IAC-15-D1.3.5x30104

BE AWARE OF THE SQUAD: LESSONS LEARNT FROM 50 CONCURRENT ENGINEERING STUDIES FOR SPACE SYSTEMS

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Early design studies, especially for advanced projects, are often considered as not-so-relevant and far from reality since the outcome is usually and “solely” a set of documents covering the overall system trades, presentations describing the related design evolution, Excel sheets providing the major system budgets and a set of 3D-drawings showing the preliminary configuration and accommodation of the spacecraft. Compared to critical procurement, integrating and testing activities, the pre-development phases – although doubtlessly very interesting for everyone - are not always sufficiently prestigious in the engineering world. However, in the last years there is an increasing effort noticeable in putting more effort into structuring and improving space development projects right from the beginning by applying various systems engineering methodologies. These include also Concurrent Engineering (CE), a collaborative, iterative and communicative approach in which all relevant disciplines including the customer, work simultaneously together in a guided and typically co-located manner. The principal engineering tasks within such an activity are clear, but the additional component of constant and intensive interaction amongst the domain representatives could create e.g. misunderstandings, irritations, displeasures and eventually a suboptimal design solution. Although the advantages of such CE studies, such as quality increase, time and cost decrease as well as mutual education of team members, far outweigh the risk carried by the elevated social component, one has to carefully be aware of the squad to guide the project in the right direction, particularly in such an early stage. As of today, the Institute of Space Systems of the German Aerospace Center (DLR) has performed about 50 CE studies, mainly lasting one to three weeks, with many different internal and external teams for exploration and satellite missions as well as launch vehicle design. During these activities, the authors have identified several basic rules for successful studies, mainly related to reducing formality, providing transparency, facilitating honesty and engaging well-balanced data sharing. The present paper describes our lessons learnt, focusing on the various communication means which are necessary within a comprehensive group of engineers and scientists, and points out the potentials and dangers when treating team members in front of others during plenary workshop sessions or before and afterwards. It summarises a set of Dos and Don’ts which should be taken into account when conducting such interdisciplinary and often multi-cultural events, in order to seriously improve the envisaged design and moreover, to elaborate on the reputation of early system studies.

I. INTRODUCTION

The present paper aims to be twofold. On the one hand it shall elaborate on the reputation and importance of system studies in general by introducing an efficient approach to provide high-quality results during early mission formulation and feasibility analyses.

On the other hand it shall debate a collection of lessons learnt the authors made while applying this efficient approach, i.e. during Concurrent Engineering studies. The focus, however, is set on the second aspect, particularly on the challenges which arise when dealing with a multi-disciplinary and multi-cultural team which is supposed to work jointly on a system design with a large trade-space, in a very short time and during several intensive iterations.

At first, we present our motivation, followed by an introduction about the details of Concurrent Engineering (CE) and how it is applied at DLR. This provides the foundation for the discussion of the lessons learnt selection which is mainly derived from activities at the DLR premises but which can be considered as general recommendations in most instances.

The paper concludes with additional considerations related to the tasks and needs of different groups involved in CE-studies as well as with a brief outlook of how we intend to further improve our processes.

II. PROBLEM STATEMENT

During the early phases many aspects of a spacecraft development are unclear. In contrast to the automotive or aircraft industry, in space almost every system is different due to the varying needs and functions with comparably not much design heritage. This requires information and analyses from many different experts in order to assess the feasibility of a certain system or to estimate for instance its performance or cost.

That means that a proper statement about the characteristics of a new space system or mission requires interdependent expert judgements of various disciplines to eventually decide if a project could be established or not. Unfortunately, these analyses are often performed over a long period of time with only few resources allocated and limited availability of the experts who are usually involved in ‘real projects’ and have to find additional time to support such a mission formulation task. In the end, these constraints could lead to design inconsistencies, oversimplifications or a not well-balanced level of details amongst the domains.

One potential way to overcome this is applying the CE-methodology which is “*a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle*”, according to ESA’s preferred definition [1]. But managing the entire team all at once is not easy either, which is now discussed in our paper.

III. BACKGROUND

III.I Concurrent Engineering

In other words, CE is a well-defined systems engineering approach, replacing traditional, sequential design-flows by integrating multi-disciplinary teams to work collectively and in parallel, in the same place, with the objective of performing the design in the most efficient and consistent way as possible.

