Concurrent Engineering Applied to Space Mission Assessment and Design

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ESA performs pre-Phase-A assessment studies as part of the definition of future space missions. To evaluate the benefits of the 'concurrent engineering' approach to these studies, an experimental design facility was created in ESTEC and used to perform an assessment of the Italian Space Agency's CESAR (Central European Satellite for Advance Research) mission. This article describes the approach adopted and the experience gained during the study, and draws preliminary conclusions on this new approach to space-mission assessment and design.

Introduction

Within the framework of its General Studies Programme (GSP), ESA performs a number of pre-Phase-A assessment studies each year. 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 resulting study report is used as an input to the industrial Phase-A design studies.

Pre-Phase-A studies are normally performed in-house at ESTEC, by technical-support specialists using a classical approach, in which each specialist prepares a subsystem design relatively independently from the others, using stand-alone tools. Design iterations at system level take place in meetings at intervals of a few weeks. This method, which is still the one most frequently used, 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, 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 mission concept to spacecraft flight (e.g. the SMART and Flexi missions).

An alternative to the classical approach is offered by 'concurrent engineering', which provides a more performant design method by taking full advantage of modern information technology. There are many definitions of the meaning of this term, but the following one best describes the thinking behind the experiment described in this article:

'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; in fact, 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, used for conceptual mission design. In ESA, the method has been studied and even already partially applied in two mission-assessment studies (Euromoon and Venus Sample Return). These examples were not concerned with the suitability of the method itself, being focussed more on the actual mission under definition rather than a re-usable infrastructure.

The objectives of the current experiment were to:
- create an experimental mission design environment (hereafter referred to as the Concurrent Design Facility, or CDF) in which the conceptual design of space missions could be addressed in a more effective way

- apply the practice of concurrent engineering 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.

A first case study was provided by the CESAR mission assessment, performed from January to March 1999, which ESA had undertaken jointly with the Italian Space Agency (ASI), on behalf of the Central European Initiative (CEI).

The approach

The means to create the facility on an experimental basis was simply to organise the existing tools and human resources already employed for space-mission assessment studies in a more effective (i.e. concurrent) way.

The concurrent-engineering approach is based on five key elements:

