Process Chain Development for Iterative, Concurrent Design of Advanced Space Transportation Systems

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Abstract

Development of advanced Space Transportation Systems (STS) at an early definition phase requires an iterative and multidisciplinary approach. High sensitivity and coupling of subsystem parameters with overall system characteristics necessitates close collaboration between domains. Rapid transfer of large amounts of data is necessary while errors and inconsistencies must be avoided. Concurrent Engineering (CE) is one approach through which to automate data sharing and minimise communication overheads. Previous effective implementation of this method at the German Aerospace Centre (DLR) Concurrent Engineering Facility (CEF) was limited to early-phase satellite design activities. Applying CE methods to STS design have been met with limited success. This paper reports on a new initiative from DLR titled Collaborative Launch vhicle Analysis (CLaVA). Within the scope of CLaVA, a flexible design environment for STS is investigated applied to the DLR CEF. The investigation led to the development of a high-level design cycle for STS. In collaboration with the aeronautical divisions of DLR a solution was identified, employing a central data model based on Model Based Systems Engineering (MBSE) methodology, implemented within a distributed environment. With modern revision control systems, it is envisioned that multiple STS concepts will be analysed in parallel in the CE environment. A preliminary test of these concepts is planned through a mock CE study.

Acronyms

BEACON	ReclaimaBle Evolutionary Ariane CONcept
CAD	Computer-Aided Design
CE	Concurrent Engineering
CEF	Concurrent Engineering Facility
CLaVA	Collaborative Launch Vehicle Analysis
CPACS	Common Parametric Aircraft Configuration Scheme
DLR	German Aerospace Centre
ELV	Expendable Launch Vehicles
MBSE	Model-Based Systems Engineering
RCE	Remote Component Environment
RLV	Reusable Launch Vehicles
SART	Space Launcher Systems Analysis
SED	Systems Engineer Decision
STS	Space Transportation System
XML	Extensible Markup Language
XSD	Extensible Markup Language Schema Definition

1. Introduction

Collaboration is critical to value creation.[1] This assertion also holds true for Space Transportation System (STS) design. The development of such systems is an iterative, multidisciplinary task with many dependencies between design disciplines. Inherent complexity of each discipline necessitates close collaboration between many different experts.[2–4] Efficient and effective communication and exchange between participating experts are therefore required.

A new project is currently underway within German Aerospace Centre (DLR), led by the Space Launcher Systems Analysis (SART) department. Titled Collaborative Launch Vehicle Analysis (CLaVA), it aims to provide a new, flexible design environment to foster collaboration between experts in STS design. Existing heritage in collaborative spacecraft design within DLR, particularly in the area of Concurrent Engineering (CE), provides a platform and experiences to build CLaVA on.[5] Additional experiences from the aeronautical divisions of DLR are investigated and applicable elements identified.

The requirements of this new design environment are being generated based on a robust design process recently developed by SART as part of the CLaVA project. This paper first introduces CE at DLR, followed by the new design process for STS. It then proposes a direction to adapt the process for use in a collaborative CE environment, using experiences and lessons learned from the aeronautical divisions of DLR. The future outlook for the CLaVA project is then outlined.

2. Concurrent Engineering

CE is a system approach with a focus on optimising engineering design cycles. It replaces the traditional hierarchical, sequential design-flow by integrating multidisciplinary teams that work collectively and in parallel; often in intense, short studies. The objective is to enable a fast, iterative and evolutionary approach to engineering design while considering all key aspects of an analysed product.[6] The need to integrate a multidisciplinary group of people together with a set of robust concurrent and collaborative technology platforms presents a unique challenge compared to a traditional sequential engineering environment.[7] This chapter describes the current implementation of a CE environment at DLR Institute of Space Systems. It then describes the role of this environment within the CLaVA project.

2.1 Application of Concurrent Engineering to the DLR Institute of Space Systems

The Institute of Space Systems within DLR applies CE methodology to space related design activities at an early project phase. For these activities, cross-functioning teams containing representatives of different domains tend to be assembled. They represent domains such as systems engineering, propulsion, communication, mission analysis, risk management and cost. Working together, the team makes informed and agreed decisions relating to design, processes, cost and quality issues. They make trade-offs between design features, material and equipment needs and evaluate reliability issues, availability requirements, cost, and time constraints.