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 and the reason the process provides the outmost positive results. The major advantages of the CE-process are:

- Very high efficiencies regarding cost and project outcome activity in early design phases.
- Close-quarters collaboration facilitates direct communication and quick data exchange.
- Team members can easily track the design progress, which increases project understanding and identification.
- Ideas/issues are discussed in a group, which not only brings in new viewpoints and possible solutions, but also assists in the identification and avoidance of mistakes.

III.II The DLR Concurrent Engineering Facility (CEF)

The CEF is DLR’s systems analysis laboratory where the 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 the communication among different domains during the design process, through the intelligent use of modern tools and communication technologies. It is divided into three design rooms with up to 21 work stations and built-in media capabilities [2].

There is a “Main Design Room”, shown in Fig. 1, where the studies are conducted and in which the plenary sessions are held. It allows for about twelve domains to be actively included. Two additional side rooms are used for group discussions during non-moderated time, or to accommodate parallel working groups or study auditors.

As of today, almost every major space agency or industry has built up such an infrastructure which indicates the utility of such a tool and its processes.

Fig. 1: CEF at DLR during a moderated plenary session with the team leader in front and all domain experts collocated in a semi-circular seating arrangement in front of their works stations.

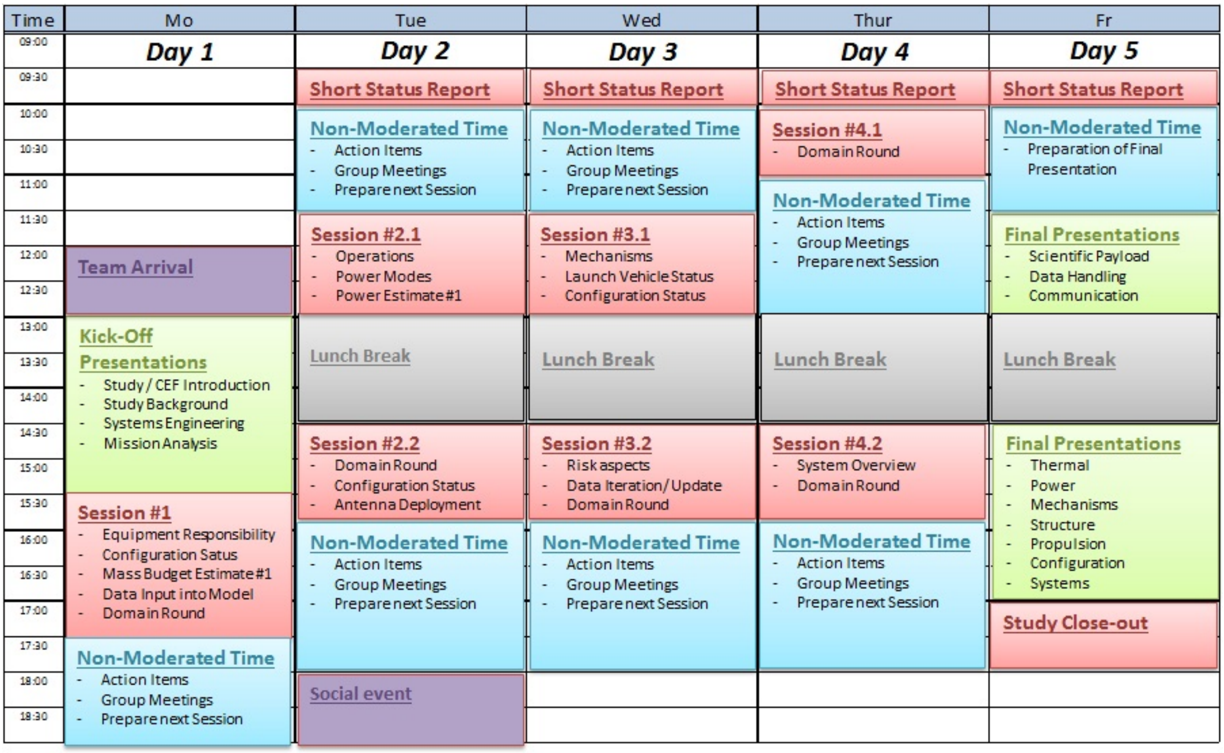

Fig. 2: Generic example schedule for a one-week study at the DLR CEF, including presentation sessions (indicated with green boxes), moderated sessions (red) and non-moderated time for individual or group tasks (blue).

