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VISION OF A NEXT-GEN CONCURRENT DESIGN FACILITY (CDF-LU)

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The current paper provides what it takes to develop a concurrent design facility and addresses the vision, capability, application, and product domains of the CDF-LU. The most significant features of lab with details of its hardware and software systems are provided. In addition the capability criteria and system engineering methods and processes as applied in the CDF-LU are addressed. This paper thus outlines a strategic process on how to develop such an advanced research laboratory
keywords: concurrent, spacecraft, design, mission, CDF,

1. Introduction

The past few years have seen a surge and renovated interest in the space industry globally. In addition to the numerous NewSpace startups and commercial ventures, multiple national space agencies have been established by countries which were traditionally not highly active in the space domain. The Grand Duchy of Luxembourg is one such nation that setup Luxembourg Space Agency (LSA) in 2018 with the goals to develop the Luxembourg space ecosystem.[1]

As an initiative to develop and attract the best talent for the growth of the space sector, LSA in collaboration with the University of Luxembourg started the Interdisciplinary Space Master (ISM) program in 2019. The ISM program is undertaken by the SNT Research Center of the University of Luxembourg. As a part of the ISM program, the SnT research centre has established an advanced space system design facility with the goal to investigate and design next generation of space missions and space systems concepts. The design facility is practicing concurrent engineering methodology and is known as the Concurrent Design Facility at Luxembourg (CDF-LU). It is currently being applied in the educational and research activities under the ISM program and is planned to be used in commercial research applications advancing the budding commercial space industry landscape in Luxembourg. The author is currently heading the CDF-LU and has been responsible for the setup and ongoing research in the CDF-LU.

The current paper provides an overview of the setup process and addresses early-stage thinking that went into CDF-LU establishment. The second section introduces the concurrent design approach and presents an overview of the literature review addressing major global concurrent design centers. The third section focuses on the key elements of a concurrent design center. Section four addresses the CDF-LU and outlines the details of the facility along with the vision, capability, and application domains of the CDF-LU. The last section summarizes the lessons learned and conclusions. The objective of this paper is to answer the question: what it takes to develop a modern concurrent design facility.

2. Concurrent Design of Space Systems

Space systems design is a multidisciplinary domain where constituting subsystems are integrated in a systems framework to meet the mission objectives. The subsystems are individually modeled using physics-based parametric analysis while they are integrated together in a systems framework using specialized synthesis processes and tools. This chapter provides a brief overview of synthesis methodologies applied for designing space systems while focusing on concurrent design approach.

2.1 *Traditional Design Vs Concurrent Design*

Typically, space systems design synthesis tools can be grouped in two major categories as shown in Fig. 1. The first category of the synthesis tools could be labeled as traditional design methodologies. Here the design process is executed in a sequential manner, from one design discipline to the next, one step at a time, passing the design from one disciplinary team to the next. The design goes through several iterations until the requirements from all design disciplines are satisfied. Although this category is most widely applied, it has drawbacks that favours a certain level of separation among the design disciplines.

Traditional design methods first emerged as manual design processes where calculations for each design discipline was conducted by-hand and results were put together in a non-integrated manner. With the

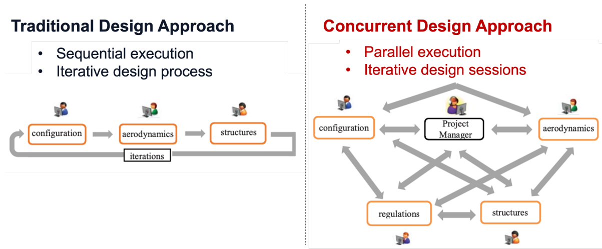

Fig. 1: Traditional and Concurrent Design Approach [ref]

advent of modern-day computers, the disciplinary analysis calculations were the first element to be done using the high computation capabilities. The disciplinary integration and information management through the framework came last and is still an actively ongoing field of improvement. Examples for traditional design methods can be commonly found in classical design processes like those provided by Raymer[2] for aircraft design; K.D. Wood[3] for launch vehicle design; Rowell and Korte's Launch Vehicle Design Process;[4] Hammond's space system design process[5] and numerous space-system design tools such as SSSP (Space Shuttle Sizing Process);[6] PrADO-Hy;[7] AVDS;[8] FLOPS;[9] ModelCenter[10] etc. A comprehensive review of the traditional space system design methods and tools can be further found in references[11] and.[12] In all these tools, the design process is usually executed in one stand-alone platform which connects all subsystem analyses together.

The second category is the modern design approach of concurrent design methodology. In this approach the design disciplines are executed in parallel to each other and thus, the information flow from one discipline to other is faster and efficient than traditional design processes. Figure [ref] shows the difference between a traditional design methodology and a concurrent design methodology. As opposed to the traditional methods, the concurrent design favours higher level of integration among design disciplines. Dedicated tools and platforms are required to enable such concurrent design execution. ESA's Open Concurrent Design Tool (OCDT)[13] and Rhea Group's Concurrent Design Platform[14] are prominent examples of such concurrent design platforms being applied in the European space industry.
The concurrent design method stemmed out of the concepts of concurrent engineering from a 1988 initiative of the USA Defense Advanced Research Projects Agency (DARPA) program to improve the product development process.[15] Since then concurrent design has been adopted and applied in the early stage design application for space systems and space mission design. A number of concurrent design centers have been established globally which are addressed next.

