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Knowledge-Based Integrated Aircraft Design

An Applied Approach from Design to Concept Demonstration

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Cover:
The cover shows framework and integrated tools inside the brain symbolizing knowledge. The future enhancements/tools are represented by circles with the arrow pointing towards the framework. All the outcomes of the framework are represented with the circles going out along with some aircraft designs.

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To my Family

"Arise, Awake, Stop not Till the Goal is Reached

-Swami Vivekananda

"Design is not just what it looks like and feels like. Design is how it works." - Steve Jobs

Abstract

The design and development of new aircraft are becoming increasingly expensive and time-consuming. To assist the design process in reducing the development cost, time, and late design changes, the conceptual design needs enhancement using new tools and methods. Integration of several disciplines in the conceptual design as one entity enables the design process to be kept intact at every step and a high understanding of the aircraft concepts obtained at early stages.

This thesis presents a Knowledge-Based Engineering (KBE) approach and integration of several disciplines in a holistic approach for use in aircraft conceptual design. KBE allows the reuse of obtained aircrafts' data, information, and knowledge to gain more awareness and a better understanding of the concept under consideration at early stages of design. For this purpose, Knowledge-Based (KB) methodologies are investigated for enhanced geometrical representation and to enable variable fidelity tools and Multidisciplinary Design Optimization (MDO). The geometry parameterization techniques are qualitative approaches that produce quantitative results in terms of both robustness and flexibility of the design parameterization. The information/parameters from all tools/disciplines and the design intent of the generated concepts are saved and shared via a central database.

The integrated framework facilitates multi-fidelity analysis, combining low-fidelity models with high-fidelity models for a quick estimation, enabling a rapid analysis and enhancing the time for a MDO process. The geometry is further propagated to other disciplines [Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA)] for analysis. This is possible with an automated streamlined process (for CFD, FEM, system simulation) to analyze and increase knowledge early in the design process. Several processes were studied to streamline the geometry for

CFD. Two working practices, one for parametric geometry and another for KB geometry are presented for automatic mesh generation.

It is observed that analytical methods provide quicker weight estimation of the design and when coupled with KBE provide a better understanding. Integration of 1-D and 3-D models offers the best of both models: faster simulation and superior geometrical representation. To validate both the framework and concepts generated from the tools, they are implemented in academia in several courses at Linköping University and in industry.

Keywords: Knowledge-Based Engineering, Aircraft Conceptual Design, Computer Aided Design, Computational Fluid Dynamics, Finite Element Analysis, XML, Multidisciplinary Design Optimization

Populärvetenskaplig Sammanfattning

Komplexiteten i designen hos och utvecklingen av nya flygplan ökar eftersom ny och mer komplex teknik, som ska göra flygplanen mer effektiva, testas och implementeras kontinuerligt. För att stödja designprocessen att minska utvecklingskostnaden och utvecklingstiden, behöver den konceptuella designfasen bättre och nya verktyg och metoder. En integration av hela processen behövs för att hålla designprocessen intakt i varje steg för att i sin tur få en bättre förståelse för flygplanskoncepten i de tidiga konstruktionsstadierna.

I denna avhandling presenteras Knowledge-Based Engineering (KBE)-metoder för användning inom konceptuell utveckling av flygplan genom att systematiskt integrera flera discipliner. KBE-metoder tillåter återanvändning av erhållna kunskaper för att öka konceptmedvetenhet och konceptförståelse i tidiga utvecklingsstadier. KBE-metoderna undersöks för förbättrad geometrisk representation och för fortsatt användning vid senare stadier i designprocessen. De utvecklade parametriseringsteknikerna är kvalitativa ansatser som ger kvantitativa resultat för såväl robusthet som flexibilitet hos designparametriseringen. En gemensam databas för delade parametrar gör att den avsedda utformningen av de genererade koncepten kan lagras centralt och är tillgänglig för andra discipliner.

En multi-fidelitetsansats, som kombinerar låg-fidelitetsmodeller (två dimensioner) med hög-fidelitetsmodell (tre dimensioner) används för en snabb uppskattning av den önskade enheten, vilket möjliggör en snabb analys och en snabbare multidisciplinär designoptimerings (MDO)-process. Geometrin vidareutvecklas och vidarebefordras till andra discipliner [Computational Fluid Dynamics (CFD), Finite Element Analysis

(FEA)] för vidare analys. Detta möjliggörs genom en automatiserad och strömlinjeformad process för konceptet för att öka kunskapen tidigt i designprocessen. Flera processer och två arbetsmetoder har undersökts, en för parametrisk geometri och en annan för kunskapsbaserad geometri för automatiserad nätgenerering för CFD.

Analysmetoderna ger snabba resultat och när de kombineras med KBE ger de en bättre förståelse och snabbare analys. Integrering av endimensionella och tredimensionella modeller erbjuder det bästa av båda domänerna: snabbare simulering och bättre geometrisk framställning. För att validera ramverk och koncept som genererats av verktygen har de implementerats i såväl akademi, i flera kurser vid Linköpings universitet, som industri.

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The research presented has been conducted at the Division of Fluid and Mechatronic Systems (FluMeS), Linköping University, Sweden together with industrial partner SAAB Aeronautics. Funding for this work was provided by VINNOVA, the Swedish National Aviation Engineering Program, NFFP5 2010-1251 "Konceptmetodik" and NFFP6 2014-0927 "CADLAB". I would like to thank the NFFP founders for this support.

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I would like to express my appreciation to all the co-authors of all my papers in this thesis. I would like to thank all my colleagues at the

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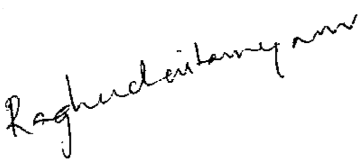
Linköping, May 2017.



Raghu Chaitanya Munjulury

Abbreviations

2-D	two-dimensional
3-D	three-dimensional
AI	Artificial Intelligence
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
DRM	Design Research Methodology
DS1	Descriptive Study 1
DS2	Descriptive Study 2
FEA	Finite Element Analysis
KB	Knowledge-Based
KBE	Knowledge-Based Engineering
KBS	Knowledge-Based System
KP	Knowledge Pattern
MDF	Multidisciplinary Design Feasible
MDO	Multidisciplinary Design Optimization
MOKA	Methodology and software tools Oriented to Knowledge based engineering Applications
PC	Power Copy
PS1	Prescriptive Study 1
SVD	Singular Value Decomposition

UDF	User Defined Feature
VR	Virtual Reality

Programming Languages, Software and Tools

`ADS`	Aircraft Design Software
`ANSYS`®	Simulation Driven Product Development
`BeX`	Berry Excel - Aircraft Conceptual Design Sizing Tool (`Excel`)
`CADLab`	Conceptual Aircraft Design Laboratory (tool suite)
`CADNexus`	Automation solutions for collaborative multi-CAD & CAE environments
`CATIA`®	3D CAD Design Software, Dassault Systémes
`CDT`	Conceptual Design Tool
`CEASIOM`	Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods
`DEE`	Design Engineering Engine
`Dymola`®	Multi-Engineering Modeling and Simulation, Dassault Systémes
`EKL`	Engineering Knowledge Language in CATIA®
`ESP`	The Engineering Sketch Pad
`Fine`^{TM}`/Open with OpenLabs`	CFD Flow Integrated Environment (NUMECA International)