III.III The DLR approach and our activities

From 2008 until 2015, more than 50 studies have been conducted in the CEF. The experiences have continuously matured the CE-process which has been adapted to integrate the system and domain expertise of DLR and its specific needs. Although mostly focused on satellite design, exploration missions and space transport systems, the CEF has furthermore enabled studies related to life support systems, space-based and terrestrial infrastructures. The experiences made throughout these variety of studies are the baseline for the here presented lessons learnt.

At DLR, CE-studies are typically conducted as intense one- or two week events, with five to ten design iterations and alternating moderated and non-moderated sessions. This is amongst others due to organisational aspects such as the limited availability of the domain representatives on site. This compact schedule has of course advantages and disadvantages compared to a more stretched approach, as it is applied for example at the ESA Concurrent Design Facility, which is described in more detail in [3].

Figure 2 shows an example schedule which is the baseline for the daily planning of the CE-study. This information is relevant for the customer as well as for the team members which are not always member of the actual project but act rather as consultants for an agreed period of time.

The customer, who is the motivating force behind the study, could be either a DLR internal or external member [4].

Any team constellation with respect to (domain) expertise, nationality, company, age and also Concurrent Engineering experience is possible. This is amongst others what makes the following considerations so important.

IV. LESSONS LEARNT

This section lists and discusses ten out of many observations we made and lessons learnt (LL) we gained in the course of the last 7 years in the DLR CEF. The order is primarily (but not exclusively) connected to the sequence of activities before and during our CE-studies and addresses mainly the social and inter-personal aspects.

While some of the points may appear very obvious, and some recommendations hopefully not that much, we have experienced that often the most logical and normal things related to team management and behaviour are the most neglected ones.

The aim of this paper is – as introduced above – to increase awareness about exactly these fundamentals which are relevant to facilitate team work in the early development phases, applying (in our case) the Concurrent Engineering methodology.

IV.I Inform, clarify and prepare (LL#1)

Many people do not clearly understand what CE is all about. How could they?

It is a modern term for a formalized "all people in one room at the same time" working approach and uses data models and tools to improve the collaborative efforts. Especially the utilization of special software (such as the central data model) leaves the impression that high-performance simulations or automated analyses are running somewhere in the background of a study or that only a few clicks lead to a sophisticated e.g. satellite design [5].

Especially the (external) customer, who is the actual project manager in many cases, seeking for consolidated design supported by using a consistency-increasing "single-source-of-truth" data base and moderated working sessions, overestimate the outcome which could be achieved after one week of intensive design work, and how they could use the data during and after the study. During the initiation phase of each CE-study it should be carefully discussed what the "service" provided in the CEF could deliver and what not.

New domain experts who work for the very first time in such an environment are often uncertain what to prepare and how to do it. Besides the fact that some of them consider such an approach as overhead (since they forget that they work in the CE-study instead of their office work and not on top of that, and actually save time), they need to know what they need to prepare for the workshop and what is later done during this event. Usually it helps to provide an introduction presentation a few weeks before and to summarize very briefly a definition of study scope which is iterated with the customer and the systems team. This increases transparency, and people have the opportunity to understand what is expected and what might be their remaining questions.

Another particular aspect of proper preparation is the organisation of presentations provided during the K/O-session and throughout the study by the team members. Usually they prepare them on their own computer with different software and deliver it in a different format (e.g. MS PowerPoint or PDF). Since the CEF represents a modern, professional infrastructure almost no one considers that their material provided could not be presented or used. But complex soft and hardware infrastructures are fragile, and adapted to a common standard, too. If someone hands over a presentation file prepared with e.g. MS Office 2013 and the work stations are equipped with the 2010 version, it might not work, especially when the hand over is done 10 seconds before the actual talk. This aspect is often underestimated. The team leader should request each file to be shared in the moderated sessions with sufficient time margin before each session for testing and back-up solution identification.

IV.II Establish rules and ethics (LL#2)

The team, composed differently almost every time, will spend at least one full week in (mainly) one room. The environment might be new for someone, but the daily working routines are clearly different amongst all study participants.

Although most of them are common sense, we experienced the need to briefly introduce some kind of house rules as part of the study and facility introduction during the K/O-presentation. Besides the rather technical explanations (e.g. how to use the work stations) they should provide the boundaries of the expected behaviour and shall also motivate to be proactively involved in the project.

