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AN OVERVIEW OF INPE'S SPACE MISSIONS INTEGRATED DESIGN CENTER (CPRIME)

Fabiano Luis de Sousa
Ronan Arraes Jardim Chagas

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Lista de Siglas e Abreviaturas / List of Acronyms and Abbreviations

Acrônimo / Acronym	**Significado / Meaning**
AEB	Agência Espacial Brasileira
AOCS	Attitude and orbit control subsystem
AIS	Agenzia Spaziale Italiana
CAR	Cadastro Ambiental Rural
CCISE	Comissão de Coordenação e Implantação de Sistemas Espaciais
CDC	Concept Design Center
CDE	Concurrent Design Environment
CDF	Concurrent Design Facility
CE	Concurrent Engineering
CEF	Concurrent Engineering Facility
CGCE	Coordenação-Geral de Engenharia, Tecnologia e Ciência Espaciais
CNES	Centre National d'Études Spatiales
COTS	Commercial of the self
CPRIME	Centro Integrado de Missões Espaciais
DETER	Detecção de Desmatamento em Tempo Real
DIMEC	Divisão de Mecânica Espacial e Controle
DISEP	Divisão de Sistemas Espaciais
DLR	Deutsches Zentrum für Luft und Raumfahrt
DSM	Design Structure Matrix
ESA	European Space Agency
GEO	Geosynchronous Earth Orbit
GSST	Galileo Solar Space Telescope
IDE	Integrated Design Environment
INCOSE	International Council on Systems Engineering
INPE	Instituto Nacional de Pesquisas Espaciais
IT	Information Technology
ITA	Instituto Tecnológico de Aeronáutica
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
M&S	Modeling and Simulation
M&S&DS	Modelling, Simulation, and Data Sharing
MDO	Multidisciplinary Design Optimization
NASA	National Aeronautics and Space Administration
OBDH	On-Board Data Handling
PEB	Programa Espacial Brasileiro
PESE	Programa Estratégico de Sistemas Espaciais
PJESOPROM	Projeto Engenharia Simultânea e Otimização de Projeto Multidisciplinar
PMM	Plataforma Multi-Missão
PNAE	Programa Nacional de Atividades Espaciais
PRODES	Programa de Monitoramento da Floresta Amazônica Brasileira por Satélite
R&D	Research and Development
TT&C	Tracking, Telemetry and Control
USA	United States of America
VBA	Visual Basic for Applications

1 Introduction

The establishment of integrated concurrent design centers has shown to be a turning point for achieving higher productivity and better design solutions in space mission conceptual design. Concept design studies that usually took months to be performed using tradition design approaches, where reduced to a few weeks, with no loss of quality. On the contrary, by making the conceptual design an activity where all disciplines related to the development of the product being conceived are taken into account simultaneously, the concurrent approach allows a greater design awareness and early identification of potential problems that would arise in later stages of the product´s lifecycle. The gain in design time provided by the concurrent integrated approach also allows more studies to be carried out, expanding the portfolio of mission proposals able to go through feasibility analysis quickly. The importance of such kind of facility is highlighted, for example, by ESA´s Concurrent Design Facility (CDF) becoming “an essential tool to support ESA decision making and risk management processes” (ESA, 2021).

In this document is presented an overview of INPE´s Space Missions Integrated Design Center (Centro de Projeto Integrado de Missões Espaciais – CPRIME). CPRIME is INPE´s concurrent facility for conceptual design of space missions and, as far the authors know, the first of such kind of facility to be established in Brazil.

Following this Introduction, in Chapter 2 a brief overview of concurrent engineering in integrated design centers for space missions is presented; in Chapter 3 is described how these features were implemented in CPRIME; in Chapter 4 a summary of the studies performed so far, and lessons learned on the construction and operation of CPRIME are highlighted, followed by the Conclusion in Chapter 5.

2 Concurrent engineering in the conception of space missions

Concurrent Engineering has been applied extensively in the design of complex systems in order to increase quality, reduce cost and time to market of new products (Dym e Little, 2004, Bogus et al., 2005; Jenney et al., 2010; INCOSE, 2011).

In the CE approach all disciplines involved in the project are taken into account simultaneously, in an integrated way, since the project´s conception (Swink, 1998; Koufteros et al., 2001). Though being a term that emerged relatively recently, in the years 1980s (Wognum et al., 2003, Fukuda, 2007), many characteristics of CE had been already presented in the design literature and product development practices (Smith, 1997).

Figure 1 shows, in a simplified way, three design approaches. In the classical sequential design, experts work individually in separate activities in time. This approach allows flexibility in activities allocation, but the quality of design would be highly dependent on the quality of information passed through the various specialists, that usually will not have the vision of the whole project. The sequential approach would also imply in a longer design time, since activities that could run in parallel may be precluded, and the whole flow of information would depend on the time spent on individual analysis. In the centralized approach a core team receives, evaluates, systemizes, and communicates the information coming from the various disciplines, taking care of the design consistency. This approach not only increases the systemic awareness, but also allows gains in time since some design activities may run in parallel, reducing the time latency, that is the “time between when information is generated and the time it is available to others who are depending on the information for the next steps in their work” (Jenney et al, 2010). In the concurrent approach the time latency is reduce sharply, since all team members are aware of the activities performed in all disciplines. It also increases the systemic awareness and project consistency since its members have a view of the whole design as it evolves.

Concurrent Engineering may be defined as "a management/operational approach which aims to improve product design, production, operation, and maintenance by developing environments in which personnel from all disciplines (i.e., design, marketing, production engineering, process planning, and support) work together and share data throughout all stages of the product life cycle" (INCOSE, 2011).

NASA uses the definition for CE as "Design in parallel rather than serial engineering fashion. It is an approach to product development that brings manufacturing, testing, assurance, operations, and other disciplines into the design cycle to ensure all aspects are incorporated into the design and thus reduce overall product development time" (NASA, 2016).

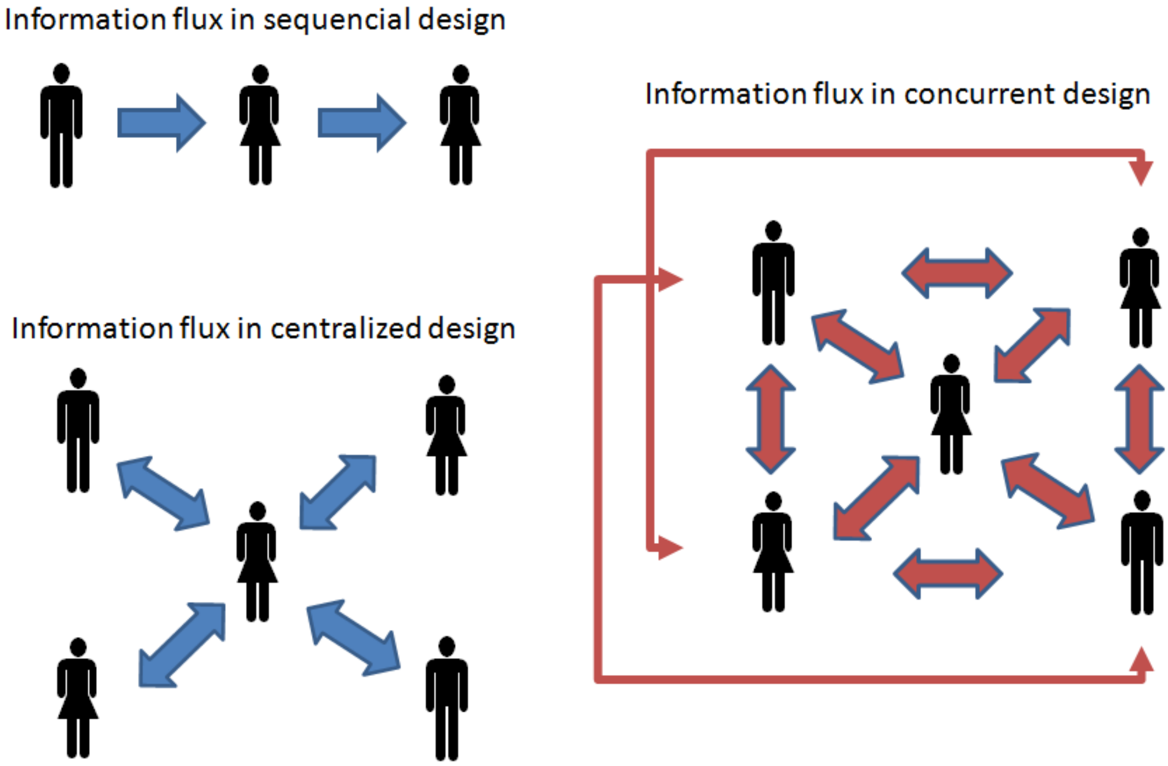

Figure 1 - Three approaches for project design (adapted from Tatnall et al., 2011).

The application of concurrent engineering in space mission concept design was first implemented at NASA´s JPL in the mid-1990s, as a facility that became to be known as Team-X (Casani and Metzger, 1995; Case et al., 2021). Still in the 1990s, other similar facilities were implemented, such as ESA´s Concurrent Design Facility (CDF) (Bandecchi et al., 1999) and the Aerospace Corporation´s Concept Design Centre (CDC) (Smith et al., 2000), and since then many of such design centers have flourished all over the world (Knoll et al., 2018; Rana, 2021).