`Hopsan`	Simulation Environment for Fluid and Mechatronic Systems
`J2`	J2 Universal Tool Kit
`KEACDE`	Knowledge-based and Extensible Aircraft Conceptual Design Environment
`MMG`	Multi-Model Generator
`modeFRONTIER`®	Optimization environment (ESTECO)
`openVSP`	Vehicle Sketch Pad (NASA open source parametric geometry)
`PADLab`	Preliminary Aircraft Design Lab
`Piano`	Aircraft Design and Competitor Analysis
`RAGE`	Rapid Aerospace Geometry Engine
`RAPID`	Robust Aircraft Parametric Interactive Design (based on `CATIA`®)
`RDS-Student`	Aircraft design software package ("Raymer's Design System")
`SUAVE`	Stanford University Aerospace Vehicle Environment
`Tango`	Aircraft Systems Conceptual Design Tool (`Matlab`®)
`Tornado`	Vortex Lattice Method (VLM) Tool (`Matlab`®, open source)
`VAMPzero`	Aircraft Conceptual Sizing Tool, DLR)
`VB`	Visual Basic: Event-Driven Programming Language, Microsoft®
`XML`	Extensible markup Language
`XSD`	Extensible markup language (XML) schema definition

`XSLT`	Extensible Stylesheet Language Transformation

Papers

The following papers ([I] till [VI]) are an integral part that forms this thesis and will be referred by Roman numerals. The papers are printed in their original-form with the exception of minor errata and adjustment of text and figures in-order to maintain same consistency throughout this thesis. The first author is the main author in all the papers with additional contribution from the remaining co-writers.

[I] Munjulury, R. C., I. Staack, P. Berry, and P. Krus (2016). "A knowledge-based integrated aircraft conceptual design framework". In: *CEAS Aeronautical Journal* 7.1, pp. 95–105. ISSN: 1869-5590. DOI: `10.1007/s13272-015-0174-z`.

[II] Munjulury, R. C., I. Staack, A. Sabaté López, and P. Krus (2017). "Knowledge-based Aircraft Fuel System Integration". In: *Aircraft Engineering and Aerospace Technology, An International Journal, Accepted for publication.* DOI: `10.1108/AEAT-01-2017-0046.R1`.

[III] Munjulury, R. C., P. Berry, D. Borhani Coca, A. Parés Prat, and P. Krus (2017). "Analytical Weight Estimation of Landing Gear Designs". In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Under review.*

[IV] Munjulury, R. C., I. Staack, A. Abdalla, T. Melin, C. Jouannet, and P. Krus (2014). "Knowledge-Based Design For Future Combat Aircraft Concepts". In: *29th Congress of the International Council of the Aeronautical Sciences.* St.Petersburg, Russia: ICAS. URL: `http://www.icas.org/ICAS_ARCHIVE/ICAS2014/data/papers/2014_0600_paper.pdf`.

[V] Munjulury, R. C., A. Abdalla, I. Staack, and P. Krus (2016). “Knowledge-Based Future Combat Aircraft Optimization”. In: *30th Congress of the International Council of the Aeronautical Sciences*. Daejeon, South Korea: ICAS. URL: http://www.icas.org/ICAS_ARCHIVE/ICAS2016/data/papers/2016_0538_paper.pdf.

[VI] Munjulury, R. C., H. Nadali Najafabadi, E. Safavi, J. Ölvander, P. Krus, and M. Karlsson (2017). “A comprehensive computational MDO approach for a tidal power plant turbine”. In: *Advances in Mechanical Engineering* 9.2. ISSN: 1687-8140. DOI: 10.1177/1687814017695174.

Papers not included

Papers mentioned below ([VII] till [XXII]) are not included in this thesis however establish a good background and contribute to this thesis.

[VII] Staack, I., R. C. Munjulury, P. Berry, T. Melin, K. Amadori, C. Jouannet, D. Lundström, and P. Krus (2012). "Parametric aircraft conceptual design space". In: *28th Congress of the International Council of the Aeronautical Sciences*. Brisbane, Australia: ICAS. URL: http://www.icas.org/ICAS_ARCHIVE/ICAS2012/PAPERS/686.PDF.

[VIII] Munjulury, R. C., R. Gårdhagen, P. Berry, and P. Krus (2016). "Knowledge-Based Integrated Aircraft Windshield Optimization". In: *30th Congress of the International Council of the Aeronautical Sciences*. Daejeon, South Korea: ICAS. URL: http://www.icas.org/ICAS_ARCHIVE/ICAS2016/data/papers/2016_0375_paper.pdf.

[IX] Staack, I., R. C. Munjulury, T. Melin, A. Abdalla, and P. Krus (2014). "Conceptual aircraft design model management demonstrated on a 4th generation fighter". In: *29th Congress of the International Council of the Aeronautical Sciences*. St.Petersburg, Russia: ICAS. URL: http://www.icas.org/ICAS_ARCHIVE/ICAS2014/data/papers/2014_0621_paper.pdf.

[X] Munjulury, R. C., A. Sabaté López, I. Staack, and P. Krus (2016). "Knowledge Based Aircraft Fuel System Integration in RAPID". In: *6th EASN International Conference On Innovation in European Aeronautics Research*. Porto, Portugal: EASN.

[XI] Munjulury, R. C., I. Escolano Andrés, A. Diaz Puebla, and P. Krus (2016). "Knowledge-based Flight Control System and Control Surfaces Integration in RAPID". In: *FT2016 - Aerospace Technology Congress*. Solna, Stockholm, Sweden: FTF - Swedish Society Of Aeronautics and Astronautics. URL: http://ftfsweden.se/wp-content/uploads/2016/11/FT2016_G07_Raghu_Chaitanya_Munjulury_full-paper.pdf.

[XII] Munjulury, R. C., A. Prat Parés, D. Borhani Coca, P. Berry, and P. Krus (2016). "Analytical Weight Estimation Of Unconventional Landing Gears". In: *6th EASN International*

Conference On Innovation in European Aeronautics Research. Porto, Portugal: EASN.

[XIII] Munjulury, R. C., P. Berry, T. Melin, K. Amadori, and P. Krus (2015). "Knowledge-based Integrated Wing Automation and Optimization for Conceptual Design". In: *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*. Dallas, Texas: American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.2015-3357.

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[XV] Munjulury, R. C., I. Staack, P. Berry, and P. Krus (2013). "RAPID - Robust Aircraft Parametric Interactive Design : (A Knowledge Based Aircraft Conceptual Design Tool)". In: *4th CEAS: The International Conference of the European Aerospace Societies*. Linköping, Sweden: CEAS, pp. 255–262. URL: https://liu.diva-portal.org/smash/get/diva2:687478/FULLTEXT02.pdf.

[XVI] Munjulury, R. C., I. Staack, and P. Krus (2013). "Integrated Aircraft Design Network". In: *4th CEAS: The International Conference of the European Aerospace Societies*. Linköping, Sweden: CEAS, pp. 263–269. URL: http://liu.diva-portal.org/smash/get/diva2:687446/FULLTEXT01.pdf.

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[XVIII] Barbosa, U. F., J. P. M. Cruvinelda Costa, R. C. Munjulury, and À. M. Abdalla (2016). "Analysis of Radar Cross Section and Wave Drag Reduction of Fighter Aircraft". In: *FT2016 - Aerospace Technology Congress*. Solna, Stockholm, Sweden: FTF - Swedish Society Of Aeronautics and Astronautics. URL: http://ftfsweden.se/wp-content/uploads/2016/11/FT2016_I03_Uandha_Barbosa-et-al_full-paper.pdf.