By applying the CE methodology early in the project phase, cross-disciplinary discrepancies are more easily reconciled. This reduces difficulties downstream in the workflow. An optimal design at an early stage reduces the need for expensive engineering changes later in the design cycle.[8]

The close-quarters collaboration fostered through the assembly of an entire design team in one room enables high efficiencies regarding cost and outcome of a design activity. This is facilitated through direct communication and short data transfer times. Team members can easily track the design progress, which increases project identification. Ideas can be discussed in groups, which bring new viewpoints, and identification and avoidance of failures and mistakes are aided.

2.2 The DLR Concurrent Engineering Facility and its Current Application to Space Transportation Systems

The core enabling collaboration platform in the Concurrent Engineering Facility (CEF) at DLR's Institute of Space Systems is the Virtual Satellite platform. It facilitates the input and storage of system, subsystem and supporting parameters such as margins and requirements. The parameter list is generated prior to the CE study and updated continuously by domain experts throughout the study.[7]

50 studies have been conducted in the CEF to date. It has enabled investigations that range from landers and compact satellites to exploration modules and experimental vehicles. Topics related to vertical farming and moon habitation have also been investigated in the CEF. Although CE methods have also been applied to STSs, the use of classical CE domains, tools and process chains has achieved limited success. This is due to strong coupling between domains and sensitivities of subsystem parameters on overall system characteristics. Virtual Satellite as a collaborative

platform is therefore currently not compatible with STS. STS design activities require a different set of domains, more sequential design tasks and a different format of data exchange. As a consequence, the method of data transfer has been inconsistent for each analysed STS concept to date, often scrapping Virtual Satellite altogether in favour of primitive excel spreadsheets.[9] A new design environment is required that allows cascade design, mixing sequential and concurrent design approaches.

3. STS Design Process

The main activity of the DLR-SART department concerns the conceptual design, analysis and optimisation of STS through iterative, multidisciplinary analyses. Based on experiences within the department, a high-level, modular design cycle at conceptual level has been created for space transportation vehicles. This chapter first gives a definition of STS, then details the design cycle for a general STS. The chapter takes into consideration conventional, expendable launch vehicles and advanced, winged, reusable concepts. Cycle commonalities between the two classes of vehicles are investigated with the process chain addressing the differences.

The chain is intended to guide the determination of STS design environment requirements. In an actual CE study, each subprocess of the chain is to be exchanged or discarded for a particular design case. The components of the process chain should therefore act as building blocks, to be selected and utilised at the discretion of the systems engineer.

3.1 Definition of STS

A space transportation system is a man-made vehicle that traverses through or beyond Earth's atmosphere. Through means of its own and without physical connection to the surface, the vehicle shall reach at one point during its operation a speed of Mach 5 or above. In the frame of the CLaVA project, a STS shall be of civilian application and have the capacity to carry a payload to orbit or a minimum point-to-point distance.

The above definition enables the inclusion of vehicles from traditional launch vehicles to hypersonic point-to-point aircraft. An example of the latter is the SpaceLiner concept that DLR-SART has previously investigated.[10] This definition also enables the inclusion of future concepts that are currently not foreseeable.

3.2 Overview of the Design Process

The design process at the highest level is identical for all STS. An initial concept is derived from the mission statement and requirements and the initial geometry is generated using empirical methods and expert experiences. Following this preliminary set-up and preparation, the sequential technical analyses of the configuration are performed. The concept is iterated until a satisfactory convergence is determined. Further iterations are initiated if assessment of the concept by either the systems engineers or domain experts implies a change in design is necessary.

The process chain is divided into three separate loops: *Loop 0*, *Loop 1* and *Loop 2*. A configuration enters the next loop at the discretion of the systems engineers once critical topics are treated. Loop 0 considers the initial set-up and preparation of the concept whereas Loop 1 and Loop 2 perform the sequential technical analyses at an increasing level of fidelity. A simplified view of the process chain is shown in Figure 1. Each loop is treated in further detail within this chapter.