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

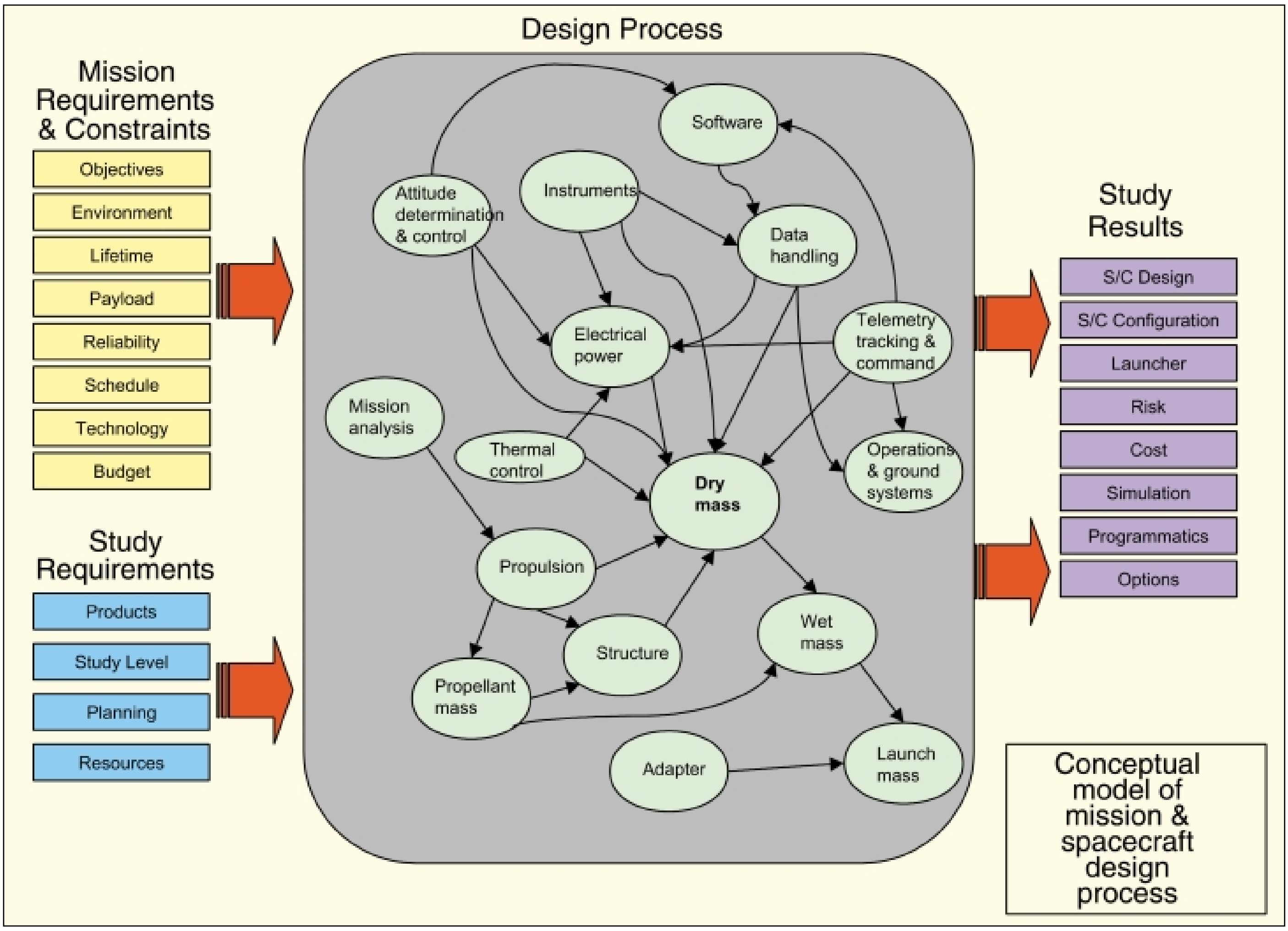
The process

The conceptual model of the design process is shown in Figure 1, which highlights the fact that a space system has many interdependencies between 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. The early assessment of the impact of changes is essential to ensure that the design process converges on an optimised solution. The concurrent-engineering approach is intended to provide the means to achieve this.

The process starts with a few meetings involving a restricted number of specialists (customer, team leader, system engineer) to refine and formalise the mission requirements, to define the constraints, to establish design drivers, and to estimate the resources needed to achieve the study objectives.

The design process is conducted in a number of sessions in which all specialists must participate. It is an iterative process that addresses all aspects of the system design in a quick and complete fashion. The simultaneous participation of all of the specialists reduces

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



the risk of incorrect or conflicting design assumptions, as 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, 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 this 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 step, 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

A group of engineering specialists working together in one room, using sophisticated tools, are all essential elements but they are not sufficient 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 concurrent-engineering approach is to create a highly motivated, multidisciplinary team that performs the design work in real time. Human resources are by far the most important element!

To work effectively, the team members must accept to:
- adopt a new method of working
- co-operate
- perform design work and provide 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 participate in every session and to:
- prepare the designs of their subsystems using the facility's computerised tools
- follow the main-stream presentation/discussion to identify possible influences of other domains on their own domain
- be ready at all times to answer questions relating 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.

The technical disciplines selected for the CESAR study are listed in Table 1.

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 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.

Table 1. The technical disciplines in the ESTEC CDF

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

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.

The facility

The team of specialists meets in the Concurrent Design Facility (CDF) to conduct design sessions. The accommodation comprises a design room, as illustrated in Figure 2, plus a meeting room and project-support office space. The equipment and layout of the CDF is 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.

In front, large projection screens can show the display of each workstation, so that the specialists can present design options or proposals and highlight any implications imposed on, or by, other domains. Video-conferencing equipment is installed to allow team members 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 archiving capability.

The infrastructure must allow its users to:

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

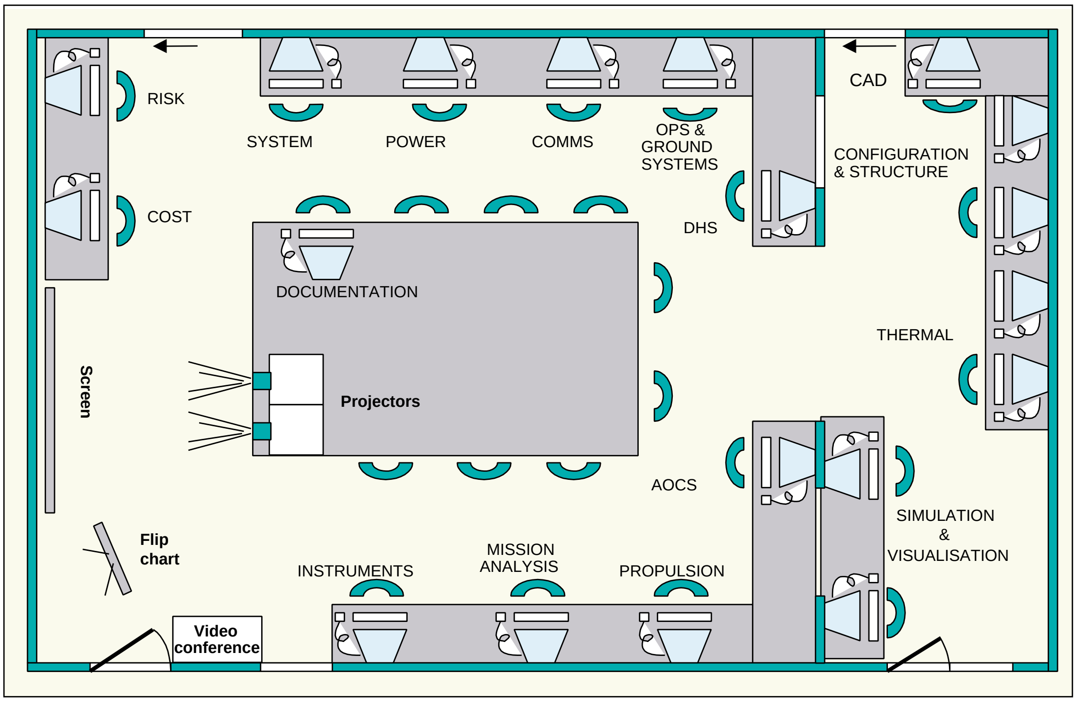


Figure 2. Constitution and layout of the ESTEC Concurrent Design Facility

In creating such an infrastructure to support the concurrent-design process, a number of important issues had to be considered.

Due to the experimental nature of the exercise, it was decided to use existing equipment and tools to build up the facility. The architecture of the system required workstations for the development of the project model and a supporting documentation system. 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. Low-power personal computers (75 to 133 MHz) were used to host the office-automation products.

Only two months were available to prepare a working system, leaving no time for the training of users. Use of existing tools with which the staff were already familiar was the only solution to this problem.

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 that are already part of the Agency's infrastructure brings many benefits.

Table 2. General tools

Function	Tools Used
Documentation storage & archiving	Lotus Notes database
Electronic communication within the team	Lotus Notes mail
Storage area for all data files	NT file server
System modelling	Excel spreadsheets
Project documentation	MS-Word
Remote audio/visual communication	Video conferencing & MS-Netmeeting

Table 3. Domain-specific tools

Domain	Tools used
Structural design, configuration & accommodation	CATIA
Thermal	ESATAN & ESARAD
AOCS	Matrix X
Mission analysis	IMAT
Mission simulation & visualisation	EUROSIM
Programmatics	MS-Project
Cost modelling and estimation	ECOM cost/technical database & small-satellite cost model

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 the fact that relevant work had already been performed under an ESA contract* in 1996. A fundamental decision was taken to split the system model into components that mirrored 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. This raised the need for 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.

Figure 3 shows the architecture of the model.

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 into the master document, prepared in accordance with the ESA standard document template.

The use of Lotus Notes® 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 purposes 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, input received by a domain model had to be transferred manually to applications running on separate workstations, with the results transferred again by hand into the Excel model for further processing or propagation to other domains.