[XIX] Catalano, F. M., À. M. Abdalla, H. D. Ceron, and R. C. Munjulury (2016). “Experimental Aerodynamic Analysis of a Fighter Aircraft with a Canard, Forward Swept Wing and Dorsal Intake operating at high incidences”. In: *FT2016 - Aerospace Technology Congress*. Solna, Stockholm, Sweden: FTF - Swedish Society Of Aeronautics and Astronautics. URL: http://ftfsweden.se/wp-content/uploads/2016/11/FT2016_H03_Fernando-Catalano_AERODYNAMIC_DORSAL_INTAKE.pdf.

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[XXII] Safavi, E., M. Tarkian, J. Ölvander, H. Nadali Najafabadi, and R. C. Munjulury (2016). “Implementation of collaborative multidisciplinary design optimization for conceptual design of a complex engineering product”. In: *Concurrent Engineering* 24.3, pp. 251–265. DOI: 10.1177/1063293X16661224.

Contents

1 Introduction

Conceptual design is the early stage of an aircraft design process where results are needed fast, both analytically and visually, so that the design can be analysed and eventually improved in the initial phases. Although there is no necessity for a Computer Aided Design (CAD) model from the very beginning of the design process, it can be an added advantage to have the model to get the impression and appearance. Aircraft configurations and high-fidelity analysis tools such as Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) increase the level of confidence in the designed product [La Rocca, 2011]. Furthermore, this means that a seamless transition into preliminary design is achieved since the CAD model can progressively be made more detailed.

1.1 Background

AIRCRAFT DESIGN is a complex process that brings different disciplines together to obtain a holistic approach. Modern aircraft have become more expensive and the time taken to build has increased considerably. Figure 1.1 shows delay in different aircraft projects. An improvement in the conceptual design is needed to decrease the overall development time and cost for an aircraft. In conceptual design the results are needed faster both analytically and visually so that the design can be modified or changed at the earliest stages.

The three main design stages in an aircraft design process are Conceptual design, Preliminary design and Detail design. After the detail design the aircraft is verified with prototype testing and full production [Brandt et al., 2004]. Different designs need to be analysed and verified

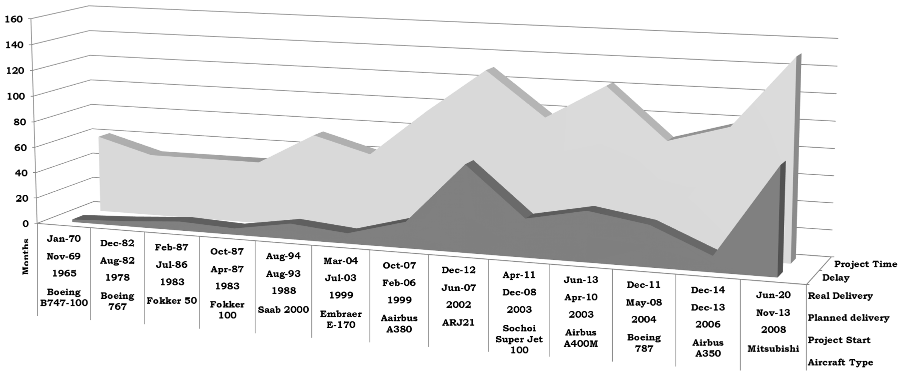


Figure 1.1 *Time delay in aircraft projects (adapted from [Schminder, 2012].*

in the conceptual design before proceeding with the preliminary design. The design has to be approved before continuing with the preliminary design as it incurs an increase in the cost of the project.

Conceptual design tools have a constant need for refinement and improvement. One much-needed enhancement is the ability to communicate between analytical design tools and the three-dimensional (3-D) environment, i.e. `CATIA`® [Catia®V5, 2016]. Data communication between conceptual design programs has always been a major obstacle, which now has a possible solution through this work. A seamless connection appeals to the designer, but it has to work both ways so that major design parameters can be changed at a later stage. For example, the position of the center of gravity may not be known with any precision until fairly late and may require an adjustment of the wing position. A Handful of software tools exist in the industry, at universities and research centers. Some have connections to CAD software, but the connection is usually not seamless and they rarely work bi-directionally [VII]. Existing aircraft conceptual design tools are [XIV]:

- Aircraft Design Software (`ADS`) [ADS, 2016]
- Aircraft design software package ("Raymer's Design System") `RDS-Student` [Raymer, 2006]
- Computerized Environment for Aircraft Synthesis and Integrated Optimization Methods (`CEASIOM`) [CEASIOM, 2016]
- Conceptual Design Tool (`CDT`) [Ziemer et al., 2011]

- J2 Universal Tool Kit [j2 Universal Framework, 2016]
- Knowledge-based and Extensible Aircraft Conceptual Design Environment (KEACDE) [Haocheng et al., 2011]
- Multi-Model Generator (MMG) [La Rocca, 2011]
- Piano - Aircraft Design and Competitor Analysis [Piano, 2016]
- Preliminary Aircraft Design Lab (PADLab) [PADLab Software, 2017]
- Rapid Aerospace Geometry Engine (RAGE) [RAGE, 2016]
- The Engineering Sketch Pad (ESP) [Haimes et al., 2013]
- Vehicle Sketch Pad (openVSP) [openVSP, 2017; Hahn, 2010]

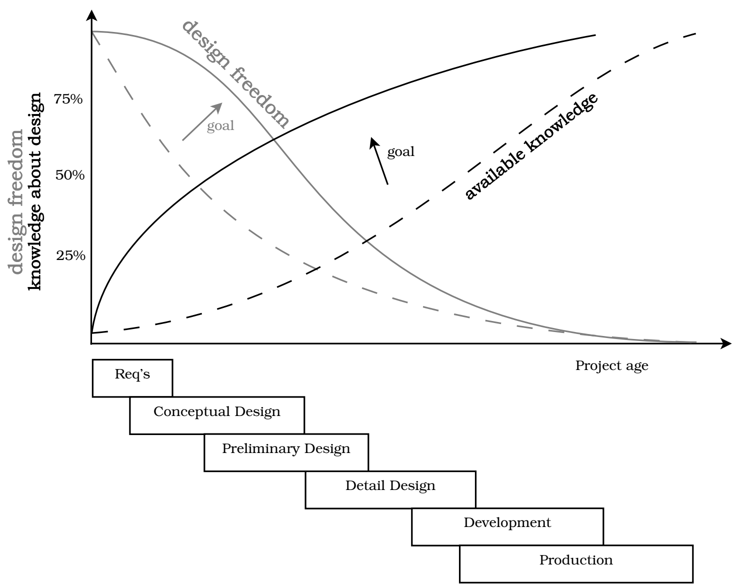


Figure 1.2 *Product life-cycle design knowledge and freedom related to design process (adapted from [Verhagen et al., 2012; Mavris et al., 2000]).*

Product life-cycle of design knowledge and freedom with respect to the design process is shown in Figure 1.2. At the beginning of the design process, the design freedom is substantial and diminishes as the design process progresses whereas the available knowledge grows as the design process advances. It is to be noted that the available knowledge does not start from zero as the knowledge from previous projects is used to develop new designs/concepts.

1.2 Aims

The research presented in this thesis addresses the following research questions. The first aim is to investigate, propose, and implement suitable modeling methodologies of the design's reuse/update of aircraft conceptual design with various fidelity levels with robust and flexible design. The second aim is to propose an approach to facilitate parameterization and provide help for further analysis. Lastly, the conceptual design is enhanced with integration of various disciplines at early stages of concept generation.

- **RQ1**: How can a Knowledge-Based Engineering (KBE) approach satisfy conceptual design needs with various fidelity levels?
- **RQ2**: Which systematic approach enables KBE/parametric modeling for an efficient Multidisciplinary Design Optimization (MDO)?
- **RQ3**: In what way can different aspects of aircraft conceptual design be integrated?

