Skoltech
Skolkovo Institute of Science and Technology

Model-based processes and tools for concurrent conceptual design of space systems

Doctoral Thesis
by

Dominik Knoll

Doctoral Program in Engineering Systems

Supervisor
Associate Professor, Alessandro Golkar
Co-Supervisor
Professor of the Practice, Clément Fortin

Model-based processes and tools for concurrent conceptual design of space systems

by

Dominik Knoll

Submitted to the Skoltech Center of Space Research
on 15th November, 2019, in partial fulfillment of the requirements for the
Doctoral Program in Engineering Systems

Last updated on Wednesday 22nd January, 2020 22:21

Abstract

In the development of complex engineering systems, such as spacecraft, the first and most crucial step is the definition and evaluation of different concepts. Model-based systems engineering, in general, and the use of concurrent conceptual design, in particular, have proven to reduce the time needed for feasibility studies of space missions. Moreover, concurrent conceptual design studies are valued for producing good quality conceptual designs and for fostering direct discussion between the customer, the involved engineering disciplines, management, and others. The benefits of concurrent conceptual design indicate a clear potential for this approach to get adopted more broadly. Therefore, we collected implicit knowledge about concurrent conceptual design from the practice of various organizations, through a survey, and confronted our findings with subject matter experts through in-depth interviews.

The core of this work consists in the formalized description of the model-based co-located conceptual design methodology. It includes a process guideline, consisting of a formal model to describe the order and interaction of activities. Also, we developed a tool to support a team's coordination during the conceptual design process. The description of our methodology helps to acquaint new people with the concurrent conceptual design approach and may serve as a baseline for implementing it in new organizations.

We verified the approach through a set of case studies on conceptual design of space systems. The study environment consisted of teams of students with limited prior knowledge and limited time. With the help of our process guideline and our collaborative tool, the project teams were able to build feasible conceptual designs.

Taking this methodology further, we describe how it can also be applied to technology planning, which often happens independently from the product life cycle. Our approach integrates technology planning and development, and conceptual design activities. Finally, we discuss the adaptation of the model-based co-located conceptual design methodology to the creation of technology roadmaps in an industrial setting and our findings.

Publications

Main author

1. Dominik Knoll, Clement Fortin, and Alessandro Golkar. Review of Concurrent Engineering Design practice in the space sector: state of the art and future perspectives. In *2018 IEEE International Systems Engineering Symposium (ISSE)*, pages 1–6, Rome, Italy, 10 2018a. IEEE. ISBN 978-1-5386-4446-1. doi:10.1109/SysEng.2018.8544387. URL https://ieeexplore.ieee.org/document/8544387/

2. Dominik Knoll, Alessandro Golkar, and Olivier de Weck. A concurrent design approach for model-based technology roadmapping. In *2018 Annual IEEE International Systems Conference (SysCon)*, pages 1–6, Vancouver, Canada, 4 2018b. IEEE. ISBN 978-1-5386-3664-0. doi:10.1109/SYSCON.2018.8369527. URL https://ieeexplore.ieee.org/document/8369527/

3. Dominik Knoll and Alessandro Golkar. A coordination method for concurrent design and a collaboration tool for parametric system models. *Concurrent Engineering*, 26(1):5–21, 3 2018. ISSN 1063-293X. doi:10.1177/1063293X17732374. URL http://journals.sagepub.com/doi/10.1177/1063293X17732374

Co-author

1. Clément Fortin, Grant McSorley, Dominik Knoll, Alessandro Golkar, and Ralina Tsykunova. Study of Data Structures and Tools for the Concurrent Conceptual Design of Complex Space Systems. In *IFIP 14th International Conference on Product Lifecycle Management 9-12 July 2017, Seville, Spain*, pages 601–611. Springer, Cham, Seville, 2017. doi:10.1007/978-3-319-72905-3_53. URL http://link.springer.com/10.1007/978-3-319-72905-3_53

2. Dmitry Smirnov, Dominik Knoll, and Alessandro Golkar. Gamespace exploration approach to complex systems design. In *Conference on systems engineering research 2016*, 2016

3. Rustam Akhtyamov, Ignasi Lluch I. Cruz, Hripsime Matevosyan, Dominik Knoll, Udrivolf Pica, Marco Lisi, and Alessandro Golkar. An implementation of Software Defined Radios for federated aerospace networks: Informing satellite implementations using an inter-balloon communications experiment. *Acta Astronautica*, 123:470–478, 6 2016. ISSN 00945765. doi:10.1016/j.actaastro.2015.12.043. URL https://linkinghub.elsevier.com/retrieve/pii/S0094576515004786

Dedicato a Maria,
madre di famiglia,
sede della sapienza,
donna di casa,
icona della Trinità.

Acknowledgments

The journey, which has led me to the accomplishment of this doctorate, has been exciting and adventurous at the same time. Looking back, I feel deeply grateful to so many people who accompanied me.

First of all, I want to thank my parents Anna and Rudolf, for my upbringing and their strong faith. Their love and permanent support allow me to fly to the heights of life. Thanks to my sisters Cornelia and Verena and to my brother Jakob for cheering for me, even when I am far away.

Special thanks go to my doctoral father, Alessandro Golkar, for providing me the opportunity to pursue research work on a topic that meets my aspiration for improving peoples' lives, by facilitating engineering team collaboration. Alessandro regularly inspired me with his ambitious visions, and his encouragement spurred me to give my best. Heartfelt gratitude also goes to Clément Fortin, for advising me on academic matters and always being ready to meet, despite his many demanding duties. He has been a great principal investigator in our industrial research project. Moreover, Clément provided me valuable personal counseling in moments of need. Thanks to Ed Crawley for co-founding Skoltech and attracting Alessandro and Clément as faculty members. I've profited greatly from Ed's wisdom, as he seeded the teaching of Critical Thinking, Systems Thinking, Systems Engineering, and Systems Architecting in the Space Center.

This doctorate would not have been possible without the support and diligence of Skoltech staff, in particular, Natalia, Ksenia, Sonya, Matthew, Dmitry, and Anna. Thanks for your commitment, and keep working on the realization of Skoltech's vision!

I was lucky to have many fantastic colleagues, namely Ignasi, Hripsime, Dmitry, Rustam, Carolina, Simone, and Nicola. Activities such as stratospheric balloon launches, discussing space endeavors, organizing student events, birthday parties, and hanging out together, make up the most pleasant memories of our PhD studies. Working together on an industrial project and delivering client-satisfying results is challenging, but doable if you have a team like I had. Thanks, Nikolay, Sergey, Ilya, Ksenia, Anastasia, and Carolina for the constructive teamwork. More thanks go to the dozens of students, who participated in the design studies spending their time and energy for my research work.

Thanks to friends and colleagues for helping to proofread this thesis: Loretta, Betsy, Patrick, Cristian, Carolina, Nicola, Valentina, and Gellert.

There are a couple of special friends who enriched my life here in Moscow. Thanks to Dominique, for the profound conversations and brotherhood, to Tatiana, for your faith, respect and enthusiasm, to Anton, for your trust, your entrepreneurial spirit, and love for nature, and to Rafail and Tania, for always welcoming me to their datcha.

Finally, I'd like to express my deepest gratitude to my community fellows: Agnieszka, Alla, Alla, Anatoly, Anna, Carlos, Cheri, Donatella, Galia, Giovanni, Laszlo, Marcel, Meta, Miguel, Ralf, Redi, Sergey, Vytautas, Wilfried and Zurab. Not only did they put up with me in hardship, but also kept believing in the best potential and sharing the engagement for universal fraternity.

Contents

List of Figures

THIS PAGE INTENTIONALLY LEFT BLANK

List of Tables

Chapter 1

Introduction

Technical systems are omnipresent in modern society and engineers are tasked to build them, such as to meet the needs of its direct users or other, indirect stakeholders. The design of technical systems is a complex task and requires deep engineering knowledge, as well as creativity to solve problems that potentially have many different solutions. Solutions can differ on a number of aspects: system architecture, technology, operations, performance or associated cost [Crawley et al., 2015]. Ideally, the performance and cost differences can be estimated, assessed and compared in the early stages of the design, and hence, support fact-based decision-making. As an example, imagine the design of a satellite constellation, providing broadband communication services via radio signals. The design goal - to cover a certain area of the earth's surface - determines the number of satellites and their respective orbits. These, in turn, require certain number of rocket launches, which result in associated costs. The dependencies between the different elements make the design a complex task.

To cope with the complexity of taking into account the entire life cycle of a product, systematic approaches are necessary. An entire discipline has developed since the middle of the last century, called Systems Engineering (SE). The International Council of Systems Engineering (INCOSE) defines it in their handbook as "an interdisciplinary approach and means to enable the realization of successful systems" [Walden et al., 2015]. Successful, in this context, means that it meets the actual needs of stakeholders. The application of systems engineering processes results in the generation of different kinds of engineering artifacts, most of them being text documents and technical drawings. For example, the stakeholder needs are formulated in natural language, translated into the more technical language of system requirements and compiled into requirements documents. During the development of the system, the requirements are used to inform technical decisions, and after manufacturing, the system is verified against its requirements [Crawley et al., 2015].

Over the last decade, a paradigm-shift has been going on in systems engineering, to replace natural language documents with models, as primary engineering artifacts. Model-Based Systems Engineering (MBSE) started with a focus on ensuring unambiguous system definition, through requirements management and conceptual models of the systems to build [INCOSE, 2007]. Already starting in the 90', the digitalization of mechanical and electrical engineering gave rise to first Product Data Management (PDM) systems and later Product Life Cycle Management (PLM) systems. Their intent was first to manage design information and later to manage all technical information over the entire life cycle of the product. While both, PLM and MBSE, aim to provide data continuity throughout the life cycle, they differ slightly in their focus. PLM focuses more on the tools and integrated tool-chain. MBSE's focus is on the processes and artifacts. Currently, various space projects are already ongoing, where MBSE is applied rigorously from the beginning, e.g. the Mars 2020 rover[1] [Fosse et al., 2015], Extremely Large Telescope[2], or the Euclid astrophysics mission [Alvarez et al., 2018]. These projects use MBSE to address the challenge of complexity, using a model as a single source of truth and allowing the different involved parties to interact with, from their specific perspective (see Figure 1-1).

1.1 Designing Space Systems

In the development of most engineering products and systems, such as those employed in space missions, the conceptual design phase is given particular importance, because this is where most of the project cost is decided upon already [Walden et al., 2015, pp.14-15]. Concept studies or feasibility studies allow organizations to obtain

---

[1] `https://mars.nasa.gov/mars2020/`

[2] `https://www.eso.org/public/teles-instr/elt/`

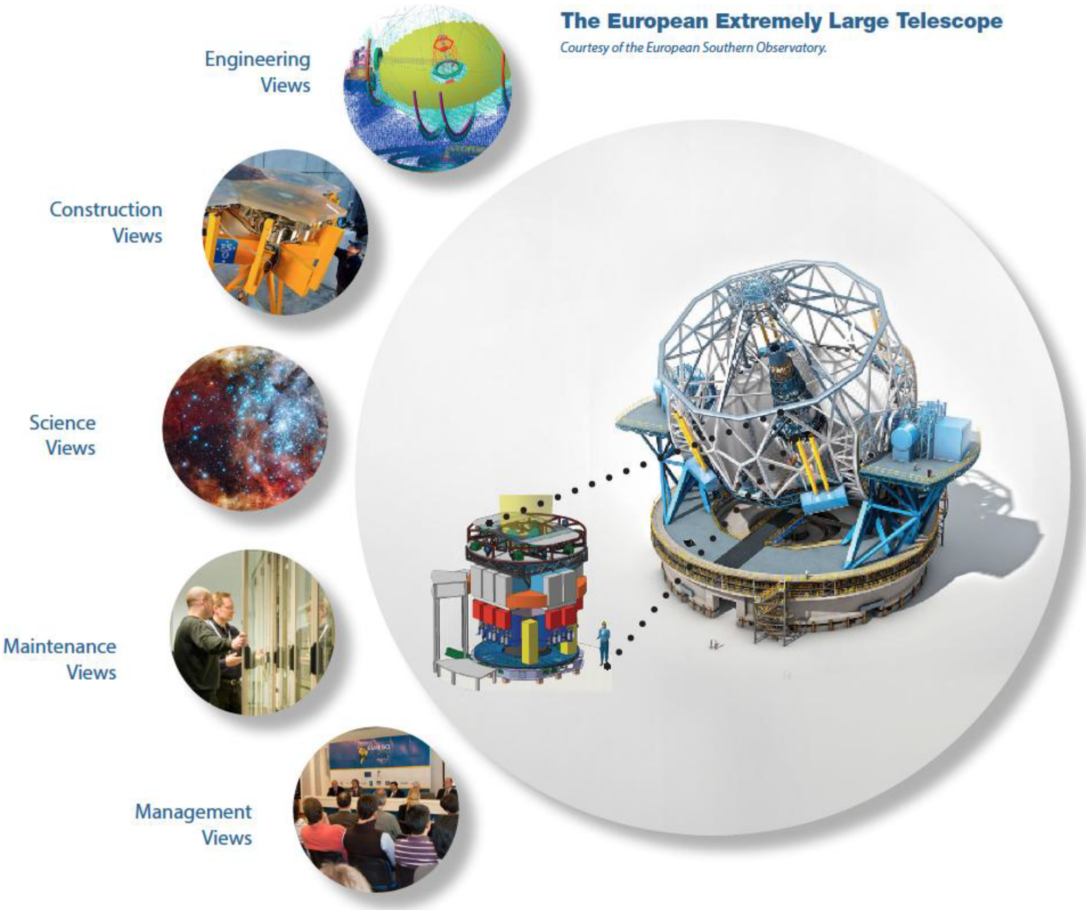


Figure 1-1: Development of the European ELT [Fosse, 2019]

an estimate of the cost and define the expected outcomes of a space mission.

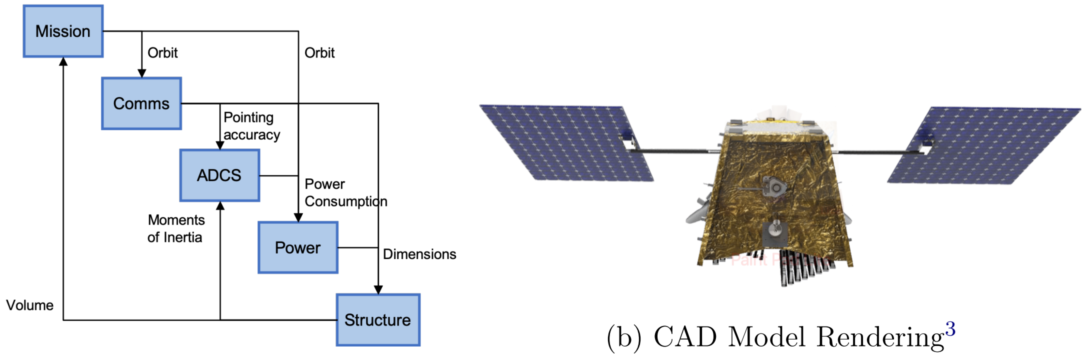
Simplified Example

To illustrate the complexity of the design of a space mission, we use a simplified concept of a communication satellite as an example. Figure 1-2a shows a simplified conceptual model with the dependencies among the design elements.

The design of the system is decomposed into the following blocks, that correspond to logical subsystems fulfilling a function or disciplines covering certain aspects of the system: Mission design, communication system, Attitude Determination and Control System (ADCS), power and structure. Mission design determines the orbits, based on where the service is needed. The communication system provides the actual

---

[3] source: `https://www.oneweb.world/technology`



(a) Simplified Conceptual Model

(b) CAD Model Rendering[3]

Figure 1-2: Example Communication Satellite

service to the final customer and also provides a channel for transmitting telemetry to the operator and receiving commands. The ADCS maintains the satellite's attitude and the antennas oriented towards the communication partners. The power system provides the satellite and all its parts with electric energy. The mechanical structure needs to host all the components, while withstanding all the loads that appear during the launch and operation of the satellite. These dependencies can, and often do form loops.

Chain of design dependencies

Continuing the example, the conceptual model reflects rules for sizing the satellite subsystems, which form dependencies. The electrical power required from all systems drives the size of the solar panels and batteries.

$Power(Comms + ADCS) \rightarrow Dimensions(Power), Dimensions(Solarpanels)$

The size of the solar panels influences the structure.

$Dimensions(Solarpanels) \rightarrow Moments\ of\ Interia(Structure)$

A larger structure leads to higher power consumption and size of reaction wheels for the attitude determination and control system.

$Moments\ of\ Inertia(Structure) \rightarrow Power(ADCS)$

The power consumption of the ADCS loops back to the sizing of the power system.

Another loop is formed by the link between the overall volume of the structure, which influences the mission design regarding the usable launch vehicle. And the launch vehicle may again influence the achievable orbit. Additional complexity comes in when the satellite should be part of a constellation, as it would be in the case of a mission to provide broadband communication. Continuous connectivity from ground requires permanent visibility of at least one satellite. This heavily drives the choices of possible orbits for the set of satellites and their relative positioning to each other. This is to be taken as an illustratory example, because in reality there are many more factors driving the design.

Outcomes of the conceptual design of a spacecraft are the size, mass, as well as the physical configuration. For example, Figure 1-2b shows the rendering of the structure of a real commercial communication satellite. As part of the study, estimates are also made for the power required onboard the spacecraft, for the data to be transmitted, and regarding the appropriate orbit or trajectory.

Due to the inter-dependencies, the design process can not be done in a straightforward procedure but it needs to go in iterations. Full awareness of the involved domain experts about the dependencies and tight information exchange is required to consolidate a design, which copes with the design dependencies and also satisfies the customer needs.

A way to involve different domain experts early on, is known as Concurrent Engineering (CE). The Concurrent Engineering approach was first systematically described as a recommended management approach for defense acquisition [Winner et al., 1988]. Traditionally a defense agency would first define the mission and system requirements and then hand them off to suppliers to design and develop the system. By doing these steps concurrently, it takes less time and allows to better reconcile requirements, technical feasibility, development time and cost. This approach to overlap subsequent life cycle phases had also proven to be effective in other industries. The biggest gain was achieved by a closer integration between detailed design and manufacturing. Traditionally, manufacturing engineers would start working only after the detailed design was completed. Problems with manufacturability required to make change requests that go back to the design engineers. Concurrent Engineering (CE) allows giving feedback regarding manufacturing, already during the detailed design. Especially for mass production, the cost of manufacturing is a factor to strongly consider already from the beginning of the design.

Concurrent Design

Starting from the late '90, space agencies started to adopt the concurrent engineering approach to do conceptual design and mission feasibility studies [Kane Casani and Metzger, 1995, Bandecchi et al., 1999]. This approach allows adapting the requirements while doing conceptual design [Ferreira, 2012, p.5], as well as taking into account later life cycle phases: detailed design, manufacturing, testing, operation, disposal. To do so, all relevant experts are involved in a co-located design study and collaborate in a digital modeling environment.

The space industry puts a strong emphasis on the conceptual design phase, because space missions are generally unique, very expensive, risky, and do not allow corrections during operation. This method for doing the conceptual design of space systems received various names: Concurrent Design (CD) [Bandecchi et al., 2000], Concurrent Engineering (CE) [Romberg et al., 2008], Integrated Mission Design (IMD) [Karpati et al., 2003]. To make the focus on the conceptual phase explicit, the term Concurrent Conceptual Design (CCD) would be more appropriate. The term concurrent in this context actually means two things: 1) a team working on different aspects of a conceptual design (*in parallel*), and 2) in the same place (*co-location*).

The Concurrent Design approach is described by different authors to rely on a set of key elements. Bandecchi et al. [2000] lists: process, team, model, facility, and infrastructure (meaning software tools). Instead, Karpati et al. [2003] lists: people, process, tools, and facility (see Figure 1-3).

The model is tightly connected to the tool and digital models are often only accessible with specific software tools. But the MBSE vision argues for the use of standardized data formats to ensure interoperability. Hence, the model can also be considered an independent element.

In synthesis, we consider the concurrent design approach to build upon the following 5 pillars:

- multidisciplinary *team* of experts,

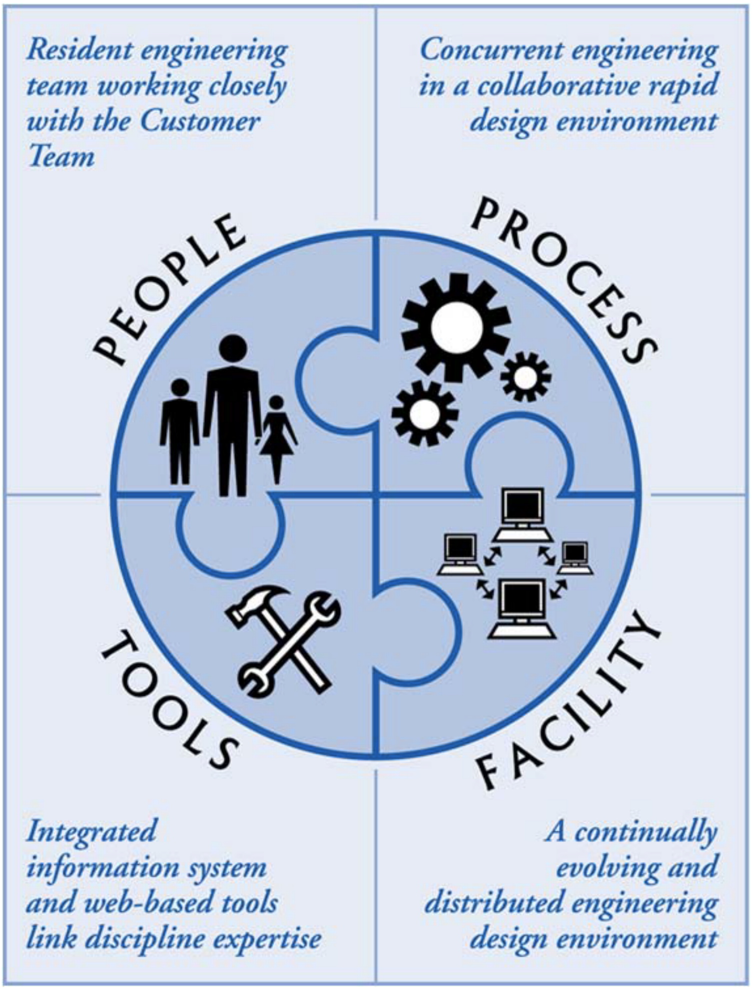


Figure 1-3: Concurrent Design - Elements [Karpati et al., 2003]

- co-location in a shared workspace (*facility*),
- an integrated system *model*,
- collaboration *tools* and
- a managed design *process*.

Following the concurrent design approach, feasibility studies are conducted in a compact period of time, integrating human expertise of all relevant engineering disciplines. Concurrent Design embodies the Model-Based Systems Engineering approach, because it relies on an integrated model to represent all relevant aspects of the system. This approach allowed for the time needed for feasibility studies to decrease significantly. As an example, ESA observed a reduction from 6-9 months to 3-6 weeks [Bandecchi et al., 2000, Di Domizio and Gaudenzi, 2008]. Time efficiency is considered to have paved the growing adoption of concurrent design approach for complex space systems. Besides that, our survey of the practice has shown additional benefits, such as increased quality of results and improved understanding between experts of different disciplines [Knoll et al., 2018a].

Many space agencies and companies have established dedicated facilities and regularly perform early concept validation and feasibility studies, using the concurrent design approach. Due to the benefits of this approach, there is the potential of applying it also to other life cycle phases and outside the space sector.

An established methodology does not exist yet, but rather each organization has its own interpretation of this approach. All implementations of concurrent design though, follow the MBSE approach, so they use interconnected multi-disciplinary modeling at the conceptual stage. With respect to the design process and the tools, there is still more to be understood and improved, in particular, the interplay between the two. To support wider adoption of this approach, a comprehensive description of a methodology is instrumental.

Our work describes a methodology (MoCoDeM) using formal models, including a guideline for the concurrent design process and support for team, through a tool. This methodology is verified through expert interviews and case studies with conceptual design studies of space missions. Moreover, we propose how the model-based conceptual design methodology could be extended to include the evaluation of new technologies, and in this way, integrate with strategic technology planning.

1.2 Scope

This work is related to further fields of knowledge (see Figure 1-4). Its focus lies on the intersection of model-based systems engineering, and design research, as well as computer-supported collaborative work and conceptual design.

Concurrent Design (CD) is a specific way of doing **Model-Based Systems Engineering** for **Conceptual Design** of complex systems. This approach is used in various flavors for feasibility studies of space missions.

The goal of our work is to give a comprehensive and formalized description of the

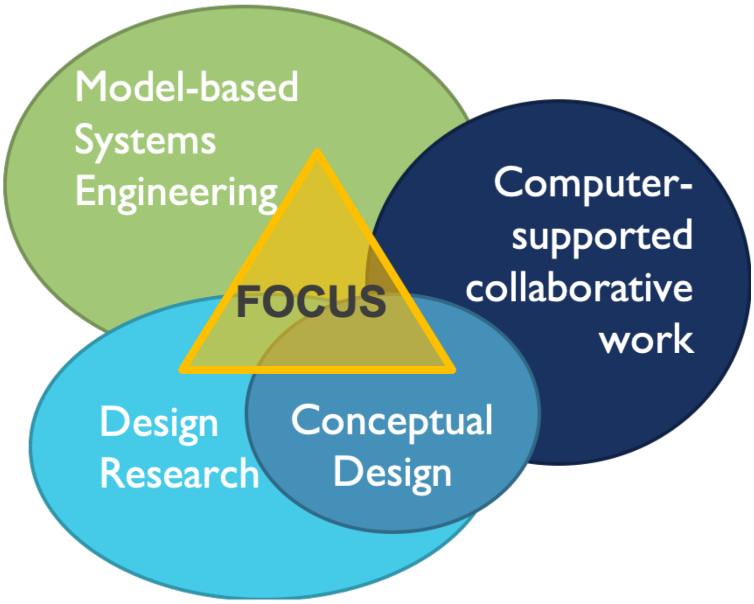


Figure 1-4: Our work's relation to fields of knowledge

CD approach. To investigate the existing practice, formulate a design methodology and test it on use cases, we engage in **Design Research** and follow the Design Research Methodology (DRM) [Blessing and Chakrabarti, 2009].

Our focus lies on the collaborative design process, for which we provide a guideline, and its support through a tool. The work also touches the field of **Computer-Supported Collaborative Work**, as far as the development of a tool to support collaboration.

1.3 Relevance

The benefits of Concurrent Design in a model-based systems engineering environment are well acknowledged by experts in conceptual design of space missions. People and organizations from the space sector or other fields, who are used to the traditional, sequential way of doing conceptual design, quickly understand the potential time reduction through the concurrent approach. Nevertheless, implementing the CD approach in an organization requires knowledge of best practices, guidelines, and eventually external consulting.

Organizations with established concurrent design facilities face the challenge of frequent people turn-over. When a significant number of participants on each design study are new to the approach, it can have a negative impact on productivity [Braukhane et al., 2015]. It is necessary to provide help for getting new people onboard.

This work provides a comprehensive description of this methodology, based on the common practice among different organizations. This forms a relevant contribution to the field of Model-Based Systems Engineering, as it can help organizations adopt this approach as well as train new people in it.

A tool for concurrent conceptual design should allow a team to collaborate on an integrated parametric system model. The tool built as part of this work (CEDESK), works as comprehensive design support for conceptual design and is ready to be used for actual concurrent design studies. While other existing tools are focused on the management of design information, our tool was built to support the concurrent design process comprised in our generic design methodology. The process emphasizes two aspects: work parallelization and team coordination. The case studies investigate the tool's impact on these two aspects. The investigation of the link between the tool and the design process make this work highly relevant.

Technology management uses roadmaps to define and document strategies for future technology development. At its best, conceptual design of future products can already consider the infusion of new technologies [Suh et al., 2010]. While the use of models in conceptual design is very common, it is not in roadmapping. Our work proposes an extension of the model-based concurrent design approach to roadmapping. We tested this approach with a major aerospace company to make technology roadmaps based on models. This industrial use case confirms the relevance of this work.

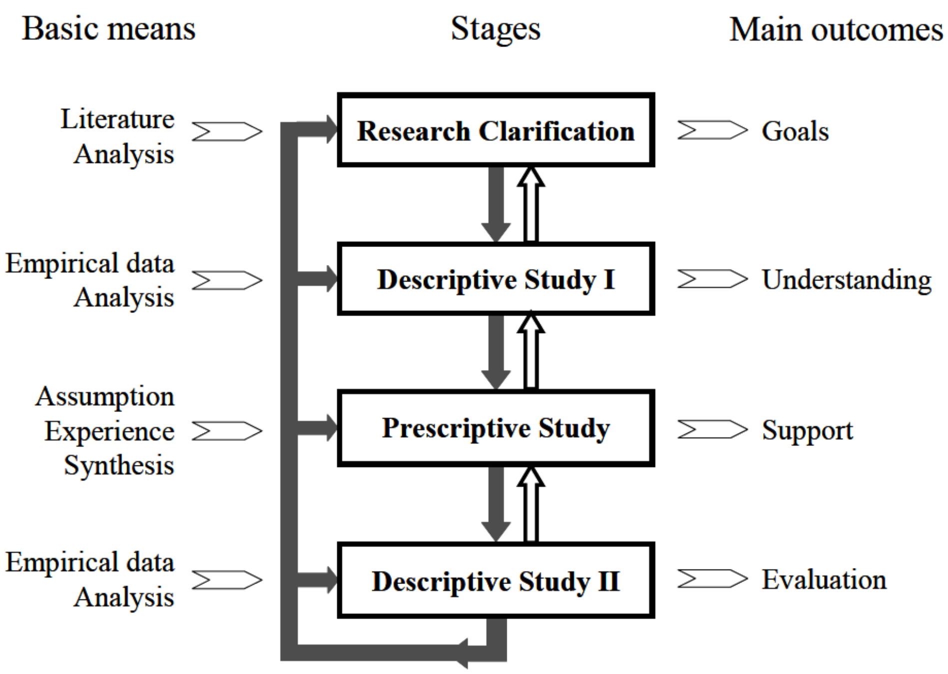


Figure 1-5: DRM Framework [Blessing and Chakrabarti, 2009, p. 15]

1.4 Research Methodology

Systems Engineering is an engineering discipline, which by nature connects to many other disciplines. Since our work primarily has to do with conceptual design, we found the Design Research Methodology (DRM) from Blessing and Chakrabarti [2009] very appropriate for our research. The framework contains a staged process as illustrated in Figure 1-5. It consists of four types of research activities, which can be performed in iterations. In fact, our research was an iterative process, going through these stages. This work summarizes the outcomes of all the stages, not in a chronological, but logical order.

Research Clarification

First, we review literature about model-based systems engineering, concurrent engineering, conceptual design, concurrent design and related topics. The outcome of this stage is contained in chapter 2.

Descriptive Study I

To understand the actual use of Concurrent Design in space industry, we conducted a structured survey among subject matter experts. The insights gained into the actual practice include what experts see as benefits and challenges, and future perspectives. The analysis of the survey results can be found in chapter 4, and parts of it were published in [Knoll et al., 2018a].

Prescriptive Study

Based on the information gathered from literature, we formulate a generic methodology for concurrent conceptual design, including a guideline for the conceptual design process (see chapter 5). We developed a support embodying the methodology in the form of a collaboration software (see chapter 6).

Early versions of the methodology and the tool appeared in [Knoll and Golkar, 2018].

Descriptive Study II

The methodology, and in particular the process guideline were verified through semi-structured interviews with subject matter experts (see chapter 7).

We tested the methodology and tool on nine conceptual design studies of space systems, all of which are described in chapter 8.

Additionally, we describe the adoption of our approach to a new field, model-based technology roadmapping. This application of our methodology is illustrated with a case study in an industrial setting (see chapter 9). The basic concepts of this were already discussed in [Knoll et al., 2018b].

1.5 Thesis Structure

The topic of the thesis, model-based processes and tools for concurrent conceptual design of space missions, develops over the following chapters. The diagram in Figure 1-6 illustrates the flow of information through the structure of the thesis.

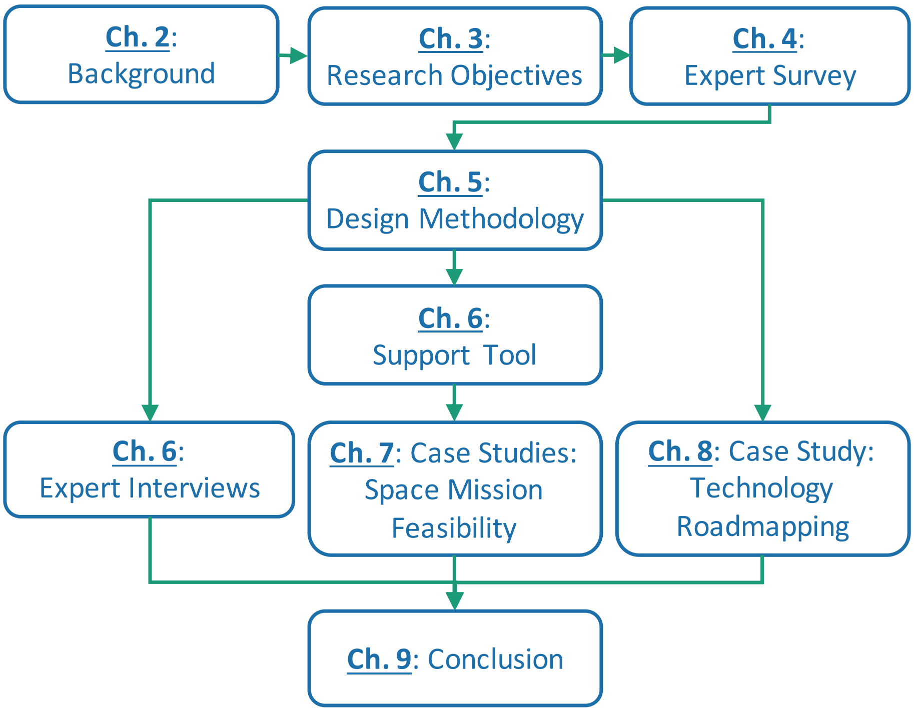


Figure 1-6: Thesis structure

Chapter 2 - Background At the beginning, we illustrate the context of the work and summarize the current state of the knowledge on the related topics.

Chapter 3 - Thesis Objectives Then, we identify the gaps to address with our work and define the *objectives* of our work. In this chapter, we also describe the chosen research approach.

Chapter 4 - Expert Survey The *survey* complements the knowledge about concurrent conceptual design for space systems found in the literature, with the one from practice. We collected knowledge and experience of subject matter experts with the help of an online questionnaire and analyzed the results for the benefits and challenges.

Chapter 5 - A Design Methodology Based on the literature review and the outcome of our expert survey, we distilled a generic *methodology* for model-based co-located conceptual design (*MoCoDeM*). This chapter also contains a formalized process guideline for conducting conceptual design studies.

Chapter 6 - Concurrent Conceptual Design Tool A *tool*, CEDESK, has been developed in correspondence with the concurrent conceptual design methodology. This chapter provides the specifications, the structure and the features, in particular, its support of the process proposed as part of the methodology.

Chapter 7 - Expert Interviews We conducted interviews with subject matter experts, who previously had answered our survey. With the interviewees we discussed and verified our process guidelines and tool support. This chapter summarizes the comments on our methodology, as well as additional insights into the actual practice, which are not covered by literature.

Chapter 8 - Conceptual Design (CD) Studies To test our methodology, we conducted a set of *case studies* dealing with the conceptual design of space missions. In this chapter, we describe each of them in detail and discuss their respective outcomes.

Chapter 9 - Technology Roadmapping (TRM) Studies Applying our methodology to technology roadmapping, comes with model-based systems engineering and co-located multi-disciplinary teamwork. We explain how this approach was tested in an industrial setting and we present the benefits and challenges of it.

Chapter 10 - Conclusion Finally, in the last chapter, we discuss our results obtained in terms of methodology, its validation through expert interviews and use cases, as well as its limitations. At last, we give an outlook on open paths for future research.

Chapter 2

Background

The aim of this chapter is to provide the necessary background to the method of Concurrent Conceptual Design. This topic of our work is embedded in the fields of Model-Based Systems Engineering and Design Research. As a foundation, we look at systems engineering before going into model-based systems engineering. Then we look at conceptual design and concurrent and collaborative engineering. The method of concurrent design is a specific way of applying model-based systems engineering to the conceptual design. Special emphasis is made on the particular application of concurrent design to space systems.

Moreover, we describe the Design Structure Matrix method, the paradigm of Trade Space Exploration, and the technique of Multidisciplinary Design Optimization.

2.1 Systems Engineering

Engineers design and produce technical systems to fulfill specific needs. Systems, by definition, consist of a number of interrelated elements to serve a defined purpose [Crawley et al., 2015]. The elements of a system themselves can be considered as systems, or the system can itself be part of a larger entity. The term system-of-interest indicates that the purpose and hence, the system boundaries are chosen differently depending on the context. When talking about the development of systems, we sometimes use the words system and product interchangeably.

Definitions

Various standardization bodies and organizations came up with definitions of Systems Engineering.

According to the standard ANSI/EIA-632, SE is "an interdisciplinary approach encompassing the entire technical effort to evolve and verify an integrated and life cycle balanced set of system people, product, and process solutions that satisfy customer needs. Systems engineering encompasses (a) the technical efforts related to the development, manufacturing, verification, deployment, operations, support) disposal of, and user training for, system products and processes; (b) the definition and management of the system configuration; (c) the translation of the system definition into work breakdown structures; and (d) development of information for management decision making." [ANSI/EIA, 2003]

And according to ISO/IEC Standard 15288, SE is an "interdisciplinary approach governing the total technical and managerial effort required to transform a set of customer needs, expectations, and constraints into a solution and to support that solution throughout its life" [ISO Central Secretary, 2015a]. It "includes the definition of technical performance measures; the integration of engineering specialties toward the establishment of an architecture; and the definition of supporting life cycle processes that balance cost, performance, and schedule objectives" [ISO Central Secretary, 2017, p. 460].

The handbook of International Council of Systems Engineering (INCOSE) defines SE as "an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. SE considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs." [Haskins et al., 2011]

Common themes in all these definitions are:

- need oriented - making sure the developed system fulfills its purpose.
- encompassing full life cycle - considering the system from inception to disposal.
- inter-disciplinary - systems engineering bridges between specialized engineering disciplines.

Often Systems Engineering is considered to be complementary to Project Management (PM). While PM is concerned with the organizational aspects of a product development project, SE is more focused on the technical aspects.

Product Life Cycle

Commonly, the life span of a product is subdivided into a set of subsequent stages. The ISO standard 15288 describes a generic life cycle that any product undergoes in a set of 6 stages [ISO Central Secretary, 2015a]. These stages indicate periods of the product's lifetime. Forsberg et al. [2005] visualized life cycle models of different organizations. As it can be seen in Figure 2-1, NASA and similarly other space agencies, use a slightly longer and structured formulation phase than the concept stage in the ISO model. The figure also shows decision gates along the product lifetime. These are moments where intermediate project deliverables are reviewed, and decisions about the continuation, halting, or canceling of the product development are taken.

Concept Stage This stage serves to clarify the user and stakeholder needs, requirements and constraints. Based on those, technical feasibility and technology readiness is assessed. Iterations are made to assure needs do not exceed feasibility. Alternative concepts to best meet the stakeholder needs are defined and assessed. More details on conceptual design are described in section 2.4.

Development Stage The design of the system is elaborated to such details that it meets the requirements. Keeping the customer involved in this stage assures that the design meets the actual needs.

Production Stage In this stage, the product is manufactured, assembled and tested. The testing is done against the specification and requirements.

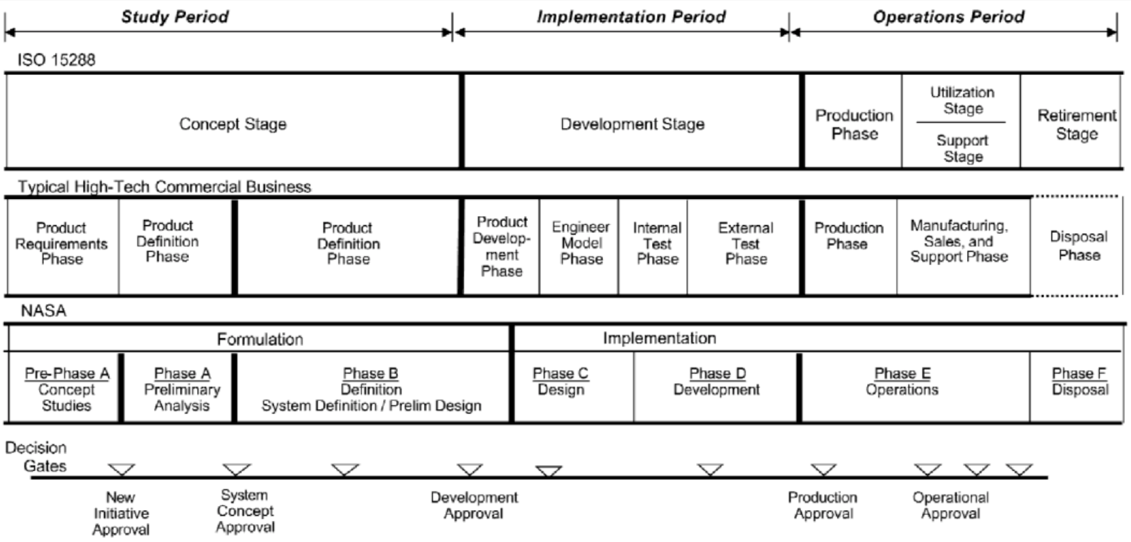


Figure 2-1: Product Lifecycle Models. Adapted from Forsberg et al. [2005, p. 87].

Utilization Stage The period of time when the system is used and serves its initial purpose to the users and stakeholders.

Support Stage To keep a system operational, typically service and maintenance operations are needed. Within this time frame the the system can degrade or lose its capability or show better endurance than expected, which can influence the decision about anticipated or postponed disposal.

Retirement Stage In this stage, the system is removed from operation in accordance with requirements and regulations.

It is common that some stages overlap in time, in particular utilization and support. The concurrent engineering approach aims to increase the amount of parallel work in order to reduce the total duration of product development. More on that in section 2.6.

According to the Defense Acquisition University, at the completion of the concept stage, 75 % of the total cost is already committed [Walden et al., 2015, fig. 2.4]. Hence, the concept stage must consider all subsequent stages and entails the most fundamental decisions, which have a strong impact on the rest of the life cycle. This makes the conceptual stage particularly worthy of research, to increase understanding of conceptual design and improve its efficacy. Also our work is focusing on the conceptual design stage.

Processes

The development of a system is achieved through a number of technical processes, each of which appears in one or more of the lifecycle stages.

> "Technical processes are used to define requirements for a system, to transform the requirements into an effective product, to permit consistent reproduction, of the product where necessary, to use the product to provide the required services, to sustain the provision of this services and to dispose the product when it is retired from service."[ISO Central Secretary, 2015a, sec. 6.4]

The two main goals of the conceptual design stage are the elicitation of stakeholder needs and the formulation of system requirements.

The documented outcome of Systems Engineering processes are intermediate artifacts. The next section describes the ongoing transition of using textual documents to models under the term Model-Based Systems Engineering [INCOSE, 2007].

2.2 Model-Based System Engineering

Traditionally systems engineering relies on documents as primary artifacts, such as requirements documents, interface definition documents, etc. Fundamental drawbacks of documents, is that the content is mainly natural language, which can easily be ambiguous, as well as inconsistencies within a document or among separate documents. In contrary, models can be used to describe a system to be developed that allow for automation, in particular automatic consistency checking [INCOSE, 2007].

Model-Based Systems Engineering (MBSE) is defined as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." [Haskins et al., 2011]. Applying MBSE to a product development process requires a modeling method, a modeling language and tools.

Models

Models are commonly used to describe certain aspects of a system and its environment. Every model has an explicitly or implicitly defined scope. Depending on the scope and the required accuracy of the representation, different types of models are used. For conceptual modeling of systems, two types are generally used: descriptive and analytic models.

The primary purpose of descriptive models is communication and documentation. Graphical languages (such as SysML, OPD, IDEF0) have proven very useful for this purpose. More on languages in the next section.

On the contrary, analytic models are used for obtaining insights. Parametric models are used a lot in conceptual design to estimate the values for key system characteristics. For spacecraft, these key figures are typically: mass, power consumption, data rate [Di Domizio and Gaudenzi, 2008]. Mathematically, these mappings from input to output parameters are transfer functions

These models rely on mathematical formulas reflecting the behavior of a system or an element of it. Analytic models of high accuracy are built on basic physical laws of nature. Less accurate models use some approximations of real phenomena. Examples are surrogate models or response surfaces derived from experiments. Additionally, such models are used to approximate the results high-fidelity simulations, which are very expensive to run.

The exchange of models is essential to allow for collaboration between different engineering disciplines as well as between organizations. In a common effort of European space organizations, a number of standards (ECSS) have been defined to ensure interoperability [Braukhane, 2015]. Moreover, the attempt to adopt SysML for MBSE in ESA, led to the creation of a specific profile and a set of guidelines, forming the SysML Toolbox [Alvarez et al., 2018].

Languages

Each of the methods mentioned above relies on certain modeling language to denote the model. "The Object-Oriented Systems Engineering Method (OOSEM) integrates a top-down, model-based approach that can be used with ... SysML to support the specification, analysis, design, and verification of systems" [Friedenthal et al., 2014]. The System Modeling Language (SysML) [Object Management Group, 2015] was developed based on UML [Object Management Group, 2005], which was successfully applied in software engineering. The conceptual framework behind SysML forsees that the model of a system consists of a set of diagrams reflecting different viewpoints. There are 9 different diagram types to describe requirements, structure and behavior. Models denoted in SysML do not support simulation and analytics [Friedenthal et al., 2014]. This shortcoming is currently being addressed, by the elaboration of the next standard, SysML 2.0.

Methods

A modeling method describes which design activities to perform, what engineering artifacts to produce and how they are denoted. Several methods have been proposed, such as OOSEM by INCOSE and OMG [Walden et al., 2015], MBSE Methodology by Vitech [Long, 2010], Harmony by Rational [Hoffmann, 2011], Arcadia by Thales [Roques, 2018] and OPM by Dori [Dori, 2011].

OOSEM, Harmony, and Vitech MBSE rely on SysML or a subset of it as a language and describe procedures for building a model. Common among these methods are the following major activities, sometimes referred to with slightly different names.

Need Analysis Identify the customer needs.

Requirement Analysis Derive the required system functionality.

Functional Analysis Identify the associated system states and modes.

Architecture Design Allocate the system functionality to a physical architecture.

These include, or are complemented by, verification activities to ensure the model is consistent in itself and the customer needs. The conceptual framework behind SysML foresees that the model of a system consists of a set of diagrams reflecting different viewpoints.

All methods claim to be tool- and vendor-neutral, but provide a reference tool.

Tools

For some of the above-mentioned methods, there are software tools that incorporate the method. For example, Vitech Core[1] reflects Vitech MBSE methodolgy, Harmony is supported by Rational Rhapsody[2], and Arcadia is implemented in Polarsys Capella[3].

Different software vendors are offering tools for the creation of models, managing versions of models, and collaboration on models. Other tools allow to connect descriptive models and analytic models made with different software, for example ModelCenter MBSE[4], or Cameo Simulation Toolkit[5]. Nonetheless, interoperability is still a stumbling block for tight collaboration [Ferreira, 2012]. Any real-world engineering project requires the collaboration of multiple engineers. In the past, transferring work from one engineering team to another meant moving paper documents. With the increasing digitalization, paper documents were replaced by digital files. Today's technology allows to share digital artifacts and have different engineering teams working on them simultaneously, and engineering practice has incorporated the vision of collaborative engineering.

2.3 Modeling Engineering Processes

The modeling of processes commonly has the goal to make them repeatable and guarantee identical outcome. This applies in general and in particular also to engineering processes. But the process of designing and developing a system also differs, as it is expected to produce new solutions to any specific problem at hand [Browning et al., 2006]. Still, a process model codifies knowledge about the organization of work.

In practice, a strong connection exists between the artifacts produced during engineering design and the process model. Eckert et al. [2017] reviewed a variety

---

[1] `http://www.vitechcorp.com/products/core.shtml`

[2] `https://www.ibm.com/us-en/marketplace/systems-design-rhapsody`

[3] `https://www.polarsys.org/capella/`

[4] `https://www.phoenix-int.com/product/mbse/`

[5] `https://www.nomagic.com/product-addons/magicdraw-addons/cameo-simulation-toolkit`

of different methods for integration of process and product models in engineering design. The result is a unifying terminology and conceptual framework of model integration. According to the authors, so far, all integration method are mainly theoretical and did not make it into practice, as none of them addresses all the required aspects.

Process models can either be descriptive, documenting the actual situation, or prescriptive, defining as it should be [Browning et al., 2006]. Process models differ depending on the purpose of the model [Heisig et al., 2010, ch. 1] Various modeling approaches have been proposed, and they differ in the aspects of processes that are covered, the methods for representation and analysis available, as well as the effort needed to build the models and the contained detail. Examples are Gantt, PERT, IDEF, DSM and UML / SysML [O'Donovan et al., 2005]. Gantt charts allow to represent activities, their dependencies and timing and commonly used in project management. The PERT / CPM method uses the same information as in Gantt charts, but also allows to analyze a project plan for its slack time and determine the tasks which are critical to the timely completion of the process.

IDEF

The IDEF family contains a set of modeling methods for different purposes. In particular, IDEF0 for functional modeling can be used to represent design processes (see Figure 2-2). The design activities (boxes) are connected by flows (arrows) of

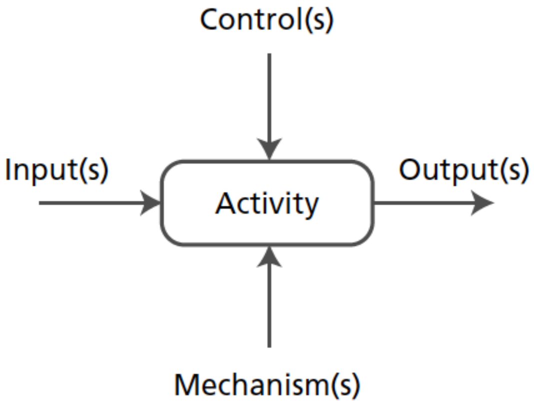


Figure 2-2: A task represented in IDEF0 [O'Donovan et al., 2005]

information and resources (inputs) and enabled by people and tools (mechanisms). The information dependencies determine the precedence of activities but the model does not specify the timing. A useful feature in IDEF0 diagrams is the hierarchical structure, which allows to zoom in on a single activity and represent its inner structure.

We applied this method in our work for the functional analysis of the integrated process of conceptual design and technology roadmapping.

Design Structure Matrix

The Design Structure Matrix (DSM) is an established and well-known method for the representation and analysis of dependency structures. Hence, its acronym is sometimes also decoded as Dependency Structure Matrix. The method was originally proposed by Steward [1981] as a method for managing the design of complex systems. DSMs allow to represent networks of elements composing a system. The DSM is a square $N \times N$ matrix, representing the interaction between the N elements. The system can be products, processes, or organizations for a wide range of applications [Eppinger and Browning, 2012].

A Process DSM represents a network of activities and their interactions. Activities can be sequential, parallel, coupled, conditional (see Figure 2-3).

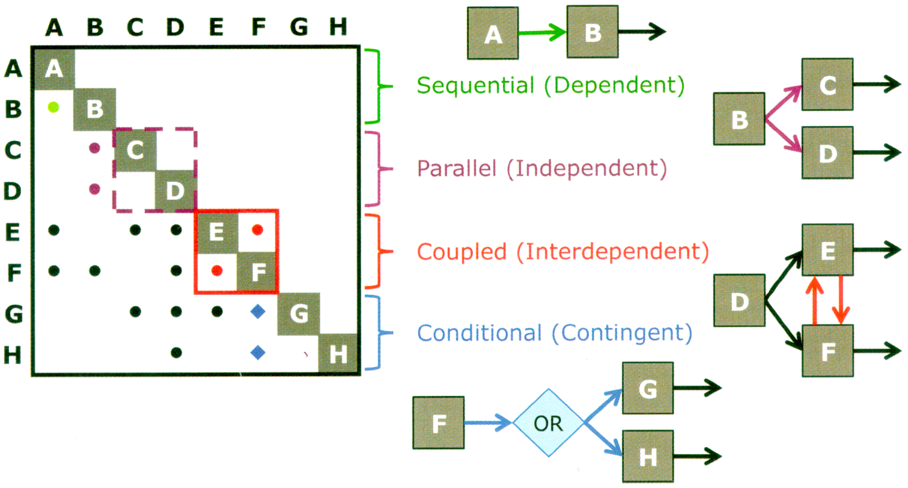


Figure 2-3: Illustration of task dependencies in a process DSM in IR/FAD notation [Eppinger and Browning, 2012, p. 134]

For DSMs, two different notations exist, which only differ in the way to read them. One contains the input in rows (IR) and the feedback above the diagonal (FAD). The other shows the inputs in columns (IC) and the feedback below the diagonal (FBD). The second is similar to read than N^2 diagrams, where the flow goes from left to right above the diagonal and from right to left below the diagonal.

A strength of the DSM method is its capability to represent loops of dependencies. Other modeling approaches for networks of activities such as PERT and Gantt charts, explicitly exclude cycles [Eppinger and Browning, 2012]. The design of a system unavoidably has to do with the coupling between its elements. This inherent coupling of elements requires the design process to go in iterations, rather than a straightforward process. Other causes of process iterations can be changing external inputs (requirements) or mistakes, etc. Such design iterations can not be avoided, and the need for redoing design steps is known as the "design churn effect" [Yassine and Braha, 2003]. But, changing the sequence of design tasks, can help to reduce the number of repeated design steps [Yassine et al., 2003].

Further in our work, we use the parameter-based DSM, where the activities are decisions on design parameters. The DSM can be automatically derived from the parametric system model for visualization and analysis.

None of the known process modeling frameworks are capable of covering the entire richness of design process [Eckert et al., 2017]. PERT and Gantt charts miss to represent the nature of the connectivity between activities and hide activity failure and iteration, which limits the understanding the complexity of design processes [O'Donovan et al., 2005]. The DSM method allows to model loops and allows for very efficient automated analysis, but for this same reason, it can not provide a time line representation. Visual diagrams like IDEF0 and SysML/UML are visual means for documentation and communication, but miss automated analysis.

Given the broad adoption of SysML, it can be considered the lingua-franca in the field of Systems Engineering [Walden et al., 2015]. Hence, we use SysML in this work to describe our design methodology. Specifically, we use block diagrams for structure, use case diagrams for team roles, and activity diagrams for describing the design process.

2.4 Conceptual Design

The development of any product or system starts with a concept stage (see section 2.1). Knowing that correcting design flaws becomes very costly in later phases of the product lifecycle [Walden et al., 2015, fig. 2.4], special attention is given to the conceptual design.

According to Pahl et al. [2007, p. 159] "Conceptual design is the part of the design process where ... the basic solution path is laid down through the elaboration of a solution principle."

The INCOSE handbook lists the following activities in conceptual stage: define problems space; exploratory research & concept selection; characterize solution space; identify stakeholders' needs; explore ideas and technologies; refine stakeholders' needs; explore feasible concepts; propose viable solutions [Walden et al., 2015, p.28].

For the concept selection, a number of methods have been proposed [Okudan and Shirwaiker, 2008]. The major difficulties are ambiguity in the stakeholder needs and uncertainty about implementation details. According to Okudan and Shirwaiker [2008], concept selection methods can be classified into six categories based on the underlying methods: decision matrices, analytical hierarchical process, uncertainty modeling, decision theory, optimization, heuristics. The selection methods distinguish also in their capabilities and the number of concepts it can reasonably handle. Most widely adopted in the space sector are concept selection methods that rely on quantifiable characteristics (Figure of Merit), such as performance, cost, development time, and risk.

According to Horváth [2006], conceptual design requires both knowledge and creativity, which is hard to formalize and even less to automate. Software tools can only support the human designers, by facilitating interaction with knowledge expressed in models. Models can represent geometry or behavior at different levels of complexity. A common kind of model used during conceptual are parametric sizing models. According to Srinivasan and Chakrabarti [2007], basic physical laws and effects are fundamental for conceptual models. Physics-based, first principle models are by nature parametric. Fortin et al. [2017] show that in conceptual design systems are primarily described by their behavior. The behavior reflects the function of the system, while leaving the form mostly unspecified.

The conceptual design of space systems, require the participation of multiple disciplines, including engineers focused on particular elements as well as specialists of later life cycle phases, such as manufacturing and operation. In order to shorten the duration of conceptual design studies, space agencies have adopted the concurrent engineering approach [Bandecchi et al., 1999].

2.5 Tradespace Exploration

While designing a system, engineers often need to take into account multiple objectives. A Figure of Merit (FOM) is the quantitative evaluation of an objective. Commonly, these objectives are in tension, meaning that one can not be improved without compromising another. For example performance should be maximized and cost minimized. Solutions with better performance generally come at a higher cost.

Engineering a system also requires to choose between options. To make the trade-off between different options the resulting system characteristics need to be evaluated. The set of possible designs spanned by all possible design options is called tradespace. Tradespaces are often visualized as data points on a two-dimensional plane. The tradespace exploration method is summarized in [Ross and Hastings, 2005]. An important concept in tradespace exploration, is pareto-optimality. A system is pareto-optimal, if it is best according to one figure of merit, while simultaneously not being worse on all the other figures of merit. Figure 2-4 shows the example of a tradespace comparing Graphical Processing Units based on the figures of merit processing power (GFLOP) and price (USD), where the line connects the Pareto-optimal products.

In the case of more than two objectives, the trade space is hard to visualize. Multi-attribute trade space exploration is a way to guide the selection of design solutions that satisfy multiple criteria based on stakeholder preferences [Ross and Hastings, 2005].

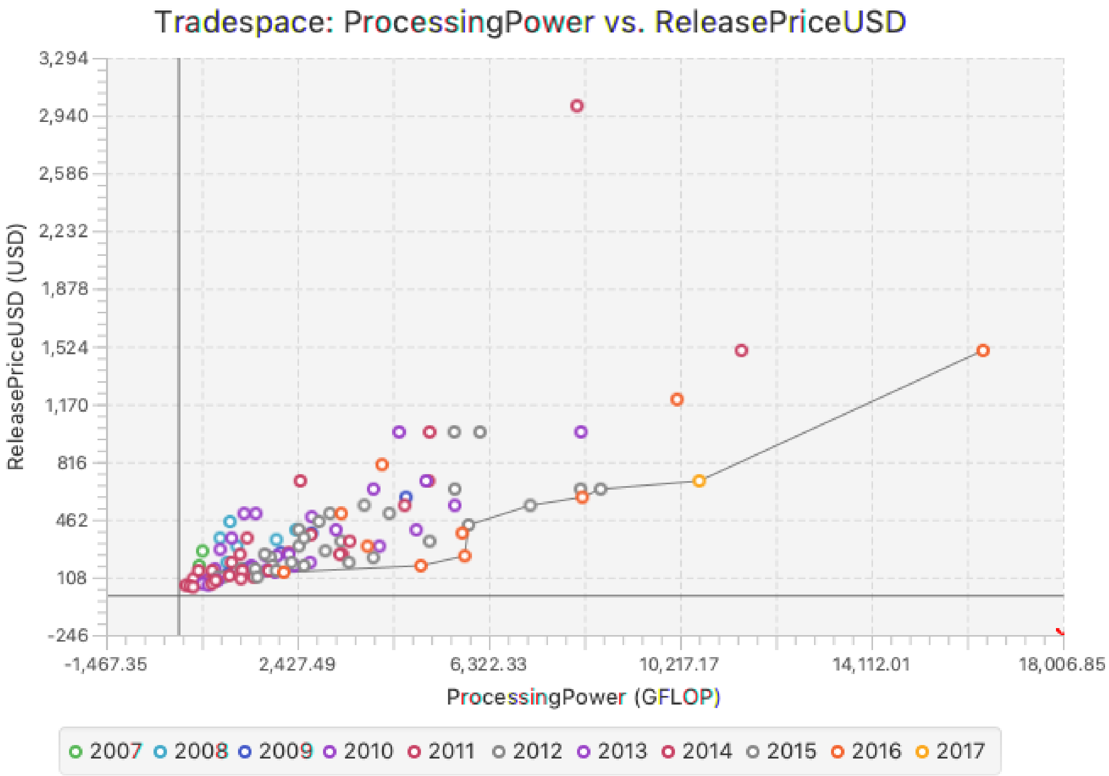


Figure 2-4: Example tradespace comparing GPUs based on processing power and price.

The method consists of the following steps:

1. Description of the system by mathematical functions mapping design parameters to figures of merit.
2. Full or partial enumeration of possible design solutions.
3. Evaluation of each design variant's figures of merit.

There are commonly two ways to enumerate the possible design options: 1) on a morphological matrix, 2) composition rules. Morphological matrices contain for each design option or parameter a set of possible values. They are simple, but in the design of complex systems, not any combination of design options results in a feasible design. This makes the evaluation of all combinations unnecessarily costly. Therefore, it is more efficient to define rules for composing a feasible design. An example is given by Shougarian [2017] describing a method to generate feasible airplane architectures from a model library and composition rules.

Once all design solutions are evaluated, it allows to compare different designs and in particular, identify the pareto-optimal solutions [Ross et al., 2004].

2.6 Concurrent Engineering

Concurrent Engineering (CE) is a management approach for complex Systems Engineering. One of the first descriptions is given in a report by the Institute of Defense Analyses as a desirable management approach for defense acquisition projects to ensure meeting user need while avoiding cost explosion [Winner et al., 1988]. That report compiled the experiences of successful implementation of concurrent engineering in over 10 major technology companies.

Definition

> "Concurrent engineering is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements." [Winner et al., 1988]

CE also made large impact in the automotive, electronics and computer industry in particular by supporting integrated product development spanning over different disciplines and lifecycle phases. An extensive description of CE as an integrated approach to product development was given by Prasad in two books on integrated product and process organization, integrated product development [Prasad, 1995, 1996].

A particular merit of CE was to bridge the gap between the fields of design and manufacturing [Borsato and Peruzzini, 2015]. Teams or organizations had more and more specialized in one or the other, and projects moving from design phase and implementation phase suffered from information loss. CE enables not only to pass on the design intentions more effectively, but also to feed back information to the design about manufacturability or even results from tests.

In a methodological analysis of CE, 7 enabling principles have been identified [Prasad, 1999]:

Principle 1: Parallel work group Multifunctional teams are working in parallel, each working on the product from its own perspective. This allows also the early involvement of suppliers into the product development.

Principle 2: Parallel product decomposition Decomposition is applied to handle complexity, and reveals dependencies among parts.

Principle 3: Concurrent resource scheduling Tasks that have been identified to be independent, can be accomplished in parallel. Tasks that show dependency require sequential work.

Principle 4: Concurrent processing The execution requires optimal routing and queuing of activities balancing workload and lead to a quality end.

Principle 5: Minimize interfaces Re-configuring the product shall allow to reduce interfaces.

Principle 6: Transparent communication A common understanding by all team members of terms and their meanings shall help to resolve conflicts and build consensus.

Principle 7: Quick processing Each of the decomposed activities is able to complete processing in short time, and information systems support friction-less exchange between teams.

Different fields of engineering have adopted the main concepts of CE differently. Table 2.1 shows how Concurrent Engineering (CE) is applied differently in various fields.

The use of CE approach to the conceptual design phase also entered into industries beyond space and defense, and attempts were made to integrate it with Multidisciplinary Design Optimization (MDO) approach [Reysset et al., 2015, Safavi et al., 2016].

Application	Activities	Phase	Parallelism
Automotive industry	overlap of detailed design and manufacturing	Phase 1+	parallel work
Defense agencies	Acquisition management	Phase 0/1	parallel work
Aerospace agencies	conceptual design, feasibility studies	Phase 0	parallel work + co-location
Technology Roadmapping	conceptual design and tradespace exploration	Phase -1	parallel work + co-location

Table 2.1: The meanings of Concurrent Engineering in different contexts

Collaborative Engineering

Related, but not identical to Concurrent Engineering is the concept of Collaborative Engineering, which, according to Lu et al. [2007], is the application of collaboration sciences to engineering. The goal is "optimizing engineering processes with objectives for better product quality, shorter lead-time, more competitive cost and higher customer satisfaction [Wang et al., 2002]. This is made possible through technology for computer-supported collaboration over local networks and the internet. It has been widely applied to product design, manufacturing, construction, enterprise-level collaboration and supply chain management [Borsato and Peruzzini, 2015].

In product design, Germani et al. [2012] identified four collaboration styles:

- Synchronous and co-located (e.g. face-to-face meetings);
- Synchronous and remote (e.g. remote meetings between different sites);
- Asynchronous and co-located (e.g. routine design activity of a team inside the same company);
- Asynchronous and remote (e.g. routine design activity of a team involving multiple companies at different geographical locations).

Each of these styles has its specific challenges and requires different tool support.

Concurrent Conceptual Design, which is the focus of our work, presumes collaboration in "synchronous and co-located" style. Although distributed concurrent design using remote collaboration was proposed [Beco et al., 2008], it did not find much adoption yet. The cost of collaboration depends on the team size, as well as on the complexity of the system at hand. Hirschi and Frey [2002] and Grogan and de Weck [2016] have shown that the time required in collaborative design grows over linearly in relation to coupling of the design tasks.

Concurrent Conceptual Design

The concurrent design approach as used by space agencies and which we refer our work to is even more specific. It focuses on the conceptual design phase of the life cycle, hence the term Concurrent Conceptual Design (CCD).

Note that some authors and organizations use Concurrent Engineering while implicitly focusing on conceptual design, e.g. [Romberg et al., 2008, Braukhane et al., 2015, Gomez et al., 2017].

2.7 Multi-disciplinary Design Optimization

Conceptual design studies aim for the evaluation of alternative designs including the potential of infusing new technology. Engineering sees an increasing availability of numerical models at various levels of accuracy and simulation tools for many, if not all aspects of technical systems. These models can be used during design, for analysis and optimization, forming the Multidisciplinary Design Optimization (MDO) or Multidisciplinary Design Analysis and Optimization (MDAO) approach. MDO is an integrative method that takes the interconnected subsystem models and applies system-wide optimization according to a utility function [Bil, 2015]. Such utility function can be performance, cost, other system characteristics or a combination of them. For cases where the utility measure is unknown, Jilla [2002] described a way to estimate the customer's perceived utility from their needs.