The most important rules (some are here presented as discrete lessons learnt) which are frequently presented to a new team, are listed in the following:

- Be in time: if one person is late he/she will let 20 others wait, or increase the risk of varying assumptions within the team if the latest status presentation had been missed.
- If you leave the facility, tell the team leader how long or whom to contact. It is understood that people have different obligations, in business as well as personally, but at least announcing unavailability and looking for a replacement is mandatory.
- During the moderated sessions, every domain has to be present and pay attention. Intensive side discussions shall be held in the dedicated non-moderated times.
- If you do not understand something, please ask at any time. Achieving a common view on the design and its status is why we are here.
- Do not take things personally. Due to stress or increased identification with the own subsystem/discipline, discussions could become hot tempered. To avoid misunderstandings and personal conflicts, a positive debate culture should be established right from the beginning.

IV.III Define responsibilities (LL#3)

Before the first design session starts, the first group task in DLR's CE-studies is to clarify responsibilities of particular equipment and parameters which could be part of various domains. Each team is different; often the experts are from different institutions or at least from different departments. Although there is standards which define or recommend what is done in which domain, there is also varying best practices amongst the companies, agencies or cultures. Typical examples are the solar panels which could be estimated by the structure or power domain, the reaction control engines which is somewhere in-between the GNC and propulsion domain, or the tanks which could be taken care of by the structure or propulsion expert.

Additionally, tools and models are used, such as the central data model which allows e.g. elaborating on the product tree, and these tools might apply different ways of presenting budgets or handling parameters. Thus, there should be a consensus on who is investigating on what and/or who is presenting which results, to avoid gaps (for example forgotten equipment) or overlaps in the design, such as double-counted harness or the solar array supporting structure.

This does not only facilitates a more smooth design process but also makes clear that this feasibility or preliminary design study is taken very serious and that the results shall be as transparent and traceable as much as possible, especially for a the subsequent project team which potentially takes over during a later stage of the development.

IV.VI Responsibility vs. accountability (LL#4)

Not only the responsibility, or the "who does what" needs to be defined, but also an atmosphere created in which the experts feel responsible for their work in general. We have observed that the team members, especially when they experience (time) pressure, they feel accountable for their work instead of responsible.

It is difficult to estimate values while knowing that they are (still) wrong. Especially when you have to type it into new and unfamiliar software tool, model or data base which everybody can access.

It has to be clear, that the single engineer has to do his/her job, but also that there is trust amongst each other which helps to proactively work on the design, make first estimates while knowing that they are not perfect at an early stage, and that this is done based on a responsibility and not on accountability.

The latter comes with the risk that the participants hesitate to guess, that they do not provide starting points since they could fear that they say something wrong. This is bad, since CE is all about working in parallel as much as possible and there has to be a starting point for almost every subsystem and thus these first guesses are of high importance.

The team has to understand that, although the experts are responsible for their output, they will not be criticized for work which is clearly in progress.

IV.V Value each other's time (LL#5)

This should not be a lessons learnt but a natural attitude. Unfortunately this is not always the case. However, we would like to provide some examples of how the interaction amongst the team could be improved with respect to that matter:

- As mentioned in the house rules, all participants should arrive in time for the plenary sessions.
- The organizers have to make clear that there is dedicated time for group discussions in order to reduce disruptions during plenary sessions.
- The customer and/or team leader should express sincere thanks to everyone for attending, as one of the first aspects to mention.
- The team members have to understand that they cannot demand immediate support or input from others in order to improve their own iterations.
- Thus, the study core team has to monitor how the members approach each other during their individual working time and set up dedicated splinter-meetings if necessary (and moderate them, too).
- When a presentation slot is set to e.g. 10 min, the presenting domain has to understand that 35 slides are just too much and that they have to be brief in their status reports or concluding talks. Here again, the team leader is responsible to keep an eye on the agenda and a well-shared presentation time in a particular session. He/she has to anticipate how much time the presenter (still) needs, what might be important for the team and hot to cut it short, preferably by using non-verbal communication, e.g. by standing up or using kind but clear hand gestures.

IV.VI Value (on-site) availability (LL#6)

Concurrent Engineering activities should preferably be done in a close-quarter fashion. But this is not always possible.

Fortunately, modern communication technologies, such as videoconference or WebEx-similar systems allow for remotely connected subject matter experts, consultants or customers.

Besides the required preparation and organization of such tools, i.e. testing the connection or exchanging the right conference numbers, these external influences have to be handled with care. The majority of the team is usually in the same room. However, there will be sessions in which external participants need to listen or need to be heard.

In order to avoid misunderstandings, the focus of such external connection has to be defined in advance. Even if the remotely connected person(s) is/are part of the management board, the customer team or if they are voluntary consultants, the people who made the most efforts in terms of travelling and arranging schedules, are the ones in that room where the study takes place.