1.3 Delimitations

The research presented in this thesis deals with knowledge-based techniques and their implementation in aircraft conceptual design. The requirement from the industrial partner is to implement the CAD geometry in `CATIA`®; nevertheless, it can be replicated in other commercial/open-source CAD software that support automation.

Cost, noise and emissions, production, operations and maintenance are omitted for simplicity. To test and verify the design methodologies, in-house and commercial software have been used. Explanations of different systems created in `Hopsan` and `Dymola`® are not handled. `Tango` methodology of design and its implementation is not focused. An implementation of the `XML` integration process with `RAPID` and `Tango` is illustrated.

Only the Multidisciplinary Design Feasible (MDF) method is used in this work for optimization. Methodologies of taxonomy and ontology are available in `Tango` are not presented in this thesis (refer to [Staack, 2016]). Automated decision support is not implemented. Some parts of the text from the author's licentiate [XIV] have been carried forward and reused with minor changes. Finally, the printed copy of this thesis mostly contains figures in black and white. For color figures refer to the online version of the thesis.

1.4 Contribution

The important contribution is the knowledge that facilitates conceptual design by reducing cost and adding value to the early design phases. Methods to efficiently design, reuse and update geometry with various fidelity levels are presented. A systematic approach is proposed that enables robust flexible geometry with the design intent. More knowledge is thus accumulated in the early phases of design that helps decisions to be made as early as possible. Further contributions to this work are:

- Facilitating a knowledge-based design approach for generating aircraft design concepts with ease [I; II; III; IV; V].
- A quantitative approach that provides qualitative results for flexibility and robustness [I; VI].
- Streamlining the generated concepts for further analysis such as CFD, FEA and MDO [IV; V; VI].
- `XML`-based data generation of the design concepts, further used to communicate with other tools/frameworks [I; IV; V].
- Aircraft systems integration at conceptual level enhanced by coupling with systems simulation [II; III].
- Analytical methods are coupled with the design concepts to obtain initial guesstimated weights [II; III].

1.5 Thesis Outline

A review of KBE is presented in Chapter 2 along with the parameterization methodology in this work. In Chapter 3, the aircraft conceptual design tool framework implementation is discussed. The data management using a centralized XML database is presented along with a quantitative approach for the parametrization methodology. The analysis features are elaborated in Chapter 4, showing the capabilities of the framework. Chapter 5 shows the implementation and applications from concept design to demonstration. Conclusions are given in Chapter 6. Future work is presented in Chapter 7 and a brief overview of the appended papers is provided in Chapter 8.

1.6 Research Methodologies

The work presented in this thesis is influenced by two main design methodologies, namely Methodology and software tools Oriented to Knowledge based engineering Applications (MOKA) and Design Research Methodology (DRM). MOKA is implemented in Knowledge-Based (KB) application RAPID where design is automated, for example number of frustums in fuselage or number of partitions in wing-like elements or systems integration. DRM is applied in case of only parametric geometry like landing gear design where no automation is performed. Both methodologies are iterative and contain several stages in each step and have similarities.

1.6.1 MOKA Methodology

The Methodology and software tools Oriented to Knowledge based engineering Applications (MOKA) methodology presented by [Stokes, 2001] is used to build all the KB elements. KBE applications can be built in modules and gradually added at different stages of the life cycle by all the people involved in the process. This is an iterative processes and the level of detail increases with each step. The process adapted here to be efficient for the research in KBE, several stages can be embedded in each step listed below:

- Identify: Identify the needs, relevant information, types of systems and technical feasibility. All the stake holders are involved in determining the type of system needed to satisfy the need.
- Justify: The scope and assets are studied and motivated, approval from management is needed to proceed.

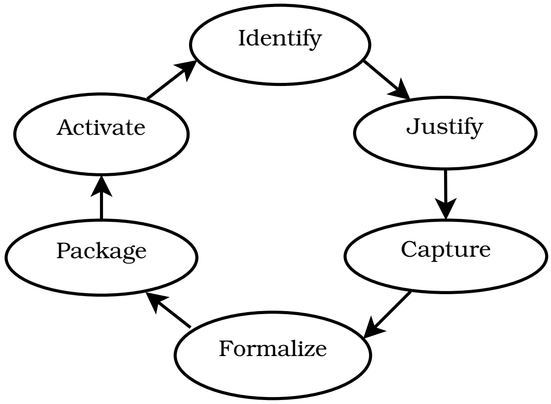


Figure 1.3 *KBE life-cycle methodology (adapted from [Stokes, 2001]).*

- Capture: The relevant information/knowledge collected is filtered. Necessary information is sorted out for the next process.

- Formalize: The knowledge obtained is converted into a design process. The flow of various processes followed in the instantiation/automation is analyzed

- Package: Knowledge templates of various components needed for are generated. The KBE application is developed.

- Activate: The automated process is put into practice, tested for the desired result, rebuilt with modifications, and verified with various existing models.

1.6.2 Design Research Methodology

The design research methodology introduced by [Blessing et al., 2009] is used for parametric geometry applications, further complemented with measures of effective parameterization on model robustness and flexibility. As illustrated in Figure 1.4, the process has four main steps. The success of the overall research is measured in *criteria* and the problem is analyzed based on the measurable criteria in *Descriptive Study 1 (DS1)*. The methods/tools to address the problem are identified and developed in *Prescriptive Study 1 (PS1)*, and finally, evaluation of the methods/-

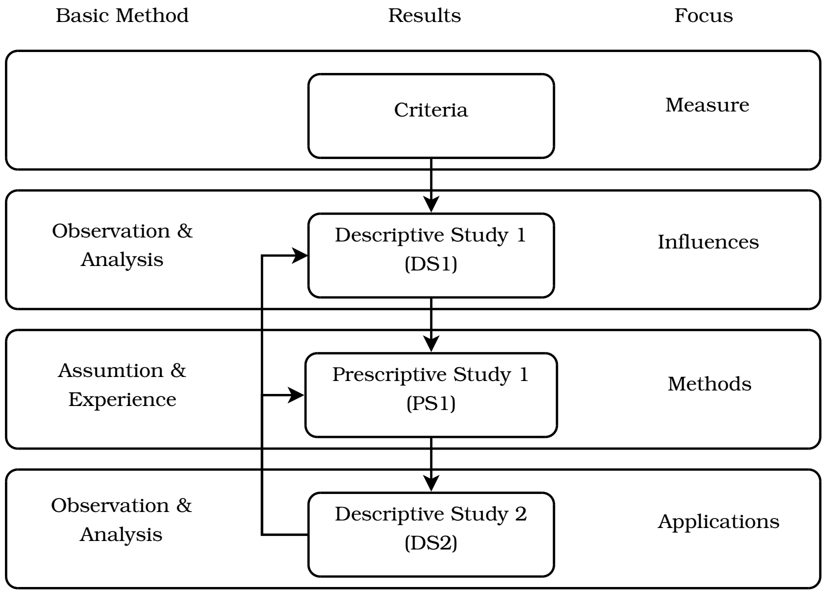


Figure 1.4 *Design research methodology used in the current research study (adapted from Blessing et al., 2009).*

tools developed earlier is performed in *Descriptive Study 2 (DS2)*.

