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The ESA/ESTEC Concurrent Design Facility

M. Bandecchi, B. Melton, B. Gardini
ESA/ESTEC, Keplerlaan 1
NL-2200 AG Noordwijk

F. Ongaro
ESA/Head Office, 8-10 rue Mario Nikis
F-75738 Paris Cedex 15

Abstract. The European Space Agency (ESA) performs pre-Phase-A assessment studies as part of the definition of future space missions. To evaluate the benefits of the Concurrent Engineering (CE) approach to these studies an experimental design facility was created in the ESA Research and Technology Centre (ESTEC) at the end of 1998 and used to perform the assessment of several missions. This article describes the adopted approach, the experience gained during the studies performed and highlights the benefits of the application of the concurrent engineering approach to space mission assessment and design.

INTRODUCTION

Within the framework of its General Studies Programme (GSP), the European Space Agency (ESA) performs each year a number of pre-Phase-A/Level 0 assessment studies. The purpose of these studies is to assess the feasibility of a new space mission from the technical, programmatic and economic points of view. This is normally achieved by producing a preliminary conceptual design of the mission and space system. The study results are used to support the mission selection process. If the mission is accepted the study report is used as an input to the industrial Phase-A design studies.

Pre-Phase-A studies are normally performed in-house at the ESA Research and Technology Centre (ESTEC), by technical-support specialists. In a classical approach, each specialist prepares a subsystem design relatively independently from the others, using stand-alone tools. Design iterations at system level take then place in meetings at intervals of a few weeks. This method has obvious advantages, such as the flexibility in the use of manpower resources and the fact that it is a well-tried and routine process. On the other hand, it has drawbacks in that it favours a certain 'segregation' in the subsystem preliminary design, reducing the opportunity to find interdisciplinary solutions and to create system awareness in the specialists. Furthermore, in such a "decentralised" approach, all the study data, acquisition and models are dispersed among the specialists. It is then very difficult, if not impossible, to re-assemble all of this knowledge, for instance to resume the study with modified requirements after some time. Last but not least, the time required for performing studies using the classical approach (6-9 months) may be incompatible with today's drive towards a shorter time-span from concept to flight (e.g. the "SMART" and "Flexi" missions of the ESA Science Programme).

An alternative to the classical approach is offered by Concurrent Engineering (CE), which provides a more performant design method by taking full advantage of modern Information Technology (IT). The enabling factor for the CE approach has been the evolution of IT. Co-location of experts from various disciplines to elucidate a preliminary design concept is not a novelty in itself. However, in the past the process and personal interactions were limited to very basic brainstorming sessions, because any numerical analysis required the use of tools which could not easily be co-located, nor interconnected nor could provide results in real time. Nowadays, with perhaps few exceptions, most of the analysis needed for a pre-Phase-A study can be performed in real time on a personal computer (PC) or on a lap-top.

There are many definitions of the meaning of "Concurrent Engineering". The following one best explains the thinking behind the approach described in this paper:

"*Concurrent Engineering is a systematic approach to integrated product development that emphasises the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle*."

The concept is not new. It was introduced in the Aeronautic industry and it is already practised in many industrial sectors throughout the product development cycle. There are also examples in the space domain, such as the well-known NASA/JPL Project Design Center (PDC), used for conceptual mission design. In the European space industry an example is provided by the Satellite Design Office (SDO) at DASA/Astrium, with the cooperation of the SE group at the Technical University of Munich. In ESA, the method had been studied and already applied in previous mission assessment studies but not with the aim of creating a re-usable infrastructure.

THE APPROACH

Prior to adopting this method and building a permanent infrastructure for its application, ESA felt the need for a demonstration. An experimental facility was then set-up at the end of 1998 with the objectives to:

- create an experimental mission design environment (hereafter referred to as Concurrent Design Facility, or CDF) in which the conceptual design of space missions could be performed in a more effective way
- apply the practice of CE to a number of test cases to identify the potential of such an approach in the various phases of space-mission development
- gather the information needed to evaluate the resources required to create a permanent facility available to all programmes.