Concurrent space design centers have usually four main components:

- A multidisciplinar team;
- A design process;
- Modelling, Simulation and Data Sharing (M&S&DS); and
- A design environment that co-locates hardware, software and multimedia tools in a facility where the team works.

The *multidisciplinary team* is composed of experts from all disciplines necessary to devise the system that would fulfill a given proposed space mission. They include technical disciplines such as structures, thermal, orbit dynamics and attitude control as well as managerial disciplines such as cost estimation and risk analysis. The design team is the most important component of a concurrent facility.

The *design process* is the series of steps that guide the design from the mission´s statement and objectives to the system concept. It is highly iterative and must be structured such that the system concept fulfils the mission´s objectives, being consistent and balanced.

The *modeling, simulation and data sharing (M&S&DS)* component is composed of dedicated disciplinary modeling and simulation (M&S) tools and engineering databases that are integrated through a centralized network, such that design parameters can be tracked and delivered quickly to all disciplines, as soon as they become available. The M&S&DS helps keep the design consistent throughout the design process.

Finally, the *concurrent design environment* consists of a physical space set up with multimedia and IT tools such that the exchange of information among the members of the design team is highly facilitated during the design sessions. It usually also includes, beyond the main design room, rooms for splitter meetings. The design environment greatly helps the flow of information and ideas during design sessions. Some examples of such environments are shown in Figure 2.

Figure 2 - Examples of concurrent design environments (ESA, 2021; Braukhane, 2020; Warfield and Hihn, 2009).

Due to the COVID-19 pandemic, design sessions had to be held entirely in remote mode at CPRIME. That is, the team members where no more collocated physically, but virtually. While this mode of participation certainly reduces the information convection between team members, with potential impacts in latency and on the exploration of the design space, it can be accomplished successfully and is an option that would be exercised, even if partially, in future studies at CPRIME. It is noteworthy that Team-X performed at least 70 studies with 100 % of remote participation (Murphy and Nash, 2021) during the pandemic, and is envisioned that there "remote participant studies will continue to be a way of life for concurrent engineering concept development studies post-pandemic" (Murphy and Nash, 2021). In fact, as a recent research study highlights (Hiln, J.M. and Chattopadhyay, 2021) full remote participation, physical collocation or hybrid modes are possible, but the effectiveness of each mode may be dependent on the complexity of the study and on the previous experience the design team had on working together.

In the following Chapter 3, it is described how the four principal elements of a concurrent facility, highlighted above, were implemented at CPRIME.

3 CPRIME

CPRIME is the result of a P&D project that began in 2013 at the Space Systems Division of INPE. Called PJESOPrOM (Projeto Engenharia Simultânea e Otimização de Projeto Multidisciplinar, in Portuguese) it had as main objective the creation at DISEP "of an integrated, multidisciplinary design environment in order to improve significantly INPE´s engineering capacity in design and analysis of new mission concepts and satellite projects" (INPE/ETE/DSE, 2014). The use of Multidisciplinary Design Optimization in the design environment allows the automation of at least part of the design process, in such a way that more solutions could be explored. Hence it was considered to be incorporated to CPRIME since the beginning. However, envisioning potential difficulties of using optimization in the conceptual phase, mainly due to the modeling of the design process (or parts of it) as an optimization problem, and the integration of multiple subsystem models, the use of MDO in CPRIME was set as a secondary objective of PJESOPrOM.

CPRIME was built in a bottom-up approach. The design environment was inspired by JPL´s Team-X and ESA´s CDF, the design process was based on Wertz´s space mission engineering process (Wertz, 2011) and all models used to design and analyze the space system, except the cost ones, were developed internally at INPE. Some commercial design and analysis tools already used by INPE´s engineering on developing satellites were also incorporated to CPRIME.

Translating Wertz (2011) space mission engineering process to the environment design of CPRIME was done in a learn-by-doing fashion. The first mission study performed at the Center was also the first time the process was exercised, and in the studies that follow it was being more and more improved to the studies´ needs and dynamics of CPRIME.

CPRIME´s facility was installed at INPE´s BETA building after carefully assessing the Center needs and the space available for its installation. The facility was completed in 2016. The team was built progressively, as more experts joined PJESOPrOM. Today CPRIME´s team is composed of a multitude of experts which are assembled as needed for a given study.

CPRIME´s name and logo were proposed and selected by its members in internal contests realized at the end of 2015 and beginning of 2016.

CPRIME is composed of four basic elements that allow the realization of the concurrent engineering approach to the space mission concept design. These elements are highlighted in Figure 3 and described in the sub-sections below.

Figure 3 - The four basic components of CPRIME.

3.1 Process

The design realization of a space system concept at CPRIME is based in the Space Mission Engineering Process described in Wertz (2011) but adapted to the concurrent environment and considering INPE´s experience on the project of space systems. It starts from identifying the mission´s objectives, which are translated into requirements and constraints to the system, followed by the system´s synthesis and the deliverable of the study results.

Broadly speaking, a study at CPRIME is divided in three phases, as presented in Figure 4.

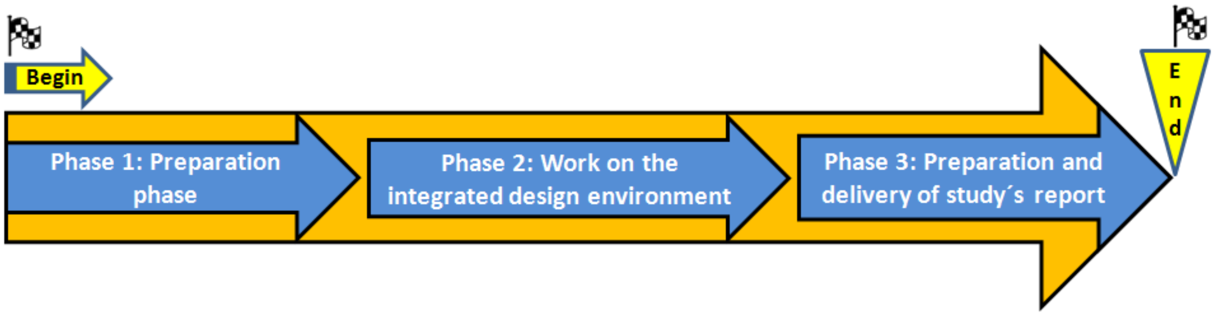

Figure 4 - Main phases of a study at CPRIME.

The main activities in Phase 1 are the understanding by CPRIME´s team of the objectives of the space mission being proposed and the definition of the study scope. In this Phase it is also defined, even if preliminary, a set of functional, operational and programmatic requirements, and constraints to the system, plus its concept of operations (ConOps). These activities are done with active participation of the stakeholder requiring the study, but usually do not involve all members of the CPRIME team that will participate in the study.

In Phase 2, candidate system solutions that fulfill the mission requirements and constraints are devised by CPRIME´s team using the Center´s integrate design environment. Although not mandatory, it is desirable that the study customer or a representative be presented at the design sessions during Phase 2, such that any doubt concerning the mission objectives, requirements or constraints could be swiftly resolved as it arises.

The system design is done in an iterative process, as illustrated in Figure 5.