"Scientists discover the world that exists; engineers create the world that never was" - Theodore von Karman

2

Intelligent Design

Artificial Intelligence (AI) is one of the fastest growing technologies [Russell et al., 2010] and has many applications [Turban et al., 2014; Sriram, 1997]. It is a division of computer science that deals with two concepts: understanding the human thought process, expressing and repeating the process in machines [Turban et al., 2014]. There are several definitions of AI. [Russell et al., 2010] organized the definitions into four categories based on the thought process, reasoning and behavior: *thinking humanly, acting humanly, thinking rationally* and *acting rationally.* If a system accomplishes the correct objective with *"what it knows"*, it is said to be a rational system. *"A rationalist approach involves a combination of mathematics and engineering"* [Russell et al., 2010].

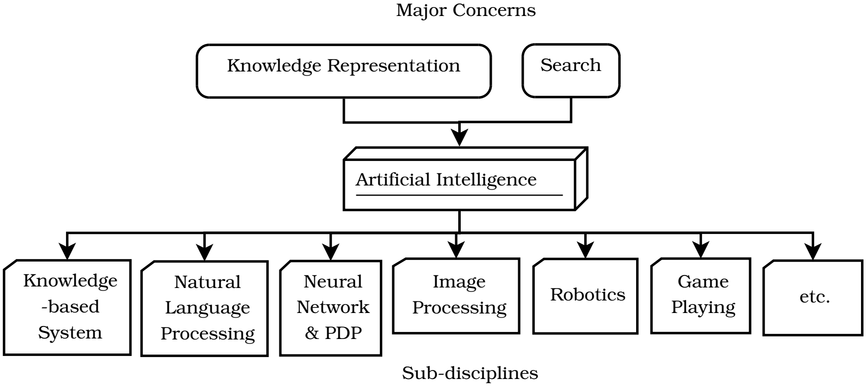


Figure 2.1 *Artificial intelligence's major concerns and sub-disciplines (adapted from [Deryn et al., 1997]).*

Major technologies in AI include *“expert systems, genetic algorithms, fuzzy logic, intelligent agents, neural networks, hybrid artificial intelligence etc.”* [Deryn et al., 1997; Negnevitsky, 2011]. The sub-disciplines of AI include *“machine learning, game playing, robotics, neural networks and parallel distributed processing (PDP), vision along with knowledge-based system”* [Deryn et al., 1997](see Figure 2.1). An application/implementation of AI in computer-aided design and manufacturing is presented by [Marx et al., 1995] and in aircraft conceptual design supported by Case-based reasoning (CBR), Rule-based reasoning (RBR) and Geometric modeling (GM) is shown by [Rentema, 2004].

2.1 Knowledge-Based Engineering and System

Knowledge-Based Engineering (KBE) is reusable information that exists in the specific method or form; this knowledge is reused either manually or automatically and the whole process of using this existing knowledge such that it adapts to the new environment is termed Knowledge-Based System (KBS) [Amadori, 2012]. KBE is a technology initiated by Concentra Corporation [Rosenfeld, 1995] and has existed for a couple of decades. More and more people have seen the need [Cooper et al., 1999] and also developed an application in aircraft design based on KBE [La Rocca and Van Tooren, 2007]. Nowadays, most CAD software is embedded with this technology as packages, e.g. knowledgeware in [Catia®V5, 2016], knowledge fusion in [NX, 2016] and expert system in [Creo, 2016], etc. [Sobieszczanski-Sobieski et al., 2015] in *Figure 9.19* presents various KBE systems evolutions along with respective vendors and KBE-augmented CAD environments. [XIV]

2.1.1 Data, Information, and Knowledge

Many definitions are available to define data, information and knowledge as mentioned below.

Data is

- *"is a group of facts or statistics that have not been assigned meaning"*[Wood et al., 1998],
- *"the set of fundamental, indivisible things"* [Debenham, 1998].

- *"understood as discrete, atomistic, tiny packets that have no inherent structure or necessary relationship between them"* [De Long, 2004; Nawijn et al., 2006].

Information is

- *"data that has been assigned meaning"*[Wood et al., 1998].
- *"the set of implicit associations between the data things"*[Debenham, 1998]. .
- *"data that is structured and put into context, so that it is transferable, but the immediate value of information depends on the potential of the user to sort, interpret and integrate it with their own experience."* [De Long, 2004].

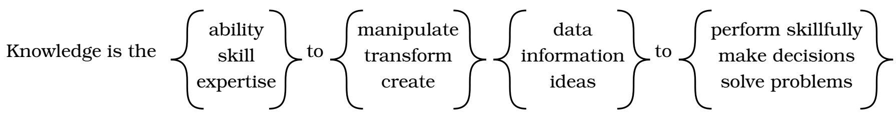


Figure 2.2 *Definition of knowledge (adapted from [Milton, 2008]).*

Knowledge is

- *"the sum of what has been perceived and learned that allows for the generation of information"* [Wood et al., 1998].
- *"the set of explicit associations between the information things"* [Debenham, 1998].
- *"implies the combination of information with the user's own experiences to create a capacity for action"* [De Long, 2004]

A summarized definition of knowledge as defined by [Milton, 2008] is presented in Figure 2.2. Let us understand data, information and knowledge with a simple example. Atmospheric values such as temperature, pressure, velocity are just numbers and signify data. Information on where these values are recorded (at which altitudes) shows the variation of these values with respect to altitude and this information can be used to make decisions. Knowledge is knowing how the atmospheric values affect the designed aircraft; a decision is reached by analyzing several sets of information. *"The movement from data to knowledge implies* *a shift from facts and figures to more abstract concepts"*[Kendal et al., 2007](see Figure 2.3). [Nawijn et al., 2006] show the knowledge accessibility levels (data, Information and knowledge) are transferred from a geometric definition to FEA.

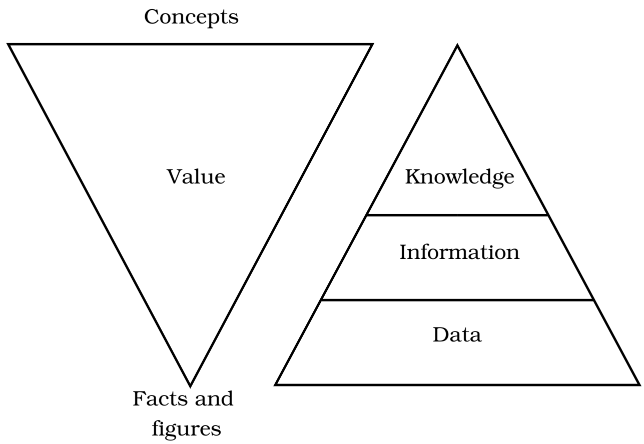


Figure 2.3 *Data, information and knowledge (adapted from [Kendal et al., 2007]).*

2.1.2 Knowledge Acquisition

"Knowledge acquisition is the accumulation, transfer, and transformation of problem solving expertise from experts or documented knowledge sources to a computer program for constructing or expanding the knowledge base" [Turban et al., 2014]. Knowledge is acquired from books, processes, databases, rules of thumb, human experts, documents, products, reports, and electronic media such as the web. A knowledge base is the foundation of an expert system, the necessary knowledge for understanding, formulating and solving problems. A software program uses the knowledge stored in the knowledge base to solve a problem under consideration. Knowledge from human experts is called *"knowledge elicitation"* is one of the hardest knowledge acquisition process as the experts might not know how to express their knowledge and reluctant to collaborate due to lack of time [Turban et al., 2014]. A step-by-step guide to acquire knowledge from expects and in practice is presented by [Milton, 2007].

2.1.3 Knowledge Representation

The knowledge obtained from various sources is structured and prepared for use by indoctrinating the knowledge in the knowledge base. The acquired knowledge is essentially represented such that it is executable by computers and understood by individuals. Knowledge is represented in the form of rules, objects, decision trees, decision tables and semantic networks [Turban et al., 2014].