2.2 *Concurrent Design Centers Around the World*

NASA at the Jet Propulsion Laboratory (JPL) setup the Project Design Centre (PDC)[ref] in 1994 as the first dedicated facility to implement concurrent engineering towards space missions and systems design applications. Since then several other international space agencies, aerospace industry leaders and academic institutions have adopted concurrent engineering practices and setup their own concurrent design environments. Table 1 provides an overview of some of the major concurrent design environments that were reviewed in detail during the setup of the CDF-LU. This review helped to define the vision and characteristics of the CDF-LU that are presented in the later chapters of this paper. First, a brief synopsis of the existing concurrent design environments is presented next.

2.2.1 *Space Agencies*

As could be seen from Table 1, most of the space agencies around the globe have invested in a dedicated concurrent engineering environment. Following the establishment of PDC at JPL in 1994, NASA setup concurrent engineering facilities at its other major centers. These included the Integrated Mission Design Center (IMDC)[16] at the Goddard Space Flight Centre (GSFC) in 1997, the Integrated Design Center (IDC) in 2003 which was later redeveloped into Engineering Design Studio (EDS) at the Langley REsearch Center (NASA LaRC), and the COMPASS team in 2006 at the Glenn Research Center (NASA GRC).
Across the Atlantic, ESA setup the first European concurrent engineering facility in 1998 in the Research and Technology Centre (ESTEC) located in Noordwik, Netehrlands [ref]. Since then, the ESA CDF has become a major design center for the European space industry and has performed over 200 design studies [ref]. Following the success of the ESA CDF, other European space agencies established their own concurrent engineering centers as can be seen in the Table 1. The French Space Agency CNES setup CIC at its PASO Research Center, the German Space Agency, DLR setup Concurrent Engineering Facility (CEF) in Bremen in 2008, the Italian Space Agency, ASI setup its own CEF in Rome in 2008. In

Facility Name	Year	Parent Organization	Country
Space Agencies			
Project Design Centre (PDC)	1994	NASA (JPL)	USA
Integrated Mission Design Centre (IMDC)	1997	NASA (Goddard)	USA
ESA Concurrent Design Facility (CDF)	1998	ESA (ESTEC)	Netherlands
EDS	2003	NASA(LaRC)	USA
Conception en Ingénierie Concourante (CIC)	2005	CNES (PASO)	France
JAXA Mission Design Centre (MDC)	2005	JAXA	Japan
COMPASS	2006	NASA (Glenn)	USA
Shenzhou Institute (SZI) Concurrent Design Facility	2007	CASC (CAST)	China
Concurrent Engineering Facility (CEF)	2008	ASI	Italy
Concurrent Engineering Facility (CEF)	2008	DLR	Germany
Concurrent Design Facility (CDF)	2011	RAL Space	UK
Australian National Concurrent Design Facility (ANCDF)	2017	UNSW	Australia
Industry			
Concept Design Centre (CDC)	1997	Aerospace Corporation	USA
Satellite Design Office (SDO)	1999	EADS/Astrium	France
Satellite Design Office (SDO)	1999	EADS/Astrium, Friedrichshafen	Germany
Satellite Design Office (SDO)	1999	EADS/Astrium, Stevenage	UK
Integrated System DEsign Center (ISDEC)	2006	Thales Alenia Space, Roma	Italy
Collaborative System Engineering (COSE)	2007	Thales Alenia Space, Torino	Italy
Univeristies			
Collaborative Design Environment (CoDE)	1994	Georgia Technical Institute (ASDL)	USA
Laboratory for Spacecraft and Mission Design (LSMD)	1999	California Institute of Technology	USA
Design Environment for Integrated Concurrent Engineering (DE-ICE)	2000	Massachusetts Institute of Technology (MIT),	USA
Space Systems analysis Lab (SSAL)	2004	Utah State University	USA
Concurrent Design Facility (CDF)	2007	École polytechnique fédérale de Lausanne (EPFL)	Switzerland
Concurrent Design Facility (CDF)	2008	International Space University (ISU), Strasbourg	France
Concurrent Design Facility (CDF)	2009	Technical University of Madrid (UPM)	Spain
Concurrent and Collaborative Design Studio (CCDS)	2015	University of Strathclyde, Glasgow	UK
Concurrent Design Facility (CDF-LU)	2020	University of Luxembourg	Luxembourg

Table 1: Major Concurrent Design Centers around the World

the UK, the first CDF was founded in 2011 by the RAL Space in Harwell Campus in Oxford.
In addition to these American and European space agencies, few other national space agencies have initiated their own concurrent engineering facilities. Japanese national Space Agency, JAXA setup the Mission Design Centre in 2005. In China, a CDF was founded by the China Academy of Space Technology (CAST) at the Shenzhou Institute (SZI) in 2007. The Egyptian Space Agency (EgSA) setup a CDF in 2012 while the Australian National Concurrent Design Facility (ANCDF) has been setup at the Canberra Center of the University of New South Wales (UNSW) in 2017.