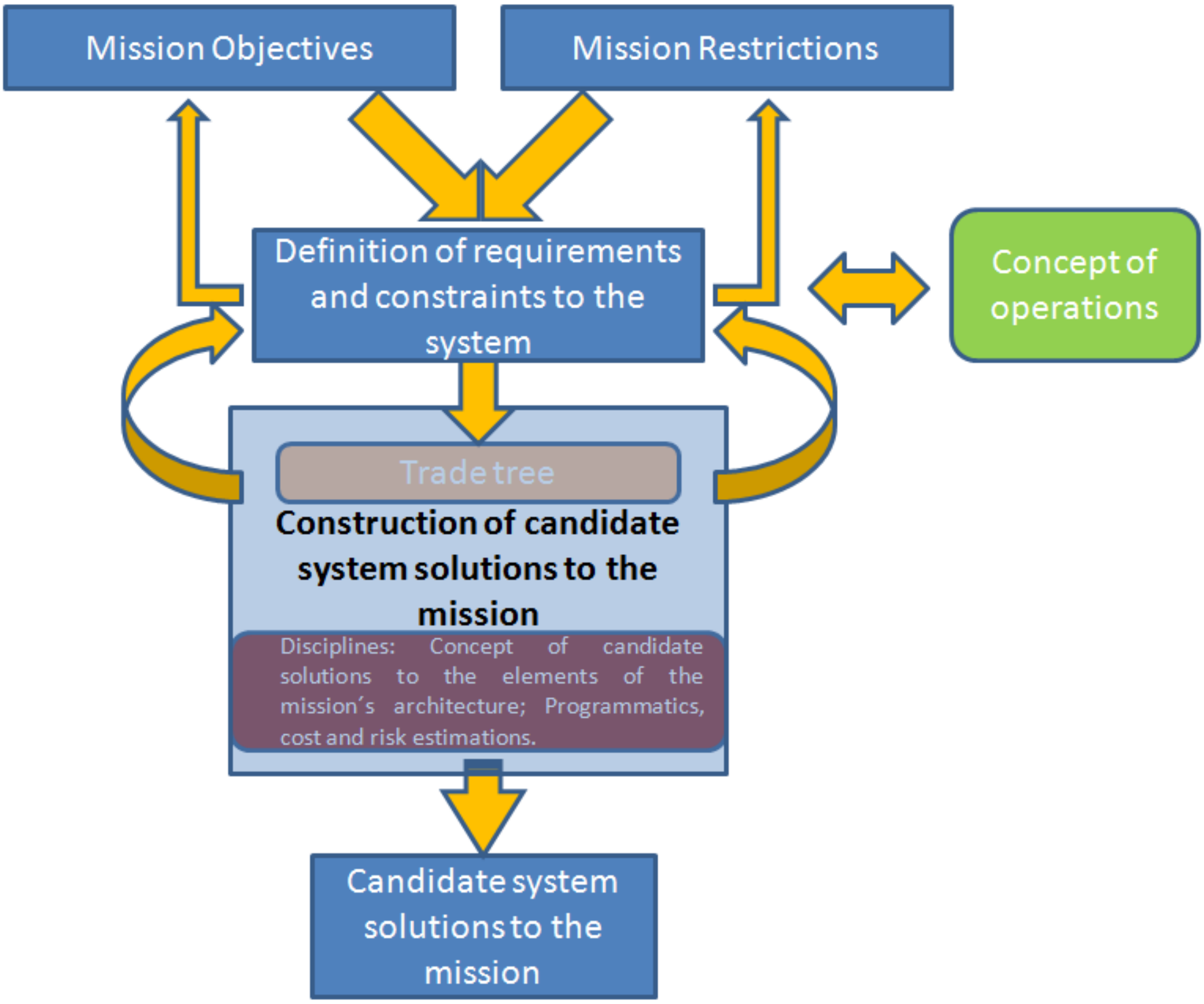

Figure 5 - Main structure of the design process.

The design activities from mission proposal to candidate system solutions are carried out in a systematic way following the stages and steps presented in Table 1.

Table 1 -CPRIME's design process steps (adapted from Wertz, 2011).

Stage	Step	Activity	Description
A	1	Declare the mission statement and its primary and secondary objectives	The mission statement describes the motivations behind the mission being proposed and how it would benefit their stakeholders. The statement is then translated in qualitative objectives that can be classified as primary (must achieve) and secondary ("nice to have").
	2	Define the mission´s stakeholders	The main stakeholders that are demanding, supporting, and/or will benefit from the mission are identified.
	3	Define the mission´s timescales	In this step is identified at least the date the system must be operational and its lifespan.
	4	Define the system´s requirements and constraints	In this step the mission goals are translated in requirements and constraints in four main subjects: • Functional requirements: "define how well the system must perform to meet its objectives"; • Operational requirements: "determine how the system operates and how the users interact with it to meet their specific needs". Here is also defined a preliminary ConOps for the mission´s space segment, stating how it would operate to achieve the missions´ objectives. • Programmatic Requirements: state goals to be met from the missions programmatic point of view; and • Constraints: "limit cost, schedule, and implementation techniques available to the system designer". The above parameters must be as quantitative (numerical) as possible.
B	5	Identify possible alternative options for the elements of the mission´s architecture	In this step are listed the elements of the mission architecture (items 1 to 8 in Figure 6) and verified, for each of them, if it can be traded, the reason for that, and what would be possible solutions.
	6	Define the mission data flow and operation modes of the mission´s space segment	In this step it is analyzed and defined how data flows (payload and service) between the elements of the space system, and what are the modes of operation of the space segment.
	7	Identification of system drivers and critical requirements	System drivers are "the principal mission parameters or characteristics which influence performance, cost, risk, or schedule and which the user or designer can control". Critical requirements are those "that dominate the space mission´s overall design".
C	8	Build a high-level trade tree of alternatives for the system drivers and/or critical requirements	Use the system drivers and critical requirements identified in Step 7 to build a trade tree with alternatives for compositions of these parameters. Chose some or all these alternatives to build concept solutions for the space system.
	9	For the alternatives chosen in Step 8, build concept solutions for the space system and iterate.	In this Step system solutions are conceived, considering all elements of the mission´s architecture, and including programmatic aspects, cost estimates and risk analysis. This activity is iterated internally and with the previous ones as necessary, until one or more viable space system concepts are conceived.

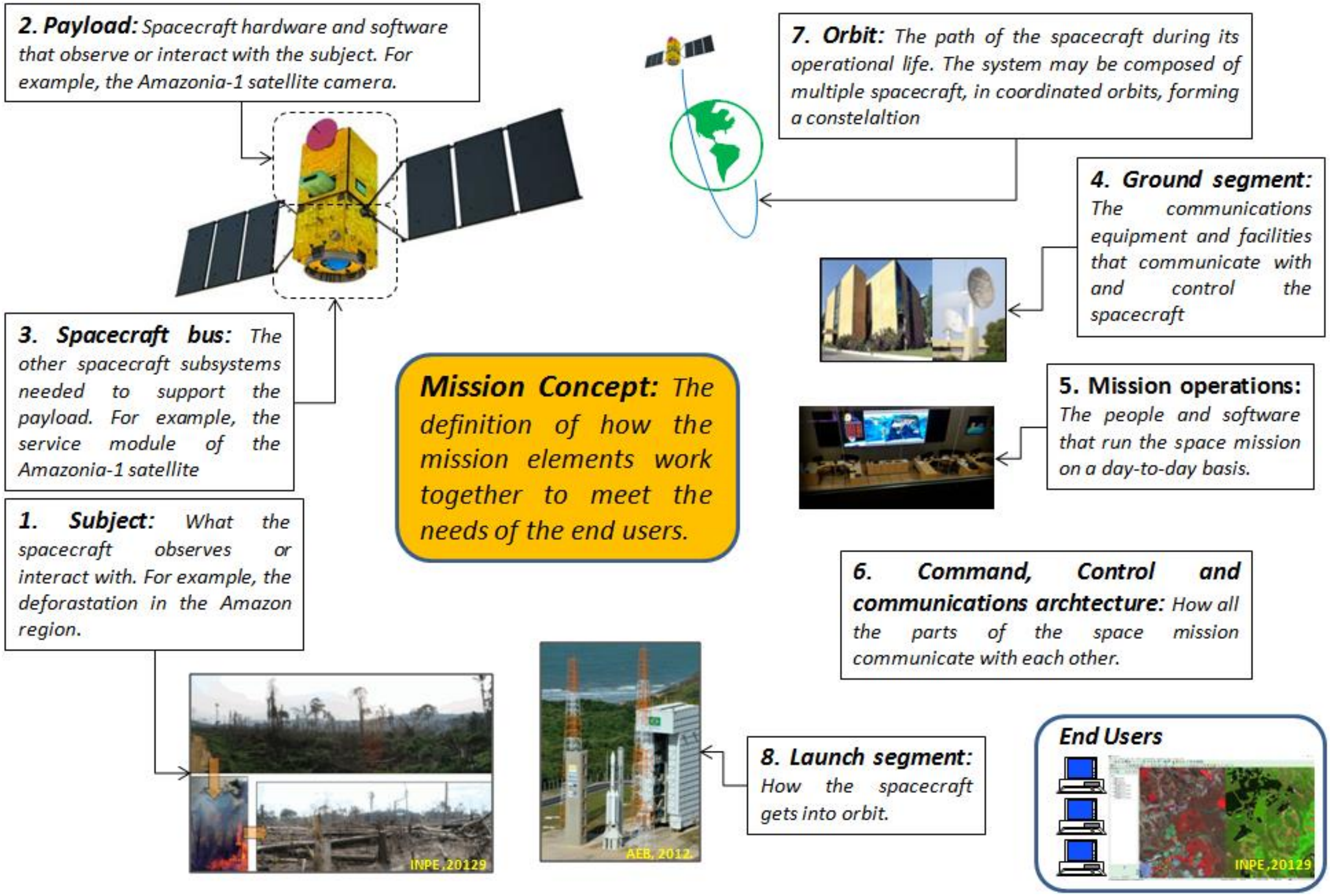

Figure 6 - Illustration of the elements of a space mission´s architecture (1 to 8). An Earth observation mission as example. In the Figure "end users are the people or equipment that actually make use of the data generated or transmitted by the spacecraft". Adapted from Wertz (2011).

Although carried out as a sequence of steps, as presented in Table 1, CPRIME´s design process is highly iterative, as already highlighted in Figure 5.

Figure 7 shows a summary of the system synthesis tasks realized in Step 9 of the design process. From the system´s requirements, constraints, and ConOps defined in Step 4, and the options resulted from the trade tree analysis, system candidate solutions are conceived following five main blocks. They comprise design, estimates and analysis of the elements of the system´s architecture. The first iteration inside Step 9 usually begins with orbit and payload design, which frequently are highly coupled, hence they are take into account together. After that, the team conceives the AOCS, propulsion, OBDH and TT&C subsystems, and defines the ground stations necessary to support the mission (Block B). From the power budgets of the equipment conceived in Blocks A and B, a first estimation of the spacecraft power consumption can be made, and the power subsystem sized (Block C). Mechanisms may be added to the design in this phase to provide, for example, movable solar arrays to the spacecraft as a result of the power analysis. With the satellite equipment defined in Blocks A to C, in Block D the structure subsystem and a first layout of the spacecraft is conceived. After this, the thermal control subsystem is sized. With a first solution for the spacecraft layout and thermal control, it is verified if the power subsystem can accommodate the resulting spacecraft total power budget. If not, the power subsystem is resized and the design iterated (Blocks C and D) until a feasible solution found. After so, it is verified if the AOCS subsystem can fulfill its functional requirements accommodating the inertial properties resulted from the spacecraft layout. If not, the subsystem is resized and another iteration (B-C-D) begins. With a viable spacecraft solution complete, possible launcher options are chosen and the design go to the final block of Step 9, the programmatic and risk analysis, and cost estimates (Block E). The syntheses activities carried out in Step 9 shall result in at least one viable solution for the system. However, it is desirable that more of these are conceived, in order to provide stakeholders with different trade-off options to implement the space mission.