2.1.4 Ontology

Ontology is the terminology that shares information in a specific domain, the elementary concepts in the domain, and the associations between them are machine-interpretable [Natalya F. et al., 2001] and the authors introduced a guide to developing an ontology. [Kuhn, 2010; Milton, 2007] present broad classification of ontologies and implementation. As shown in Figure 2.4, products developed based on ontology enhance the knowledge-based design with context-dependent knowledge management [Danjou et al., 2008]. One example is *protégé* [*protégé*, 2017], an open source ontology editor for intelligent applications that could be used in this context.

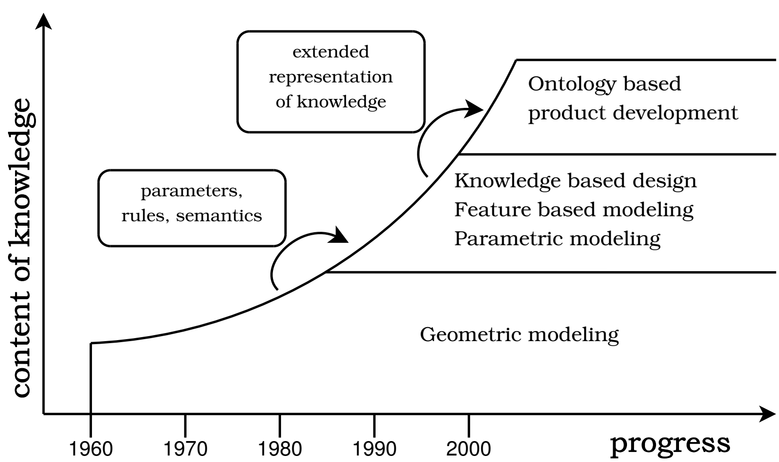


Figure 2.4 *Development of CAD process (adapted from [Danjou et al., 2008]).*

2.1.5 KBE in the Present Work

KBE / Knowledge-Based System (KBS) is performed in `CATIA`® using the Power Copy (PC) and the User Defined Feature (UDF) wherever necessary. `VB` scripts use the PC and Knowledge Pattern (KP) uses UDF to save the knowledge that is created for automation. PC or UDF is a set of features stacked together that can be reused at a later stage. A catalog is needed to store the location of the UDF. The KP algorithm script is written using the `EKL` to control the UDF. UDF is used repeatedly to obtain a desired configuration. The UDF can also be updated depending on the requirement and used accordingly. Creating the initial KBS is time-consuming and the user needs to have some knowledge of the system in case of modifying it; however, once it is built there are numerous uses for it and it could help the user build the necessary system faster and in less time. Figure 2.5 by [Wojciech, 2007] shows that by adopting KBE the time taken for the routine tasks can be minimized.[XIV]

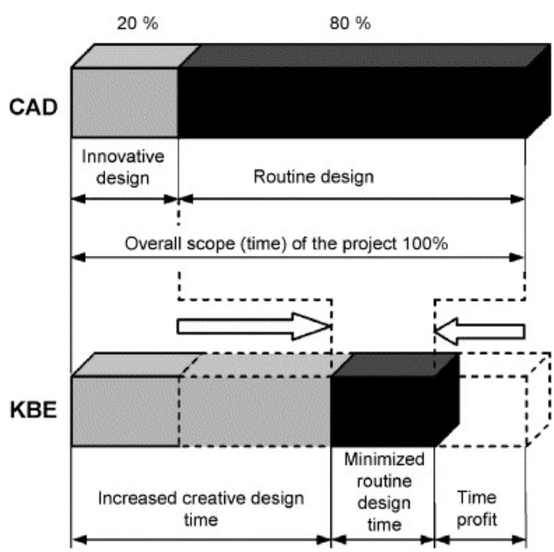


Figure 2.5 *Design time by adapting KBE (adapted from [Wojciech, 2007]).*

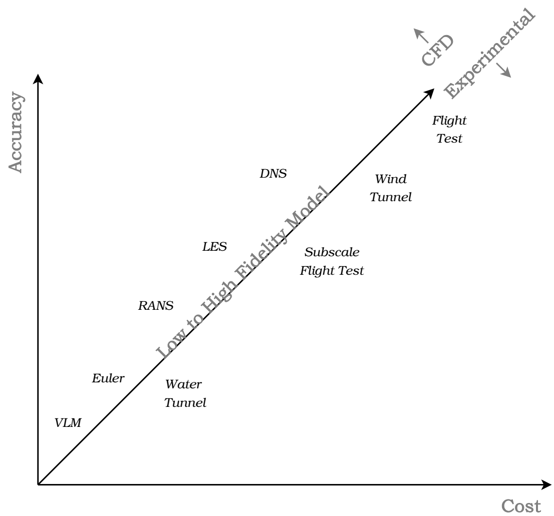


Figure 2.6 *Multi-fidelity CAD, CFD, and experimental models (adapted from [Tomac, 2014; Schminder, 2012]).*

2.2 Level of Fidelity

The frameworks are similar to Paper [I] and as shown in Figure 3.1 have the additional disciplines/capabilities are `CEASIOM` ([Rizzi et al., 2012]), `VAMPzero` ([Böhnke et al., 2011]), `DEE` [La Rocca and Van Tooren, 2007] and `SUAVE` [Lukaczyk et al., 2015]. [Tomac, 2014] (see Figure 2.6) shows that the geometry created can be propagated from low and high fidelities for CFD in `CEASIOM`. Accuracy increases and is compensated by the cost, similar to experimental models [Schminder, 2012; Tomac, 2014]. The geometry created as such cannot be used for preliminary design. All the above mentioned frameworks use the in-house tools developed by the respective institution/research organization. The main reason to use the commercial tools in this framework is to facilitate direct implementation of the tool framework in the industry. This will reduce the time for the industry to implement the framework as it need not redo all that has been done. Figure 2.7 shows the model fidelity levels that are present in this work, similar to those presented by [Nickol, 2004]. In contrast, it could also be represented by analysis types variing from Level-0 to Level-3 [Moerland et al., 2015]. Know-how about the tools in Figure 2.7 is presented in Chapter 3, the analysis features in Chapter 4 and the implementation and applications in Chapter 5.

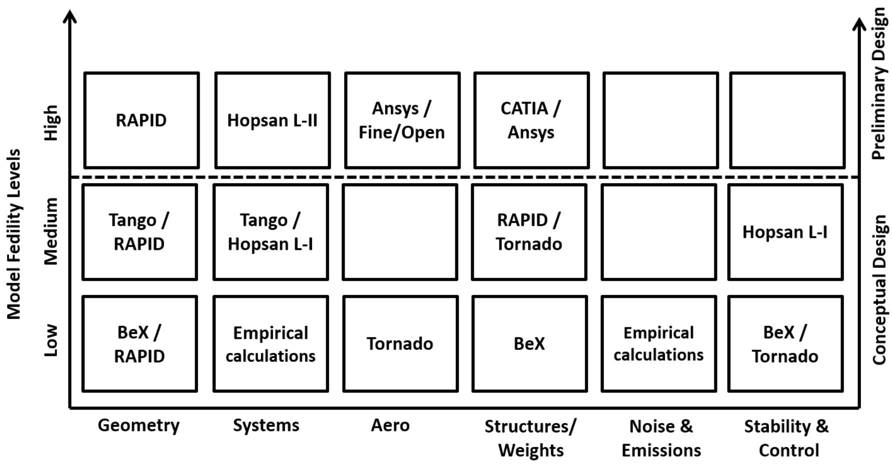


Figure 2.7 *Model fidelity levels used in this framework (adapted and modified from [Nickol, 2004]).*

2.2.1 KBE in MDO

A complex product increases the complexity of the MDO process as several disciplines need to work together and essential resources such as computational time increase ([Silva et al., 2002]). A quick analysis can be performed using a low-fidelity model, although to gain a better understanding of the product a high-fidelity model is necessary. The geometry is mostly created in CAD software with all the parameters and exported to other tools for analysis such as CFD, FEA, and system simulation. A parametric model offers a seamless flow between different disciples. CAD-neutral formats such as STEP, STL, IGES, etc. can be exchanged between most of the tools for CAD, CFD, and FEA. The Common Data Model (CDM) for CAD and Computer Aided Engineering (CAE) presented by [Gujarathi et al., 2011] contains relevant information for design and analysis. In an optimization process, the parametric data is modifiable and shared by all the disciplines (see [Samareh, 2001]). For a reliable parameterization, geometry and fewer design variables and shorter setup time, a CAD system is important [VI].