Due to the experimental nature of the exercise, it was decided to build up the facility using existing equipment and tools. Available computers (mostly PC's) were used to host the basic software, mainly consisting of office-automation products and domain specific engineering tools, already employed for space-mission assessment studies. Other more sophisticated tools required the use of dedicated workstations. Initially the effort was concentrated on the set-up and integration of the tools and equipment.

In parallel to the implementation of the infrastructure a case study was selected and initiated in the facility to prove the approach and measure its performances on a real mission. The reference mission provided the requirements for the implementation of the first prototype of the CDF integrated design model.

The specialists were trained "on-the-job" to understand and use the new method and to work as a Team: they actually defined and contributed to the implementation of the design environment.

The outcome of the exercise confirmed the suitability and the value of the method which achieved quality results in a much shorter time. The whole exercise, including the set-up of the infrastructure lasted three months, while the case study mission design was completed in ten half-day sessions distributed over a six week period. The result was encouraging and soon after more studies were planned for implementation.

The key elements on which the CDF implementation has been based are:

- a process
- a multidisciplinary team
- an integrated design model
- a facility, and
- an infrastructure.

These elements are described in order below.

THE PROCESS

The conceptual model of the design process is shown in Figure 1, which highlights the fact that a space system has many interdependencies between

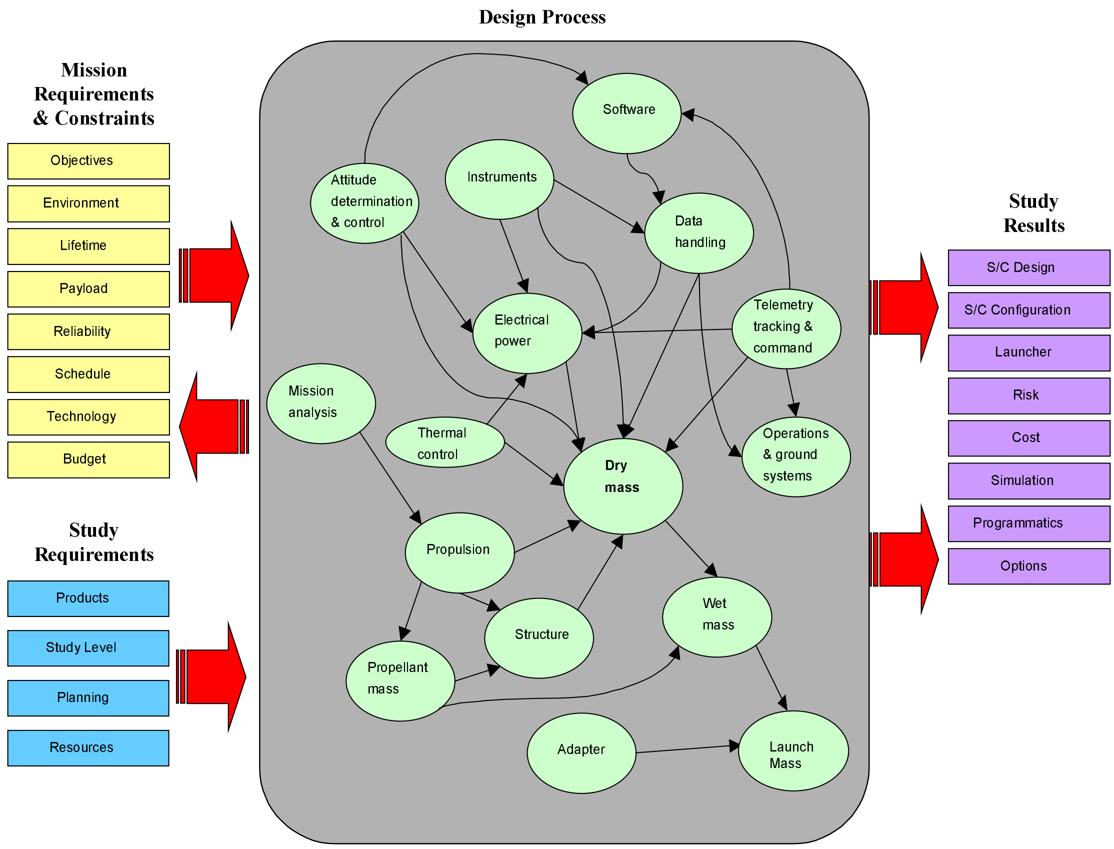

Figure 1 - Conceptual model of the mission and spacecraft design process

components. This implies that the definition and evolution of each component has an impact on other components and that any change will propagate through the system. Early assessment of the impact of changes is essential to ensure that the design process converges on an optimised solution. The CE approach is intended to improve the means of achieving this early review and verification, step by step.