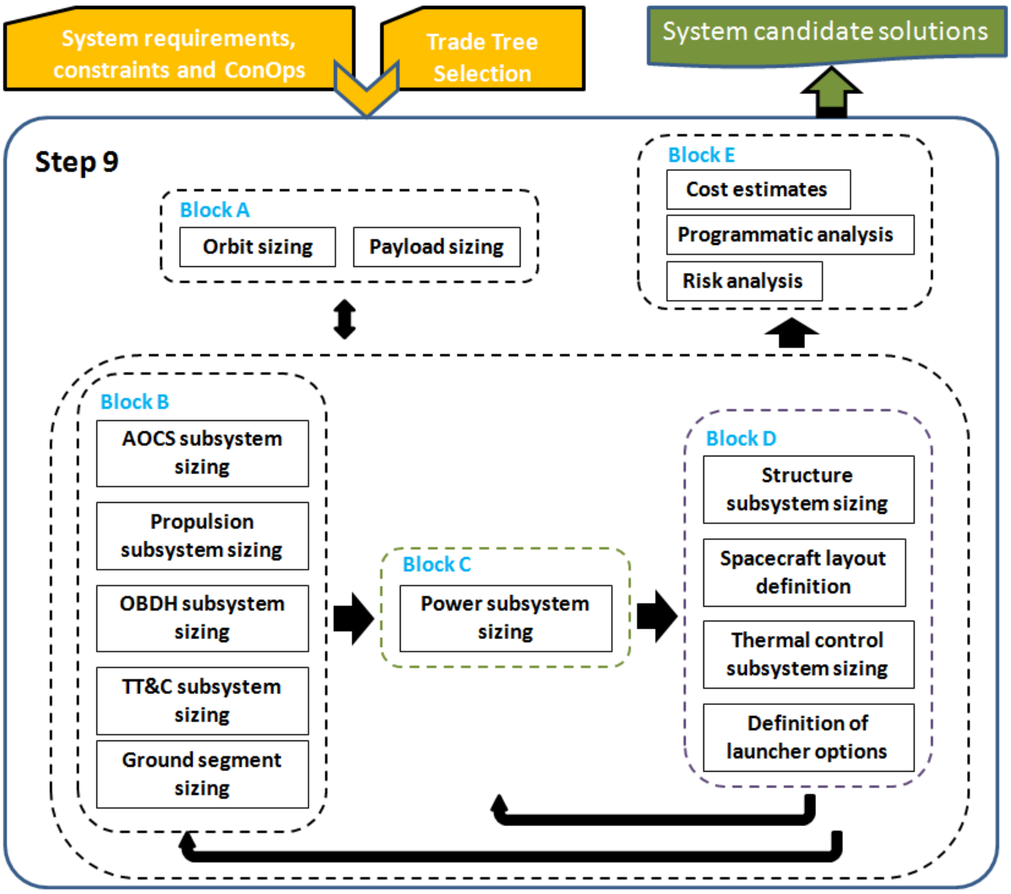

Figure 7 - Typical sequence of activities in step 9 of the design process.

It is important to note that the design procedure described in the previous paragraph and illustrated in Figure 7 may be altered in many ways, depending, for example, on the kind of space mission, or specific requirements imposed to the system. For example, to be accomplished, a proposed mission may require a constellation of satellites, which may or may not be of the same type, or even may be additions to existing spacecraft already in orbit. This would imply in different design runs of blocks B to D, for instance, if new different spacecrafts are to be added to an existing constellation. On the other hand, if the constellation is new and all its satellites are equal, the design sequence would essentially be the same as depicted in Figure 7. In another possible case, a programmatic requirement or cost constraint may lead to the use of an existing platform or payload for the spacecraft. If an existing platform is required to be the satellite´s service module, there will be only the sizing of the ground segment and definition of launcher options in the design sequence B to D, and a viability analysis will have to be performed to verify if the platform is adequate to the considered mission, including its capacity to accommodate the payload. Although a particular system design may not go through all the sizing activities presented in Figure 7, the main structure of the iterative process shown on it can be applied to the conception of any space system.

It must be emphasized that the space system design is a highly iterative process, with the results of one Step not being only an input for the next one, but also a feasibility check point for the previous ones. In fact, for example, it may be found out at the end of Step 9 that no system design is feasible within a given cost or schedule constraint. This would lead to the relaxation of some functional requirement or even a mission´s goal, such that at least one feasible system candidate solution can be conceived.

At the end of Phase 2 a presentation of the study results is done for the study customer. This may include a simulation of the ConOps using CPRIME´s ForPlan simulator (Chagas et. Al., 2019)

Finally, in Phase 3 a study´s report is prepared by CPRIME´s team and delivered to the costumer.

3.2 Modelling, simulation, and data sharing at CPRIME

Modelling, simulation and data sharing is extensively used in concurrent facilities to enable the swift conception of design solutions, as well as to keep the consistency of design parameters, among the disciplines that make up the space mission. A system of integrated spreadsheets, provide a convenient way to share data, perform parametric calculations and consolidate system data such as power and mass budgets. Such approach was used in the early establishment of pioneering space mission concurrent centers such as Team-X (Warfield and Hihn, 2009), ESA´s CDF (Bandecchi et al., 1999) and Aerospace´s CDC (Smith at al., 2000), and was also the first choice to be implemented at CPRIME.

The integrated modeling environment conceived for CPRIME consisted of spreadsheets connected to a central data base that archived the design parameters. The spreadsheets function as frontends to input and retrieve data, as well as design tools and local data bases for specific disciplines, as appropriate. For example, the project of the AOCS subsystem is done using a design procedure embedded in an Excel workbook as illustrated in Figure 8.

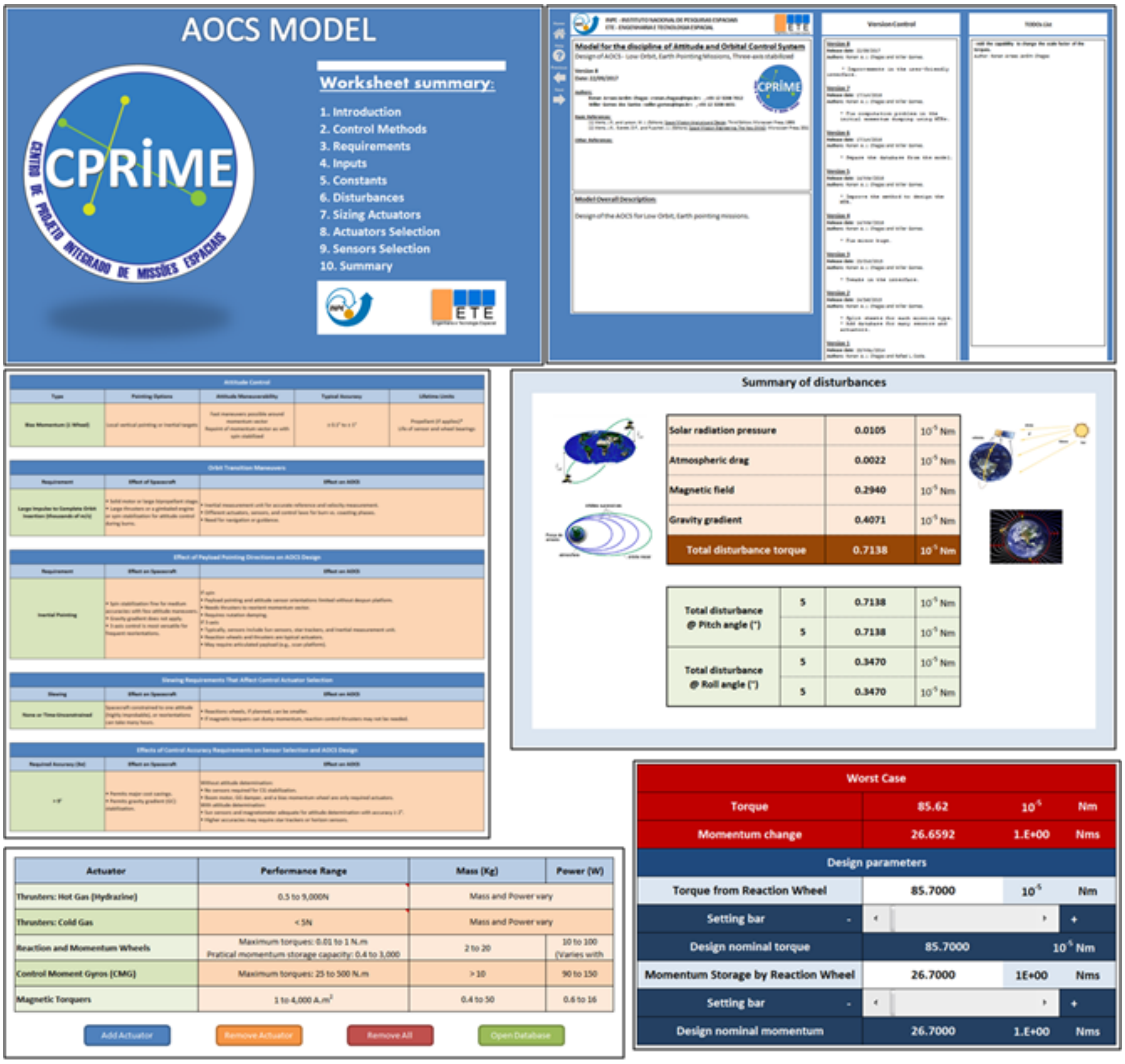

Figure 8 - Mosaic of some worksheets belonging to AOCS´s modeling workbook (Santos and Chagas, 2018).

