manifold. Within DLR CE studies which most often last one week (full time) and contain 3 to 5 design cycles the focus is also on the very early phases.

Related tasks are usually:

- To perform system trades and/or a system option selection
- To generate system budgets and functional diagrams
- To define mission sequences (modes) and payload utilization scenarios
- To assess the cost of a mission
- To perform trades on subsystem level
- To accommodate the required spacecraft components into an overall configuration
- To revise system requirements and to derive subsystem requirements

Phase B Studies

Within the last 4 years, the DLR Institute of Space Systems performed more than 30 Concurrent Engineering studies [5] were 5 projects have reached already Phase B level:

- AsteroidFinder / Compact Satellite; Phase B sessions
- Mobile Asteroid Surface Scout (MASCOT), 4thstudy, February 2011
- NanoSat CLAVIS (Plug&Play Sat)
- Compass-II CubeSat; external study with the University of Applied Sciences in Aachen, Germany
- Gossamer (GOS-FLdc study); Solar Sail mission demonstrator based on CLAVIS

The approach and results of the AsteroidFinder Phase B sessions are extensively described in [6]. In brief, seven monthly 2-3 day sessions (S1-S7) have been conducted, each dedicated to one or more different topics, respectively steps of the running Phase B, as can be seen in Fig. 1.

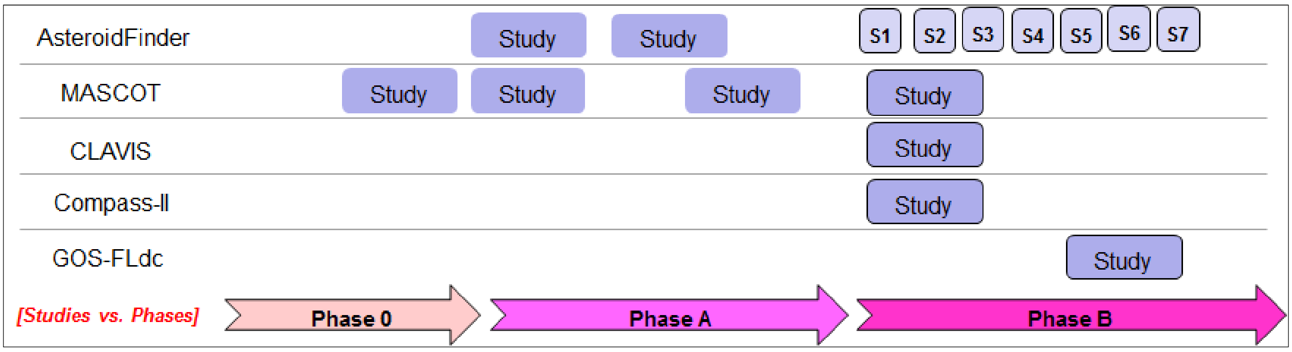

Fig. 1. DLR CE studies and sessions (S) with link to Phase B

Additionally, three 1-2 week Phase 0/A studies for the DLR asteroid landing package MASCOT between 2009-2011, a phase B design consolidation study with the Japanese and French Space Agencies (JAXA; CNES) focussed on the interface definition amongst the subsystems and to the Hayabusa-II mother spacecraft. Furthermore, two CubeSat design activities have been conducted in the CEF, mainly related to both bus design adaptations and the final definition of payload interfaces. In both cases, the classical data model, i.e. the ESA Integrated Design Model (IDM) work books, has not been used for data exchange since both projects had already their own parameter management structures. The same is valid for the Gossamer-study which has been conducted on request for a design modification.

NEED OF CONCURRENT ENGINEERING IN PHASE B

Along with the question if the CE approach as such is applicable in higher project phases, one could ask if there is actually a need to perform e.g. phase B tasks in this highly-interactive and collaborative manner, or if the work of a single domain is to different to discuss jointly on system level. In the following there are some examples of typical space systems engineering activities for Phase B. Table 2 lists these tasks, categorized in rather (not exclusively) technical- and management-related work. They provide the baseline for the identification of the actual differences between feasibility analyses (Phase A) and preliminary design (Phase B) in the next section.