2.2.2 *Space Industry*

Concurrent design approach has also been adopted and applied in the commercial aerospace industry since the early 1990s. Among the major industry players, the Aerospace Corporation in the US was the first to establish the Concept Design Center (CDC) in 1997.
In the European aerospace industry landscape, EADS/Astrium established three Satellite Design Centers in 1999 at its facilities in France, Germany and the UK. Thales Alenia Space also setup two concurrent design centers, ISDEC at its Rome facility in 2006 and COSE in its Torino facility in 2007. Typically, the industry-based design centers work under the proprietorship of the organization. These design centers usually develop their own specialized tools and methods and rarely share the details of methods used in the design studies. Their work and applications are usually tailored and biased towards the capabilities of the host company. Due to these factors these design centers share very limited information in public domain. In addition to these permanent facilities, industry players regularly participate in concurrent design studies with agencies and academic institutions in research and development projects. Airbus ref [] concurrent design study is one such example.

2.2.3 *Universities*

In addition to the space agencies and commercial industry, concurrent design approach is also applied in academic environments. Table [ref] provides a list of significant concurrent design centers established in various universities in the USA and Europe. University of Luxembourg is the latest to join this list has setup the Concurrent Design Facility (CDF-LU) in 2020. Although, the major application of an academic concurrent design center is in teaching the students, most are also involved in conducting research in this domain and occasionally work with the industry and agencies on design studies and projects.

3. Key Elements of a Concurrent Design Center

The review of existing concurrent design centers provided some insightful findings that were applied during the development of the CDF-LU. Most concurrent design centers have a few common aspects that could also be attributed as the key elements that are required to practice and implement concurrent design engineering. These key elements are addressed in three major categories, namely; 1) Team, 2) Hardware, and 3) Software.A n overview of the key elements is presented in Table 2.

3.1 *Team*

A concurrent design center is a working facility where the design team works for long hours at a stretch. The design team is composed of multiple participants who collaborate in a multidisciplinary environment. Although a concurrent design center is an engineering facility that is composed of a number of hardware and software elements, the author believes its the people of the design team who are the most important element of the concurrent engineering.
A concurrent design study is generally composed of several team members who work together in different roles and capacity to fulfil mission objectives. The structure and composition of the team can vary depending on the nature and scope of the study. Similarly, the role and position of team members can also differ from one center to the other based on the objective of the study. Osborn[17] lists three major categories of team members as follows:

- *Project Owners*: The project owners are generally those who define the project, have the final purview over the outcome, and sometimes fund the design study. Project owners could be the internal managers, scientists, customers or a stakeholder from an external organization. Although it is not mandatory, the project owners are usually active participants in the design sessions. Having the project owners directly involved in the design session can provide quick decision-making capability and help accelerate the design process.

- *System Engineers*: The system engineers are generally team leaders and also go by different titles like the chief design engineer or study lead. System engineers are mainly involved in defining

TEAM	
Project Manager	Define, plan and oversee timely execution of project tasks and deliverable
Synthesis/SE	Develop and execute the overall systems synthesis tasks
Specialists	Disciplinary specialists
External Support	Customer, Consultant
HARDWARE	
Workstation	PCs, laptops etc
Server	IT server
Visualization	Large display screens for effective visualization and collaboration
Communication	HQ Video Conferencing Equipments (Camera, Mics)
SOFTWARE	
Library	Central, standardized space for storing and managing references, data, knowledge (Excel, Mendley, JabRef)
Analysis	Discipline-specific analytical tools, methods (Excel, MATLAB, Python etc.)
Integration/Synthesis	A framework to integrate disciplines into a logical, mathematical, physics-based process and modeling (ModelCenter, STK, RHEA CDP4 etc.)
Visualization	Software for generating and visualizing product models (CAD, ProE, Catia, Visio, Illustrator etc.)
Management	Project definition, planning, and management (MS Project)
Documentation	Creating reports, software tutorials etc (Word, Latex etc.)

Table 2: Key Elements of a Concurrent Design Center

the initial requirements of the project and setting up the model before the design sessions begins, and during the design session act as the communication interface among disciplinary teams and as the interface with the project owners. They are also responsible for making the design decisions, resolving conflicts between disciplinary teams, and providing leadership before, during, and after the design sessions. In some facilities these functions are also distributed and performed by more than one person.

- *Disciplinary Specialists*: The disciplinary specialists are responsible for conducting engineering analysis for various disciplines involved in the study. The number and composition of the disciplines can change depending on the nature of the system and scope of the study. Further, each discipline can have one or more specialists responsible. In these instances, there can be one specialist who can act as the disciplinary lead and interface with the system engineer and other disciplines.