There are many different MDO tools available on the market, capable of integrating numerical models of multiple disciplines and their respective tools. Main feature of these tools is the efficient computation of the interconnected models and the optimization of the design with respect to given utility functions (figures of merits). Along with appropriate visualization of results these enable the exploration of the design space, or trade space. This approach can be automated and allows to capture a large design space.

Coarse parametric sizing models useful for conceptual design are available for families of products with a long history of development. E.g. for satellites, see [Wertz et al., 2011], for planes see [Raymer, 2012], for ships see [Papanikolaou, 2014], and similar standard textbooks for other well-known systems.

For systems without design legacy, it is quite hard to find or make parametric system models in order to apply multidisciplinary design optimization. Building an integrated model based on parametric model of subsystems requires that the interfaces between the subsystems are already defined beforehand. Depending on the level of detail of the model, straightforward calculation may be impossible, because they require optimization steps or design iterations. For example, the design of an airplane's propulsion system and its air-frame mutually depend on each other, wherefore the design needs to be re-iterated. This makes it harder to implement automated trade space exploration.

Comparison of MDO and CCD

Since design automation is not applicable in all cases, it may be worthwhile to compare different approaches. In Table 2.2 we illustrate the differences of MDO and the CCD approach.

The most significant difference and choice of CCD is that it explicitly values human experts and their interaction as a source of creativity. MDO, on the other hand, because it relies on automation, allows to extensively cover the design space, up to the validity range of the numeric models.

After all, the two approaches do not fully exclude each other. Depending on the availability of models which can be evaluated automatically, they are likely to be included into a concurrent design environment [Reysset et al., 2015, Safavi et al., 2016].

Feature	**MDO**	**CCD**	**References**
People			
Role	model preparation	model preparation, trade-off discussion	
Team	offline	co-location	Austin-Breneman et al. [2012]
Process	model-driven	expert-driven	Oberto et al. [2005], Morse et al. [2006], Avnet [2009], Ferreira and Gil [2012]
work sessions	asynchronous	synchronized	
number of evaluated designs	high	low	
Integrated Model			Schaus et al. [2010, 2011], Daniele Gianni et al. [2014], ECSS [2010]
model preparation	beforehand	beforehand, during design	
model use	automated	human operated	
Tools			Meenakshi et al. [2013], Fischer et al. [2017a], Hepperle [2012], Ferreira and Grogan [2010], Di Domizio and Gaudenzi [2008]
data and workflow mgmt	needed	needed	
visualization	optional	needed	
Infrastructure			Romberg et al. [2008], Braukhane and Quantius [2011], Golkar [2016]
collaborative workspace	virtual	physical	

Table 2.2: Comparison of MDO and CD

2.8 Concurrent Conceptual Design of Space Missions

The use of the concurrent engineering approach in the conceptual design phase had its origins in the NASA JPL - Team X [Kane Casani and Metzger, 1995]. Today Team X defines itself as "a cross-functional multidisciplinary team of engineers that utilizes concurrent engineering methodologies to complete rapid design, analysis and evaluation of mission concept designs" [Caltech, 2015]. Many other organizations have established their own concurrent design facilities. Here a few examples from space agencies, companies and universities:

- NASA Goddard Space Flight Center has the Integrated Mission Design Center (IMDC) [Karpati et al., 2003].
- At NASA Glenn Research Center there is Concurrent Mission and Systems Design (COMPASS) [McGuire et al., 2011].
- At ESA/ESTEC they have the Concurrent Design Facility (CDF) [Bandecchi et al., 2000].
- DLR has the Concurrent Engineering Facility (CEF) [Romberg et al., 2008].
- At CNES there is CIC, which stands for Centre d' Ingénierie Concourante [Bousquet et al., 2005].
- At the Aerospace Corporation they have the Concurrent Design Center (CDC) [Aguilar et al., 1998].
- The Technical University of Lisbon established the Student Concurrent Design Environment [Silveira, 2009].
- At Skoltech we have the Concurrent Engineering Design Laboratory [Golkar, 2016].

At JPL, the approach has developed further to also allow architecture studies in the Innovation Foundry A-Team [Ziemer et al., 2013]. Appendix A reports all 44 concurrent design facilities that we know of.

At the ESA CDF, Concurrent Design is defined as "a systematic approach to integrated product development that emphasizes the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life cycle." [Bandecchi et al., 2000] To make sure the design process is reaching its goal the decision making also requires moderation and leadership [Hatamura, 2006]. Indeed Gomez et al. [2017] characterizes CD as "working within a guided process, the concurrent access of all experts to a shared database, and the direct verbal and medial communication between all subsystem experts".

This approach has gained popularity since it can help to reduce the time and cost for the conceptual design phase. Di Domizio and Gaudenzi [2008] have found reduction from 6-9 months down to 3-6 weeks, and Karpati et al. [2003] reports a reduction from over 3 months to less than a week. Concurrent engineering leverages multidisciplinary teams of experts collaboratively working on a systems design. The team of experts is usually co-located in a shared work space, it is supported by appropriate discipline-specific design tools and a data exchange tool. The team follows a coordinated process to produce a consolidated system design [Braukhane and Quantius, 2011, Braukhane, 2015]. Feasibility studies as they are done in the aerospace industry use concurrent design in order to develop system architectures and evaluate possible design alternatives given available technology [Ferreira, 2012]. For the case, when all involved disciplines have models, which can be automatically evaluated, there is a method proposed by Morse et al. [2006] to improve the outcome of concurrent design studies with sensitivity analysis in order to understand the trade space around point designs.

The way space agencies do concurrent conceptual design, they apply all 7 concurrency principles (namely parallel work group, parallel product decomposition, concurrent resource scheduling, parallel processing, minimize interfaces, transparent communication, and quick processing) as describe in Prasad [1999], but instead of virtual teams they bring people together in a designated design facility. This is to leverage effective direct human communication for design trade-offs.

A survey on the current practice has revealed that the duration of mission feasibility studies is typically around 9 working days [Knoll et al., 2018a]. People with expertise in different fields are put together in a collaborative work space to design in parallel and closely coordinate to effectively achieve cohesive and feasible product or system designs. It relies on the following five key elements: a process, a multidisciplinary team, an integrated design model, an infrastructure and a facility [Bandecchi et al., 2000]. Since "infrastructure" and "facility" might be mistakenly interchanged, we prefer to replace "infrastructure" with tools, meaning in particular software, whereas hardware is meant to be part of the "facility". A corresponding definition is found in Karpati et al. [2003] (see Figure 1-3).

2.8.1 Team

The team is formed, based on the expertise required to design subsystems that fulfill functions in the system. This presumes a preliminary analysis of the required system functions and decomposition into sub-functions. These get assigned to different experts on the team, while a systems engineer leads the team through the design process and coordinates the teamwork [Wall et al., 1999, Bandecchi et al., 2000, Braukhane and Quantius, 2011]. According to these authors, people are the most vital element of concurrent design. Their expertise, capability of engineering judgment and negotiation bring the real benefit to this method. The involved engineers need to have experience in designing subsystems of a spacecraft. To give a valid contribution to the conceptual design process, the experts are expected 1) to be capable of making quick estimates for the sizing of the subsystem or build conceptual models of their respective subsystem or aspect, 2) to be able to explain design rationals and discuss design trade-offs, in order to work productively in a collaborative setting [Braukhane and Bieler, 2014].

Companies and agencies use matrix organization, where people reside in discipline-specific departments, and projects like a mission design study draw the personnel from across these departments. Bandecchi et al. [2000] for example reports the following disciplines to be commonly involved: Configuration, Structure, Simulation, ADCS, Propulsion, Mission Analysis, Ground Systems and Operations, Communications, OBDH, Power Systems, Thermal Systems, Instruments, Mechanisms, Programmatics, Risk, Cost. Similar team compositions are reported by Bousquet et al. [2005], Braukhane and Quantius [2011], Iwata et al. [2015].

Another important aspect to conduct effective CCD studies, is the involvement of the customer of the mission study. Hence, there is a permanent customer representative part of the team ready to respond to clarification questions and [Iwata et al., 2015, Gomez et al., 2017].

2.8.2 Model

The model used in CCD represents the system of interest encompassing the structure, configuration and design parameters. For the sizing of a system and its subsystems, it is common to use parametric models. Subsystem models can encapsulate analytic or behavioral models, but appear to the system simply as a mapping of input to output parameters. On of the first descriptions of a comprehensive data model for the case of a satellite system design is given in [Di Domizio and Gaudenzi, 2008]. In essence, it is a set of parameters for each subsystem, design inputs and sizing outputs. Figure 2-5 shows the respective data model in a UML class diagram.

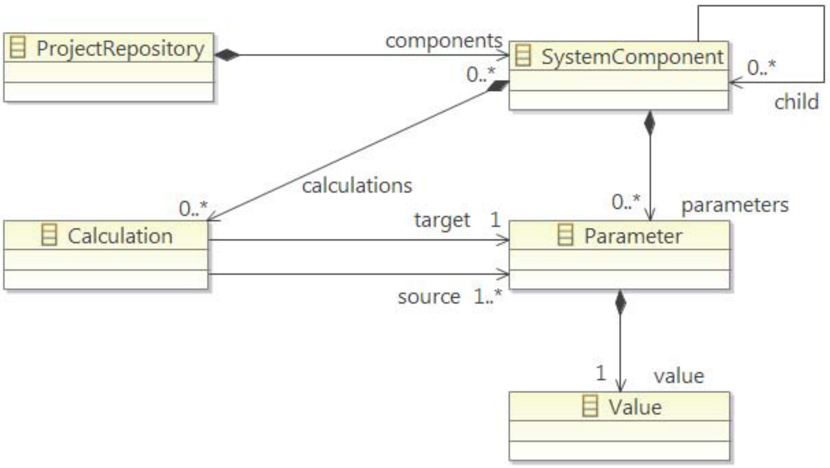


Figure 2-5: Essential data model for CCD [Schaus et al., 2013]

This structured approach allows to properly represent the dependencies between the sizing models, which were primarily calculation spreadsheets [Bousquet et al., 2005]. While being easy-to-use by the single discipline expert, technically it is very hard to keep a set of linked spreadsheets consistent without a centralized data storage and managed access control. It requires an infrastructure to maintain a shared system model and to allow different discipline experts interacting with it.

European space agencies and companies have elaborated a technical memorandum, which contains a unique data model for CCD studies. The quasi-standard ECSS-E-TM-10-25A [ECSS, 2010] is vendor-independent and should guarantee interoperability between different tools, such as generic and domain specific design software used by engineers of various disciplines. The standard covers the data format for storing the system breakdown structure, and for each element parameters and other attributes. It also allows to store variants of the system, as different design options are developed throughout a study. Moreover, the standard defines a web-based Application Programming Interface (API) access the shared data model, to allow tools (clients) to interact with a centralized model storage (server).

An important aspect of parametric models is the semantic consistency in terms of unambiguous interpretation of data by the use of standards such as the "Quantities, Units, Dimensions and Values" (QUDV) in [Object Management Group, 2010, Annex C5]. Based on the QUDV standard, automatic unit conversion can be realized, for example, values in meters to feet, given their specified relationship [Schaus et al., 2013].

A similar approach was taken by NASA, but the data model builds on top of SysML [Wagner et al., 2012, Karban et al., 2016]. This way not only structured parametric models can be represented, but also behavioral models. Moreover, it allows to have a single model, and different disciplines use their viewpoint to interact with the model [Delp et al., 2013, Kulkarni et al., 2016].

Researchers at the German Space agency (DLR) developed a conceptual data model that covers the information needs not only of the conceptual design phase but also of later life cycle phases [Fischer et al., 2017b,a].

2.8.3 Tools

Data exchange tools implementing such a standard enable collaboration among disciplines, and at best interact with domain-specific models or tools. This architecture is shown in Figure 2-6, adapted from [Bandecchi et al., 2000].

The architecture shown in Figure 2-6 has been implemented for ESA in the OCDT [ESA, 2014], which use is limited to ESA member states. The public version of it is Concurrent Design Platform (CDP) [Fijneman and Matthyssen, 2010], which is now open source. These two tools implement the ECSS-E-TM-10-25A [ECSS, 2010].

For a similar purpose the German Aerospace Agency (DLR) developed Virtual Satellite (VirSat) [Schaus et al., 2010], and the Jet Propulsion Laboratory, Califor-

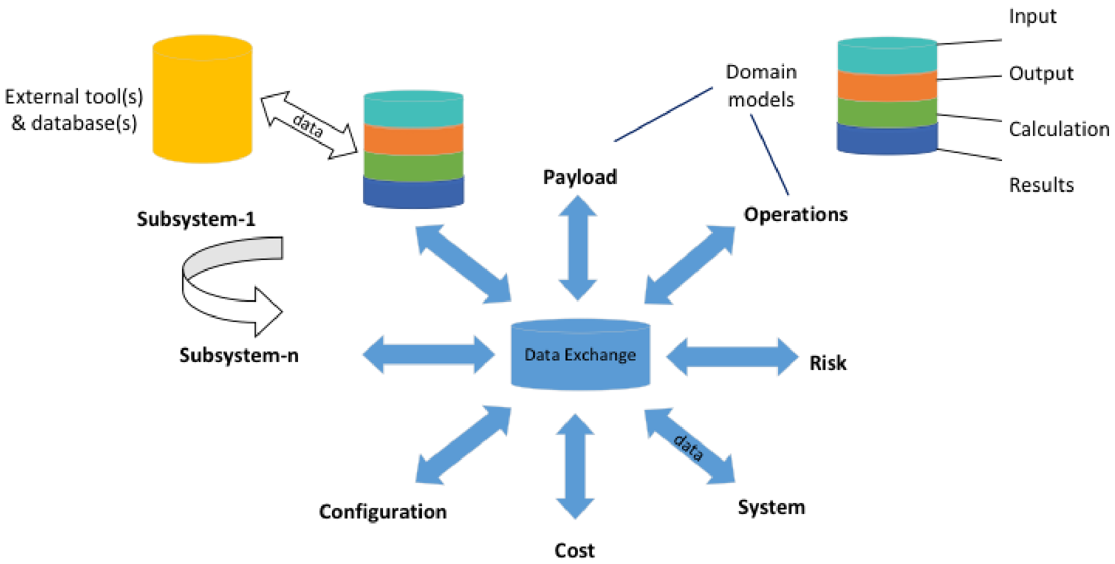


Figure 2-6: A central data exchange connecting all domain models. Adapted from Bandecchi et al. [2000].

nia Institute of Technology, United States of America (JPL) developed OpenMBEE [NASA JPL, 2016]. But not only agencies are commissioning or building tools in-house, also start-up companies are offering collaborative tools for parametric conceptual design. Valispace is one of them [Valispace, 2017]. See Table C.1 in the appendix for a comparison of commonly used tools for conceptual design studies in space agencies.

The tools made for parametric conceptual design are focusing on enabling a team to collaborate on a model, by regulating concurrent modifications and assuring consistency. They do not enforce any specific way of building a tool, nor do they provide guidance for the user. Still, they are based on certain assumptions about the process. Some tools require the user to follow the logic of "load, edit, save" or "checkout, modify, check-in", and regulates this way concurrent modifications. VirSat as a desktop application, for example, is explicitly based on the source code versioning system Subversion (SVN). Other tools apply and propagate changes in real time, without explicit load and save operations by the user. Valispace as a web application, for example, automatically updates and notifies other team members of changes affecting their calculations.

Tools for concurrent conceptual design are required to be flexible to accommodate many different models and kinds of missions [Karpati et al., 2003]. More recent work of Karpati et al. [2011] described the collaboration support in terms of information flow among team members. Avnet [2016] has found that the system model and the coordination are related to a team's shared mental model. But, no direct relationship was revealed between the system model and the coordination.

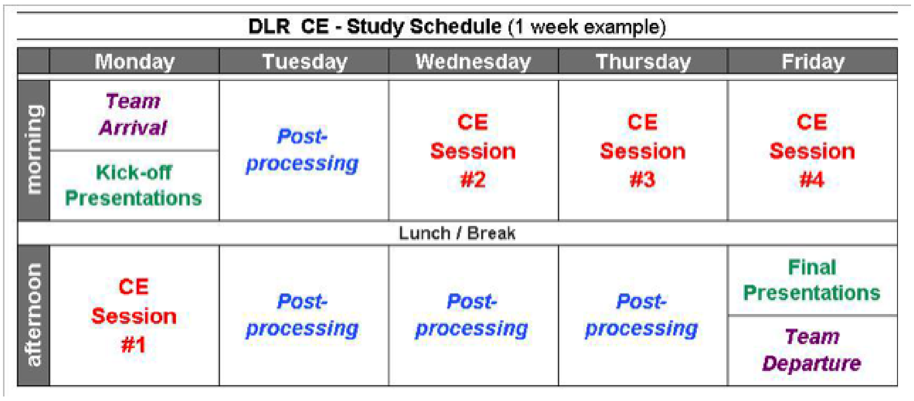
Research Gap

Regarding the interplay of tools and the CCD process, all that has been found is reported above. This represents an opportunity for more research to be done. Based on common patterns of CCD processes, a tool can provide more specific support for it, in terms of collaboration as well as coordination.

2.8.4 Process

The process of preliminary design studies for space missions has, according to Bandecchi et al. [2000], as principal inputs mission requirements and constraints as well as study requirements, and produces study results (S/C Design, S/C Configuration, Launcher, Risk, Cost, etc.). After preparation, the study is performed in so-called design sessions. In these design sessions, the participating design experts join in collocated collaborative work, to discuss and evaluate design options and communicate design decisions. According to the size and complexity of the project and the availability of the required experts the sessions are scheduled over the duration of one or more weeks [Braukhane and Quantius, 2011]. In between the design sessions the discipline experts also work on their respective part of the project, in order to post-process or prepare for design sessions.

An example of how the work schedule looks like in DLR is shown in Figure 2-7. A driving factor in packing the study into one week is the availability of experts [Braukhane and Quantius, 2011]. More precisely, many domain experts do not reside in Bremen, where the facility is located, and need to take business trips for participating in a study. Hence, to save costs the amount and duration of business trips is kept minimal. The downsides of the condensed study period are that it limits the use of time-consuming analyses with discipline-specific tools and less options at



DLR CE - Study Schedule (1 week example)

	Monday	Tuesday	Wednesday	Thursday	Friday
morning	Team Arrival Kick-off Presentations	Post-processing	CE Session #2	CE Session #3	CE Session #4
Lunch / Break					
afternoon	CE Session #1	Post-processing	Post-processing	Post-processing	Final Presentations Team Departure

Figure 2-7: Example of a schedule used in DLR [Braukhane and Quantius, 2011].

system level can be studied. Braukhane and Quantius [2011] also point out the need for appropriate tutorials to get new people on-board as quickly as possible. Karpati et al. [2003] reports a very similar schedule of compact studies with 4 days of design sessions.

The process of concurrent design is often referred to follow a spiral-like approach [Bandecchi et al., 2000, Karpati et al., 2003, Braukhane and Quantius, 2011]. The reason is the iterations revising the different aspects of the system (see Figure 2-8). At the beginning the design starts from very coarse estimates to more and more refined ones, and reaching convergence on a feasible design.

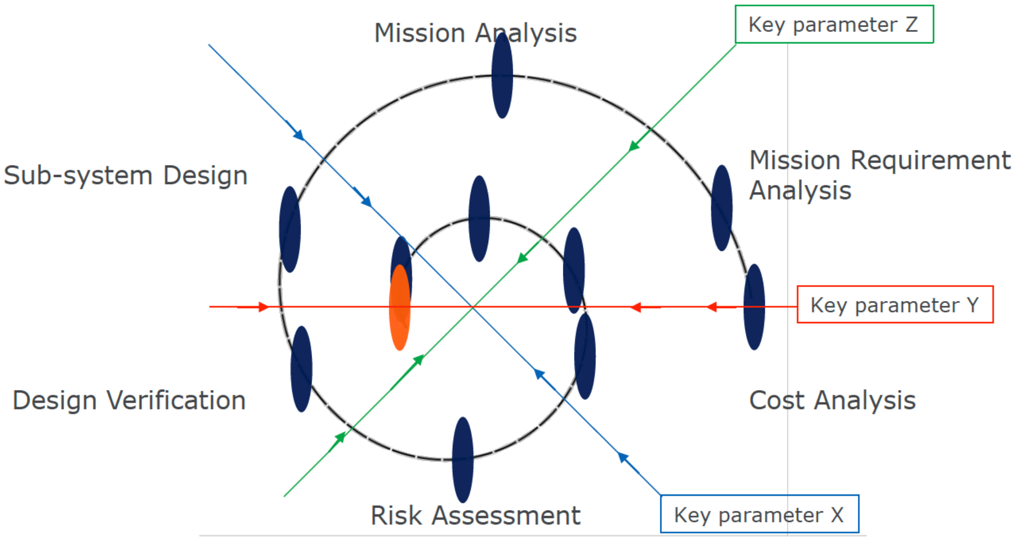


Figure 2-8: Concurrent Design - Spiral Process [ESA ESTEC, 2019].

Iwata et al. [2015] in a review of concurrent design practice among several US and UK CDFs, does not report any details about the process.

What we find documented is the general principle of periodically holding roll-calls during the concurrent design sessions. There, each discipline needs to report key engineering parameters to allow effective dissemination of information and design issues to all team, including the client [Karpati et al., 2003].

In a first approach, the concurrent design process was tried to be organized in three subsequent iterations. The first finishes with a "straw man", the second with a "baseline" and the last, with a "final convergent baseline". This process model demonstrated be applicable only to a few kinds of studies. Consequently, Karpati et al. [2003] describes a distinction into 4 types of concurrent design studies: 1) Proposal effort in response to a NASA Announcement of Opportunity (AO), 2) Early mission formulation a) Validate feasibility b) Explore and trade multiple options, 3) Advanced concepts for future missions, and 4) Special studies or system architecture trades. Similarly, at COMPASS, they distinguish 3 types of studies: Feasibility study (2 weeks), Design and Exploration of Trades (1 month), Conceptual Design Study (6 months) [McGuire et al., 2011].

Besides the working schedule, we are interested in how the concurrent design process is structured.

In McGuire et al. [2011], we found a high-level schema of the process, covering the entire study. The respective flow diagram is shown in Figure 2-9. The four major activities "establishing", "pre work", "design study with concurrent team", and "post work", also contain some more detail. Note, that the diagram shows the design iterations.

Other work has been done to provide templates and process diagrams in the form of SysML diagrams [Infeld et al., 2018]. This MBSE template can be used during concurrent design sessions to guide the process as well as the artifacts to be produced.

An overview on the processes documented in literature is shown in Table 2.3. From this summary, it can be seen that the authors roughly agree on the phases of the CD process. But beyond that, the descriptions differ or lack of details with respect to the schedule.

Organization	Reference	Phases	Schedule	Design Activities	Note
Aerospace Corp.	Aguilar et al. [1998]	study planning, concurrent design session, wrap-up activities			
ESA	Bandecchi et al. [2000]	preparation phase, design phase			
DLR	Braukhane and Romberg [2011]	Initiation, Preparation, Study, Processing	One-week schedule		
DLR	Romberg et al. [2012]	preparation phase, study phase, post-processing			
DLR	Gomez et al. [2017]	Initiation, Preparation, Study and Processing			
NASA GSFC	Karpati et al. [2003]	Preparation phase, Execution phase	Multi-week schedule		"... need for design iterations."
NAS JPL	Morse et al. [2006]	Pre-Sessions, Sessions, Post-Sessions, Report			
NASA GRC	McGuire et al. [2011]	Establish the Study Definition, Pre Work, Design Study with Concurrent Team, Post Work	Multi-week schedule	3 phases containing 14 sub-activities	"... design process is iterative."
NASA GSFC	Infeld et al. [2018]	Study initiation, Preparation, Pre work, Session		4 phases containing 28 activities	SysML diagrams, considering multiple design options
NASA, Aerospace Corp., RAL	Iwata et al. [2015]				cross-organizational CDF comparison, Budget Flow-Charts

Table 2.3: Summary of CD processes

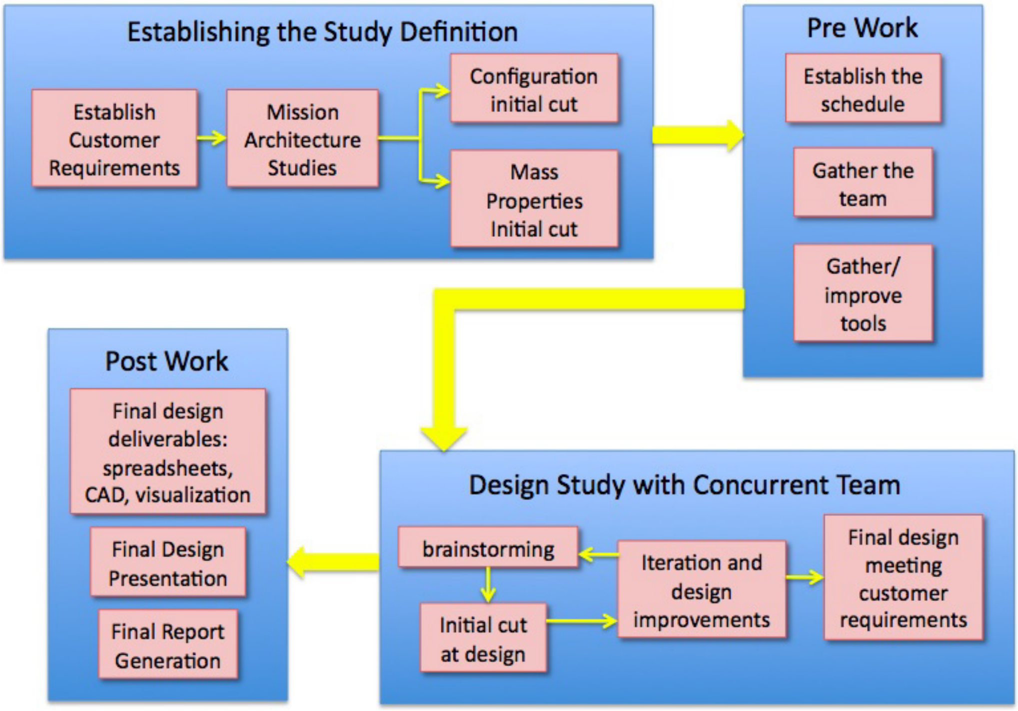


Figure 2-9: Concurrent Design - Team Process [McGuire et al., 2011]

Research Gap

The most detailed models by McGuire et al. [2011], Infeld et al. [2018] describe the process schematically at a high level. These models do not give detail on the structure of the design iterations and how they are performed.

2.8.5 Facility

Concurrent design facilities (CDFs) are established within organizations that want to carry out concurrent design studies regularly. The facility is staffed with personnel for coordinating the activities and maintaining the infrastructure. The study coordinators are usually part of the facility's permanent staff.

In terms of structure and equipment, many facilities are also similar. For the ESA CDF see Bandecchi et al. [2000], for the German DLR's facility see Romberg et al. [2008], for Skoltech's CEDL see Golkar [2016]. As an example, Figure 2-10 shows the desk arrangement and their allocation to discipline experts in the CDF at DLR.

A CDF hosts concurrent design studies, and provides the location for people to

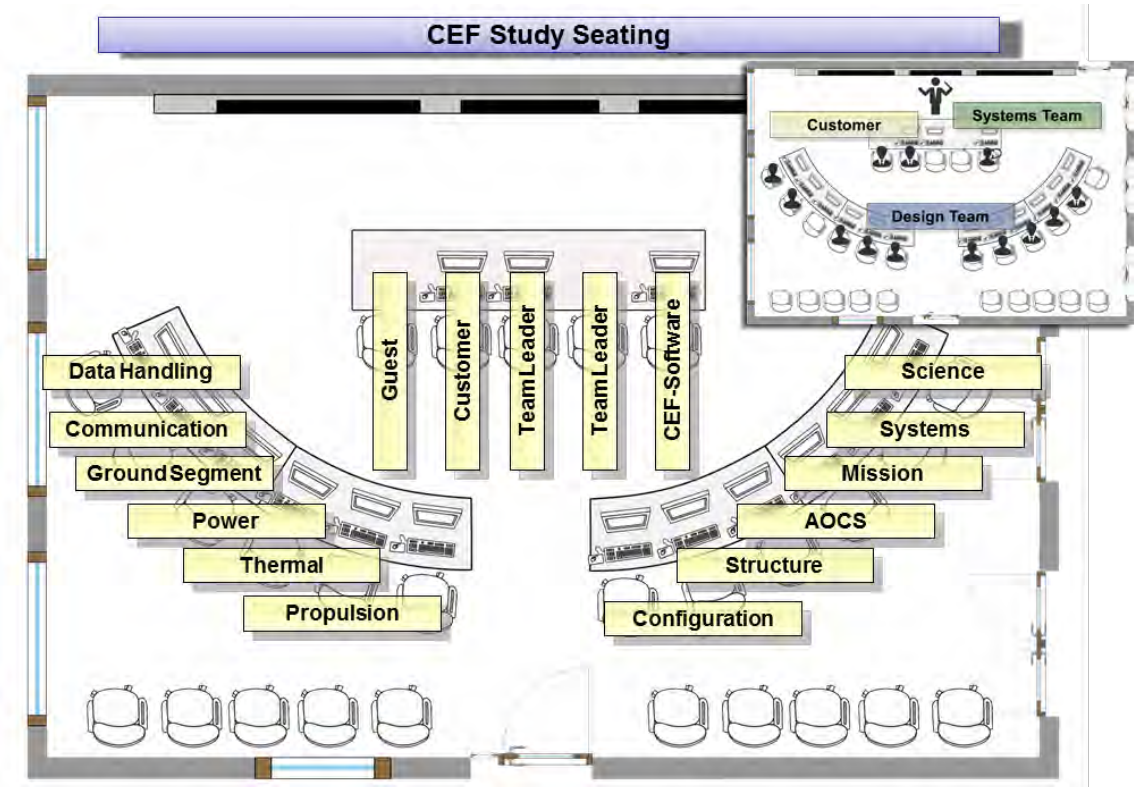


Figure 2-10: Discipline seat allocation in a CDF [Gomez et al., 2017]

gather for the duration of the studies. All of them have a main design room, and also have connected meeting rooms for parallel working sessions.

Common equipment of the main design room are:

Shared screens for the presentation of intermediate engineering results. The visualization is considered to be very important to reach a shared understanding and enable effective discussions.

Video conferencing allows to connect remote participants into the room. This includes means for team conversations and the sharing of screens content.

Workstations for the study participants. They consist of desks with a computer, connected to the network and to the shared screens and videoconferencing equipment. In most facilities, the workstations have a fixed arrangement and allocation to specific engineering disciplines. Golkar [2016] describes the potential benefits and challenges of realizing a facility with flexible desk arrangement and mobile computers.

Not to neglect are the social aspects of concurrent design facilities [Braukhane et al., 2015]. Firstly, the time study participants spend in informal conversations helps building the relationships which later ease professional collaboration. Appropriate space for coffee brakes can facilitate the team building [Braukhane and Bieler, 2014]. Secondly, within organization a facility receives a certain brand, e.g. "a fancy/enjoyable place", which can be due to appealing architecture or latest technology for visualization, collaboration and videoconferencing. This has a positive influence on the likeliness of engineers to engage in subsequent concurrent design studies.

2.9 Technology Roadmapping

Technology roadmaps are an increasingly popular tool for strategic management of technology development and supporting decision-making in Research and Technology (R&T) investments. In this context we distinguish R&T from R&D. Where R&D is more oriented to short/medium term product development, and R&T is more oriented towards technology maturation for strategic, long-term goals.

Garcia and Bray [1997] writes: "Technology roadmapping provides a way to identify, evaluate, and select technology alternatives that can be used to satisfy the need." A similar definition with respect to the needs of science and technology is given by [Kostoff and Schaller, 2001].

Roadmapping is one step of technology management and can best be described in this context. The obvious analogy is how conventional maps are used in road navigation (Figure 2-11) [Knoll et al., 2018b]. Choosing a route first requires to identify the current position on a map. Secondly, potential destinations are identified on the map. Thirdly, a desired destination is selected according to individual decision criteria (as for instance, distance or road tolls), which are combined into a utility function. In a for-profit corporation, this utility function is generally the expected return of the planned R&T investment. Only after that, the route to the destination is defined. Correspondingly, technology management includes these three activities: 1) technology assessment, 2) technology roadmapping, and 3) technology planning [Knoll et al., 2018b].

Figure 2-11: Route planning metaphor for technology roadmapping [Knoll et al., 2018b]

Roadmapping and planning is done upstream to the actual product life-cycle, and the goal is to screen a large number of possible system architectures and various technologies to be infused into products [Suh et al., 2010]. Technology roadmapping deals with the identification of desired targets for the development of new technology. A technology roadmap is a plan that matches short-term and long-term goals with specific technology solutions to help meet those goals. It is a plan that applies to a new product or process, or to an emerging technology. Developing a roadmap has three major uses:

- it helps reach a consensus about a set of needs and the technologies required to satisfy those needs,
- it provides a mechanism to help forecast technology developments, and
- it provides a framework to help plan and coordinate technology developments.

There exist different practices to build technology roadmaps. Phaal et al. [2004] propose a "T-Plan fast-start approach" based on workshops to identify and assess technology development within a company. Most commonly, technology roadmaps are formulated and maintained as visual charts depicting projects and milestones over a time. In fact Moehrle et al. [2013] writes "a technology roadmap is nothing less than a graphical representation of technologies, often relating objects like products or competencies and the connections that have evolved between them in the course of time."

Figure 2-12 shows a schematic roadmap covering 3 layers: market, product and technology and a horizontal time axis. Very similar, a generic roadmap from Rinne [2004], where the time line is implicit but the connections between the elements are shown.

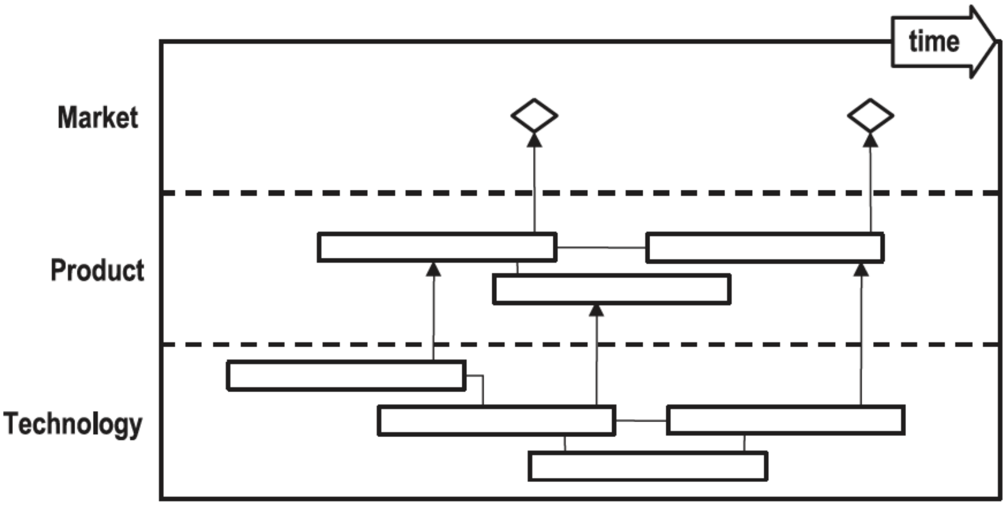


Figure 2-12: A schematic technology roadmap [Phaal et al., 2004]

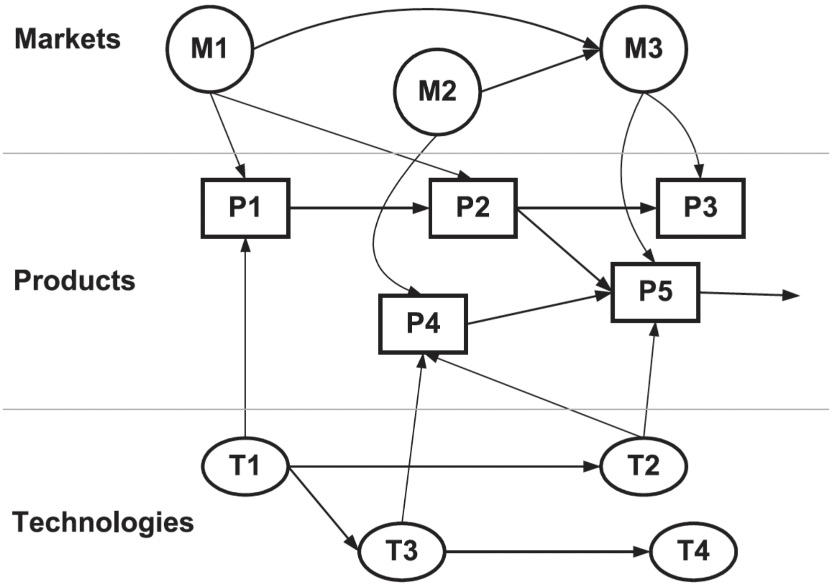


Figure 2-13: A generic roadmap [Rinne, 2004]

The limitation of such charts is that they do not carry the rationale, and with progress and changing conditions they become easily out-dated. For that same reason, these roadmaps are also hard to maintain. Being snapshots of specific moments in time hinders their effective use over long periods [Rinne, 2004]. This lack of an explicit connection, between their technology targets and the underlying scientific and engineering rationale, make target verification and validation difficult [Knoll et al., 2018b].

Nevertheless, most organizations see the value of the roadmapping process for discovery and consensus building, more than as a quantitative tool to support technology investment decisions and associated targets [Rinne, 2004]. As a result, technology roadmaps reflect the intuition of experts and judgment of senior executives [Bray and Garcia, 1997, Garcia and Bray, 1997, Bernal et al., 2009].

Alternatively, roadmapping can rely on analytics and forecasting of the evolution of performance characteristics over time. When studying the influence of technology infusion into products, integrated product models are needed to estimate the impact on the overall system performance. In a rigorous process, such estimates are generated with the help of parametric system models. These estimates of potential system performance are used for planning technology development in order to support next-generation products [de Weck and Chang, 2003].

An information-based approach to generate roadmaps was proposed and demonstrated by Gausemeier et al. [2009]. Their approach relies on an innovation database about technologies for principal functions. User input about a product ideas is then broken down into principal functions and related information about the technologies is aggregated as a roadmap.

More recent work, from Arendt et al. [2012] has shown the quantitative technology assessment using trade space exploration analysis to identifying the Pareto front of a given technology, and forecasting the evolution under uncertainty. Yuskevich et al. [2018] applied two-dimensional Pareto front forecasting using historical data of technology evolution. In a competitive market, the historical data can also be used to simulate the strategic decision making. Using the forecasted Pareto fronts Smirnova et al. [2018] described how to predict strategic options, in terms of marketable product designs.

2.10 Summary

This chapter provided the necessary background from the literature. We discussed the context of our work, namely Systems Engineering and Model-Based Systems Engineering. Closer to our topic, we described the role of conceptual design in the product lifecycle, as well as the modeling of engineering processes. Further, we explored the methods of tradespace exploration and multidisciplinary design optimization.

We presented an overview of the broad topic of Concurrent Engineering and its application in different industry sectors. Finally, we gave a more in depth review of the literature on the use of Concurrent Conceptual Design for feasibility studies of space missions.

The next chapter sets the objectives for the following parts of the thesis.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 3

Thesis Objectives

The introduction gave the context of Model-Based Systems Engineering and its use in conceptual design of space systems. The previous chapter presented the background knowledge and state-of-the-art in the literature related to our topic, Concurrent Design as a specific form of MBSE for the conceptual design phase. The review of existing research on Concurrent Conceptual Design (see section 2.8) revealed gaps with respect to tools and processes. In this chapter, we define the goals and derive the specific questions to be addressed in our research.

3.1 Goals

We acknowledge that engineering in general, and concurrent design in particular, are very much driven by humans. Basically, the design process is the result of the interaction between people and their supporting tools. Our work contributes to the related fields of model-based systems engineering and design research, by addressing the gaps identified in literature.

The goal of this thesis is three-fold. First of all, we aim to get a better understanding of the concurrent design approach and its dynamics. Secondly, we want to provide support for new teams adopting this approach for the conceptual design of space mission. Thirdly, we strive to extend the application of this approach to the field of technology roadmapping.

Improve understanding

Clearly, the concurrent design approach is not new and a significant amount of publications exists. But a gap, identified in subsection 2.8.4, is that most of them originate from single organizations, and no common description of the actual design process exists. Our intent is to integrate findings in literature and experience from practitioners, especially from different organizations, and describe a generic methodology. Interviews with subject matter experts from space agencies and companies shall be conducted to obtain more information on the used processes. Generalizing from the practice of different organizations, a generic, formal model of the process shall be developed.

Propose supporting tools

Leading and participating in concurrent design studies, we experienced how important the ease-of-use of tools and guidance are, in following a structured process. Building upon the design methodology, we propose specific support for the design process built into the collaborative modeling tool. The current design support tool focuses on the system model, while neglecting the process (see subsection 2.8.3). Using the generic process model derived from the practice, a tool can be designed that can give guidance to the users and assist in coordinating the collaboration. Our aim is to contribute to a shift from data-centric to process-centric tools.

Extend for new applications

With our process guideline and the related tool, we want to facilitate the adoption of this methodology to other areas as well. Potential technologies to be infused into a product are important to consider during conceptual design. Likewise, technology planning could benefit from closer integration with conceptual design. We propose a way to extend the concurrent design approach to the creation and maintenance of model-based technology roadmaps. Such roadmaps could become more robust sources for decision making, if they were based on models. The application of collaboration in an MBSE environment to roadmapping shall be explored.

3.2 Research Questions

The general objective, as already mentioned above, is to provide a comprehensive description of the Concurrent Design (CD) approach, which provides guidance for teams to effectively perform conceptual design studies of complex systems.

Based on a generic description of the CD approach, we will focus on the roles of the process and tools.

3.2.1 Design Methodology

The review of the literature about concurrent conceptual design has revealed the need for a design methodology. The general approach of Concurrent Conceptual Design (CCD) is widely used by space organizations, but it requires people who are prepared for this specific type of teamwork [Ferreira, 2012]. The teams are formed for each conceptual design study according to the required engineering expertise. As a consequence, frequently there are people on the team, who are new to CCD [Braukhane, 2015]. Moreover, our survey shows (see chapter 4) that some organizations struggle to find enough people with both, engineering expertise, and familiarity with the specific way of working in CCD. One way to address the lack of experts, is providing support for training with a well-documented methodology.

Each organization employing CCD has its specificity, and there are many different ways to do the conceptual design of a system. We found organization-specific descriptions in [Bandecchi et al., 2000] from ESA, in [Romberg et al., 2008] from DLR, in [McGuire et al., 2011, Iwata et al., 2015] from NASA. Ferreira [2012] describes an integrated design methodology, but does not provide verification for it. The different implementations of CCD have a set of commonalities: a multi-disciplinary team, a collaborative environment, the resulting artifacts are models. Following the MBSE vision [INCOSE, 2007], it makes sense to formalize the concurrent design methodology using models. According to Heisig et al. [2010] there is great potential in the modeling of design methods and processes to improve their manageability.

Hence, we formulate our first research question as follows.

RQ1 *"Is there a generic design methodology for the concurrent design of complex space systems in an MBSE environment?"*

To answer this question, we extract the common elements from the approaches implemented in different organizations. The resulting Model-based Co-located Conceptual Design Methodology (MoCoDeM) shall be a formalized description of CCD. It combines knowledge of various organizations and represents a generic synthesis. A similar effort to formalize the concurrent design method used in NASA JPL was recently published in [Infeld et al., 2018].

The methodology we developed is validated through interviews with practitioners and subject matter experts. Moreover, we tested in real design studies, whether this methodology enables a team to build a conceptual design model of the system, and check the concepts feasibility.

The proposed and verified methodology can serve as a baseline for implementing the concurrent design approach in new environments, as well as to train people in the approach.

3.2.2 Tools and Processes

The practice of concurrent conceptual design shows common patterns in terms of process. To make the best use of the available time, work is parallelized wherever applicable. In general, design dependencies and propagation of changes lead to a highly non-linear process, which is not understood, and even less planned [Yassine et al., 2003, Shapiro et al., 2015]. The concurrent design process, as described in literature, primarily relies on the experience of the systems engineer to organize work. This challenge of managing the process non-linearity is confirmed by our survey (see chapter 4). Likewise, experts report the difficulty of unequal work distribution among team members [Braukhane and Bieler, 2014]. For the design process to produce a result, the teamwork needs to be coordinated.

The tools used in concurrent design are built around the data model [Di Domizio and Gaudenzi, 2008, Fischer et al., 2017a]. Their purpose is to enable team members to modify the shared system model [Schaus et al., 2010, Voirin, 2010]. In the existing literature, tools are considered data-centric and process-agnostic. In practice, tools often embody or implicitly favor a specific way of working.

This brought us to the following research question.

RQ2 *"How can a tool guide the team collaboration through the design process and coordinate the work?"*

Our hypothesis is that a tool able to support parallel or overlapping work, allows to speed-up the design process. The visualization of dependencies assists the moderator to coordinate the work, such that unnecessary rework can be avoided, by properly sequencing the participants' synchronization. A tool that reflects a process guideline, indicates the steps of the design study and assists the design team in their work.

The usefulness of the proposed tool support is verified in case studies and evaluated for its efficacy. Hereby this work contributes to the knowledge on the interplay of processes and design tools in CCD. Finally, the adoption of CCD is facilitated by the improved tool support.

3.2.3 Extension

With the proposal of a generic methodology, the question arises about the scope of its validity, and the ways to adapt it to fields, other than the one where it originated.

Technology roadmaps, as described in management literature, are the product of negotiation, and serve to share a common vision [Garcia and Bray, 1997]. The definition of the targets for technology is based on expert estimates [Phaal et al., 2004, Kerr et al., 2006] Ideally though, these targets should be based on evidence coming from R&T projects. In this way, technology to be infused into products could be evaluated more reliably [Suh et al., 2010]. So far no general approach exists for modeling roadmaps and linking to technology development.

RQ3 *"How can the methodology be adapted to the creation and maintenance of model-based technology roadmaps?"*

For an industrial research project, we formulated the concurrent roadmapping approach, based on MoCoDeM. This approach considers the parallel development of interdependent roadmaps, with a co-located team in a model-based environment. This approach is implemented and tested in the technology management department of a major aerospace company. The use case illustrates the application of MoCoDeM to Technology Roadmapping. Using the CCD approach beyond its originating field of conceptual design studies represents a novelty.

3.3 Summary

In this chapter, the goals of our research were set and research questions were motivated and defined.

Our research applies the established framework of Design Research Methodology (DRM). Based on that, we developed the work in a set of stages and used methods such as surveys, interviews, developed design support and tested it in case studies.

In the next chapter, we describe in detail the survey conducted among concurrent design practitioners.

Chapter 4

Expert Survey

We know about the use of Concurrent Design (CD) in space organizations primarily from announcements or publications on the establishment of a dedicated facility. Our literature review has revealed that many articles give insights into the work of single concurrent design facilities. According to our research there are more than 40 facilities built over the last 20 years in many agencies, companies and universities, all over the globe. While some of the facilities carry the terms "concurrent engineering" or "concurrent design" in their names, others do not. Nevertheless, their purpose and general approach are very similar.

To get an understanding of the practice, we decided to investigate the commonalities and differences between different organizations. Through a survey, we try to quantify the benefits, challenges and trends, along all 5 pillars of CD: team, tools, model, process, facility. This provides us with indications on where the application of the concurrent engineering approach for conceptual design of space missions can be improved.

4.1 Online Questionnaire

We surveyed subject matter experts in space agencies and industry on their experience with the concurrent engineering approach to conceptual design. With the help of the ESA Conference Bureau, we reached out to all experts who participated in the conference most relevant to our topic: Systems Engineering and Concurrent

Engineering for Space Applications (SECESA). The complete survey and all results are included in Appendix B. A summary of this survey was published in [Knoll et al., 2018a].

4.1.1 Population

The 20 respondents to the survey came from 15 different organizations' concurrent design facilities, located in Brazil, China, France, Germany, Italy, Russia, UK and USA. From the participants of SECESA conference, we know of 44 facilities (see Appendix A) and our estimate is that up to 100 such facilities may exist worldwide. Our sample covers 30% of the known population and at least 15% of the potential population. If it was a random sample, the results could not be generalized to the entire population, but our sample is a good representative, because it includes all the world leading facilities using CCD for space mission feasibility studies from NASA, ESA and DLR.

Based on the variability of the answers, we can estimate the statistical significance of our sample. For questions on which we report proportions, the margin of error for a confidence level of 95% is ± 22%. The questions for which we report an average over the 20 responses, we used the 1-sample t-test to compute the probability that our responses are the result of pure chance (p-value). As indicated below, for all averaged values, the respective p-value was computed to be less than 1%, which means a confidence level of 99%.

The respondents are qualified staff members of CDFs with 65% of them counting more than 5 years of experience. They are active in the roles of facility manager, team lead, systems engineer, discipline expert, and others.

4.1.2 General

The data shows that CDFs are operated as engineering support units. A large majority of design studies (95%) are initiated by principal investigators outside the concurrent design facility.

Six motivations to use concurrent engineering were asked to be ranked between

0 and 5. The most important reasons are "quality of results" and "time efficiency", both with an average rank of 4.3 (p«1%) followed by "connecting people" with a rank of 4.2 (p«1%). Lowest and most diverse answers were given about the importance of repeatable results (see Figure 4-1).

Respondents were asked to rank a set of eight challenges of concurrent design on a scale of 0 to 7 with 7 being the biggest challenge. The top three are "expert availability" with an average rank of 5.3 (p«1%), "integrated tool chain" with an average rank of 4.9 (p«1%) and "capturing engineering knowledge" with an average rank of 4.7 (p«1%) (see Figure 4-2).

4.1.3 People and Team

With respect to the responsibility of forming the team for the concurrent design study, 70% of the respondents agree that this is the duty of the CDF core staff.

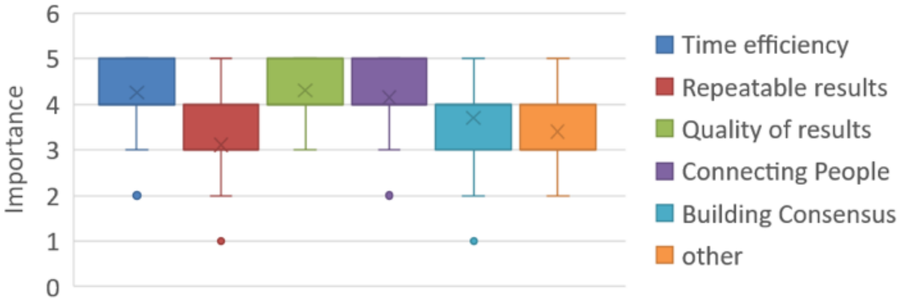


Figure 4-1: Benefits of Concurrent Design

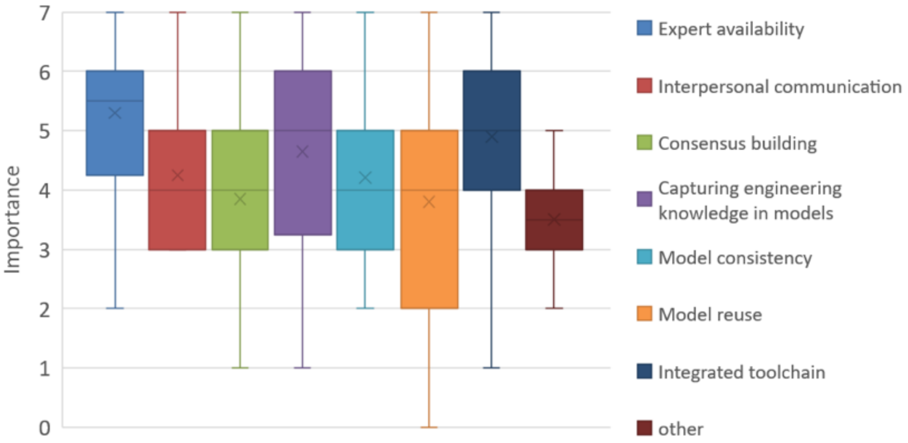


Figure 4-2: Challenges of Concurrent Design

It is also very common practice (65%), that experts from other organizations get involved in design studies. On the choice of the team size there is significant variety among CDFs (see Figure 4-3). In a few words, the average minimum team size is 6.2 people, the average typical size is 13 people, and the average maximum team size is 20 people, with confidence level above 99%.

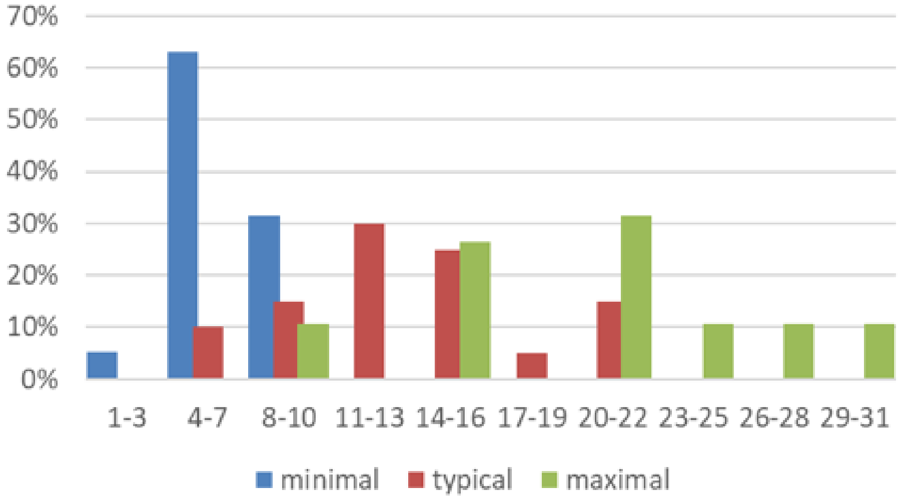


Figure 4-3: Distribution of the team sizes

Although co-located work is a building block of concurrent design, the data also shows that remote participation is quite common. Only 15% of the respondents confirmed that their studies run exclusively with people on-site, whereas 55% affirm to sometimes having remote participation, and other 30% have remote participation on a regular basis.

The preparation of a study team leader greatly varies among different organizations, but many respondents report “on the job training”, meaning that team leaders learn from participation in concurrent design studies in various roles. Besides that, leaders are prepared by mentoring and studying manuals. Some respondents mention that it requires a talent.

A challenge mentioned by several experts, consists in the balancing of workload, such as keeping the team motivated and actively engaged throughout a study.

The trend, which is considered by 40% of the respondents to have an influence on concurrent design studies, is the lack of experts. This is confirmed also in the challenges described by the respondents, repeatedly mentioning the turnover of people from one study to another, and the need to get newcomers familiar with the concurrent design methodology quickly.

This need can be addressed with more widely available training materials.

4.1.4 Tools and shared model

The majority of concurrent design centers (45%) rely on in-house developed and proprietary software for the exchange of design information. The other 40% of the tools are either open source or free, and only 10% use commercial software. There are very few tools that are used by more than one organization. This demonstrates that there is potential for tool vendors, and the need for standardization to achieve interoperability.

For 65% of the respondents the training needed for their tool is up to one day. Training is crucial because, as reported above, many studies have people without previous CD experience. As it is shown later, the average duration of a study is around 9 days. Hence, one day of training can be a significant portion of the time available for a design study. This underlines the particular need for tools that are easy to use and learn. Tools that are used across many organizations would reduce the need for training on proprietary tools.

The fact that model-based systems engineering is becoming more and more popular can be seen from the use of descriptive modeling (50%) and requirements management tools (50%). Models are commonly reused through reference designs (55%) and curated model libraries (45%).

Challenges related to the concurrent design tools that were reported in various forms, are to the ease of use, to keep required training low, in order to cope with frequent people turnover. Tools need to balance the ease of use and modeling rigor, but also guarantee consistency of the design model. Another challenge reported is the integration of tools for analysis and simulation and interoperability, as well as more insightful visualization of the system to be designed. Among the future trends, most influential on concurrent design tools, are "real-time collaboration" (55%), "integration with Product Life Cycle Management systems" (50%) as well as "augmented reality" (50%) (see Figure 4-4).

4.1.5 Process

The vast majority of organizations, given the years of experience, have established clear procedures. 80% of the respondents affirm to have a process for the overall design study, and 66% also have a defined process for single design sessions. The total duration of concurrent design studies on average is 9.6 days, with a confidence interval of ± 3 days (see Figure 4-5). Studies are carried out by the majority of respondents (65%) in a compact period of time, whereas the rest span the study over a longer period of time.

The process is meant to produce feasible designs. For 35% of the respondents a single design point is enough, 50% usually produce two or three design variants and the remaining 15% aim at producing more designs. The evaluation of feasible

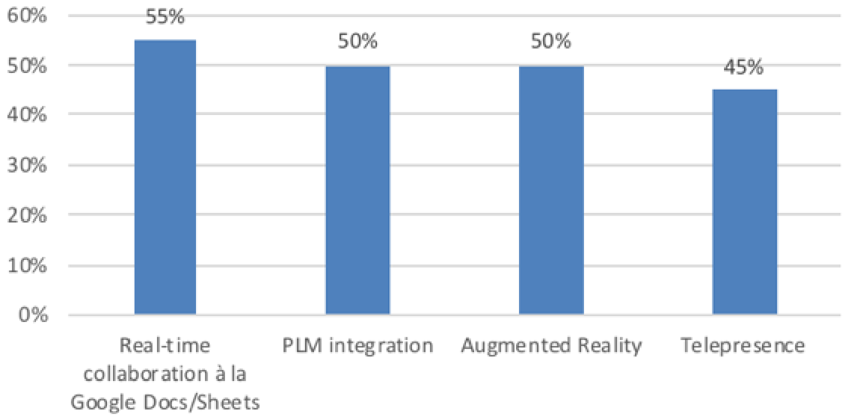


Figure 4-4: Trends influencing tools

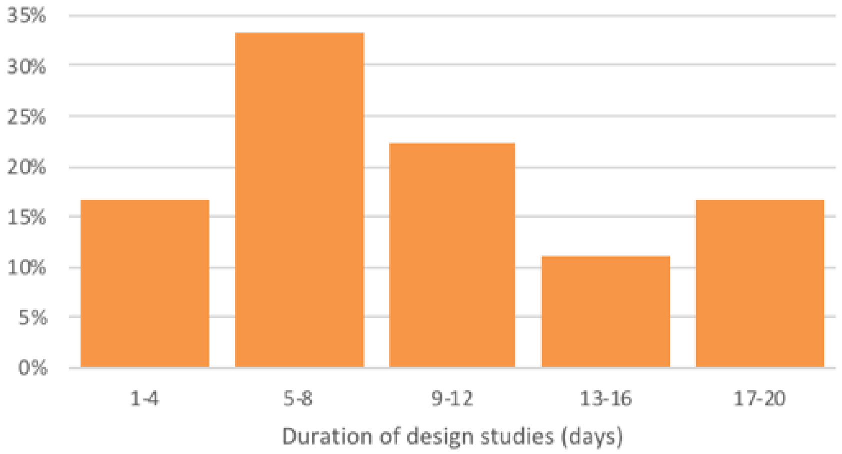


Figure 4-5: Distribution of study duration

designs is very commonly done according to figures of merit, such as mass (90%), cost (85%), power (80%), and communication (75%), as shown in Figure 4-6. It is interesting to note that all respondents widely agree that the study results are always documented in the form of models (90%), reports (85%) and presentations (85%).

Figure 4-6: Design evaluation criteria

On the process aspect, challenges reported by the survey participants regard the management of the varying workload and keeping the degree of details adequate for the next project stage. The trend that has been voted most important (70%) for the concurrent design process is the agile methodology. This means that design studies are expected to have more or quicker iterations with useful intermediate results.

4.1.6 Infrastructure and facility

Facilities have been established starting in the 90's and their number is steadily growing (see Figure 4-7). On average, the facilities have been in operation already for around 13 years. Consequently, the majority (78%) of them already have undergone refurbishment/modernization at least once, and some (12%) even several times. All facilities older than 10 years have already undergone refurbishment. The seat capacity of facilities varies between 10 and 40 (see Figure 4-8), with an average of 22 seats for designers and 11 seats for observers.

Most facilities are equipped with dedicated computers for the study participants to work on (60%), whereas the rest of the facilities accommodate computers brought by participants.

The features of concurrent design facilities were asked to be ranked by their importance on a scale from 0 to 5. By far, the most important features are "structured data sharing", with an average rank of 4.5 (p«1%) and "visualization capabilities", with a rank of 4.1 (p«1%) (see Figure 4-9). The data also shows that importance of conferencing depends on the amount of remote participation. Facilities that have exclusively on-site participants rated videoconferencing much lower (2) than ones that have regular remote participation (3.8).

The respondents agree (65%) that a concurrent design facility can only partially be replaced by a well-equipped meeting room. The biggest challenge is the mainte-

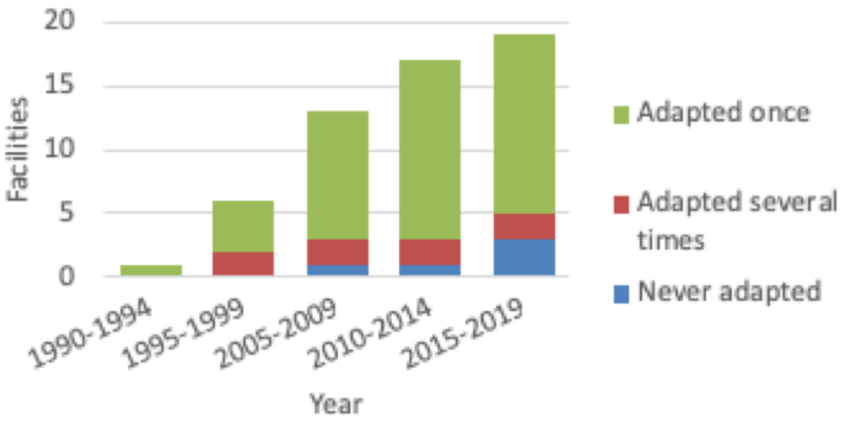


Figure 4-7: Number of facilities established and adapted over the years

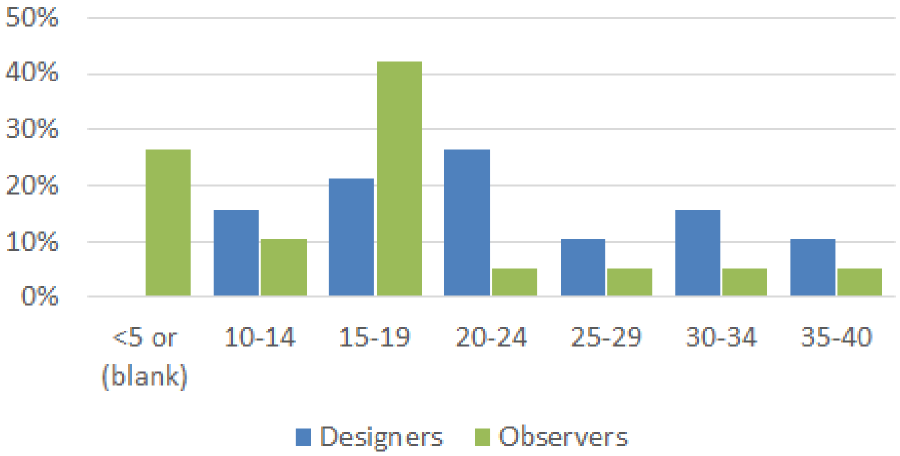


Figure 4-8: Distribution of facility capacities

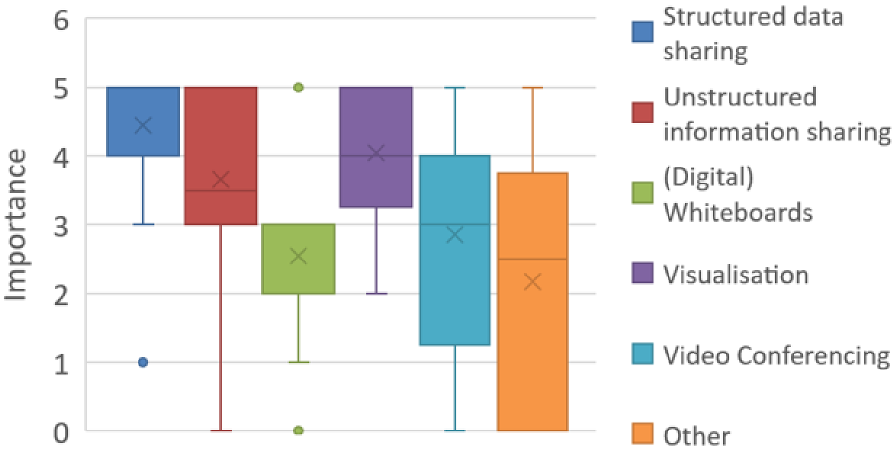


Figure 4-9: Importance of facility features

nance of IT systems, keeping them up to date and dealing with obsolescence. This is also confirmed by the trends which respondents deem to have an influence on the future evolution of concurrent design facilities. The most important trend (70%) is the shift towards computers brought into the facility by the study participants, and equipment obsolescence (30%) (see Figure B-14).

4.2 Key Results

Here is a summary of the results from the survey, which influenced the elaboration of our methodology.

Benefits

The survey partially confirmed what was already found in literature. *"Time efficiency"* and *"quality of results"* are deemed the primary benefit of Concurrent Design for space missions. Another important benefit is that concurrent design studies bring together and connect people.

In relation to the concurrent design facility, the survey respondents widely agree on the importance of *"structured data sharing"* and *"visualization"* capabilities.

Challenges

From the responses to our survey, we identified that the following two challenges are the most pressing to practitioners of concurrent conceptual design of space systems: A) expert availability, B) integrated tool chain.

Despite the association that Concurrent Design generally means co-location, it is very common to have remote participants. The remote participation is a compromise to involve experts with knowledge on a specific aspect of the space mission, who can not be brought on-site for the entire CCD study.

Expert availability

The ideal participants in concurrent conceptual design studies should have deep knowledge in their own discipline as well as capability to think of the inter-dependencies with other aspects of the space mission. Moreover, participants should have good communication and negotiation skills. People with such skill sets are rare and highly requested for many projects in organizations. Hence their availability for concurrent design studies is limited. Because of that, those actually participating in concurrent design studies change frequently, leading to a significant part of the team being new to the concurrent design approach.

According to our survey, it is very common to have participants coming from other organizations, who very likely are new to the concurrent design approach. Both factors underline the need to get newcomers acquainted with the approach quickly.