The process starts with a preparation phase in which some representatives of the engineering team (team leader, system engineer, selected specialists) and of the Customer meet to refine and formalise the mission requirements, to define the constraints, to identify design drivers, and to estimate the resources needed to achieve the study objectives.

Then the study kick-off takes place and the design process starts. It is conducted in a number of sessions in which all specialists must participate. This is an iterative process that addresses all aspects of the system design in a quick and complete fashion.

The simultaneous participation of all the specialists reduces the risk of incorrect or conflicting design assumptions, because each major decision is debated and agreed collectively. In this way the design progresses in parallel and allows those disciplines that were traditionally involved at a later stage of the process the opportunity to participate from the beginning and to correct trends that might later invalidate the design.

The customer is invited to participate in all sessions along with other specialists of his/her choice (e.g. study scientist, project controller), so that they can contribute to the formulation of the study assumptions, answer questions from the team and follow the evolution of the design. This includes the possibility to discuss and correct in real-time any orientation of the design not in line with their expectations.

The first design session starts with the customer presenting the mission requirements and constraints to the team. In subsequent sessions, each specialist presents the proposed option or solutions for his/her domain, highlighting/discussing the implications for the other domains. Out of the debate a baseline is retained and the related values recorded in a shared database.

One key factor is the ability to conduct a process that is not dependent on the path followed. At any stage it must be possible to take advantage of alternative paths or use ‘professional estimates’ to ensure that the process is not blocked by lack of data or lack of decisions.

THE TEAM

Human resources are by far the most important and crucial element!

A group of engineering specialists working together in one room, using sophisticated tools, are all contributing factors but they are not sufficient by themselves to create a collaborative environment. On the contrary, it might become the place where conflicts are amplified. Above all else, the group of specialists must work as a team.

A fundamental part of the CE approach is to create a highly motivated multi-disciplinary team that performs the design work in real-time. The challenge, the novelty of the method, the collective approach, the co-operative environment, the intense and focused effort and a clear and short term goal are all essential elements that contribute to personal motivation.

To work effectively the team members had to accept to:

- use a new method of working
- co-operate
- perform design work and give answers in real-time
- contribute to the team spirit.

This is more difficult than it might first appear, because it puts more pressure on the engineers, who are required to:

- prepare the design of their subsystems using the facility’s computerised tools
- follow the main-stream presentation/discussion and to identify possible influences of other domains on their own domain
- be ready at all times to answer questions related to their domain
- adapt the model of their subsystem to changes in the mission baseline
- record design drivers, assumptions and notes, which will form the basis for the preparation of the final report.

Table 1 lists the technical disciplines typically selected for a mission assessment.

POSITION
Systems
Instruments
Mission analysis
Propulsion
Attitude and Orbit Control
Structures/Configuration
Mechanisms/Pyros
Thermal Control
Electrical Power
Command and Data Handling
Communications
Ground Systems and Operations
Simulation
Cost Analysis
Risk Assessment
Programmatics

Table 1 - The technical disciplines in the ESA/ESTEC CDF

For each discipline a 'position' is created within the facility and assigned to an expert in that particular technical domain. Each position is equipped with the necessary tools for design modelling, calculations and data exchange (as described below).

The choice of disciplines involved depends on the level of detail required and on the specialisation of the available expertise. On the other hand, the number of disciplines has to be limited, especially in the first experimental study, to avoid extended debate and to allow a fast turn-around of design iterations.

THE MODEL

The design process is 'model-driven' using information derived from the collection and integration of the tools used by each specialist for his/her domain.