Table 2. Phase B tasks (excerpt)

Technical-related Activities (*w/o any order*)	Management-related activities (*w/o any order*)
Bread-boarding / Testing	Completion of Project Plan
Subsystem (S/S) Simulations	Final Release of Work Breakdown Structure (WBS)
Structural Concept	Cost Estimation
Identification of Critical Technologies	Initial Risk Assessment
Interface Definitions (to Payload and S/S)	Quality Assurance Planning
Functional Block Diagram	Margin Philosophy Definition
Requirements Breakdown (Finalize Tech. Reqs.)	Contractor Acquisition
AIV / AIT plan	

Furthermore, operational activities like communication frequency-, ground segment-, and launch vehicle selection have to be prepared as well as the mission operations planning. It is clear that not all these tasks might be worked out in a CE like environment but there is a high potential of improving the design by bringing all experts back on one table. Many activities require intensive communication amongst the disciplines and the clear definition technical interfaces, tasks and responsibilities. A survey created amongst the DLR AsteroidFinder team after the series of Phase B sessions [6] indicated that 93% of the participants considered the CE approach as beneficial [7].

PHASE 0/A VERSUS PHASE B DESIGN

This section describes the different aspects of both feasibility analysis and preliminary design. The main relevant differences are:

- Requirement breakdown
- Level of technical detail
- Amount of parameters (and dependencies)
- Purchase of hardware
- Consideration of test activities
- The increase of team members
- External contracts

Requirements

During Phase B, for the system requirements review (SRR), the project has provide a comprehensive set of technical requirements covering all disciplines. The high-level requirements have to be broken down, specified, iterated with the design team and be clearly documented with unambiguous definitions and possibly rationales. Traceability has to be ensured which most likely requires a supporting software such as DOORS (IBM tool) or CORE (by “Vitech”).

Parameters and level of detail

One of the major differences when changing from Phase A to B is the strong increase of parameters to be handled, due to the increasing level of detail. Whereas in Phase 0/A the number of parameters to be shared amongst the disciplines is in the range of hundreds to a few thousands, in Phase B the number increases by at least one order of magnitude. For example, a set of orbital parameters, basic information about the efficiencies, size and mass of solar arrays and the batteries could sufficiently demonstrate feasibility, but static values and a series of worst-case assumptions are no longer applicable for the preliminary design. The more detailed power control and conditioning unit (PCDU) design requires parameters such as ripple factors for the voltage accuracy and also simulations of the operational modes providing varying illumination angles and energy demands in order to optimize the energy source and storage units.

Software, models and detailed knowledge is needed. The increased level of detail reduces also the understanding of other subsystems in one special field and requires also increasing trust from the systems engineering team. Clear inputs and outputs have to be defined in order to exchange the right values at the right time.

Hardware and test activities

Theory does not always verify the design. Many activities and components require hardware tests besides simulations and calculations. These activities take time and rely on the availability of facilities. This includes software verification facilities as well as thermal vacuum chambers or shakers for structural and mechanical tests. In order to achieve a reliable “yes” or “no” for a certain function of a mechanism or the evidence that the structure withstands the launch loads, the Assembly, Integration and Verification/Test (AIV/AIT) team has to plan the order of tests, execute them and consider and request time margins for uncertainties or re-design activities.

Team members and contractors

The increased amount of detailed work leads also to an increased number of personnel within the project. Each domain responsible might be backed up by a second person to compensate unavailability or just to share the work, especially when it comes to a split between hard- and software design. During the MASCOT- and the Compass-II CE studies with Phase B background there were also two systems engineers available, one for mechanical-, one for electrical design.

Additionally external contractors could take over special tasks for manufacturing and for testing of smaller components. This, again, requires clear interfaces and a lot of communication.

HOW TO PERFORM PHASE B TASKS APPLYING CE

The differences are now generally described and it is clear. In the next step there has to be the discussion of how these differences can be handled using CE.

Common approaches, activities and methods

All tasks have a certain process, tool or environment which helps to dealing them. The testing phase starts with breadboards before the real engineering or flight models are built, hardware-in-the-loop tests are one of the first steps coming from the virtual environment to the real component testing and external development and manufacturing requires specifications in order achieve the right product. Furthermore, there are verification matrices which support test planning, also with respect to cost and time, MS Office tools for creating functional block diagrams, Cost Estimation Relationships (CERs) for cost assessments, fault detection, isolation and recovery (FDIR) techniques for product assurance as well as simulation and design tools for e.g. part assembly, stress analyses, thermal analyses or orbital behaviours.