We have experienced several times that the presence of someone on the phone or screen takes away a lot of attention from the on-site personnel [6], either due to the perceived need of honouring the external's (maybe spontaneous) attendance or due to his/her position.

Again, it is the team leader's task to organize the tele/videoconference as such, that the team members are not slowed down and do not need to put their work on hold due to for instance excessively polite or detailed discussions with the remotely connected.

IV.VII Value effort (LL#7)

In the beginning of the study, the participants have to have the same understanding of the mission and the related problems, requirements and project status. This shall be ensured by an initial Kick-off (K/O) presentation session (see also first green box in Fig. 2), in which usually the customer perspective incl. mission objectives, the particular study objectives (i.e. the event task list) as well as the current status regarding the system (e.g. requirements and mass budget) and mission analysis (e.g. trajectories, orbital positioning) is presented. This session, for which some key team members prepared themselves in order to present the essentials of the mission to the team, shall be treated similarly to a conference session. Even if everything is clear from what the person has presented, at least the team leader has to address at least one question to the presenter about something which is supposedly very important for the study (i.e. to emphasize this aspect again) or to pick up an issue which might be misleading and could create misinterpretations during the upcoming sessions. This does not only introduces the communicative and interactive character of such a CE-study from the very beginning, but also values the effort the team member has made prior to the event and in the K/O-session.

The same is true for any other intermediate presentation, since there has to be a continuously interactive spirit which shall help the experts to involve themselves to the highest possible degree.

Moreover, it is important that the core team of a CE-study, for instance the team leader or systems engineer, feels responsible to ask the 'silly questions' right from the start, which shall reduce the hesitation of each team member to do the same in order to seek clarification regarding the technical problems.

IV.VIII Value needs (LL#8)

For the project leader or team leader it has to be clear that they have invited various co-workers to do their work in a different environment. Thus, the environment itself, i.e. the CEF in this case, should be attractive to the team members so that they overcome the barrier of working in a different, likely more noisy office compared to the one they are used to on a daily basis. The facility shall serve the basic needs, such as:

- a place for breaks (and actually sufficient time to have some),
- sufficient space to leave/use their working material such as laptops, literature and personal belongings,
- simple tools to express themselves and which help to speak the same language, such as white boards, pens and paper, which are often favoured over fancy things such as smart boards or e.g. mind mapping software,
- access to printers, (wireless) LAN connection,
- and, of course, free coffee (seriously!).

IV.IX Understand information assimilation (LL#9)

During CE-studies there is a lot to discuss. Not everybody needs to know everything, but everybody is in principle exposed to a way broader set of information as usual, which on the one hand is an advantage since it increases mutual understanding and education, but on the other hand requires certain information filtering on the individual basis.

For the most relevant information, there is two key observations the authors made:

The essential information has to be repeated at least three times, because somebody is always not listening or there is too much information to be processed on the "receiving side". The most prominent examples are the announcement of session starting times, the need of having the technical data inserted in the data model or the information where certain templates are and when e.g. the final presentation slides are expected to be delivered, respectively finished.

On the contrary, not all information shall be presented at once. Whereas at DLR, we originally included the data model tutorial in the K/O-session, we shifted it after a while into the first working session and present only the basic functions the team needs to use and only mention that there is more capabilities we could explain on demand. The entire team has to understand that just because someone said or wrote anything, this does not necessarily stick or cannot be considered by the other(s) instantly (or even forever).

Additionally, for presentations there should be no acronyms. Even if there are standards for technical parameters and terminology, in order to surely understand and compare the information, the cryptic abbreviations should be removed from the slides. EPS for example could be interpreted as electrical power system or electrical propulsion system, DST might be a domain specific tool or a disruptive space technology, and MA refers to mission analysis but is (in Germany) also an often used acronym for co-worker (Mitarbeiter).

Within the presentations, especially the initial and final ones, one need to present the assumptions made in addition to the requirements considered. Only if these are comprehensible, as obvious as they might appear, the design decisions can be understood by the other domains during and especially a few weeks after the study

The team leader has to illustrate to the participants every now and then the relevance of dirty notes which could be quickly presented during each session, instead of a super-sophisticated presentation which needs to be prepared until the very last moment (in which it is usually too late for the rest to compare e.g. the assumptions).