It must be noted that these three categories does not necessarily include all team members at every concurrent design centers. Instead they provide a broad range of roles that are played by one or multiple people. Developing a competent team is a time consuming task. Further, the experience of the team members individually and the entire team as a unit plays an important role in the success of the design sessions. Generally speaking most of the team members are physically present in the center during a design session. Occasionally a few team members or external experts can also join the sessions remotely. This feature has become even more critical in the recent times since the outbreak of the Covid-19 pandemic.

3.2 Hardware

The ability to efficiently communicate and collaborate between team members (both, in-person and remotely) is a crucial requirement for a concurrent design center. Certain hardware elements are required to enable this collaborative environment. These hardware elements largely affect the efficiency and operational capacity of the center. The significant hardware elements in this regards are as follows:

- *Facility*: The facility refers to the configuration layout of the design center or the room itself. The size and shape of the room determines how many workstations can be setup which further influences how many participants can collaborate in the design study. Although remote participation is a possibility and is occasionally required, the number of participants physically present in the facility is still an important driver. Further, how the workstations are arranged, how other hardware elements are setup in the facility also defines the overall configuration of the concurrent design center.

- *Workstations*: A concurrent design center usually have multiple workstations occupied by the team members. Generally these workstations host permanent desktop computers but in some cases also have the option for participants to use personal laptop computers. A crucial requirement is that these computers are connected to other hardware elements in order to facilitate an integrated collaborative engineering experience.

- *Server*: In most concurrent design centers the workstation computers are connected to a central server through which exchange of information occurs between workstations. This server is generally a dedicated server device inside the facility, but in some cases, one of the workstation computer or a remote virtual machine can also act as the server space. The server provides a mutual cyberspace platform where the modeling framework integrates data and analysis from all disciplines. The server can also act as a repository for the saving the design sessions and databases of past missions, systems, subsystems, hardware equipment etc. to support future design studies.

- *Display*: Almost all concurrent design centers contain one or multiple central display screens. The purpose is to display the content of the workstations to the whole team at the same time. For this reason, the display has to be a large screen with enough resolution that the content is visible to all the participants. Having a large central display screen ensures that the entire team is aware of the status of the design. This feature also allows the team to discuss and take real-time decisions with pertinent information visualized immediately to everyone. Further, large display devices are also needed in teleconference sessions with remote participants. Although projectors are a common and cheaper way to implement large display screen, they often lack the clarity and efficiency of high-end expensive display devices such as a videowall or a large touchscreen display.

- *Cameras and Microphones*: While a large display screen is required primarily for sharing information among team members, cameras and microphones are required mainly for teleconferencing with external participants. Most concurrent design centers have a dedicated suite of several cameras and microphones on the workstations such that all workstations can participate in a teleconference session. Even though not its main purpose, these devices can also allow to record and save design sessions if needed.

- *Auxiliary Devices*: In addition to the above mentioned hardware devices, many concurrent design teams use several auxiliary devices for further ease of collaboration and increasing the efficiency of the design team. Digital smartboards are a common example in this category. ESA CDF regularly uses 3-D printing facility to examine tangible prototypes of the system concepts being designed in the CDF. Another example could be that of NASA Langley's EDC team using virtual reality (Microsoft Hololens) technology.

3.3 Software

While the hardware elements facilitate a collaborative environment, the concurrent engineering of space system require a wide range of software tools. Some commonly used software tools in various concurrent design centers are discussed next categorized according to primary support function they provide.

- *Disciplinary-specific analysis*: Design is a multidisciplinary domain where various disciplines are integrated in a holistic system solution. These disciplines are also represented as subsystems for a space systems and can vary from one space system to other. Some typical disciplines involved in space-system design include propulsion, communication, aerodynamics, structures, geometry, trajectory, mission analysis, power, attitude control et al. Each of these disciplines is mathematically solved using a parametric analysis method. The analysis could be performed by a commercially available program (eg. STK) or self-developed programs/codes using any standard computing environments such as C++, Matlab, Python, Excel etc.
  These tools are mainly used (and sometimes developed) by domain experts for their disciplinary analysis and are required on the workstations hosting domain specialists.

- *Concurrent engineering platforms*: Most concurrent design centers use a platform that implements concurrent engineering. The Open Concurrent Design Tool (OCDT) developed for and applied in the ESA-CDF [ref] is an open-source concurrent engineering platform. It is composed of two entities, first an SQL-based database server that facilitate exchange of information between all workstation, and second a client-facing Excel add-on application called the CONCORDE. One workstation in the CDF is dedicated as hosting the OCDT server, while CONCORDE plug-in is installed on every workstation. Using the CONCORDE plugin in the MS Excel, each workstation can connect to the OCDT SQL-server, and work on a common model with which parametric information exchange is facilitated. RHEA Group's CDP4 (recently changed to COMET) is another similar concurrent engineering platform that is being applied at several European concurrent design centers. In addition to these off-the-shelf available platforms, some concurrent engineering centres have developed their own applications which facilitate concurrent design engineering.