Why a model? A parametric-model-based approach allows generic models of various mission/ technological scenarios to be characterised for the study being performed. A parametric approach supports fast modification and analysis of new scenarios, which is essential for the real-time process. It acts as a means to establish and fix the ground rules of the design and to formalise the responsibility boundaries of each domain. Once a specific model is established it is used to refine the design and to introduce further levels of detail.

A first activity in the modelling process is to acquire or establish the model suited to the mission scenario before it can be parameterised to perform the iterative design process. Each model consists of an input, output, calculation and results area. The input and output areas are used to exchange parameters with the rest of the system (i.e. other internal and external tools and models). The calculation area contains equations and specification data for different technologies in order to perform the actual modelling process. The results area contains a summary of the numeric results of the specific design to be used for presentation during the design process and as part of the report at the end of the study.

Figure 2 shows the architecture of the model.

THE FACILITY

The team of specialists meets in the Concurrent Design Facility (CDF) to conduct design sessions. After about one year of successful activity and 10 studies performed in the initial experimental facility, a new and permanent facility has been built at ESTEC. The accommodation comprises a design room, as illustrated in Figure 3, plus a meeting room and project-support office space.

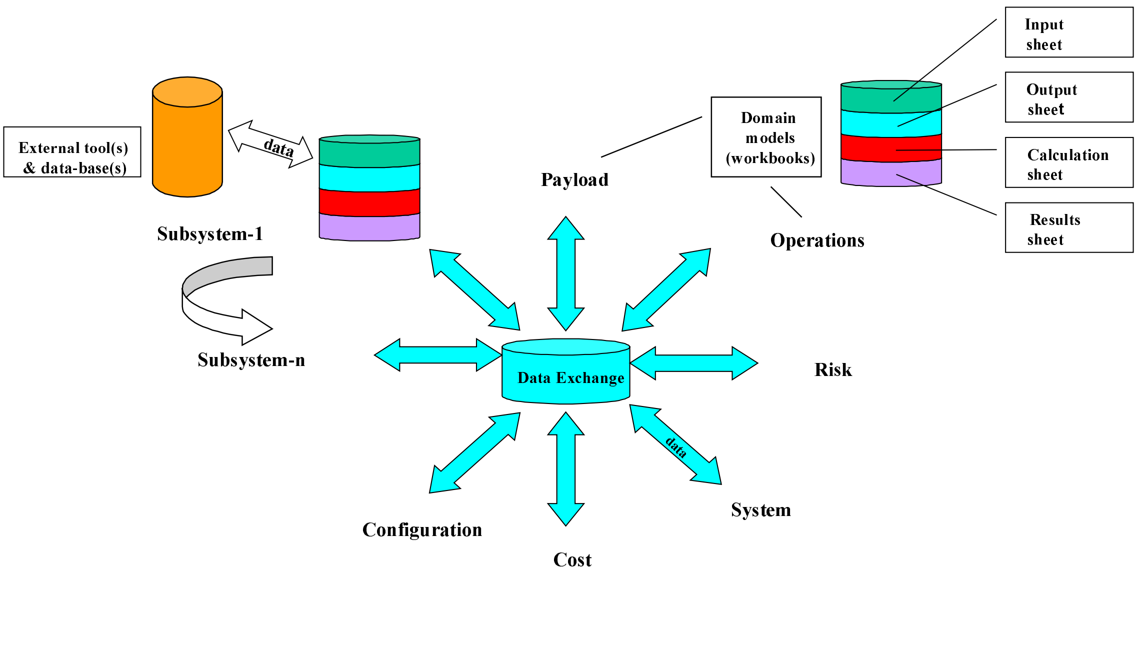

Figure 2 - Architecture of the software model

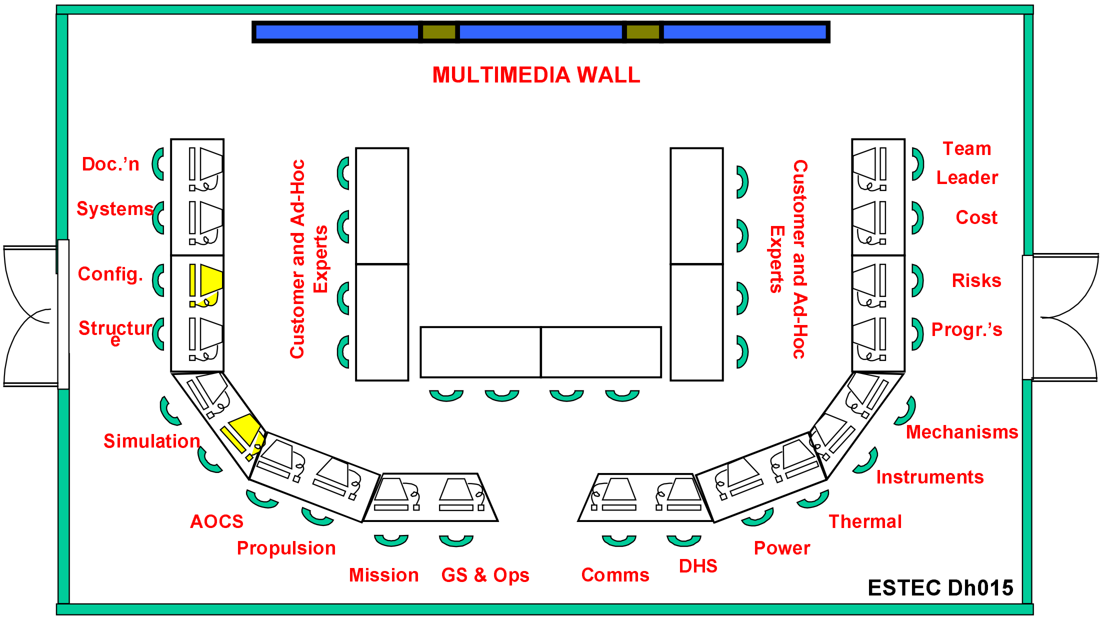

Figure 3 - The ESA/ESTEC Concurrent Design Facility Layout

The equipment location and the layout of the CDF are designed to facilitate the design process, the interaction, the co-operation and the involvement of the specialists. In particular, the disciplines with the most frequent interaction or other affinities (e.g. data/model sharing) are located close to each other. The central table is dedicated to the customer, support specialists and consultants.