Integrated tool chain

Most, if not all, discipline experts participating in a concurrent design study use some form of knowledge base or discipline specific tool. The development of a conceptual design requires all experts to share the information that is of mutual relevance. A shared integrated system model covers all that common information. The required information infrastructure is shown in Figure 2-6. One part of this challenge consists in the automated data exchange between all the domain specific tools through a shared model. The other part of this challenge refers to the capability to facilitate human collaboration. To facilitate the team in collaboration, the tool needs to provide guidance for the synchronization of concurrent work.

We made it our goal to address these challenges with our design methodology. The documentation of the methodology in chapter 5, develops the process guideline broadly, and chapter 6 describes the support for the processes through a software tool.

4.3 Open Questions

The answers to the survey also exposed challenges and opened paths for future research that go beyond this work.

Distributed Work

Co-located work, considered a cornerstone of concurrent design, has been questioned many times and concepts such as distributed concurrent design have been proposed [Beco et al., 2008]. Our survey shows that remote participation is quite common. Mostly because highly specialized experts cannot be freed up of other duties, or because of limited resources available to bring all experts on-site for the entire period of a design study. Because video-conferencing does not provide the same quality of communication as face-to-face meetings, study leaders choose to hold at least the study kick-off as an in-person meeting, in order to help establish personal relationships. Current technological developments renew the promise of enabling effective remote collaboration with the help of augmented and virtual reality [Nee et al., 2012, Choi et al., 2015]. A positive impact of augmented reality tools in the automotive maintenance has been described by [Jetter et al., 2018]. But whether this technology can also improve collaboration in distributed concurrent design is a question for further research.

Real-time collaboration

Despite the continuous evolution of the tools for concurrent design, experts still expect major improvements. Survey respondents name ease-of-use, concurrent editing of the model, interoperability and integration with domain-specific, analytical tools as ongoing challenges. Spreadsheets are a simple and frequently used way to build simple parametric models. Today state-of-the-art tools already allow real-time collaboration on spreadsheets, e.g. Google Sheets. Given the broad availability of spreadsheet tools, many organizations maintain collections of validated models. Although there are more advanced languages and tools for parametric models, for example ones based on Modellica, none have reached wide adoption in concurrent conceptual design so far. A decisive factor is surely the existence of legacy in organizations, which would require highly labor-intensive migration of existing models to newer tools. Gopsill et al. [2013, 2015] have proposed a more comprehensive approach to rethink the engineers' collaboration, in the form of a social media framework for engineering design communication.

Model from scratch

Parametric modeling is an important part of the concurrent design approach for feasibility studies. The literature, referred by the survey participants, generally presumes the existence of such models. Baseline models for the sizing of spacecraft are, for example, explained in [Wertz et al., 2011]. Such models embody years or decades of design heritage.

When starting from a blank sheet, quantitative models can only be derived from first-principles, such as laws of physics. Otherwise, when similar systems have already been built, quantitative models can also be derived from the data collected about existing systems. Still, finding or choosing parametric models that describe a system with an appropriate level of detail, remains an open challenge. Ways of guiding this crucial step in the conceptual design should be subject of further research.

Drawings

Engineers often express and communicate their ideas with the help of simple drawings. To reduce ambiguity in diagrams, various formalized languages have been invented (e.g. IDEF0, SysML, OPM). The responses to our survey suggest that none of them is adopted broadly. This could be due to people's lack of familiarity with those languages or their appropriateness. Further research should address the question, which modeling techniques are most appropriate for concurrent design, given the limited time of design studies and the teams heterogeneous knowledge background.

4.4 Conclusion

Our survey investigated the state-of-the-art of concurrent design as practiced by space agencies, companies and research institutes. Due to the limited sample, the data does not allow for quantitative generalization, but provides qualitative indications. Our survey has revealed important challenges, some of which we aim to address with our methodology.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 5

A Design Methodology

The general objective of this work is to provide a comprehensive description of the concurrent conceptual design approach. This approach was developed based on the findings in literature and the expert survey described in the previous chapters. In this chapter we define a methodology for conceptual design of complex systems in an MBSE environment. According to Gericke et al. [2017], a design methodology is:

> "... a clearly and explicitly articulated approach to producing designs for a class of systems, that specifies in more or less detail the activities to be carried out, the relationship and sequencing of the activities, the methods to be used for particular activities, the information artifacts to be produced by the activities and used as inputs to other activities, and how the process is to be managed, as well as (tacitly or explicitly) the paradigm for thinking about the design problem and the priorities given to particular decisions or aspects of the design or ways of thinking about the design." [Gericke et al., 2017]

We call our methodology model-based co-located conceptual design methodology (MoCoDeM). During the literature review phase, it was discovered that there are many commonalities found among the various implementations of concurrent conceptual design, currently being utilized by different organizations within the space sector. Although this methodology originated and was first implemented in the early phases of space mission design, we consider it to be generic enough to be applied to other fields as well.

The description of this particular way of organizing conceptual design in a collaborative process within a model-based systems environment, aims to help introducing conceptual design to new people and organizations. This methodology also contains a generic, formalized process for running concurrent design studies. This can be used by a moderator, a team lead or any team member as a guideline which steps to follow throughout the study.

We will validate this method using a survey and interviews with subject matter experts from different organizations, as well as performing different case studies.

5.1 MoCoDeM - Overview

We propose this methodology for the conceptual design of complex systems, based on co-located work of a multi-disciplinary team in a Model-Based Systems Engineering environment.

The methodology itself is described using models, with SysML as a formal language. MoCoDem builds upon the 5 pillars of concurrent conceptual design: facility, team, processes, tools, model. Figure 5-1 shows how these key elements are interconnected using a SysML package diagram.

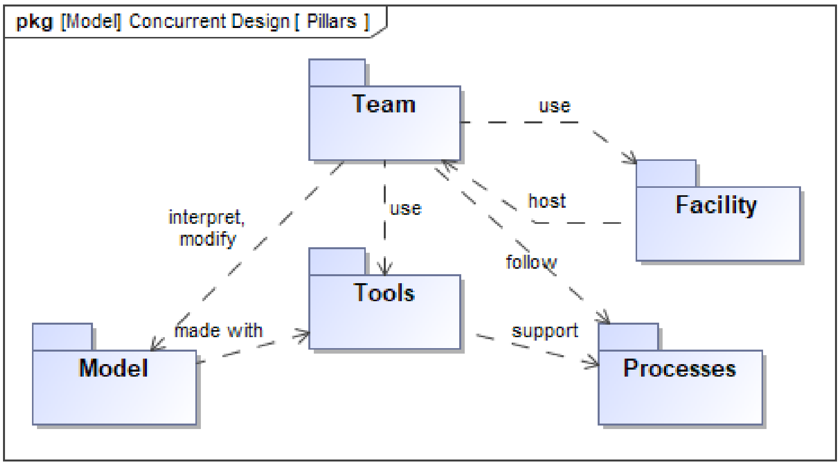


Figure 5-1: Concurrent Conceptual Design - Elements and Interactions

The staff of concurrent design facilities organize concurrent design studies. Together with the customer, they form a single team. The facility hosts the team for the concurrent and co-located design sessions. The team makes use of the environment (e.g. meeting room, kitchen), equipment (e.g. screens, videoconferencing) and the expertise (e.g. moderator) provided by the facility.

The team creates and shares a common model of the system (e.g. diagrams, spreadsheets). Digital models are always read and modified using software tools. The tools that are used allow the team to collaborate on a shared model (single source of truth).

Concurrent design studies always follow some kind of process, which can be an implicit or explicit set of procedures and rules. The tools employed can be a reflection and/or prescription of the design process.

In the following sections we will describe each of the 5 key elements separately. We give articular attention to the organization of the design *processes*, as well as the *tools* to support collaboration on parametric integrated system models for conceptual design.

5.2 Facility

Concurrent design facilities are, as described in the literature, organizational units with associate staff, which also contain a number of rooms and equipment. The staff is responsible for the operations of the facility, as well as organizing the process of concurrent design studies.

The facility needs to accommodate the team and provide the technical means to enable the teams to collaborate. At Skoltech we experienced the rare opportunity to design and build a laboratory for concurrent design and its equipment systems, by leveraging on the experience developed by the international community over the last thirty years in building and operating facilities of this kind [Golkar, 2016].

A proper facility requires a main design room for the concurrent design sessions with the full team, along with the ability to allow stakeholders and visitors to observe the teamwork in action. Additional meeting rooms allow for splinter or break-out sessions with parts of the team.

All rooms are equipped with desks and seats. The main design room was planned to be flexible and adaptable taking into consideration teams of various sizes. Therefore, the desks can be re-arranged in different layouts, and the screens are configurable to show content from any participant's computer.

A facility needs screens or projection walls as well as whiteboards for drawing and writing. Computers can either be desktop workstations or laptops. In our case the second was preferred because they could be moved or reassigned more easily.

The development of our facility Concurrent Engineering Design Laboratory (CEDL) went through different stages. At the beginning there was a concept of the facility's structure as shown in Figure 5-2.

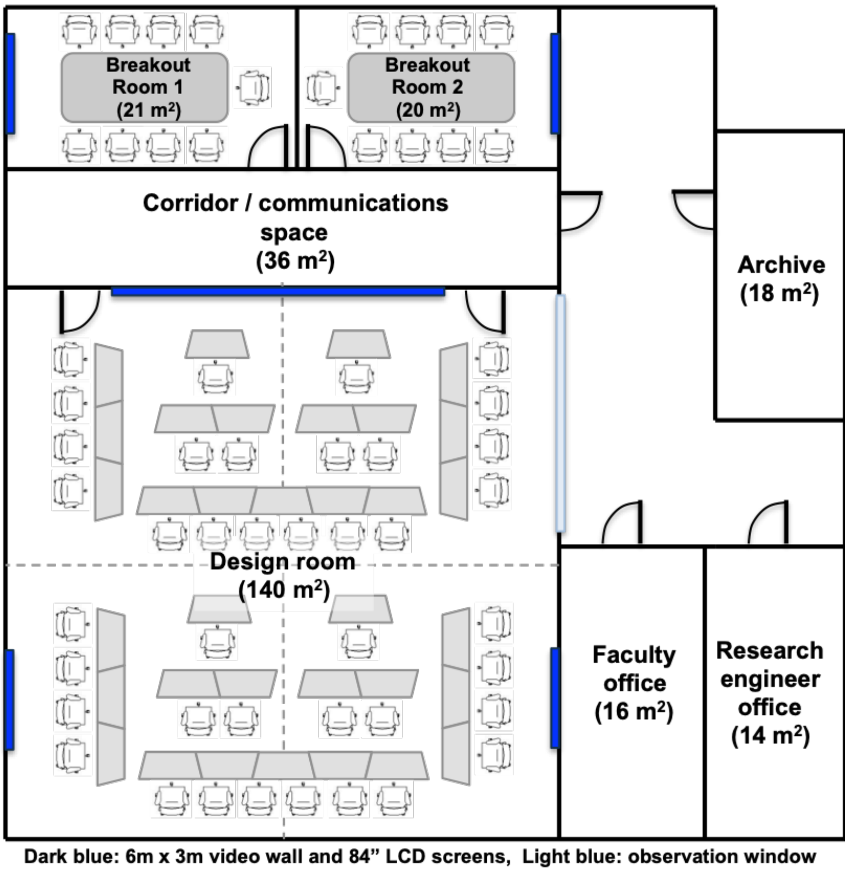


Figure 5-2: An initial concept of rooms for the facility

The architects used this initial concept to design the space and provided renderings, such as Figure 5-3 of the main design rooms.

With the facility available, we defined a configuration for hosting concurrent design sessions. A model plan of the table layout as well as the use of the screens is shown in Figure 5-4.

Figure 5-3: An architects rendering of the main design room

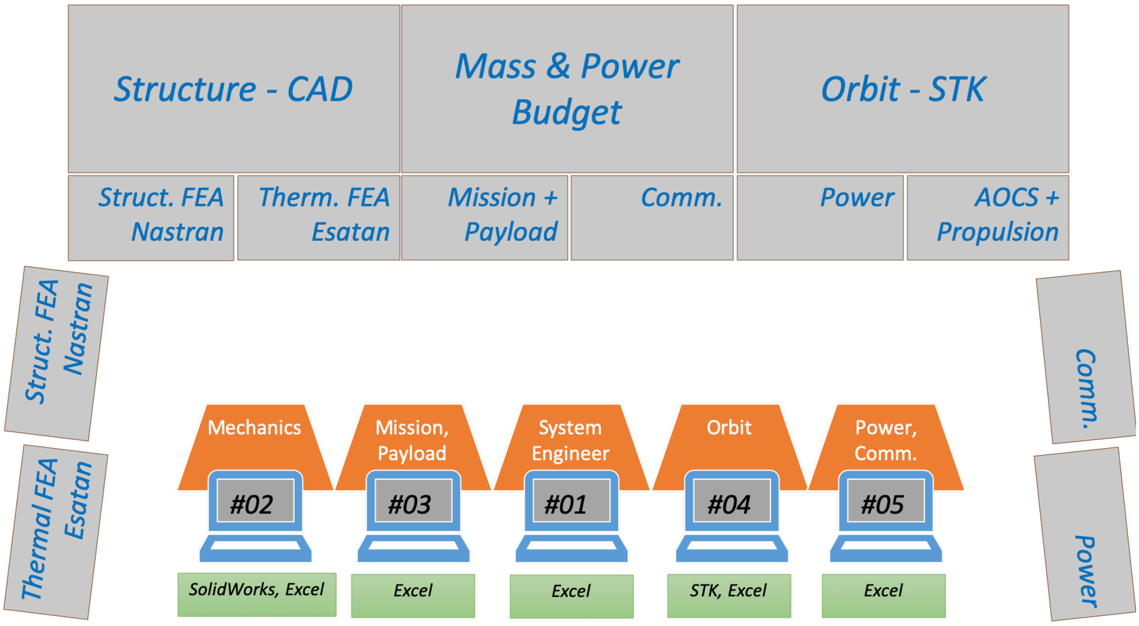


Figure 5-4: The layout of CEDL planned for a specific design study

The setup was implemented and verified in a dedicated pilot study (see section 8.2), as illustrated in Figure 5-5.

Figure 5-5: CEDL configured and used according to the plan

The lessons learned from the construction and operation of the Concurrent Engineering Design Laboratory (CEDL) were described in Golkar [2016].

5.3 Team

The concurrent design approach engages multidisciplinary teams to work in an integrative way. People are involved in the team according to different roles: study customers, technical authors, domain experts, team leaders, systems engineers and assistant systems engineers.

There are 3 major activities that these people are involved in: They participate in studies, prepare study model, and develop model template. Their roles and their engagement in activities is shown in a SysML use case diagram in Figure 5-6.

Roles and their responsibilities:

Participant The participant role is shared by all actors in a team, and all other roles are specializations of this basic role.

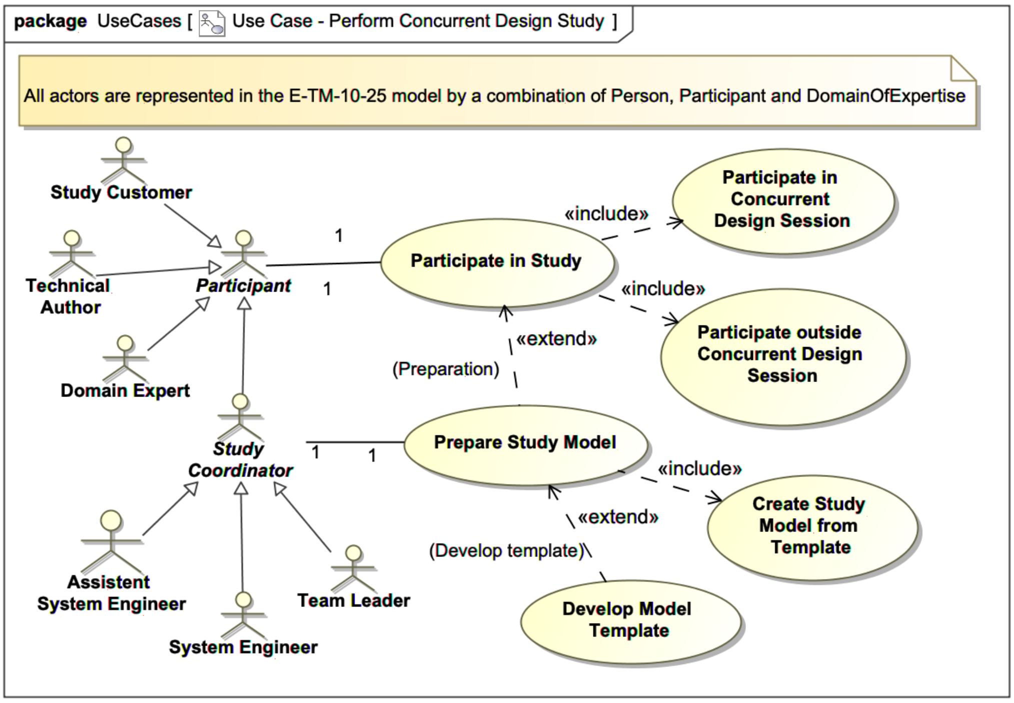


Figure 5-6: Actors and activities in a concurrent design study, from ECSS-E-TM-10-25A [ECSS, 2010, Appendix C]

Study Coordinator Some participants have a coordinating role and are responsible for the preparation of the model. This role is further specialized into System Engineers, Assistant System Engineers and Team Leaders.

Study Customer The customers initiate concurrent study with the CDF. Since they are the primary stakeholders, they hold an important role throughout the entire study. At initiation, they are responsible for providing the mission goals, define the study objectives and available resources for the study. It is common to have the customers participate in the concurrent design sessions, in order to have their direct contribution taken into consideration.

Team Leader, Moderator The team leader, is part of the CDF staff and responsible for organizing the entire process of a design study, much like a project manager. Moreover, those holding this role help in the moderation of concurrent design sessions, making sure that schedules are kept, discussions remain both focused and positive. That's why this role is sometimes referred to as the moderator or the facilitator.

Systems Engineer The systems engineer role is also part of the CDF staff. They make sure that any needs are properly elicited and clarified during the study preparation sessions as well as ensure that requirements get properly identified and gradually elaborated. During the concurrent design sessions, they take care of the integrated design model consistency and ensure that any and all design decisions lead towards a feasible design. Finally they are responsible for the concurrent design study reaching its prescribed set of objectives.

Assistant Systems Engineer The assistant systems engineer supports the systems engineer in their duties. This role is particularly concerned with the modeling as well as making sure that the other team members contributions are reflected in the integrated system model.

Domain Expert Domain experts are engineers and specialists, who have the necessary expertise to determine the size and designs of their respective parts of the system. They are required to be able to communicate the design drivers, choices and outcomes of their specific parts, such that others can understand them and make adjustments to their own decision making accordingly.

For each design study, the systems engineer, defines the set of disciplines to be involved, based on the customers study objectives. The number of disciplines which can potentially contribute can be quite numerous, so team size can become the most significant contributor to the cost factor of a study. As a reference, see Table 7.1 which lists the domains of expertise.

Technical Author The technical authors function in support of the team. They assist in the writing of the documents, not only during the preparation, but also during the conclusion of a study. Of particular importance is the documentation of the outcome of the study, especially if it is used in a call for proposals, or other external funding approval procedures.

People participating in a concurrent design study can eventually play one or more roles.

5.4 System Model

In concurrent conceptual design, systems are designed by experts of different disciplines, collaborating together. The disciplines relate to physical subsystems (e.g. propulsion, instruments) or design aspects (e.g. mission, cost). Each discipline models their respective part based on defined parameters, so that these models can be linked together to form an integrated systems model. The parametric system model is used to estimate the primary characteristics, or figures of merit (outputs), based on requirements, along with system architecture and design decisions (inputs). Parametric discipline models have input and output parameters. Internally, each model performs a mapping from the input parameters to the output parameters. Externally, models are connected by linked parameters: one model's input parameter takes the value from another model's output parameter.

5.4.1 Discipline / Subsystem Model

The parametric model of a discipline/ subsystem is described as a mapping of a vector of input parameters to a vector of output parameters. Figure 5-7 shows a representation of a subsystem model as a SysML internal block diagram.

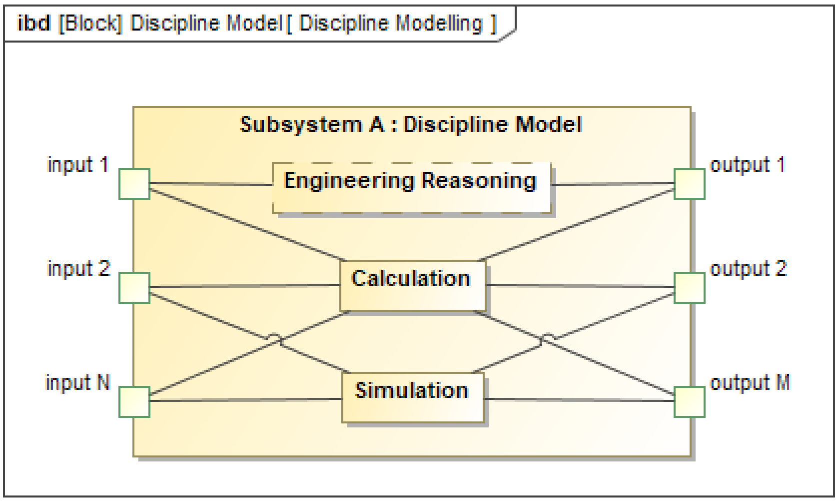


Figure 5-7: Parametric Modeling - Single Discipline

In mathematical notation, a subsystem model is described as:

The inputs form vector $\vec{u}$, the outputs form a vector $\vec{v}$.

$\vec{u} = [u_1, ..., u_N]$, where N is the size of the input vector.

$\vec{v} = [v_1, ..., v_M]$, where M is the size of the output vector.

Sizing models for subsystems map design parameters (inputs) to characteristics (outputs). The mapping denotes as $\vec{u} \mapsto \vec{v}$. $\vec{v} = F(\vec{u})$, where $F : \mathbb{R}^N \mapsto \mathbb{R}^M$ is the real valued transfer function.

This mapping can be an analytical function, a complex simulation, or engineering decision based on heuristics or prior knowledge from experiments. Subsystem models can be built with a wide range of tools: Excel™(spreadsheets), MATLAB® (scripts), different simulators, etc.

Discipline experts generally have preferred tools and keep a set of models ready to use when needed. Different organizations also follow knowledge management approaches to capture and maintain the knowledge embodied in the tools an models.

5.4.2 Integrated System Model

The parametric system model is used to estimate the primary characteristics, or figures of merit (outputs), based on requirements, system architecture and design decisions (inputs).

The inputs form a vector $\vec{X}$, the outputs a vector $\vec{Y}$. The design is based on the mapping between input and output denoted as $\vec{x} \mapsto \vec{y}$. Because a system is always composed of elements or subsystems, the mapping is the result of all subsystem models and their dependencies. Figure 5-8 illustrates the interconnected subsystems models forming an integrated system model as a SysML internal block diagram.

In mathematical terms the integrated parametric system model can be described by the vectors of input and output parameters. The vector of input parameters is composed of all subsystem inputs:

$\vec{X} = [x_{1,1}, ..., x_{1,N_1}, x_{2,1}, ...x_{2,N_2}, ..., x_{K,1}, ..., x_{K,N_K}]$, where K is the number of subsystems, and N_k is the number of input parameters of subsystem k.

The vector of output parameters is made of all subsystem outputs:

$\vec{Y} = [y_{1,1}, ..., y_{1,M_1}, y_{2,1}, ...y_{2,M_2}, ..., y_{K,1}, ..., y_{K,M_K}]$, where K is the number of subsystems, and M_k is the number of output parameters of subsystem k.

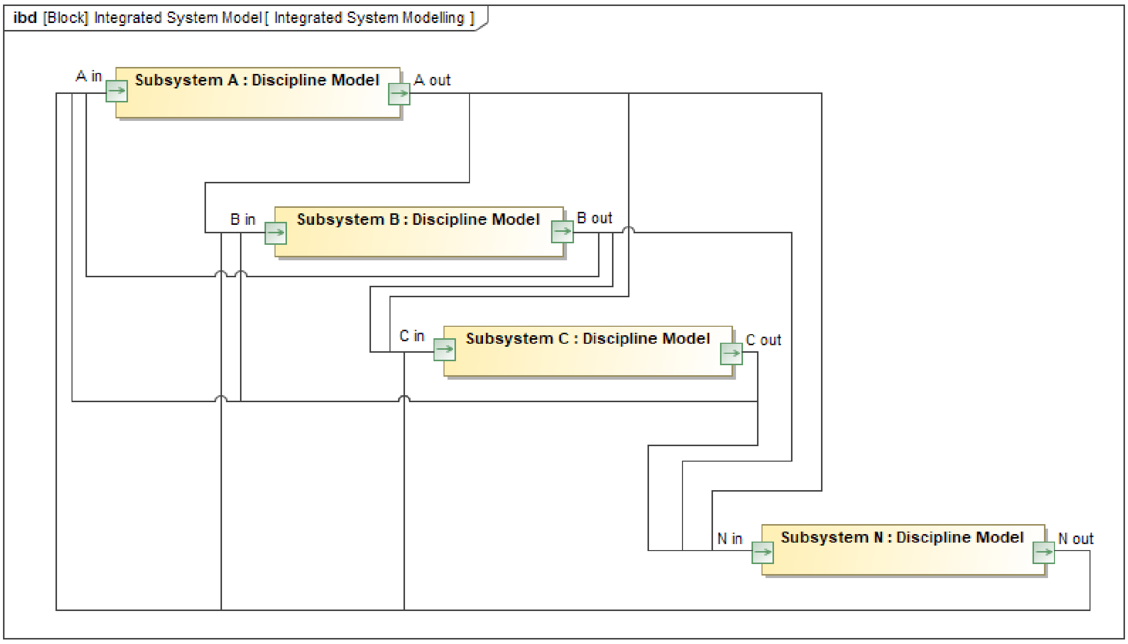


Figure 5-8: Parametric Modeling - Integrated System Model

Dependencies

Subsystems are connected such that the input parameters of one subsystem receive their inputs from the output parameters of other subsystems.

$x_{i,j} = y_{k,l}$ denotes input parameter j of subsystem i receives it's value from output parameter l of subsystem k.

Hence we define the dependency relationship as $D \subset \{K \times K\} = \{(x_i, y_k)\}, \forall x_{i,j} = y_{k,l} \cap i, k \in K \cap j \in N_i \cap l \in M_k$.

Figure of Merit

Figures of merit are used to characterize and evaluate the designs according to criteria relevant for the stakeholder, e.g. cost or performance.

A Figure of Merit (FOM) is a metric of the entire design, based on its design parameters, or a subset of them. Typically, system designs are evaluated according to several FOMs.

$FOM_i = f(\vec{X})$, where $f : \mathbb{R}^* \mapsto \mathbb{R}$

Based on these definitions, we can derive measures to asses the outcome of a design study, in terms of optimality or diversity.

Optimality of design

An intuitive approach is to evaluate the optimality of the resulting design solution(s). Such an evaluation could use the FOMs defined at the beginning of the design study, specifying the optimality criteria: minimization or maximization. Design solutions can be compared according to several FOMs applying the concept of pareto-optimality (see section 2.5).

The evaluation of design solutions requires the existence of alternative solutions. If the study produces more than one design, their relative optimality can be evaluated. Depending on the subject of the design study, alternative solutions may either be rare or non-existent. Some may exist but may be unknown to the team. This means that design optimality can be used as a metric only in a few cases.

Diversity of designs

When a study is meant to produce two or more alternative designs, it's desirable that they differ from each other. As a measure of diversity among different designs we use the product of the variance of the FOMs.

$FOM'(\vec{X}) = normalize(FOM(\vec{X}))$ is the normalization of the figure of merit to a value range of $[0,1]$.

$diversity = \Pi_i^{foms} Var^D(FOM'_i)$

The values are in a range of $[0,1]$, where 0 means no diversity and 1 maximum diversity.

This measure can be applied when different solutions exist or are produced by the design study. Depending on the subject of the design study, alternative solutions may either be rare or non-existent. Some may exist but may be unknown to the team. Hence, this metric can only be evaluated in few design studies.

5.5 Process

The early stages of system design involve concept development and creative problem solving. The design process needs to take into account the dependencies between the system's parts. As a consequence, the method used should focus on facilitating an orderly collaboration between discipline experts, in order to tackle all interactions between the parts for which they are responsible. This need for communication can be represented as a network, as can be seen in the example diagram in Figure 5-9.

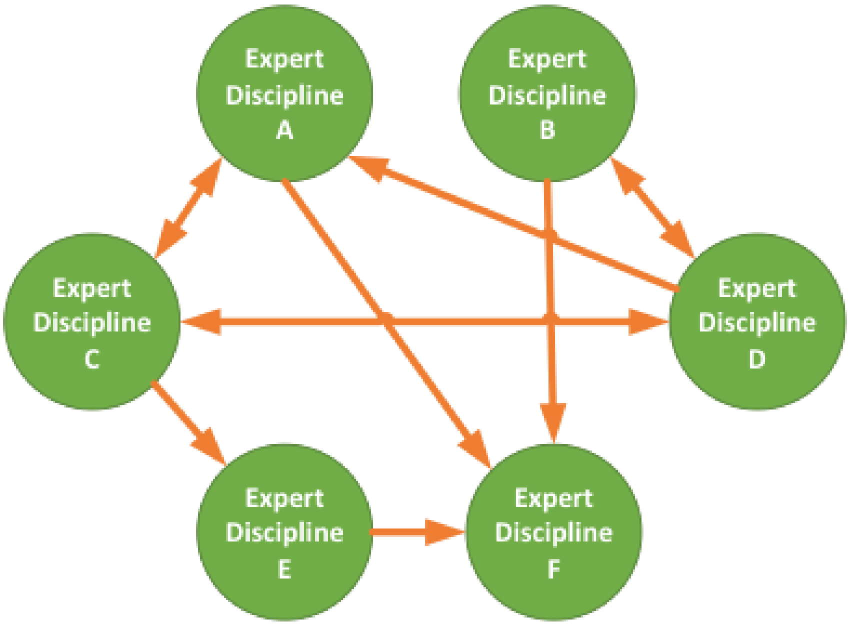


Figure 5-9: People interaction throughout a concurrent design study

In current practice, the facilitation of a concurrent design study is entrusted to a team leader who has working experience as a system engineer and has already participated in concurrent design studies. The personal and professional skills of the team leader will greatly influence the design study's outcome. Hence, the proposed method should support the team leader coordinating the above-mentioned interaction of people in the entire team.

Since people will be designing in a concurrent fashion, this means that their work will tend to overlap, therefore, due to the dependencies among the disciplines, changes in designs need to be communicated to each team member when they occur. Hence, there are two different perspectives: (1) from a people's perspective, the disciplines work in parallel. (2) From the model perspective, the design decisions are taking place in a temporal sequence.

A measure for parallelization of work is the degree of concurrency, which is the ratio of the amount of time tasks overlap, to the entire duration of all tasks [Prasad, 1999]. To maximize the degree of concurrency, different methods have been proposed, based on the assumption of known task duration and fixed information needs and availability [Hu et al., 2003, Srour et al., 2013]. In conceptual design, the tasks of the disciplinary experts consist in making design decisions and refining the system model. Assumptions on the duration of these tasks, and on the information needed or it's availability, are hard to make.

Our proposed method aims to guide the interaction of people collaborating on the design, while keeping a consistent record of the design decisions taken. Going forward, we concentrated on the model perspective, while trying to support collaboration among people.

5.5.1 Process Levels

We identified three logical levels of activities carried out during the process: at the top level, there is the entire study, at the intermediate level, there is the single design iteration, and at the bottom level, there is the single discipline contributing to the design. As shown in Figure 5-10, each level covers a different time scale. The study includes one or more design iterations. Each design iteration consists of a sequence of changes to the system model made by discipline experts, which lead to a consolidated system design.

In case the need arises and time permits, there may be several design iterations, a once completed design is revised according to the previously defined set of FOM. This corresponds to mapping the obtained design to the trade space, hence we call this step Trade Space Exploration (TSE).

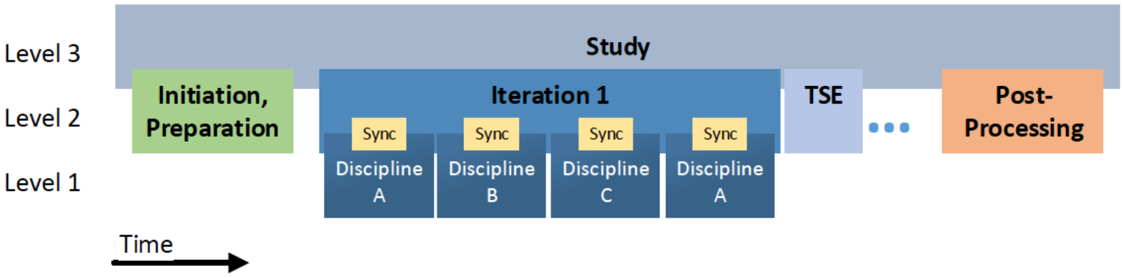


Figure 5-10: The logical levels of activities during a design study

5.5.2 Process Guideline

This description of a generic process of concurrent design is meant to serve as a guide for adopting the methodology in new environments. From the practice described in the literature (see chapter 2) and reported by people who had participated in concurrent design studies, we extracted a generic model of the concurrent design process. This description can serve as a guideline for participants rather than a strict ruleset. We use SysML activity diagrams as a formal graphical notation. In this notation activities are shown as rounded rectangles, and arrows with dashed lines indicate the flow of control. The decision points are depicted by a diamond shape and the outgoing lines indicate a condition. Objects are denoted as rectangles and arrows with continuous line indicate the flow of objects. Comments are depicted by rectangles with a folded corner and a dashed line indicates the item the comment relates to.

Conceptual design study

Conducting a conceptual design study is a complex process composed of several activities (see Figure 5-11). For the more complex activities which are marked in blue, there are separate diagrams, describing their internals.

For a customer, a concurrent design starts with the analysis of operational needs and ends with a report showing the solution concept and the system requirements.

Initiation Once a customer has expressed their need to perform a concurrent design study, the preparation starts with collecting and documenting mission requirements. Then, study constraints are identified (budget, technology, confidentiality).

Preparation In the preparation step, the objectives of the design study are defined together with the customer. As a result of a preliminary analysis of the required high-level functions, the required disciplines are determined. Based on the availability of discipline experts and the concurrent design facility a schedule is defined. During preparation or at the start of the first design sessions, a joint meeting of the full design team is held with customer representatives. The purpose of the meeting

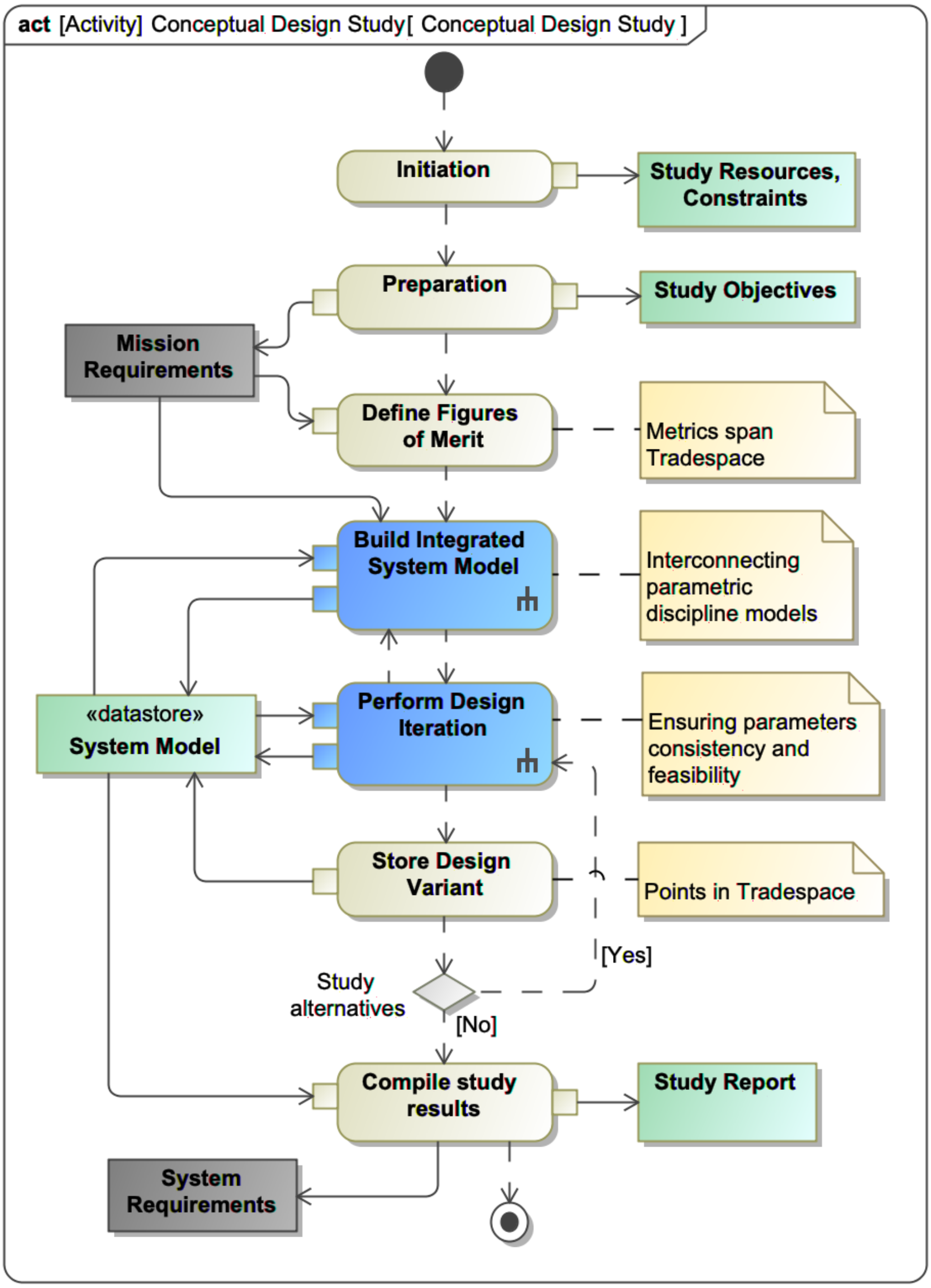


Figure 5-11: The overall process of a concurrent design study

is to clarify the mission requirements and the role of each study participant.

Define Figures of Merit Figures of merit are attributes of the system that characterize its performance, cost, value or other qualities. These are used in order to compare different design concepts. The most common figures of merit in feasibility studies of spacecraft include:

- spacecraft mass – determines the requirements on the launcher carrying the spacecraft to orbit
- power consumption – is important to the design of the system, so as to balance both generation and consumption of power during operations
- data generated for telemetry, command and customers – is needed to determine the requirements for storage and communication
- cost of development – paired together with the value provided to the customer, is used to evaluate a mission's economic viability

Build Integrated System Model In order to collaborate on a conceptual design, a model is built which includes all of the necessary discipline perspectives. Some of the disciplines are responsible for the conceptual design of a physical subsystem (e.g. propulsion, communications), while other disciplines are concerned with non-physical, or transversal issues (ed. cost, schedule). This activity is composed of sub-activities, explained in further detail later in this section.

Perform Design Iteration At the core of the design study are the concurrent design iterations. The goal of each iteration is to consolidate the design by making sure all input parameters take values which are correspondent to the mission requirements, or to the output values produced by other subsystems. Since dependency relationships of subsystems are transitive and can form cycles, the design of subsystems potentially needs to be re-iterated. The process of a single design iteration is described in the next section. Throughout the design study, an arbitrary number of design iterations can occur, and they are stored in order to keep the state of the system model. The design iteration is itself composed of other sub-activities, described below.

Store Design Variant Once a design iteration is complete, which means that the parametric model is consistent, a snapshot of the integrated system model is taken for future consultation. In its simplest form a snapshot consists of all the values of design parameters and the figures of merit. The values of the Figures of Merit (FOMs) form a point on the tradespace. In a more advanced form, the configurations of all of the analytic models involved are stored as well.

Compile Study Report At the completion of a conceptual design study, one or more resulting system designs, which were shown to satisfy the mission requirements, need to be documented and characterized according to common or mission specific performance measures (e.g. mass, cost, risk, schedule). For the continuation of the project, in the case of the approval of the results of the design study, the system requirements contained in the documentation will serve as a starting point for the detailed design phase.

Build Integrated System Model

The process of building an integrated parametric system model can either start from a blank sheet or from the re-use of models taken from previous conceptual design studies. Figure 5-12 and the paragraphs detail the case when one starts from scratch.

Decompose System The system's high-level functions are derived from the mission requirements. Then, subsystems are defined which incorporate these functions and are assigned to discipline experts who are members of the team. The system's breakdown structure is encoded and stored in the system model.

Define Subsystem Interfaces For each discipline or subsystem, experts will define which are the essential design parameters (input) and resulting attributes (outputs).

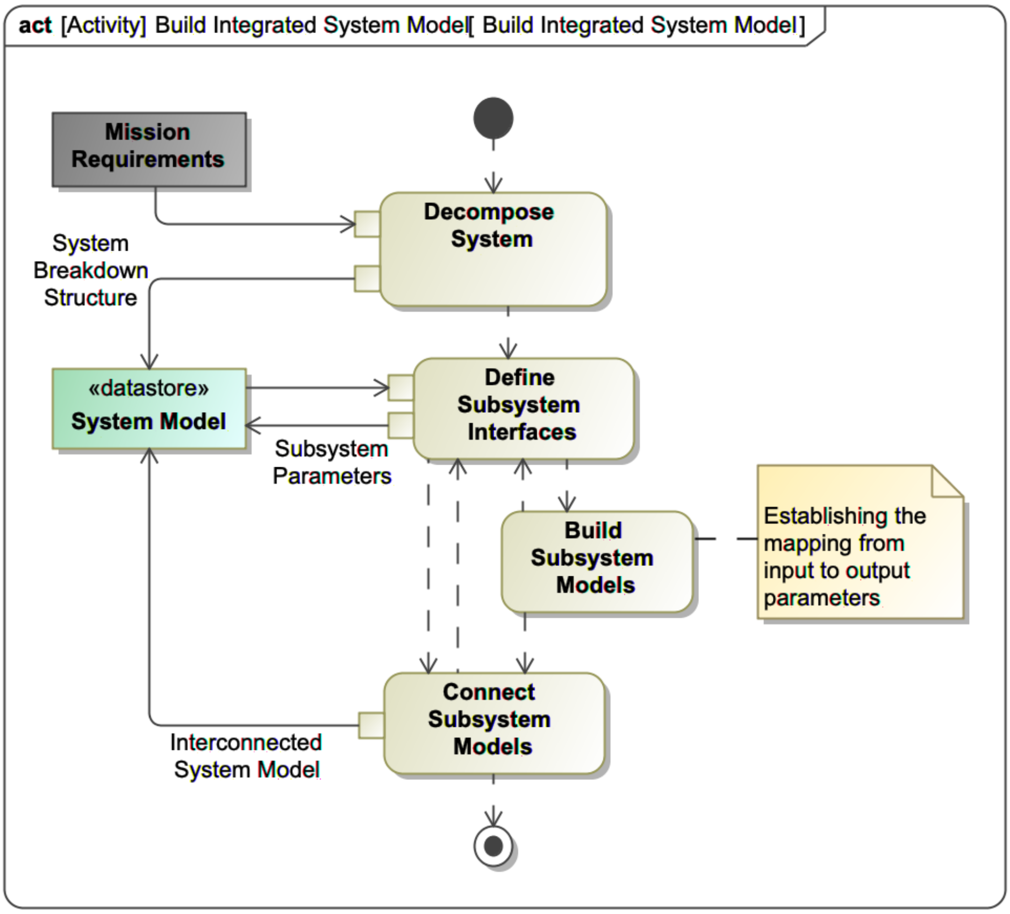


Figure 5-12: The process of building the integrated system model

Build Subsystem Models In this step, discipline experts shall come up with models for their respective subsystems. Parametric models map design parameters to estimates of the essential characteristics of the subsystem. These characteristics either contribute to the figures of merit of the overall system (e.g. mass) or influence the design of other subsystems. These models can either be based on first-principles of physics or based on heuristics. Simplified analytical models for preliminary sizing may exist for many subsystems with a design history.

Connect Subsystem Models The discipline experts together with the team lead identify the source for each input. When starting with new models from scratch, this is a non-trivial task. It happens, that for certain parameters, no other subsystem may be providing that parameter as an output, and it must be then decided which discipline shall produce and be responsible for it. For some inputs, if no other source can be identified, the value can be determined freely by the discipline expert. It can also happen that more than one subsystem claims to be able to produce a certain output, it then must be decided which discipline shall produce and be responsible for it, and which other disciplines take it as an input. In this step the subsystem model interfaces are refined, in order to be able to interconnect them.

Design Iteration

During a design iteration, the team is consolidating the conceptual model of the system, based on the mission requirements and in order to satisfy all dependencies within the system model (Figure 5-13).

From the parametric dependencies among elements in the system model a Design Structure Matrix (DSM) can be derived [Eppinger and Browning, 2012]. We used a weighted DSM, where the weight was determined by the number of parameters linking two subsystems. Applying a clustering algorithm to the DSM allows us to determine which are the more closely dependent subsystems and can propose a sequence which is best to synchronize the subsystem models with the integrated system model. This method was successfully applied to integrated concurrent engineering [Yassine and Braha, 2003, Chen, 2005, Avnet and Weigel, 2010].

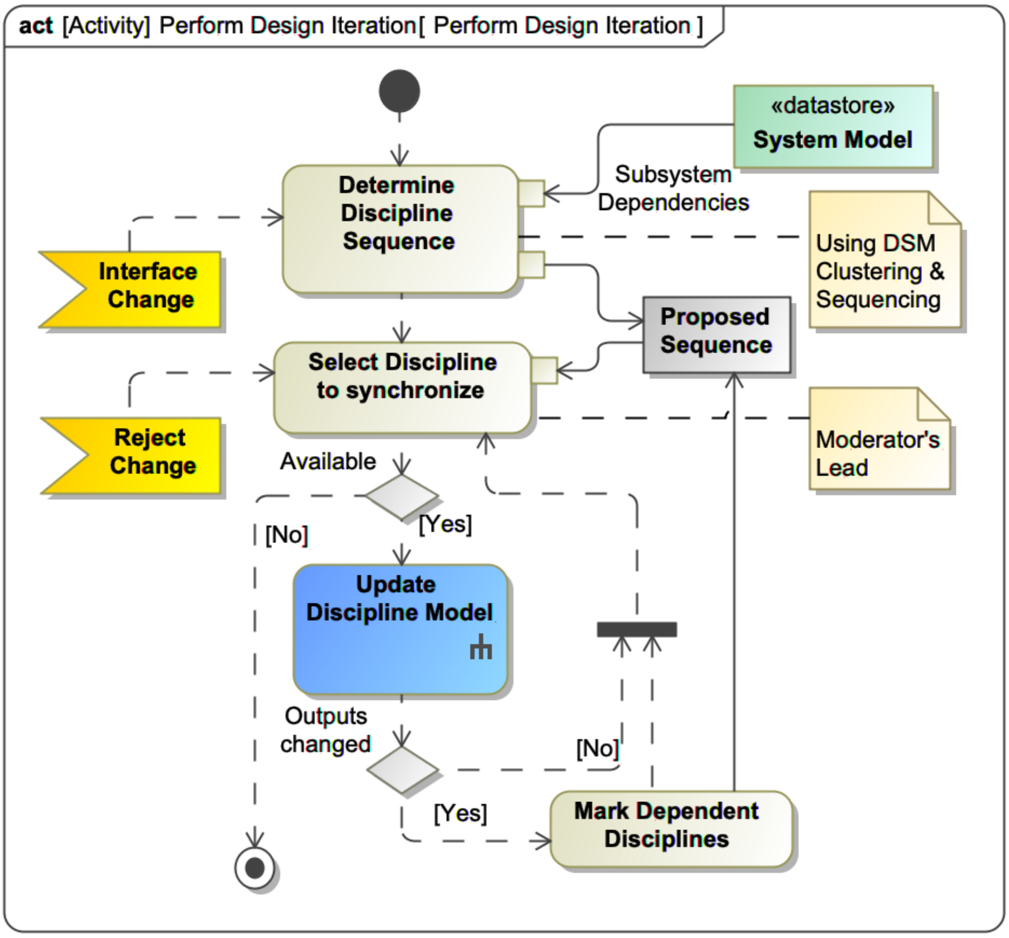


Figure 5-13: The process of a single design iteration

Based on this proposed sequence, the team leader moderating the design study calls one discipline at a time, to provide updates with respect to their subsystem model.

The procedure of preparing and performing this update is described in a separate procedure in the next section. After that, depending on whether the subsystem's output parameter values have changed significantly, the sequence is either updated or not. A significant change is one that exceeds the applied margins. Design margins are a common way to cope with uncertainty and are defined by organizational policies [McManus and Hastings, 2005]. Typically the margins are between 10% and 30% [Thunnisen, 2004]. If the outputs change more than that, then the disciplines which depend on them are required to update their subsystem model. In case the update of a discipline model leads to changes of the subsystem interfaces and thereby also it's dependencies, the sequence needs to be recalculated. Moreover, it can happen that a discipline, instead of updating its outputs, may reject the proposed modifications. This evokes a negotiation process between the respective disciplines, under the guidance of the team leader, where an agreement on the changed parameter values shall be reached.

Once there are no more disciplines in the sequence, it means that the integrated system models has converged and represents a feasible conceptual design and this signals that the iteration has finished.

Update Discipline Model

A discipline expert, when updating a subsystem model, performs a simple sequence of activities (see Figure 5-14).

First, the values for the input parameters, which are connected to other subsystems, are updated from the shared system model. Depending on the kind of model, the designer either executes a calculation, simulation or makes decisions based on prior knowledge. The discipline expert can either perform one or a combination of all of these activities. After that, the design expert checks their results for feasibility. If the feasibility is not given, then any changes on the inputs shall be rejected. Only when everything is okay, are the subsystem's output parameters updated. In

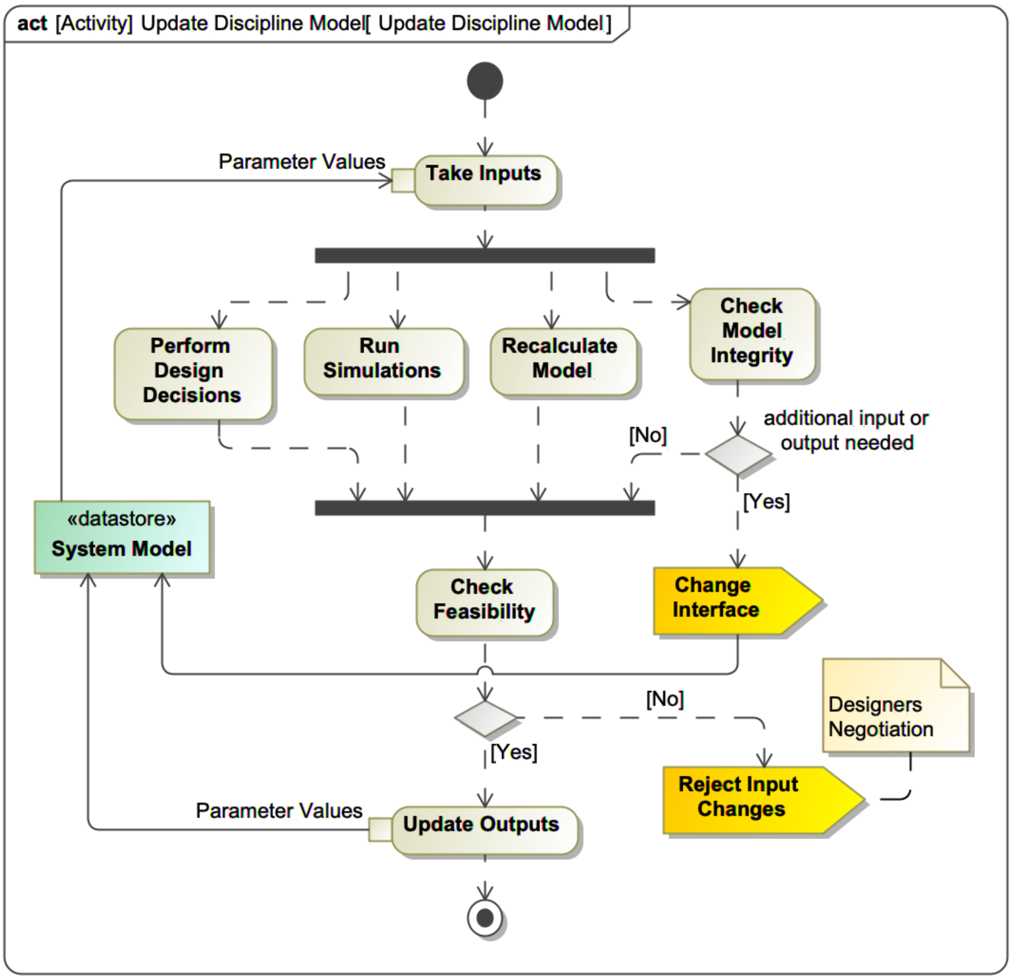


Figure 5-14: The process of updating a discipline model

parallel, the experts check the model for integrity, and in case additional input or output parameters are needed, the interface is modified accordingly. Finally, the changes to the parameters are then stored in the shared system model.

5.5.3 Characterizing the Process

The analysis of the design process can best be described using mathematical formalism. The conceptual design of a system uses an integrated parametric system model (see section 5.4).

Definitions

Time The design of a system is the result of a chain of design decisions on the architectural, as well as the subsystem levels. Design decisions for a subsystem can cause the outputs to change as well. Due to the connections between subsystems, other subsystem's inputs may change.

The values of the input and output parameters can evolve over time. A global clock is used as a reference point for time taking, providing a discrete timestamp t_{event} for any event which occurs.

Design Changes The input and output parameters may change over time, so the vector input parameters should be denoted as $\vec{X}^t$, and the output parameters $\vec{Y}$, both at time step t.

$\Delta\vec{X}^{t+1} = \vec{X}^{t+1} - \vec{X}^t$ is the change of all input parameters at time step $t+1$.

$\Delta X_i^{t+1} = X_i^{t+1} - X_i^t$ is the change of input parameter i at time step $t+1$.

Design Steps To elaborate on a change to the design of any subsystem, it may take any finite amount of time to complete.

ts_i is the time that a design step of subsystem i started, te_i is the time that the design step ended.

$sd = t_{step\ end} - t_{step\ start}$ is the duration of the design step.

Study Features

The conceptual design process is influenced by a set of parameters, which are determined during the preparation step.

Number of Disciplines The number of disciplines affects the team size and number of experts that need to coordinate their work. The decision of which disciplines to involve depends on the level of detail the conceptual study will entail. Our survey has shown, that the typical team size is between 6 and 20 members, an on average number of 13 people (see chapter 4).

Study Duration Represents the amount of time that the teams dedicate for the completion of the design study. Typically, the total duration is around 9 days, scheduled in a compact period of time ,rather than spread out over a longer period (see chapter 4).

Design Variants This is the number of design solutions that a study aims to produce. It is frequently one, but two or even three are not at all that uncommon (see chapter 4). For each design variant, the team completes a design iteration, bringing the parametric system model to convergence. This parameter defines a target for the team on the amount of work to accomplish within the allocated study period.

Blank sheet design vs. Legacy reuse The decision, whether to start a new design from scratch or build upon previously elaborated conceptual models, has a significant impact on the process and outcome of the design study. In the case of reusing systems or subsystem models, the step "building system model" requires much less time. In the case that the design starts from a blank sheet, the team is less constrained if they wish to find and use new solution concepts.

Process Metrics

The execution of the conceptual design process is characterized by a set of metrics, which can be evaluated either during or upon conclusion of the the design process.

The duration of an iteration is the result of the total actual study and the number of design variants which were achieved. The design process is a set of design steps, which make changes to the parametric system model. These are oriented in a proper direction in order to converge on a feasible solution. A design iteration converges, when the changes of subsystem outputs are less than a certain threshold $\Delta x_{k,i} \leq \epsilon * x_k \forall k \in K, i \in N_k$, where $\epsilon \in [0, 1]$ is the threshold. This threshold is set according to the policy for design margins (e.g. 0.15 for 15%). The convergence of all the subsystem models also presumes that the values of the parameters make up a feasible design.

The duration of an iteration is defined as:

$d = t_{iteration\ stop} - t_{iteration\ start}$

The lesser the time a design iteration takes, the more iterations can be performed within a design study.

Interconnectedness The conceptual design of subsystems are interconnected, when the sizing of one subsystem requires information from another subsystem. These dependencies can be extracted from the links in the integrated parametric model and represented in a Design Structure Matrix (DSM). The ratio of existing dependencies to the potential connections, can be used as a metric of the interconnectedness. In mathematical terms it is the matrix density of the DSM.

For the design process, it means that the more connections there are, the greater the chance that a design change will cause a chain reaction of other changes [Yassine and Braha, 2003].

Degree of Concurrency A fundamental idea behind concurrent design is the parallelization of work [Prasad, 1999]. The higher the achievement of this measure, the more time is saved due to parallelization. For concurrent engineering, different methods have been proposed to maximize the degree of concurrency, based on the assumption of known task duration, and fixed information needed and it's availability [Hu et al., 2003, Srour et al., 2013]. In our case of conceptual design the duration of the design steps and information needed or it's availability, is hard to estimate beforehand. Hence, our process uses the dependency information only to coordinate the contributions of the discipline experts on the shared system model, by keeping consistent records of the design decisions taken.

The degree of concurrency can be defined as the ratio of the amount of time design steps overlap, against the total duration of all design tasks. We used a definition following Hu et al. [2003].

$o_i = ts_i - te_{i-1}$ is the overlap of design step i and $i-1$.

$c_i = 1 - \frac{o_i}{d_{i-1}}$ is the measure of concurrency of two partially overlapping design steps, assuming that they overlap ($o_i > 0$). Figure 5-15 provides a graphical illustration of overlapping design steps.

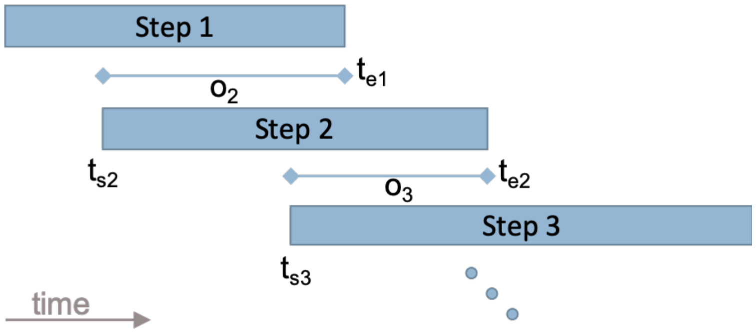


Figure 5-15: Concurrent design steps overlapping

We can extend the measure of concurrency to a set of concurrent design steps, where S is the number of steps.

$C = \frac{\Sigma_{i=1}^{S} o_i}{te_S - ts_1}$

This value is 0 when there is no overlap. If two design steps take the same amount of time and happen simultaneously, the degree of concurrency is 1. If more than 2 design steps happen simultaneously and have full or partial overlap the degree of concurrency can be more than 1. Ultimately the value is bound by the number of steps: $C < S - 1$.

This metric gives a good indication about the amount of design steps taken in parallel, but it is not sufficient to characterize the efficiency of the concurrent design process. It can well be that the degree of concurrency is high, but as a consequence of the dependencies, many design steps need to be repeated, because the inputs for the subsystem have changed and require re-evaluation of the subsystem model.

To avoid rework on the subsystem models, the sequence of synchronization matters (see section 2.3). Because of this, our process guideline builds a proposed sequence of discipline updates, based on the design dependencies. A DSM which was built on the links in the parametric model was used for sequencing.

5.5.4 Operational implementation

So far we have illustrated the logical organization of the design process. Additionally, the process should be translated into a practical working schedule. Organizing a concurrent design study basically requires the proper planning of the activities, the people and the infrastructure. An overview of the activities according to allocations is shown in Table 5.1

What	**When**	**Who**	**Where**
preparation	weeks between initiation and CDF sessions	customer, study coordinator	virtual or physical meetings
build system model	before and first CDF sessions	study coordinator, domain experts	offline and in CDF
design iterations	CDF sessions	full team	in CDF

Table 5.1: Activity allocations

The term 'CDF session' describes a period of time where the entire team comes together in the Concurrent Design Facility for collaborative work. It's important to note that there can be one ore more design iterations and one or more CDF sessions. Generally a design iteration takes more than one CDF session.

The team coordinator, when crafting the schedule for the CDF sessions, needs to take into account each experts' availability. A general principle for creating the work schedule for a concurrent design team, is to alternate periods of working all together into the CDF, and periods of offline work, where the discipline experts work individually on their subsystem models.

In the course of design sessions, the study coordinator may see the need for closer discussions between only 2 or 3 disciplines. In such cases the team breaks up and holds splinter-meetings in separate rooms.

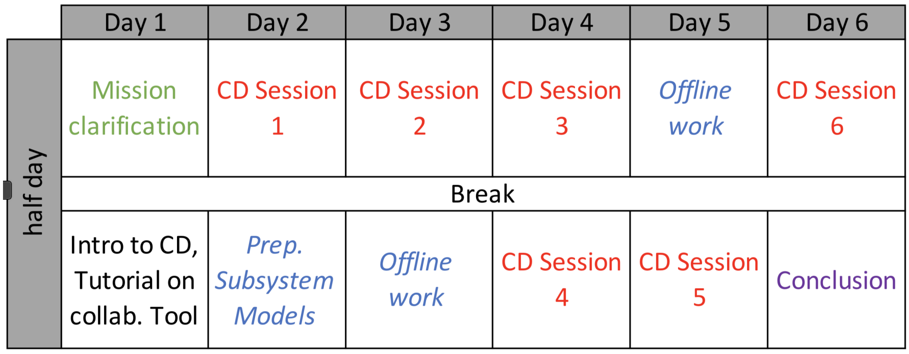
Let's consider as an example the setting of a master level course of 2 months on space mission design, where the course project shall use a concurrent design study. The study extends over 6 weeks, where within each week, one half day[1] is dedicated to the concurrent design sessions. Figure 5-16 illustrates an example schedule.

5.6 Summary

This chapter presents the comprehensive methodology for model-based co-located conceptual design. The methodology (MoCoDeM) was devised from literature re-

---

[1] depending on the organization it can be 3-5 hours



	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
half day	Mission clarification	CD Session 1	CD Session 2	CD Session 3	*Offline work*	CD Session 6
	Break					
	Intro to CD, Tutorial on collab. Tool	*Prep. Subsystem Models*	*Offline work*	CD Session 4	CD Session 5	Conclusion

Figure 5-16: Example schedule for a CD study

view and expert survey, as well as the author's learning from conducting conceptual design studies with a co-located team and within a Model-Based Systems Engineering environment. It included the description of formalized models of the 4 pillars: facility, team, model, process.

The next chapter will illustrate the 5th pillar, the tool we developed to support the team in working on the model and following the process.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 6

Concurrent Conceptual Design Tool

We analyzed tools referenced in the literature about concurrent engineering in conceptual design as practiced by space agencies. In line with the methodology MoCoDeM, described in the previous chapter, we need a tool for Concurrent Conceptual Design (CCD) based on parametric models. Models used in the conceptual design of space systems primarily describe the system's behavior. In fact, [Fortin et al., 2017] found out that only around 20% of the parameters in CCD describe geometry. There are MBSE tools, such as CameoSystemsModeler™[1] for example, which are used to make descriptive models of systems' decomposition structure and subsystems' interactions in the form of SysML diagrams. Although parametric models can be built in SysML, they are not a good fit for multi-user collaboration.

MDO tools, like ModelCenter®[2], deal with parametric models of any kind, but focus on automated analysis and optimization, while CCD keeps experts actively involved during the design process.

PLM systems, such as ENOVIA[3] or Teamcenter®[4] for example, have their strength in supporting design and manufacturing and hence, the management of geometric models. PLM systems also allow to leverage knowledge accumulated in an organization by managing models in a way to facilitate their reuse. Such knowledge-based engineering approach is particularly advantageous when system designs can

---

[1] `https://www.nomagic.com/products/cameo-systems-modeler`

[2] `https://www.phoenix-int.com/product/modelcenter-integrate/`

[3] `https://www.3ds.com/products-services/enovia/`

[4] `https://www.plm.automation.siemens.com/global/en/products/teamcenter/`

be derived from models available for a product family [Prasad and Rogers, 2005]. The fact that the integration of knowledge management into product development tools remains challenging, is confirmed by Chandrasegaran et al. [2013]. While tool vendors are continuously extending the scope of PLM systems, in order to include different kinds of models, the tools' strength are geometric models. For the focus on behavioral models in CCD [Fortin et al., 2017], PLM systems are not a good fit.

We analyzed these tools and compiled a comparison [Knoll and Golkar, 2018]. An updated version of the comparison is available in Appendix C, Table C.1. A discriminating characteristic of the tools is the specialization on certain life cycle phases. Furthermore, the tools differ in the focus and level of abstraction of parametric models.

Tools specialized on CCD focus on the conceptual design phase and allow collaboration on parametric models. Examples are: VirSat[5] from DLR, CDP[6] from RHEA, Valispace[7].

We tested these tools to verify their ease-of-use and whether they could be adapted to fit our methodology. We made the following observations that later informed the development of our own tool:

- None of the tools allowed for customization, nor did they provide extension points to log design activities for research purposes.

- Excel™ is a common and easy-to-use tool for making simple parametric discipline models, but it is not adequate for being primary user interface, for the interaction with the system model, as in CDP for example.

- Third-party engineering tools are typically installed as desktop applications, which makes it difficult to integrate with web based applications, like Valispace did.

- There is no need to incorporate discipline specific functionality, such as the visualization of the 3D geometry, as in VirSat for example.

---

[5] `https://www.dlr.de/sc/en/desktopdefault.aspx/tabid-5135/8645_read-8374/`
[6] `https://www.rheagroup.com/cdp`
[7] `https://www.valispace.com/`

6.1 Requirements

The tool we developed focuses on this primary function: exchange parametric model information between discipline experts. In other words, it was not meant to replicate any functionality of discipline-specific engineering tools, but rather integrate those with a shared parametric system model for easy exchange among engineering disciplines.