- *Collaboration tools*: These software tools mainly provide for means to exchange information between different stakeholders including remote participants. The information could be in form of factual parametric information or files. This requires some form of digital storage space (to store common files) and shared databases (to exchange factual and parametric information). Further, a form of digital whiteboard or sketchpad is another way in which collaborative information could be exchanged among team members. There are numerous software options and applications to perform each of these tasks individually.
  As an alternative, a number of online commercial platforms provide these and several additional collaboration services in one place. Google, Microsoft, Cisco and few other notable companies provide a suite of tools (both online and/or as applications) to collaborate much more efficiently.

4. CDF-LU

This section addresses the Concurrent Design Facility at the University of Luxembourg (CDF-LU). The facility is situated in the Interdisciplinary Centre for Security, Reliability and Trust (aka SnT Research Center) at the Kirchberg Campus of the University of Luxembourg. The CDF-LU was established in September 2020 under the Interdisciplinary Space Master (ISM) program at SnT in collaboration with the Luxembourg Space Agency (LSA). Following subsection provide further details of the facility.

4.1 *Facility Overview*

Room Configuration: The CDF-LU room is a 80 sq. m. rectangular room that houses a multimedia ecosystem consisting of nine workstation with 14 permanent desktops, microphones, speakers, cameras and large display screens. The overall configuration layout of the facility is shown in Fig 2. The facility is developed for the dual-use purpose of academic application under the ISM curriculum setting and research applications beyond the ISM program.

Workstations: The CDF-LU has nine workstations with two seating spaces per workstations. Seven workstations are arranged in a oval arc to be used by the ISM students in the academic setting and by subsystem specialists in the research setting. The remaining two workstations are used by Professors in the teaching setting and occupied by system engineer and/or project owner during the research application. Every workstation can house maximum of two desktop computers. As can be seen in the Fig [ref], all workstations host one or more desktop computers. Several workstations have empty space for adding additional computers if needed during the project. All the permanent desktops are connected to the microphones and are equipped with aerospace engineering software (Auto CAD, STK etc.) and coding tools (MATLAB, Python etc.).

Multimedia Devices: CDF-LU host a number of multimedia equipment which allows efficient collaboration between team members both, in physical and remote participation modes. These devices include nine Sennheiser microphones, four 360-degree Panasonic cameras (C1 to C4 in Fig [ref]), two QSC speakers, and two large LG display screens (S1 and S2 in Fig[ref], each screen is 218 cm large). In addition to these devices, the CDF-LU room is also equipped with a Cisco Webex device which is used with the multimedia equipment for teleconferences and remote working sessions.

An Integrated Ecosystem: All multimedia devices are connected to the permanent desktops and makes

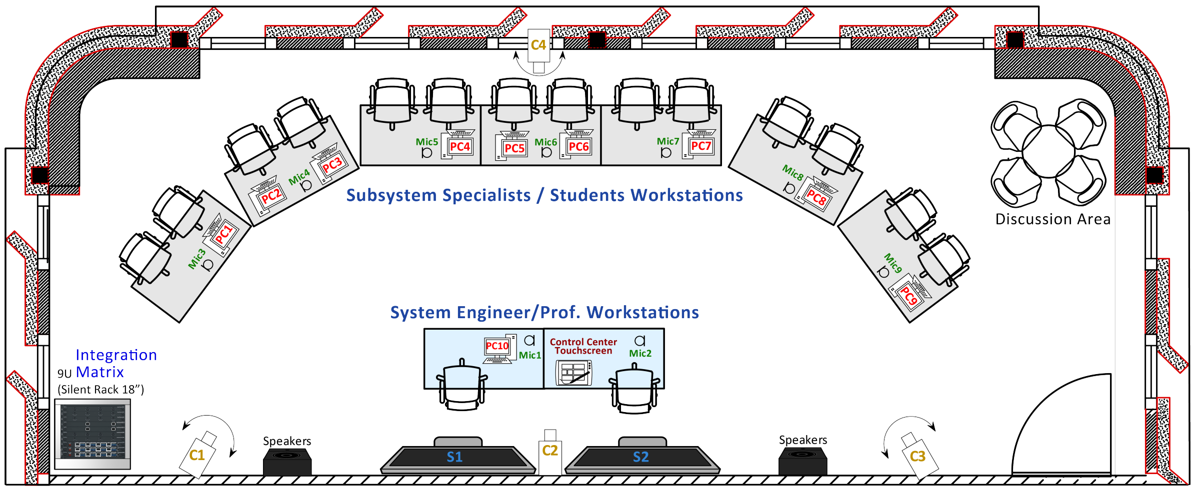

Fig. 2: CDF-LU Layout and Configuration

an integrated ecosystem. Every workstation desktop is connected to the microphone, the speakers, and can be displayed on the large screens individually or simultaneously. This integration of all audio and video channels in the facility is handled by a device that is internally referred to as the Integration Matrix. This device is an ultra-high bandwidth 4K videowall processor by Extron (Quantum Ultra) and is housed in a standard 9U rack. This integrated ecosystem is controlled by a central control system which is present at the system engineer/prof workstation. The control system is 10 inch touchscreen tablet with a custom-built user interface software. It allows user to control all multimedia devices including how they are connected to each other and how they operate in teleconference mode.