3.2.1 Loop 0

Loop 0 defines the mission statement and the project definition. Market analyses and customer validation are performed ensuring proper requirements are drawn up. The project definition, mission statement and high-level requirements are then translated into an implementation strategy. Initial concepts and technology choices are identified through consultation with the customer. Consideration is taken to incorporate both inside and outside ideas by tapping into industry, government, academic and the public, collectively called the knowledge base. Loop 0 subprocesses are summarised in Figure 2.

3.2.2 Loop 1

The execution of the implementation strategy is done in Loop 1. Figure 3 displays the subprocess components of this loop. The system definition has the initial task to construct a preliminary quantitative model of the vehicle based on the requirements, suggested concept and technology choices. This is accomplished through best estimates, empirical methods or a rapid initial staging program. A rough parametric geometry, number of stages, initial propellant and

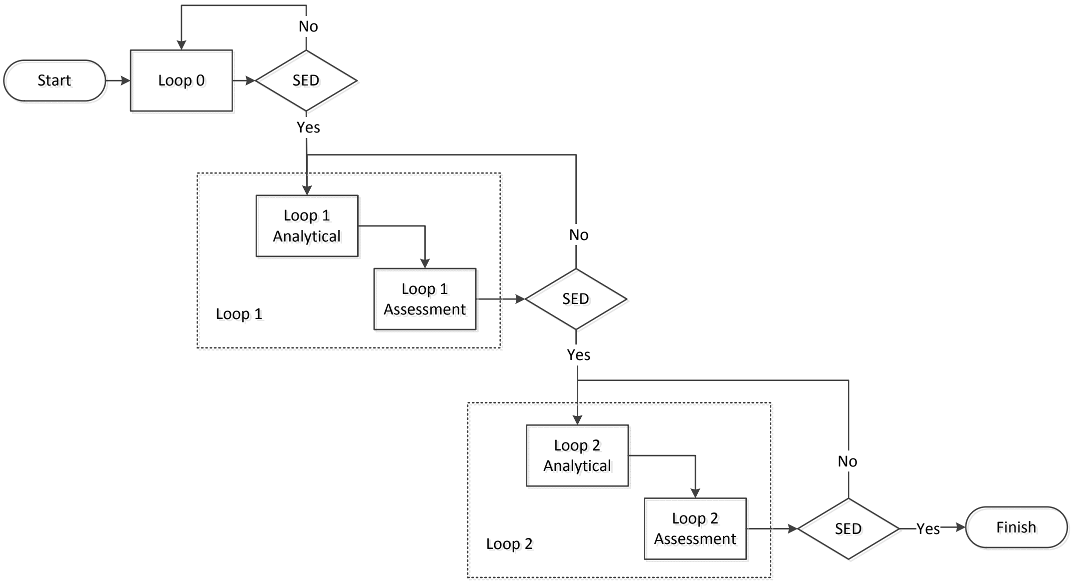

Figure 1: High-level process chain divided into three separate loops. Loop 0 performs the initial set-up and preparation of the project. Loop 1 performs initial sizing and performance estimations whereas Loop 2 performs more in-depth calculations on system and subsystem level.

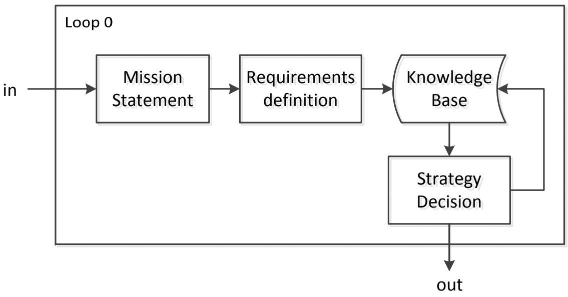

Figure 2: Loop 0 subprocesses contain the mission statement of the project, requirement definition and implementation strategy.

mission sequence are also defined. The propulsion system is then sized using fast empirical or analytical methods, focusing on system-level performance and mass estimations. The engine and nozzle mass as well as performance characteristics such as specific impulse and thrust or mass flow rate are generated.