In response to the challenge revealed in the survey, that of limited expert availability (section 4.2), the tool shall be easy to learn an use. To match the needs of CCD and in line with ECCS-E-TM-E-10-25A [ECSS, 2010], the tool shall meet the following requirements:

Req-1 Allow users to build a hierarchically decomposed system model, with parameters associated to each element of the model and possibility to define parameter links.

Req-2 A team of users shall store the model on a shared repository, and keep local copy while working on their respective part.

Req-3 Multiple users shall be able to work in parallel on the same system model.

Req-4 The tool shall allow to assign permissions for different model elements adherent to their respective discipline.

Req-5 Upon storing changes to the shared model, the user shall be given the possibility to resolve conflicting changes.

Req-6 The tool shall allow to couple parameters from the system model with existing calculation spreadsheets.

A tool which limits itself to this functionality can be relatively easy to learn and use.

To address the challenge "integrated tool chain", revealed in the survey (section 4.2), specific features shall support the team in performing conceptual design in an orderly manner.

Req-7 The tool shall be shipped with an inbuilt documentation about the process guideline.

Req-8 To allow the team to see the status of the work and the effects of changes, the tool shall visualize the dependencies in the system model as N^2-Diagram.

Req-9 The team leader shall be provided with a function to calculate the optimal order of disciplines, using a DSM sequencing algorithm.

These features, explicitly supporting the coordination during the design process, are not available in existing tools. Hence, we developed CEDESK as a tool implementing MoCoDeM.

6.2 Tool Concept

Concurrent Engineering Data Exchange Skoltech (CEDESK) is a tool to facilitate co-located collaborative model-based conceptual design for complex engineering systems. This type of tool is also known as data exchange for concurrent engineering studies. Multidisciplinary design teams can use CEDESK to facilitate their work together, by building shared parametric models of their system of interest.

6.3 Software Architecture

A common architecture that supports data sharing and collaboration is the client-server architecture. CEDESK implement this architecture as illustrated in Figure 6-1. The server part embodies the central model repository and consists of a relational database, and the client part consists of a desktop application (Req-2).

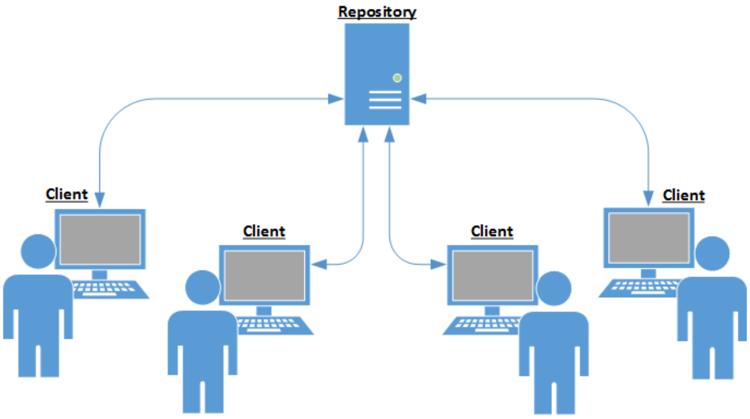


Figure 6-1: The client-server architecture of CEDESK

The application was implemented in Java™in order to be able to run on all major desktop platforms, such as Windows®, MacOS™, and Linux™. Multiple clients can connect to a server at the same time and work on the same model (Req-3). Model synchronization is built on top of atomic database transactions. The data storage relies on a MySQL™ from Oracle [2016] database and the client application uses the Hibernate™ Object Relational Mapping from Redhat [2014] framework to store models in the database.

The user interface is built with JavaFX™ technology. Moreover, CEDESK makes use of various open-source libraries for logging, access to workbook files, spreadsheet-like user interface components, and handling of graph data structures.

6.4 User Interface

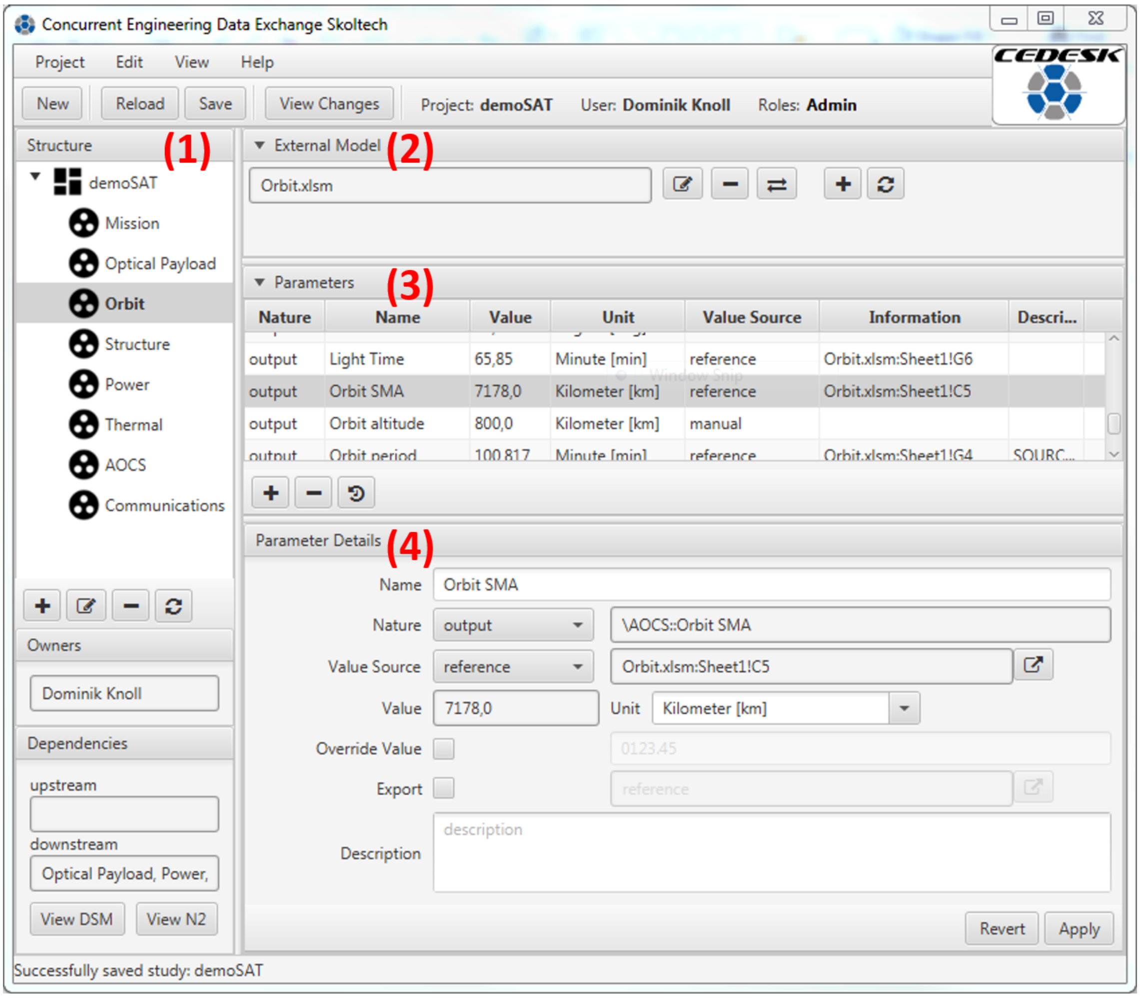
The client application is the primary user interface for the user to access the central study repository and to interact with the models. Similar to many collaborative design tools, with CEDESK, users load projects from the repository, then operate on a local working copy, and it can then be saved back to the repository when needed (Req-2, Req-3). Figure 6-2 shows a screenshot of the client application's main window.

At the top, the name of the current study, the logged-in user, and their active roles are displayed. According to the roles, a user is assigned; one can either view or modify a subsystem, its parameters, and external models (Req-3).

The user interface consists of four major parts enabling the user to work with the system model (see numbers in Figure 6-2).

(1) Shows the structure tree for the systems hierarchical decomposition. The buttons allow users to add, modify, and delete model nodes (Req-1). The screenshot above shows the model of the "demoSAT" spacecraft and its subsystems.

(2) This is the list of external models belonging to a model node (Req-6). External models (files of third-party tools) can be attached, detached, and opened with the respective tool, directly from there, with the appropriate buttons. In



External Model: Orbit.xlsm

Nature	Name	Value	Unit	Value Source	Information	Descri...
output	Light Time	65,85	Minute [min]	reference	Orbit.xlsm:Sheet1!G6	
output	Orbit SMA	7178,0	Kilometer [km]	reference	Orbit.xlsm:Sheet1!C5	
output	Orbit altitude	800,0	Kilometer [km]	manual		
output	Orbit period	100,817	Minute [min]	reference	Orbit.xlsm:Sheet1!G4	SOURC...

Owners: Dominik Knoll

downstream: Optical Payload, Power,

Name: Orbit SMA

Nature: output \AOCS::Orbit SMA

Value Source: reference Orbit.xlsm:Sheet1!C5

Value: 7178,0 Unit: Kilometer [km]

Override Value ☐ 0123.45

Export ☐ reference

Description: description

Successfully saved study: demoSAT

Figure 6-2: The main screen of CEDESK

the screenshot above, an Excel™ workbook "Orbit.xslm" is attached to the subsystem "Orbit" which was selected on the left.

(3) Shows the list of parameters belonging to a model node (Req-1). The buttons on the bottom allows a user to add a new parameter, remove an existing parameter, and see the version history of a parameter.

(4) This is the area for parameter details, which also allows for immediate editing (Req-1). In particular, this editor allows a user to create a link to another parameter or to set up the reference to external models.

There is the possibility to clone a study by exporting the full system model to an XML archive and then re-importing it with a new name. This can save a user time when building a new model based on similar conceptual design studies. Basic knowledge management capabilities are implemented in the form of a model library, with the possibility to store, search, and instantiate models from a component library as laid out in [Fortin et al., 2017].

A feature invisible to those designers who are using the tool, but of high relevance to researchers, is the detailed logging of user activities. The application logs each action such as loading and saving of models as well as modifications to the models' structure and parameters, along with all of the relevant meta data such as the related entity, time and user information. The log is stored in the same central database as the modeling information. This allows for a deeper analysis of the logs even after a design study is completed.

Upon close inspection of the various screenshots provided as examples, it can be noted that the application changes its appearance. As the screenshots originate from different operating systems (Windows®, MacOS™, and Linux™), the application windows slightly differ in style. This also demonstrates the cross-platform capability of CEDESK.

6.5 Modeling Capabilities

The data model in CEDESK is structured similar to ECCS-E-TM-E-10-25A, as much as it concerns parametric system models (Req-1). The primary model entities represent the system structure, its parameters, units of measures, users, and roles. Figure 6-3 describes the data structures, using the graphical notation of a UML class diagram.

A study is composed of a system model, which is a tree structure of model nodes. A node represents the parametric model of an engineering discipline or a system component. Each model node contains a set of parameters and a set of external models. External models encapsulate files made by third-party engineering tools. Parameters are of one of the following natures: input, internal, or output. All parameters have a numerical value and can be associated with a unit of measure. The value is obtained either from manual entry, from a link to another parameter, or a calculation based on other parameters.

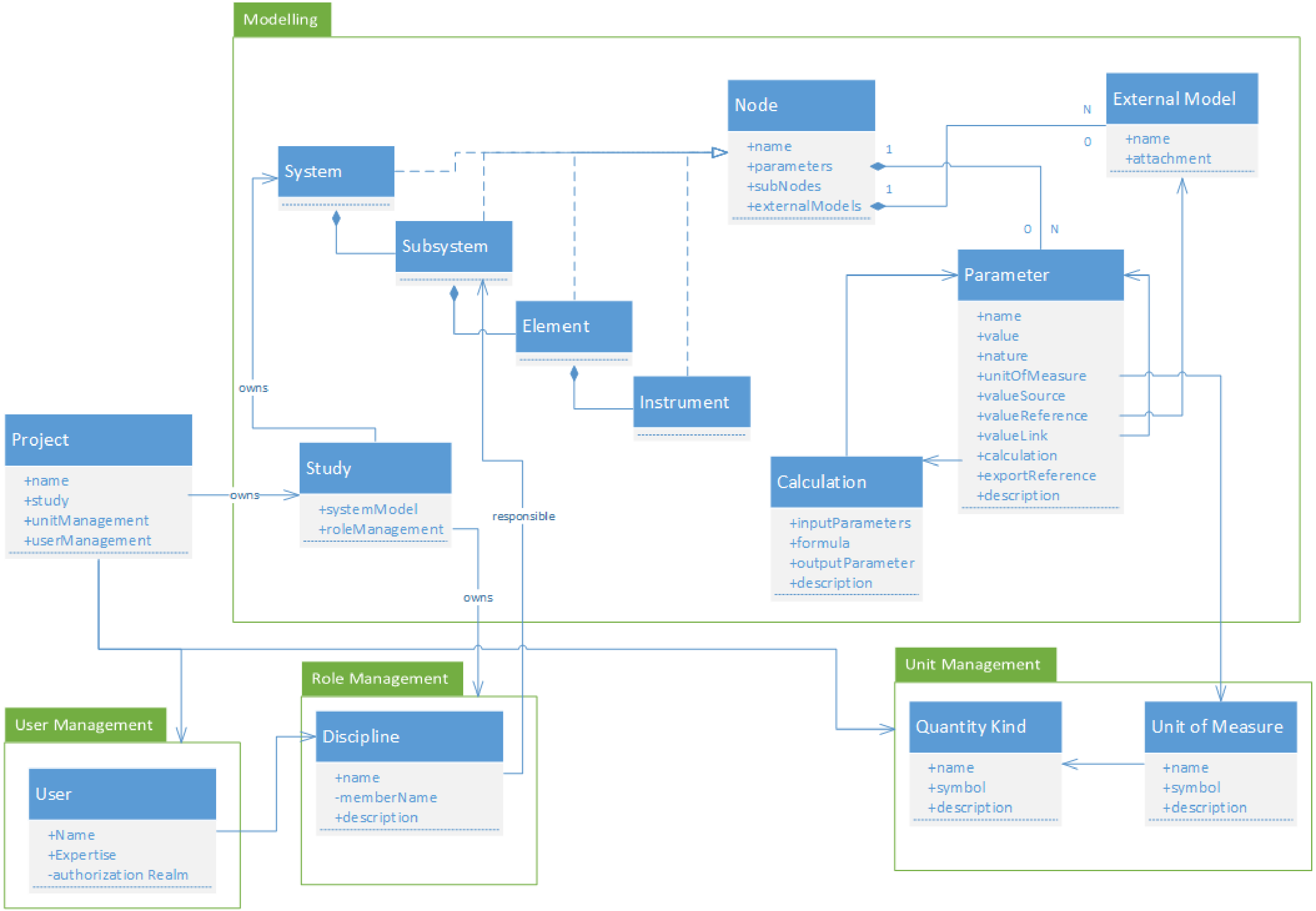


Figure 6-3: Data structures for integrated system models in CEDESK

Each model node, such as system, subsystem, element or component encapsulate a parametric model, with input and output parameters. Figure 6-4 shows how parametric models work in CEDESK: values of input parameters are fed into a calculation, a simulation or a human design decision and values for output parameters are produced.

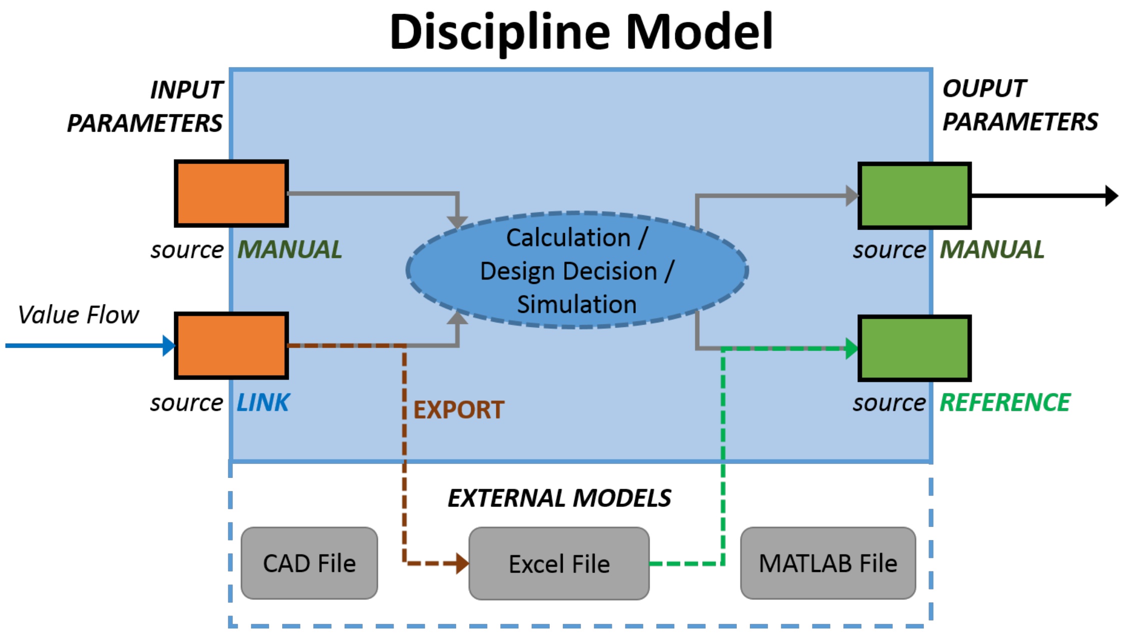


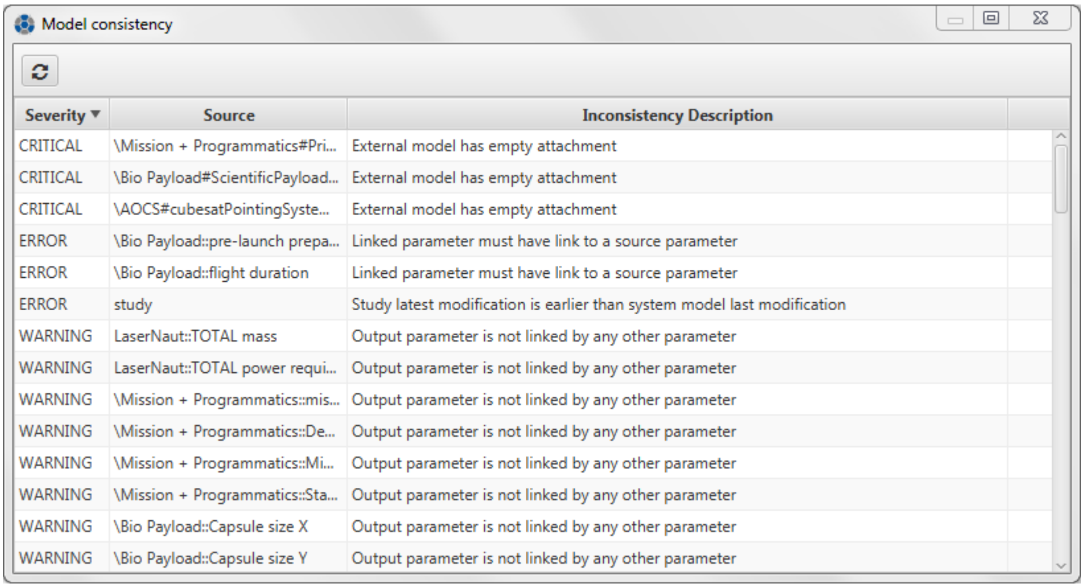
Figure 6-4: Structure and information flow in a parametric discipline model in CEDESK

An input parameter can obtain its value either from manual setting or from a link to another subsystem's parameter. Actually, only output parameters are visible to other subsystems and can be linked. An output parameter can obtain their value from setting it manually or from a reference to an external model. In the example shown in Figure 6-2, the parameter obtains its value from a reference to a specific cell from the Excel™ workbook "Orbit.xlsm:Sheet1!C5". Whenever the value of a parameter is obtained from a link or an external model, there is an option to override the value. This is useful at the beginning of the concurrent conceptual design, when a discipline engineer works with assumptions before being provided with calculated values by another discipline. Finally, a parameter can also export its value to an external model (e.g. to a cell of an Excel™ spreadsheet).

6.6 Consistency Check

Making sure that the integrated design model does not contain inconsistencies is a major concern. Some changes to the model that would introduce inconsistencies are blocked by the user interface right away. For example, links can only be established to output parameters, and removing a parameter that is already linked is restricted. The tool also ensures that the units of measure of two linked parameters will always correspond.

For incomplete models or inconsistencies that can occur in the model, the tool offers the ability to run a model check. The issues of the model are categorized by severity: critical, error, warning. An example of the result of such a check is shown in Figure 6-5.



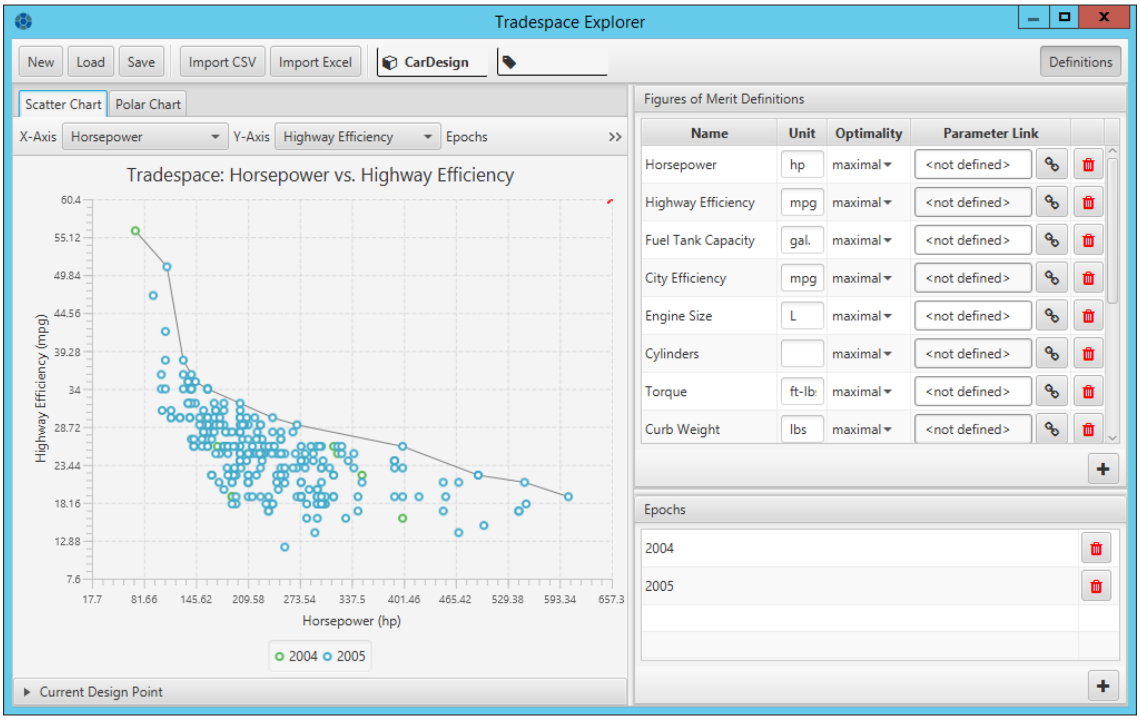
Severity ▾	Source	Inconsistency Description
CRITICAL	\Mission + Programmatics#Pri...	External model has empty attachment
CRITICAL	\Bio Payload#ScientificPayload...	External model has empty attachment
CRITICAL	\AOCS#cubesatPointingSyste...	External model has empty attachment
ERROR	\Bio Payload::pre-launch prepa...	Linked parameter must have link to a source parameter
ERROR	\Bio Payload::flight duration	Linked parameter must have link to a source parameter
ERROR	study	Study latest modification is earlier than system model last modification
WARNING	LaserNaut::TOTAL mass	Output parameter is not linked by any other parameter
WARNING	LaserNaut::TOTAL power requi...	Output parameter is not linked by any other parameter
WARNING	\Mission + Programmatics::mis...	Output parameter is not linked by any other parameter
WARNING	\Mission + Programmatics::De...	Output parameter is not linked by any other parameter
WARNING	\Mission + Programmatics::Mi...	Output parameter is not linked by any other parameter
WARNING	\Mission + Programmatics::Sta...	Output parameter is not linked by any other parameter
WARNING	\Bio Payload::Capsule size X	Output parameter is not linked by any other parameter
WARNING	\Bio Payload::Capsule size Y	Output parameter is not linked by any other parameter

Figure 6-5: Inconsistency check in the integrated design model

6.7 Tradespace Exploration

The conceptual design elaborated during a conceptual design study is commonly evaluated according to a few characteristics, or Figure of Merits. In the case in which the system to be designed can be associated to a bigger family of products (e.g. communication satellites), the new design is compared with other planned or existing solutions. A very powerful tool for this comparison is the tradespace chart (see section 2.5). The integration of tradespace exploration and parametric modeling is not available in any other tool.

CEDESK has the related functionality of tradespace exploration built-in. The respective screen is shown in Figure 6-6. This part allows a user to create tradespaces,



X-Axis Horsepower
Y-Axis Highway Efficiency

Name	Unit	Optimality	Parameter Link
Horsepower	hp	maximal	<not defined>
Highway Efficiency	mpg	maximal	<not defined>
Fuel Tank Capacity	gal.	maximal	<not defined>
City Efficiency	mpg	maximal	<not defined>
Engine Size	L	maximal	<not defined>
Cylinders		maximal	<not defined>
Torque	ft-lb	maximal	<not defined>
Curb Weight	lbs	maximal	<not defined>

2004
2005

Figure 6-6: The tradespace explorer in CEDESK

define the respective figures of merit (left upper part), and visualize tradespace charts (left side). The screenshot shows the data points, that were imported for the comparison of car designs.

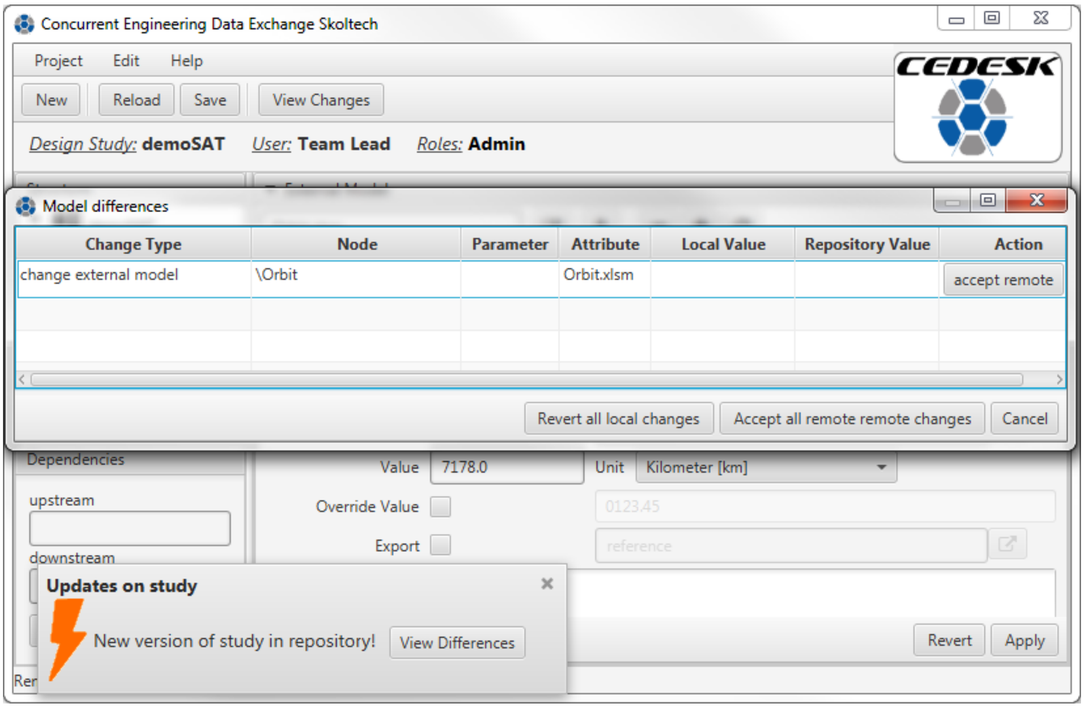
Data points represent designs that are characterized by a name, and values for a set of FOMs, as well as the epoch (year) the design was made. During the import of the data points from spreadsheets in CSV, XLS and XLSX format, the user can choose the meaning given to each column, whether it contains the name, a FOM or the epoch.

The definition of the figures of merit allows for the selection of a figure of merit optimality criteria. In the example, the FOM "horsepower" is set to maximal. A FOM for cost, would be set to minimal. On the top left, the user can choose which FOM to be shown on which axis of the chart. A line connects the data points which form the Pareto-front among the known designs.

FOMs can also be linked to parameters of the design model. For example, the parameter of engine size and horsepower of the design model can be connected to the figures of merit of the cars tradespace. In this way, any state of the current design can be compared to all existing designs in terms of these FOMs. This allows for immediate feedback between the concurrent design and analysis of competitive products.

6.8 Collaboration

To enable multiple users to work on a project, CEDESK also furnishes a user management feature, which allows for the assignment of users and roles (Req-4). A quick turn-around in collaboration is facilitated by notifications to the user, whenever changes have been stored to the model repository. Changes made by other team members or the user's own unsaved changes can be reviewed in a dedicated window, as shown in Figure 6-7 (Req-5).



Design Study: **demoSAT** User: **Team Lead** Roles: **Admin**

Change Type	Node	Parameter	Attribute	Local Value	Repository Value	Action
change external model	\Orbit		Orbit.xlsm			accept remote

Value 7178.0 Unit Kilometer [km]

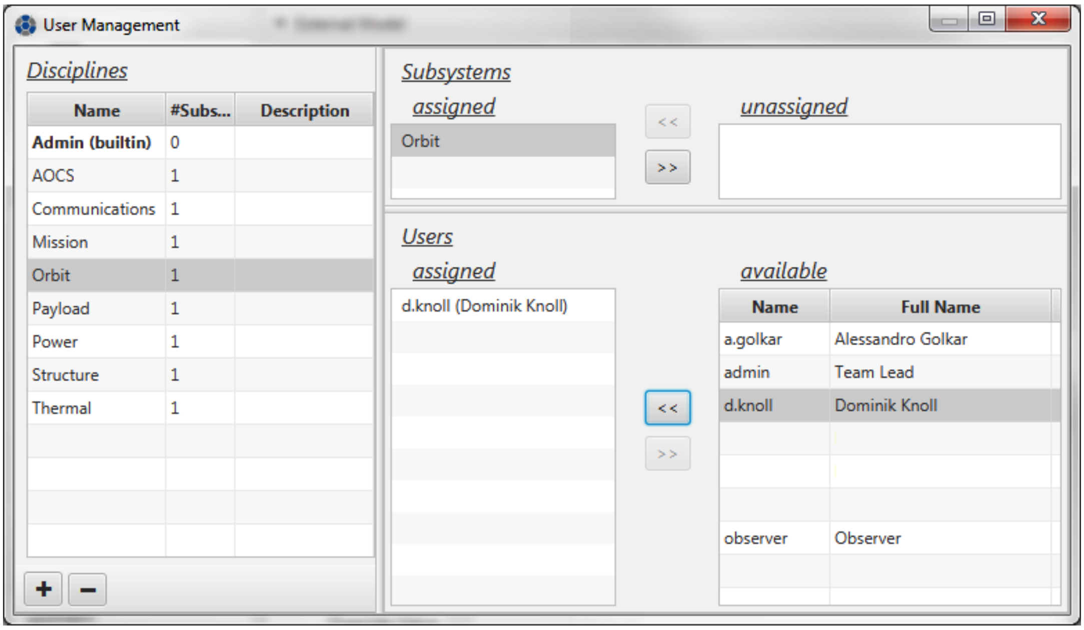
Updates on study

New version of study in repository!

Figure 6-7: Change notification and possibility to review changes

Whenever a user stores the system model, the tool not only saves the latest state of it, but also keeps track of each modification. All changes to the structure of the model and parameters are recorded and a full version history is kept. This allows the reconstruction the complete state of the model back to any stored version as part of posterior analysis. The tool provides functionality to tag the state of the system model at any point in time. The user can also restore any tagged version from the history.

To distinguish the responsibilities of study participants over parts of the system, the tool implements access control based on roles Figure 6-8. Roles can be created for all disciplines. Model nodes can be associated with roles, and roles associated with users.



Disciplines

Name	#Subs...	Description
Admin (builtin)	0	
AOCS	1	
Communications	1	
Mission	1	
Orbit	1	
Payload	1	
Power	1	
Structure	1	
Thermal	1	

Subsystems

assigned

Orbit

unassigned

Users

assigned

d.knoll (Dominik Knoll)

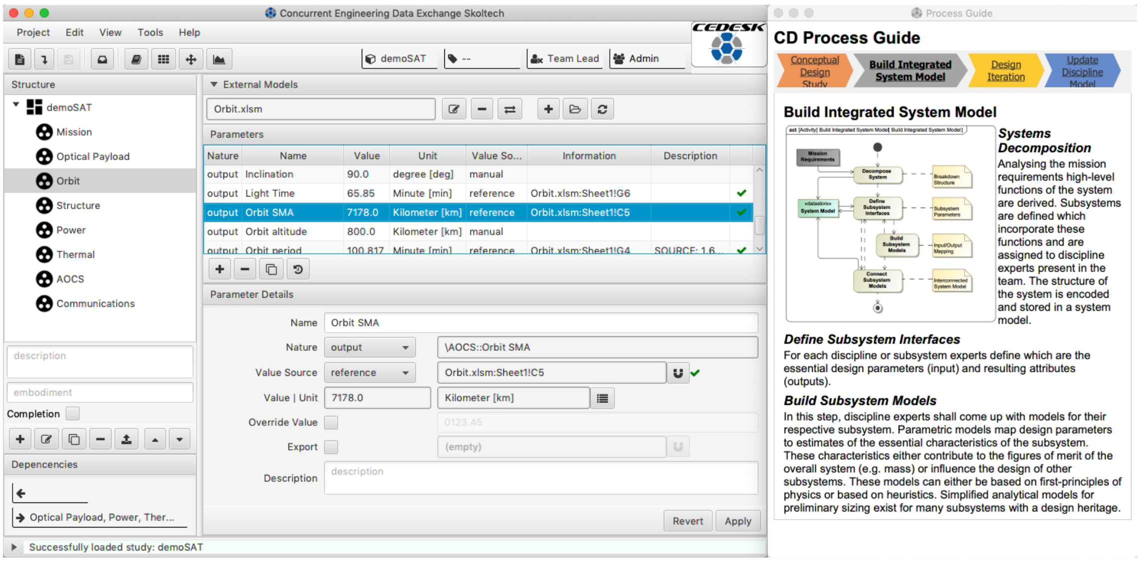
available

Name	Full Name
a.golkar	Alessandro Golkar
admin	Team Lead
d.knoll	Dominik Knoll
observer	Observer

Figure 6-8: The discipline and user management

6.9 Process Guide

The aim is to assist the user in following the proposed design methodology. Therefore, we included the process model and description into the tool, such that it is available for consultation during the concurrent design sessions. Figure 6-9 shows the interactive documentation containing all the process guideline (Req-7), as described in subsection 5.5.2. This allows newcomers to learn about the process on-the-fly, and gives all team members awareness about the current activities.



Nature	Name	Value	Unit	Value So...	Information	Description	
output	Inclination	90.0	degree [deg]	manual			
output	Light Time	65.85	Minute [min]	reference	Orbit.xlsm:Sheet1!G6		✓
output	Orbit SMA	7178.0	Kilometer [km]	reference	Orbit.xlsm:Sheet1!C5		✓
output	Orbit altitude	800.0	Kilometer [km]	manual			
output	Orbit period	100.817	Minute [min]	reference	Orbit.xlsm:Sheet1!G4	SOURCE: 1.6...	✓

Name: Orbit SMA
Nature: output \AOCS::Orbit SMA
Value Source: reference Orbit.xlsm:Sheet1!C5 ✓
Value | Unit: 7178.0 Kilometer [km]
Override Value ☐ 0123.45
Export ☐ (empty)
Description: description

Successfully loaded study: demoSAT

CD Process Guide

Build Integrated System Model

Systems Decomposition
Analysing the mission requirements high-level functions of the system are derived. Subsystems are defined which incorporate these functions and are assigned to discipline experts present in the team. The structure of the system is encoded and stored in a system model.

Define Subsystem Interfaces
For each discipline or subsystem experts define which are the essential design parameters (input) and resulting attributes (outputs).

Build Subsystem Models
In this step, discipline experts shall come up with models for their respective subsystem. Parametric models map design parameters to estimates of the essential characteristics of the subsystem. These characteristics either contribute to the figures of merit of the overall system (e.g. mass) or influence the design of other subsystems. These models can either be based on first-principles of physics or based on heuristics. Simplified analytical models for preliminary sizing exist for many subsystems with a design heritage.

Figure 6-9: The process guide integrated into CEDESK

6.10 Coordination

An important goal of CEDESK is to support the team leader in coordinating the design effort. A graphical representation of the dependencies is given in the form of an N^2-Diagram (see Figure 6-10) (Req-8). The boxes in the diagonal represent the subsystems, and the lines indicate the parameter links. The arrows at the end of the lines show the direction of information flow. The width of a line reflects the number of parameter links, and at the bend in the lines the names of the parameters are shown.

The tool allows users to interact with the chart by clicking on single arrows and subsystems to highlight them (see red border). Moreover the user can change the order in which the subsystems are arranged via the buttons at the top, and export a snapshot of the chart as a picture. Charts not only give a view of the static parameter links between the subsystems, but also their status. The arrow tip is shown in blue, if the value of the output parameter is explicitly overwritten at the input parameter. The arrow line turns blue when the output value is not yet propagated to the input parameter.

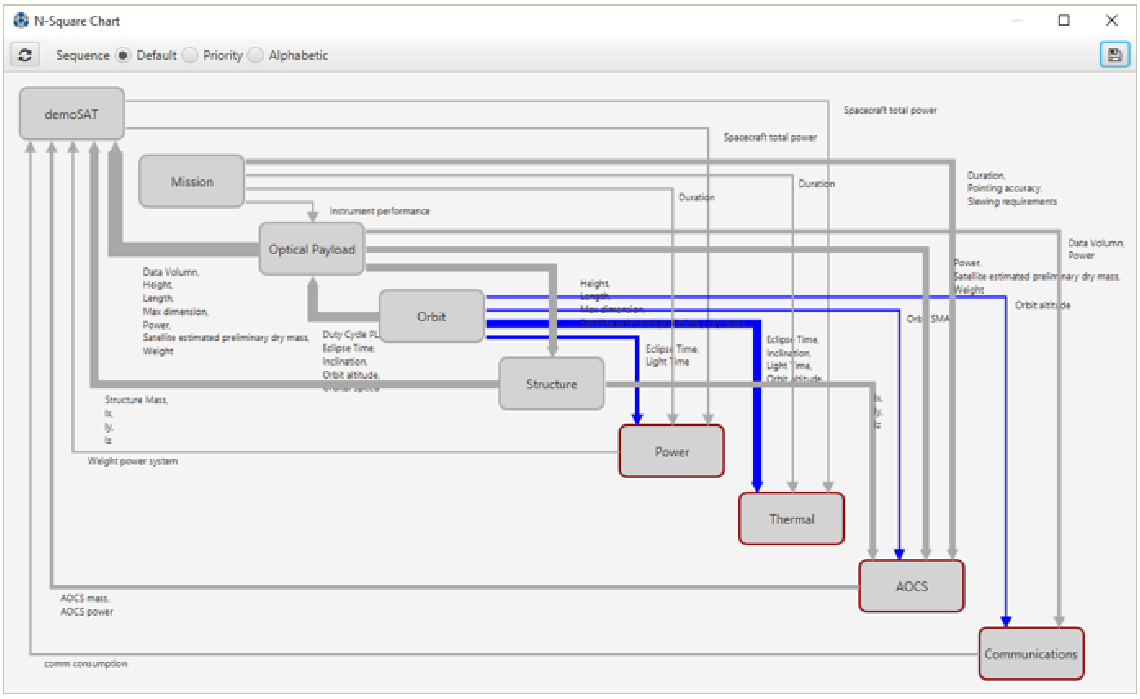
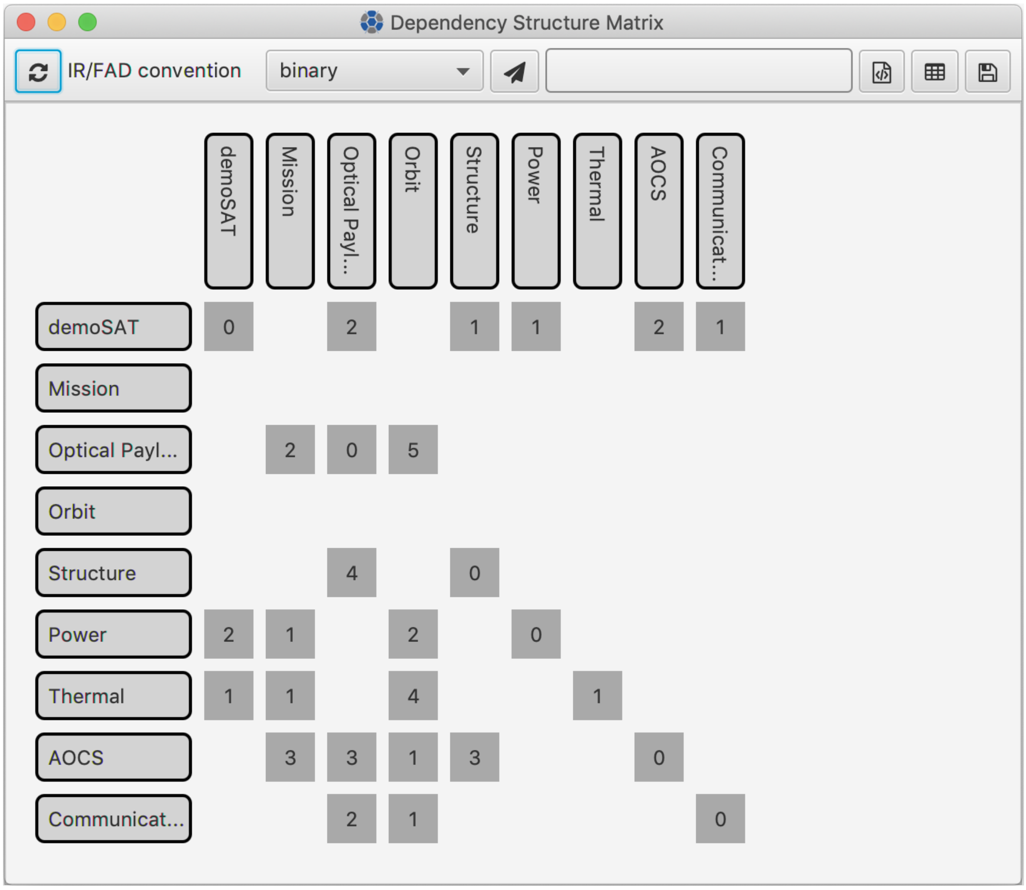


Figure 6-10: The subsystem dependencies visualized in a N^2-Diagram

The user can choose to have the view updated automatically at any change made to the model in the repository. This allows a team lead or moderator to use this view to observe the design process and the propagation of changes in real-time.

Another view in the application allows the user to visualize the dependencies among subsystems in the form of a Design Structure Matrix (DSM). The cells of the matrix in Figure 6-11 show the number of parameters linked from the subsystem in that row, to the subsystem of that column. The user can interact with the chart by using the mouse. Hovering over a cell lists the names of the parameters, and by clicking on a cell it will highlight the two involved subsystems. The interface offers the user the possibility to run a DSM clustering/sequencing algorithm (Req-9). The results are shown on the same view, just through the re-arranging of the discipline names and marking the clusters with a square.

A moderator or team lead can use this discipline sequence to minimize rework.



IR/FAD convention: binary

	demoSAT	Mission	Optical Payl...	Orbit	Structure	Power	Thermal	AOCS	Communicat...
demoSAT	0		2		1	1		2	1
Mission									
Optical Payl...		2	0	5					
Orbit									
Structure			4		0				
Power	2	1		2		0			
Thermal	1	1		4			1		
AOCS		3	3	1	3			0	
Communicat...			2	1					0

Figure 6-11: A visualization of the subsystem dependencies in the form of a DSM

6.11 Distinctive Features

This application was designed and developed to provide the necessary functionality, which supports the user throughout the concurrent design study. Like all other available tools, CEDESK allows teams to store and share the integrated parametric model as specified in section 6.1 The following features are not available elsewhere and represent innovation in the area of tools for concurrent conceptual design:

Consistency check Is an automated analysis which reveals possible mistakes in the parametric models, and helps the team to make corrections accordingly.

Tradespace Explorer This tool can import and visualize competitive solutions in terms of key system characteristics (Figure of Merit). Thereby the concurrent design teams have the ability at any moment of the design study, to compare the design with the best-in-class.

Coordination With the visualization of dependencies as interactive N^2-diagrams, concurrent design teams have the ability to see the changes as they are propagated. The automatic generation of the DSM based on the parameter links allow the user to better decide the order in which the various disciplines make updates.

6.12 Summary

This chapter provided an ample description of the software tool developed mainly by the author. Further information on technical details about the source code and software components can be found in the appendix section D.1 and in the developers guide on the website `https://cedesk.github.io`

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 7

Expert Interviews

For the verification of our approach, we conducted interviews with subject matter experts, who already had participated in our survey (section 4.1). We talked to five experts from five organizations, such as NASA, ESA and DLR, who are leading in the field of Concurrent Conceptual Design (CCD). Besides space agencies, we also covered research centers and industry.

The first part of the interviews was dedicated to the verification of the process guideline (subsection 5.5.2), included in our approach. In a second part, we tried to capture the experts' respective experience of CCD, focusing on processes and tools.

Before that, we summarize the organizational context in which the concurrent design facilities operate, as it can have significant influence on the use of the CCD approach.

7.1 Organizational Context

Within organizations concurrent design facilities (CDFs) are known for the specific purpose of bringing people together for collaborative design sessions. Depending on the organization, CCD finds different implementations. Nevertheless, it is common to all facilities where our interviewees work, that they are staffed with a relatively small group of people with the qualification of systems engineers. Their task is to provide support to concurrent design studies in different roles. The facility provides the service to run concurrent design studies commissioned by other units of the organization. Within an agency, it could be the science directorate requesting a concurrent design study based on a proposal received from a academic researchers. In a company, it could be the sales department requesting a conceptual design study in response to a call for proposals launched by a funding agency. Upon commissioning a study for a mission, the amount of dedicated resources is defined.

The team for a specific design study is formed, drawing experts coming from engineering units within the organization or from external partners. The size of the team can vary significantly depending on the complexity of the mission, the scope of the study, and the available budget. Our interviewees reported that their organizations all have a matrix structure. It means that projects like mission design studies draw from expert pools of departments specialized on different engineering disciplines and business aspects. As an example for a space agency, Table 7.1 lists the 30 disciplines available in ESA ESTEC.

AIV/Programmatics	EMC & Harness	Navigation / GNC
Antenna/Sub-Millimeter Wave	Flight Software Systems	On-board Payload Data Processing
AOCS	Flight Vehicles& Aerot.Eng.Sect.	Optics/Instrument
Chemical Propulsion	Ground Segment	Power
Communications	Ground SW Systems & Functional Verification	Radiation
Configuration / Structures	Independent Safety	Risk
Cost	Instrument/Payload	Robotics
Data handling	Life & Phys Science Instrument	Solar Generators
Debris Office	Mechanisms	Systems
Electric Propulsion	Mission Analysis	Thermal

Table 7.1: Possible Domain Experts

Over the years, the study leaders from concurrent design facilities have learned, which experts are more likely to participate and are more productive in concurrent design studies. Nevertheless, it was reported that there are newcomers on basically every design study. This requires special attention to make sure these people learn the concurrent design process and the usage of the available collaborative tools.

7.2 Process

As we talked our interviewees through our process model, they confirmed that our model in general reflects the actual design process they experience in their environment. The visual representation was considered useful for communication purposes. Several interviewees pointed out that there is not a "one size fits all" process. Each study comes with specific needs and characteristics, and requires to be treated individually. Hence, it is common that the process, as it may be defined within the organizations, gets tailored to the specific needs of a project. All facilities have their proprietary mechanisms to estimate the required efforts in terms of money or man hours based on the customer needs. This is used for the agreement with the customer on funding and expected study outcome.

In the following we summarize the comments regarding the process model formalized in SysML activity diagrams, shown in subsection 5.5.2.

Conceptual Design Study The interviewed experts found our process model at this level of abstraction to correspond to reality. Basically, the overall process is agnostic to the specifics of each disciplines analysis, as they are left up to the domain experts.

An additional detail in the preparation step is that certain high-level architectural decisions might be taken already during the preparation. For example, in the case of research on a planetary surface, the trade-off could be in-situ measurement versus remote sensing, giving different science return at different cost. The preparation phase can take up to a third of all the time from the initial request to the delivery of the results. Agreeing on the initial requirements and defining the appropriate figures of merit, in some organizations can take a couple of weeks.

The number of design variants that the concurrent study shall produce is defined by the customer and constrained by the time or budget allocated for it. Besides one baseline solution, some facilities try to prepare at least one alternative solution.

It was noted that the generated study report generally contained the system requirements along with the feasible concept, risk analysis and cost estimates. Another outcome of a design study that occurs in practice, is that a follow-up study is needed.

Build Integrated System Model A important factor already mentioned in our process guideline is the starting point for the system model. Our activity diagram assumes the case where a study starts from a blank page, and the system model has to be built from scratch. Interviewees confirmed that this model in broad terms describes their reality.

If a study can make use of model templates, the process is simpler and the effort reduced. Indeed, most but not all our interview partners are used to an intermediate case, where the system decomposition is partly taken from templates. The templates are then adapted in each project, and the subsystem models are contributed by discipline experts drawing from the design heritage of their respective home departments.

Our process guideline allows for both cases, building the model from scratch and reusing existing models. The major part of building the model is done during the preparation phase and the models can be used in the design sessions for analysis and making decisions.

Design Iteration According to the interviewed experts, the sequence of discipline updates in general is determined by the study lead based on their experience. In this point, our process model does not describe the actual practice, but as it could be.

The interviewees considered the automatic sequence based on the dependency information innovative. A concern raised by one interviewee was that the system model could potentially contain a large number of interconnections, which could potentially render the sequencing based on the DSM impractical. It was confirmed, that many interconnections indicate that the model is too detailed for conceptual design. In order to keep the dependencies to the minimum necessary, practitioners prefer to have the systems engineer manage the definition of the subsystem interfaces.

Another way to coordinate concurrent teamwork used by one of our interviewees is a chart, where each discipline continuously reports it's current state in a stop-light manner: green - up to date, orange - busy updating, red - waiting for inputs. This method assists the moderator to decide the sequence of discipline updates on-the-fly. It is a heuristic coordination method, which aims to reduce the waiting time and to keep the design process flowing.

In this aspect, our process model is more prescriptive then descriptive. Hence, further validation through practical design studies is needed.

Update Discipline This sub-process is rather straight forward, and the experts confirmed that it describes the reality well. A specific activity happening in practice is that sometime the model is not recalculated, but replaced, due to major concept changes, e.g. change the power source from solar batteries to RTG. Additionally, the feasibility check is not only necessary within a discipline, but also at a system level. Our process model considers the system budgets (e.g. mass, power, etc.) to be checked by the systems engineers.

Schedule An important comment was given regarding the implementation of the process in a schedule for the concurrent design sessions and the agenda for each session. After all, the teamwork relies on humans, who can vary unpredictably in mood and availability. Hence, the moderator needs to be ready to adopt the schedule due to people coming late, being sick, or being in a bad mood.

All our interviewees agreed that the activities "Preparation", "Define Figures of Merit" and "Compile Study Report" are done in asynchronous collaboration. Partly, also "Build Integrated System Model" is also done before gathering the full team into the facility. Only the activities "Design Iteration" and "Store Design Variant" presume co-located teamwork, but frequently some experts are connected via video conferencing.

Overall, the feedback on our process model confirmed that it corresponded to reality. Further we describe additional insights gained regarding the processes in different organizations.

Types of Design Studies

Some organization also established classes of design studies. NASA JPL for example defined a clear schema of concept maturity levels (CML)[Wessen et al., 2013]. Depending to which level the concept is already developed the design study takes a different form. Our process model fits only to certain kinds of studies.

Several organizations established a tailored process of Cubesat studies [Zarifian et al., 2015, Jahnke and Martelo, 2016]. The standard form factor and the heavy use of COTS components, puts strong constraints on the design space. But it also allows design studies to provide a more detailed description of the solution, which is similar to a preliminary design.

Some facilities host design studies not only for concept feasibility verification, but also for the preliminary design of missions. Due to the difference in duration, team size and expected outcome, the processes for executing these studies are adapted.

Training

A recurring theme in our interviews was the need for training newcomers. People joining the staff of Concurrent Design Facility are mainly trained on the job. This primarily means participating in concurrent design studies and secondly studying internal documentation. The experts confirmed that there are no general descriptions of the concurrent design methodology available. Most of the publications used, and referred by our interviewees are from their own organization. Conferences on concurrent design or aerospace are the principal occasion for exchange of ideas between practitioners of different organizations.

Most interviewees frequently have to deal with people on the team, who are new to the concurrent design approach. This means, in each study session time needs to be dedicated to explain the way of working, and the respective tools. Some of our interviewees report that the the study plan always takes into consideration additional staff to support the team in using proprietary collaboration tools. Other organizations are trying to grow a more stable pool of participants to reduce the need for training.

Our work is addressing the need to train new people by providing a generic description of the methodology and in particular the design process.

7.3 Modeling and Tools

Another topic we paid particular attention to in our interview is the aspects of modeling related tools.

Model Library

One of the reasons for introducing the MBSE approach is the potential savings due to model re-use. Regarding the models, all our interviewees confirm that they are undertaking efforts to better manage their organizations knowledge in the form of models.

At a system level, several organizations make use of templates based on the type of mission. One organization has distinguished 4 types of interplanetary missions (inner and outer solar system, orbiting, and landing). Another organization has templates for earth observation and communication missions.

Models at discipline level are traditionally maintained by the respective department. Our interviewees report a transition towards centralized model libraries shared within the entire organization. This requires more rigor in the documentation of models, in particular regarding the range of validity of analytic models. The models are validated on a set of standard cases. With the growing heritage of conceptual design studies, there is potential to find models that are validated on a wide range of design cases. Some experts describe that certain discipline models have reached high levels of automation, including design decision trees. Nevertheless the responsibility remains with the human experts even if they only supervise the calculation of the models check the results.

One interviewee reported, that the migration of existing models in spreadsheets onto a new technology such as SysML is rather time consuming, and can take up to a decade.

Tool Integration

The linking of domain specific tools with the integrated system model is still a challenge. Facilities using a proprietary tool struggle with limited interoperability with analytic tools. As a consequence, some interviewees admit that with certain disciplines (e.g. Configuration) parameter values are exchanged via voice, instead of a collaboration tool.

Nevertheless, experts note a growing integration of analytic tools, which improves the responsiveness of the disciplines during the design sessions. Due to the continuous improvement of technology, simulation tools can produce more accurate results in shorter time.

Collaboration

The tools used by our interviewed experts are partly proprietary and partly publicly available. Of those publicly available, we note that their primary function is to storage of the model, and allow multiple users access while managing permissions. To support collaboration on a shared model, they assure model consistency despite concurrent modifications.

Although the tools focus is on the data model, each of them implies a certain way of working. None of these tools provides explicit support for coordinating the discipline experts' work. Where a tool is used for coordination, such as the stop-light chart mentioned above, it is independent of the shared data model.

7.4 Summary

This chapter reports about the interviews we performed with experts of different organizations, who had already participated in the online survey described in chapter 4. Our interviewees are top-level experts in setting up and leading Concurrent Conceptual Design studies for space missions.

We discussed our generic process model with them to verify its correspondence to reality. In general the experts found the model a proper abstraction of their actual processes. The description of certain activities requires more detail. For example, the step of building the integrated system model only captures the case of starting from scratch. In reality, a team more often re-use previous models, unless this bias shall be explicitly excluded. Where our model diverges from actual practice is the sequencing of disciplines within a design iteration. This is a novelty in the concurrent design process, which needs to be tested in practice.

With regards to modeling and tools we obtained additional insights into the practice in each Concurrent Design Facility. All of our interview partners reported ongoing efforts to improve knowledge management and consistent use of model-based tool chains. The experts in these facilities are the forerunners in implementation of MBSE. Certain standards, like the new SysML 2.0, are the result of their experience and realized with their respective contributions. The integration of data management and process management is still in it's infancy, and these aspects require further research to be done.

Chapter 8

Conceptual Design Studies of Space Missions

The conceptual design of a product is a dynamic process, with complex interplay of people and tasks. Each real design study comes with a unique combination of people, their skills and characters and concrete design tasks. This makes it hard to conduct studies in a controlled environment. At the same time, controlled experiments hardly reflect real situations of design exercises. As it is common practice in design research, we performed a set of case studies. The goal is to test our Model-based Co-located Conceptual Design Methodology (MoCoDeM), and verify if and how well it addresses the research questions set forth in chapter 3.

We organized a set of Concurrent Conceptual Design (CCD) studies for space missions in our Institutes Concurrent Engineering Design Laboratory (CEDL). Finding participants for design studies is challenging, because it requires people with knowledge in space engineering willing to dedicate time, and motivated to perform a real design task. A pool of candidates were students attending the "Satellite and Mission Design" course, which requires a course project in the form of a conceptual design for a space mission. This course is delivered each year at Skoltech, and it provides an extended testbed (6 weeks) to apply our methodology and to gather data about the design process. Additionally, we managed to recruit volunteers for 4 more design studies.

As our survey showed, it is frequent that there are newcomers in a design study, and a goal of our work is describe the methodology that help newcomers to adopt easily. Our case studies with mostly newcomers are a hard test for entire teams to adopt the methodology.

Overview

The design studies were set up similar to the practice in established CDFs in terms of team size and overall duration, as we revealed through our survey (see chapter 4). An overview on all the design studies is shown in Table 8.1.

ID	Project name	Participation	Team size	Duration	Sessions
Pilot Studies					
1	Dumbo	coursework	8	6 weeks	6 á 3h
2	BeeSAT	coursework	8	6 weeks	6 á 3h
3	DemoSAT	volunteers	7	1 week	3 á 3h
4	LaserNaut	volunteers	7	2 weeks	8 á 3h
Case Studies					
5	GLISS	coursework	12	6 weeks	6 á 3h
6	RadMonConst	coursework	9	2 weeks	6 á 3h
7	ComConst5G	coursework	7	2 weeks	6 á 3h
Comparative Study					
8	OgonSat-A	volunteers	4	1 day	3 á 1.5h
9	OgonSat-B	volunteers	4	1 day	3 á 1.5h

Table 8.1: Case Studies Overview

All of them followed a common research methodology, but served different purposes.

Pilot Studies

The pilot studies (1-4) focused on the definition of the methodology and testing the collaboration tool. We performed these design studies to check whether the tool allows a team to build an integrated system model by connecting disciplinary models in spreadsheets. Following the methodology, the design teams were able to complete the conceptual design studies. At the same time they revealed shortcomings of the tool, which limited concurrent modifications of the system model. The experiments also unveiled functionality with which the tool could explicitly support the process.

Case Studies

The case studies (5-7) tested the process guideline and the tool's process support in realistic design scenarios. The goal was to check if the described design process reflects the reality of a design study. The hypothesis we tested in these design studies was: do the activities described in the process guideline lead a team to conclude a conceptual design? Teams of students who were mostly new to space mission feasibility studies adopted our methodology to perform conceptual design studies. Performing the design activities according to our guideline they successfully completed their task. The teams took advantage of tool features supporting the coordination during the design iteration.

Comparative Study

The comparative study (8, 9) evaluated the effectiveness of process guideline to reduce the duration of design iterations. In this studies, we tested our hypothesis whether the support we developed reduces the duration of a design iteration. Two teams were given the same task to design a spacecraft for one mission and a partially pre-built system model. One of the teams was left to coordinate spontaneously, while the other was instructed to follow the process guideline in particular for the design iteration. In the same time the first team concluded 1 design iteration, the second team made 3 design iterations. This supports our hypothesis that the process guideline reduces the duration of a design iteration.

The following sections are dedicated to the description of each of the case studies and the respective results. Each section contains a table, summarizing the design of the case study, in a common format taken from Blessing and Chakrabarti [2009, p.84].

Pilot Studies

8.1 Study 1 and 2 – Dumbo & BeeSat

These two case studies were the first ones, where method and tool were initial. They were performed as part of the course "Spacecraft and Mission Design" in November and December 2015. We describe them together, because they share the same setting, and only differ in the design task and team.

The case studies were set up to test the supporting tool in a real conceptual design project. Table 8.2 documents the characteristics of the study design.

Dimension	**Experiment (Case Studies 1 + 2)**
Aim, research questions, hypotheses	Test the parametric design support by the data exchange tool.
Nature of Study	Interventional
Theoretical basis	Concurrent Engineering approach: Conceptual Design using Parametric Models
Unit(s) of analysis	parametric design: process and result
Data-collection method	recording model changes
Role of researcher	Observer
Time constraint	Limited to course project
Continuation	Continuous data collection.
Duration	6 weeks, 6 sessions a 3h
Observed process	Starting point: system requirements, discipline assignment. Deliverable: conceptual design
Setting	Skoltech CEDL
Task	Realistic
Number of cases	2
Case size	8 and 8 people
Participants	Master students of various background.
Object	The project consists in consolidating a parametric design to a feasible and close to optimal solution.
Coding and analysis method(s)	From the logged design decisions (modifications to parameters) reconstruct the sequence and causality of the changes.

Table 8.2: Design of Case Studies 1 and 2

8.1.1 Mission and Team

The goal is to design a system with capabilities complementary to the European Commission's Copernicus infrastructure. The two teams were given inter-related missions: a set of high-resolution Earth Observation satellites and a constellation of communication satellites for fast transfer of the voluminous observation data. Over the course of the project the two teams realized that the two systems are tightly interdependent. As a consequence, the teams decided to merge the two separated system models into a single one, so that the parametric dependencies can be realized more efficiently.

EO Satellites – Dumbo

The observation shall provide high-resolution and frequently updated images complementing the current system mainly for land monitoring, ice, snow and aerosol measurements. For that purpose, the satellites have a multi-spectral imager focused on achieving a higher resolution. To provide high quality data at short delays, the satellite shall use a data relay via a communication satellites via an optical communication link. The satellite shall have a preferable Cubesat form factor of 3 or 6 units.

The team made of 8 students organized itself in the disciplines: Mission, Payload, Orbit, Structure, Power, Thermal, ADCS, Communications, Propulsion, Laser-Comm.

Communication Satellites – BeeSat

The communication satellites serve to relay data from the observation satellites to the ground. The orbits are chosen such to maximize the time available for receiving data. The inter-satellite optical communication module is designed such to be capable of pointing, acquiring, tracking and data transmission. The down-link via radio frequency is designed to provide the necessary capacity and availability.

The team made of 8 students organized itself in the disciplines: Mission, Payload, Orbit, ADCS, Power, Structure, OBDH, Communications, Thermal

8.1.2 Design Process

The process proposed to the two teams comprised the following steps:

Mission analysis and system breakdown Based on the mission requirements and a concept the architecture of the system is defined. As a result the system's composing elements are identified. This step happens very early on and immediately reflects in the organization of the team and the assignation of roles.

This step has correspondence in the process guideline (section 5.5.2): the activity "Decompose System" in the step "Build Integrated System Model"

Discipline modeling Each discipline expert starts building a parametric model using the formulas provided in a textbook for conceptual spacecraft design, such as [Wertz et al., 2011]. The primary goals of these models are to estimate key characteristics, such as power, mass and cost of the subsystem based on the design inputs.

The process guideline calls this activity "Build Subsystem Models".

Connecting disciplines The discipline experts identify the source for each input. For parameters which miss a source, it must be decided which discipline shall provide it.

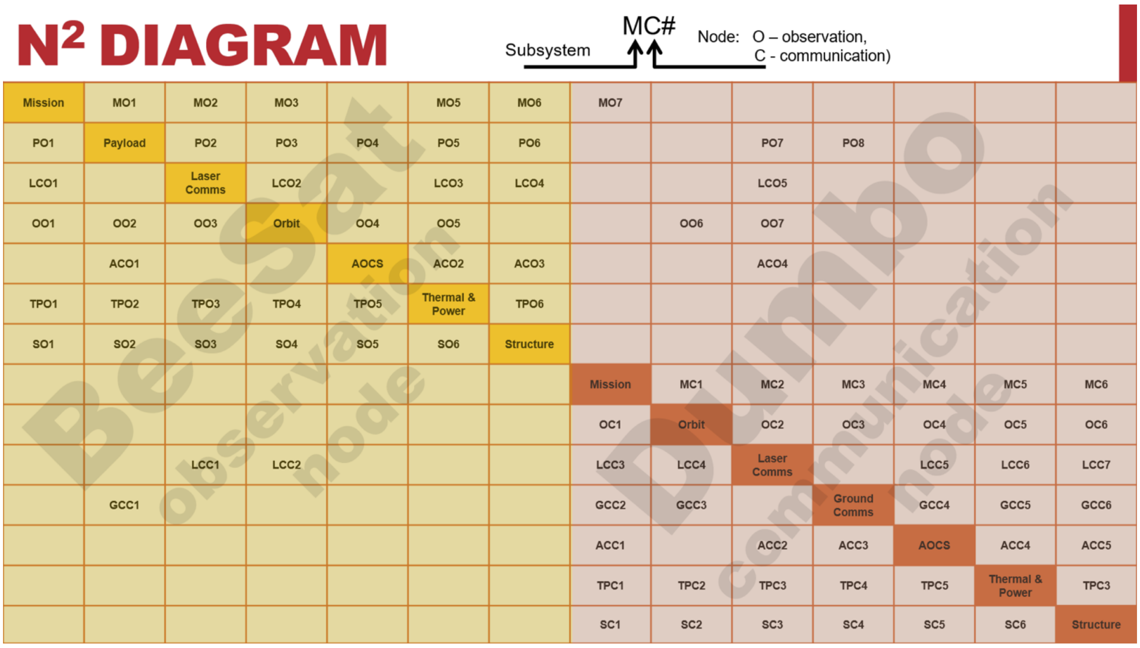
In the process guideline this activity is called "Define Subsystem Interfaces".

Consolidating integrated model In this step the discipline experts iteratively adopt inputs they get on the subsystem models from other disciplines and update their respective outputs. This process should make the model to converge on a feasible design.

This step corresponds to the activity "Design Iteration" in the process guideline.