Another example of a M&S tool developed at CPRIME, is the ForPlan simulator (Chagas et. al., 2019). It is used to verify dynamically functional scenarios devised for the mission. In Figure 9 a mosaic of the graphic interfaces of the simulator is shown.

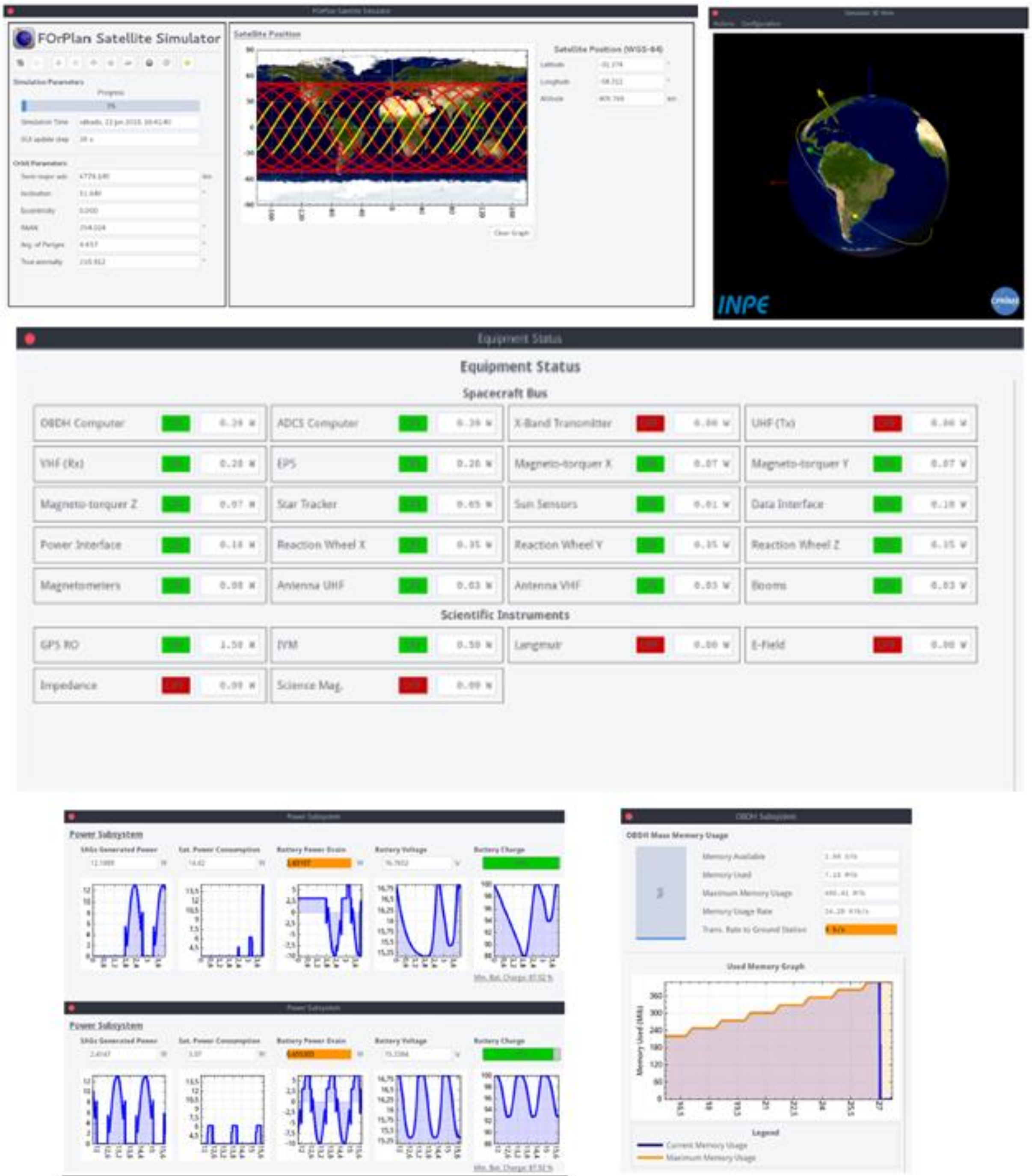

Figure 9 - Mosaic of graphic interfaces of Forplan simulator (adapted from Chagas et al., 2019).

Two systems to exchange data were developed. In the first one, VBA interfaces were created based on the mapping of the inputs to, and outputs from, each discipline in the design environment. This mapping was done using the DSM technique, which showed to be a very useful tool to capture dependencies and identify design loops in the concurrent process of designing a space mission (Avnet and Weigel, 2010). Figure 10 shows the input and output interfaces for the discipline "Power".

The integrated system of worksheets with interfaces such as the ones shown in Figure 10 was used operationally at CPRIME, and though it showed to be useful in communicating and systemizing data, it missed in flexibility. The data fields were fixed, so if a new variable not present in the list of fields was to be used, it could not be included swiftly in the integrated system and had to be considered in a separate control sheet. This led to the development of a new system. In this new system, there is no fixed parameter filling field, but data are included in the system via a worksheet, following a hierarchy that tracks any parameter included in the database, to its related component in the mission architecture. In this way in principle any parameter can be included, as needed, as the design evolves, giving great flexibility to the data system. The system went through testing and showed great potential, to fulfill the needs of sharing, consistency and flexibility. Nevertheless, it is still to be used operationally at CPRIME. In Figure 11 is shown the data hierarchy and main user interface of the system.

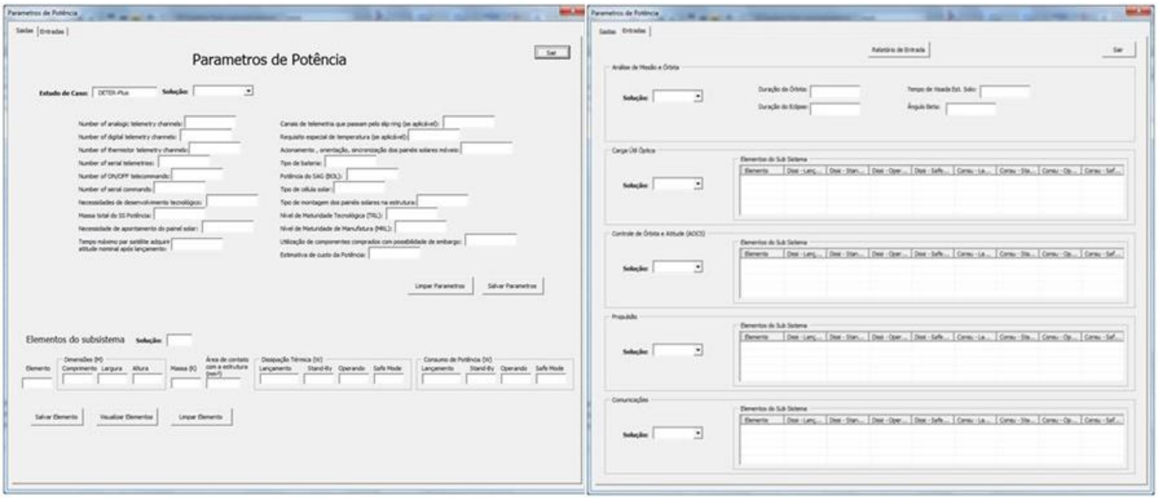

Figure 10 - Input and output interfaces for the discipline Power in the first implementation of the data exchange system (Pinto, 2017).

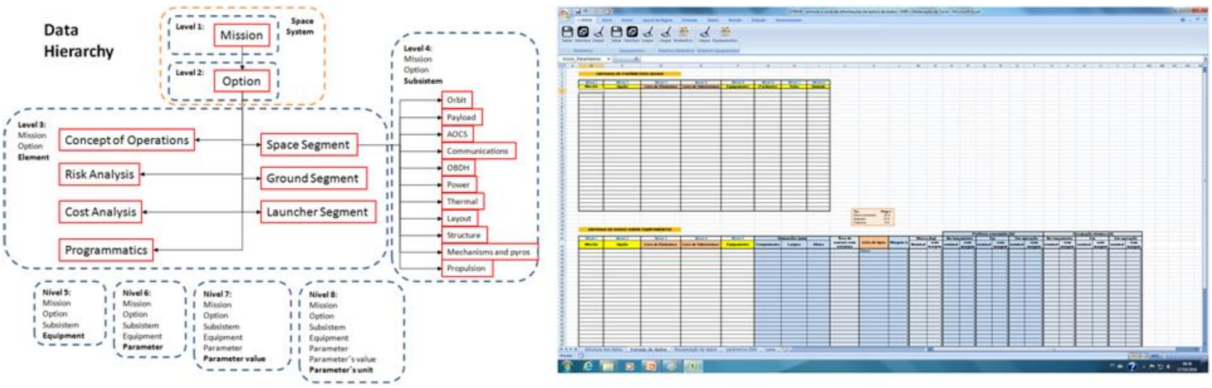

Figure 11 - Data hierarchy and data sharing workbook of the second implementation of the data exchange system (adapted from Pinto, 2017).