The parametric contour geometry is used to construct an aerodynamic database using engineering handbook methods. The contour geometry and staging data are also used to determine a first dry mass estimate through fast engineering methods and empirical models. Margins, propellant loading, fairing masses if applicable and the previously-calculated engine and nozzle masses are added to complete the mass model of the vehicle. The stability of concepts with lifting surfaces can also be determined.

The completed mass model, propulsion and aerodynamic models enable the simulation of the ascent and descent trajectories providing the vehicle performance. Often, the resulting performance and trajectory will be unsatisfactory requiring further iterations and changing of input parameters.

The assessment phase of Loop 1 investigates, on a high level, the feasibility of the concept through a holistic approach. The phase takes into consideration diverse but highly-interconnected aspects such as environmental impact, safety, cost and production. These assessments conducted early in the design process ensure that critical, technical and also non-technical issues are detected such that appropriate action can be taken. Once a converged design is found that addresses the critical concerns raised by the assessment block, the system engineer can release the design package to

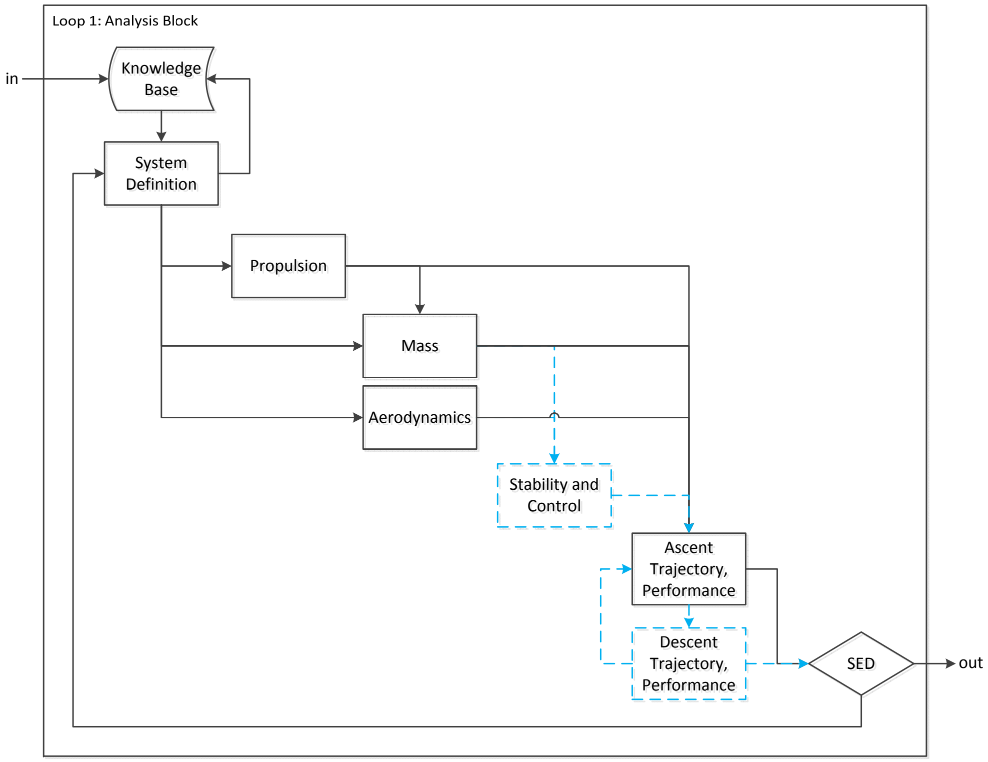

Figure 3: Loop 1 contain the initial quantitative system definition and technical analyses in the areas of propulsion, mass, aerodynamics, control and trajectory. Blue dashed lines indicate that the subprocesses are applicable to re-usable winged or lifting-body concepts only.

the next loop through a Systems Engineer Decision (SED) gate. If no convergence is found or critical concerns cannot be addressed, the design is either pivoted or scrapped altogether. The assessment block is shown in Figure 4.