2.2.2 CAD-based and CAD-free Approaches

A CAD-based approach uses any third-party software to create parametric models with the feature-based approach while a CAD-free approach uses spline surfaces to parameterize and modify the discrete surfaces. In a CAD-free system, the surface grid is generated by the use of B-spline patches; the coordinates and numbers of the original patch are utilized for the modification of the geometry. The number of surfaces/faces remain the same, so the grid is generated rapidly and the range of coordinates always has fixed limits. In a CAD-based system, the modification of the geometry results in the generation of new faces and coordinates of each surface grid are changed after each modification. The coordinates are normalized and later de-normalized after each modification and depending on the face the coordinates are extracted [Fudge et al., 2005]. *"Mesh based evolution"* of the structural model mostly two-dimensional (2-D) is obtained by eliminating or modifying the element in the domain during an FEA [Keane et al., 2005].

The geometry created with a CAD-free approach involves many parameters [Kenway et al., 2010]. This will have a substantial impact on the design process and also increases the computational cost, i.e. they demand clusters, especially for problems involving optimization. Therefore, it is essential to reduce the number of parameters for a geometrical description. In this context, methods have been developed to overcome the issues, e.g. the universal parametric method [Kulfan, 2008]. This method uses shape and class functions to describe both 2-D and 3-D geometries. Sobster [Sóbester and Powell, 2013] presents the impact of the number of parameters on computational cost [in the design space exploration] in a MDO process. The relational design methodology has been proposed to reduce the number of parameters for optimization (see Section 2.2.4 and Section 3.3).

2.2.3 Design Parameterization

A parametric geometry helps explore many design modifications of the concerned product. [Shah, 2001] and [Davis, 2013] have presented the history, progress and classification of parametric modeling. *"Automatic change propagation, geometry re-use, and embedded design knowledge"* are the main benefits of using parametric models. Associativity between the parameters helps propagate the modification to all the features in the design (e.g. point, line, curve, surfaces, solids). Parametric modeling has become a standard in CAD software (see [Rhino, 2016; Catia®V5, 2016; Creo, 2016]) and is becoming a standard in the MDO process. Conciseness, flexibility, and robustness are the three main entities that affect the number of parameters used to define the model. [Bodein et al., 2013; Koini et al., 2009; Turrin et al., 2011; Baek et al., 2012; Abt et al., 2001; La Rocca and Tooren, 2009; Amadori, 2012] show the advantages of using parametric modeling. [VI]

The propagation-based system uses known values to compute the unknowns; a constraint-based system solves sets of discrete and continuous constraints. These are the two common parametric systems as mentioned by [Beesley et al., 2006]. [Hoffmann et al., 2005] present other methods such as the graph-based approach, the logic-based approach, algebraic methods, etc. In a CAD-centric method, these modeling techniques have an influence in the MDO process as the geometry and parameters are later used for analysis in CFD, FEA, systems simulation, and MDO [Welle et al., 2012; Hwang et al., 2012]). [VI]

2.2.4 Effective Parameterization

In a KBS there is a requisite for effective parameterization to obtain a good working system. In this circumstance, there can be different layers of parameterization involved in the entire aircraft (Figure 2.8). In `RAPID`, there are several layers of relational design, thus making it a complex model. Global references are the first set of parameters to initialize the positions of different objects such as fuselage, wing, horizontal tail, vertical tail, canard, engine, etc. The second set of parameters gives the initial layout/shape of the aircraft, e.g. fuselage length, height and width, that give effective dimensions to different objects and forms the bottom-up approach in `RAPID`.[XIV]

- **Global references**: Main positions of all the objects such as fuselage, wing, horizontal tail, vertical tail canard, and engine
- **Interrelated references**: These are the references needed to size the aircraft. For example, the vertical tail reference area is dependent on the fuselage and its position from the origin; the horizontal tail and canard reference area depends mainly on their respective positions from global origin and the wing area. An overall two-dimensional sketch is obtained after completion of this phase.
- **Relational references**: These are the references that help give the shape / volume of the aircraft. For example, instantiation of number of fuselage frustums or number of wing partitions, etc.

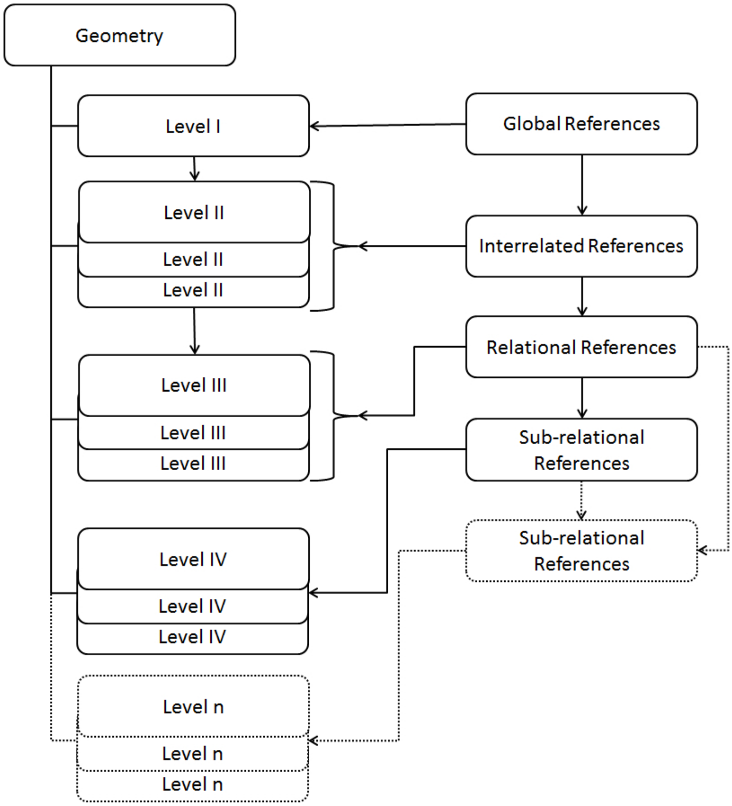


Figure 2.8 *Design methodology applied in* RAPID.

- **Sub-relational references**: These area the relational parameters that are available after instantiation of the instances of a number of frustums or number of wing parameters. There can be several layers of sub-relational references depending upon where the instances follow.