A workbook codifies the main design process, from requirements to a summary of the study´s results. This workbook is held by the systems chair but can be accessed by any design team member during the study. A mosaic of screen shots of the "systems workbook" is shown in Figure 12.

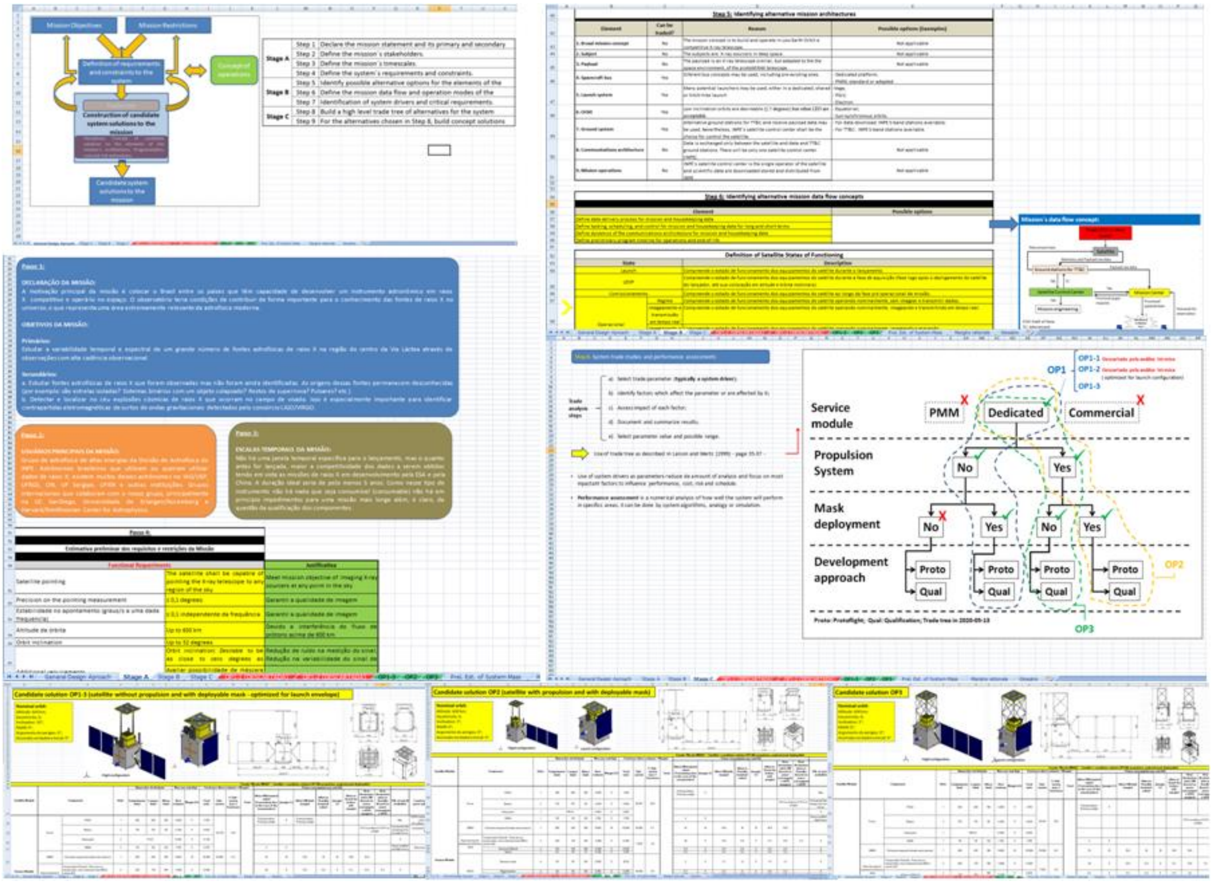

Figure 12 - A mosaic of screen-shots of the MIRAX´s study systems workbook. The design process is codified in the workbook, which also includes a summary of the space system conceived. In the case of MIRAX, three viable options for the satellite were conceived.

Computers in the integrated environment are connected via a dedicated intranet, which, if necessary, can operate without connection to the internet.

Beyond in house modeling and simulation tools, commercial software such as Microsoft Office, SolidWorks, STK, and ThermaklDesktop/Sinda are also used at CPRIME.

In Figure 13 is illustrated the integrated modeling and data sharing architecture devised for CPRIME.

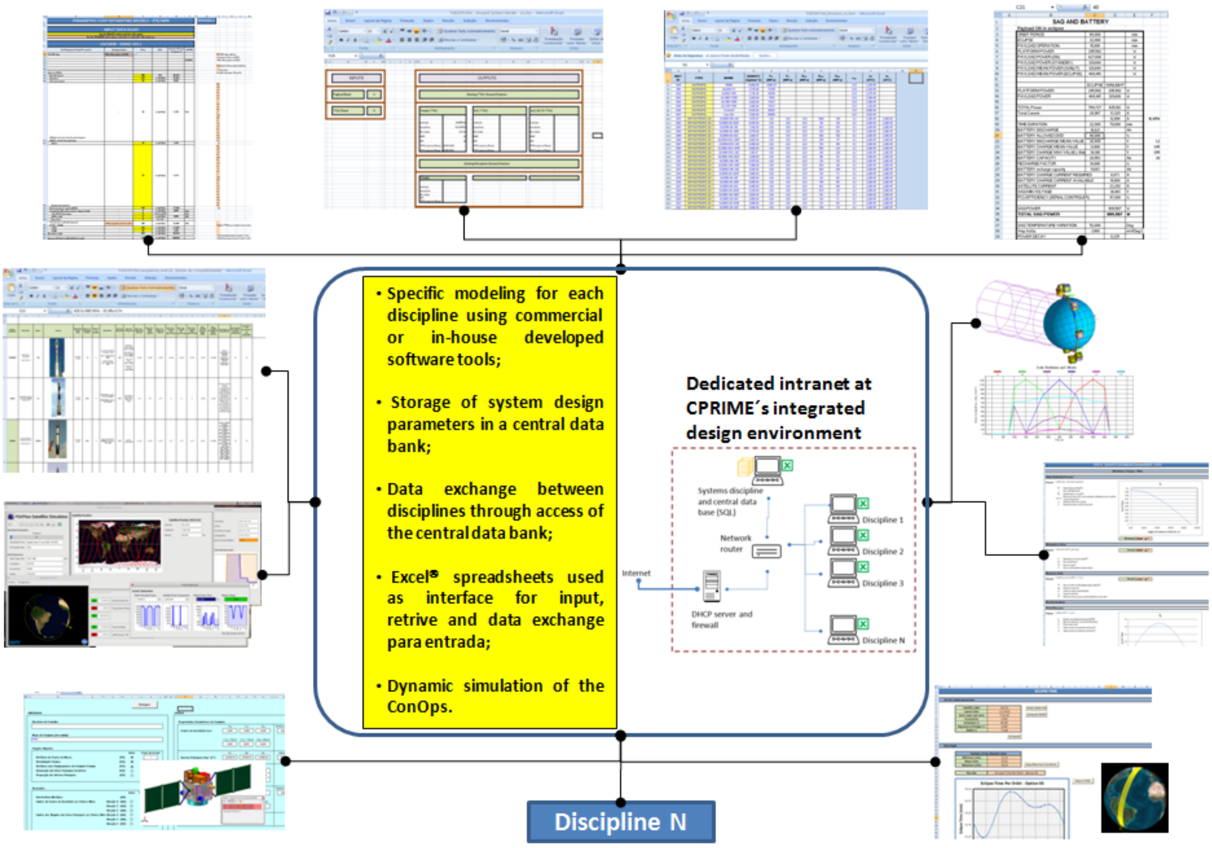

Figure 13 - CPRIME's integrated modeling architecture.

3.2.1 Design optimization at CPRIME

Optimization has been shown to be a powerful tool for assisting the design of spacecraft (Mosher, 1999; Taylor, 2000; Muraoka et al., 2006; Hassan and Crossley, 2008; Croisard et al., 2010; Wang et al., 2013; Hwang et al., 2014; Cuco et al., 2015; Shi et al., 2017; Berrezzoug et al., 2019; Kalita and Thangavelautham, 2020), allowing a broader search for solutions in the design space, which would lead to better designs. This approach has also been proposed to be used for conceptual design of space systems at concurrent integrated environments (Schuman et al., 2005; Guo and Guadagni, 2012, Fillippi et al. 2018, Garcia-Pérez, 2020).

At CPRIME the use of optimization to assist system conception was planned from its inception (INPE/ETE/DSE, 2014). In fact, potential applications to orbit design (Chagas et al., 2014) and multidisciplinary orbit/optical-payload/propulsion design (Chagas et al., 2015) have been demonstrated. Nevertheless, it must be said that design optimization is still not incorporated as a standard feature of CPRIME´s design process. As pointed out by Schuman et al. (2005), "system-level optimization, running as a background process during integrated concurrent engineering sessions, is potentially advantageous as long as it is judiciously implemented". This means that numerical models representative of the system being designed, or of at least parts of it, must be readily available, or easily adaptable, to be integrated to optimization tools during the design sessions. This implies that a library of models representative of different types of missions/systems, payloads and subsystems must be available prior to the design sessions, and that they must be easily customized to perform optimization runs over the system being conceived (or parts of it) for a given space mission study. Moreover, the design team must be willing and trained in using those tools. All these aspects have made elusive the implementation of design optimization in CPRIME so far. Nevertheless, we believe that the potential gains resulting from the implementation of optimization tools to the CPRIME´s design process, is worth the effort necessary to do so, and this remains one of the main R&D goals of the Center.