3.2.3 Loop 2

In Loop 2, a more comprehensive quantitative assessment of the concept is performed. Figure 5 displays the subprocess components of this loop. Through system definition, additional design characteristics are incorporated into the model. Empirical methods and best estimates are replaced with higher-fidelity calculations in domains such as electrical, mechanical, thermal, propulsion, aerodynamics, load and structure and if applicable stability and control. Similar to Loop 1, one major objective is to calculate the masses of each subsystem in order to assemble an overall system mass budget. This updated mass budget is used to re-calculate the ascent and descent trajectories thus attaining the resulting performance of the concept. The parametric contour geometry of Loop 1 is replaced by a higher-fidelity Computer-Aided Design (CAD) model, aiding in the sizing of the subsystems. For conventional slender rockets, additional ascent control investigations can also be performed.

Once convergence is reached, a holistic assessment of the vehicle is conducted investigating diverse aspects such as environmental impact, safety, cost and production methods. Compared to Loop 1, the assessment contains higher-fidelity qualitative and quantitative tools and internal processes.

4. Collaborative and Concurrent Design Process for STS

The proposed tool to be developed within the frame of the CLaVA project aims to provide the CEF with the means to collaboratively and concurrently analyse STS designs. This chapter provides an overview of key identified components from the aeronautical divisions of DLR. These components are investigated for application on STS design and the CEF, taking into consideration the STS design process. The chapter concludes with a description of a planned mockup CE study with the intention of testing the design process and the collaborative, concurrent aspects of the CLaVA design philosophy.

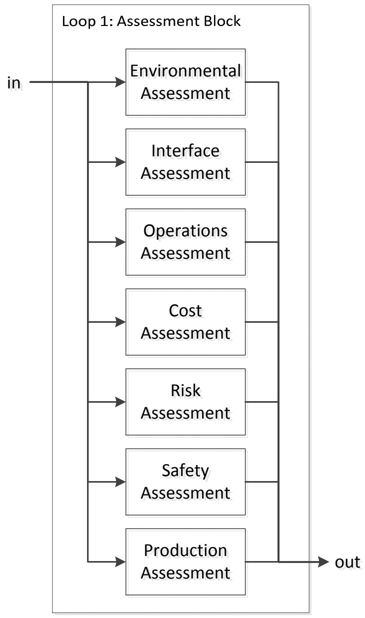

Figure 4: Multidiciplinary and holistic assessment of the concept in order to determine its feasibility.

4.1 Model Based Systems Engineering Through Common Parametric Aircraft Configuration Scheme

Model-Based Systems Engineering (MBSE) is an approach that replaces document-based design practices currently used for STS at DLR. Instead of producing and managing large amounts of documentation requiring manual inspection and information retrieval, a centralised database is created to store the states of a project. Dependencies and interfaces between different subsystems can be defined within the model with each change propagated through the system.[11]

Within the aeronautical domain, DLR has implemented a central data model for aircraft design called Common Parametric Aircraft Configuration Scheme (CPACS). Implemented as a Extensible Markup Language Schema Definition (XSD) for the Extensible Markup Language (XML) data format, the schema enables storage and access to standardised data for any discipline and accompanying tool connected to the database.[4, 12] CPACS employs a hierarchical tree-structure for its database. Deeper branches of the tree represent increased level of detail. CPACS is therefore capable of handling data for multiple levels of geometric and analysis fidelity. Moving from Loop 0 to Loop 2 analyses of the STS design process chain is therefore supported.

4.2 Remote Component Environment

A platform linking locally hosted tools to the CPACS server-side database is provided by a distributive environment called Remote Component Environment (RCE).[4] As many parameters during design of STS are time-dependant and therefore data-heavy, this link between tools and database has the potential to significantly improve the rate of data exchange compared to Virtual Satellite, which lacks this coupling. An instance of RCE can be installed at each local server and computer involved in the CE design activities for STS, forming a network. A central relay instance may be used to serve as a connection point between the RCE instances and the CPACS database.

RCE enables the inclusion of individual STS design tools using mapping files in XML format. This file is managed by the local tool expert. Updates and debugging of the tools can be accounted for locally with minimum support by the CLaVA software development team. Coupling between the tools through the RCE environment form the building blocks of the STS design process.