The integrated ecosystem implements easy and efficient collaboration between the team members and provide different mode options to enable a truly collaborative and concurrent engineering environment. An example of such feature is that in one of the operation modes, the press of the microphone button on the workstation would immediately display the computer's content on the large screen visible to the whole team. Alternatively, in the teleconference mode, press of the microphone button would zoom the camera on the workstation such that the CDF team member is immediately visible to the remote participant and the content of the CDF member's workstation is shared in the teleconference call. Additionally, both large screens put together can display all workstations simultaneously, thus making entire team's work visible to everyone. This feature is found particularly useful in the teaching mode. Further, the CDF sessions could be recorded via the Cisco device with the option to store the recording on Cisco cloud.

Concurrent Design Platforms: The features described until now constitute the physical aspect of the CDF-LU. These devices implements a collaborative working environment. But the essential ingredient of a concurrent design facility is the concurrent engineering platform which requires two key elements. First is a shared server space and second is a concurrent engineering software. Both of these combined together integrate all workstations to exchange parametric information and allow the design team to work concurrently on the same design model.

In the CDF-LU, the shared server space is implemented in two alternate ways. First server option is setup through a virtual machine environment that is running in the University of Luxembourg's High Performance Computing platform.[18] Second server option is implemented locally on a desktop computer in the CDF-LU itself. A dedicated server is being installed in the CDF-LU at the time of writing this paper that will be physically connected to all workstations through ethernet cables.

For the concurrent engineering software, CDF-LU is using two industry standard platforms. These are ESA's Open Concurrent Design Tool (OCDT) and RHEA Group's Concurrent Design Platform(CDP4.0). Both platforms applies model based system engineering approach by means of an SQL-based database server that facilitates exchange

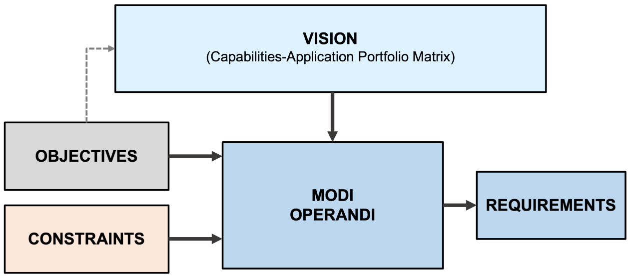

Fig. 3: CDF-LU Establishment Process

of information through a design model.

4.2 Establishment Process

The establishment of a concurrent design center is a challenging task. As explained in the previous section, a concurrent engineering facility requires setup of numerous hardware and software elements before it can be functional. If done correctly, such a setup can be a significantly expensive and time-consuming process. Hence, careful thought and planning is needed to ensure that the time and resources invested in setting up the facility are worth the effort. Several aspects were considered during the setup of the CDF-LU as discussed next. It should be noted that although the following discussion is specific to the CDF-LU, the underlying factors are generic in nature and could be addressed for any other CDF. The overall process is outlined in Fig 3.

Objectives: The primary objective of CDF-LU is to apply the lab in two main settings. First under the academic curriculum in the ISM program where it is being used as a teaching unit. Second setting is to use the CDF-LU in the research activities conducted at the SNT research center. This dual application objective was a major driver of the setup process.

Constraint: Like any other project, setting up the CDF-LU also had some constraint associated with it. The size and shape of the room was the most significant constraint in this regard which influenced the workstations' arrangement in the lab and installation of other hardware devices. Few other minor constraints were faced during the installation process driven by the limitation of the hardware elements (multimedia devices, the integration matrix and control center). Most of these constraints were addressed with an alternative option through a software alternative.

Vision: The objective define the primary goal of a project and constraints define the limitations. These two aspects are accompanied by the vision for the project which defines a tangible long-term goal. It is especially important to have this long-term goal in sight at the early stages of a project as some early-decisions might play crucial role in later part of the project. The CDF-LU vision is defined to develop a broad portfolio of capabilities (design, feasibility, planning, forecasting, strategy etc.) and apply them towards a diverse range of applications (satellites, rockets, spaceplanes, rovers). This is established in terms of a *Portfolio* matrix which identifies the type of applications and capabilities to be developed. The Portfolio is described in detail in the next subsection.

Modi Operandi: The three aspects mentioned above were utilized to create the Modi Operandi for CDF-LU. The Modi Operandi defines precisely different ways in which the facility is going to operate. For the CDF-LU, the objective of applying the lab in a dual setting acted as the main driver in this regards. The operations of a teaching activity are different from a research study. Similarly, the capability and applications defined under the portfolio could also dictate different operational scenarios. All these considerations were take into account while defining the operational scenarios.