3.3 Concurrent design environment facility

The concurrent design environment facility at CPRIME is composed of a design room and two meeting runs that can be used for splinter meetings as necessary. In the design room a working station is set for each discipline. The stations are arranged such that disciplines that have more interaction are closer to each other. A multimedia system allows the screen of any station be projected in one or both available projector screens. A digital board is also available in additional to screen boards placed on the walls of the design room. All computers are connected via a dedicated intranet. Figure 14 shows an illustration of CPRIME´s facility. It is located at INPE´s "Beta" building, in the Institute´s Space Systems Division.

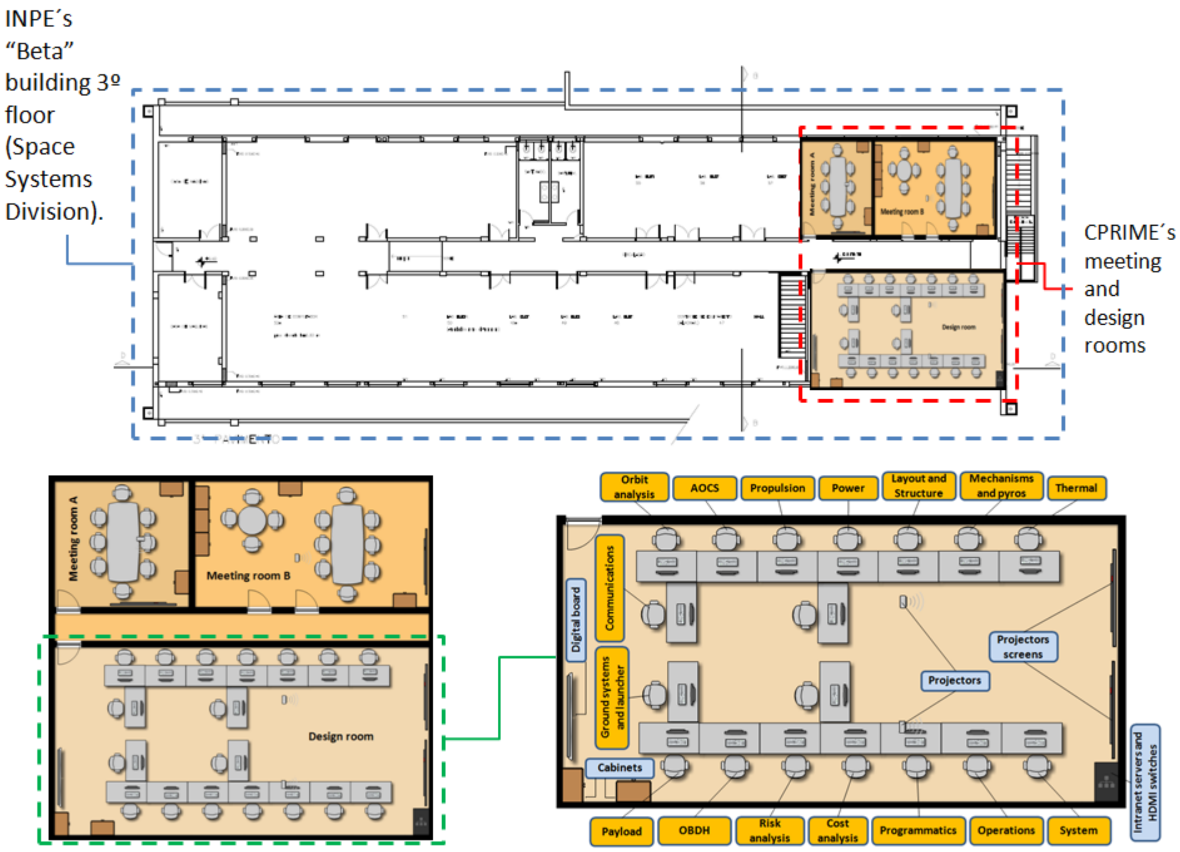

Figure 14 - Illustration of CPRIME's facility.

3.4 Multidisciplinary team

The concept of a space system is a complex multidisciplinary task, and the design team is arguably the most important aspect of any concurrent facility. In fact, as pointed out by Tatnall et al. (2011), "human resources are by far the most important element of the process". At CPRIME the team is comprised mainly of individuals from INPE´s space systems division, but experts from other areas of INPE are also enrolled on the studies, as necessary.

In the construction of CPRIME, an effort was made to have at least two persons potentially available to be enrolled as responsible for a given discipline during a study. This was done since most of the experts that participate on CPRIME´s studies also work in other projects. Hence, having more than one person per discipline familiar with CPRIME´s process would make human resources shortage less likely and avoid potential decrease in productivity that naturally may happen due to the learning curve of a newcomer to the process.

CPRIME´s studies are led by a team leader, who has been the same person responsible for the discipline "Systems". It would be more appropriate, as is done at ESA´s CDF (Biesbroek, 2012), that these positions in each study were occupied by different persons, but the combination of team leader and systems expert in a single person has been working well so far at CPRIME.

The baseline disciplines considered during a study at CPRIME are shown in Figure 15. They resemble basically the ones that exist in ESA´s CDF (Tatnall et al., 2011). They comprise technical and managerial aspects of the development of a space mission, taking into account all elements of the mission architecture. One expert should be assigned as the "focal point" to each discipline, but in some cases the same expert may tackle more than one, close related disciplines. For example, a single expert may deal with the disciplines "layout" and "structure" in a study. However, it is not advisable to have a single person assigned as the "focal point" to more than one discipline. It may be perfectly justifiable that an expert be a focal point for one discipline, and help other experts in related disciplines, though.

Depending on the scope of the study all or a subset of disciplines are taken into account. For example, a study may focus on the assessment of operational viability of a mission where the satellite is already available. Other example would be the use of existing platforms without propulsion. In these and in many other possibilities, only a subset of CPRIME´s baseline disciplines would be required to perform the study and the team will be assembled as necessary to fulfill the analysis required by the study´s scope.

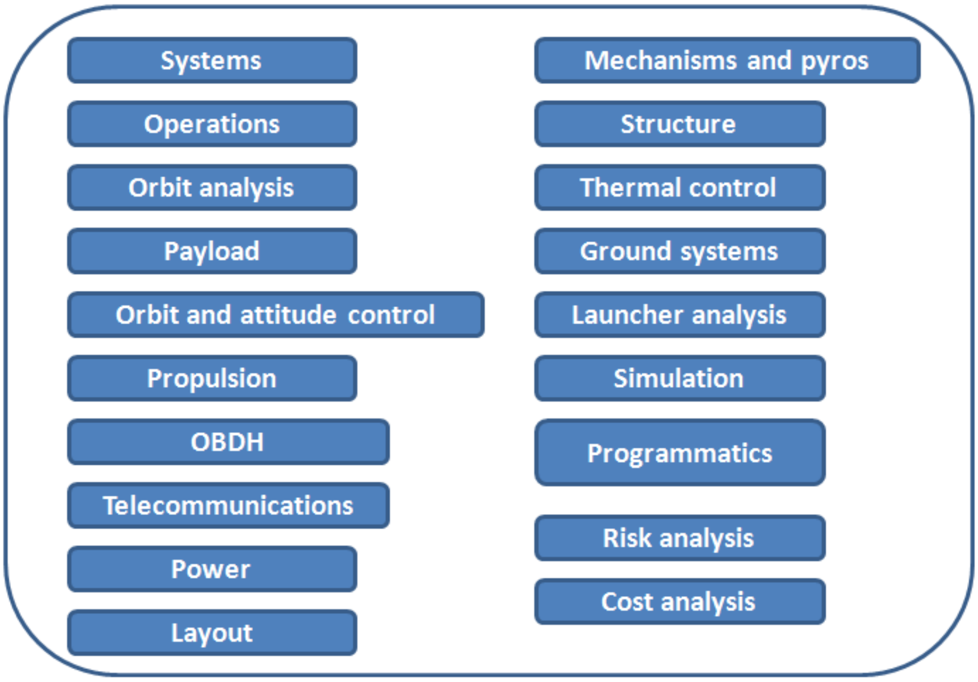

Figure 15 - Baseline disciplines take into account in a study at CPRIME.

Teamwork and cooperation are essential in any concurrent design environment. The flow of information and the full exploration of the concurrent approach, though supported by dedicated hardware and software tools, are basically dependent on the motivation and integration of the team, which the team leader may pay close attention. In Figure 16 is shown a mosaic of photographs taken during a study at CPRIME.