4.3 Workflow Management

Through RCE, CPACS, and the STS process chain, CLaVA has identified a set of rigid technical solutions and procedures to be used for STS design in a CE environment. The environment must however also encourage flexibility and

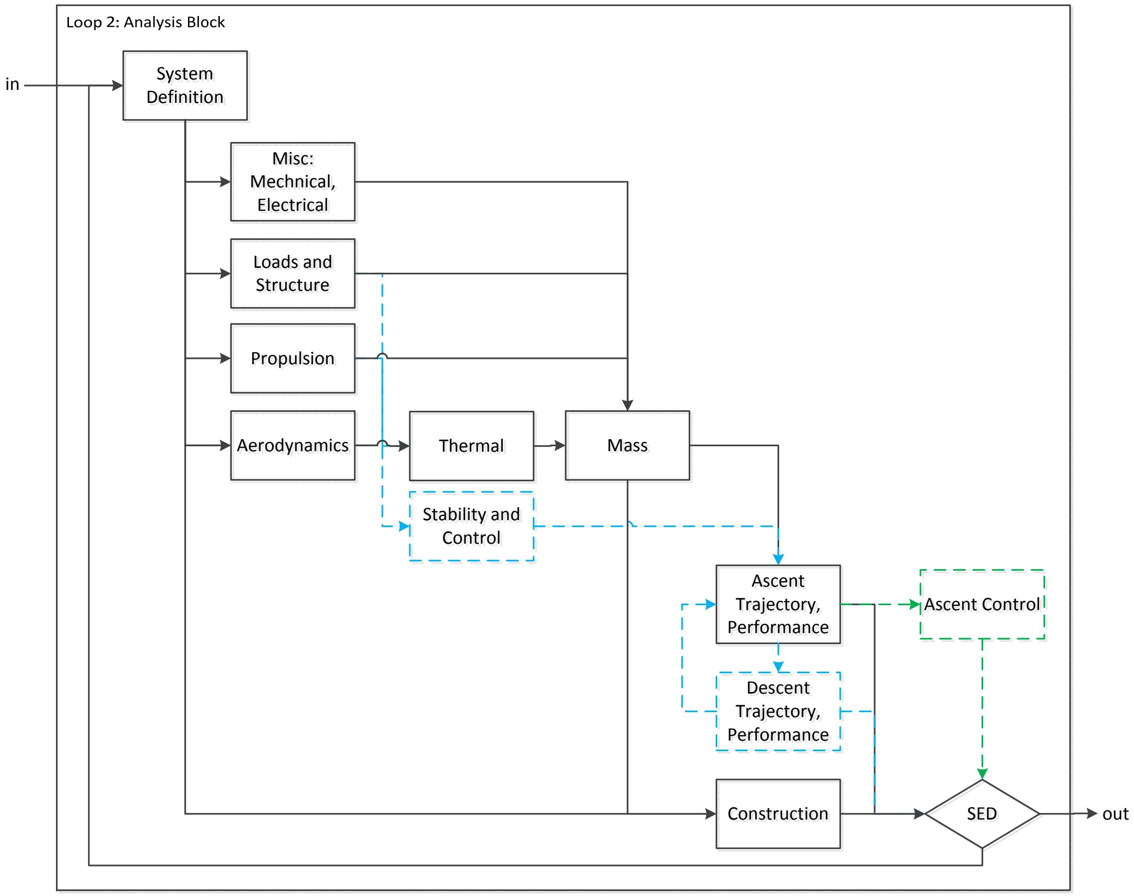

Figure 5: Loop 2 contains more detailed system and subsystem analyses. Blue dashed lines indicate that the subprocesses are applicable to re-usable winged or lifting-body concepts only. Green indicates that the subprocesses are applicable to conventional, slender rockets.

tailorability such that a wide variety of design cases can be investigated, some of which may not even be foreseeable today.