Dependency Model Analysis

The teams also spent significant effort to elaborate in detail all the design interfaces between the involved disciplines and visualized these connections in a matrix



Mission	MO1	MO2	MO3		MO5	MO6	MO7						
PO1	Payload	PO2	PO3	PO4	PO5	PO6			PO7	PO8			
LCO1		Laser Comms	LCO2		LCO3	LCO4			LCO5				
OO1	OO2	OO3	Orbit	OO4	OO5			OO6	OO7				
	ACO1			AOCS	ACO2	ACO3			ACO4				
TPO1	TPO2	TPO3	TPO4	TPO5	Thermal & Power	TPO6							
SO1	SO2	SO3	SO4	SO5	SO6	Structure							
							Mission	MC1	MC2	MC3	MC4	MC5	MC6
							OC1	Orbit	OC2	OC3	OC4	OC5	OC6
		LCC1	LCC2				LCC3	LCC4	Laser Comms		LCC5	LCC6	LCC7
	GCC1						GCC2	GCC3		Ground Comms	GCC4	GCC5	GCC6
							ACC1		ACC2	ACC3	AOCS	ACC4	ACC5
							TPC1	TPC2	TPC3	TPC4	TPC5	Thermal & Power	TPC3
							SC1	SC2	SC3	SC4	SC5	SC6	Structure

Figure 8-1: Manual N^2-Diagram of VITC (Dumbo & BeeSat)[1]

form (see Figure 8-1[1]). For each cell with connections an interface (named with a alphanumeric code) was described. During this design study, the collaboration tool did not yet feature the automatic creation of N^2-Diagrams.

8.1.3 Design Outcome

The teams for both missions, the EO satellite (BeeSat) and the Communications satellite (Dumbo), concluded the concurrent conceptual design studies. As part of the study outcome they produced mass and power budgets, as well as CAD drawings of the preliminary configuration of the satellites (see Figure 8-2 and Figure 8-3).

Both projects were presented and passed an examination similar to a preliminary design review. Finally, the student teams produced a comprehensive report with all the results of the concurrent design studies, including trade-off analyses for design options at subsystem level.

---

[1] Credits to the student teams

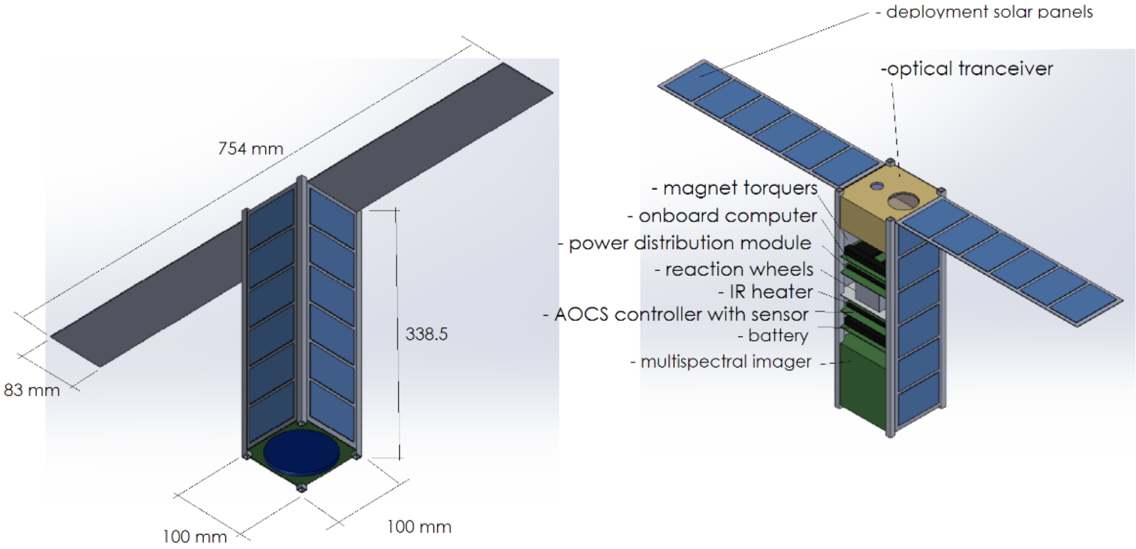


Figure 8-2: CAD model of BeeSat[1]

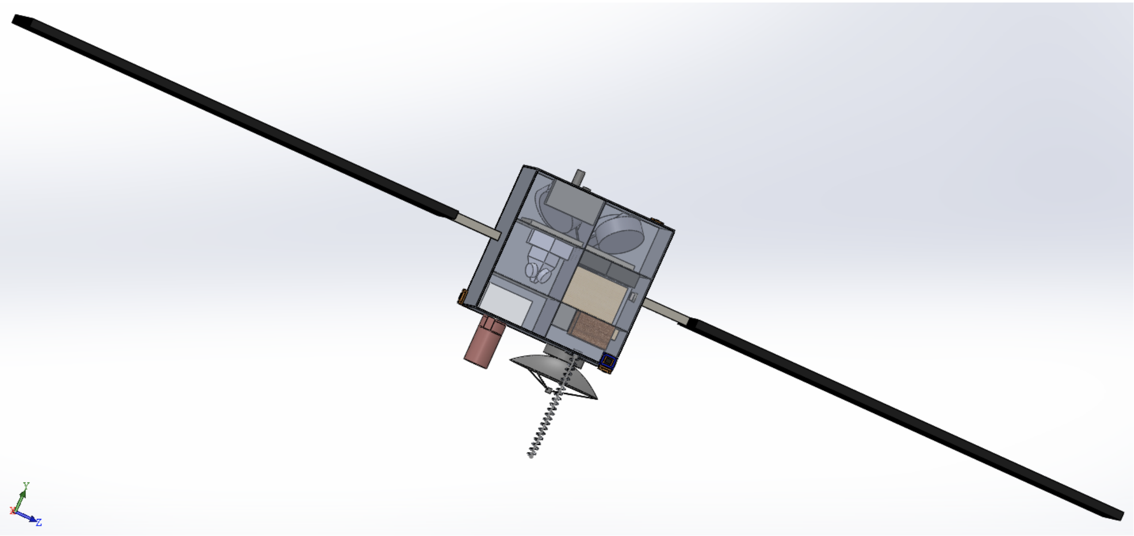


Figure 8-3: CAD model of Dumbo[1]

8.1.4 Observations

- Almost no student had prior knowledge on subsystem disciplines. As a consequence, it took them a significant amount of time to build parametric models for their subsystems.

- The role of moderator and System Engineers coincided in the same person.

- Students had a very hard time to establish the parametric dependencies between the sizing models of individual subsystems.

- The students found it more practical to manually elaborate a N^2-Diagram (see Figure 8-1). Only later they built the parametric model and the links in CEDESK.

- It is important to distinguish between subsystem requirements (derived from system requirements) and design inputs (resulting from other disciplines calculation). To keep the number of links low, they shall only be used to pass design information between subsystems.

- Many times in-person negotiation is quicker than propagating a parameter value in the tool and then refuse the change.

- Taking into account the concept of operations, the model needs to somehow reflect different operational states.

8.1.5 Summary

What we learned about the design process is that the structure of model continues evolving during design iterations. The method shall handle the situation of adding new parameters and links during design iteration. Adding new dependencies may change order of synchronization.

In support of the team, we concluded that the tool should generate a N^2-Diagram from the model on-the-fly. This visualization can also show the changes to be propagated, and by that indicate the disciplines that need to be updated.

8.2 Study 3 – DemoSAT

This case study was conducted as an academic exercise with a team of volunteers. The sole purpose of it was to test the process guideline, in particular the coordination of the work during the design iteration. Given the limited availability of the volunteers, the duration was reduced to the bare minimum. To keep the difficulty of the concept study low, we chose a textbook-like satellite mission.

The main characteristics of our design experiment are documented in Table 8.3.

Dimension	**Experiment (Case Study 3)**
Aim, research questions, hypotheses	Test the parametric design support by the data exchange tool.
Nature of Study	Interventional
Theoretical basis	Concurrent Engineering approach: Conceptual Design using Parametric Models
Unit(s) of analysis	parametric design: process and result
Data-collection method	recording model changes
Role of researcher	Team-Lead, Observer
Time constraint	Test project
Continuation	Continuous data collection.
Duration	1 weeks, 3 sessions a 3h
Observed process	Starting point: pre-built system model, system requirements, discipline assignment. Deliverable: improved conceptual design
Setting	Skoltech CEDL
Task	After an example from the textbook
Number of cases	1
Case size	7 people
Participants	Postdocs, PhD and Master students of various background.
Object	The project consists in consolidating a parametric design to a feasible and close to optimal solution.
Coding and analysis method(s)	From the logged design decisions (modifications to parameters) reconstruct the dynamics of the design process.

Table 8.3: Design of Case Study 3

8.2.1 Mission and Team

The mission chosen for this study was similar to the well-known FireSat example from SMAD textbook Wertz et al. [2011]. A different goal was set for the observation. Instead of detecting fire in the infrared spectrum, the satellite should make observations in the range of visible light. The observations desirably should cover the territory of the Eurasian continent.

The team was formed of postdocs, doctoral and master students, where most of them had prior experience in conceptual design of space systems. The system's architecture was already defined, and the model broken down in the following subsystems: Mission, Optical Payload, Orbit, Structure, Power, Thermal, AOCS, Communications. The disciplines were assigned such that each volunteer took care of one or two subsystems he/she was most familiar with.

8.2.2 Design Process

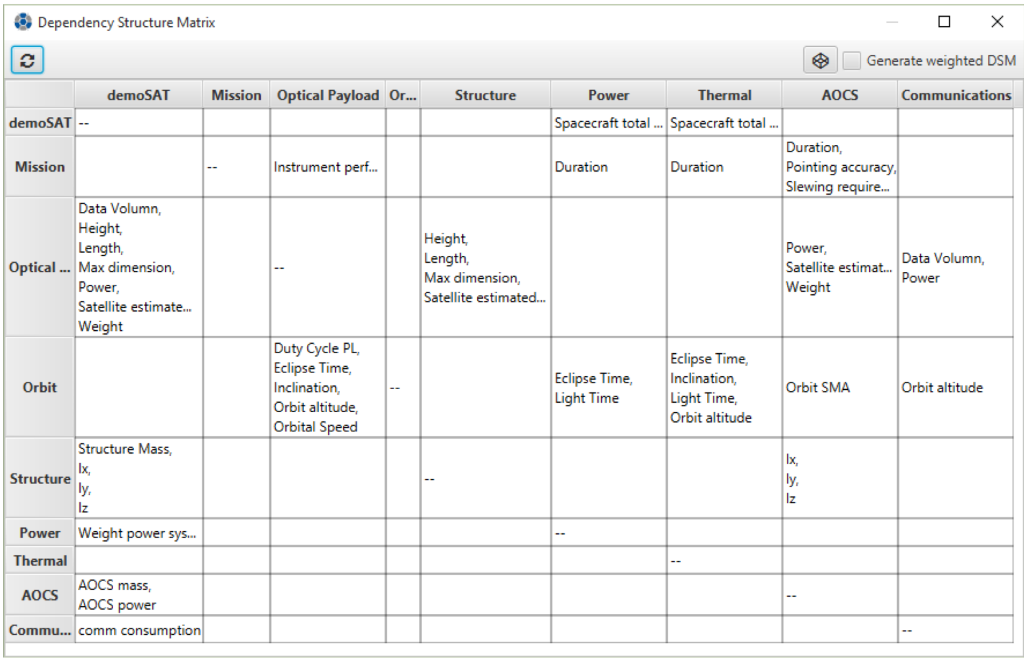
The scope of this case study was focused on the process and tool. The condensed experiment consisted in 3 concurrent design sessions, lasting 3 hours each. To reduce the experiment to the core activities, the design started from a previously built system model. The design sessions started with translating the mission requirements, where applicable, into subsystem requirements and values for the subsystem sizing models.

Design Iteration The goal of a design iteration is to make sure the inputs and outputs of the difference subsystem models are consistent. While members eventually could make changes in parallel, due to the dependencies uncoordinated changes are likely not to lead to consistency. According to our method, the discipline dependencies should be used to determine a sequence for the synchronization. The parameter links in the integrated system model are used to make dependency structure matrix, on which a clustering/sequencing algorithm is applied. During the teamwork session, the members one after the other explain their design considerations, discuss changes, and apply them to the model. Following the proposed sequence should minimize the need for repeated changes to the same subsystem, and hence reduce the amount of design steps.

8.2.3 Dependency Modeling

As described above, our method uses the parameter linkage information in the integrates system model to form a design structure matrix. The entries in the matrix can either be binary, 1 if a link exist and 0 otherwise, or weights of real values. The number of linked parameters can be considered as a proxy for the strength of the dependency between two subsystems.

The tool generated the DSM based on the parameter links, as shown in Figure 8-4. The rows and columns are named after the subsystems. A cell in row A and column B contains the parameters flowing from subsystem A to subsystem B.



	demoSAT	Mission	Optical Payload	Or...	Structure	Power	Thermal	AOCS	Communications
demoSAT	--					Spacecraft total ...	Spacecraft total ...		
Mission		--	Instrument perf...			Duration	Duration	Duration, Pointing accuracy, Slewing require...	
Optical ...	Data Volumn, Height, Length, Max dimension, Power, Satellite estimate... Weight		--		Height, Length, Max dimension, Satellite estimated...			Power, Satellite estimat... Weight	Data Volumn, Power
Orbit			Duty Cycle PL, Eclipse Time, Inclination, Orbit altitude, Orbital Speed	--		Eclipse Time, Light Time	Eclipse Time, Inclination, Light Time, Orbit altitude	Orbit SMA	Orbit altitude
Structure	Structure Mass, Ix, Iy, Iz				--			Ix, Iy, Iz	
Power	Weight power sys...					--			
Thermal							--		
AOCS	AOCS mass, AOCS power							--	
Commu...	comm consumption								--

Figure 8-4: DSM for DemoSat generated by CEDESK

For the visualization and the clustering algorithm, we used existing MATLAB® code made by Thebeau [2001], see appendix section D.3. Figure 8-5 shows the weighted DSMs, where the size and color of the dot represents the weight. At the top, it shows original one, and at the bottom, after running the clustering algorithm.

The visual representation, as well as the derived sequence, were used to guide the concurrent design process.

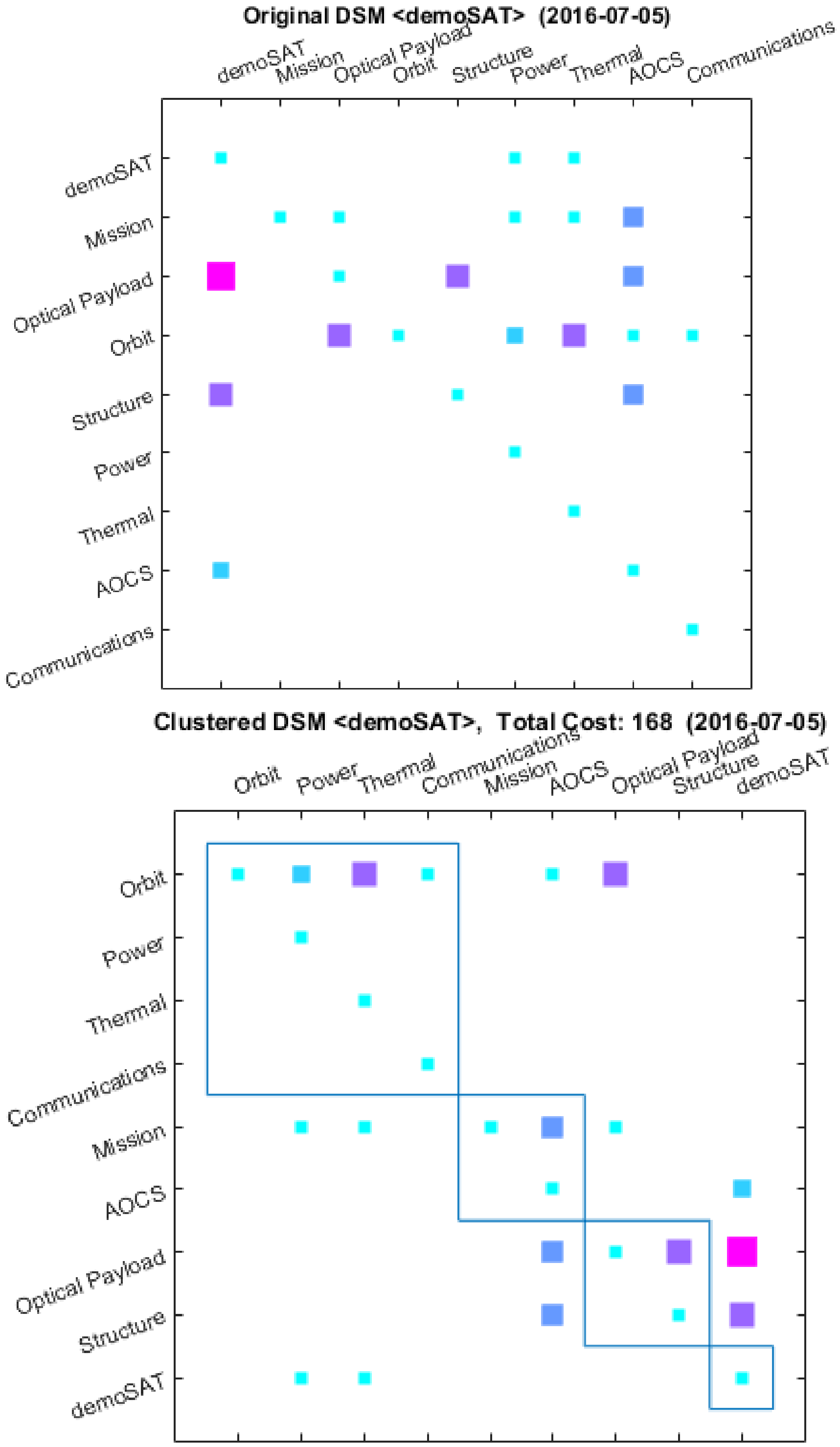


Figure 8-5: Original and clustered DSM for DemoSat

8.2.4 Observations

- The team started from a pre-configured integrated system model. As a consequence the time to build parametric models was saved.
- All volunteers had some knowledge on subsystem disciplines, but they needed to get acquainted with the provided models for sizing the subsystems.
- The author needed to cover the roles of moderator, system engineer, tool maintainer and observer. This is too much workload for a single person!
- Because of limitations of the tool, parallel work was inhibited, and updates to the model could be made only in a strict sequential order.

8.2.5 Summary

The case study was short in duration and focused on the process and tool. The participant were volunteers with knowledge in space and systems engineering. The team was equipped with a model of a system built previously after a textbook example. The design task was not a real mission, but an academic exercise. While the team was held to design to the best of their knowledge, the actual outcome was of minor relevance for the case study.

During the design sessions the visualization of the dependencies gave useful guidance to decide which discipline to consider next. Shortcomings of the tool revealed the importance of the possibility for discipline experts to concurrently modify the system model.

8.3 Study 4 – LaserNaut

This case study followed a need for a conceptual design study for a potential Cubesat mission. There were two colleagues working on payloads and the goal was to investigate the feasibility of integrating them on a single platform.

The goal of this case study was to test our method and the collaboration tool in a real conceptual design project. Table 8.2 documents the characteristics of the study design.

Dimension	**Experiment (Case Study 4)**
Aim, research questions, hypotheses	Test the parametric design support by the data exchange tool.
Nature of Study	Interventional
Theoretical basis	Concurrent Engineering approach: Conceptual Design using Parametric Models
Unit(s) of analysis	parametric design: process and result
Data-collection method	recording model changes
Role of researcher	Team-Lead, Observer
Time constraint	Test project
Continuation	Continuous data collection.
Duration	2 weeks, 8 sessions a 3h
Observed process	Starting point: pre-built system model, system requirements, discipline assignment. Deliverable: improved conceptual design
Setting	Skoltech CEDL
Task	After an example from the textbook
Number of cases	1
Case size	7 people
Participants	Postdocs, PhD and Master students of various background.
Object	The project consists in consolidating a parametric design to a feasible and close to optimal solution.
Coding and analysis method(s)	From the logged design decisions (modifications to parameters) reconstruct the dynamics of the design process.

Table 8.4: Design of Case Study 4

8.3.1 Mission and Team

The mission for this conceptual design study was to demonstrate the technology of two independent payloads onboard a single nano satellite.

Optical communication terminal This terminal should allow to establish laser-based inter-satellite communication for nano-satellites. Optical communication would allow to greatly increase data delivery of earth observation satellites through a network of relay satellites and enable resource sharing like a federated satellite system [Golkar and Lluch I Cruz, 2015]. Previous tests of this technology on ground and high-altitude balloons showed promising results [Briatore et al., 2017]. The design of this terminal for nano-satellites was a research project of a few colleagues.

Incubator for biomedical experiments This instrument should allow multi-disciplinary biomedical research in space by using a novel multi-organ-on-a-chip platform. Such a platform would enable complex drug testing in microgravity. The design of this miniaturized incubator to fit on a satellite was a colleagues master's thesis in collaboration with Harvard Medical School [Moreno et al., 2018].

None of the two payloads was ever implemented on nano-satellites. Provided a potential launch opportunity, the form factor of the platform has to be 3 unit Cubesat.

The team was formed of postdocs, doctoral and master students, where most of them had prior experience in conceptual design of space systems. The system's architecture was already defined, and the model broken down in the following subsystems: Mission, Optical Payload, Orbit, Structure, Power, Thermal, AOCS, Communications. The disciplines were assigned such that all volunteers took care of one or two subsystems they were most familiar with.

8.3.2 Design Process

The primary goal of this case study was to observe the design process, towards a meaningful system concept meeting the mission goals. The team started from a skeleton of an integrated system model, with most subsystem models inherited from the DemoSat study. No further preparation of the concurrent design study besides gathering the team were made.

To complete the design study, two subsequent activities were planned.

Refine System Model At the beginning the mission requirements need to be translated into system requirements and encoded into parameters for the subsystem models. Given the specificity of this mission, this will produce significant changes to the existing system model.

The process guideline calls this activity "Build Integrated System Model", with the variation of starting from a template model.

Design Iteration The design iteration shall bring the integrated system model to a consistent state. This requires that all subsystems are sized/designed using the inputs from requirements or provided by others. In particular the overall system budgets have to conform with the constraints of power, mass and possible launchers given by the mission.

This activity exactly reflects the step "Design Iteration" from the process guideline.

8.3.3 Dependency Modeling

The parameter links between subsystem models form dependencies which can be represented in a weighted Design Structure Matrix. The weights of the matrix corresponds to the number of linking parameters. The collaboration tool exported that information such that it could be processed with a matlab script for anlysis and visualization (see section D.3). We can apply algorithms to DSM to group more strongly linked subsystems (clustering) and this way reduce the size of feedback loops (see section 2.3). Figure 8-6 shows the DSMs before and after clustering. The size of the dots in the matrix and their color represent the dependency weight. Important to note is that the subsystem "LaserNaut" collects information from many other subsystems to form the system budgets. Therefore, it is by default assigned the last position.

For the coordination of the team member's work we effectively used the visual representation of the dependencies and the computed sequence.

8.3.4 Design Result

The choice of this mission to rely on the industry standard of 3 unit Cubesat, allowed to consider during the design the use of already existing, Commercial and Off-The-Shelf (COTS) components. This way the design is more detailed than a usual concept study. The team chose a flight proven satellite platform with known characteristics in terms of provided power and available space for payload.

The main design work went into the optical communications terminal and the cell incubator. Their respective design underwent several changes, particularly due to the negotiation about the distribution of the available volume for each payload.

In the end both payloads came up with feasible technical designs. The configuration of the satellite and the payload is shown as renderings in Figure 8-7[2] and Figure 8-7[3].

A challenge raised during the concurrent design sessions for the biological payload is related to the launch schedule. Usually small satellites are integrated on the launcher weeks before the launch. Because of the limited lifetime of living cells, the instrument needs to be loaded with living cells shortly before the launch. Being the satellite a secondary payload of a bigger launch, the possibility to adapt the schedule for our instrument seemed low.

8.3.5 Summary

This design study was not only an academic exercise, but driven by two of the participant's need to verify their concepts for payloads in the context of a Cubesat mission. A few of the the participants were new to the concurrent design approach. Provided with an introduction to our methodology, and the author acting as a study coordinator the team managed to follow the proposed design process. The

---

[2] Credits to the Simone Briatore

[3] Credits to the Carolina Moreno

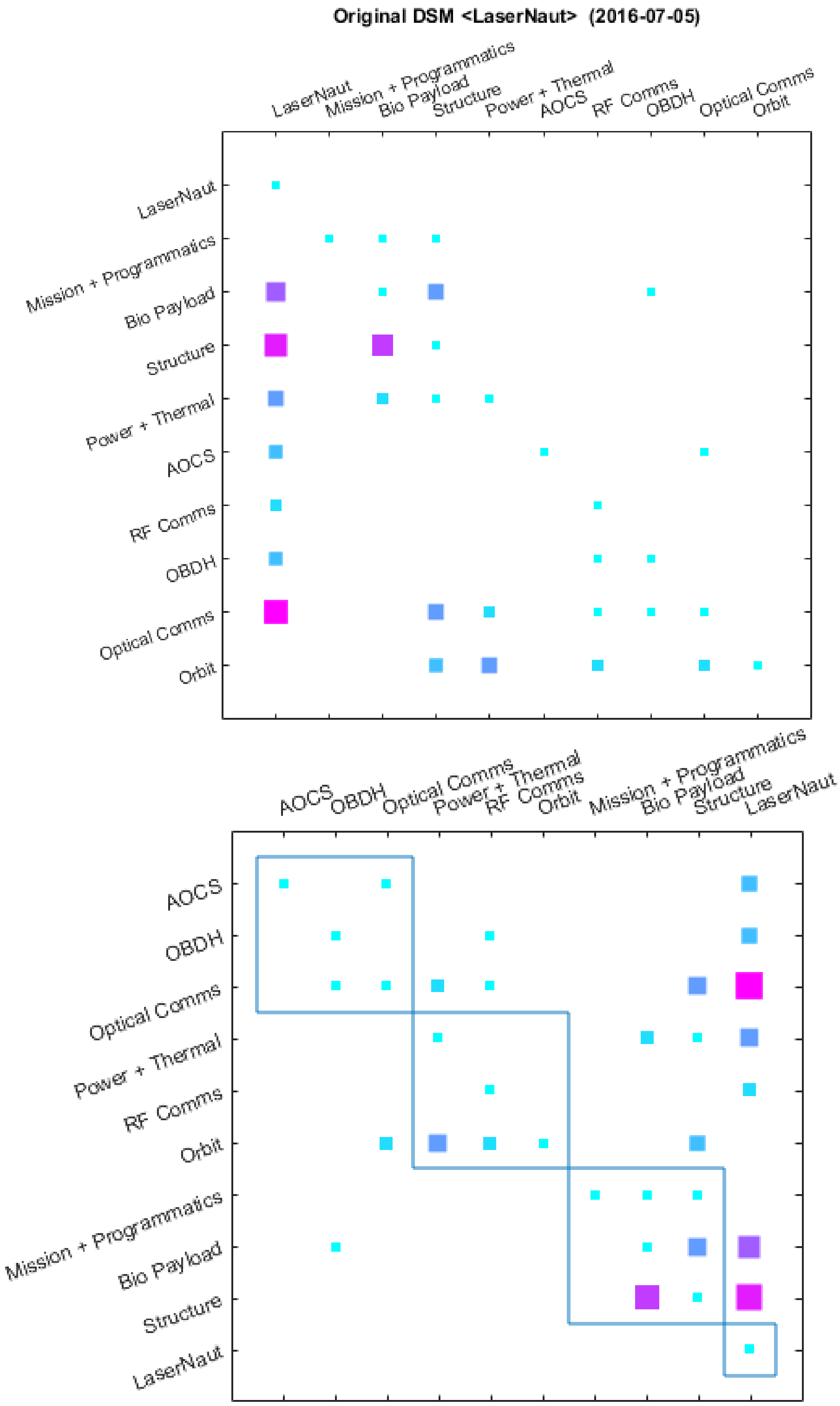


Figure 8-6: Original and clustered DSM for LaserNaut

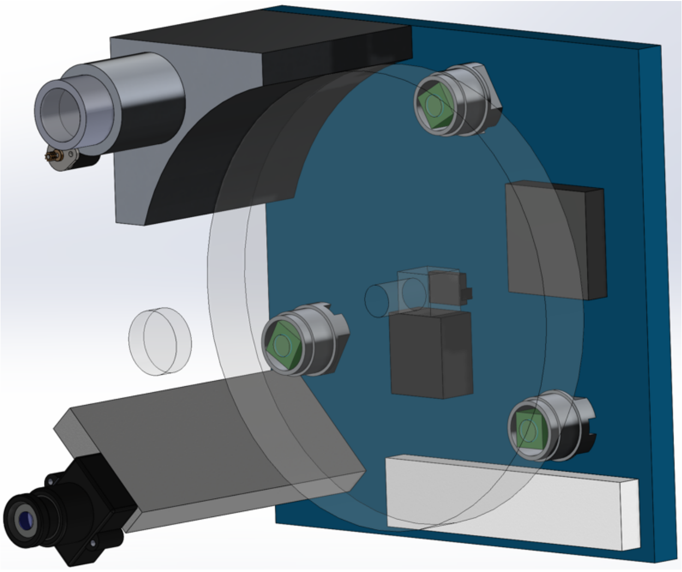


Figure 8-7: Configuration of the optical payload[2]

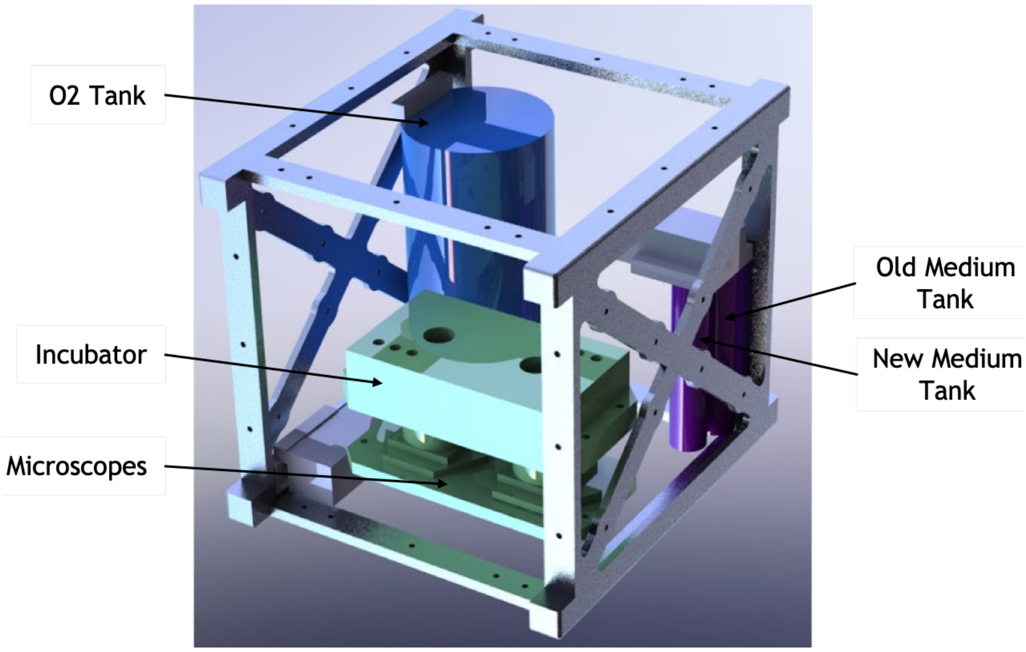


Figure 8-8: Configuration of the biological payload[3]

collaboration tool at the moment of this case study did not allow for parallel work. Hence, while one discipline made changes to the model, the rest of the team needed to wait. This imposed a strictly sequential process, but the sequence followed the design dependencies.

Conclusions from Pilot Studies

The pilot studies were performed to help refining the design methodology and test the tool in realistic use by design teams. The learning gained from these experiments suggested to enrich the design process model to cover also the modification of interfaces between disciplines. During the design studies the tool demonstrated to provide the basic functionality for a team to build an integrated system model. Besides that, the teams revealed shortcomings of the tool when they wanted to modify to the system model in parallel. To facilitate team coordination, concurrent modifications should be reconciled automatically. Moreover, it became evident that the tool can use the dependency information encoded in the system model to provide support in coordinating the teamwork.

Case Studies

8.4 Study 5 – GLISS

This case study was conducted based on the course projects with "Spacecraft and Mission Design" in November and December 2016. Differently from other case studies, the mission was set by an external partner, who wanted to compare the concept developed internally with the concept that the student team would come up with.

The goal of this case study was to test our method and the collaboration tool in a real conceptual design project. Table 8.5 documents the characteristics of the study design.

Dimension	**Experiment (Case Study 5)**
Aim, research questions, hypotheses	Test the parametric design support by the data exchange tool.
Nature of Study	Interventional
Theoretical basis	Concurrent Engineering approach: Conceptual Design using Parametric Models
Unit(s) of analysis	parametric design: process and result
Data-collection method	recording model changes
Role of researcher	Team-Lead, Observer
Time constraint	Limited to course project
Continuation	Continuous data collection.
Duration	6 weeks, 6 sessions a 3h
Observed process	Starting point: system requirements, discipline assignment. Deliverable: conceptual design
Setting	Skoltech CEDL
Task	Realistic, commissioned by outside customer
Number of cases	1
Case size	12 people
Participants	Master students of various background.
Object	The project consists in consolidating a parametric design to a feasible and close to optimal solution.
Coding and analysis method(s)	From the logged design decisions (modifications to parameters) reconstruct the dynamics of the design process.

Table 8.5: Design of Case Study 5

8.4.1 Mission and Team

The mission for this conceptual design study was set in agreement with an external partner, who acted as a customer for a team of students.

The goal is to design a constellation of communication satellites capable of providing for broadband internet connectivity. The customer requires the system to operate in radio frequencies of the Ka- and Ku-band. This service should effectively address the digital divide in Russia between cities and rural areas. The potential customers of this service need fixed and mobile broadband connectivity in remote areas of Russia. The provided service should also cover machine-to-machine communication. To become a commercially viable service, cost effectiveness of the space segment, as well as affordability of the end user terminals should be considered.

The course' 12 students organized themselves as one team and grouped by the following disciplines: Orbit + Constellation, Structure, Power + Thermal, ADCS + Propulsion, Communications, OBDH, Ground Segment.

8.4.2 Study Process

The available session time of 3 hours per session was split in concurrent team work and independent off-line work. The design study anticipated the process guideline from our approach (see section 5.5.2). Since the students have no prior knowledge on the design process, the actual design sessions were preceded by introductory sessions. The single sessions were planned was as follows:

Introduction to CD An introductory lecture about the methodology of concurrent conceptual design. Explanation of parametric modeling for conceptual design and hands-on training on CEDESK collaborative design tool.

Concurrent Design Sessions 1-5 At first all disciplines shall define their respective subsystem interfaces. Basically each discipline needs to understand the outputs it shall provide, and which inputs it needs therefore. The process guideline calls this step "Define Subsystem Interfaces".

Then connections between the individual models of disciplines are established. In case of mismatches or unmet needs of some disciplines the team finds how the information can be provided. The process guideline describes this activity as "Connecting Subsystem Models".

These core design sessions aim to iteratively consolidate the integrated system model, such that the parameter values are propagated consistently between all subsystem models. This activity follows the description of "Design Iteration" in the process guideline.

The final session is meant for concluding the conceptual design and make the team ready for the project presentation. This corresponds to the step "Compile Study Results" in the process guideline.

Offline work Between concurrent design sessions the team members work individually on the parametric models of their respective subsystem. This corresponds to the step "Build Subsystem Models" in the process guideline.

Activity Analysis

The concurrent design was embedded in the course and provided with a predefined time frame of 6 sessions over 6 weeks. Also, beside the concurrent sessions, students worked individually.

The collaborative tool recorded all design activities and allow for posterior analysis. Changes made to the parameters, can be either creation, update and deletion. The cause of an update, can be either a users' manual change, a change propagated from a linked parameter, a calculation or import from a spreadsheet. The evolution of these changes over time is shown in Figure 8-9. We can read from the chart, that many changes to the model were made "offline", meaning outside the concurrent sessions.

From the chart we can see how the types of changes to the model evolve over time. This means that the team initially focused on building the model, predominantly creating parameters. In later sessions the focus changes to using the model to perform design iterations, by manly updating the parameters, either from links to

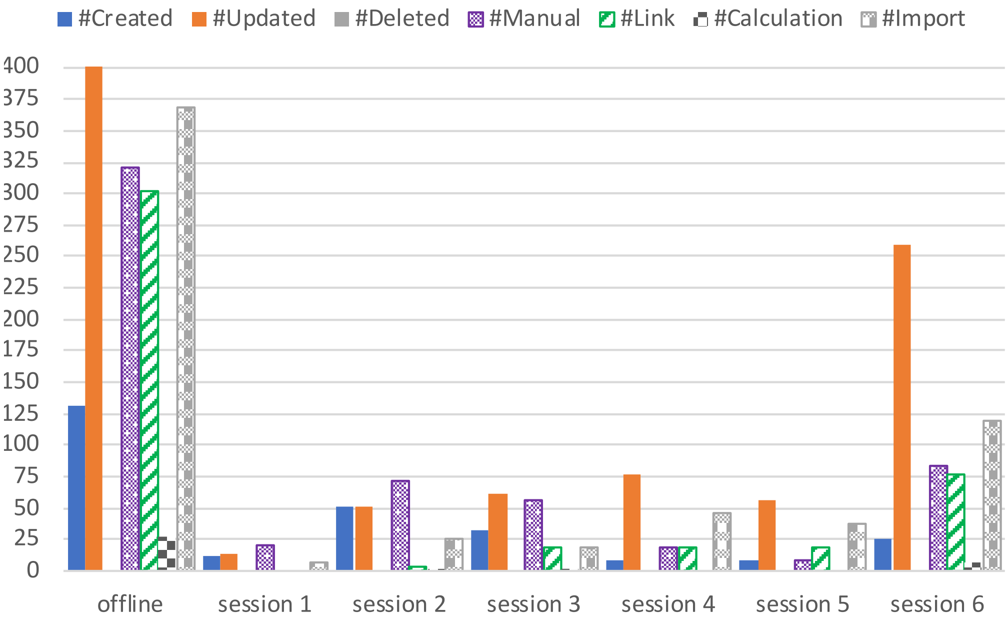


Figure 8-9: History of parameter changes for GLISS

other parameters, or from spreadsheets.

This analysis shows that the actually performed design activities relate to the activities of the intended design process.

8.4.3 Dependency Modeling

The parameter links determine the information flow during the design process. Visualizing them gives the team understanding of the dependencies. The N^2-diagram generated by CEDESK (Figure 8-10) has the evident flaw of being hard to read. This is firstly due to the poor automatic diagram layout produced by the tool, and secondly because of the big number of dependencies introduced related to parameters for geometric dimensions. This indicates a system model, which atypically included too much geometric information.

Like in the previous case study, we use the DSM to represent the dependencies and perform analysis on it. The weight of the dependency is expressed by the number of links. CEDESK generated the DSM in the form of a chart, and also ran a clustering algorithm on it. These matrices in Figure 8-11 follow the IR/FAD notation, meaning the inputs of an element are indicated in the same row and feedback loops appear above the diagonal. The numbers correspond to the weights,

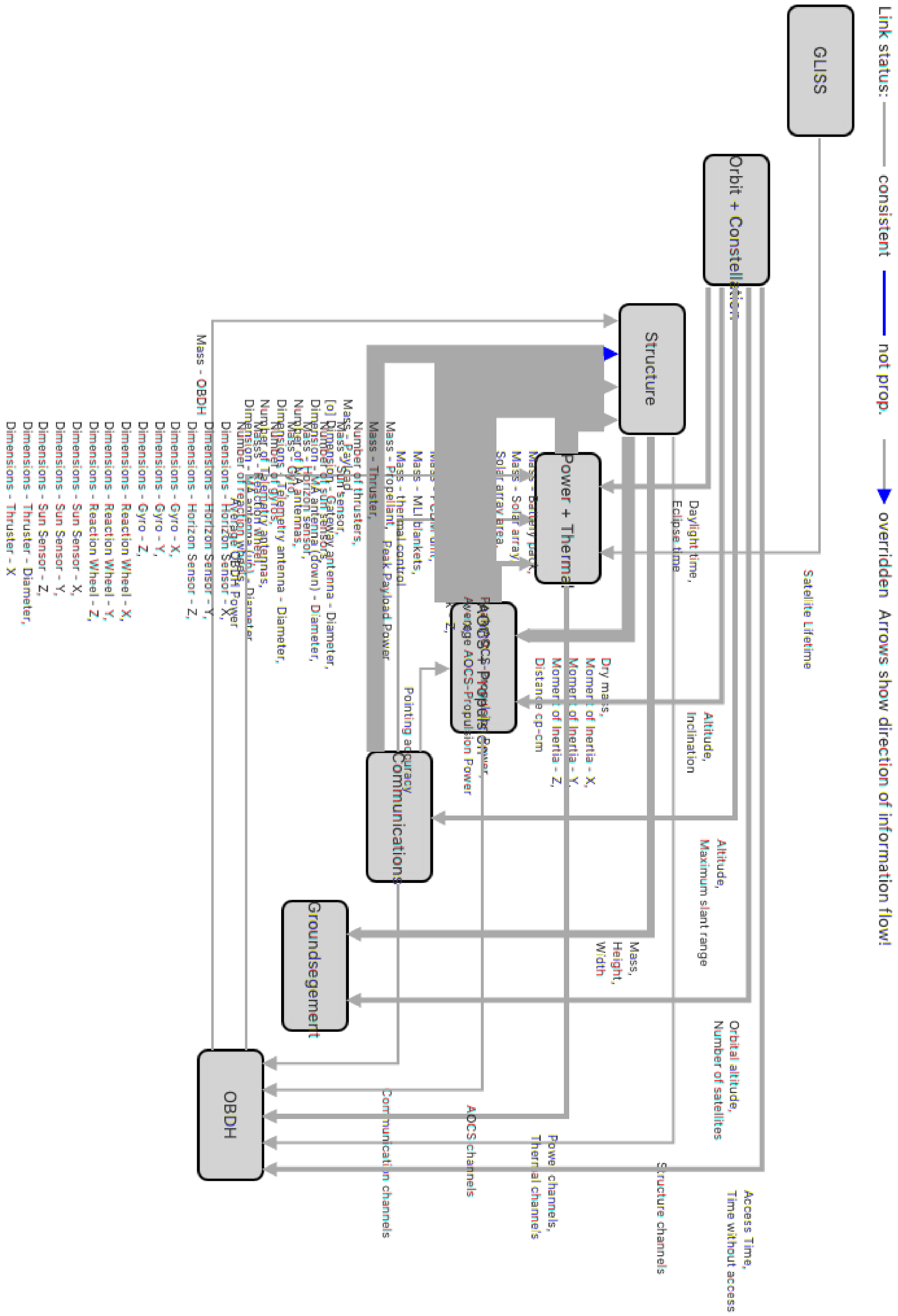
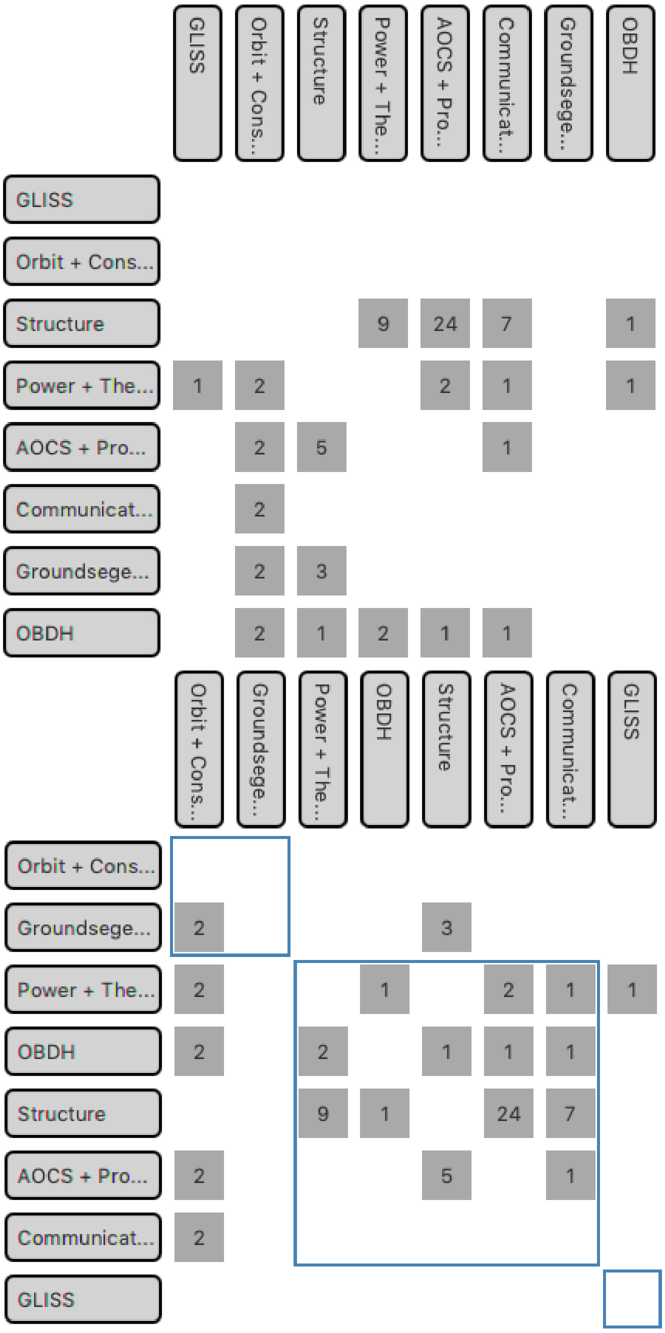


Figure 8-10: Automatic N²-Diagram for GLISS



	GLISS	Orbit + Cons...	Structure	Power + The...	AOCS + Pro...	Communicat...	Groundsege...	OBDH
GLISS								
Orbit + Cons...								
Structure				9	24	7		1
Power + The...	1	2			2	1		1
AOCS + Pro...		2	5			1		
Communicat...		2						
Groundsege...		2	3					
OBDH		2	1	2	1	1		

	Orbit + Cons...	Groundsege...	Power + The...	OBDH	Structure	AOCS + Pro...	Communicat...	GLISS
Orbit + Cons...								
Groundsege...	2				3			
Power + The...	2			1		2	1	1
OBDH	2		2		1	1	1	
Structure			9	1		24	7	
AOCS + Pro...	2				5		1	
Communicat...	2							
GLISS								

Figure 8-11: Original and clustered DSM for GLISS

eg. structure receives 9 inputs from Power + Thermal, 24 from AOCS, 7 from Communications, etc. The original DSM shows the subsystems in the order as it was defined by the team. The clustered DSM, reflects the same dependencies, but the order was changed for more strongly dependent subsystems to stay closer.

In a further analysis, we extracted from the audit log of parameter changes, the number of changes to linked parameters. The number of changes per subsystem dependencies represented in a DSM is shown in Table 8.6. By pairwise comparison of the number of links and the changes we see that there is a significant correlation of 0.92. There are a few links which were created and never modified, but on average a parameter is modified 4.48 (standard deviation 4.28). This indicates that the links served for design iterations.

	AOCS + Propulsion	Communications	GLISS	Ground Segment	OBDH	Orbit + Constellation	Power + Thermal	Structure
AOCS + Propulsion					1		6	140
Communications	4				1		9	63
GLISS							1	
Ground Segment								
OBDH							2	3
Orbit + Constellation	4	11		2	2		32	
Power + Thermal					2			114
Structure	30			14	1			

Table 8.6: DSM of propagated changes from GLISS

8.4.4 Design Outcome

Through the concurrent design study the team came up with a feasible mission concept. This included an analysis of the market demand, possible implementation schedule, and concept of operations. Part of the outcome were mass and power budgets, as well as a CAD drawing of the preliminary configuration of the satellite Figure 8-12[4].

The project was presented twice in the form of design reviews to the external partner, who acted as customer. Finally, the team produced a comprehensive report

---

[4] Credits to the student teams

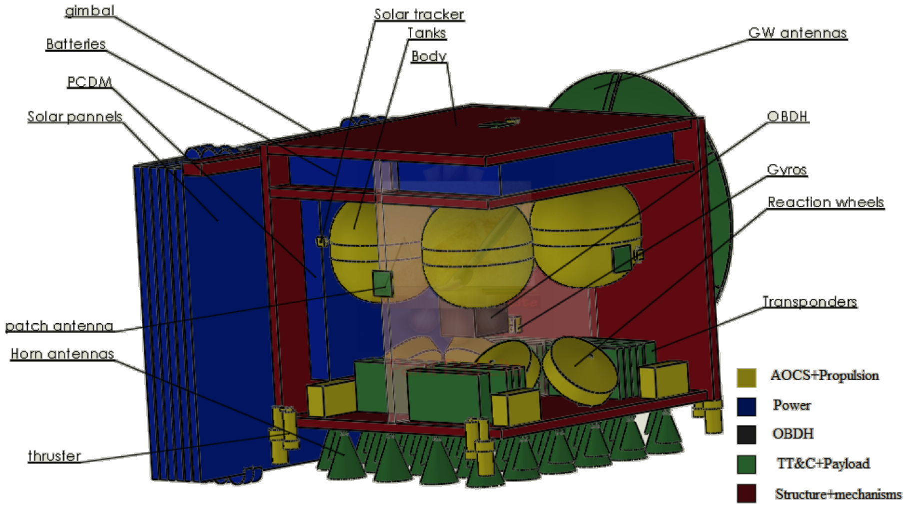


Figure 8-12: CAD model of GLISS[4].

with all the results of the concurrent design studies, including trade-off analyses for design options at subsystem level.

8.4.5 Summary

This design study had as a customer a commercial company, which added motivation for the students to produce a meaningful conceptual design. None of the students had previous experience with the concurrent design approach. After an introduction provided to our methodology, the team was able to complete the conceptual design study and produce a solution concept.

Because the tool did not allow for parallel work, the disciplines needed to apply their changes to the model sequentially. A flaw of the automatically generated N^2-Diagrams is that they easily become incomprehensible, when the number of parameter links is more than 5.

The analysis of model changes allow to deduce the the actually performed design activities, which reflect the intended design process. Further analysis of the changes on linked parameters confirmed that changes are propagated from source to target and drive the sequence of disciplines.

8.5 Study 6 and 7 – RadMonConst & ComConst5G

These two case studies are the most exhaustive ones, because the method and tool were fully developed. They were performed as part of the master level course "Spacecraft and Mission Design" in February and March 2019. We describe them together because they share the same setting, and only differ in the design task and team.

The case studies were designed to test the process guideline and the supporting tools. Table 8.7 documents the characteristics of the study design.

Dimension	**Experiment (Case Studies 6 + 7)**
Aim, research questions, hypotheses	Test the applicability of the process guideline, and the process support in the tool.
Nature of Study	Interventional
Theoretical basis	Concurrent Engineering approach: Conceptual Design using Parametric Models
Unit(s) of analysis	parametric design: process and result
Data-collection method	Audio, Video, of design sessions, after questionnaire, recording model changes
Role of researcher	Observer // Study moderator
Time constraint	Limited to course project
Continuation	Continuous data collection.
Duration	2 weeks, 6 sessions a 3h
Observed process	Starting point: system requirements, discipline assignment. Deliverable: conceptual design
Setting	Skoltech CEDL
Task	Realistic
Number of cases	2
Case size	7 and 9 people
Participants	Master students of various background.
Object	The project consists in consolidating a parametric design to a feasible and close to optimal solution.
Coding and analysis method(s)	From the logged design decisions (modifications to parameters) reconstruct the sequence and causality of the changes.

Table 8.7: Design of Case Studies 6 and 7

8.5.1 Missions and Teams

The class was divided in two teams. Each team received a different mission for which they should come up with a feasible conceptual design. Both missions are meant to design a constellation of satellites.

Radiation Monitoring Constellation (RadMonConst)

The scientific mission goal is to measure the cosmic radiation in range from low to high earth orbit over an extended period of time. The obtained data is meant to be used for updating the existing models about radiation levels at different altitudes. The radiation measuring instrument will be provided by a partner institute. In order to keep the launch costs low, it is advised to choose a standard Cubesat form factor of either 6 or 12 units.

The team was composed of 9 master students, of which 2 had experience with spacecraft design and testing of equipment. The students organized themselves into 8 disciplines: Systems Engineering & Mission Design, Payload, Power, Thermal, ADCS & Propulsion, Structure, OBDH, Communication.

Communication Constellation for 5G (ComConst5G)

The mission goal is to provide broadband data connectivity for end-users via radio waves. Ideally the satellites shall provide coverage on all earth surface. To make the intended communication service commercially viable, the cost factor should be considered attentively.

The teams was composed of 7 master students, for whom it was their very first experience in designing a satellite. The students organized themselves into 7 disciplines: Systems Engineering, Mission & Propulsion, Communications, Power & Thermal, ADCS, Structure, OBDH.

8.5.2 Work Schedule

The concurrent design was embedded in the course and provided with a predefined time frame of 6 sessions. The available time of 3 hours per session was divided equally among the two teams, such that we could observe them independently. The design study was setup to follow the process guideline from our approach (see section 5.5.2). Since the students have no prior knowledge on the design process, the actual design sessions were preceded by introductory sessions. The schedule was set up as shown in Figure 5-16, and the single sessions were planned was as follows:

Introduction to CD (1 hour) General introduction into the methodology of concurrent conceptual design and the use of parametric models for estimation of mission feasibility.

Introduction to CEDESK (1 hour) Explanation of the concepts and capabilities of the CEDESK tool for exchanging data of conceptual design models. The students were given hands-on training with the software to build a simple parametric model.

Concurrent Design Session 1 (1.5 hours) The goal set for the first design session was to define subsystem interfaces, which corresponds to a step in the process guideline called "Define Subsystem Interface". Basically each discipline needs to understand the outputs it shall provide, and which inputs it needs therefore.

Concurrent Design Session 2 (1.5 hours) The second session is dedicated to establishing the connections between the individual models of disciplines. In case of mismatches or unmet needs of some disciplines, the team needs to decide how the information can be provided. The process guideline describes this activity as "Connect Subsystem Models".

Offline work Between concurrent design sessions the team members work individually on the parametric models of their respective subsystem. This corresponds to the step "Build Subsystem Models" in the process guideline.

Concurrent Design Session 3-5 (1.5 hours) These core design sessions aim to iteratively consolidate the integrated system model, such that the parameter values are propagated consistently among all subsystem models. This activity follows the description of "Design Iteration" in the process guideline.

Design Wrap-Up (1.5 hours) The final session is meant for concluding the conceptual design and make the team ready for the project presentation. This corresponds to the step "Compile Study Report" in the process guideline.

8.5.3 Team support

To assist the teams in the concurrent design sessions, we provided each of them with a moderator. The moderators understood the team's mission and were able to give hints on design decisions. But most importantly, they had previously participated in concurrent design studies and knew the process guideline from our approach. The moderator's primary role was to facilitate the discussion and negotiation of design decisions between discipline representatives.

8.5.4 Observed Design Process

Within the co-located work sessions both teams started to follow the design process according to the work schedule. Before the start, the teams had clarified their mission statement, basic requirements and a presumed system breakdown structure.

To analyze the progress in the design, we take the log of changes made to the parametric model. We distinguish between 3 types of changes: creation, update and deletion of a parameter. Besides that, a parameter can retrieve its value from 4 sources: *manual* input, *link* to another subsystem, a *calculation* based on other parameters, *import*ing from a spreadsheet.

First we analyze the data of "ComSat5G" team. Figure 8-13 shows the number of parameter changes over the different sessions. The creation of new parameters (blue bars) are higher in the first sessions, but already in the third session the number of updated parameters (orange bars) takes over. Another trend is the decreasing number of manual changes (violet bars), and the increasing number of updates caused by links (green bars). After session 3 the amount of changes is significantly

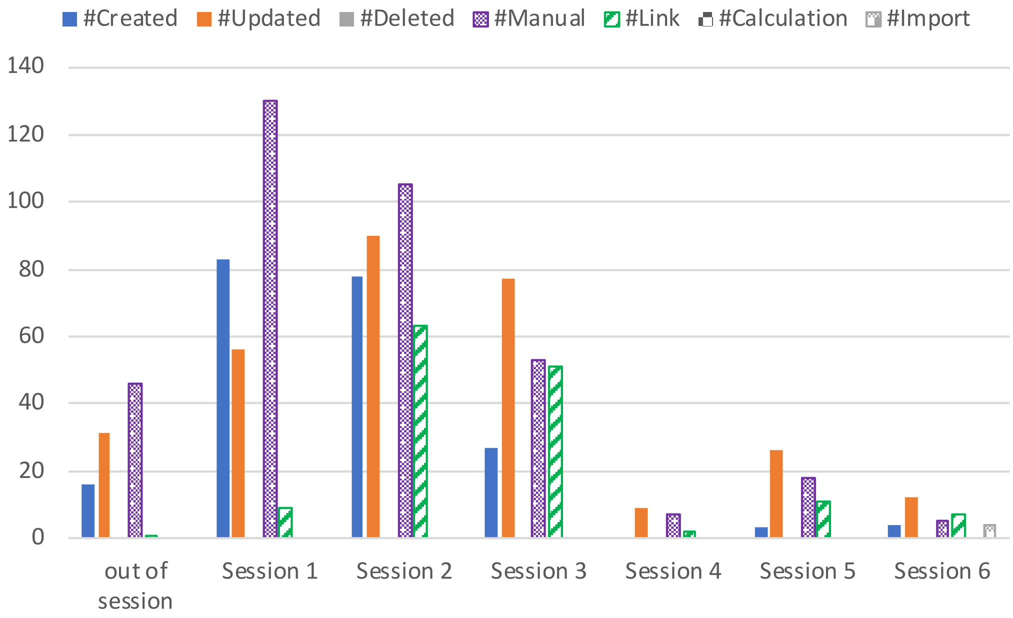


Figure 8-13: ComSat5G parameter changes

lesss. This indicates, that the team has passed from building the model to performing design iterations on few parameters.

For the "RadMonConst" team, the evolution of parameter changes are in shown in Figure 8-14. The number of parameters created and updated grows strongly until a maximum in session 3. After that, in sessions 4 to 6 the number of updates (orange)

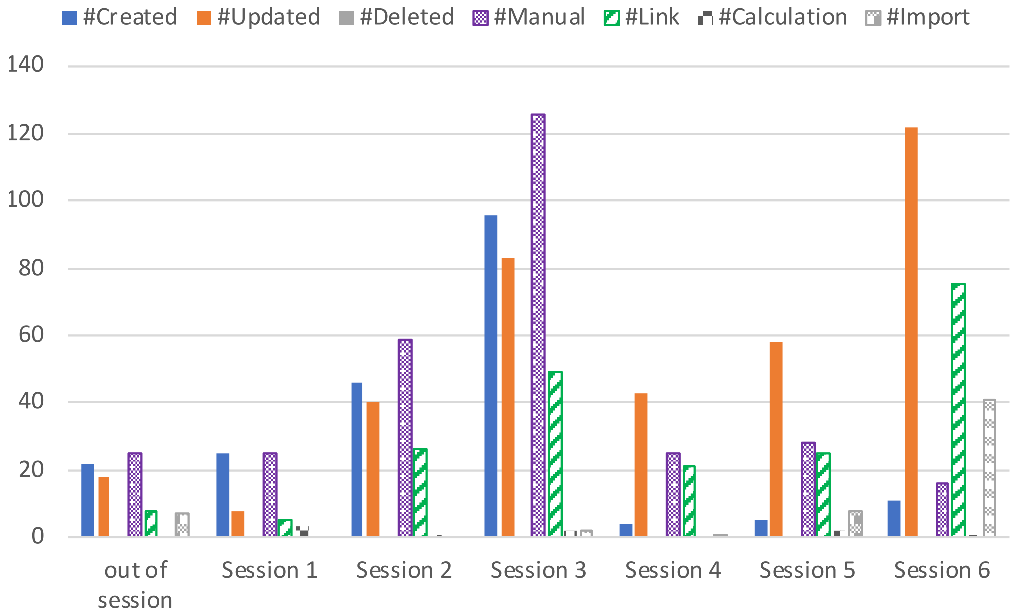


Figure 8-14: RadMonConst parameter changes

grow together with the changes caused by links (green) and imports (grey). This indicates the shift from creating the model from scratch, to modifying parameters for consolidating the system design.

Both teams change the design activities reflecting the different steps of the intended design process.

Concurrency Analysis

One goal of the concurrent conceptual design method is to maximize the work in parallel. To measure the degree of concurrency (see subsection 5.5.3) we analyze the activity logs written by the tool. We group activities which single users do between loading and storing the integrated system model, and consider this a design step. The design steps of different users overlap and form a design session. Based on the activity logs we determine the duration of the session and the overlap of all contained design steps. The ratio between total session duration and overlaps, results in the degree of concurrency.

The analysis of the activity logs gives us statistics about the concurrent design sessions (see Table 8.8). Theses sessions mostly coincided with the design sessions scheduled with the entire team. The tool's log also reveal design activities performed outside the moments of teamwork. During sessions where more than 1 user took part the data show a degree of concurrency well above 0. This confirms the teams capability to accomplish design tasks in parallel, and the tools support for effective collaborative and parallel work.

8.5.5 Interactive support

The tool used by the teams to collaborate on the integrated system model, CEDESK, provided specific support for the process. One way of supporting the team was the visualization of dependencies via automatically generated N^2-Diagrams. The diagram shows all N subsystems on the diagonal, and arrows for the dependencies formed by linked parameters. Naturally, this diagrams evolves together with the system model. During the activities "connecting the subsystem models", dependencies are added. While performing "design iteration" values propagate from output

session start	session stop	duration	overlap	ratio	#users
2/22 14:34	2/22 14:56	0:21:40	0:00:00	0.0	1
3/4 14:07	3/4 16:35	2:28:09	3:22:55	1.37	7
3/6 07:09	3/6 12:46	5:36:50	14:50:05	2.64	7
3/11 10:53	3/11 16:29	5:36:04	4:04:00	0.72	3
3/12 08:02	3/12 08:08	0:05:24	0:00:00	0.0	1
3/13 14:15	3/13 16:59	2:43:48	0:54:20	0.33	5
3/13 17:01	3/13 17:03	0:01:40	0:00:00	0.0	1
3/15 09:37	3/15 11:30	1:52:56	1:26:19	0.76	6
3/15 11:31	3/15 11:31	0:00:16	0:00:00	0.0	1
3/15 11:40	3/15 11:43	0:03:17	0:00:00	0.0	1

Table 8.8: Work sessions of ComSat5G team

parameters of one subsystem model to the input parameters of another subsystem model.

The visualization of this automatically generated diagram allowed the team to always have a clear picture of the dependencies. Figure 8-15 and Figure 8-16 contain the N^2-Diagrams of the two teams as the tool showed them at the end of the design study. Unfortunately the text in the diagrams overlap and are hard to read, due to a flaw in the automatic diagram layout. The user of CEDESK can select any eventually unreadable label and it gets highlighted.

Observing the team, this view was actively used to understand, which subsystem(s) are affected by changes done on a specific subsystem. The highlighted arrows (see Figure 8-16) also indicate the links, where changes to parameters still need to be propagated.

This aspect of the tool, the live visualization of dependencies and change propagation, demonstrated to support the team also in coordinating the design work.