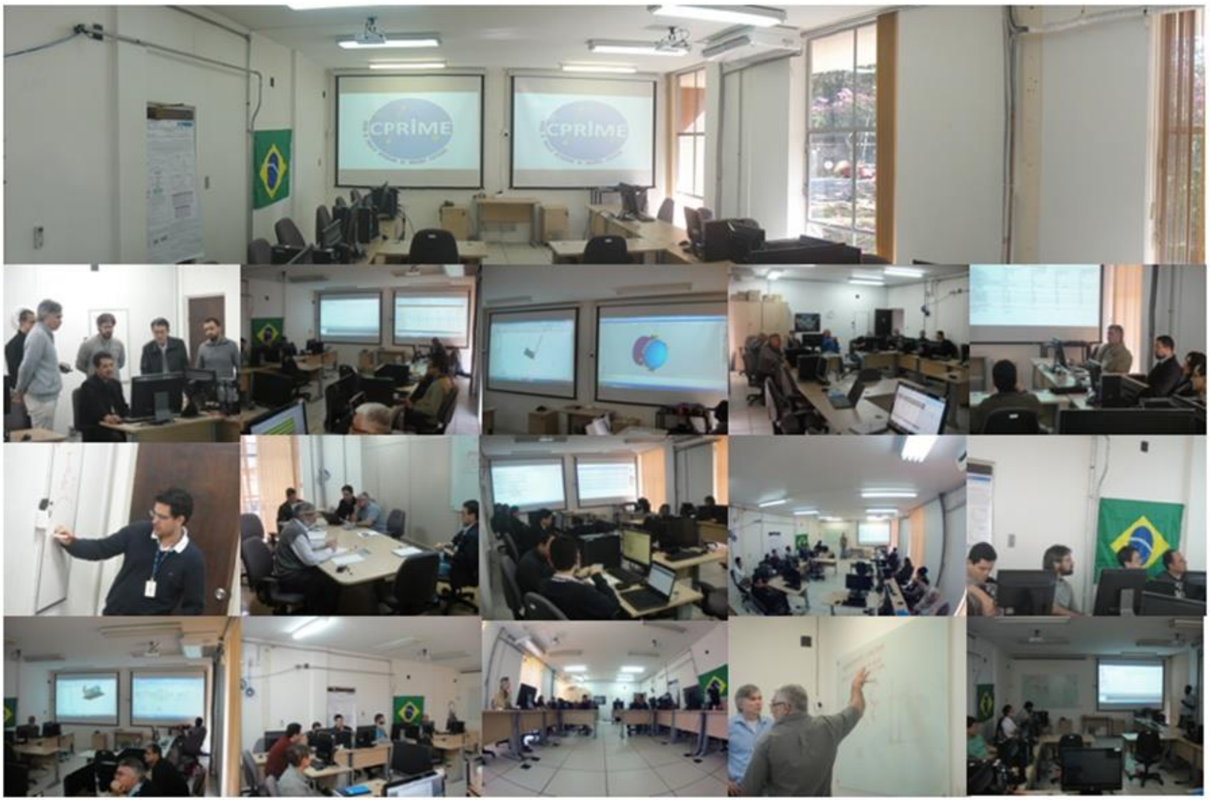

Figure 16 - Mosaic of moments of a study at CPRIME.

4 Studied performed so far and lessons learned

As of December 2022, 15 studies were performed at CPRIME. Some of the early studies were realized with the main purposed of exercising the design process and/or as a way to prepare the Center for potential demands. However, even in these studies, the drive was a potential real demand. For example, in the DETER-Plus study, the main purpose was to exercise and consolidate the conceptual design process. However, the objectives and requirements of the mission study case were posed by the head of the programs DETER/PRODES, envisioning and upgraded version of this monitoring system. Hence, the study results were in fact candidate solutions to fulfill such mission.

Table 2 lists the studies performed so far at CPRIME. They comprised optic and SAR Earth observation missions in LEO, and scientific missions in LEO and GEO. Moreover, a study about a telecommunication mission using a GEO satellite was also performed, but in this case with the main purpose of raising the knowledge of CPRIME´s team over the technology and design aspects of such kind of mission. The satellites conceived at CPRIME´s studies range, in terms of mass category, from nanosat to big size (several tons).

Table 2 - Summary of studies performed at CPRIME as of December 2022.

ID	Short name①	Main scope	Year②
01	PMM-HR	High resolution Earth observation mission using the PMM.	2014
02	DETER-Plus	Concept design of a space system for monitoring the brazilian biomes and improvement of CPRIME´s design process.	2015

ID	Short name①	Main scope	Year②
03	CAR	Concept and viability analysis of a mission to fulfill the monitoring demands of "Cadastro Ambiental Rural" (CAR) and environment management of Brazilian biomes.	2015
04	Equars	Concept and viability analysis of Equars scientific satellite.	2016
05	SAR	Exercise CPRIME´s team on the conception of a SAR space mission.	2016
06	D-Equars	Re-analyis of Equars mission with updated requirements.	2016
07	SPORT	Analysis of SPORT cubesat concept of operation in regard to the utilization of INPE´s ground facilities.	2017
08	GSST	Concept and viability analysis of Galileo Solar Space Telescope satellite.	2018
09	Payloads to VLM-1	Analysis of possible INPE´s candidate payloads for the first fly of VLM-1.	2018
10	GEO-Telecom	Exercise to understand the requirements, design and technological aspects of a geo-synchronous telecommunication mission.	2018③
11	CBPMM-SAR	SAR mission in the scope of CBERS Program using the PMM as platform.	2019
12	novoMAPSAR	Earth observation SAR mission using the PMM	2019
13	MIRAX	Scientific satellite with a X-ray observatory payload.	2020
14	Catarina Constellation	Orbit analysis for a data relay constellation of nanosats.	2021
15	BiometSat	Scientific 6U cubesat Earth observation mission for environment monitoring.	2022

OBS: ①Short name for the purpose of this document. ②Refers to the year the study´s report was issued. ③No report for the GEO-Telecom study was produced.

Some general observations and lessons learned can be drawn from the 15 studies carried out so far at CPRIME:

- The use of multimedia and white boards to communicate ideas and carry out technical discussions during a design session showed to be paramount on solving problems and evolving solutions. In fact, as pointed out by Tatnall et al. (2011), "the cornerstone of success in CE is communication". Nevertheless, it is possible to perform a study with 100% remote participation. In this case, it would be very important that the team members had prior experience on at least one study.
- At the beginning of a study, make clear what is its scope. Remind the team of this, at each new design session.
- Make at least one meeting with the stakeholder demanding the study and the design team, so that team members can clarify directly with him/her eventual doubts about the study´s scope, and the mission´s objectives, requirements, and constraints. It is desirable that the stakeholder follow the study as the solutions are conceived and evolved. At least, he/she may have to be available to clarify doubts, and help on decision making, concerning the expectations of the stakeholder vis-à-vis analysis results that may arise during the study.
- In a given study, it is important that the majority of the members have prior experience on the CE design process to avoid or minimize delays and misunderstandings due to members

not being familiar with the flow of information and design steps taken during a design session.

- At the start of each design session, begin with an explanation of where the study is and what are the goals to be reached at the end of the session.
- Follow the design process strictly. It is the backbone where the normally semi chaotic CE environment holds. This is important to avoid "jumps" to potential solutions without take into account all mission aspects, what may result in unbalanced, or poor, solutions.
- Keep all team members "on the same page", concerning where the study is, what was already accomplished and what is the latest information about the design parameters. This can be accomplished by proper team leading and a data management tool. In CPRIME, this tool is still the systems workbook, which codifies the design process and critical parameters that describes the mission being studied.
- Keep subsystem models documented, up to date, and easily available.
- It is very important to maintain an updated data archive of spacecraft COTS, as well as equipment used in prior missions, for payloads and service model components/equipment. This information is used to assess technologic availability, make or buy strategies, possible layout configurations for the spacecraft and other design parameters. Not having such database, will increase the uncertainties associated with the design conceived for the spacecraft. In the case the database is not up-to-date, the study latency is increased (due to the time spent on search for the information on-the-fly), or worst, good solutions may be missed.
- A study´s design time (Phase 2 of CPRIME´s process, see Figure 4) is highly dependent on the time allocation of the design team to the study. With proper allocation, it was possible to carry out a design time study at CPRIME in 6 weeks. In fact, for the CAR mission, the total study´s time, from request to delivery of the final report, took approximately 10 weeks!
- As pointed out by Tatnall et al. (2011), ""a fundamental part of the concurrent engineering approach is to create a highly motivated, multi-disciplinary team that performs the design work in real-time", what includes to deal with potential conflicts and different personalities that naturally are present in a group of people working together. Such challenges to team leaders are a characteristic of CE environments (Biesbroek, 2012; Braukhane and Bieler, 2014).
- It is very important that the facility has a permanent core team of specialists for interfacing with stakeholders proposing new studies, such that a preliminary assessment of the study is done and is scope well understood, in such a way that a proper planning for its execution can be made. This core team would be also responsible to verify if the Center is in a ready state (all components that compose the integrated design environment, and specialists, can be accessed immediately as needed) to accept new studies.
- A dedicated team to keep the facility´s IT infrastructure and develop tools to store and share design parameters is also very important. In fact, this is critical to provide the Center with a working integrated design model.

5 Conclusion

It has been almost 10 years since the beginning of what became CPRIME. Through these years a capability has been built and evolved to provide INPE with the capacity of making conceptual studies and viability analysis of space missions, in a fast and efficient way.

Being the first of its kind in Brazil, CPRIME was proposed and built inspired by the success of CE Centers that exists in USA and Europe, mainly NASA´s Team-X and ESA´s CDF.

The ability to respond rapidly to feasibility analysis demands of new space missions, providing technical as well as programmatic, cost and risk analysis, is a powerful capability added to INPE´s decision making process for proposing new projects. It fits very well in the new strategy of "mission adoption" implemented by AEB for the PNAE 2022-2030 (AEB, 2022), since with CPRIME, INPE increases its capability to perform and document more, and timely, new space mission proposals, which can be submitted to be adopted by AEB. In fact, CPRIME is a "tool" that can be used by AEB or other PEB´s stakeholders, as already have been done, for concept and/or feasibility analysis of space missions, helping these organizations with technical analysis, in support to decision making.

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