One proposed solution to these opposite requirements is modelled on an aeronautical working group at DLR. The workflow management within this group involves a number of systems integrators whose roles are to choose and exchange individual analysis modules of different fidelity levels.[13] The exact nature of the interactions and interdependencies between design domains and thus the work flow is therefore specific to the individual design case and the level of fidelity of the analyses. As new concepts are generated using building blocks of previous analyses, and existing concepts are modified, pivoted and evolved, the preserved knowledge and experience should aid to increase the effectiveness of a study.

The strong coupling between design domains for STS leads to a sequential design process that cannot be efficiently implemented in a CE environment today. To adapt this collaborative process into a concurrent one, the system engineers can opt to investigate multiple concepts or even variants of a single concept simultaneously in a cascade design process. Modern revision control methodologies such as branching, forking and merging of the data model can be employed to keep track of the various changes.

4.4 Reclaimable Evolutionary Ariane Concept Concurrent Engineering Study

The proposed CLaVA-ReclaimaBle Evolutionary Ariane CONcept (BEACON) CE study is aimed to take place end of June 2015, serving to test the design process. In addition it shall investigate the collaborative-concurrent cascade process by analysing three variations of the same concept at once. The cascade of the three sequential, iterative design processes, as could be implemented in the CE environment, is shown in Figure 6.