Analysis of Design Steps

A second goal of the concurrent conceptual design method is to minimize the rework necessary because of uncoordinated changes. We can obtain the order in which discipline experts made changes to the integrated system model using the log of the

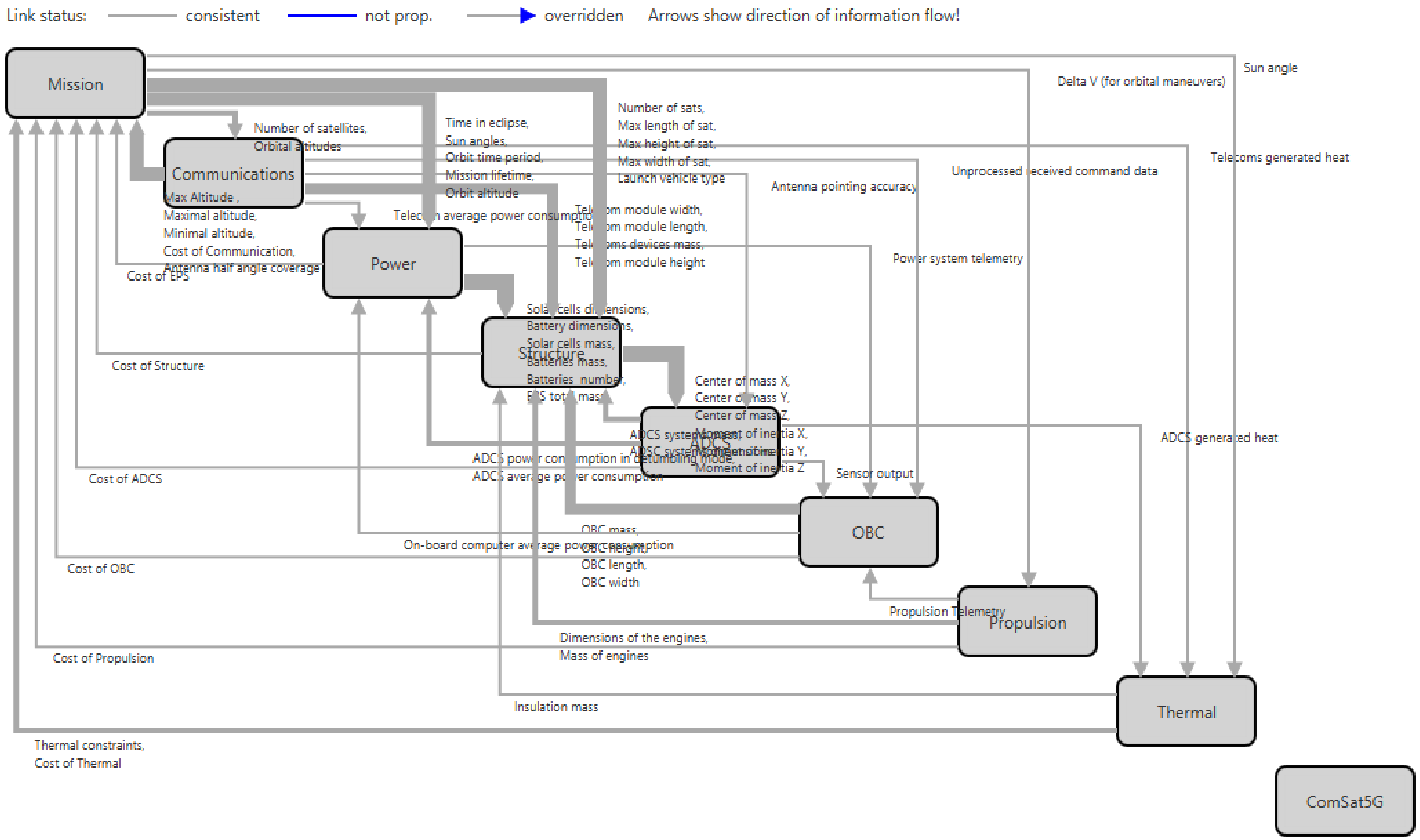


Figure 8-15: Automatic N^2-Diagram of ComSat5G

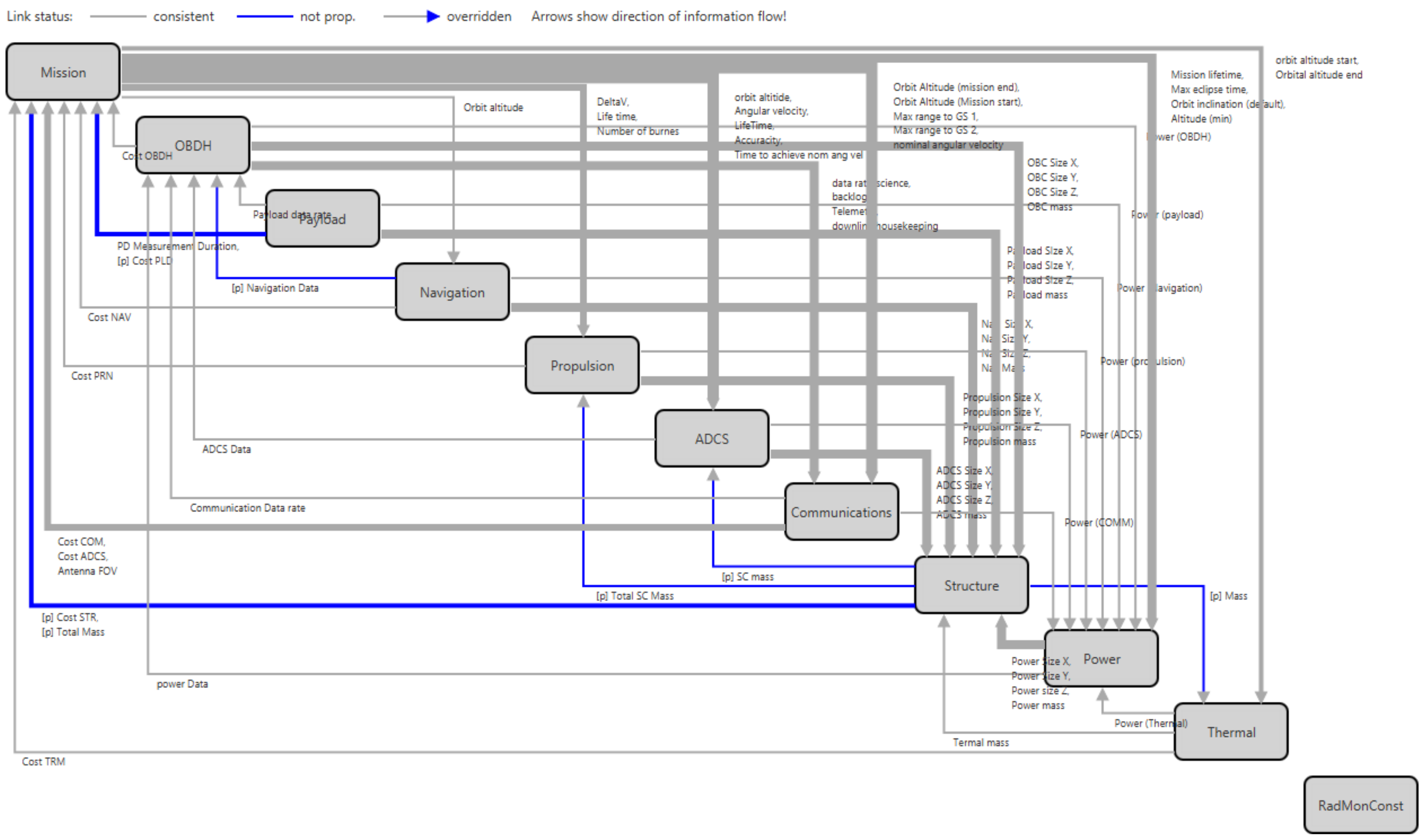


Figure 8-16: Automatic N^2-Diagram of RadMonConst

data exchange tool. A visual representation of part of the change history is shown in Figure 8-17. The horizontal axis is time, and on the vertical axis are the different subsystems. The small grey circles represent changes made to subsystem models, and the number besides it is the internal revision number. Arrows connecting circles represent influences of changes in one revision to another.

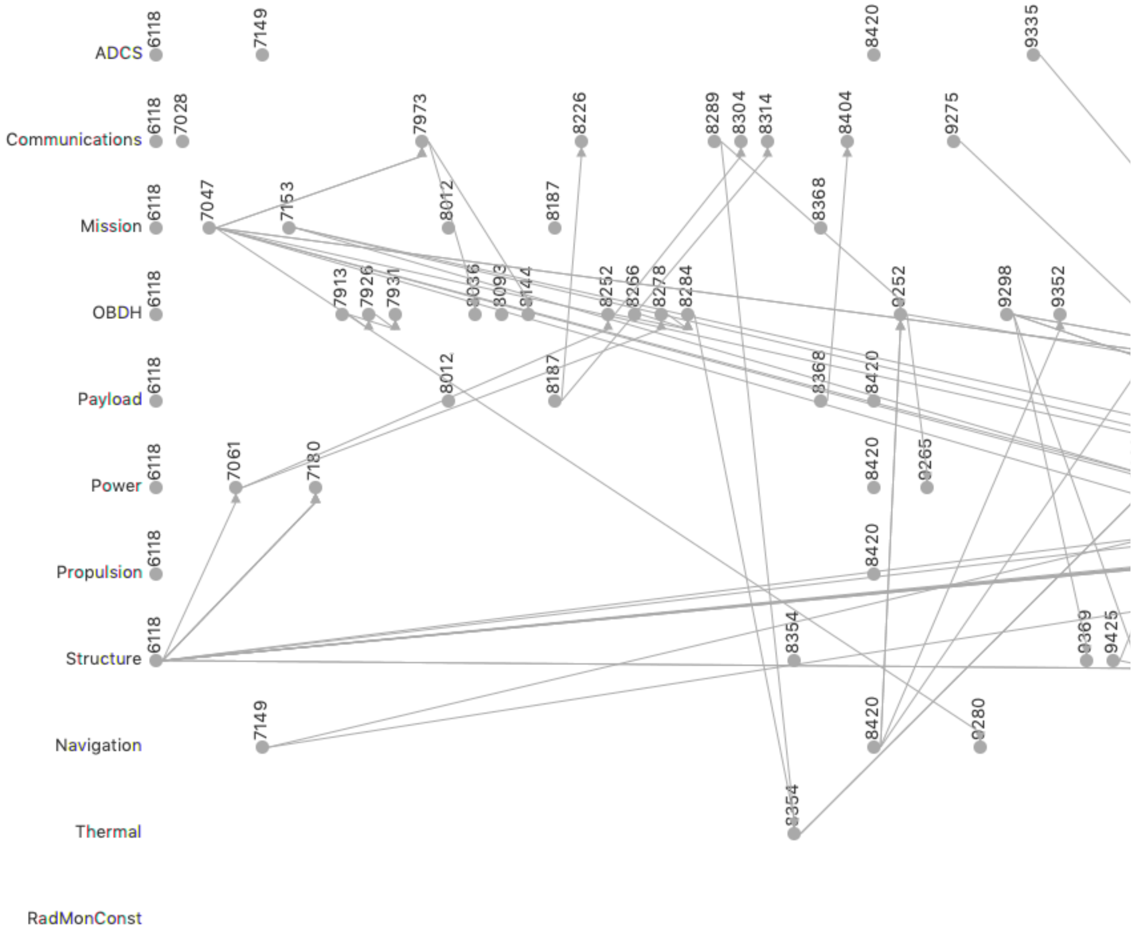


Figure 8-17: Partial sequence of model changes and their connections (RadMonConst).

Each revision (design step) contains changes to parameters of one or more subsystems. Output parameters of one subsystem are often linked by another subsystems' input parameters. Subsequent changes to such linked parameters, can be considered to have causal relationship. Changes on a parameter of one subsystem are propagated to another subsystem, following the established links. The parameter links between subsystems can be represented as a design/dependency structure matrix

(DSM). The values in the cells of a DSM (weights) can be given different meanings. We use two different types: weights based on the number of linking parameters, and weights based on the number of changes that were propagated during the design process. To see whether the propagated changes directly reflect the establishment of a link, we perform a pairwise comparison of the weights in the two matrices.

RadMonConst The two DSMs are shown in Table 8.9 and Table 8.10. The number of changes is always higher or equal than the number of links, with an average distance of 3.3 and a ratio of 3.1. The correlation between the respective weights is 0.64.

ComSat5G The two DSMs are shown in Table 8.11 and Table 8.12. The number of changes is always higher or equal than the number of links, with an average distance of 1.8 and a ratio of 1.8. The correlation between the respective weights is 0.87.

In both cases the correlation is above 0.5 and and the ratio is above 1. This means that each established link also served to propagate a value change. Hence the links served to perform design iterations. The ratio of changes per link can be taken as a proxy for the number of repetitions of the discipline update. Indeed, the fact that team "RadMonConst" has a ratio of 3.1 and team "ComConst5G" a ratio of 1.8 corresponds to the difference in their activity profile. The data of the first, showed a more continuous engagement (see subsection 8.5.4).

8.5.6 Results of conceptual design

The conceptual design produced parametric subsystem models and built and integrated system model. Using this model the teams managed to form power and mass budgets for their systems, and made simulations on the orbital dynamics. Moreover, the teams came up with preliminary configurations of the satellites in the form of CAD drawings, of which renderings are shown in Figure 8-18 and Figure 8-19 [5].

---

[5] Credits to the student teams

	ADCS	Communications	Mission	Navigation	OBDH	Payload	Power	Propulsion	Structure	Thermal
ADCS					1		1		4	
Communications			3		1		1			
Mission	5	5		1			4	3		2
Navigation			1		1		1		4	
OBDH		4	1				1		4	
Payload			2		1		1		4	
Power					1				4	
Propulsion			1				1		4	
Structure	1		2					1		1
Thermal			1				1		1	

Table 8.9: Static DSM of parameter links from RadMonConst

	ADCS	Communications	Mission	Navigation	OBDH	Payload	Power	Propulsion	Structure	Thermal
ADCS					2		5		11	
Communications			3		3		2		1	
Mission	13	6		1			12	7		3
Navigation			1		10		2		5	
OBDH		4	2				7		12	
Payload			4		4		4		10	
Power					5				9	2
Propulsion			1				9		11	
Structure	5		3					4		8
Thermal			2				3		1	

Table 8.10: DSM of propagated changes from RadMonConst

	ADCS	Communications	Mission	OBC	Power	Propulsion	Structure	Thermal
ADCS			1	1	3		2	1
Communications	1		5	1	1		4	1
Mission	2	2			8	1	5	1
OBC		1	1		1		1	
Power			1	1			6	
Propulsion			1	1			2	
Structure	6		1					
Thermal			2		1		1	

Table 8.11: Static DSM of parameter links from ComSat5G

	ADCS	Communications	Mission	OBC	Power	Propulsion	Structure	Thermal
ADCS			2	2	7		3	1
Communications	2		10	1	1		16	
Mission	2	6			14	1	8	2
OBC	6	1	2		3	1	2	
Power			3	2			8	
Propulsion			3	1			3	
Structure	10		2		1			
Thermal			4		1		2	

Table 8.12: DSM of propagated changes from ComSat5G

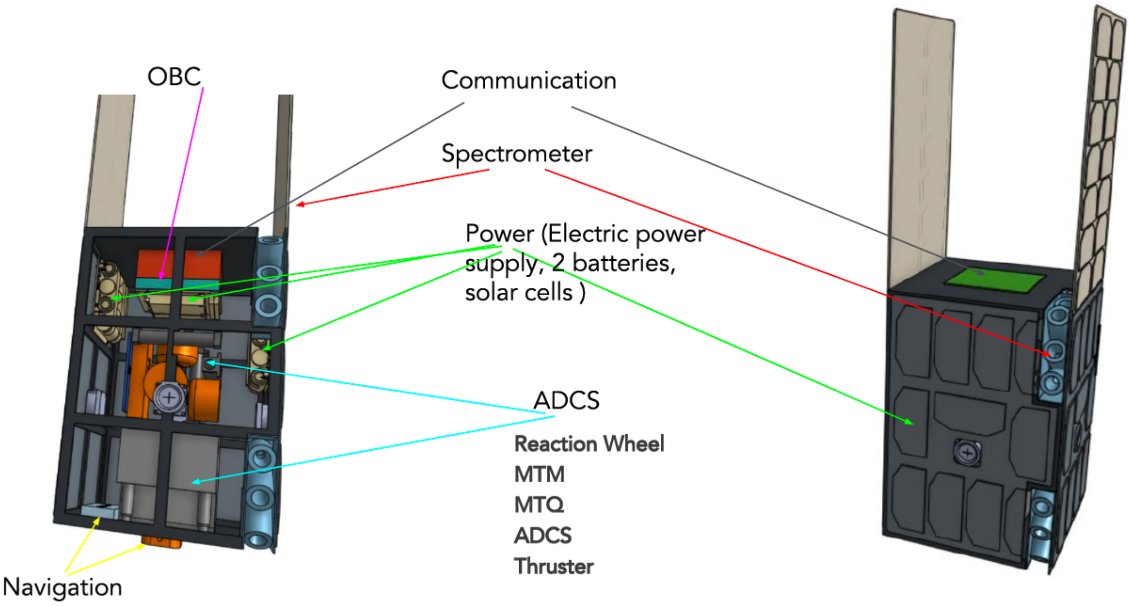


Figure 8-18: Configuration of RadMonConst satellite[5]

8.5.7 Observations

The data has shown two teams with slightly different activity profiles. The ComConst5G team had high activity at the beginning, while RadMonConst team only gradually grew active. This corresponds to our in-situ observation of different team behavior.

Achievements

- Both teams managed to elaborated conceptual designs following the proposed methodology. The projects were presented the obtained and passed an examination similar to a preliminary design review.

- The process guideline gave clear indications which steps to follow. In particular having defined the overall figure of merits, the budgets at the beginning helped to keep the later activities focused. Moreover, the procedure to build an integrated system model gave clear orientation.

- The process can cope with changes to the interfaces between subsystems. It happened repeatedly that new parameters and dependencies were introduced during the design process.

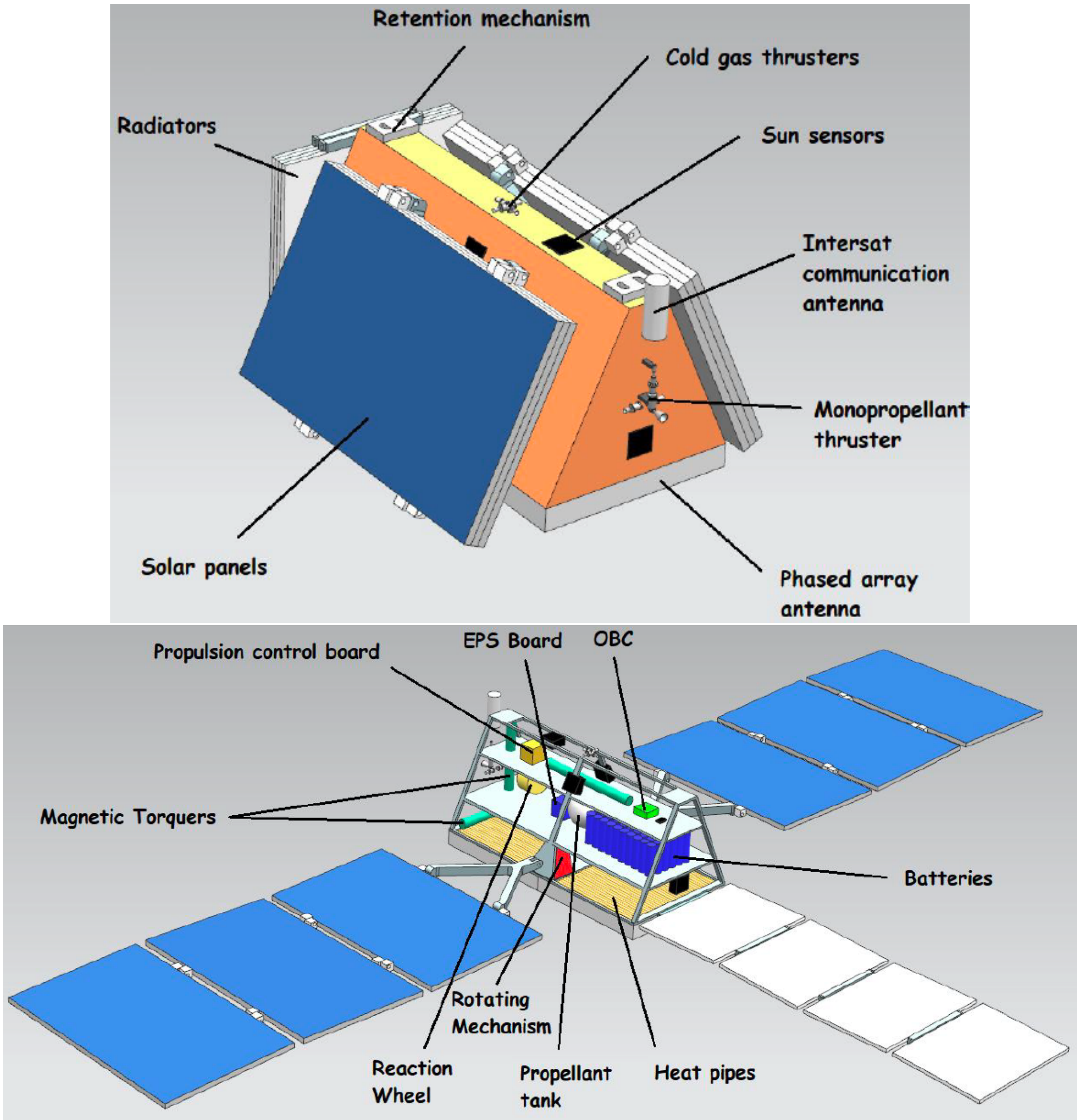


Figure 8-19: Storage and deployment configurations of ComConst5G satellite[5]

- The tool enabled the collaboration on the integrated parametric system model. The team frequently used the built-in visualization of dependencies and changes to be propagated via the N^2-Diagram.

Challenges

- Students easily confuse the conceptual design (parametric sizing) and detailed design or implementation. Parameters connecting the disciplines are mixed up with operational connections.

- For non-experts in conceptual design it is hard to choose appropriate model accuracy. E.g. to what degree the operations need to be accounted for in terms of power, thermal, inertia, maneuvers, visibility of communication or observation target, etc.
- Parametric models cannot capture complex information, e.g. geometry (component shape), time series (communication profile).
- Tool reliability is important, so that users don't lose accomplished work and need to redo their contributions.

8.5.8 Feedback

After the concurrent design studies were completed, we performed a survey among the students who participated in the case study using an anonymous online questionnaire. The purpose was to reveal whether the concurrent design approach was perceived to facilitate the conceptual design of the space mission. The quantitative questions used a Likert scale: 1 disagree, 5 agree, with an expected average of 3. In total, 7 students filled the questionnaire, which forms a 44% of all 16 study participants. For the average on all answers, we calculated the statistical interval using a confidence of 95%.

Sessions are useful The statement *"I found the concurrent design sessions (in the breakout room) useful for our project"* had an average answer of 3.7 ± 0.4. This is above the expected average, meaning that generally students found the design sessions useful for their project.

Offline work is useful The statement *"I found the individual work before and after sessions useful for our project"* had an average answer of 4.1 ± 0.76. This value well above the expected average underlines the usefulness of the periods of offline work for the concurrent design study.

Approach appreciation The statement *"I appreciate the overall approach of concurrent conceptual design?"* had an average answer of 4.7 ± 0.2. This high value and small interval tells clearly, that the students appreciated the concurrent design approach.

Adaptation The statement *"I changed my behavior and adapted to the concurrent conceptual design approach?"* had an average answer of 3.86 ± 0.44. The value only slightly above the expected average means, that the participants are undecided whether the practiced concurrent design approach had an influence on their behavior.

Besides these quantitative evaluation of the concurrent design approach, the students also provided comments. Benefits attributed to the approach are the clarity of the goals and the collaborative environment. Challenges reported are the creation of parametric models and the stability of the tool.

8.5.9 Summary

This case study with a group of master students has confirmed that the prior experience of the team members with concurrent design makes a significant difference. The participants were all novices, in conceptual design of space craft, as well as in concurrent design. This is particular to the environment of a university, where the primary purpose of doing concurrent design studies is learning. With the course project the students actually learned a new to them conceptual design approach.

The students were able to complete the task of a feasibility study applying our proposed concurrent conceptual design method. Both teams followed the process guideline and managed to build conceptual models and consolidate a design concept. Our in-situ observations and posterior analysis confirmed that the teams were supported and actively relied on the tool to coordinate during teamwork sessions.

Conclusions from Case Studies

The goal of the case studies was to test the process guideline and respective support for it by the tool. To check whether the our process model corresponds to what the participants actually did, we analyzed the activities logged by the collaboration tool. The modifications to the system model by the team members were grouped into design activities. The different design activities over the course of design study reflected the stages of the process. Additional analyses have shown high correlations of the DSM of the parameter links and the changes propagated between the discipline models. This confirms the importance of the design dependencies to determine the discipline sequence.

All teams in these design studies successfully created conceptual designs following process guideline available within the tool. This is particularly relevant, as the majority of the participants were new tho the concurrent design approach. The teams made use of the coordination support in the tool in the form of the dependency-based sequencing and the visualization of the change propagation.

Comparative Study

8.6 Study 8 and 9 - OgonSat-A & OgonSat-B

The purpose of this case study was to test the effect of using the process guideline on the duration of design iterations. In common practice the design iteration is guided by the team leader based on experience. Our process guideline proposes to determine the sequence of disciplines based on the parametric dependencies. The goal is to determine, whether the duration of the design iteration is less when the team uses this sequence instead of spontaneous coordination. To compare the two ways of managing the design iteration, two independent design studies with distinct teams but the same conceptual design task were conducted.

This case study was conducted as an academic exercise with teams of volunteers. Given the limited availability of the volunteers, the overall duration of design study was reduced to the bare minimum. To limit the difficulty of the concept study, we chose a textbook-like satellite mission.

The main characteristics of our design experiment are documented in Table 8.13.

8.6.1 Mission and Team

The mission chosen for this study was similar to the well-known FireSat example from SMAD textbook [Wertz et al., 2011]. The mission goal is to detect forest fires through the heat signatures in the infrared spectrum. The observations desirably should cover the territory of the Russian Federation.

The two teams were formed of four Master or PhD students each. On each team there were 3 people with some prior experience from one or two conceptual design studies for space missions, and 1 person without. This composition was chosen to resemble conditions in established CDFs, where it is frequent to have participants new to Concurrent Design (see chapter 4).

The system's architecture was already defined, and the model broken down in the primary subsystems. The participants were assigned only the subsystems Payload, Power, AOCS, Communications, while the other subsystems remained unmanaged.

Dimension	**Experiment (Comparative Study)**
Aim, research questions, hypotheses	How does following a design process affect the duration of a design iteration?
Nature of Study	Interventional, Comparative
Theoretical basis	Concurrent Engineering approach: Conceptual Design using Parametric Models
Unit(s) of analysis	parametric design: process and result
Data-collection method	recording model changes
Role of researcher	Observer
Continuation	Continuous data collection.
Duration	1 day, 3 sessions a 1.5h
Observed process	Starting point: system requirements, discipline assignment, subsystem models. Deliverable: conceptual design
Setting	Skoltech CEDL
Task	Realistic, Simplified
Number of cases	2
Case size	4 people
Participants	MSc and PhD students of Space and Engineering Systems.
Object	The project consists in consolidating a parametric design to a feasible and close to optimal solution.
Coding and analysis method(s)	From the logged design decisions (modifications to parameters) reconstruct the sequence and causality of the changes.

Table 8.13: Design of Comparative Case Study

Where possible, the participants were assigned to disciplines they had prior knowledge about.

8.6.2 Design Process

This case study focused on the design process, in particular the design iteration. The condensed experiment consisted in 3 design sessions, lasting 1.5 hours each. Focusing on the process of the design iteration, the design started from a previously built system model. This model contained the system breakdown structure and parametric models for each subsystem. For each of the subsystems, the respective interfaces were defined by their input and output parameters. The participants were provided with textbook excerpts and tutorials describing the formulas and design reasoning for their respective subsystems.

The experiment was set up in four steps: Introduction, Build Subsystem Models, Connect Subsystem Models, Design Iteration. The latter three are activities from the process guideline (see subsection 5.5.2).

Introduction (1 hour) First, the teams were given a general introduction to Concurrent Design and the space mission to design using parametric models. Then, we explained the participants the concepts and capabilities of the CEDESK for collaborating on conceptual design models. The volunteers received a hands-on training with the software to build a simple integrated system model.

Build Subsystem model (1.5 hours) Separated time was dedicated for the participants to study the design reasoning using textbook materials, and get acquainted with the models for their respective subsystem.

Connect Subsystem Models (1.5 hours) At the beginning of the design sessions, the team was instructed to establish the connections between the parametric models of the subsystems. The team members introduces these parameter links into the shared integrated system model. By doing so, each team member also develops mental awareness on the design dependencies.

The links between the subsystems are visualized using CEDESKs function for generating N^2-diagrams, shown in Figure 8-20 and Figure 8-21.

A comparison of the two underlying system models reveals only minor differences. The amount of parametric dependencies in OgonSat-A and OgonSat-B are 20 and 21 respectively. Hence, the interconnectedness is 0.31 for OgonSat-A and 0.33 for OgonSat-B. While the overall amount of connections differs only by 1, the number of different connections is 3. These differences are due to links reflecting slight difference how the team decided to summarize the mass and power budgets. Hence, they do not impact the design iteration.

Both teams used the N^2-diagram to monitor the design dependencies and inform their decision making.

Design Iteration (1.5 hours) The goal of a design iteration is to make change the design such that the inputs and outputs of the difference subsystem models become consistent and the feasibility of the design is assured. During the design steps, the members to communicate their design considerations, discuss changes, and apply them to the model.

The first design iteration started with a set of system requirements for one variant of the system, and subsequent iterations used modified system requirements (see Table 8.14). These requirements were chosen such to affect the design of the Payload, the Power system, and the Communication system, and hence require parameter changes on all subsystems.

Requirement	**Variant 1**	**Variant 2**	**Variant 3**
Infrared image sensor	2 bands around 900nm wavelength	3 bands around 1000nm wavelength	3 bands around 1200nm wavelength
Ground resolution	100m x 100m	200m x 200m	50m x 50m
Orbital altitude	700km	800km	600km

Table 8.14: System Requirements for Design Iterations

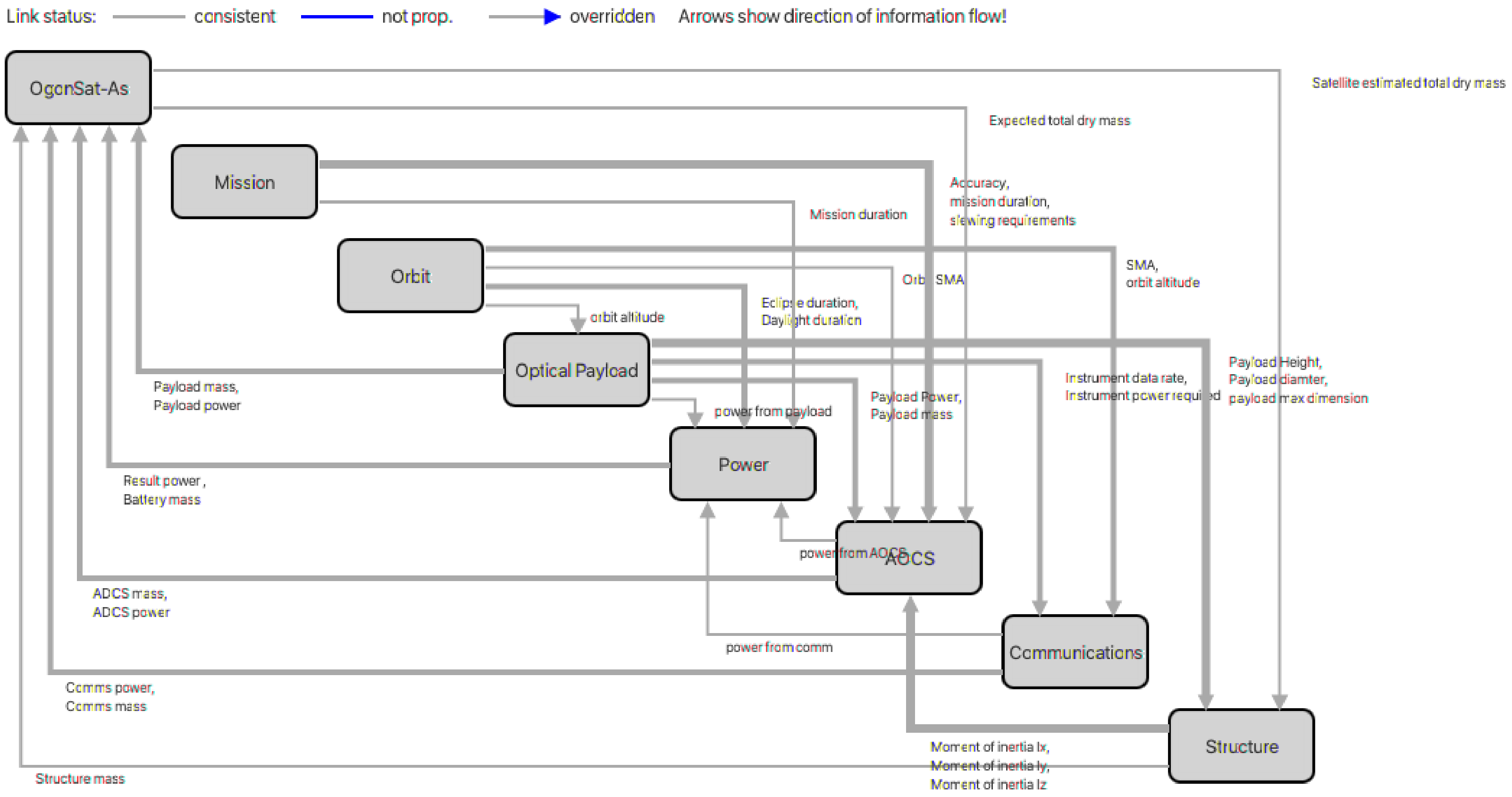


Figure 8-20: Automatic N^2-Diagram for OgonSat-A

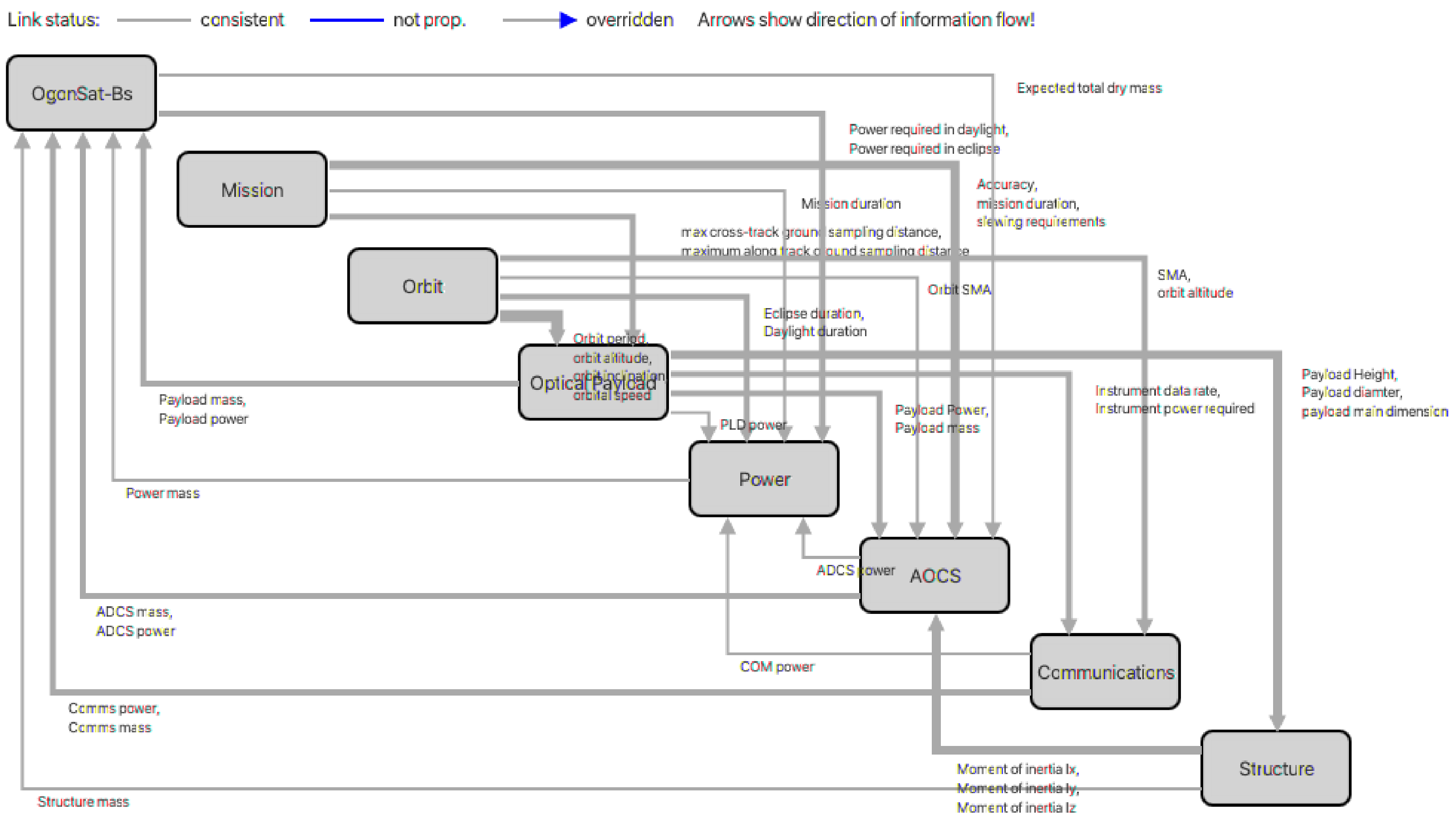


Figure 8-21: Automatic N^2-Diagram for OgonSat-B

A/B Study

Control The team of project "OgonSat-A" was not given a precise procedure how to organize the design iteration. The team members decided on the sequence of disciplines ad-hoc. Without taking systematic account for the design dependencies, it is expected to take longer for the team to converge the system model.

During the session allocated for design iterations, the team managed to converge the system model for Variant 1. Consequently, the duration of the design iteration was 1.5 hours.

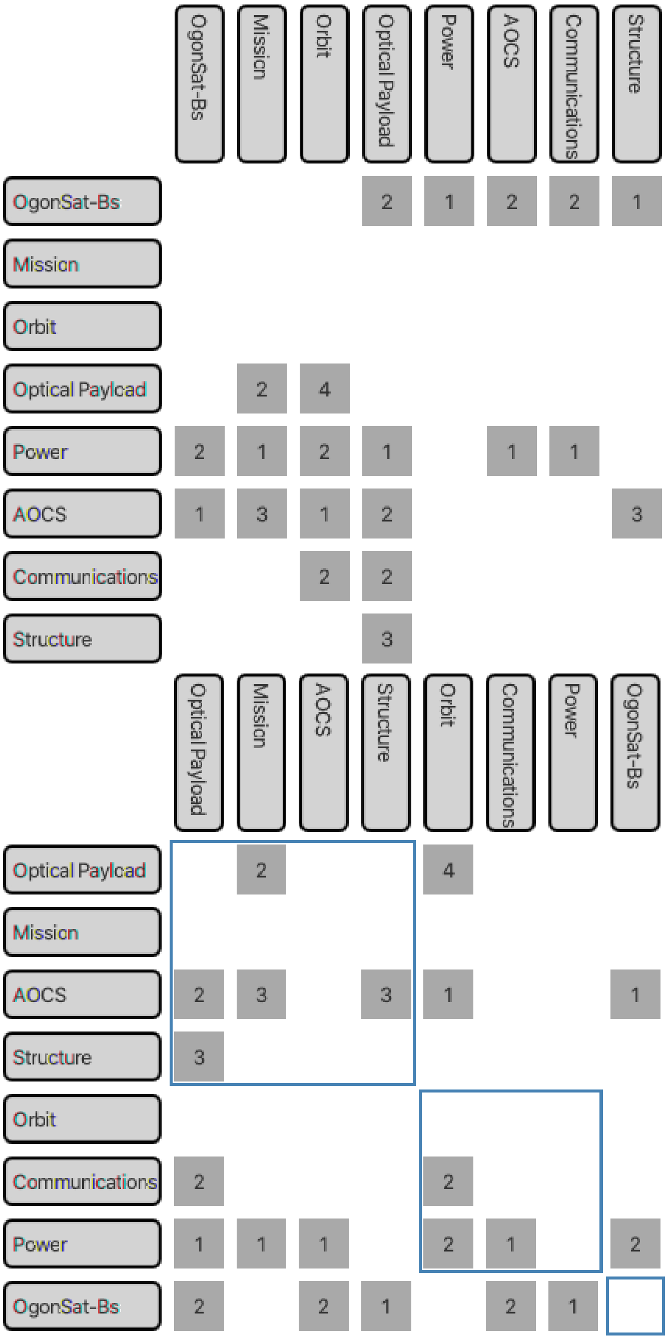
Treatment The team of project "OgonSat-B" was instructed to closely follow our process guideline. The sequence for the disciplines was computed using the DSM clustering and sequencing algorithm available within the CEDESK (see section 6.10). The matrices in Figure 8-22 follow the IR/FAD notation (inputs in row, feedback above diagonal) and show the original and clustered DSMs. Following the proposed sequence should minimize the need for repeated changes to the same subsystem, and hence reduce the amount of design steps.

Over the time allocated for design iterations, this team completed designs for each of the 3 variants. Consequently, the duration of the design iteration was 0.5 hours.

Comparison The difference in duration of design iteration between the team A and team B is significant: 1.5 versus 0.5 hours. This means that using the DSM based sequence, as proposed in our process guideline, team B demonstrated 66% shorter design iteration than team A. Hence, in this experiment the application of our process guideline lead to a significant increase in time efficiency of the design iteration.

8.6.3 Summary

In this case study we focused on the design process, comparing two different approaches to the coordination of disciplines during the design iteration. The design task was based on a textbook example, and the team was provided with previously



	OgonSat-Bs	Mission	Orbit	Optical Payload	Power	AOCS	Communications	Structure
OgonSat-Bs				2	1	2	2	1
Mission								
Orbit								
Optical Payload		2	4					
Power	2	1	2	1		1	1	
AOCS	1	3	1	2				3
Communications			2	2				
Structure				3				

	Optical Payload	Mission	AOCS	Structure	Orbit	Communications	Power	OgonSat-Bs
Optical Payload		2			4			
Mission								
AOCS	2	3		3	1			1
Structure	3							
Orbit								
Communications	2				2			
Power	1	1	1		2	1		2
OgonSat-Bs	2		2	1		2	1	

Figure 8-22: Original and clustered DSM for OgonSat-B

built subsystem and system model. The participants were volunteers with knowledge in space and systems engineering. While the team was held to design to the best of their knowledge, the resulting conceptual was of minor relevance for the case study.

The two coordination approaches in the design iteration gave significant difference in terms of time efficiency. The DSM based discipline sequence resulted in 66%

shorter design iterations than the ad-hoc discipline coordination. This result of a single comparative design experiment does not allow for generalization. Repeated experiments would allow to exclude factors, such as the differences in the team members in terms of discipline knowledge and prior design experience. Nevertheless, this result indicates that the application of our process guideline can increase the time efficiency of design iterations in Concurrent Conceptual Design studies. To substantiate this hypothesis, a larger number of repeated experiments would be required. Unfortunately, such a prolonged effort would expand beyond the scope of this work.

8.7 Overall Analysis

The 9 case studies were carried out during 3.5 years, over which our understanding of the methodology grew. The first 4 design studies served as pilots to refine the definition of our methodology and to test the collaborative design tool CEDESK. Then, we conducted 3 design studies, which applied the process guideline and the tool's process support in realistic design exercises. Finally, a comparative study was performed to evaluate the impact of the process guideline on the duration of design iterations.

All the Concurrent Conceptual Design studies had different missions and teams, with only a few people participating in more than one. We analyze the design studies according to characteristics defined our methodology (see subsection 5.5.3), in particular the study features: Duration of study, Number of Disciplines, Design Variants; and the process metrics: Interconnectedness, Degree of concurrency, Duration of Iteration.

A summary of the characteristics is shown in Table 8.15, hiding those that are the same for all design studies.

Interconnectedness The first two projects merged their models into one for easier management of the dependencies between them within CEDESK. The dependencies between the two projects are relatively few (see Figure 8-1). Due to that, the number of actual is much less than the potential dependencies, hence the inter-

ID	Project Name	Duration (net hrs)	Disciplines	Design Variants	Interconnectedness	Deg. of Conc.
Pilot Studies						
1	Dumbo	18	11	1	0.07	
2	BeeSat	18	8			
3	DemoSAT	9	9	1	0.24	
4	LaserNaut	24	9	1	0.29	
Case Studies						
5	GLISS	18	7	1	0.31	
6	RadMonConst	18	10	1	0.36	0.9
7	ComConst5G	18	8	1	0.5	0.98
Comparative Study						
8	OgonSat-A	4.5	4	1	0.31	0.74
9	OgonSat-B	4.5	4	3	0.33	0.97

Table 8.15: Summary of the case studies

connectedness (density of the DSM) is very low in comparison to the other projects.

From our experiments it seems that there is no correlation of the interconnectedness and other metrics. So it remains an open question, if this measure plays any decisive role in concurrent conceptual design.

Degree of Concurrency The degree of concurrency was measured only in the case studies 6 to 9. The values close to 1 mean that the design steps, if done strictly sequentially, they would have taken almost twice as long. To make this numbers easier to interpret we can translate this into an average overlap. For that we assume all task duration and taking into account the different number of disciplines.

The average overlap between all tasks would have been 53% for study 6, 57% for study 7, 57% for study 8 and 66% for study 9. The high percentage of overlap for all 4 studies indicates that the tool effectively enables the teams the parallelization of work. The high degree of concurrency of study 9 with a team of only 4 people provides evidence that they were most actively working in parallel.

Duration of Iteration As each design iteration produces one design variant, the duration of an iteration is the study duration divided by the number of performed design iterations. All studies, with exception of the last two, targeted to produce a single design variant, and consequently the duration of the study equals the duration of the iteration. In the comparative study, the target was to produce as many design variants as possible in a fixed amount of time. Design study 9 applied the process from our methodology to direct the design iteration and produced 3 design variants. The study 8 coordinated the design iteration spontaneously and produced 1 design variant.

The difference in amount of work accomplished in the same time indicates a positive influence of following the process guideline on the time efficiency of the design study. Besides that, the study 9 also managed to achieve a higher degree of concurrency, as mentioned above. While our experiments suggest a positive influence of process guidance on the time efficiency, the identification of the detailed relationship requires more extensive experiments.

Chapter 9

Technology Roadmapping and Conceptual Design

One of our research objectives is to extend the use of concurrent conceptual design to new areas. A research collaboration with the department for strategic technology management of a major aerospace company ,gave us the chance to design and test the application of concurrent engineering approach to technology roadmapping.

Certainly, companies would benefit from technology roadmaps, which give clear purpose and keep track of existing R&T projects and technological capabilities, demonstrators, products, services, as well as emerging technology trends. The concrete needs of our industrial partner inspired our work, and directly influenced the development of our methodology.

Such roadmaps would serve to determine R&T budgets, to decide whether to make specific technology investments or not, and to define new demonstrator projects [Knoll et al., 2018b]. For it to be a reliable source for decision making, technology roadmaps should be regularly updated, and should clearly demonstrate the linkage of proposed technology investments to the strategic drivers of the organization; furthermore, they should demonstrate the feasibility and rationale of technology targets, through rigorous engineering analysis. To be effective technology management tools, roadmaps need to incorporate inputs across the entire organization, including R&T, engineering, product policy, corporate strategy, support functions and outside partners - such as suppliers - while keeping track of developments of competitors and other relevant external entities.

Models provide the basis for rigorous management of future technology investments, and allow for identification of synergies across multiple technology areas. In this chapter we describe how we applied the Model-based Co-located Conceptual Design Methodology (MoCoDeM), to develop model-based technology roadmaps.

9.1 Model-based Roadmapping

Concurrent Roadmapping (CR) extends the concept of CE, where subsequent life cycle phases overlap in time. The Figure 9-1 in an extended lifecycle model illustrates the relation of technology roadmapping with the product development. Technology roadmapping and R&T development are distinct activities, but they occur in parallel and in certain ways precede product development.

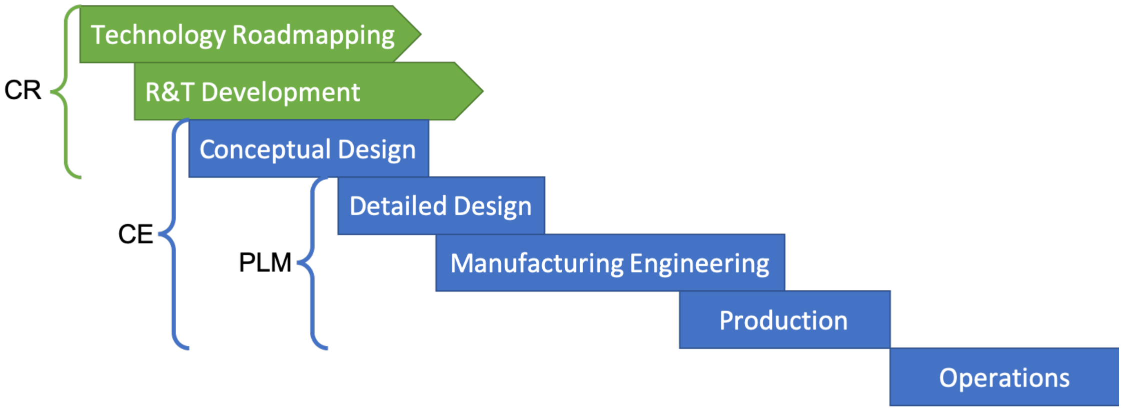


Figure 9-1: Product Lifecycle extended upstream

Concurrent Roadmapping is about the integration of technology roadmapping and conceptual design. Conceptual design of future products takes into account the planned outcomes of R&T. Vice versa, technology roadmapping obtains technology demands from the conceptual design.

There are two levels of corporate roadmapping that can implement new model-based methodology. That of a single roadmap, and the other of the entire portfolio of roadmaps. Both of them happen in parallel, but they are inter-dependent.

Single Roadmap Similarly to conceptual design, the creation and maintenance of a single roadmap is a collaborative process. It requires the inputs coming from multiple disciplines, to negotiate and build an integrated coherent model of the roadmap. By doing so, the roadmap targets are set, verified and documented with models. We described this approach partially in [Knoll et al., 2018b].

Portfolio of Roadmaps Any organization that has a range of products is likely to need separate roadmaps for each of them. The goal is to create and maintain a set of roadmaps, define a coherent strategy and leverage on synergies between various R&T efforts. This requires considering the roadmaps, not independently, but as interrelated parts of a bigger system, the portfolio. Hence, a collaborative approach allows for the consideration of the needs and targets of different roadmaps concurrently.

In the following sections, we explain the methodology applied at both levels. As CCD studies happen in dedicated facilities (CDFs), such environments can also serve concurrent roadmapping, to bring experts together and integrate knowledge across the organization. Moreover, in the case of an integrator, technology roadmapping may very well also involve suppliers.

Applying the concurrent design approach in technology roadmapping aims to achieve two goals: 1) provide engineering rationale for roadmap targets, 2) explicitly account for inter-dependencies between all involved disciplines.

9.2 Concurrent Roadmapping - Single Roadmap

This section reports work we published in Knoll et al. [2018b] and puts it in the context of our Model-based Co-located Conceptual Design Methodology (MoCoDeM). Accordingly, we describe here the specialization of the methodology to the case of creating a single technology roadmap. The ways to employ multi-disciplinary teams and a concurrent facility are adopted without modifications. The role of the customer is played by the person in charge of the roadmap, the so-called roadmap owner.

9.2.1 Model

The architecture of the roadmap is described in an OPM diagram capturing its essential information. The generic form a roadmap architecture as is shown in Figure 9-2.

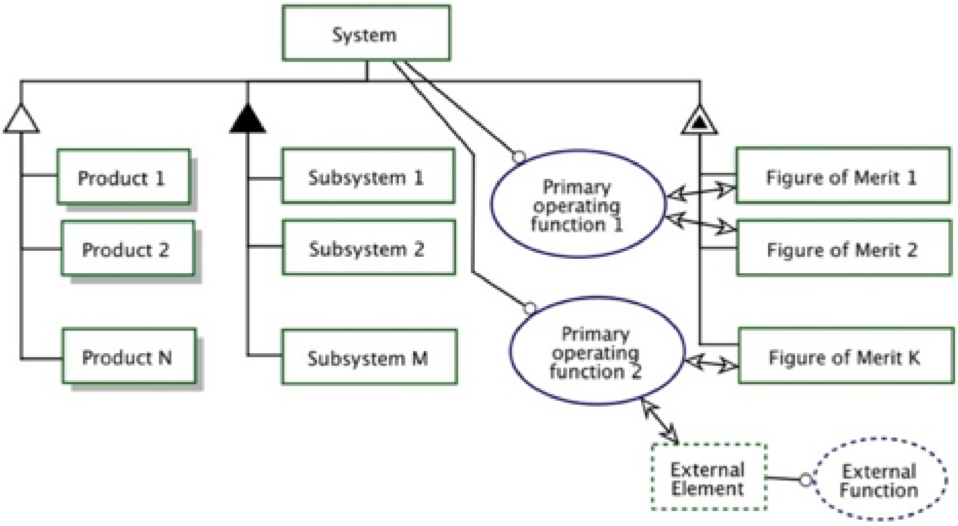


Figure 9-2: OPM diagram of a notional roadmap architecture model

The roadmap architecture model contains the following elements:

- A list of existing products and services associated with the roadmap.
- The decomposition of the roadmap into subsystems (PBS), showing elements of technological relevance to the roadmap.
- The primary operating functions of the elements relevant to the roadmap, eg. systems, products, services, processes, components, materials.
- Figures of merit associated with the roadmap and their relation to the primary operating functions (e.g. which FOMs affect which primary operating functions and vice versa).
- External functions and elements affecting the elements of the roadmap.

Such an architecture model of a roadmap expresses its essence, in a condensed graphical form. As usual for descriptive models, its purpose is communication and documentation.

Besides this graphical representation, model-based roadmaps consist of data, and a parametric model.

- Definitions for all FOMs, consisting of name, unit of measure, and future trends (e.g. average annual rate of improvement,) and related technical models.
- List of current and proposed R&T projects and demonstrators.
- A list of alternative/competitive technologies and their characteristics.
- The Technology Readiness Level (TRL) for each technology.
- Where applicable, financial models shall be included to allow the estimate the expected return on a technology development effort, using the Net Present Value (NPV).
- A technical model of a roadmap describes the technology embodiment as a product concept.

The technical model is key to the reliability of the roadmap. It is used for the conceptual design of the system of interest of a roadmap, and consists of a set of statistical or mathematical models, allowing to evaluating the FOMs of interest for different moments in the future, using the expected technology characteristics.

9.2.2 Process

Applying the Model-based Co-located Conceptual Design Methodology involves a multidisciplinary team for conceptual design. We divide the roadmapping process into three steps: Formulating, Modeling, and Landscaping. These steps are in analogy to the process guideline of our methodology (see section 5.5.2): *Preparation*, *Build Integrated System Model*, and *Design Iteration*.

Formulating

Creating the roadmap architecture model, and collecting the background information is part of the *Preparation* step. Each involved discipline expert shall prepare the parametric models to be used. Sometimes, FOMs may be computed by complex numerical simulations (e.g. fluid dynamics simulations, finite elements analyses). However, for a FOM to be used during the roadmapping exercise, it shall be possible to estimate it quickly (on the order of seconds or few minutes). If the original model underlying the FOM requires substantial execution time, it is advisable to create surrogate models. Using these models, a number of possible designs can be evaluated according to the FOMs. The resulting designs can be compared using tradespace exploration (see section 2.5). If the current products or technologies are not on the current best-achievable Pareto front, it may be possible to improve the product or technology by merely redesigning it, without investing in new or improved technologies. If, however, the current product or technologies are on or near the PF, then new technologies or improved technologies are needed to further improve, i.e. “push” the pareto front closer to the Utopia point.

The characteristics of technologies in terms of FOMs, can be obtained in one of the following methods:

- Rough order of magnitude estimates collected from expert surveys using the Delphi method, as described by Bloem da Silveira Junior et al. [2018].
- Fitting a S-curve model on historical data of past FOM trends, as described by Nieto et al. [1998].
- Expert point estimates. Since this method relying on a single data point has the highest chance of error or bias, the estimates should be documented with description and motivation.

Modeling

The purpose of modeling is to create a parametric model for the roadmap. The Product Breakdown Structure (PBS), the identified design variables and FOM models, are combined into an integrated roadmap model. Building the technical model corresponds to the *building of an integrated system model* in the process guideline of our methodology (see section 5.5.2).

In some cases, where the entire system model is expressed in mathematical formulas, the calculation of optimal values for the design parameters can be automated, using dedicated MDO tools. In the more general case, where engineering reasoning is not encoded in analytical models, to store such models and propagate changes between linked subsystem models, a collaboration tool, as the one described chapter 6.

Using a collaboration tool, each domain expert defines the design variables of their respective element. Then, the experts link the design variables and FOMs to reflect the interdependencies among elements, as described in the roadmap model. Finally, parametric models shall be inserted, that map the design variables as inputs to FOMs as outputs, for example, in the form of spreadsheets. Models ideally are taken from the model inventory during the formulation step or built ad-hoc for the roadmapping exercise. Many times, companies already can leverage a heritage of low fidelity models for product sizing. It is essential that the used models are validated and benchmarked against either existing systems with empirical data, or point designs at a higher level of fidelity, spanning the design space. The outcome of modeling is an integrated system model that can be used to evaluate a technology embodiment on a range of possible design parameters.

Landscaping

This step corresponds to *design iteration* step of the process guideline of our methodology (see subsection 5.5.2).

The purpose of landscaping is to map possible designs using state-of-the-art and future technology characteristics. The state-of-the-art is given by the Pareto front of today, which is the set of non-dominated designs among existing products. Using the FOM trends identified during the Formulating step, the team projects the evolution of the PF over time, for instance, over a fixed set of time increments (e.g. 5 year increments). Designs resulting from the projected FOM values define the so-called "Future PF".

The tradespace is populated by enumerating all design options, evaluating them according to the FOMs. For conceptual designs where complete analytical models exist, automation can be applied for enumeration and evaluation leveraging MDO tools. In the general case, our methodology relies on the concurrent conceptual design method, where a multi-disciplinary team elaborates the design. The number of design options that can be evaluated depends primarily on the time necessary for the evaluation of a single design, and the time available for the landscaping.

Based on the Pareto analysis, the team identifies those preferred designs, in terms of FOMs, that should be used as targets for the roadmap.

9.2.3 Tool Support

This process needs to be supported by tools for storing the conceptual design model, their respective evaluations, and visualization of tradespace as FOM charts. The tool presented in chapter 6, CEDESK, incorporates all the necessary features. It allows the definition of a tradespace, with according FOMs, and these can be linked to parameters of the integrated system model. Any version of the model can be tagged with a label to specify a design variant, and visualized as a design point on FOM charts in CEDESK Tradespace Explorer.

9.3 Concurrent Roadmapping - Portfolio

In this section, we describe the adaptation of MoCoDeM to updating the roadmap portfolio and conceptual product design. A Concurrent Design Facility (CDF) is used the same way it is described in the methodology. As for the team aspect of our methodology, the customer is the person in charge of a roadmap (roadmap owner). Each roadmap employs a multi-disciplinary team, to define its model, and the negotiation between roadmaps is handled by the roadmap owners.

9.3.1 Model

A core concept for defining model-based roadmaps are capabilities, which are used to describe the targets and requirements of roadmaps.

Capabilities are defined by key characteristics of a system, which could be a product, a component or an industrial process. For example, the fuel consumption of a car, the heat generated by a processor, or the time to overhaul a water turbine.

Besides quantifiable characteristics, also called Figures of Merit (FOMs), there are also qualitative characteristics (e.g. a motor uses fuel combustion or electricity). In the context of technology planning, it is important to note that capabilities are subject to time (e.g. fuel consumption of cars decrease over the years).

Roadmaps describe the capability they are targeting, and also the developments they rely on. Hence, the roadmap for a product can state to provide a certain performance, based on the availability of a capability provided by a component. This arranges roadmaps in a hierarchical structure, in analogy to the Product Breakdown Structure. The links between different roadmaps can be described as capabilities offered or demanded at a certain time, using one or more FOMs.

Together with my colleague Ilya Yuskevich, we elaborated a graph representation of these portfolios using a visual notation, based on elements from OPM [ISO Central Secretary, 2015b]. Figure 9-3[1] illustrates the basic elements (items are named after a NASA roadmap). Rounded rectangles with red border represent roadmaps, in this example, for a mars helicopter drone. A rounded rectangle with blue border represents R&T projects, in this case a project for rechargeable batteries. Orange ovals represent capabilities, in this example, with the FOMs battery capacity and mass. Roadmaps and R&T projects specify the targeted TRL level, as well as the allocated budget. The line with an arrow indicates that the roadmap plans

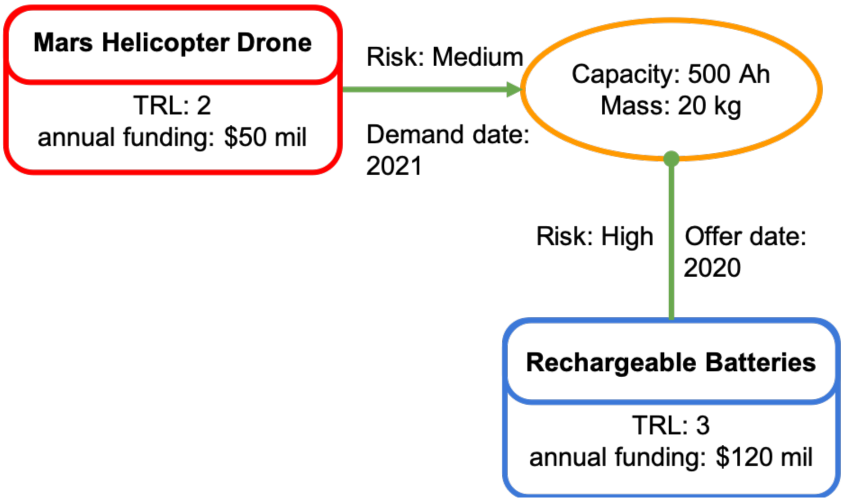


Figure 9-3: Example of graphical modeling of connected roadmaps[1]

---

[1] Credits to Ilya Yuskevich

to provide that capability. The line with the circle represents the need of another roadmap by the year 2023 of that same capability.

Formalizing the entire roadmap portfolio in this way allows different kinds of analysis. We proposed for example, the total budget of a roadmap including all the contributing roadmaps and projects. Moreover, an automated check is possible whether a roadmaps targets can be achieved based on the demanded capabilities, or the accumulated risk for a roadmap meeting it's targets.

9.3.2 Process

The overarching process of Concurrent Roadmapping also deals with the portfolio of roadmaps by modeling and explicitly managing the connections between roadmaps. We performed an analysis of this process adopting the basic structure from the MBSE method ARCADIA [Roques, 2018]. To describe the functional analysis of this process, we used IDEF0 as a graphical notation, which has strong heritage in modeling of information processing [Menzel and Mayer, 1998] . In essence, it describes functional blocks connected by arrows(see Figure 2-2). Each block carries the name of a function and the arrows represent either inputs, resources, controls, or outputs.

The process of elaborating and refining a technology roadmap needs to take into account the entire portfolio of roadmaps. While each roadmap can evolve independently, it is important to incorporate updates of other, related roadmaps and to communicate updates to other, related roadmaps. Within a roadmap the conceptual design of a single product/system/subsystem applies logical decomposition and for (each) composing element, related roadmaps are identified and the relationships characterized in detail. This information is exploited to make sure the roadmap portfolio is consistent, synergies are exploited better, roadmaps are aligned with corporate strategy, and to provide the best value for the money invested in R&T. In summary, Technology Planning and Roadmapping, is concurrently doing conceptual design of systems/products and technology roadmaps. The further description takes the viewpoint of a moderator of the concurrent design facility, where most of the related work takes place.

The process of elaborating a roadmap includes the creation/update of the conceptual design of a corresponding product/system and update of the related roadmaps.

Top View

From an outside view, the process of concurrent roadmapping is like a black box (Figure 9-4).

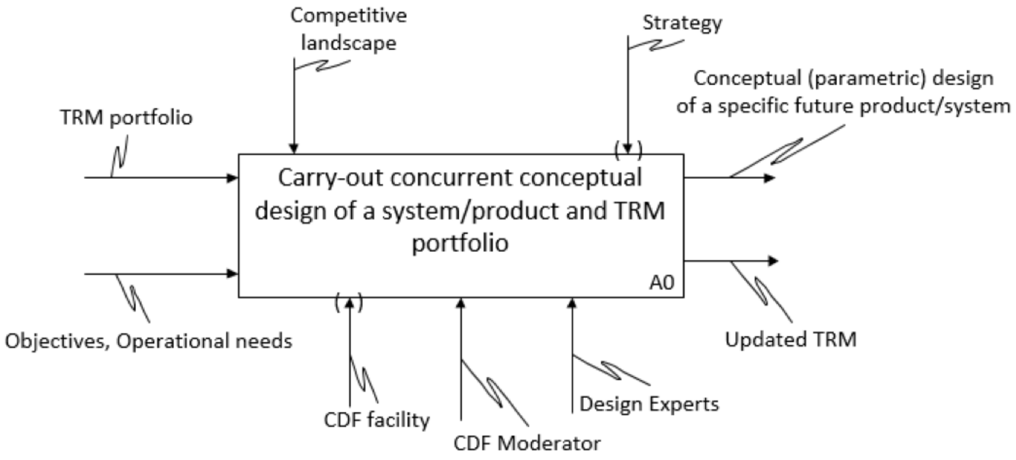


Figure 9-4: Top-level diagram for the Concurrent Roadmapping process

This process takes two *inputs* (arrows from the left):

TRM portfolio - the set of technology roadmaps, each with figures of merits, and their hierarchical organization.

Objectives and operational needs Mission requirements of stakeholder needs for the product/system of interest.

Two *controls* are fed into that process (arrows from above):

Competitive landscape The information about existing and announced competing products, their performance and cost.

Corporate strategy The company's goals in terms of market and intermediate steps to them.

The process uses three *resources* (arrows from below):

CDF - the workspace for co-located teamwork on conceptual design.

A moderator to facilitate the various steps of the concurrent design process.

Design experts for the product/system of interest, including disciplines of engineering, manufacturing, marketing.

The process produces two *outputs* (arrows on the right):

Updated TRM The roadmap of interest with new refinements and updates.

Conceptual Design - the model-based representation of the future product/system.

Detailed Steps

At a more detailed level, we identified that this process consists of several distinct functions (see Figure 9-5).

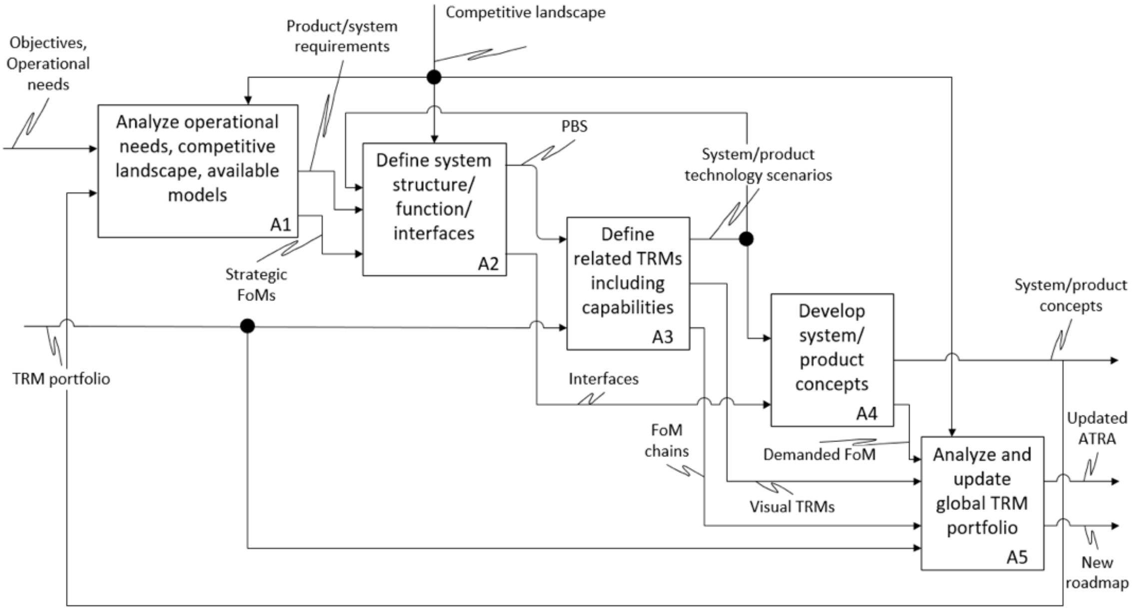


Figure 9-5: Diagram for the process of concurrent conceptual design of a system/product and TRM portfolio

A1 Analyze operational needs, competitive landscape, available models The creation or update of a technology roadmap needs a clear understanding of the needs that the product/system is meant to address and an understanding of what other solutions are already on the market. This process step is composed of smaller sub-steps.