Requirements: The operational scenarios lead to defining requirements for the hardware and software elements of the lab. These requirements clearly defined what type of hardware and software elements should be installed, how a hardware element should be setup, how different elements should interact, and how these elements should perform. The Modi Operandi and Requirements documents were the primary method of communication with the prime contractors and internal teams handling the acquisition and installation of the lab and IT department that would provide the support to the CDF-LU. Both these documents were regularly iterated with inputs from other stakeholders.

4.3 CDF-LU Portfolio

A concurrent design center can be thought as a sophisticated and complex tool that facilitate concurrent engineering applications with a team of multiple participants. As the name implies, concurrent

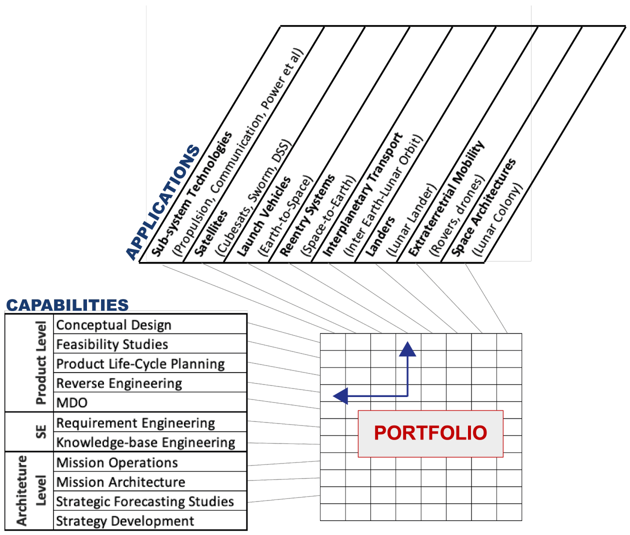

Fig. 4: CDF-LU Vision: Capability-Application Portfolio Matrix

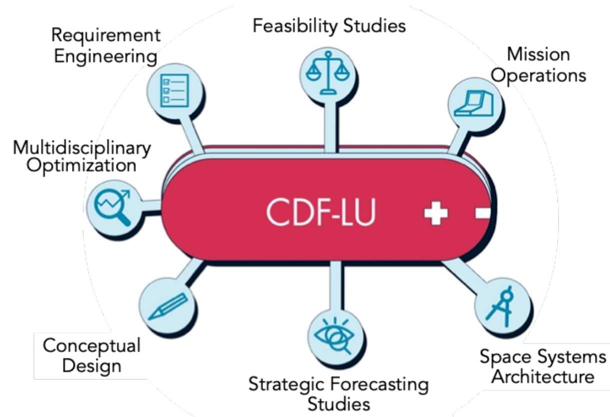

Fig. 5: CDF-LU is envisioned to be a modular and flexible setting

engineering means that different components of an engineering problem are addressed and solved at the same time (i.e. concurrently). Concurrent design is one special category of concurrent engineering where various subsystems of the space system are designed in parallel. Thus, the ability to conduct a concurrent design study is a core capability of a concurrent design center. Similar other capabilities could also be attributed towards a concurrent design center. These could include Requirements Engineering, Feasibility Studies, Multidisciplinary Optimization, Strategic Forecasting etc. Further, a concurrent design center could be applied for different types of space systems including but not limited to satellites, launchers, reentry vehicles etc. The CDF-LU aims to develop a broad range of capabilities (design, feasibility, planning, forecasting, strategy etc.) and apply them towards a diverse category of products (satellites, rockets, spaceplanes, rovers). This combination of capabilities and product applications results in different application scenarios which are outlined in a *Portfolio Matrix*. This *Portfolio* represents the long-term vision for the CDF-LU and is shown in Fig. 4.

It can be seen from the portfolio that one combination of a capability and application could be very different from another combination. For example, *Conceptual Design* (a capability) of a *Satellite* (an application) is a very different from *Conceptual Design* (same capability) of a *Launch Vehicle* (different application) since both systems (satellite and launch vehicle) have very different mission profile and subsystems. Similarly, *Conceptual Design* of a new *Mission Architecture* is different from *Reverse Engineering* of a past *Mission Architecture*. It is apparent that every capability and application combination would require a different set of data, knowledge, and tools. Further the composition of the engineering team would also change with capability-application combination. In this regard, a capability-application combination could be thought of representing a unique configuration for the CDF-LU. To successfully meet all (or maximum number) of capability-application combinations, CDF-LU should strive for a modular and flexible configuration which is adaptable corresponding to capability-application combinations. A good analogy is a swiss army knife, a modular tool-set which can become a different tool (like a knife, scissor, screwdriver etc.) as per the requirement. Similarly, CDF-LU is envisioned to be a modular and flexible setting which could adapt to the requirements of the task (capabilities) and the product (applications). Figure 5 depicts this analogy of CDF-LU equivalent to a modular swiss army knife.

Clearly, developing new databases and software tools (analysis methods, codes etc.) that could comprehensively cover all capability-application combinations in the portfolio is a monumental task and would require gradual efforts over the coming years.