The facility is equipped with computer workstations each dedicated to a technical discipline. The majority of the workstations are identical, powerful PC's. The CAD and Simulation positions are housed in dedicated workstations. To the front, a Multimedia wall supporting two large projector screens and a 'Smart Board®' has been installed. Each screen can show the display of each workstation, so that the specialists can present and compare design options or proposals and highlight any implications imposed on, or by, other domains. Video-conferencing equipment is installed in the facility to allow team membersand/or other specialists to participate in sessions from remote sites.

THE SOFTWARE INFRASTRUCTURE

An infrastructure to implement the Concurrent Design Facility outlined above requires:

- tools for the generation of the model
- integration of the domain models with a means to propagate data between models in real time
- a means to incorporate domain-specific tools for modelling and/or complex calculations
- a documentation-support system
- a storage and archive capability.

The infrastructure must allow its users to:

- work remotely from the Facility both within ESTEC and in other centres
- exchange information easily between the normal office working environment and the Facility environment.

In creating such an infrastructure to support the concurrent design process a number of important issues had to be considered. The solution adopted was to base the infrastructure on the products already available either within the office-automation domain or within the technical domain of the participating engineers. As a result, no additional licences were required for the major software products to be employed.

Table 2 identifies the general tools chosen as basic infrastructure items used by all team members, while Table 3 identifies the domain specific tools used by the domain experts.

Although driven by the constraints identified above, the choice of tools has, in fact, proven to be satisfactory when looking to the future. Using tools already part of the Agency's infrastructure brings many benefits.