Refine and quantify objectives and needs of a potential customer to produce a list of top-level performance characteristics (strategic FOMs) and their values.

Define operational modes and states of the system.

Analyze competitors' landscape using available data about competitive products trough a tradespace. Calculating all product's distance to the corresponding efficient frontiers [Yuskevich et al., 2018]. After this, strategic FOMs might be refined. This Pareto analysis requires specific tool support.

Perform game-theoretic strategy simulation using data about competitive products, past and forecasted pareto fronts. For potential competitors' choices the respective best responses are calculated applying a game theoretic approach. Depending on the chosen time horizon and estimated competitor's choices, the tool for game-theoretic strategy simulation produces a list of rationally optimal strategic options [Smirnova et al., 2018]. This game-theoretic simulation requires specific tool support.

Define the requirements for the system.

A2 Define system structure/function/interfaces To define the system, it is necessary to identify the top-level functions, and decompose the logical structure (PBS). Based on that, the interfaces with the outside and between the elements are defined.

This process step is composed of smaller sub-steps.

Analysis of needs of the market and requirements by taking into account the strategy. The process involves an analysis of competitors, a study of the elements represented within the system/product. This is to ensure marketability of the system/product by understanding how the system/product would be directly used by the end-user.

Design Logical Architecture of the system/product in such a way, that it is not limited to any particular technology and/or capabilities while providing as much detail as possible. In the later conceptual design, the logical architecture serves to define the physical architecture. The design is described using any kind of descriptive model, such as SysML, OPM, or similar.

Define subsystem concepts of each subsystem for coordination of work flows and use of resources. Each subsystem concept should contain characteristics of its capabilities.

Define interfaces for describing design flows between subsystems.

A3 Define related TRMs including capabilities Knowing the logical structure of the product/system to be designed, the functional elements can be mapped to relevant technologies. For these technologies the associated technology roadmap is identified. The relevant Figure of Merit (FOM)s are defined, which allow the characterization and comparison of alternative technologies. Alternative technologies allow the definition of different scenarios. This process step is composed of smaller sub-steps.

Establish related TRMs for dependent technologies and products through capabilities required for the roadmap of interest. The exact values for the FOMs are estimated later, during conceptual design, by means of parametric models, Delphi surveys or Pareto-frontier forecasting tools.

Establish links between projects and capabilities by putting the links between demanded and offered capabilities.

Visualize TRM and related TRMs and connections This needs a tool for graphical representation of the complex network of entire portfolio TRMs, and facilitate eventual analyses (risk-schedule-cost assessment, consistency check, scenarios comparison, etc.). A more detailed illustration of this graphical modeling of roadmaps can be found in subsection 9.3.1.

A4 Develop system/product concepts This step corresponds to the concurrent conceptual design of a single roadmap as described in section 9.2.

A5 Analyze and update global TRM portfolio With the estimated capabilities of technologies and the portfolio of technology roadmaps at hand, the analysis identifies inconsistencies and gaps, for which new roadmaps or changes to other roadmaps are proposed. This process step is composed of smaller sub-steps.

Check consistency of demanded and offered capabilities by matching demanded capabilities by the roadmap of interest to the offered capabilities by corresponded TRMs (and vice versa) and avoiding uncovered demands.

Define new roadmaps if during CD study, capabilities or new products/technologies/services have been identified that are not covered by any existing roadmap.

Propose demanded FOMs, FOM links, projects, milestones if during CD study existing roadmaps have been reviewed, it is required to document the new findings, in particular, FOM links, projects, and milestones.

Perform TRM maturity assessment based on the degree a roadmaps information can be used for budgeting decisions. We propose to have experts assess roadmaps according to a defined set of criteria, and using the Delphi method to reach an agreement. Appropriate Delphi surveys shall be supported by a tool.

9.3.3 Tool Support

The process of Concurrent Roadmapping consists of activities that requires a specific support. There are two types of activities happening in parallel: 1) roadmapping and 2) conceptual design. Figure 9-6 depicts the concept of the integration of these activities in a toolkit.

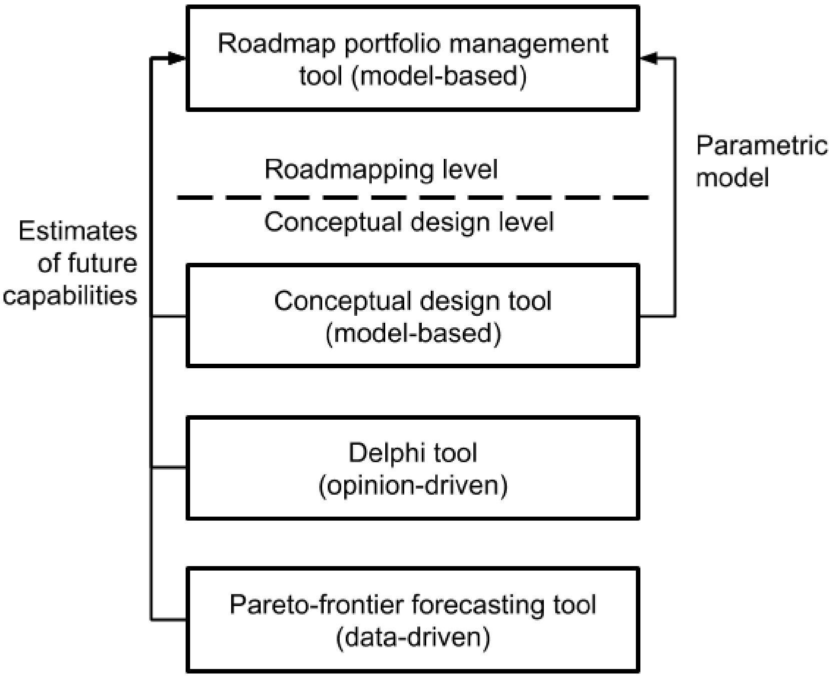


Figure 9-6: Toolkit for capabilities formalization and quantification

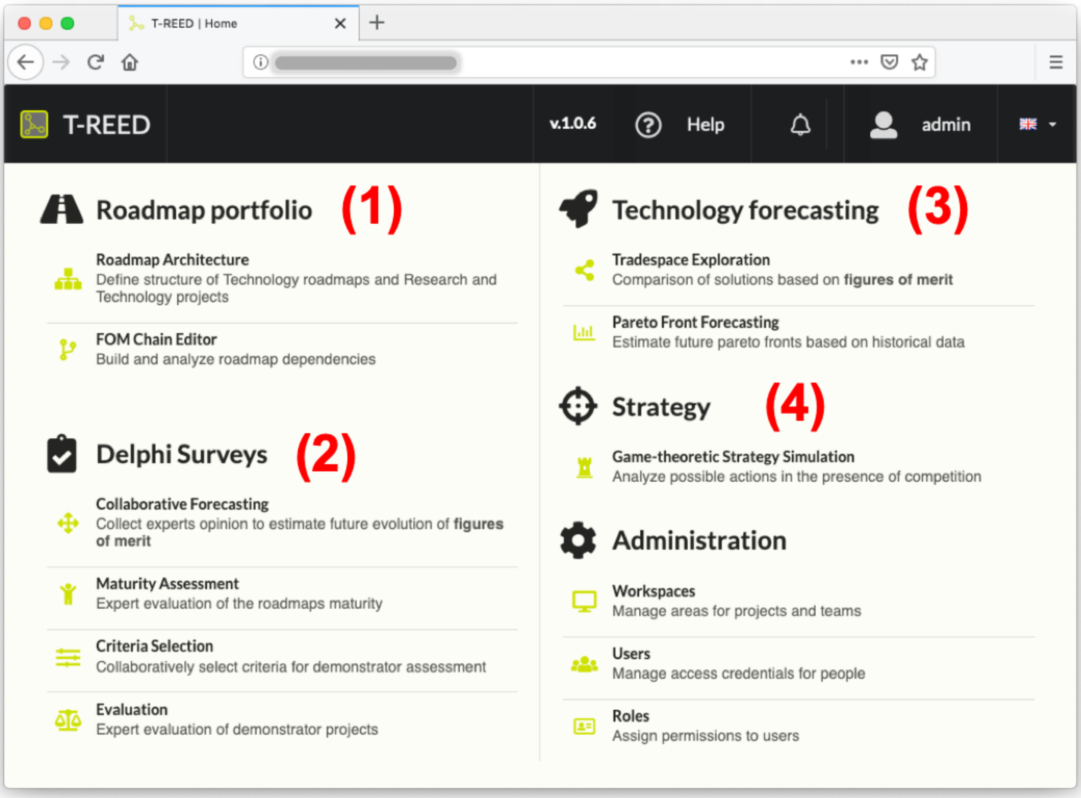
The goal of conceptual design level activities is to find values of FOMs, schedule, risks and communicate them to the roadmapping level. To do so, the design team performs conceptual design of new products or services. To facilitate a conceptual design, our envisioned tool includes the use of the model-based, opinion- or data-driven approaches. The goal of the roadmapping-level activities is to effectively incorporate new data into the TRM portfolio, to ensure consistency and attainment of strategic goals.

Conceptual Design

The tool CEDESK presented in chapter 6 incorporates the necessary features. It enables the creation of an integrated system model in a collaborative manner. Moreover, it allows defining a tradespace according to FOMs that can be linked to parameters of the integrated system model. The model can be tagged at any point in time with a label to specify a design point, and this design point can be visualized on the FOM chart.

Others

To support the activities described in the process that are specific to roadmapping, a complete toolkit was realized. The author defined the functionality required to support the industrial partner, and the implementation of this tool was done by two professional software developers. The web-application (T-REED) shown in Figure 9-7 contains a module for each need. The numbers in the figure above indicate the modules: 1) for the management of portfolios of roadmaps, 2) to conduct delphi-surveys related to roadmapping, 3) to perform pareto-front forecasting, and 4) to simulate strategic decision making.



Roadmap portfolio (1)

Roadmap Architecture
Define structure of Technology roadmaps and Research and Technology projects

FOM Chain Editor
Build and analyze roadmap dependencies

Delphi Surveys (2)

Collaborative Forecasting
Collect experts opinion to estimate future evolution of **figures of merit**

Maturity Assessment
Expert evaluation of the roadmaps maturity

Criteria Selection
Collaboratively select criteria for demonstrator assessment

Evaluation
Expert evaluation of demonstrator projects

Technology forecasting (3)

Tradespace Exploration
Comparison of solutions based on **figures of merit**

Pareto Front Forecasting
Estimate future pareto fronts based on historical data

Strategy (4)

Game-theoretic Strategy Simulation
Analyze possible actions in the presence of competition

Administration

Workspaces
Manage areas for projects and teams

Users
Manage access credentials for people

Roles
Assign permissions to users

Figure 9-7: T-REED web application for concurrent roadmapping

Roadmap portfolio

The graphical modeling language described in subsection 9.3.1 was implemented similar to a diagram drawing tool. Figure 9-8 shows the graphical user interface. The right side contains a pane showing the diagram, and on the left, the user can choose elements to add on the diagram.

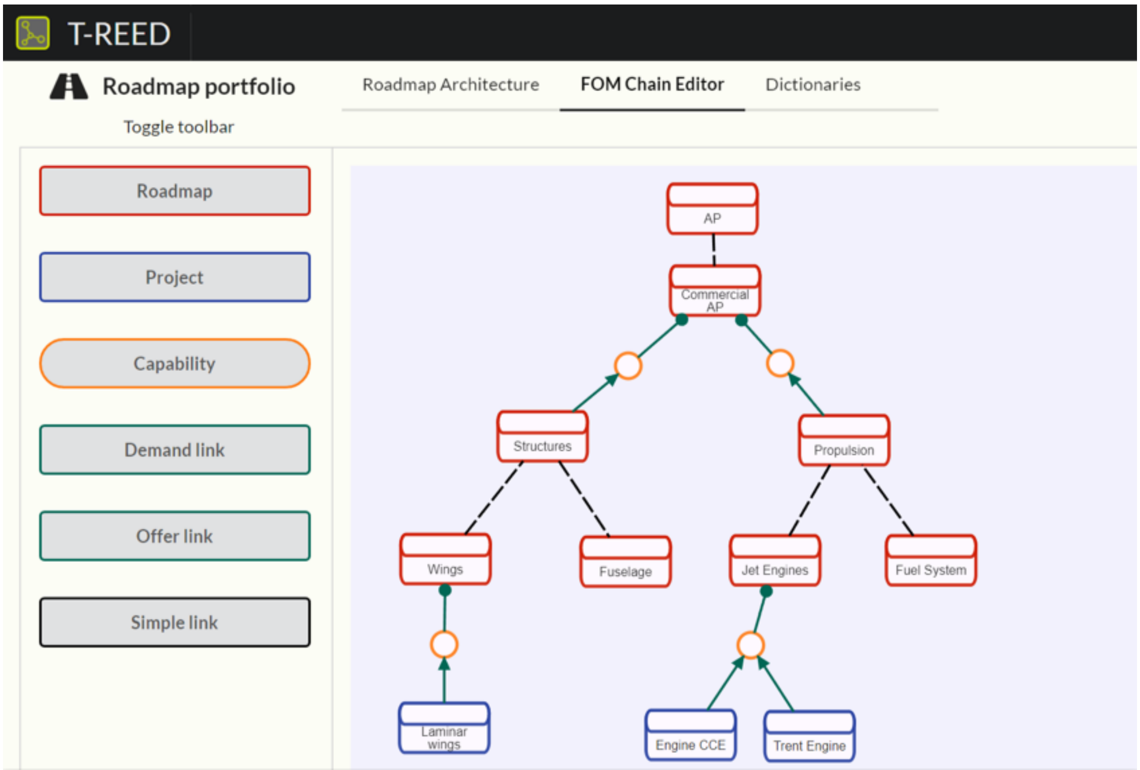


Figure 9-8: T-REED module for modeling interconnected roadmaps

Delphi Surveys

This module for conducting Delphi surveys is an online questionnaire tool similar to Google Forms. But, beyond basic survey functionality, to support the Delphi method, it can repeat questionnaires in rounds, while showing the respondents the aggregated and anonymized results of previous rounds. This allows to elicit experts' opinions in a well-structured manner and can help to produce consistent results. For the purpose of technology planning an roadmapping the Delphi surveys can be used to produce forecasts on the future performance of a technology, or an assessment of roadmaps' maturity.

Product Name	**FOM 1**	. . .	**FOM N**	**Year**
product X	4	. . .	7	2004
. . .				
product Z	5	. . .	1	2007

Table 9.1: Example of tradespace data with time reference

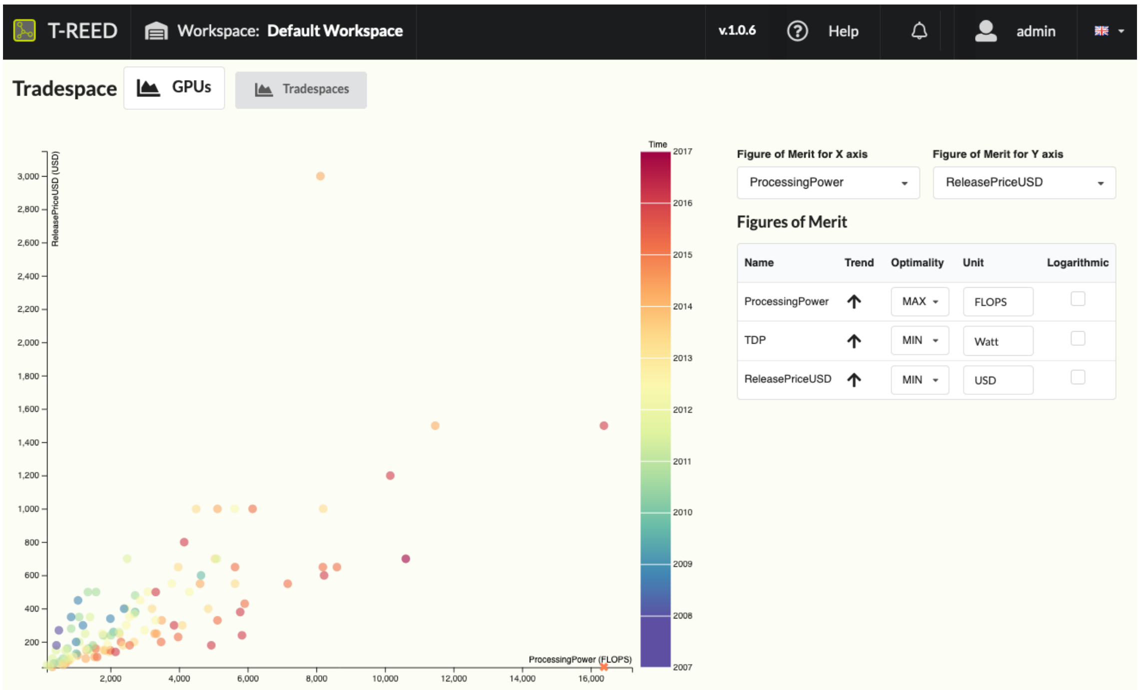


Figure of Merit for X axis: ProcessingPower

Figure of Merit for Y axis: ReleasePriceUSD

Figures of Merit

Name	Trend	Optimality	Unit	Logarithmic
ProcessingPower	↑	MAX	FLOPS	☐
TDP	↑	MIN	Watt	☐
ReleasePriceUSD	↑	MIN	USD	☐

Figure 9-9: T-REED module for tradespace visualization

Technology Forecasting

Tool is also equipped with a module for forecasting of technological development based on historical data. The historical data needs values for two or FOMs for each product together with the year the product was announced or appeared on the market. The data shall be structured as illustrated in Table 9.1.

The tool allows importing such tradespace data from spreadsheets, giving the user the possibility to choose the meaning of the data contained in each column. The data is visualized in a FOM chart with freely selectable axes, as shown in Figure 9-9. Based on such data, the tool can compute the Pareto fronts for the past years and produce forecasts using an algorithm described in [Yuskevich et al., 2018].

Strategy Simulation

Another module allows the simulation of strategic behavior based on previous products of market competitors. The behavior of market players is extracted from historical information in the form of tradespace data and it relies on forecasted pareto fronts. The tool can simulate a number of steps ahead and propose strategic decisions that are optimal in terms of game-theory.

9.4 Application

The methodology we described was implemented step-wise in the technology planning and roadmapping department of our industrial partner. The diversity of products and markets, on the one hand, and the vast range of components, technologies and research projects, on the other hand, required a well-structured approach to roadmapping.

Since the corporate technology strategy is critical for competition, we are required to keep confidentiality and are not able to name the actual subjects of concern.

For illustration purposes, we use the example roadmap of a Solar Electric Airplane (SEA), as published in [Knoll et al., 2018b]. The purpose of this roadmap is to define the targets for a competitive future airplane using electric propulsion capable of long endurance through the harvesting of solar energy.

Portfolio Definition

At the beginning, the entire set of R&T projects across different product divisions was inventoried and categorized. This was done in a workshop involving project leaders and R&T managers. Projects that had similar scope were grouped and roadmaps were formed. Each roadmap was given a concise mission and it was assigned to a roadmap owner.

Roadmap Modeling

The roadmap owners were put in charge to collect the required data, such as existing products and competitors, contributing R&T projects, define the key characteristics in terms of FOMs. We defined a canvas for storing these data in a structured manner. This allowed also to assess the information completeness as a proxy for a roadmap's maturity.

The technology roadmapping department also offered training in the Object-Process-Method (OPM) to the roadmap owners, such that they could build architecture models of their roadmaps. The OPM diagrams served mainly for summarizing the roadmaps structure and dependencies. A notional example of a roadmap architecture model is shown in Figure 9-10. It shows the existing airplanes on the left, and next to it, the decomposition into primary subsystems Product Breakdown Structure (PBS). At the right, there are the Figures of Merit (FOM) and, to the left of them the operational functions of the plane.

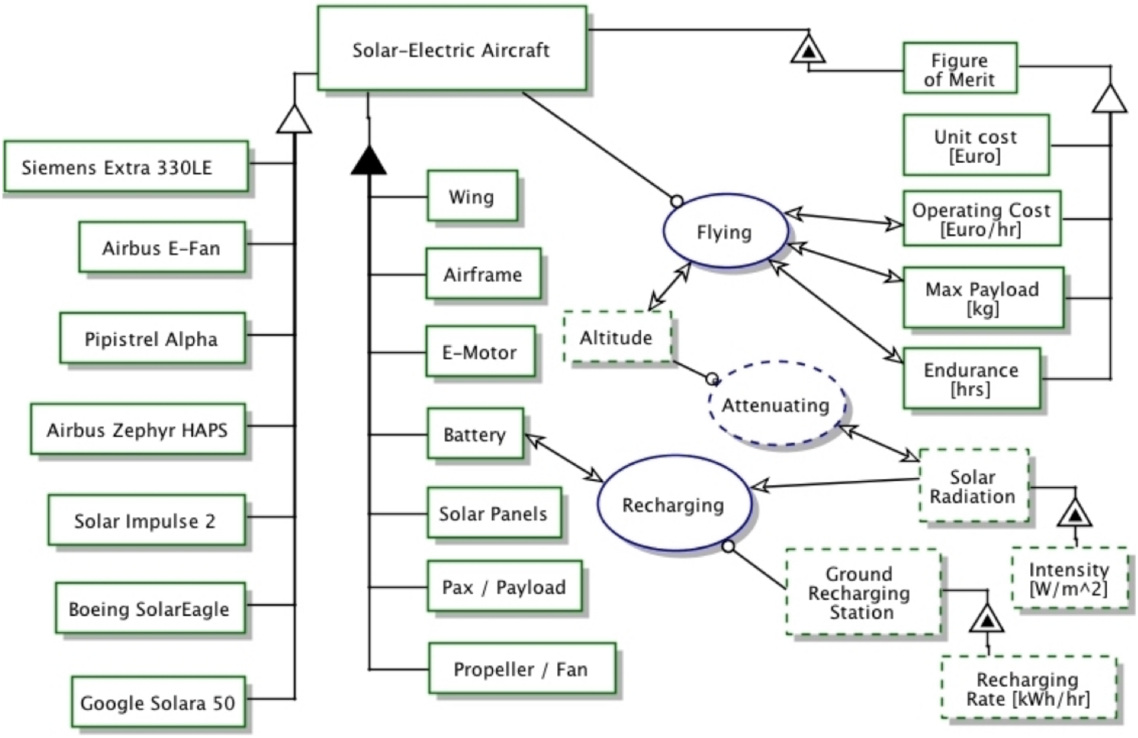


Figure 9-10: OPM diagram of a notional example roadmap [Knoll et al., 2018b]

By collecting the data and modeling the architecture, the roadmap owner have accomplished the step "formulating" of our proposed process (see subsection 9.2.2).

The next step on the CR process involves the parametric modeling.

Concurrent Sessions

Based on the relevant subsystems and FOMs, each roadmap owner formed a team of experts. The teams gathered for co-located design sessions in the technology roadmapping CDF. The CDF sessions' primary result was that experts from across the company exchanged on their related work, who otherwise would not have exchanged. This organizational and human factor was not contemplated in our methodology. Unlike expected, the teams spent a singnificant amount of time to discuss the definition of the goals and the definition of the FOMs. The elaboration of the architecture model as well as the parametric models found little attention. An survey on the information gathered for the roadmaps that around 10% of the roadmaps were fully modeled according to our methodology. As a consequence, in the next step of "landscaping", the teams did not use analytic models but estimates from the expert to define the technology targets of the roadmaps.

Portfolio Modeling

The roadmaps were analyzed for their inter-dependencies and arranged in a DSM. Clustering of the DSM informed the grouping of the roadmaps into layers. The roadmaps were organized in a hierarchical structure of 4 layers. At the top there were roadmaps for different systems-of-systems. Underneath there were roadmaps of each of the company's product. Then there were roadmaps for components and and capabilities. At the bottom there were roadmaps for so called technology bricks. All R&T projects were directly associated to the roadmaps. The connections among roadmaps were subject to further elaboration throughout the course of the project. Connections could be proposed unilaterally, by one roadmap owner, and later confirmed when the second involved roadmap owner agrees. In a next step, dependencies were characterized in more detail by stating the Figure of Merit, that is provided or demanded. Subsequently, the concurrent sessions were arranged to define the links between roadmaps as capabilities, as described in our approach (see subsection 9.3.1). To make sure the people involved were able to grow into the new roadmapping approach, management decided to gradually increase the detail of the portfolio model. As a consequence, the completed adoption of the model-based portfolio was delayed.

To illustrate the resulting model of a portfolio we use a fictional car manufacturer. The portfolio in Figure 9-11 shows three layers of roadmaps. The product "car" at the top, its subsystems (e.g. engine) at the second level, and components (e.g. batteries) at the third level. At the bottom in blue, the technology research projects.

9.5 Summary

The method presented in this chapter uses a novel approach to technology roadmapping. Strictly relying on models for the assessment infusing technology into products is significantly different from common practice in technology roadmapping. Usual methods aim at finding consensus about the development targets, and strategies to get there. The outcome of roadmapping exercises is most commonly summarized in text or charts that do not contain the rationale behind, and make re-use almost impossible.

The proposed method of Concurrent Roadmapping was appreciated by our contact persons in the roadmapping department. Over the course of our research collaboration, we realized that they faced difficulties implementing it at full scale. Parts of the methodology needed to be be introduced step-by-step. Around 60 CDF sessions were held for the creation of roadmaps. It turned out that the roadmapping teams had difficulties building the models. Only a small part of the roadmaps were equipped with the architecture and parametric models foreseen in our approach.

Benefits

Our approach instead follows the model-based engineering paradigm. This requires the involved experts to provide parametric models that underpin the achievability of estimated targets. As in other MBSE efforts, the creation of the model-based roadmaps requires a higher initial effort. The pay-off comes with easier re-use and maintenance. The relevance of this is confirmed by Garcia and Bray [1997], Phaal

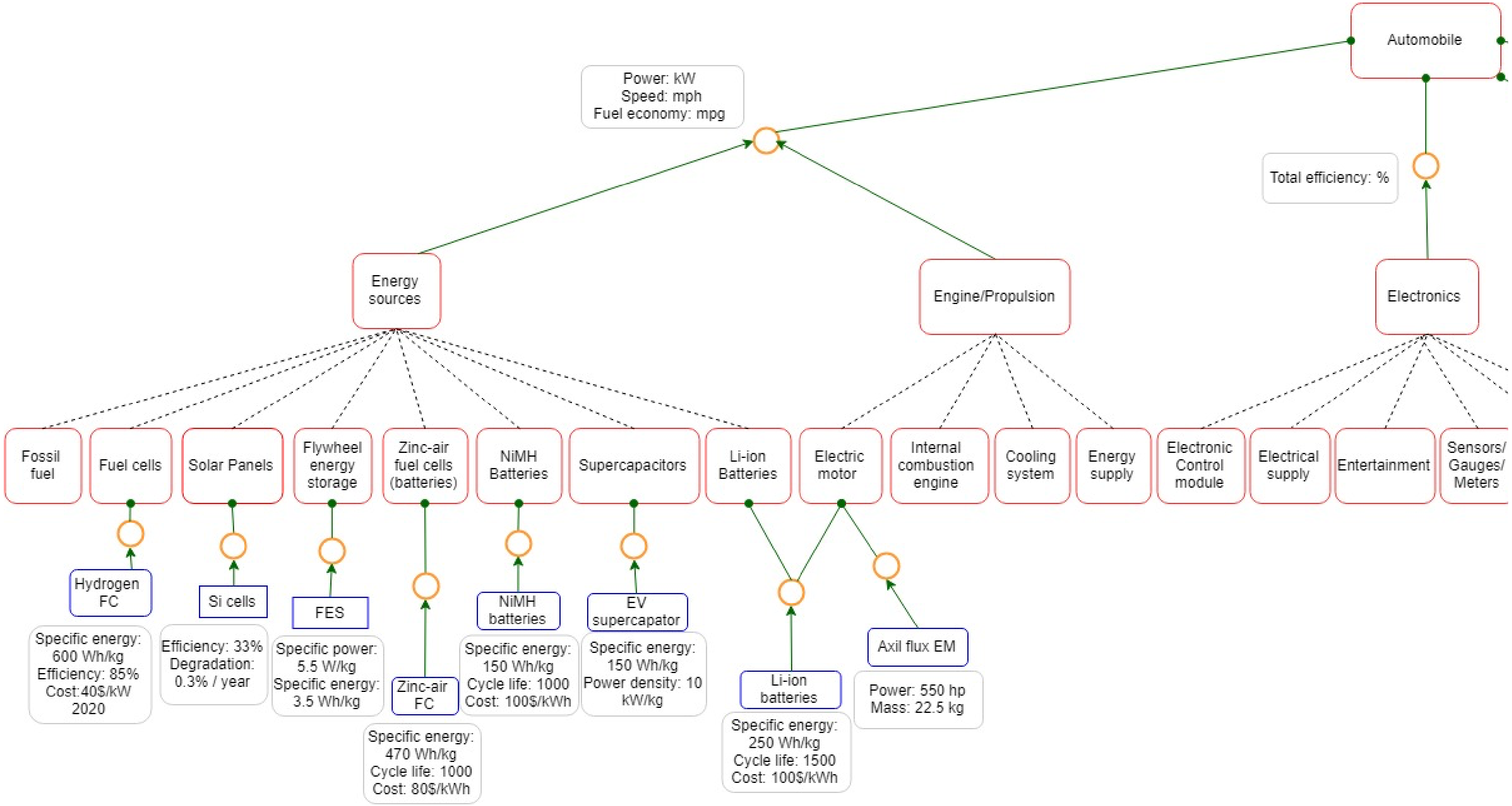


Figure 9-11: Extract from an example portfolio of interconnected TRMs

et al. [2012] who describe "critique and validate" and "review and update" just as important as the creation of the roadmap.

From purely methodological, technical point of view, the co-located design sessions serve to build the conceptual design models. In reality, the human factor is never to be underestimated. Bringing people from across a big organization together to collaborate on defining a technology roadmap creates new connections and relationships. As known from behavioral psychology, people who have met each other in person are more likely to show cooperative behavior [Berkman et al., 2015]. Hence, the overall outcome of the co-located roadmapping sessions goes beyond the produced artifacts.

Challenges

Along with the advantages of using model-based co-located conceptual design for building technology roadmaps, come also challenges.

Conceptual Modeling

The creation of OPM diagrams to represent the roadmap architecture pushed the roadmap owners to frame their work in a specific way and helped to document in a more consistent way, over the wide range of roadmaps. Besides that, it was perceived by various experts involved, as bringing relatively little benefit. That's mainly due to the fact that the OPM diagrams were a mere graphical representation of the roadmap. They are like a specific view on the roadmap data and parametric models. But if the models are disconnected and need to be built and maintained separately, they become a burden.

The method of conceptual modeling using parametric models is well known in some engineering disciplines, and less in others. At product or system level, coarse parametric system models are available for families of products with large design heritage, such as cars, ships, airplanes. For relatively new systems, such as automated vehicles, or technologies, such as augmented reality, such parametric sizing models hardly exist.

This limits the building of parametric models to be used in conceptual design. Analytical models are then to be replaced by informed estimates of experts. The systematic elicitation of qualified opinions may also require experts beyond the roadmapping team. Doing that as part of the concurrent design process is an open challenge.

Organizational Inertia

The introduction of model-based roadmaps aims to provide facts for decision making. Managers of corporate technology development, like other decision makers, need to have trust into the people and process preparing the data for their decisions. We observed that a newly introduced method, and moreover proposed by people from outside the organizations, has a hard time to gain the trust of the decision makers.

To implement changes in an organization, it is not enough to have top-level management make the decision. People stick to acquired routines, because it is safe and less demanding than searching for new answers to a problem. Changing an organization requires to motivate people to leave the known path.

Chapter 10

Conclusion

In the previous chapters, we described a design methodology for Concurrent Conceptual Design and verified it through expert interviews. Further on, we illustrated a set of case studies where we put the methodology to test. In this last chapter, we discuss the results, the limitations of our work, and provide an outlook on future work.

10.1 Discussion

With this work, we want to contribute to the fields of model-based systems engineering and conceptual design. The goals were to improve the understanding of the Concurrent Conceptual Design approach, propose supporting tools for it, and to extend its use. Therefore, we revisit the research question set out in the beginning.

Design Methodology

RQ1 *"Is there a generic design methodology for the concurrent design of complex space systems in an MBSE environment?"*

In response to this question, we investigated the practice of different organizations, documented in literature, and through an expert survey and interviews. This allowed us to extract a generic methodology we called Model-based Co-located

Conceptual Design Methodology (MoCoDeM). This comprehensive description of a methodology for concurrent conceptual design represents a novelty in the field for the following reasons. Firstly, it is generic and not tied to a specific organizational setting, while approaches described in literature are usually originating from a single space agency. Secondly, it uses a formal language to model several aspects, using SysML, the language of choice in Systems Engineering. Thirdly, we have verified and validated the methodology.

Previous related work, as Ferreira [2012] for example, provides a methodology, but its description is not based on models and it lacks of a verification of the methodology. Recently, Infeld et al. [2018] from NASA has shown a full MBSE template for concurrent design studies. It includes the definition of modeling elements, a basic structure for the complete study model, as well as a high-level diagram for the design process. Instead, our description of the design process provides more detail on the construction of the integrated system model and the design iteration. As a result, our process guideline can serve as a baseline for new implementations of Concurrent Conceptual Design of space systems.

Interviews Our methodology and the process guideline at its core has been subject to discussion with subject matter experts (chapter 7). The practitioners confirmed that our process model corresponds in most aspects with the reality they encounter, when setting up and conducting concurrent design studies. The textual description of the process is kept at a very high level, without going into much detail. Experts commented, that in practice, the preparation step, for example, consists of sub-activities, which are not covered well in our description.

Design Studies We conducted concurrent design studies applying our methodology and following the process guideline (chapter 8). To conduct realistic Concurrent Conceptual Design studies for space missions for purely academic purposes is difficult, because qualified experts are hard to attract. Likewise, it is hard to find an organization, which allows to test a design methodology in their environment, if it is not already proven. Hence, we settled with students and researchers from our institute.

One of the goals was to verify if the methodology enables people new to the approach to perform a Concurrent Conceptual Design study. The teams recruited for the case studies were students and researchers, who had little or previous experience in concurrent design. We observed that all teams followed the methodology and managed to produce conceptual designs. Anyway, this does not allow us to conclude that our methodology was the sole factor to success. Our case studies do not allow us to distinguish how individual capabilities, communication skills and personal motivation contributed to the successful design studies. To do so, more comparative studies would be required, using different team compositions.

Since the participants in the design studies did not have deep disciplinary knowledge, the engineering models remained at the level of what they learned from the SMAD textbook [Wertz et al., 2011]. This meant that the resulting conceptual designs are not comparable with those made in space agencies or companies. Space mission design is solving open problems, which means, that multiple correct or optimal solutions exist. Hence, it is hard to objectively measure the quality or optimality of a conceptual design. Good heuristic assessment could only be provided by professional space mission designers, who were not available for our research. Nevertheless, the results of all design studies underwent design reviews by more experienced space engineers, checking the soundness of the solution concepts.

Coordination Support

RQ2 "How can a tool guide the team collaboration through the design process and coordinate the work?"

The collaborative tool we developed, CEDESK, reflects the proposed design methodology MoCoDeM. The pilot studies validated its basic functionality to support multiple users in building and refining a parametric system model. A unique feature of the tool is the integrated process guide (see section 6.9). Similar tools do not feature any process related help. The tools used in concurrent design facilities, at least those openly available, are focused on managing the data. This allows the tool to be used by different organizations without dealing with their specific way of working. Consequently, the teams need to communicate and manage the process independently from the model data.

We found conferences dedicated to modeling and management of engineering processes Heisig et al. [2010], Schabacker et al. [2015]. Researchers from this community argue that the process and the design are strongly interconnected and explicit integration improves the design outcomes.

According to our process, the sequence in which the discipline should update the system model, is determined based on the parametric dependencies, using the DSM clustering and sequencing. In current practice, this order is determined by the study coordinators, based on their experience. For the experts we interviewed, our approach could be beneficial but needs to be proven in practice. Due to the limited amount of case studies we could perform, we lack the evidence of regarding improved process efficiency, when using sequence based on dependencies instead of heuristics.

Complementary to the automatic sequencing, the tool also provides a live view of the dependencies and the propagation of changes, using the N^2-Diagrams. The effect of this support could not be quantified, but participants found it helpful to see the disciplines affected by the latest change, and thereby direct the team's focus.

Since the public release of CEDESK as open source software in June 2017, we saw active interest from a number of organizations. In response, we conducted demonstrations, helped with the setup and gave tutorials on getting started with CEDESK. Moreover, we received feedback of the tool being used during space mission design courses at other universities.

Extension

RQ3 "How can the methodology be adapted to the creation and maintenance of model-based technology roadmaps?"

Roadmaps based on models similar to model-based engineering artifacts have the advantage of easier maintenance and allow for automation [Knoll et al., 2018b].

Traditional roadmaps are limited in their use as they are based on static information (e.g. PowerPoint charts) that is not explicitly linked to the underlying engineering analysis [Moehrle et al., 2013].

In chapter 9 we described a way to apply our design methodology to roadmapping. The Concurrent Roadmapping (CR) method allows to formulate and update model-based technology roadmaps, using the Concurrent Design approach. The multi-disciplinary approach includes all involved disciplines – encompassing technical, product policy, strategy, and other relevant inputs. Our work contains an industrial use case where we implemented CR in a Concurrent Design environment and expert teams build integrated models. Integrated system models enable repeatability and reliability of the roadmapping process. The modeling of a single technology roadmap for the technology infusion evaluation uses the processes and tools covered by CEDESK for Concurrent Conceptual Design. We proposed a new visual representation and created an appropriate toolkit for modeling and managing portfolios of interrelated roadmaps. This new representation can be considered complimentary to the conventional representation of roadmaps focusing on the technology evolution over time.

Our industrial partner appreciated the methodology and tools for Concurrent Roadmapping we defined. In the CDF of our partner around 60 concurrent roadmapping sessions were held. The implementation faced two challenges: 1) limited experience in the roadmapping team with conceptual modeling, 2) the organization's inertia to significantly change the way strategic decisions are prepared. These factors of knowledge management and organizational change need to be properly accounted for.

10.2 Limitations

The discussion already mentioned a few limitations related to the validation. In our prescriptive study, we described a generic design methodology for Concurrent Conceptual Design, including a process guideline, as well as a tool incorporating the methodology and the process. The process guideline was verified in a number of expert interviews. The tool and the process guideline were tested in a number of design studies, conducted over several years. Initial pilot studies were used to inform the definition of the design methodology and test the collaborative design tool. Further, case studies verified the model of the overall design process. A final comparative study tested the reduction of design iteration duration by the use of dependency-based scheduling of design disciplines.

The most influential factor, limiting the number of case studies we could perform, is the availability of people.

- A case study demands a significant amount of time from the participants. That is particularly true when the design task is realistic space mission design. Simpler design tasks could be constructed, but they remain artificial and do not reflect reality.

- The participants should have the necessary disciplinary knowledge for the design of a subsystem of a spacecraft. Without this knowledge the design decisions can be arbitrary and the resulting design of low quality.

- The participants should be motivated to produce a meaningful design as a result. If the participants do not have such a goal, their behavior does not reflect reality.

For this reasons, we used several teams of students doing a conceptual design study as part of a course. They have a realistic design task and are motivated to deliver a feasible conceptual design to get their grade.

Given the small number of case studies, our results do not allow for generalization. To proof effectiveness of our methodology and the improvement provided through the use of our process guideline and tool a wider range of case studies would be required.

10.3 Future lines of work

The results of this work open new perspectives for possible future research.

Standardization

The generic process model and its initial validation form a good baseline for implementing it with new teams or in new organizations. Improving the process model, through more validation and confrontation with practitioners, would allow to develop an industry standard out of it. As standardized data formats support tool-interoperability; likewise, a standardized process could support collaboration between organizations.

Guide for process tailoring

Future work may enrich the process model, covering in more detail the actors and resources associated with each activity. Based on that, a method for tailoring the generic process for a specific project can be defined. Furthermore, a richer process model allows to run simulations, which can be used to estimate the duration upfront. Such a tailoring method and estimation tool would be useful for the definition of the required resources for a study.

Process-centric tools

In our vision, future tools for collaborative design shall explicitly support design processes. A special interest group of the Design Society called "modeling and management of engineering processes" also works on the integration of design model and process model [Heisig et al., 2010, Schabacker et al., 2015]. Although Concurrent Conceptual Design is considered a very creative and agile method, different stages with different needs for information can be identified [Ferreira, 2012]. The different needs can be supported by specialized user interfaces. Further research shall be done to ensure best usability and efficient design workflow.

Given the need to tailor established design processes for specific projects, a collaborative design tool should provide also support for that. Specific research is needed to define the basic design process elements and a graphical notation describing design work-flow. For each of the design steps, specialized user interfaces shall be defined, which allow the designers to interact with a conceptual design model. A tool built on this ground would enable design process customization and execution.

This is how we envision the future of MBSE, and we would like to contribute to the realization of this vision.

Glossary

ADCS Attitude Determination and Control System. 3, 4, 37, 135, 153, 161

API Application Programming Interface. 39

CAD Computer Aided Design. 170

CCD Concurrent Conceptual Design. 6, 15, 32–34, 37, 38, 41, 51, 53, 55–58, 60, 68, 103–105, 121, 128, 131, 186, 191, 215–217, 219, 221

CD Concurrent Design. xii, xiii, 6–9, 12, 34, 35, 43, 53, 55, 59, 63, 67, 68, 101, 153, 162, 178, 180, 203, 219, 253, 254, 259, 261, 262

CDF Concurrent Design Facility. xiii, 35, 42, 45, 46, 60–62, 79, 80, 100, 121, 126, 129, 132, 178, 191, 196, 200, 210, 211, 219, 254, 255, 265, 267

CDP Concurrent Design Platform. 39, 104

CE Concurrent Engineering. 5, 29–32, 51, 190

CEDESK Concurrent Engineering Data Exchange Skoltech. 10, 14, 106–111, 113, 114, 116, 118, 139, 142, 155, 165, 166, 180, 181, 184, 186, 196, 204, 217–219, 271, 272

CEDL Concurrent Engineering Design Laboratory. xi, 45, 76–78, 131, 134, 140, 145, 152, 160, 179

CNES Centre national d'études spatiales, National Centre for Space Studies, France. 35

COTS Commercial and Off-The-Shelf. 126, 148

CR Concurrent Roadmapping. 190, 198, 204, 210, 211, 219

CSCW Computer-Supported Collaborative Work. 9

DLR Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Center. xi, 35, 39, 41, 42, 45, 55, 60, 104, 121

DR Design Research. 15

DRM Design Research Methodology. 9, 11, 58

DSM Design Structure Matrix. xi, xii, 15, 24, 25, 92, 98, 99, 106, 117–119, 124, 142, 143, 147, 149, 155, 157, 158, 170–172, 177, 184, 185, 187, 210, 218, 272

ECSS European Cooperation for Space Standardisation. 20, 38, 39

ELT Extremely Large Telescope. 2, 3

EO Earth Observation. 135

ESA European Space Agency. 7, 20, 35, 39, 45, 55, 59, 60, 121, 122

ESTEC European Space Research and Technology Centre. 35, 122

FOM Figure of Merit. xiii, 26, 27, 83, 84, 86, 90, 112–114, 118, 192–197, 201–205, 207, 209, 210, 261

GPU Graphical Processing Unit. 27, 28

IDEF0 ICAM DEFinition for Function Modeling. 20, 23–25, 71, 198

INCOSE International Council of Systems Engineering. 1, 16, 21, 26

JPL Jet Propulsion Laboratory, California Institute of Technology, United States of America. 34, 35, 39, 40, 56, 126

MBSE Model-Based Systems Engineering. 2, 6–8, 10, 15, 19, 20, 43, 51, 53–55, 73, 74, 101, 103, 127, 129, 198, 211, 216, 222

MDAO Multidisciplinary Design Analysis and Optimization. 32

MDO Multidisciplinary Design Optimization. 15, 30, 32–34, 103, 195

MoCoDeM Model-based Co-located Conceptual Design Methodology. 8, 56, 58, 73, 100, 103, 106, 131, 190, 191, 193, 196, 215–217

NASA National Aeronautics and Space Administration, United States of America. 34, 35, 39, 55, 56, 60, 121, 126, 197, 216

NPV Net Present Value. 193

OBDH Onboard Data Handling. 37, 135, 153, 161

OCDT Open Concurrent Design Tool. 39

OMG Object Management Group. 21

OOSEM Object-Oriented Systems Engineering Method. 20, 21

OPD Object-Process Diagram. 20

OPM Object-Process-Method. xiii, 21, 71, 192, 197, 202, 209, 213, 257

PBS Product Breakdown Structure. 192, 194, 197, 201, 209

PDM Product Data Management. 2

PF Pareto front. 194, 195, 207

PI Principal Investigator. 253, 254

PLM Product Life Cycle Management. 2, 63, 103, 104, 258

PM Project Management. 17, 254

R&D Research and Development. 47

R&T Research and Technology. 47, 57, 189–191, 193, 197, 198, 208–210

SE Systems Engineering. 1, 11, 16, 17, 19, 29, 51, 216, 254

SECESA Systems Engineering and Concurrent Engineering for Space Applications. 59, 60

SVN Subversion. 40

SysML System Modeling Language. 20, 21, 25, 39, 44, 71, 74, 78, 81, 82, 87, 103, 123, 128, 129, 202, 216, 257

TRL Technology Readiness Level. 193, 197

TRM Technology Roadmap. xiii, 199, 200, 202–204, 212

TSE Trade Space Exploration. 15, 86

UML Unified Modeling Language. 21, 25, 38, 109

VirSat Virtual Satellite. 39, 40, 104

THIS PAGE INTENTIONALLY LEFT BLANK

Bibliography

Joseph A. Aguilar, Andrew B Dawdy, and Glenn W. Law. The Aerospace Corporation's Concept Design Center. *INCOSE International Symposium*, 8(1):776–782, 7 1998. ISSN 23345837. doi:10.1002/j.2334-5837.1998.tb00110.x. URL `http://doi.wiley.com/10.1002/j.2334-5837.1998.tb00110.x`.

Rustam Akhtyamov, Ignasi Lluch I. Cruz, Hripsime Matevosyan, Dominik Knoll, Udrivolf Pica, Marco Lisi, and Alessandro Golkar. An implementation of Software Defined Radios for federated aerospace networks: Informing satellite implementations using an inter-balloon communications experiment. *Acta Astronautica*, 123:470–478, 6 2016. ISSN 00945765. doi:10.1016/j.actaastro.2015.12.043. URL `https://linkinghub.elsevier.com/retrieve/pii/S0094576515004786`.

Jose Lorenzo Alvarez, Hans-Peter de Koning, Daniel Fischer, Marcus Wallum, Harold Metselaar, and Michael Kretzenbacher. Best Practices for Model Based Systems Engineering in ESA Projects. In *2018 AIAA SPACE and Astronautics Forum and Exposition*, Reston, Virginia, 9 2018. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-575-3. doi:10.2514/6.2018-5327. URL `https://arc.aiaa.org/doi/10.2514/6.2018-5327`.

ANSI/EIA. ANSI/EIA 632-2003 Processes for Engineering a System. Technical report, American National Standards Institute (ANSI)/Electronic Industries Association (EIA), Philadelphia, PA, USA, 2003. URL `https://www.sae.org/standards/content/eia632/`.

Jonathan L. Arendt, Daniel A. McAdams, and Richard J. Malak. Uncertain Technology Evolution and Decision Making in Design. *Journal of Mechanical Design*, 134(10):100904, 2012. ISSN 10500472. doi:10.1115/1.4007396. URL `http://mechanicaldesign.asmedigitalcollection.asme.org/article.aspx?articleid=1484825`.

Jesse Austin-Breneman, Tomonori Honda, and Maria C. Yang. A Study of Student Design Team Behaviors in Complex System Design. *Journal of Mechanical Design*, 134(12):124504–124504, 11 2012. ISSN 1050-0472. doi:10.1115/1.4007840. URL `http://dx.doi.org/10.1115/1.4007840`.

Mark S. Avnet. *SOCIO-COGNITIVE ANALYSIS OF ENGINEERING SYSTEMS DESIGN: SHARED KNOWLEDGE, PROCESS, AND PRODUCT*. PhD thesis, Massachusetts Institute of Technology, 1 2009.

Mark S. Avnet. A Network-Based Analysis of Team Coordination and Shared Cognition in Systems Engineering. *Systems Engineering*, 19(5):395–408, 9 2016. ISSN 10981241. doi:10.1002/sys.21341. URL `http://doi.wiley.com/10.1002/sys.21341`.

Mark S. Avnet and Annalisa L. Weigel. An application of the Design Structure Matrix to Integrated Concurrent Engineering. *Acta Astronautica*, 66(5-6):937–949, 2010. ISSN 00945765. doi:10.1016/j.actaastro.2009.09.004. URL `http://dx.doi.org/10.1016/j.actaastro.2009.09.004`.

M. Bandecchi, B. Melton, and F. Ongaro. Concurrent Engineering Applied to Space Mission Assessment and Design. *ESA bulletin*, 1999. URL `http://www.esa.int/esapub/bulletin/bullet99/bande99.pdf`.

Massimo Bandecchi, Bryan Melton, Bruno Gardini, and Franco Ongaro. The ESA/ESTEC concurrent design facility. In *Proceedings of the EuSEC 2000*, volume 1, page 329–336, 2000. ISBN 3896759353.

Stefano Beco, Andrea Parrini, Carlo Paccagnini, Fred Feresin, and Arne Tøn. Grid-based Virtual Collaborative Facility : Concurrent and Collaborative Engineering for Space Projects. In Richard Curran, Shuo-Yan Chou, and Amy Trappey, editors, *Collaborative Product and Service Life Cycle Management for a Sustainable World*, pages 77–85. Springer London, London, 2008. ISBN 9781848009714. doi:10.1007/978-1-84800-972-1_8. URL `http://dx.doi.org/10.1007/978-1-84800-972-1_8`.

Elliot T. Berkman, Evgeniya Lukinova, Ivan Menshikov, and Mikhail Myagkov. Sociality as a Natural Mechanism of Public Goods Provision. *PLOS ONE*, 10(3):e0119685, 3 2015. ISSN 1932-6203. doi:10.1371/journal.pone.0119685. URL `https://dx.plos.org/10.1371/journal.pone.0119685`.

Luis Bernal, Utz Dornberger, Omar Torres, and Trevor Byrnes. Technology Roadmapping. Technical Report June, University of Leipzig, International SEPT Program, 2009. URL `http://www.vgu.edu.vn/fileadmin/pictures/studies/MBA/Handbook_Roadmapping.pdf`.

Cees Bil. Multidisciplinary Design Optimization: Designed by Computer. In *Concurrent Engineering in the 21st Century*, pages 421–454. Springer International Publishing, Cham, 2015. doi:10.1007/978-3-319-13776-6_15. URL `http://link.springer.com/10.1007/978-3-319-13776-6_15`.

Lucienne T.M. Blessing and Amaresh Chakrabarti. *DRM, a Design Research Methodology.* Springer London, London, 2009. ISBN 978-1-84882-586-4. doi:10.1007/978-1-84882-587-1. URL `http://link.springer.com/10.1007/978-1-84882-587-1`.

Luiz A. Bloem da Silveira Junior, Eduardo Vasconcellos, Liliana Vasconcellos Guedes, Renato Machado Costa, and Luis Fernando A. Guedes. Technology roadmapping: A methodological proposition to refine Delphi results. *Technological Forecasting and Social Change*, 126(September 2017):194–206, 2018. ISSN 00401625. doi:10.1016/j.techfore.2017.08.011.

Milton Borsato and Margherita Peruzzini. Collaborative Engineering. In *Concurrent Engineering in the 21st Century*, pages 165–196. Springer International Publishing, Cham, 2015. doi:10.1007/978-3-319-13776-6_7. URL `http://link.springer.com/10.1007/978-3-319-13776-6_7`.

P W Bousquet, J Sire, and F Vigeant. Concurrent Engineering at CNES. *56th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law*, pages 1–11, 2005. doi:10.2514/6.IAC-05-D1.3.06. URL `http://arc.aiaa.org/doi/10.2514/6.IAC-05-D1.3.06`.

A. Braukhane and D. Quantius. Interactions in space systems design within a Concurrent Engineering facility. In *2011 International Conference on Collaboration Technologies and Systems (CTS)*, pages 381–388. IEEE, 5 2011. ISBN 978-1-61284-638-5. doi:10.1109/CTS.2011.5928714. URL `http://ieeexplore.ieee.org/document/5928714/`.

Andy Braukhane. Evolution of the European Concurrent Design Tool for Space-based System-of-Systems studies. In *AIAA SPACE 2015 Conference and Exposition*, pages 1–12, Reston, Virginia, 8 2015. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-334-6. doi:10.2514/6.2015-4438. URL `http://arc.aiaa.org/doi/10.2514/6.2015-4438`.

Andy Braukhane and Torsten Bieler. The Dark Side of Concurrent Design: A Story of Improvisations, Workarounds, Nonsense and Success. In *6th International Conference on Systems & Concurrent Engineering for Space Applications*, 10 2014. URL `http://elib.dlr.de/92977/`.

Andy Braukhane and Oliver Romberg. Lessons Learned from One-Week Concurrent Engineering Study Approach. In *Proceedings of the 17th International Conference on Concurrent Enterprising (ICE 2011)*, 2011. ISBN 978–3–943024–05–0. URL `www.ice-conference.org`.

Andy Braukhane, Volker Maiwald, Antonio Martelo, Dominik Quantius, and Oliver Romberg. BE AWARE OF THE SQUAD: LESSONS LEARNT FROM 50 CONCURRENT ENGINEERING STUDIES FOR SPACE SYSTEMS. In *66th International Astronautical Congress (IAC)*, 10 2015. URL `http://elib.dlr.de/98729/`.

O.H. Bray and M.L. Garcia. Technology roadmapping: the integration of strategic and technology planning for competitiveness. In *Innovation in Technology Management. The Key to Global Leadership. PICMET '97*, pages 25–28. IEEE, 1997. ISBN 0-7803-3574-0. doi:10.1109/PICMET.1997.653238. URL `http://ieeexplore.ieee.org/document/653238/`.

Simone Briatore, Rustam Akhtyamov, and Alessandro Golkar. Design and flight test results of high speed optical bidirectional link between stratospheric platforms for aerospace applications. In Alexander M. van Eijk, Stephen M. Hammel, and Jeremy P. Bos, editors, *Laser Communication and Propagation through the Atmosphere and Oceans VI*, volume 10408, page 3. International Society for Optics and Photonics, SPIE, 8 2017. ISBN 9781510612730. doi:10.1117/12.2273808. URL `https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10408/2273808/Design-and-flight-test-results-of-high-speed-optical-bidirectional/10.1117/12.2273808.full`.

Tyson R. Browning, Ernst Fricke, and Herbert Negele. Key concepts in modeling product development processes. *Systems Engineering*, 9(2):104–128, 2006. ISSN 1098-1241. doi:10.1002/sys.20047. URL `http://doi.wiley.com/10.1002/sys.20047`.

Caltech. Jet Propultion Laboratory - Team X, 2015. URL `http://jplteamx.jpl.nasa.gov/`.

Senthil K. Chandrasegaran, Karthik Ramani, Ram D. Sriram, Imré Horváth, Alain Bernard, Ramy F. Harik, and Wei Gao. The evolution, challenges, and future of knowledge representation in product design systems. *Computer-Aided Design*, 45 (2):204–228, 2 2013. ISSN 00104485. doi:10.1016/j.cad.2012.08.006. URL `https://linkinghub.elsevier.com/retrieve/pii/S0010448512001741`.

Shi-Jie (Gary) Chen. An Integrated Methodological Framework for Project Task Coordination and Team Organization in Concurrent Engineering. *Concurrent Engineering: Research and Applications*, 13(3):185–197, 2005. ISSN 1063-293X. doi:10.1177/1063293X05056462.

SangSu Choi, Kiwook Jung, and Sang Do Noh. Virtual reality applications in manufacturing industries: Past research, present findings, and future directions. *Concurrent Engineering*, 23(1):40–63, 3 2015. ISSN 1063-293X. doi:10.1177/1063293X14568814. URL `http://journals.sagepub.com/doi/10.1177/1063293X14568814`.

Edward Crawley, Bruce Cameron, and Daniel Selva. *System Architecture: Strategy and Product Development for Complex Systems*. Prentice Hall, Boston, 1 edition edition, 4 2015. ISBN 978-0-13-397534-5. URL `http://www.pearsonhighered.com/educator/product/System-Architecture-Strategy-and-Product-Development-for-Complex-Systems/9780133975345.page`.

Daniele Gianni, Daniele Gianni, Volker Schaus, Andreas Gerndt, Marco Lisi, and Pierluigi De Simone. Interface Management in Concurrent Engineering Facilities for Systems and Service Systems Engineering: A Model-based Approach. In *INCOSE Italian Chapter Conference on Systems Engineering (CIISE2014)*, Rome, Italy, 11 2014. URL `http://ceur-ws.org/Vol-1300/ID08.pdf`.

Dassault Systems. ENOVIA, 2016. URL `https://www.3ds.com/products-services/enovia/`.

Olivier L. de Weck and Darren D Chang. Quantitative Assessment of Technology Infusion in Communications Satellite Constellations. *21st International Communications Satellite Systems Conference and Exhibit*, pages 1–12, 2003. ISSN 0146-3705.

Christopher Delp, Doris Lam, Elyse Fosse, and Cin Young Lee. Model based document and report generation for systems engineering. *IEEE Aerospace Conference Proceedings*, 2013. ISSN 1095323X. doi:10.1109/AERO.2013.6496926.

D. Di Domizio and P. Gaudenzi. A Model for Preliminary Design Procedures of Satellite Systems. *Concurrent Engineering*, 16(2):149–159, 2008. ISSN 1063-293X. doi:10.1177/1063293X08092488. URL `http://cer.sagepub.com/cgi/doi/10.1177/1063293X08092488`.

DLR. Virtual Satellite 3, 2016. URL `https://software.dlr.de/p/virsat/home/`.

D Dori. *Object-Process Methodology: A Holistic Systems Paradigm*. Springer Berlin Heidelberg, 2011. ISBN 9783642562099. URL `https://www.springer.com/gp/book/9783540654711`.

Claudia M. Eckert, David C. Wynn, Jakob F. Maier, Albert Albers, Nikola Bursac, Hilario L. Xin Chen, P. John Clarkson, Kilian Gericke, Bartosz Gladysz, and Daniel Shapiro. On the integration of product and process models in engineering design. *Design Science*, 3:e3, 3 2017. ISSN 2053-4701. doi:10.1017/dsj.2017.2. URL `https://www.cambridge.org/core/product/identifier/S2053470117000026/type/journal_article`.

ECSS. Space engineering - Engineering design model data exchange (CDF). Technical report, European Cooperation for Space Standardization, Noordwijk, The Netherlands, 2010. URL `http://escies.org/ftp/ecss.nl/TMs/ECSS-E-TM-10-25A(20October2010).pdf`.

S.D. Eppinger and T.R. R. Browning. *Design Structure Matrix Methods and Applications.* MIT Press, 2012. ISBN 978-0-262-01752-7. doi:10.1017/CBO9781107415324.004.

ESA. Open Concurrent Design Tool, 2014. URL `https://ocdt.esa.int/`.

ESA ESTEC. ESA Concurrent Design Facility CDF. Technical report, European Space Research and Technology Centre, 2019. URL `http://esamultimedia.esa.int/docs/cdf/ESA_CDF_Infopack_2019_16x9_rev1.pdf`.

Ivo Ferreira and Paul Grogan. Data Management, Collaboration, and Model Integration for Space Exploration System Analysis and Design. In *AIAA SPACE 2010 Conference & Exposition*, Reston, Virigina, 8 2010. American Institute of Aeronautics and Astronautics. ISBN 978-1-60086-966-2. doi:10.2514/6.2010-8808. URL `http://arc.aiaa.org/doi/10.2514/6.2010-8808`.

Ivo Miguel Lopes Ferreira. *Enhancing the conceptual design phase of complex engineering systems with an integrated methodology and support tools*. PhD thesis, Universidade Técnica De Lisboa Instituto Superior Técnico, 2012. URL `http://in3.dem.ist.utl.pt/edam/docs/2012-thesis-Ivo-Ferreira.pdf`.

Ivo M.L. Ferreira and Paulo J.S. Gil. Application and performance analysis of neural networks for decision support in conceptual design. *Expert Systems with Applications*, 39(9):7701–7708, 7 2012. ISSN 09574174. doi:10.1016/j.eswa.2012.01.045. URL `https://linkinghub.elsevier.com/retrieve/pii/S0957417412000589`.

M Fijneman and A Matthyssen. Application of Concurrent Design in Construction, Maritime, Education and Other Industry Fields. In *Proceedings of the 4th International Workshop on System & Concurrent Engineering for Space Applications (SECESA 2010), Lausanne, Switzerland*, 2010.

Philipp Martin Fischer, Meenakshi Deshmukh, Volker Maiwald, Dominik Quantius, Antonio Martelo Gomez, and Andreas Gerndt. Conceptual data model: A foundation for successful concurrent engineering. *Concurrent Engineering*, 26(1):55–76, 3 2017a. ISSN 1063-293X. doi:10.1177/1063293X17734592. URL `http://journals.sagepub.com/doi/10.1177/1063293X17734592`.

P.M. M. Fischer, D. Lüdtke, C. Lange, F.-C. Roshani, F. Dannemann, and A. Gerndt. Implementing model-based system engineering for the whole lifecycle of a spacecraft. *CEAS Space Journal*, 9(3):351–365, 9 2017b. ISSN 1868-2502. doi:10.1007/s12567-017-0166-4. URL `http://link.springer.com/10.1007/s12567-017-0166-4`.

Kevin Forsberg, Hal Mooz, and Howard Cotterman. *Visualizing Project Management*. John Wiley & Sons, Inc., Hoboken, New Jersey, 3rd edition, 2005. ISBN 0-978-0-471-64848-2.

Clément Fortin, Grant McSorley, Dominik Knoll, Alessandro Golkar, and Ralina Tsykunova. Study of Data Structures and Tools for the Concurrent Conceptual Design of Complex Space Systems. In *IFIP 14th International Conference on Product Lifecycle Management 9-12 July 2017, Seville, Spain*, pages 601–611. Springer, Cham, Seville, 2017. doi:10.1007/978-3-319-72905-3_53. URL `http://link.springer.com/10.1007/978-3-319-72905-3_53`.

Elyse Fosse. Model-based Systems Engineering. In *INOSE International Workshop 2019*, 2019. URL `http://wiki.omg.org/MBSE/lib/exe/fetch.php?media=mbse:incose_mbse_iw_2019:2019_iw_mbse_101.pdf`.

Elyse Fosse, Ann Devereaux, Corey Harmon, and Mallory Lefland. Inheriting Curiosity: Leveraging MBSE to Build Mars2020. In *AIAA SPACE 2015 Conference and Exposition*, pages 1–7, Reston, Virginia, 8 2015. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-334-6. doi:10.2514/6.2015-4617. URL `http://arc.aiaa.org/doi/10.2514/6.2015-4617`.

Sanford Friedenthal, Alan Moore, and Rick Stiner. *A Practical Guide to SysML: The Systems Modeling Language*. Morgan Kaufmann, Amsterdam; Boston, 3 edition edition, 11 2014. ISBN 978-0-12-800202-5.

Marie L Garcia and Olin H Bray. Fundamentals of Technology Roadmapping. Technical report, Sandia National Laboratories, 1997. URL `http://prod.sandia.gov/techlib/access-control.cgi/1997/970665.pdf`.

Juergen Gausemeier, Volker Brink, Stephan Ihmels, Martin Kokoschka, and Felix Reymann. Strategic product-and technology-planning with the innovation-database: A field-proven approach from the market-oriented product idea up to an operational development roadmap. *Proceedings of the IEEE International Conference on Industrial Technology*, 2009. doi:10.1109/ICIT.2009.4939494.

Kilian Gericke, Claudia Eckert, and Martin Stacey. What do we need to say about a design method? *Proceedings of the 21st International Conference on Engineering Design*, 7(August):101–110, 2017. ISSN 22204342. doi:10.1002/9780470087954.ch8.

Michele Germani, Maura Mengoni, and Margherita Peruzzini. An approach to assessing virtual environments for synchronous and remote collaborative design. *Advanced Engineering Informatics*, 26(4):793–813, 10 2012. ISSN 14740346. doi:10.1016/j.aei.2012.06.003. URL `https://linkinghub.elsevier.com/retrieve/pii/S1474034612000560`.

Alessandro Golkar. Lessons learnt in the development of a Concurrent Engineering Infrastructure. *INCOSE International Symposium*, 26(1):1759–1769, 7 2016. ISSN 23345837. doi:10.1002/j.2334-5837.2016.00259.x. URL `http://doi.wiley.com/10.1002/j.2334-5837.2016.00259.x`.

Alessandro Golkar and Ignasi Lluch I Cruz. The Federated Satellite Systems paradigm: Concept and business case evaluation. *Acta Astronautica*, 111:230–248, 2015. ISSN 00945765. doi:10.1016/j.actaastro.2015.02.009. URL `http://dx.doi.org/10.1016/j.actaastro.2015.02.009`.

Antonio Martelo Gomez, Stephan Siegfried Jahnke, Andy Braukhane, Dominik Quantius, Volker Maiwald, and Oliver Romberg. Statistics and Evaluation of 60+ Concurrent Engineering Studies at DLR. In *Proceedings of the International Astronautical Congress, IAC*, 9 2017. URL `http://elib.dlr.de/114620/`.

James A. Gopsill, Hamish C. McAlpine, and Ben J. Hicks. A social media framework to support engineering design communication. *Advanced Engineering Informatics*, 2013. ISSN 14740346. doi:10.1016/j.aei.2013.07.002.

James A. Gopsill, Hamish C. McAlpine, and Ben J. Hicks. Supporting engineering design communication using a custom-built social media tool - PartBook. *Advanced Engineering Informatics*, 2015. ISSN 14740346. doi:10.1016/j.aei.2015.04.008.