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

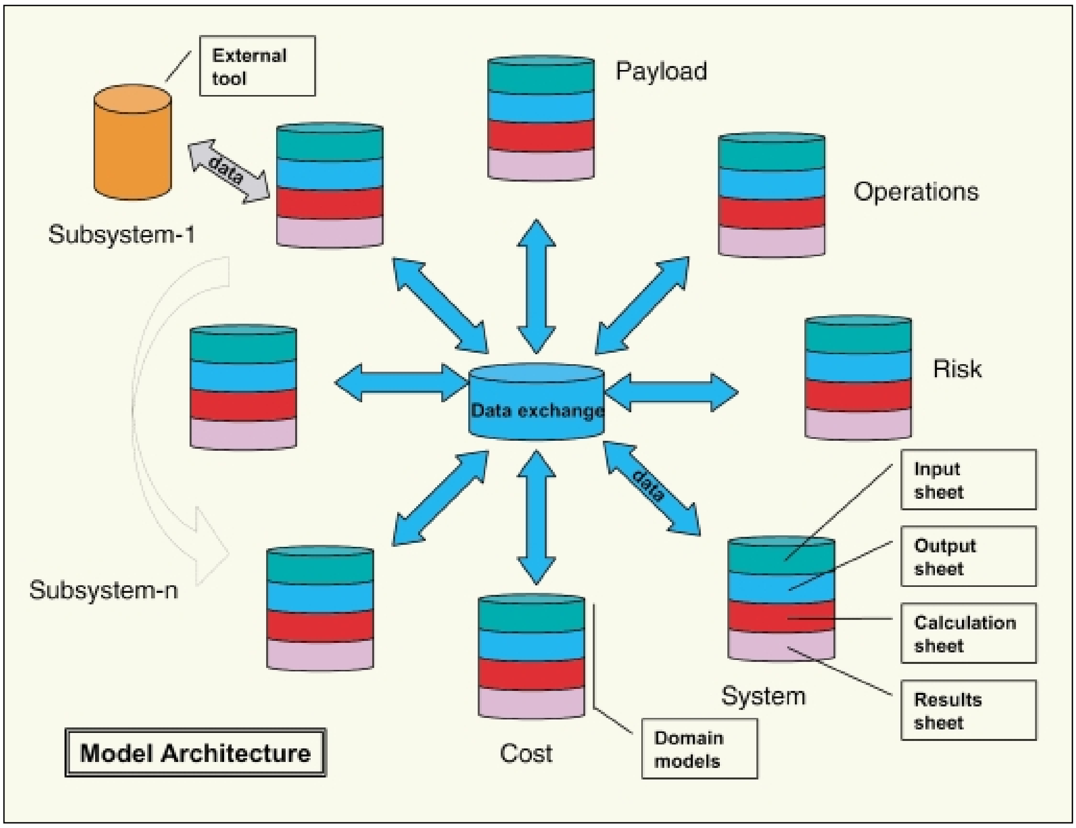

Figure 3. Architecture of the software model

Each domain workbook is comprised, as a minimum, of an input, output, model and results worksheet. In practice, multiple sheets are used for the modelling to give clarity to the major parts of the model and to ease display of the model during design sessions. The input and output sheets implement the data exchange with other domains as well as external tools. Figure 3 shows the conceptual architecture.

During a design session, discussion will lead to the necessity to perform an update to the model to reflect decisions or test hypotheses (e.g. to demonstrate the impact of changing the type of solar cells). Key parameters controlling the selection of the technology would be updated in the appropriate domain model. This will result in a new set of output parameters that must initially be restricted to the generating domain and not propagated to the rest of the system. If a decision is taken to propagate the data, then the locally held values are saved in the domain output sheet. The next step is to update the shared data area by propagating the domain output sheet. At this stage, the data is available to other domains should they decide to use it (i.e. other domain models are not triggered). The last step is to trigger the affected domains to read the new input data and to execute the model.

This process must be repeated until the impact of the change has been propagated to the point where iterations no longer have a significant effect. Clearly, the possibility for several, if not endless, iterations arises since two or more domains may be affected by each other's output!

This aspect of the infrastructure is a candidate for improvement in the longer term and will enhance the concurrency of the design process. An example of such an improvement would be the export of geometrical 3-D spacecraft-configuration data to the simulation system, which uses geometric models for the spacecraft visualisation.

Conclusions

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. 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.

Figure 4. The study team, gathered in the ESTEC Concurrent Design Facility

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 a 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 experiment has shown the benefits of centralising system-engineering tools as part of an integrated facility. This approach can give focus to developments that in the past have been mostly independent. The approach also lends itself to activities other than pre-Phase-A mission assessments. The same principles could be applied to individual module/sub-system/instrument design and extended to cover other phases of the mission development life-cycle, in line with the goals of concurrent engineering in general. Use of the facility to support training, reviewing and proposal evaluation could also be investigated.

The case study has indicated that a conceptual design could be performed in a much shorter time and at a lower cost than with traditional methods. Clearly, further resources would be needed to implement a permanent facility, with fully trained users and populated databases, before such gains can be fully exploited.

The success of the first study output was confirmed by a thorough review conducted by an ESA Board using the procedures normally followed in the Agency, but taking advantage of the model and the facility, for both presentation and explanation of the chosen design. The study results were judged by the review team to be more detailed and internally consistent that those produced via the classical approach.

The CESAR study alone is, of course, not sufficient for a complete validation of the method. More studies, preferably in different mission domains, should allow a better assessment of the consequences of adopting the method in general, plus identification of the advantages and disadvantages of the approach. A second study is now in progress in the ESTEC CDF for an ESA solar-orbiting science mission, and others are currently being proposed.

Finally, a decision to set up a permanent facility should be addressed, once sufficient experience with the method has been obtained.

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