For the system model, the choice of Microsoft Excel® spreadsheets was driven not only by its availability and the existing skills of the team, but by

Function	Tools used
Documentation storage & archive	LotusNotes data base
Electronic communication within the team	LotusNotes mail
Storage area for all data files	NT file server
System modelling	Excel spreadsheets
Project documentation	MS-Word
Remote audio/visual communication	Video conferencing & Net meeting

Table 2 - General Tools

Domain	Tools used
Structural Design, Configuration & Accommodation	CATIA
Attitude & Orbit Control	Matrix X
Mission Analysis	IMAT
Mission Simulation & Visualisation	EUROSIM
Programmatics	MS-Project
Cost Modelling and Estimation	ECOM Cost/Technical Database & Small Satellite Cost Model

Table 3 - Domain-specific Tools

the fact that earlier work had alread been performed under an ESA contract* in 1996. A fundamental decision was taken to split the system model into components that mirror the domains of expertise of the team members, allowing work to be performed on the modelling independently and in parallel and without the reliance on a single modelling expert. The distribution of the model required a mechanism to exchange relevant data between domains in a controlled manner. This was solved by preparing a shared workbook to integrate the data to be exchanged, with macros to handle the propagation of new data in a controlled way.

A significant output of any pre-Phase-A study is the study report. The use of Microsoft Word® allowed each engineer to prepare their section of the report as a sub-document that was then incorporated in the master document, prepared in accordance with the ESA standard document template.

The use of LotusNotes® as the mail and document repository tool gave ESA-wide access to the project information, providing (subject to access control) a facility to browse, access or contribute to the study documentation.

The domain-specific tools brought by each expert had to be integrated into the infrastructure of the facility. For the purpose of the initial study, data exchanges between the tools and the Excel model were kept to a minimum, to avoid cost and the delay incurred by software development. In cases where tools were also implemented as spreadsheets, the interfacing was simple and even automated. In other cases, and in particular for applications running on separate workstations, ad hoc interfacing had to be developed in order to allow the results of specific calculations to be transferred into the Excel model for further processing or propagation to other domains.

This aspect of the infrastructure is a candidate for improvement in the longer term and will enhance the concurrency of the design process. In some specific cases (e.g. the interface between domain specific tools) it was found more convenient not to use the centralised data exchange, but rather to create a direct interface between those applications. An example of such an interface is the transfer of geometrical 3-D data of the spacecraft-configuration to the simulation system, which uses geometric models for the spacecraft visualisation.

ACHIEVEMENTS

Since the start of the project, nine main missions have been assessed in the CDF, as listed in Table 4.

Name	Mission
CESAR	Ionospheric and Magnetospheric Mini-Satellite
Solar Orbiter	An Out-of-Ecliptic, near to Sun Observer
MISS	Meteorology using Imager & Sounder
WSO/UV	An Ultra-Violet Space Observatory
MeSE	Mercury Lander and Surface Element
Eddington	Stellar Physics and Planet Finder Explorer
MASTER	Mars Lander and Asteroid Fly-By
STORMS	3 Spacecraft Constellation for the Study of Magnetospheric Storms
HYPER	Hyper Precision Atom Interferometry in Space

Table 4 - Main missions studied in the CDF to date

As these missions cover a variety of space applications, they have given the opportunity to test the approach against different objectives, requirements and space system types and to enhance and extend the model.

* *Spacecraft Modelling: A Spacecraft Integrated Design Model* – System Requirements Document and User Manual, Matra Marconi Space (UK), December 1996.

The design phase of these studies was completed in an average period of five weeks, in which six to ten plenary design sessions were conducted in the CDF. The overall time to complete a study, including the preparation and the documentation/reporting phase, totalled a maximum of three months. In this time substantial technical and programmatic reports have been produced. Furthermore the design process, in particular for the scientific missions, generally included two or three major interactions between the engineering team and the science team. These meetings are held in the CDF and take full advantage of the concurrent approach and tools. This aids a better and mutual understanding of the technical issues at an earlier stage of the assessment studies. Different mission scenarios, trade-offs, and options can be prepared, presented, adapted and agreed quickly. This in turn results in a clear formulation of the essential design drivers and the major mission and payload requirements and system constraints.