Justin S. Gray, John T. Hwang, Joaquim R. R. A. Martins, Kenneth T. Moore, and Bret A. Naylor. OpenMDAO: an open-source framework for multidisciplinary design, analysis, and optimization. *Structural and Multidisciplinary Optimization*, pages 1–30, 3 2019. ISSN 1615-147X. doi:10.1007/s00158-019-02211-z. URL `http://link.springer.com/10.1007/s00158-019-02211-z`.

Paul T. Grogan and Olivier L. de Weck. Collaboration and complexity: an experiment on the effect of multi-actor coupled design. *Research in Engineering Design*, 2 2016. ISSN 0934-9839, 1435-6066. doi:10.1007/s00163-016-0214-7. URL `http://link.springer.com/10.1007/s00163-016-0214-7`.

C Haskins, K Forsberg, M Krueger, David Walden, and R. Douglas Hamelin, editors. *Systems Engineering Handbook: a Guide for Systems Life Cycle Process and Activities*. International Council on Systems Engineering, v. 3.2.2 edition, 2011. ISBN 9781118999400.

Yotaro Hatamura, editor. *Decision-Making in Engineering Design*. Decision Engineering. Springer-Verlag, London, 2006. ISBN 1-84628-000-1. doi:10.1007/1-84628-261-6. URL `http://link.springer.com/10.1007/1-84628-261-6`.

Peter Heisig, P. John Clarkson, and Sandor Vajna, editors. *Modelling and Management of Engineering Processes*. Springer London, London, 5 2010. ISBN 978-1-84996-198-1. doi:10.1007/978-1-84996-199-8. URL `http://link.springer.com/10.1007/978-1-84996-199-8`.

Martin Hepperle. Electric Flight - Potential and Limitations. In *Energy Efficient Technologies and Concepts of Operation*, Lisbon, 10 2012. URL `http://elib.dlr.de/78726/`.

N. Hirschi and D. Frey. Cognition and complexity: An experiment on the effect of coupling in parameter design. *Research in Engineering Design*, 13(3):123–131, 2002. ISSN 0934-9839. doi:10.1007/s00163-002-0011-3. URL `http://link.springer.com/10.1007/s00163-002-0011-3`.

Hans-Peter Hoffmann. *System Engineering Best Practices with the Rational Solution for System and Software Engineering*. IBM Software Group, release 3. edition, 2011.

Imre Horváth. On some Crucial Issues of Computer Support of Conceptual Design. In *Product Engineering*, pages 123–142. Kluwer Academic Publishers, Dordrecht, 2006. doi:10.1007/1-4020-2933-0_9. URL `http://link.springer.com/10.1007/1-4020-2933-0_9`.

Jinmin Hu, Jianxun Liu, and Brian Prasad. A Constraint-driven Execution Plan for Maximizing Concurrency in Product Development. *Concurrent Engineering*, 11(4):301–312, 2003. ISSN 1063293X. doi:10.1177/1063293X03038568.

INCOSE. *Systems Engineering Vision 2020*. INCOSE, 2.03 edition, 2007. URL `http://www.incose.org/ProductsPubs/pdf/SEVision2020_20071003_v2_03.pdf`.

Samantha I. Infeld, David Goggin, Kevin Vipavetz, and Trevor Grondin. A SysML Model Template for NASA Concurrent Engineering Studies. In *2018 AIAA SPACE and Astronautics Forum and Exposition*, Reston, Virginia, 9 2018. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-575-3. doi:10.2514/6.2018-5392. URL `https://arc.aiaa.org/doi/10.2514/6.2018-5392`.

ISO Central Secretary. ISO/IEC/IEEE 15288:2015 Systems and software engineering – System life cycle processes. Technical report, International Organization for Standardization, Geneva, CH, 2015a. URL `https://www.iso.org/standard/63711.html`.

ISO Central Secretary. ISO/PAS 19450:2015 Automation systems and integration Object-Process Methodology. Technical report, International Organization for Standardization, Geneva, CH, 2015b. URL `https://www.iso.org/standard/62274.html`.

ISO Central Secretary. ISO/IEC/IEEE 24765:2017 Systems and software engineering - Vocabulary. Technical report, International Organization for Standardization, Geneva, CH, 2017. URL `https://www.iso.org/standard/71952.html`.

Curtis Iwata, Samantha Infeld, Jennifer Medlin Bracken, Melissa McGuire, Christina McQuirck, Aron Kisdi, Jonathan Murphy, Bjorn Cole, and Pezhman Zarifian. Model-Based Systems Engineering in Concurrent Engineering Centers. In *AIAA SPACE 2015 Conference and Exposition*, pages 1–13, Reston, Virginia, 8 2015. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-334-6. doi:10.2514/6.2015-4437. URL `http://arc.aiaa.org/doi/10.2514/6.2015-4437`.

Stephan Siegfried Jahnke and Antonio Martelo. Special Characteristics of Concurrent Engineering Studies dealing with Cubesat Missions and their Impact on the CE Process. In *Systems Engineering and Concurrent Engineering for Space Applications*, Madrid, 2016.

Jérome Jetter, Jörgen Eimecke, and Alexandra Rese. Augmented reality tools for industrial applications: What are potential key performance indicators and who benefits? *Computers in Human Behavior*, 2018. ISSN 07475632. doi:10.1016/j.chb.2018.04.054.

Cyrus D Jilla. *A Multiobjective, Multidisciplinary Design Optimization Methodology for the Conceptual Design of Distributed Satellite Systems*. PhD thesis, Massachusetts Inst. of Technology, Cambridge, MA, 2002.

E. Kane Casani and Robert M Metzger. Reengineering the project design process. *Acta Astronautica*, 35(Supplement 1):681–689, 1995. ISSN 00945765. doi:10.1016/0094-5765(94)00236-F. URL `https://linkinghub.elsevier.com/retrieve/pii/009457659400236F`.

Robert Karban, Frank G. Dekens, Sebastian Herzig, Maged Elaasar, and Nerijus Jankevičius. Creating system engineering products with executable models in a model-based engineering environment. In George Z. Angeli and Philippe Dierickx, editors, *SPIE Astronomical Telescopes + Instrumentation*, page 99110B, Edinburgh, United Kingdom, 8 2016. doi:10.1117/12.2232785. URL `http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.2232785`.

G. Karpati, J. Martin, M. Steiner, and K. Reinhardt. The Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center. *IEEE Aerospace Conference Proceedings*, 8(Imdc):3657–3667, 2003. ISSN 1095323X. doi:10.1109/AERO.2003.1235549.

Gabriel Karpati, John Panek, George Polacek, Bruce Campbell, and Mark Avnet. Information Flow In A Concurrent Engineering Lab And The Tools That Enable It. In *AIAA SPACE 2011 Conference & Exposition*, Reston, Virigina, 9 2011. American Institute of Aeronautics and Astronautics. ISBN 978-1-60086-953-2. doi:10.2514/6.2011-7241. URL `http://arc.aiaa.org/doi/10.2514/6.2011-7241`.

C.I.V. Kerr, L. Mortara, R. Phaal, and D.R. Probert. A conceptual model for technology intelligence. *International Journal of Technology Intelligence and Planning*, 2(1):73, 2006. ISSN 1740-2832. doi:10.1504/IJTIP.2006.010511. URL `http://www.inderscience.com/link.php?id=10511`.

Dominik Knoll and Alessandro Golkar. A coordination method for concurrent design and a collaboration tool for parametric system models. *Concurrent Engineering*, 26(1):5–21, 3 2018. ISSN 1063-293X. doi:10.1177/1063293X17732374. URL `http://journals.sagepub.com/doi/10.1177/1063293X17732374`.

Dominik Knoll, Clement Fortin, and Alessandro Golkar. Review of Concurrent Engineering Design practice in the space sector: state of the art and future perspectives. In *2018 IEEE International Systems Engineering Symposium (ISSE)*, pages 1–6, Rome, Italy, 10 2018a. IEEE. ISBN 978-1-5386-4446-1. doi:10.1109/SysEng.2018.8544387. URL `https://ieeexplore.ieee.org/document/8544387/`.

Dominik Knoll, Alessandro Golkar, and Olivier de Weck. A concurrent design approach for model-based technology roadmapping. In *2018 Annual IEEE International Systems Conference (SysCon)*, pages 1–6, Vancouver, Canada, 4 2018b. IEEE. ISBN 978-1-5386-3664-0. doi:10.1109/SYSCON.2018.8369527. URL `https://ieeexplore.ieee.org/document/8369527/`.

R.N. Kostoff and R.R. Schaller. Science and technology roadmaps. *IEEE Transactions on Engineering Management*, 48(2):132–143, 5 2001. ISSN 00189391. doi:10.1109/17.922473. URL `http://ieeexplore.ieee.org/document/922473/`.

Tejas Kulkarni, Kevin DeBruin, Adam Nelessen, Kevin A. Reilley, Russell Peak, Stephen J. Edwards, and Dimitri N. Mavris. A Model Based Systems Engineering Approach Towards Developing a Rapid Analysis and Trades Environment. In *AIAA SPACE 2016*, pages 13–16, Reston, Virginia, 9 2016. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-427-5. doi:10.2514/6.2016-5472. URL `http://arc.aiaa.org/doi/10.2514/6.2016-5472`.

James Long. Model-Based Systems Engineering For Project Success: The Complete Process. *INCOSE International Symposium*, 20(1):1502–1644, 7 2010. ISSN 23345837. doi:10.1002/j.2334-5837.2010.tb01154.x. URL `http://doi.wiley.com/10.1002/j.2334-5837.2010.tb01154.x`.

S.C-Y. Lu, W. Elmaraghy, G. Schuh, and R. Wilhelm. A SCIENTIFIC FOUNDATION OF COLLABORATIVE ENGINEERING. *CIRP Annals*, 56(2):605–634, 2007. ISSN 00078506. doi:10.1016/j.cirp.2007.10.010. URL `https://linkinghub.elsevier.com/retrieve/pii/S0007850607001606`.

Melissa McGuire, Steven Oleson, Maria Babula, and Timothy Sarver-verhey. Concurrent Mission and Systems Design at NASA Glenn Research Center: The origins of the COMPASS Team. In *AIAA SPACE 2011 Conference & Exposition*, page 20, Reston, Virigina, 9 2011. American Institute of Aeronautics and Astronautics. ISBN 978-1-60086-953-2. doi:10.2514/6.2011-7240. URL `http://arc.aiaa.org/doi/10.2514/6.2011-7240`.

Hugh McManus and Daniel Hastings. A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems. *INCOSE International Symposium*, 15(1):484–503, 7 2005. ISSN 23345837. doi:10.1002/j.2334-5837.2005.tb00685.x. URL `http://doi.wiley.com/10.1002/j.2334-5837.2005.tb00685.x`.

Deshmukh Meenakshi, Volker Schaus, Philipp M. Fischer, Dominik Quantius, Volker Maiwald, and Andreas Gerndt. Decision Support Tool for Concurrent Engineering in Space Mission Design. In *Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment*, pages 497–508. Springer London, London, 2013. doi:10.1007/978-1-4471-4426-7_43.

Christopher Menzel and Richard J. Mayer. The IDEF Family of Languages. In *Handbook on Architectures of Information Systems*, pages 209–241. Springer Berlin Heidelberg, Berlin, Heidelberg, 1998. doi:10.1007/978-3-662-03526-9_10. URL `http://link.springer.com/10.1007/978-3-662-03526-9_10`.

Martin G. Moehrle, Ralf Isenmann, and Robert Phaal, editors. *Technology Roadmapping for Strategy and Innovation*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2013. ISBN 978-3-642-33922-6. doi:10.1007/978-3-642-33923-3. URL `http://link.springer.com/10.1007/978-3-642-33923-3`.

Carolina Moreno, Alessandro Golkar, and Rupert Gerzer. Design and Development of a CubeSat Platform for Supporting Human Physiological in-vitro Studies in Space. In *69th International Astronautical Congress (IAC)*, pages 1–5, Bremen, Germany, 2018.

Elisabeth Morse, T. Leavens, B. Cohanim, C. Harmon, Eric Mahr, and Brian Lewis. Next-Generation Concurrent Engineering: Developing Models to Complement Point Designs. In *2006 IEEE Aerospace Conference*, pages 1–15. IEEE, 2006. ISBN 0-7803-9545-X. doi:10.1109/AERO.2006.1656160. URL `http://ieeexplore.ieee.org/document/1656160/`.

NASA JPL. Open Model Based Engineering Environment, 2016. URL `http://www.openmbee.org/`.

A. Y.C. Nee, S. K. Ong, G. Chryssolouris, and D. Mourtzis. Augmented reality applications in design and manufacturing. *CIRP Annals - Manufacturing Technology*, 2012. ISSN 00078506. doi:10.1016/j.cirp.2012.05.010.

Mariano Nieto, Francisco Lopéz, and Fernando Cruz. Performance analysis of technology using the S curve model: the case of digital signal processing (DSP) technologies. *Technovation*, 18(6-7):439–457, 1 1998. ISSN 01664972. doi:10.1016/S0166-4972(98)00021-2. URL `http://linkinghub.elsevier.com/retrieve/pii/S0166497298000212`.

NoMagic. MagicDraw, 2015. URL `https://www.nomagic.com/products/magicdraw`.

R.E. Oberto, Erik Nilsen, Ron Cohen, Rebecca Wheeler, P. DeFlono, and Chester Borden. The NASA Exploration Design Team: blueprint for a new design paradigm. In *2005 IEEE Aerospace Conference*, pages 4398–4405. IEEE, 2005. ISBN 0-7803-8870-4. doi:10.1109/AERO.2005.1559745. URL `http://ieeexplore.ieee.org/document/1559745/`.

Object Management Group. Unified Modeling Language (UML) 2.0, 2005. URL `https://www.omg.org/spec/UML/2.0`.

Object Management Group. OMG Systems Modeling Language (SysML) 1.2, 2010. URL `https://www.omg.org/spec/SysML/1.2/`.

Object Management Group. OMG Systems Modeling Language (SysML) 1.4, 2015. URL `https://www.omg.org/spec/SysML/1.4/`.

Gul E Okudan and Rohan A. Shirwaiker. Concept selection methods–a literature review from 1980 to 2008. *International Journal of Design Engineering*, 1(3): 243–277, 2008.

Oracle. MySQL, 2016. URL `https://www.mysql.com/`.

Brendan O'Donovan, Claudia Eckert, John Clarkson, and Tyson R Browning. Design planning and modelling. In *Design process improvement*, pages 60–87. Springer London, London, 2005. doi:10.1007/978-1-84628-061-0_3. URL `http://link.springer.com/10.1007/978-1-84628-061-0_3`.

G. Pahl, W. Beitz, J. Feldhusen, and K.H. Grote. *Engineering Design*. Springer-Verlag London, 3rd edition, 2007. ISBN 9781846283185.

Apostolos Papanikolaou. *Ship Design*. Springer Netherlands, Dordrecht, 2014. ISBN 978-94-017-8750-5. doi:10.1007/978-94-017-8751-2. URL `http://link.springer.com/10.1007/978-94-017-8751-2`.

Robert Phaal, Clare J.P. Farrukh, and David R. Probert. A framework for supporting the management of technological knowledge. *International Journal of Technology Management*, 27(1):1, 2004. ISSN 0267-5730. doi:10.1504/IJTM.2004.003878. URL `https://www.inderscienceonline.com/doi/abs/10.1504/IJTM.2004.003878`.

Robert Phaal, Clive Kerr, Dominic Oughton, and David Probert. Towards a modular toolkit for strategic technology management. *International Journal of Technology Intelligence and Planning*, 8(2):161, 2012. ISSN 1740-2832. doi:10.1504/IJTIP.2012.048475. URL `http://www.inderscienceonline.com/doi/abs/10.1504/IJTIP.2012.048475`.

Phoenix Integration. ModelCenter, 2015. URL `http://www.phoenix-int.com/product/modelcenter-integrate/`.

Biren Prasad. *Concurrent Engineering Fundamentals: Integrated Product and Process Organization, Volume I*. Prentice Hall, Upper Saddle River, N.J, 1995. ISBN 978-0-13-147463-5.

Biren Prasad. Enabling principles of concurrency and simultaneity in concurrent engineering. *AI EDAM*, 13(03):185–204, 6 1999. ISSN 0890-0604. doi:10.1017/S0890060499133055. URL `http://www.journals.cambridge.org/abstract_S0890060499133055`.

Brian Prasad. *Concurrent Engineering Fundamentals, Volume II: Integrated Product Development*. Prentice Hall PTR, Upper Saddle River, N.J, 1 edition edition, 9 1996. ISBN 978-0-13-396946-7.

Brian Prasad and Jeff Rogers. A Knowledge-Based System Engineering Process for Obtaining Engineering Design Solutions. In *Volume 3: 25th Computers and Information in Engineering Conference, Parts A and B*, volume 2005, pages 477–488. ASME, 2005. ISBN 0-7918-4740-3. doi:10.1115/DETC2005-85561. URL `http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1588184`.

Daniel Raymer. *Aircraft Design: A Conceptual Approach 5e and RDSWin STUDENT*. American Institute of Aeronautics and Astronautics, Inc., Washington, DC, 1 2012. ISBN 978-1-60086-921-1. doi:10.2514/4.869211. URL `https://doi.org/10.2514/4.869211http://arc.aiaa.org/doi/book/10.2514/4.869211`.

Redhat. Hibernate ORM, 2014. URL `http://hibernate.org/orm/`.

Aurélien Reysset, Marc Budinger, and J.-C. Mare. Computer-aided definition of sizing procedures and optimization problems of mechatronic systems. *Concurrent Engineering*, 23(4):320–332, 12 2015. ISSN 1063-293X.

doi:10.1177/1063293X15586063. URL http://cer.sagepub.com/cgi/doi/10.1177/10632.

RHEA-Group. CDP™ – Concurrent Design Platform, 2019. URL http://www.rheagroup.com/products/cdp/.

Martin Rinne. Technology roadmaps: Infrastructure for innovation. *Technological Forecasting and Social Change*, 71(1-2):67–80, 1 2004. ISSN 00401625. doi:10.1016/j.techfore.2003.10.002. URL http://linkinghub.elsevier.com/retrieve/pii/S0040162503001288.

O. Romberg, A Braukhane, and Holger Schumann. Status of the concurrent engineering facility at DLR Bremen. In *German Aerospace Congress*, 2008. URL https://elib.dlr.de/56028/.

O Romberg, A Braukhane, D Quantius, and V Maiwald. Statistics and evaluation of 30 + Concurrent Engineering Studies at DLR. In *5th International Workshop on Systems Engineering for Space Applications (SECESA), Lisbon*, 2012.

Pascal Roques. Capella: A System Modeling Solution. In *Systems Architecture Modeling with the Arcadia Method*, pages 25–50. Elsevier, 2018. doi:10.1016/B978-1-78548-168-0.50002-5. URL http://linkinghub.elsevier.com/retrieve/pii/B9781785481680500025.

Adam M. Ross and Daniel E. Hastings. The tradespace exploration paradigm. *INCOSE International Symposium*, 15(1):1706–1718, 7 2005. ISSN 23345837. doi:10.1002/j.2334-5837.2005.tb00783.x. URL http://doi.wiley.com/10.1002/j.2334-5837.2005.tb00783.x.

Adam M. Ross, Daniel E. Hastings, Joyce M. Warmkessel, and Nathan P. Diller. Multi-Attribute Tradespace Exploration as Front End for Effective Space System Design. *Journal of Spacecraft and Rockets*, 41(1):20–28, 1 2004. ISSN 0022-4650. doi:10.2514/1.9204. URL http://arc.aiaa.org/doi/abs/10.2514/1.9204.

Edris Safavi, Mehdi Tarkian, J. O lvander, H. Nadali Najafabadi, and Raghu Chaitanya Munjulury. Implementation of collaborative multidisciplinary design optimization for conceptual design of a complex engineering product. *Concurrent Engineering*, 24(3):251–265, 9 2016. ISSN 1063-293X. doi:10.1177/1063293X16661224. URL http://cer.sagepub.com/cgi/doi/10.1177/1063293X16661224.

Michael Schabacker, Kilian Gericke, Nikoletta Szélig, and Sándor Vajna, editors. *Modelling and Management of Engineering Processes*. Springer Berlin Heidelberg, Berlin, Heidelberg, 2015. ISBN 978-3-662-44008-7. doi:10.1007/978-3-662-44009-4. URL http://link.springer.com/10.1007/978-3-662-44009-4.

Volker Schaus, P Fischer, D Lüdtke, A Braukhane, O Romberg, and A Gerndt. Concurrent engineering software development at german aerospace center-status and outlook. In *4th International Workshop on System & Concurrent Engineering for Space Applications*, 2010.

Volker Schaus, Karsten Großekatthofer, Daniel Ludtke, and Andreas Gerndt. Collaborative Development of a Space System Simulation Model. In *2011 IEEE 20th International Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises*, pages 164–169. IEEE, 6 2011. ISBN 978-1-4577-0134-4. doi:10.1109/WETICE.2011.30. URL `http://ieeexplore.ieee.org/document/5990022/`.

Volker Schaus, Philipp M. Fischer, and Andreas Gerndt. Taking Advantage of the Model: Application of the Quantity, Units, Dimension, and Values Standard in Concurrent Spacecraft Engineering. *INCOSE International Symposium*, 23(1): 878–888, 6 2013. ISSN 23345837. doi:10.1002/j.2334-5837.2013.tb03060.x. URL `http://doi.wiley.com/10.1002/j.2334-5837.2013.tb03060.x`.

Daniel Shapiro, Bahram Hamraz, Anita F Sommer, and P John Clarkson. Investigating the impact of changes in iteration-likelihoods on design process performance. *Concurrent Engineering*, 23(3):250–264, 9 2015. ISSN 1063-293X. doi:10.1177/1063293X15588202. URL `http://journals.sagepub.com/doi/10.1177/1063293X15588202`.

Narek Rouben Shougarian. *Towards Concept Generation And Performance-Complexity Tradespace Exploration of Engineering Systems Using Convex Hulls*. PhD thesis, MIT, 2017.

Vasco José da Silveira. *Development of a concurrent design facility based on ESA CDF : Application to aircraft design*. PhD thesis, Universitade Technica de Lisboa, 2009.

Dmitry Smirnov, Dominik Knoll, and Alessandro Golkar. Gamespace exploration approach to complex systems design. In *Conference on systems engineering research 2016*, 2016.

Ksenia Smirnova, Alessandro Golkar, and Rob Vingerhoeds. A game-theoretic framework for concurrent technology roadmap planning using best-response techniques. In *2018 Annual IEEE International Systems Conference (SysCon)*, pages 1–7. IEEE, 4 2018. ISBN 978-1-5386-3664-0. doi:10.1109/SYSCON.2018.8369615. URL `https://ieeexplore.ieee.org/document/8369615/`.

V Srinivasan and Amaresh Chakrabarti. GEMS of SAPPhIRE : A Framework for Designing ? In *13th National Conference on Mechanisms and Machines (NaCoMM07)*, pages 1–8, 2007.

Issam M. Srour, Mohamed-Asem U. Abdul-Malak, Ali A. Yassine, and Maysaa Ramadan. A methodology for scheduling overlapped design activities based on dependency information. *Automation in Construction*, 29:1–11, 1 2013. ISSN 09265805. doi:10.1016/j.autcon.2012.08.001. URL `http://linkinghub.elsevier.com/retrieve/pii/S0926580512001422`.

Donald V. Steward. The design structure system: A method for managing the design of complex systems. *IEEE Transactions on Engineering Management*, EM-28(3):71–74, 1981. ISSN 0018-9391. doi:10.1109/TEM.1981.6448589. URL `http://ieeexplore.ieee.org/document/6448589/`.

E S Suh, M R Furst, K J Mihalyov, and O de Weck. Technology Infusion for Complex Systems: A Framework and Case Study. *Systems Engineering*, 13(2): 186–203, 2010. doi:10.1002/sys.20142.

Ronnie Emile Thebeau. *Knowledge management of system interfaces and interactions from product development processes.* PhD thesis, Massachusetts Institute of Technology, 2001. URL `http://hdl.handle.net/1721.1/29168`.

Daniel P. Thunnisen. Method for Determining Margins in Conceptual Design. *Journal of Spacecraft and Rockets*, 41(1):85–92, 1 2004. ISSN 0022-4650. doi:10.2514/1.9211. URL `https://arc.aiaa.org/doi/10.2514/1.9211`.

Valispace. Valispace, 2017. URL `http://www.valispace.com/`.

Jean-Luc Voirin. Method & Tools To Secure and Support Collaborative Architecting of Constrained Systems. *27:th International Congress of the Aeronautical Sciences*, 2010.

David A. Wagner, Matthew B. Bennett, Robert Karban, Nicolas Rouquette, Steven Jenkins, and Michel Ingham. An ontology for State Analysis: Formalizing the mapping to SysML. In *2012 IEEE Aerospace Conference*, pages 1–16. IEEE, 3 2012. ISBN 978-1-4577-0557-1. doi:10.1109/AERO.2012.6187335. URL `http://ieeexplore.ieee.org/document/6187335/`.

David D. Walden, Garry J. Roedler, Kevin J. Forsberg, R. Douglas Hamelin, and Thomas M. Shortell, editors. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities.* Wiley, Hoboken, New Jersey, 4 edition edition, 7 2015. ISBN 978-1-118-99940-0.

Stephen D Wall, David B Smith, and Lynda J Koenig. Team structures and processes in the design of space missions. In *Aerospace Conference, 1999. Proceedings. 1999 IEEE*, volume 2, pages 35–42. IEEE, 1999.

Lihui Wang, Weiming Shen, Helen Xie, Joseph Neelamkavil, and Ajit Pardasani. Collaborative conceptual design—state of the art and future trends. *Computer-Aided Design*, 34(13):981–996, 11 2002. ISSN 00104485. doi:10.1016/S0010-4485(01)00157-9. URL `https://linkinghub.elsevier.com/retrieve/pii/S0010448501001579`.

J R Wertz, D F Everett, J J Puschell, and Jeffery John Puschell James Richard Wertz, David F. Everett. *Space Mission Engineering: The New SMAD.* Space technology library. Microcosm Press, 2011. ISBN 9781881883166.

Randii Wessen, Chester S. Borden, John K. Ziemer, Robert C. Moeller, Joan Ervin, and Jared Lang. Space Mission Concept Development using Concept Maturity Levels. In *AIAA SPACE 2013 Conference and Exposition*, pages 1–18, Reston, Virginia, 9 2013. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-239-4. doi:10.2514/6.2013-5454. URL http://arc.aiaa.org/doi/10.2514/6.2013-5454.

Robert I. Winner, James P. Pennell, Harold E. Bertrand, and Marko M. Slusarczuk. The Role of Concurrent Engineering in Weapons System Acquisition. Technical report, INSTITUTE FOR DEFENSE ANALYSES, 12 1988. URL http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA203615.

Ali Yassine and Dan Braha. Complex concurrent engineering and the design structure matrix method. *Concurrent Engineering*, 11(3):165–176, 9 2003. ISSN 00000000, 1063293X. doi:10.1177/106329303034503. URL http://cer.sagepub.com/cgi/doi/10.1177/106329303034503.

Ali Yassine, Nitin Joglekar, Dan Braha, Steven Eppinger, and Daniel Whitney. Information hiding in product development: The design churn effect. *Research in Engineering Design*, 14(3):145–161, 9 2003. ISSN 09349839. doi:10.1007/s00163-003-0036-2. URL http://link.springer.com/article/10.1007/s00163-003-0036-2.

Ilya Yuskevich, Rob Vingerhoeds, and Alessandro Golkar. Two-dimensional Pareto frontier forecasting for technology planning and roadmapping. In *2018 Annual IEEE International Systems Conference (SysCon)*, pages 1–7. IEEE, 4 2018. ISBN 978-1-5386-3664-0. doi:10.1109/SYSCON.2018.8369565. URL https://ieeexplore.ieee.org/document/8369565/.

Pez Zarifian, Travis Imken, Steve E. Matousek, Robert C. Moeller, Matthew W. Bennett, Charles D. Norton, Leigh Rosenberg, Farah Alibay, Sara Spangelo, Payam Banazadeh, Raul Polit Casillas, and Jessie Kawata. Team Xc: JPL's collaborative design team for exploring CubeSat, NanoSat, and SmallSat-based mission concepts. In *2015 IEEE Aerospace Conference*, pages 1–10. IEEE, 3 2015. ISBN 978-1-4799-5379-0. doi:10.1109/AERO.2015.7119221. URL http://ieeexplore.ieee.org/document/7119221/.

John K. Ziemer, Joan Ervin, and Jared Lang. Exploring Mission Concepts with the JPL Innovation Foundry A-Team. In *AIAA SPACE 2013 Conference and Exposition*, Reston, Virginia, 9 2013. American Institute of Aeronautics and Astronautics. ISBN 978-1-62410-239-4. doi:10.2514/6.2013-5431. URL http://arc.aiaa.org/doi/10.2514/6.2013-5431.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix A

Facilities

These are the concurrent design facilities that we are aware of, 22 within and 22 outside of Europe.

Table A.1: Concurrent Design Facilities in Europe

Centre national d'études spatiales (CNES)	Centre d'Ingénierie Concourante (CIC)	France	Toulouse	Agency
Thales Alenia Space - France	Concurrent Engineering Facility (CDF)	France	Cannes	Industry
International Space University (ISU)	Concurrent Design Facility (CDF)	France	Strasbourg	University
Airbus Defence and Space - France	Space Code	France	Toulouse	Industry
Airbus Defence and Space - Germany	Space Code	Germany	Friedrichshafen	Industry
Deutsches Zentrum für Luft- und Raumfahrt	Concurrent Engineering Facility (CDF)	Germany	Bremen	Agency
OHB Systems	Concurrent Engineering Facility @ OHB (CEFO)	Germany	Bremen	Industry
Technischen Universität München (TUM)	Space Mission Concept Center (S2C2)	Germany	Munich	University

Table A.1: Concurrent Design Facilities in Europe

Affiliation	**Concurrent Engineering Centre**	**Country**	**City**	**Type**
Agenzia Spaziale Italiana (ASI)	Concurrent Engineering Facility (CDF)	Italy	Roma	Agency
Centro Italiano di Ricerche Aerospaziali (CIRA)	Concurrent Engineering Facility (CEF)	Italy	Capua	Agency
Thales Alenia Space - Italy	Collaborative Systems Engineering Centre (COSE)	Italy	Turin	Industry
Thales Alenia Space - Italy	Integrated System Design Center (ISDEC)	Italy	Rome	Industry
La Sapienza Università	Concurrent Design Facility (CDF)	Italy	Rome	University
European Space Agency - ESTEC	Concurrent Design Facility (CDF)	Netherlands	Noordwijk	Agency
European Space Agency - ESEC	Academy Training & Learning Center	Belgium	Redu	Agency
Universidade Técnica de Lisboa	Concurrent Design Facility (CDF)	Portugal	Lisbon	University
Universidad Politécnica de Madrid	Concurrent Design Facility (CDF)	Spain	Madrid	University
École polytechnique fédérale de Lausanne (EPFL)	Concurrent Design Facility (CDF)	Switzerland	Lausanne	University
University of Strathclyde	Intelligent Computational Engineering Laboratory (ICE)	United Kingdom	Glasgow	University
Airbus Defence and Space - UK	Space Code	United Kingdom	Stevenage	Industry

Table A.1: Concurrent Design Facilities in Europe

Affiliation	**Concurrent Engineering Centre**	**Country**	**City**	**Type**
University of Southampton	Concurrent Design Facility (CDF)	United Kingdom	Southampton	University
Harwell Institute / Rutherford Appleton Laboratory (RAL) Space	Concurrent Design Facility (CDF)	United Kingdom	Oxford	Industry

Table A.2: Concurrent Design Facilities outside of Europe

Japan Aerospace Exploration Agency (JAXA)	Emergence Studio	Japan	Tsukuba	Agency
Skolkovo Institute of Science and Technology (Skoltech)	Concurrent Engineering Design Laboratory	Russia	Moscow	University
Victorian Space Science Education Centre (VSSEC)	Concurrent Design Facility (CDF)	Australia	Melbourne	University
University of New South-Wales Camberra - ADFA (UNSW Camberra)	Australian National Concurrent Design Facility (ANCDF)	Australia	Camberra	University
The Aerospace Corporation	Concept Design Center (CDC)	U.S.	El Segundo, California	Industry
NASA Jet Propulsion Laboratory (JPL)	Product Design Center (PDC)	U.S.	Pasadena, California	Agency
NASA Goddard Space Flight Center (GSFC)	Integrated Design Center (IDC)	U.S.	Greenbelt, Maryland	Agency
NASA Glenn Research Center (GRC)	COMPASS	U.S.	Brook Park, Ohio	Agency

Table A.2: Concurrent Design Facilities outside of Europe

Affiliation	**Concurrent Engineering Centre**	**Country**	**City**	**Type**
NASA Langley Research Center (LaRC)	Engineering Design Studio (EDS)	U.S.	Hampton, Virginia	Agency
Aerospace Systems Design Laboratory (ASDL)	Collaborative Design Environment (CoDE)	U.S.	Atlanta, Georgia	University
Naval Postgraduate School	Spacecraft Research and Design Center - Spacecraft Design Laboratory	U.S.	Monterey, California	University
Thompson-Ramo-Wooldridge (TRW)	Integrated Concept Development Facility (ICDF)	U.S.	Redondo Beach, California	Industry
California Institute of Technology (Caltech)	Laboratory for Spacecraft and Mission Design (LSMD)	U.S.	Pasadena, California	University
Utah State University	Space Systems Analysis Laboratory (SSAL)	U.S.	Logan, Utah	University
Ball Aerospace	Space System Rapid Design Center (RDC)	U.S.	Boulder, Colorado	Industry
Massachusetts Institute of Technology (MIT)	Design Environment for Integrated Concurrent Engineering (DE-ICE)	U.S.	Cambridge, Massachusetts	University
NASA Johnson Space Center (JSC)	Human Exploration and Development of Space Integrated Design Environment (HEDS-DIE)	U.S.	Houston, Texas	Agency
National Reconnaissance Office (NRO)	NRO Analysis Center (NAC)	U.S.	Chantilly, Virginia	Intelligence agency

Table A.2: Concurrent Design Facilities outside of Europe

Affiliation	**Concurrent Engineering Centre**	**Country**	**City**	**Type**
APL Concurrent Engineering Laboratory (ACE Lab)	Johns Hopkins University Applied Physics Laboratory (JHU/APL)	U.S.	Baltimore, Maryland	University

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix B

Survey

To obtain a picture of the actual practice of concurrent design in the space sector, we performed a survey among subject matter experts from space agencies and companies. We used an online questionnaire composed of 50 questions.

B.1 Terminology Clarification

The survey contained an introductory page to make sure respondents get acquainted with the terminology we use.

> By *Concurrent Design* we mean an integrated multi-disciplinary system development approach. Each *design study* is carried out for a specific purpose. Many organizations have established *facilities* (building and hardware) and equipped them with appropriate *tools* (software) for people to work closely together. The *process* structures the work in individual and collaborative design sessions.

B.2 Survey Participants

We did ask for the respondents names, but we keep them anonymous.

Organizations

- Aerospace System Engineering Shanghai Institute

- ArianeGroup
- CNES
- DLR Institute of Space Systems
- ESA, ESTEC & ESA, GSP
- Instituto Tecnológico de Aeronáutica, Brazil
- NASA Jet Propulsion Laboratory, Goddard Space Flight Center, Langley Research Center
- OHB System AG
- RHEA Group
- Skoltech
- STFC-RAL Space
- Thales Alenia Space Italia S.p.A.

Role *What is (are) your role(s) with respect to concurrent design in your organization?*

Concurrent Design Facility Manager, Facility Lead, Team Leader, Systems Engineer, Lecturer for Concurrent Design of Space Systems, Software Developer, Business Unit Manager, Discipline Experts: Cost, Payloads, Programmatics, Process & Methods Improvement.

Experience *How many years do you fill this (these) roles(s)?*

65% of the respondents have more than 5 years of experience.

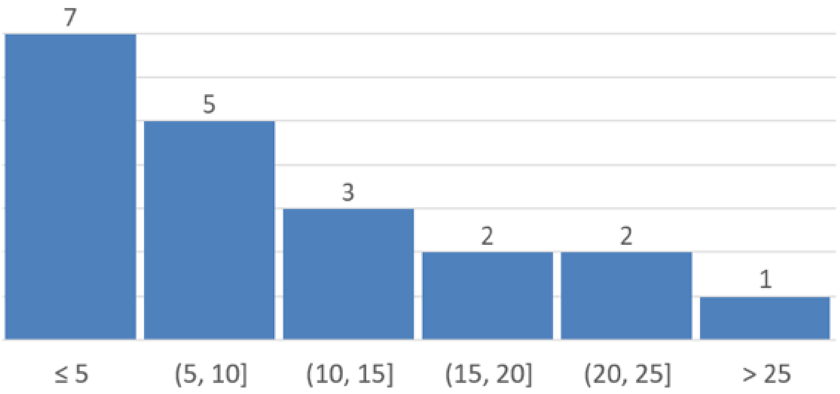


Figure B-1: Distribution of Years of Experience

B.3 General

Study Initiation *Concurrent design studies are initiated by . . .*

100% PI from other organizational units

Outside client *Do you conduct concurrent design studies for third-party organizations?*

35% never, 35% rarely, 30% yes

Study Types *What are the types of studies performed in a concurrent setting?*

Mostly: Feasibility studies, conceptual design studies, trade studies; Phase 0 / A / B1 design studies.

Also: Proposal, reviews; trade-off during phase C/D phases; strategic planning, technology development planning; concept of operations, initial architecture and system development; mission, payload, science case.

Benefits *What makes the concurrent design approach valuable for your organization?*

Quality of results: 4.3 (72%), Time efficiency: 4.3 (71%), Connecting People: 4.2 (69%), Building Consensus: 3,7 (62%), Repeatable results: 3.1 (52%), other: 3.4 (57%).

Figure B-2 show the distribution in a boxplot.

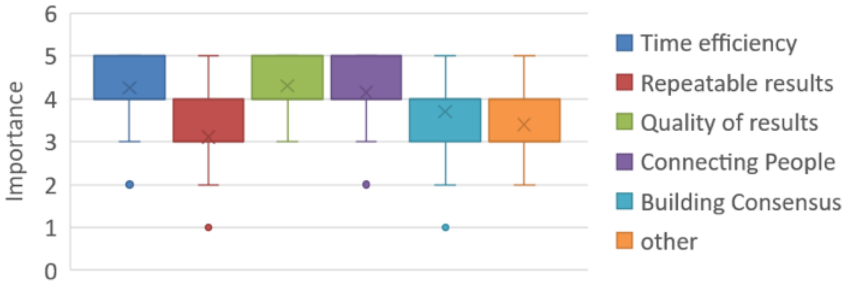


Figure B-2: Benefits of CD Studies

Challenges *What's the most challenging part of concurrent design studies?*

Expert availability: 5.3 (76%), Integrated toolchain: 4.9 (70%) Capturing engineering knowledge in models: 4.7 (66%), Interpersonal communication: 4.3 (61%), Model consistency: 4.2 (60%), Consensus building: 3.9 (55%), Model reuse: 3.8 (54%), other: 3.5 (50%).

Figure B-3 show the distribution in a boxplot.

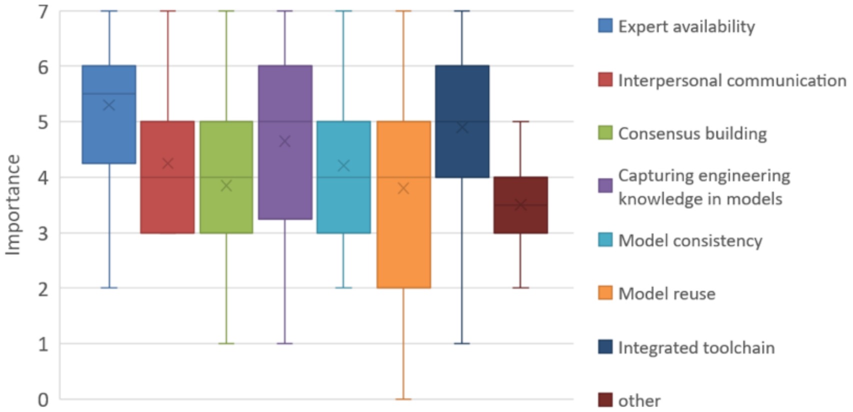


Figure B-3: Challenges of CD Studies

B.4 Team

Team Formation *Who is responsible to form the team for a CD study?*

70% CDF staff, 30% Principal Investigator

Moderator Training *How is a moderator trained for their job?*

Experience by participating in multiple CDF studies; on the job, gradual participation, some dedicated courses (e.g. SE/PM), experience of project management more than 10 years; Training Courses, Experience, Personal Talent; eLearning; Operating Manual with the process and roles, and then experience in many studies as a SE;

Team Size *What's the minimal/typical/maximal size of teams?*

Minimum team size is 6.2 people on average, ($\sigma = 1.85$). Typical size is 13 people on average, ($\sigma = 4$). Maximum team size is 20 people on average, ($\sigma = 5.9$).

The distribution is shown in Figure B-4.

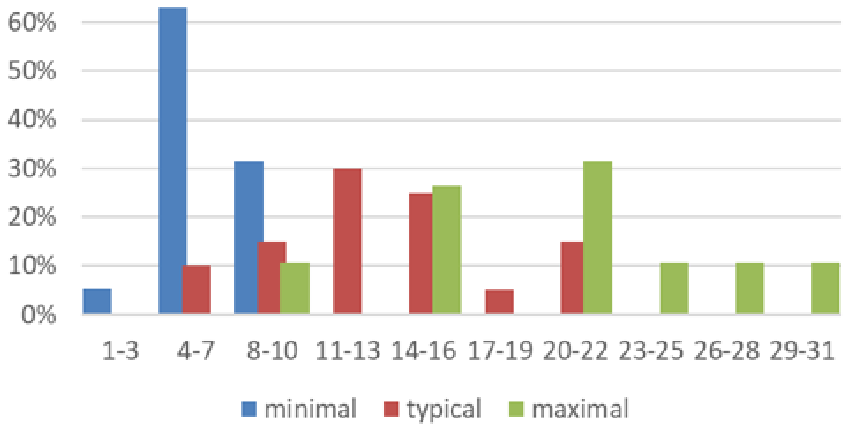


Figure B-4: Distribution of Team Sizes

Staff Roles *Which roles are filled by CDF staff?*

Facility support, System Admin; Moderator, Coordinator, Facilitator; Team Leader, Study Lead, Assistant Study Lead, Systems Engineer, Systems Engineer Assistant, Cost and Mission; Engineering Disciplines + Systems Engineer + Lead Engineer

Outside Participants *Are people from other organizations involved?*

65% Regularly, 35% Exceptionally; 0% Never

Participation *People are participating in concurrent sessions . . .*

15% exclusively on-site, 55% sometimes, 30% regularly from remote

Publications *Are there publications about your way of managing the team in concurrent design?*

- SECESA publications
- DLR Bremen CEF papers from e.g. Romberg, Martelo, Quantius, Maiwald, Braukhane (and others)
- A. Braukhane et al. (2015) Be aware of the squad: Lessons learnt from 50 Concurrent Engineering Studies for Space Systems. 66th International Astronautical Congress (IAC), 11.-16. Okt. 2015, Jerusalem, Israel.
- R. Biesbroek, Team Work and Team Behaviour : Findings of a CDF Team Leader, SECESA 2012

- C. Iwata et al., “Model-Based Systems Engineering in Concurrent Engineering Centers,” in AIAA SPACE 2015 Conference and Exposition, 2015, pp. 1–13.

Challenges

- Availability of experts, turn over management, people mindset
- To ensure proper and balanced communication, as well as motivating engineers to iterate from rough to detailed technical parameters (and not only when the precise number is available)
- How to balance the requirements in the team through negotiation or by compromise.
- Keeping everyone engaged and focused on the topic, as team members usually have many other (competing) tasks
- Ensuring that everyone is familiar with the concurrent engineering methodology.
- Continuous participation in all moderated sessions
- Team members that are new to concurrent engineering (or very infrequent) that are not ready to plug into our collaborative tools and platform
- Making team members feel necessary for the success of the Study
- Focused discussion, convergence of ideas, getting to a single decision
- Preparation is exceptionally important: setting objectives, agenda, staffing, etc.
- dealing with evolving technologies and implementation approaches
- Getting a study really going, to the point where everybody can start to participate.
- Achieving the correct balance of input from everyone. Moderation is critical to allow everyone to communicate, and to reduce wasted time (i.e. going around in circles).

Trends *What are the trends foreseeably influencing your team(s)?*

40% lack of experts

Others:

- Innovation, interest of the projects
- Customer expectations not in line with technical feasibility or resources allocations; lack of trust from the team
- CE experience (often the same people are attending), tool use and technology increase/change, lack of data bases
- Full multi-disciplinary digital engineering, need for more training on sophisticated MBSE to handle complexity and reduce cost/schedule
- Lack of funding specifically for concurrent engineering labor, and through this a teams commitment to regular participation

B.5 Tools, Common Model, Shared Data

Name *What's the name of the tool is used for maintaining a shared model?*

OCDT, CDP, IDM-CIC, CEDESK, Virtual Satellite, Excel, Capella, Foundry Furnace, Nexus, OneNote, MagicDraw, Pan Galactic Engineering Framework, PERA

Origin *The tool is?*

45% proprietary/built in-house, 15% open source, 30% free, 10% commercial

Heritage *For how long has that tool been used?*

Average: 5.25 years; Standard deviation: 3.11 years.

Training *What is the training effort for new users on this tool?*

65% one day or less. The distribution is shown in Figure B-5.

Connectivity *Is the tool for the shared model . . .*

50% standalone; 50% connected to domain specific tools

Requirements Management *Are you using any tool for managing requirements?*

50% yes; 50% no

Descriptive Models *What descriptive modeling languages are you using?*

40% SysML, 10% OPM

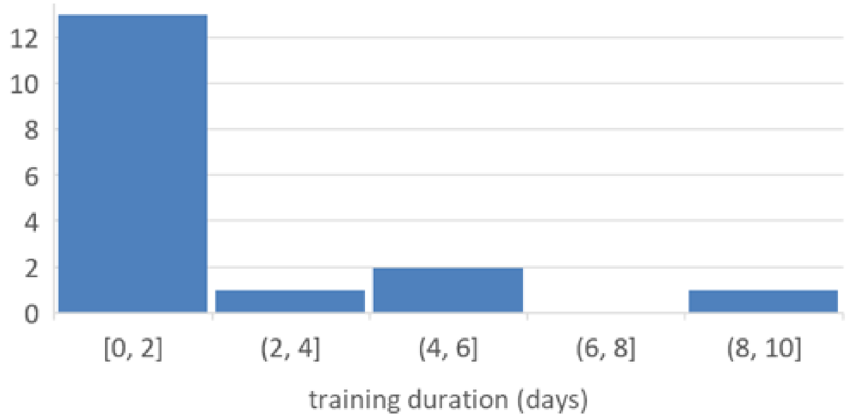


Figure B-5: Distribution of Duration of Training on the Tool

Model reuse *Are models reused in different studies?*

55% reference designs; 45% well curated library

Publication *Are there publications about your tools used in concurrent design?*

- SECESA papers, posters
- OCDT publications
- Fischer, Philipp M. und Deshmukh, Meenakshi und Maiwald, Volker und Quantius, Dominik und Martelo Gomez, Antonio und Gerndt, Andreas (2016) Conceptual Data Model - A Foundation For Successful Concurrent Engineering. In: International Systems & Concurrent Engineering for Space Applications Conference. Madrid, Spain

Challenge *What do you find most challenging about the tools aspect of concurrent design?*

- Stability, performance, data protection, on- and off-site collaboration, concurrent model access
- Concurrent and dynamic calculation with multiple solvers in a unified model; integration of user defined tools, interactive incorporation into the system model; Trades and Optimization
- Tools integration, interoperability, digital continuity between phases and with PLM
- Balance ease of use and modeling rigor

- Teaching consistent and disciplined use, input reliability and consistency
- Ergonomics, ensuring the participants are comfortable using the tools, require minimal training (1-2 hours), and assistance for less technically flexible participants

Trends *What trends are foreseeably influencing your tools?*

See Figure B-6.

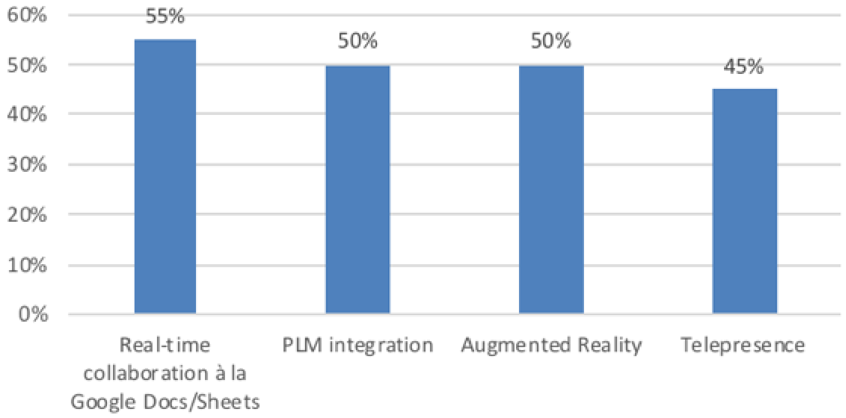


Figure B-6: Trends Influencing CD Tools

Other:

- Parametric Approach
- Deep Learning
- MBSE Plug and Play Tools
- Collaborative Engineering

B.6 Process

Study Process *Does your organization have a clearly defined process for managing CD studies (setup, execute, report)?*

65% Yes; 25% more or less, 10% no

Design Session Process *Do you have a clear procedure for conducting concurrent design sessions?*

60% Yes; 35% more or less, 5% no

Variants *Are studies aiming to produce a single or several feasible design?*

35% one; 50% two/three; 15% many

Duration *How many days (effective working time) is the typical duration of studies?*

Average: 9.61 days. The distribution is shown in Figure B-7.

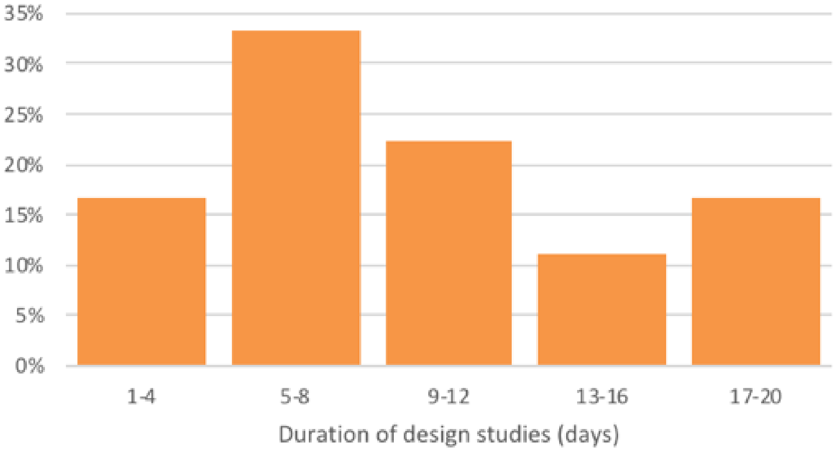


Figure B-7: Distribution of Design Studies Duration

Study session *The concurrent design sessions are . . .*

65% packed in a short period, 35% spread over a longer period

Out of session time *How much time study participants spend on average for preparation and post-processing of concurrent design sessions? (relative to the time in concurrent sessions)*

See Figure B-8.

Figures of Merit *What are the figures of merit of the designed system most studies need to report?*

See Figure B-9.

Other: Accomodation, Configuration, dV Budget, Scientific performance

Outcome *How are the results of the study documented?*

90% models; 85% reports; 85% presentations

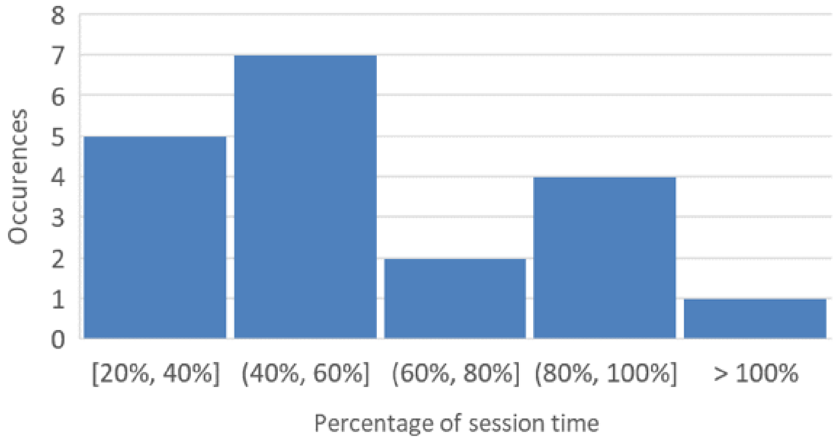


Figure B-8: Additional Time Spent Outside CD Sessions

Figure B-9: FOMs used for System Evaluation

Publication *Are there publications about your way to conduct concurrent design?*

- SECESA publications
- Martelo Gomez, Antonio und Jahnke, Stephan Siegfried und Braukhane, Andy und Quantius, Dominik und Maiwald, Volker und Romberg, Oliver (2017) Statistics and Evaluation of 60+ Concurrent Engineering Studies at DLR. In: Proceedings of the 68th International Astronautical Congress (IAC), 25.-29. Sep. 2017, Adelaide, Australien.
- `https://esamultimedia.esa.int/docs/cdf/CDF_infopack_2017.pdf`
- C. Iwata et al., "Model-Based Systems Engineering in Concurrent Engineering Centers," in AIAA SPACE 2015 Conference and Exposition, 2015, pp. 1–13.

Challenge *What do you find most challenging about the process aspect of concurrent design?*

- To assess what can be achieved in which period of time and what not (considering the prototype design and diverse team of people).
- Keeping the right level of detail for the stage and available information, and getting good consistent documentation of assumptions, constraints, and risks.
- Adjusting to particular study needs for each new project.
- Work-load distribution; motivating the team and getting quality inputs on time.
- Defining clear tasks for team members, especially for the first couple of sessions.
- Global optimization vs. local optimization of single discipline; Trade-off management and technology maturity evaluation.
- Transition to real knowledge management; Continuous improvement.
- Helping people to understand that there needs to be a structured process.
- Process non-linearity; It is difficult to express as a workflow diagram.

Trends *What trends are foreseeably influencing your process(es)?*

See Figure B-10.

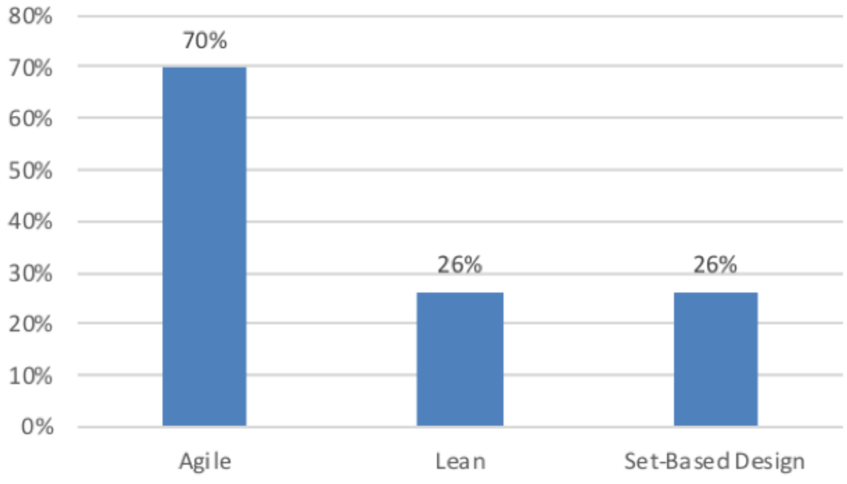


Figure B-10: Trends influencing CD process

B.7 Infrastructure, Facility

Establishment *What year the facility was established?*

See Figure B-11.

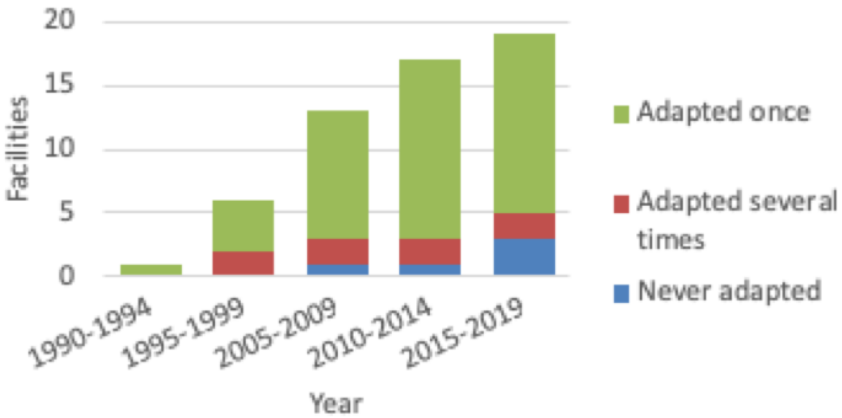


Figure B-11: Evolution of number of facilities established and adapted

Average year: 2005,4; Average age 13 years.

The bars in Figure B-11 show the cumulative number of facilities.

Refurbishment *Since then, was it refurnished/modernized?*

74% yes; 11% several times; 16% no.

The evolution of the facilities is shown in Figure B-11.

Designer seats *How many seats are available for active study participants?*

Average: 22. The distribution is shown in Figure B-12.

Observer seats *How many observers can be hosted (on top of active study participants)?*

See Figure B-12.

Average: 11. The distribution is shown in Figure B-12.

Computers *The computers used during studies are . . .*

60% dedicated machines; 40% brought by the participants

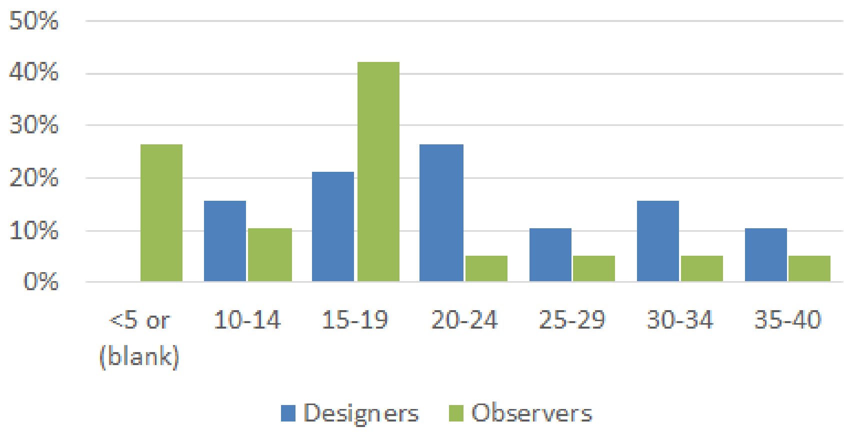


Figure B-12: Distribution of number of seats in facility

Key Features *Rank the features of your facility according to their importance*

See Figure B-13.

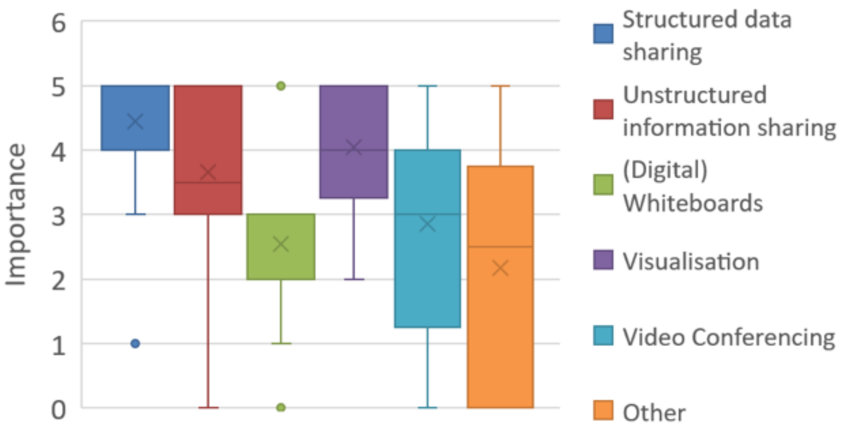


Figure B-13: Importance of facility features

Structured data sharing: 4.5 (74%), Visualization: 4.1 (68%), Unstructured data sharing: 3.7 (61%), Video Conferencing: 2.9 (48%), (Digital) Whiteboards: 2.6 (43%), Other: 2.2 (36%)

Flexibility *The facility is adopted to the needs of a study …*

5% a little; 45% furniture arrangement; 30% only the seat allocation (20% no opinion)

Replacement *Can concurrent design facilities be replaced by well-equipped meeting rooms?*

10% no; 65% partially; 25% completely

Challenge *What do you find most challenging about the facility aspect of concurrent design?*

- Visualization of complex data; Screen sharing; Touchscreen
- The information sharing and communicating among different disciplines, accumulation of discipline knowledge.
- Maintenance and renovation; up-to-date IT hardware and connectivity
- Availability of room in company / need to construct a new facility
- Resist to other solicitation to use the facility for other purposes
- External participation; Linking with remote participants; Trips reduction
- Ventilation; Noise

Trends *What trends are foreseeably influencing your facility?*

See Figure B-14.

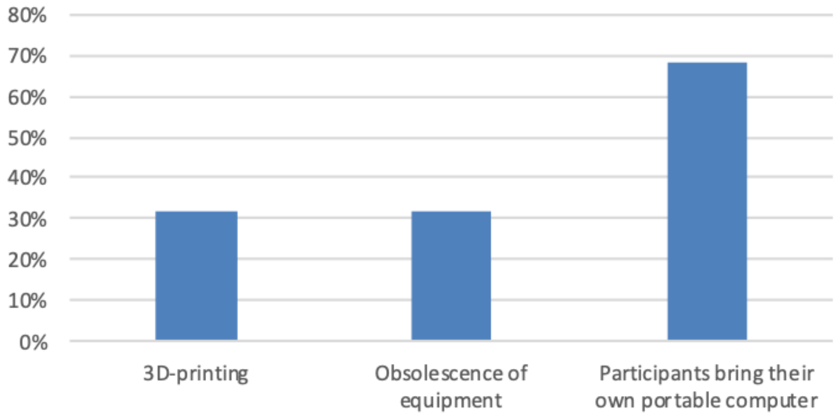


Figure B-14: Trends influencing CDFs

Other:

- Use of Virtual Reality and Augmented Reality
- Visualization and more external participants
- Concurrent Engineering is not facility dependent

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix C

Tool Comparison

We analyzed and compared the tools in use CDFs for conceptual design of space missions. The tools can be split in two categories: those focused on conceptual parametric modeling (see Table C.1), and others (see Table C.2). This comparison is not meant to be exhaustive, but it covers the tools reported in the survey (see Appendix B) and that are not proprietary to the facility.

Table C.1: Comparison of Tools, I

Group	**CONCURRENT CONCEPTUAL DESIGN TOOLS**					
Tool	IDM	VirSat 4[1]	OCDT	CDP 4[2]	Valispace[3]	CEDESK[4]
References	Bousquet et al. [2005]	Schaus et al. [2010], DLR [2016]	ESA [2014], Braukhane [2015]	Fijneman and Matthyssen [2010], RHEA-Group [2019]	Valispace [2017]	Knoll and Golkar [2018]
Aspect						
Multi-User Support	Yes	Yes	Yes	Yes	Yes	Yes
Lifecycle Phase Focus	conceptual design	conceptual design	conceptual design	conceptual design	conceptual design	conceptual design
Parametric modeling Focus	behavior	behavior and geometry	behavior	behavior	behavior	behavior
Version Control	Limited	Yes	Yes	Yes	No	Limited
Primary User Interface	Excel™	Own client	Excel™	Own client, Excel™	Own Web	Own client
Integration With 3rd Party Tools	No	No	Yes	Yes	Yes	Limited
Availability	ESA community	Open Source	ESA community	Open Source	Commercial	Open Source

Table C.2: Comparison of Tools, II

Group	**PLM TOOL**	**MDO TOOLS**		**SYSTEMS ENGINEERING TOOLS**	
Tool	ENOVIA[5]	Model Center[6] 11.2	OpenMDAO[7] 2.6	Magic Draw[8]	Open MBEE[9]
References	Dassault Systems [2016]	Phoenix Integration [2015]	Gray et al. [2019]	NoMagic [2015]	Kulkarni et al. [2016], NASA JPL [2016]
Aspect					
Multi-User Support	Yes	Yes		Yes	Yes
Lifecycle Phase Focus	design, manufacturing	design	design	conceptual design	design
Parametric modeling Focus	geometry and geometry	analysis and optimization	analysis and optimization	description	description
Version Control	Yes	No	No	Limited	Yes
Primary User Interface	Own client	Own client	Python Code	Own client	MagicDraw
Integration With 3rd Party Tools	Yes	Yes	No	Yes	Yes
Availability	Commercial	Commercial	Open Source	Commercial	Open Source

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix D

Software Resources

D.1 CEDESK

Concurrent Engineering Data Exchange Skoltech (CEDESK) was conceived, designed and implemented by the author and his colleague Nikolay Groshkov.

Use

Installation packages of the tool are available for Windows, MacOS and Linux on the website `https://cedesk.github.io`. This website also provides an introductory users guide, as well as a guide for developers.

Contribution

It was released in July 2017 as open source under the Apache License[1]. The source code is published on GitHub `https://github.com/cedesk/data-exchange`.

Compatibility

The software is compatible and was last used with:

- Java Development Kit, version 1.8.0_202
- Maven, version 3.3.9
- MySQL Community Server, version 5.7.25 (also tested with version 8.0.16)

---

[1] `www.apache.org/licenses/LICENSE-2.0`

D.2 jDSM

jDSM is a Java library for representing and analyzing Design Structure Matrix. It was originally made to analyze any Java software with regards to modularity.

This library was found as open source project on Sourceforge `http://jdsm.sourceforge.net/index.html`. It was developed and published in 2008 by Roberto Milev, as part of his master's thesis at the Technology Innovation Management program at Carleton University, Ottawa, Canada. Since then, no further development happened.

For the inclusion of DSM algorithms into CEDESK, this library was adapted by the author of this thesis and is available on GitHub `https://github.com/cedesk/jdsm/`.

This code was last used with Java Development Kit, version 8.

D.3 Matlab DSM

The MATLAB® macro for analyzing DSMs was found at `http://www.dsmweb.org/en/dsm-tools/research-tools/matlab.html`.

We adapted the original code for our research and made it available on GitHub `https://github.com/djknoll/dsm_matlab/`.

This code was last used with MATLAB® version 2018b.