Applying CE methodology

The question is now what can be supported by the means of CE? There are several tasks which very likely cannot be performed neither in the CEF nor by generally applying the CE methodology, as mentioned hardware-in-the-loop tests of for instance. But for others, the active and iterative involvement of several disciplines in a CE way can be more promising.

Verification and Validation (V&V) planning

V&V affects any physical subsystem as well as many programmatic aspects. Prepared by the systems team, a dedicated (set of) session(s) including the AIV team, technicians and test lab heads could identify several options of how to organize the flow of test activities including cost estimations and definition of time margins. Similar activities could also be applied for the definition of the overall project schedule in order to provide real time assessments to the project leader and to indicate required inputs as well as critical issues to the rest of the team.

System functions definition

In order to achieve a common understanding for the tasks of the system components, the functional block diagram is one tool to present the different relationships amongst them. Since all subsystems are involved, a dedicated session for the finalization of such an overview could be held with the entire design team. The preliminary versions from Phase A most likely have to be updated in order to incorporate the latest redundancy concepts or interfaces amongst the bus elements and the payload.

Conducting reviews

As reviews already include the presence or at least the presentations of all relevant disciplines there might not be much additional value to gain when applying CE. However, in order to optimize the review item dispositions (RIDs) clarification, the CEF infrastructure could be used to improve the (spatial) ability of forming splinter groups in order to immediately react on the comments of the reviewer and work out solutions or clarifications which can be presented in an upcoming clarification session (right after the actual review).

Cost & risk estimation sessions

Although the cost and risk estimation is an on-going tasks in which the individual disciplines have to be consulted frequently, dedicated sessions as also described in [8] for the risk assessment would provide valuable input to the systems engineer, cost engineer or product assurance responsible and forces the domain engineers to carefully revise their statements before the meeting and together with (maybe even in front of) the entire team.

Trouble shooting & problem specific task force

As already done in the DLR CEF, emerging problems or new options lead to a review of the design if they significantly impact the further development (e.g. a mechanism failed x times the test) or the final performance (e.g. the new technology could reduce the solar array size by factor 2). Such emergency sessions cannot be planned upfront but should somehow be included in the overall CE and project timeline.

Requirement check and tracking

As done during the AsteroidFinder session, the entire set of requirements has been discussed with the whole team [6]. This finally led to a common understanding and consistent documentation but was very demotivating for the participants since often requirements have been discussed which do not affect the design of other disciplines.

DISCUSSION, PROPOSAL AND RECOMMENDATIONS OF ADAPTATIONS

The areas in which CE could be beneficial for preliminary (and detailed) design as described in the former section mainly refer to topic-dedicated sessions, compared to the more general system design tasks performed during Phase 0-A studies. There, the single sessions had also a certain focus like the definition of operational modes, discussion of redundancy concepts or propulsion trades but where rather a mixed with other high-level discussions. There are several options which have to be investigated regarding the application of processes and the use of tools.

Processes

So far there are only a few findings how to effectively apply the established CE process to the higher phases of space projects. In contrast to the current (DLR) approach where Phase B studies have been conducted based on request, there has to be a view on the overall development timeline.

As already tested, having monthly sessions with 1-3 days in a row, this approach could be kept, but the number of days and time in between could be adjusted. During the AsteroidFinder sessions [6] the main topics per session appeared and were a mixture of both system design and special problems. But in reality and depending on the project, this generic approach could be problematic. The different areas as stated exemplary in the previous section could be clearly communicated in the beginning in order to provide a guideline and transparency to the project team, saying what task should be concentrated on in which order, depending on the system deliverables.

Instead of equally distributed sessions with a similar number of days, the CE-applicable tasks and topics could be grouped which might lead to a full week study including three topics (e.g. project schedule, test schedule, test requirements definition), probably with two iteration cycles and off-line work in between. One or two months later, a cost & risk session takes place for one day, cross-checking the differences between earlier assumptions and current hardware expenses, as well as test results and failures for further risk assessment. In between, both the facility and team should keep margins for design re-iterations, especially after test and integration activities. However, these examples are a set of thoughts and need to be put in the right order with a team matrix (i.e. who is doing what at which time).