4.4 Current Applications

The CDF-LU is currently being applied in multiple studies and projects. While the previous section described the long-term vision defined for the CDF-LU, the current section now provides overview of the ongoing activities in the direction towards realizing the long-term vision. An overall summary of ongoing

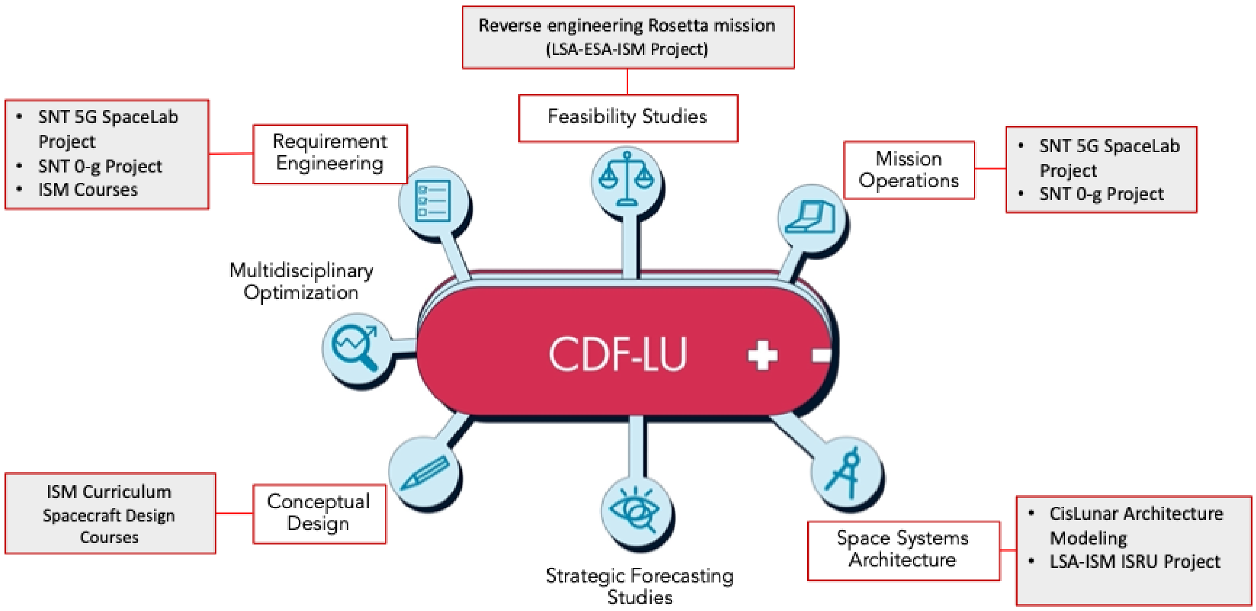

Fig. 6: CDF-LU application in different ongoing projects

projects and the capabilities they address is represented in Fig 6. As can be seen, the CDF-LU is involved in several projects in varying role and towards different applications. The following describes three applications case-studies

System Design: CDF-LU has been applied for the spacecraft design studies initially under the curriculum activities of Interdisciplinary Space Master (ISM) program. The ISM class applies CDF-LU in the design projects undertaken in the space mission and spacecraft design course. The design course follow a project-driven approach where the student team develops a space mission and system concept over the duration of a semester of the design course. Two design studies have been performed by student teams so far. Apart from the ISM courses, CDF-LU has also performed spacecraft design studies as part of ongoing research. ESA's OCDT and Rhea Group's CDP4 design platforms have been used to perform model-based concurrent design engineering in these design studies.

Space-system Architecture Modeling A space system is a collection of constituent subsystems that is developed with the primary objective of operating in space to accomplish a space mission. A Space Systems Architecture is collection of multiple space systems working towards a common objective. NASA's Artemis Program as a currently ongoing example is aimed towards developing a cislunar space system architecture. Designing a space system architecture is a complex task and deals with system-of-systems modeling. The CDF-LU is working in this domain where goal is to design an architecture and its constituting space systems. One of the ongoing project, initiated in collaboration with LSA and ESA, is a redesign study of ESA's 2005 Rosetta mission where in-space refueling at a propellant depot is being investigated. This study addresses space system architecture as it involves designing a mission that includes a launch vehicle, a deep-space spacecraft, a comet-lander spacecraft, and an in-space propellant depot. The initial results of the Rosetta reverse engineering study are presented in reference []. In addition to the Rosetta redesign study, space system architecture modeling is also being addressed in an internal research study where the space architecture is focused on Lunar space-resource mining goals.

Mission Operations

5. Conclusion

5.1 *Lessons Learnt*

Early planning is crucial Vision Portfolio (Capabilities-Applications Matrix) provides foresight and supports planning Define application scenarios via Modi-operandi Analyze constraints and requirements Adopt, develop, and apply standardized processes, workflow, documentation et al. Team development and software setup take time Value

Creation : Applications develop capabilities (and vice-versa)

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