Two teams of 20-25 discipline specialists each have been trained in the use of the CDF. Four complex scientific missions (i.e. the candidates for the next scientific "flexi" missions) were studied in a total period of three months by the two teams working independently and sharing the facility in order to perform the studies in parallel.

LESSONS LEARNED AND FUTURE OUTLOOK

As often happen, the adaptation of a process to take full advantage of a new method is not straightforward. For a time the process goes on as before, taking partial advantage of the new method, but suffering from resistance to change. Adopting a new method often needs a change in the mentality of the people involved, and only when these actors are convinced can the method itself be fully exploited.

The team members were drawn from specialists who had other technical responsibilities in addition to supporting the assessment studies. Acceptance was achieved by their involvement in a working environment that proved to be efficient in the use of their time and effective in application of IT support.

Furthermore, the use of the method may well result in the need for organisational changes external to the facility, in order to obtain maximum benefit.
Such organisational evolution is outside the scope of this paper.

The iterative approach to the mission design allows the depth of the final product to be controlled. It is possible to study a mission at very high level in a very short time, or to go to detailed design over a longer period. Furthermore, capturing the design in a model allows breaks in the programme of work for reflection, without the loss of information during the inactive period.

The assessment studies performed in the CDF have shown the benefits of centralising system-engineering tools as part of an integrated facility. In fact they have also identified further opportunities beyond the pre-Phase A studies where the concurrent engineering approach can be very beneficial by ensuring consistent engineering methods and standards and the efficient use of the manpower. Other potential applications for the CDF that are being considered are:

- Payload Instruments Conceptual Design. The same principles applied to the design of the overall space system could be effectively applied to the design of the instruments composing the on-board payload. This could be supported by a number of disciplines and tools already available in the CDF complemented by those supporting payload instruments analysis and design, e.g. optics, sensors.

- Definition of the System Requirements. Following in-house pre-assessment study, ESA procedures require an "Invitation To Tender" (ITT) to be issued to Industry. A key component of the ITT is the System Requirement Document (SRD) which defines the main technical requirements for the spacecraft and mission design. The CDF experience has shown that "reverse engineering" on the pre-assessment study results can ensure efficient, consistent and realistic requirements to be generated for the SRD compilation.

- Proposal Evaluation. Industrial proposal evaluation would be the next natural step for the usage of the CDF. In this case it might be necessary to complement the core team, by other project and management representatives.

- Project Design Reviews. The principles of concurrent engineering are fully applicable to Design Reviews at various stages of a Project.

Extensions of the CDF design functions to other phases of the development life-cycle beyond the pre-Phase-A will require careful investigation.

More studies of new space missions are planned to be executed in the facility. This activity will have to be combined with the consolidation and evolution of the CDF infrastructure, in particular software, methodology and procedures. Some areas liable for improvements are currently being investigated:

- The application of an advanced and uniform Graphical User Interface (GUI) linked to embedded discipline model databases.

- The production of document formats to enable direct information interface with the CDF discipline models.

- The improvement of the database for the collection of the data produced during the studies.

The internal system models and databases baseline in the CDF require regular update to ensure standards and ever-evolving space engineering technologies are embedded and validated.

CONCLUSIONS

In the past 18 months, the ESA Concurrent Design Facility has evolved from an experimental facility into a functioning, operational and accepted component of the ESA in-house mission assessment design process.

In the frame of the ESA activities quality results have been obtained with a minimum of resources accelerating the preparation process of new missions in their early conceptual phases.

The assessment studies have shown that a mission design at the level of pre-Phase-A can be efficiently performed via the CDF in a much shorter time and with higher quality results than with traditional methods.

The outcome of the studies performed by the CDF Team was judged by the Customer to be more detailed and internally consistent than those produced via the classical approach.

The specialists using the CDF have indicated their satisfaction at responding and contributing more effectively, interactively and transparently to the evolution of the complete system design, rather than contributing only their individual design elements in isolation.

The CDF has proved to be a unique and valuable tool for the training and re-training of engineers in space system design within a very dynamic and constructive working environment.

The CDF approach and results have contributed in generating a consensus "in-house" that CE is the right approach towards the production of high quality space engineering system designs.

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