Tools

In order to support the more detailed design steps, a set of commercial tools is required. This is the case with and without CE. If parts of the activities have to be performed co-located in the CEF (or another Design Facility) there has to be access to the data, files and also the tool licenses. Furthermore the software should be installed also on the available work stations since these are connected to the common server and media management system.

Having all project data stored on an e.g. subversion (SVN) server, the domain engineers should continue working with it also from the design facility which has to provide access in order to avoid duplication of the files. Software which is needed amongst others are simulation tools (like Matlab/Simulink), Finite Element Method (FEM) software like Patran/Nastran, thermal analyses- (e.g. ESATAN, Thermal Desktop) and CAD tools like CATIA, Autodesk Inventor or UniGraphics as well as management supporting tools for requirement management, project scheduling and knowledge management.

As a central element, the data model should be as such that the team is able to use it already before the preliminary design phase as well as afterwards in order to avoid “workarounds” and an increased parameter management effort as for the DLR CubeSat studies (see “Phase B studies” section above).

The central data model could also be enhanced with a feature to compare simulation (or calculated) data with hardware test results. This would furthermore improve the identification of uncertainties in the modelling phases for future applications. Additionally, it could be connected to the configuration item list, stating amongst others the different hardware models and their replacement according to the defined model philosophy.

OPEN ISSUES AND QUESTIONS

Basically, all the proposals made in the previous section are basis for discussion at this stage. At least, the timeline of the Phase B activities have to be analysed in detail in order to provide more mature proposals of effective CE in the preliminary design phase.

Some additional open questions to be answered are:

- How to motivate the program and project management in order to increase awareness of implementing certain CE elements already in the initial Phase (0) such as data models for sustainable parameter evolution?
- How to create scalability for such models and tools to make them applicable for several project phases?
- How to deal with confidential data and the involvement of contractors?
- How to react on re-design activities in the usually time-critical project schedules?
- What is the ratio of off-line work to plenary sessions within a session/study phase and amongst them?
- Can the potential improvement of CE in Phase B (and beyond) somehow be quantified?

CONCLUSIONS

The customer satisfaction and positive results of the Concurrent Engineering studies performed so far in the CEF of the Institute of Space Systems, internally as well as with other entities motivates the DLR CE team to proceed with the further development of CE strategies for Phase B.

This shall be achieved not only in a “learning by doing” manner but preferably in a more structured way: identifying the needs of the space system design processes, potential applications and modifications of the current CE methodologies (or certain process elements) having in mind the entire development cycle of a space system.

This paper shall provide a baseline for discussion providing examples for potential areas of CE application, important aspects to be considered during the research as well as the identification of challenges and uncertainties. In the development process of complex systems such as a spacecraft, a lot of people and technical support elements are involved and have to be equipped with clear roles, tasks and an outline of the project course.

OUTLOCK

The DLR Institute of Space Systems, primarily the CEF operating department at this stage, plan to link the CE activities to projects which enter higher phases in the near-term future. The Institute members are generally aware of the efficient approach and the probability of concerns due to the consideration of CE as an additional effort is low.

Furthermore we will continue with supporting the internal as well as international data model and software development in dedicated research activities, in particular for the distributed use of the model, features like CAD preparation, sensitivity analyses, parameter standardization and general design step organization.

It is of high interest to exchange ideas, experiences and lessons learnt regarding programmatic, technical and personal/personnel challenges amongst the international CE community in order to proceed with the analyses regarding the use of CE in higher project phases.

ABBREVIATIONS

AR	Acceptance Review
CAD	Computer Aided Design
CDR	Critical Design Review
EOLR	End of Life Review
FQR	Fight Qualification Review
FRR	Flight Readiness Review
IBM	Company: International Business Machine Corporation
LRR	Launch Readiness Review
ORR	Operational Readiness Review
PDR	Preliminary Design Review
PRR	Preliminary Requirements Review
QR	Qualification Review
SRR	System Requirements Review

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