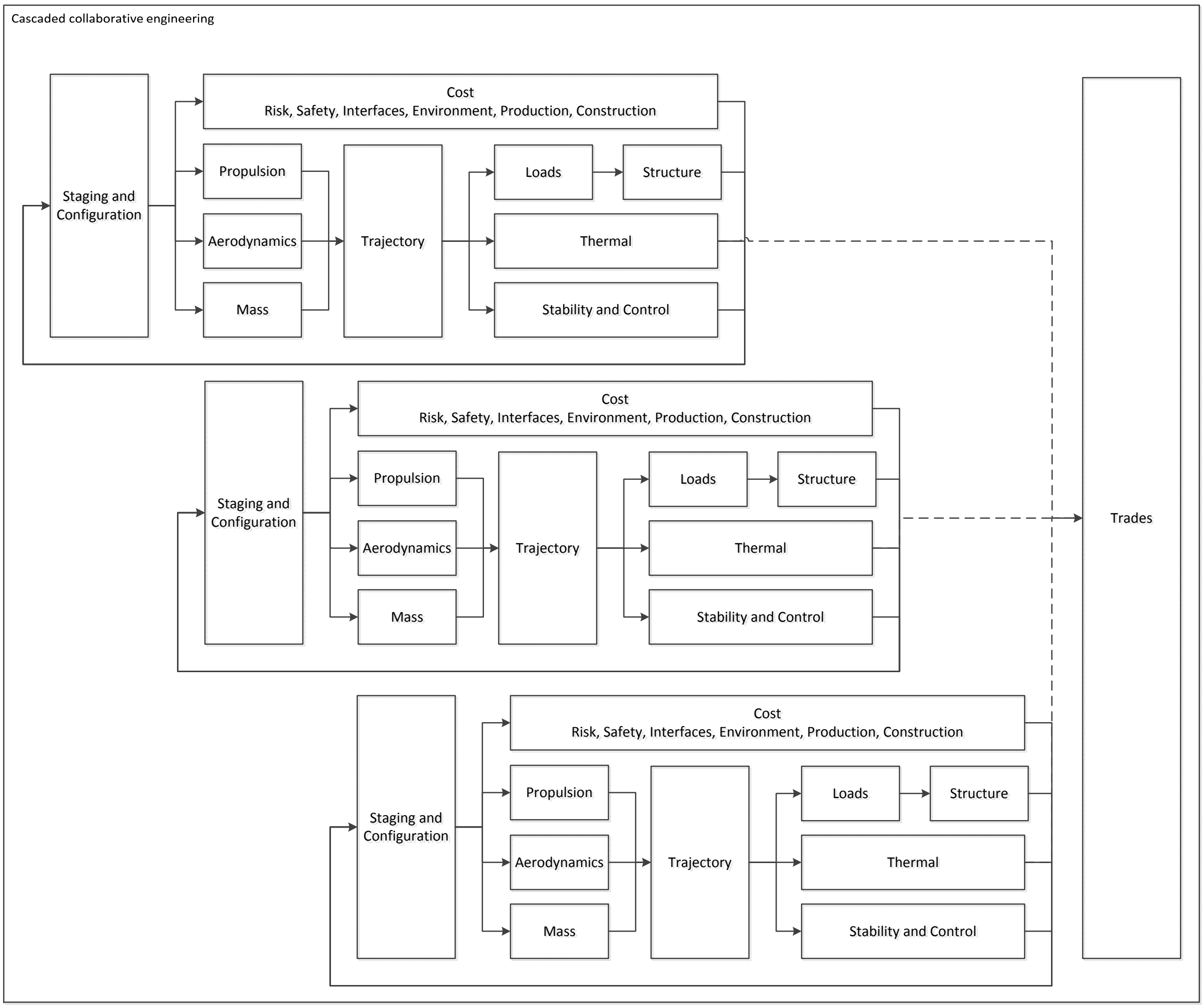

Figure 6: Cascaded CE design process with three concurrent concepts, each analysed in sequence.

Within the BEACON study, pre-processing, analysis and post-processing times for each used analysis and optimisation tool is to be classified and rated. The critical path between concurrent processes are to be determined in order to permit effective distribution of the workload and assist with CE study scheduling. The strengths of the interdependencies between domains and design steps with varying fidelity levels are to be determined. Domains with weak interdependencies to the parameters being investigated do not need to be subject to further analysis until higher model fidelity is required. Non-critical steps can, in this way, be identified and removed from the design process.

5. Conclusion

This paper summarises the process of STS design for early-phase conceptual studies. It presents an adaptation of the proposed process to a CE environment within the frame of the CLaVA project. The investigation of the design process revealed that a baseline work flow structure could be utilised for both Expendable Launch Vehicles (ELV)s and Reusable Launch Vehicles (RLV)s. For the former class, the core performance block consists of parallel aerodynamics, propulsion and mass analyses feeding into the trajectory simulation. The latter STS-class requires the iterative consideration of the descent trajectory, as well as control and stability within the core technical performance block.

Literature studies and assessments outside the space transportation design sector shows that DLR STS design processes and supporting infrastructures are lagging behind integrated engineering practices in other sectors. Increased collaboration and improved engineering practices through implementation of a collaborative design environment for STS analysis is therefore essential.

The design approaches described in this paper encompass the early stages of development of a platform for collaborative and concurrent STS design. The integration of the design process in a distributive environment and realisation of a central data model based on MBSE philosophies will be performed in subsequent activities. Aside from formally defining and improving design processes and advancing the technical capabilities of the launcher analysis groups within DLR, fostering effective collaboration between engineers has been, and will continue to be, the main focus of this project.

The outcomes of this paper shall be used as a guide for the CLaVA software requirements definition. It shall also serve as “best practices” for ELV and RLV design processes. Furthermore, it shall assist future concurrent design activities within the DLR CEF. The proposed CLaVA-BEACON study taking place in June 2015 shall serve to validate the design cycle. If necessary, the study shall enable further streamlining of the process.

The investigation outlined in this paper also highlighted that the design of optimal, innovative and robust STSs poses a challenge for engineers and managers due to the complexity and sensitivity of the design parameters and disciplines. More predominant than technical complexities are the external constraints; budget, projected launch cost, development time and political boundary conditions. To produce pioneering STS concepts that satisfy these constraints, DLR must not only strengthen and guide the cooperation between discipline experts, but also identify and fill gaps in its STS design processes. The introduction of new expertise, and identification and filling of knowledge gaps shall be supported within the frame of CLaVA.

Processes and supporting software tools constitute two main areas in any multidisciplinary collaborative approach. A cooperative design environment such as CLaVA will, however, be subjected to a third critical element; the human component. A highly-coordinated approach as described in this paper can only be as effective as the people and the organisational culture behind it. Human factors that both enable and prevent collaboration need to be addressed. Features that make the design environment more user-friendly will not be sufficient. Strategies for effective roll-out and utilisation need to be devised to ensure that resistance to change does not diminish the effectiveness and distribution of the environment.

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