IV.X Monitor work load (LL#10)

Performing the work in e.g. one week (full-time) which could have been done in the course of several months (with only a low percentage of time) is efficient, but also ambitious. Since it is not so easy to deal with other projects in CE-studies (which is also contradictory to the idea, at least considering the DLR approach), the differences in terms of work load amongst the domains are very apparent.

Whereas some engineers have to provide a lot of information in the beginning (such as the mission analyst or the payload responsible), others remain in a waiting position until there is enough data available to work with (for example fore the thermal design or antenna layout). Especially the configuration engineer is becoming busier throughout the days, which is due to the increasing confidence of the subsystem experts about their component characteristics such as dimensions, orientations or connection points. One of the first lessons learnt we took over from ESA was the split of structural analyses and the (3-dimensional) computer-aided design. Moreover, there were cases during our studies in which we had to install even a second configuration engineer who solely generates part-files based on sketches from the various experts and that the main designer was responsible for the accommodation within the assembly-file.

In any case, the "low work load phases" should be used to set up models, look for references, to prepare slides for later presentations or to just help each other out. If there has been a constant imbalance of work observed, the team leader and the relevant domain engineers might need to think about re-allocation of the resources.

Concurrent Engineering – with a team preferably located in one dedicated room – offers great potential to collaborate. But it has to be identified, agreed upon and shared wisely.

V. ADDITIONAL CONSIDERATIONS

Concurrent Engineering, properly applied, has many additional beneficial aspects compared to the more classical approaches.

But as described in the not all-encompassing list of lessons learnt above, there has to be some rules and conditions and a certain awareness in order to deal with a big and multi-disciplinary, often inter-cultural team in one room for a considerable amount of time.

It is no question that CE-studies require a team leader who moderates and guides the team towards the agreed and expected study results. Especially from the social point of view it is his/her responsibility:

- to be aware of the agenda and to show control, which provides confidence and trust, and the people can go ahead with their work and do not feel inclined to "shadow-lead the show",
- to define what is part of the study, and what not, i.e. to elaborate on, present and monitor the actual study objectives, which are typically a sub-set of the overall project objectives,
- to distribute the tasks and trigger the work, as well as to note down open issues, organize splinter meetings and, in the end, ask for results,
- and to manage the "alpha-animals" and the shy ones in order to provide everyone with the equal opportunity to speak.

Furthermore, the team leader should be the only one who repeatedly paraphrases what has been said and this solely to create and ensure a common understanding amongst the team members. Especially for him/her it is unfortunately relatively easy to upset participants, either by being too pushy, unorganized, nit-picking or by violating privacy rules, such as sharing someone's personal screen to the presentation wall (via the CEF media management system), without asking.

Once introduced to the work ethics during the CE-study, the various domain experts on the other hand should be aware of their own time-management as well, and that they shall contribute proactively to the system design, share their data with others (who need this as an input) and document their trades, decisions, rationales and results. They have to find the balance of how long they can be involved in splinter-discussions and what amount of time they need to spend alone, in silence, reading, researching or simulating something for the next design iteration.

On top of that, they have to leave their comfort zone and tell the team leader or systems engineer if they figure out, that they most likely cannot complete their task. This is important and the basis for either re-organizing the upcoming session or distribute the work differently, as already pointed out within LL#10.

VI. SUMMARY AND CONCLUSION

The here discussed paper presented ten major lessons learnt the authors from the DLR CEF leading team have identified, plus a few general observations and considerations which appear to be useful for successful CE-studies.

In summary, it can be said that the with valuing effort, time and availability, ensuring transparency and proper information flow, and considering the needs, responsibilities and the work share of all team members, one provides a promising basis for a positive outcome of such compact design exercises. Additionally, when some team members present excellent work, the remaining feel encouraged to do the same.

The here presented results and discussions will be used to continuously educate ourselves and to stress the fact that routine is sometimes dangerous.

Although only one team leader might be needed, at DLR we try to implement two for each study, in order to take over in case of sickness or other sudden unavailability, to support taking notes and organizing splinter-meetings as well as to comment on each other's team management and to share their observations and opinions right away.

This paper can be considered as an extension of [6] and [7], in which the critical interaction instances, as well as the dark sides of Concurrent Engineering are discussed, particularly what could go wrong and what is going wrong and how the people did/do deal with it.

The authors hope that the here presented lessons learnt will help newly established CE-facilities as well as engineers which enter the business of Concurrent Engineering to make use of these recommendations as a starting point when they are confronted with dealing with the human factors of such an intensive, serious but very promising approach as Concurrent Engineering.

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