2.2.5 Parameterization Example

The propagation of the design changes is made possible with a careful correlation of the geometry features (see [Silva et al., 2002]). The two important factors enabling a successful update of the geometry are type and number of parameters. The following Section enlightens the parameterization implementation in this work with an example with reference to Section 2.2.4. To create "n" number of points with a reference from the given coordinate system, there is a necessity for “3n” parameters even if all the points are to be of the same length in the Z direction. If all the four points used to create a rectangle as shown in Figure 2.9 are created with a reference from the given coordinate system, then twelve parameters are needed. To reduce the number of parameters, an efficient parametrization is necessary, i.e. relational parametrization. The above-mentioned example is modified for the efficient parametrization by using only less than half of the parameter needed. [XIV]

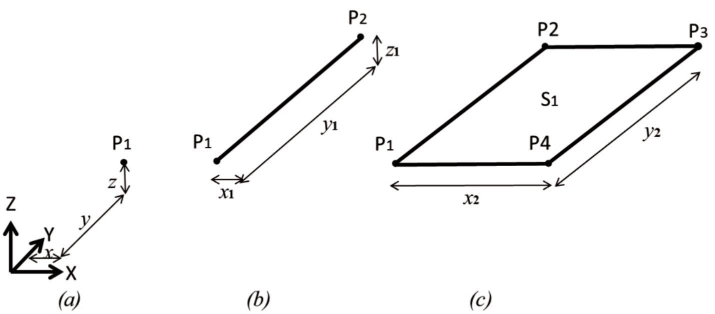


Figure 2.9 *Parametrization example.*

To effectively create a point P_1 from a given coordinate system, three coordinates (x, y, z) are required. Point P_2 is created from point P_1 along the Y-axis with a distance (y_1). Doing so reducing the number of variable parameters need to be defined to one parameter. Points P_3 and P_4 are created from points P_2 and P_1 respectively along the X-axis with a distance (x_2). In total, the number of parameters needed from the relational parametrization is only five. Two more parameters are needed to modify the shape of the rectangle to obtain any quadrilateral. In Section 3.3 practical applications of the parameterization is presented for better understanding of effective parameterization. From Table 3.3 it can be observed that the robustness of the kinked wing has increased approximately 30% through effective parameterization. [Kulfan, 2008] presents a parametric geometrical method that can be applied to obtain a wide rage of geometry objects. [XIV]

"To know what you know and what you do not know, that is true knowledge." - Confucius

3 Conceptual Aircraft Design Laboratory

A data-centric conceptual aircraft design framework named `CADLab` (Conceptual Aircraft Design Laboratory) has been developed for a seamless CAD integration. The intentional naming ambiguity with the usual abbreviation of "CAD" for Computer Aided Design highlights one of the unique topics that characterize this framework besides the extended usage of KBE and system architecture design. A CAD tool is the natural means for geometry modeling. Furthermore, the direct usage of CAD helps geometry propagation from the conceptual design to the preliminary design by adding new elements to the existing geometry.

The framework consists of three modules: A sizing/CAD module, an estimation, analysis and assessment module, and a simulation & system architecture module, shown in Figure 3.1. All the modules communicate and interact with a central `XML` database. Enabling parallel functionality is one of the development targets of this framework. The highly KBE based CAD and aircraft sizing module serves for a fast setup of the initial design, usually based on a conceptual sizing. The main part of this module is `RAPID` (see Figure 3.3), a geometry-oriented design tool implemented in `CATIA`®.

After instantiating the geometry and the related primary structure, the design analysis is conducted for aerodynamic, weight and structure, trim and flight envelope as well as propulsion and system performance. This analysis functionality is mainly based on semi-empirical (statistical) data and the Vortex Lattice aerodynamic analysis, conducted in `Tornado` [Melin, 2000]. Within this module the required missions are

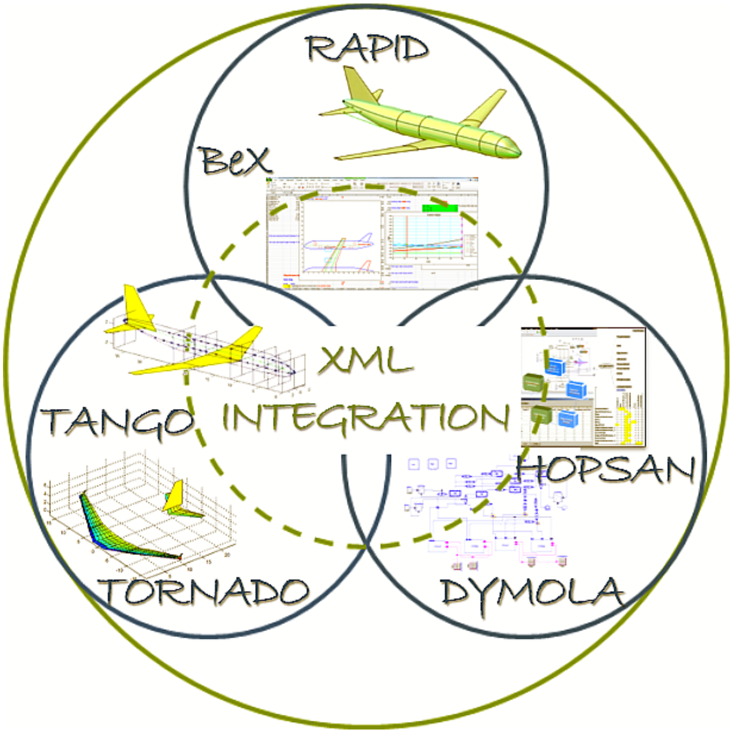


Figure 3.1 *CADLab framework.*

calculated based on the available data and the results are presented to the user. It can take additional data into consideration usually the structural weight and the supersonic wave drag (papers [IV; V]) from RAPID and the system performance and weight properties of the simulation & system architecture module. The third module, simulation & system architecture is used for more detailed investigations. This addresses problematics like system architecture design, system integration and the analysis of system interaction; these capabilities are used for example, to investigate different control/actuator architectures or to investigate positive and negative system interferences. This is especially necessary for tightly coupled systems like the nowadays highly electrically driven on-board systems of civil passenger aircraft. Stability and control design - inevitably included in the flight control system of unstable configurations – is also a topic addressed in this module, supporting the user with (faster than real time) simulations which allow the designer to investigate and understand the system characteristics and capabilities. These

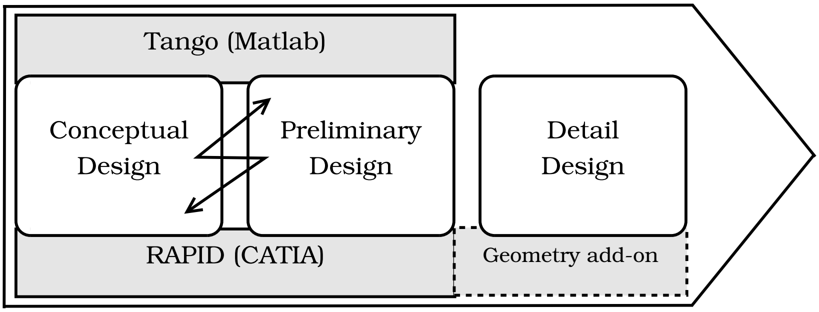


Figure 3.2 *Parallel implementation [I; VII].*

features had been enabled by the extended usage of KBE processes during the simulation model instantiation.

To maintain flexibility, both `RAPID` and `Tango` are implemented in parallel (see Figure 3.2). The user/developer can choose his/her preferred work process and the data is exchanged between the two programs at any point in time. More and more details are added as the design moves from conceptual to preliminary and detail design. The geometry is frozen as the design proceeds to detail design; all the manufacturing drawings are developed in the detail design process and later the demonstrator is developed (see Figure 5.7).

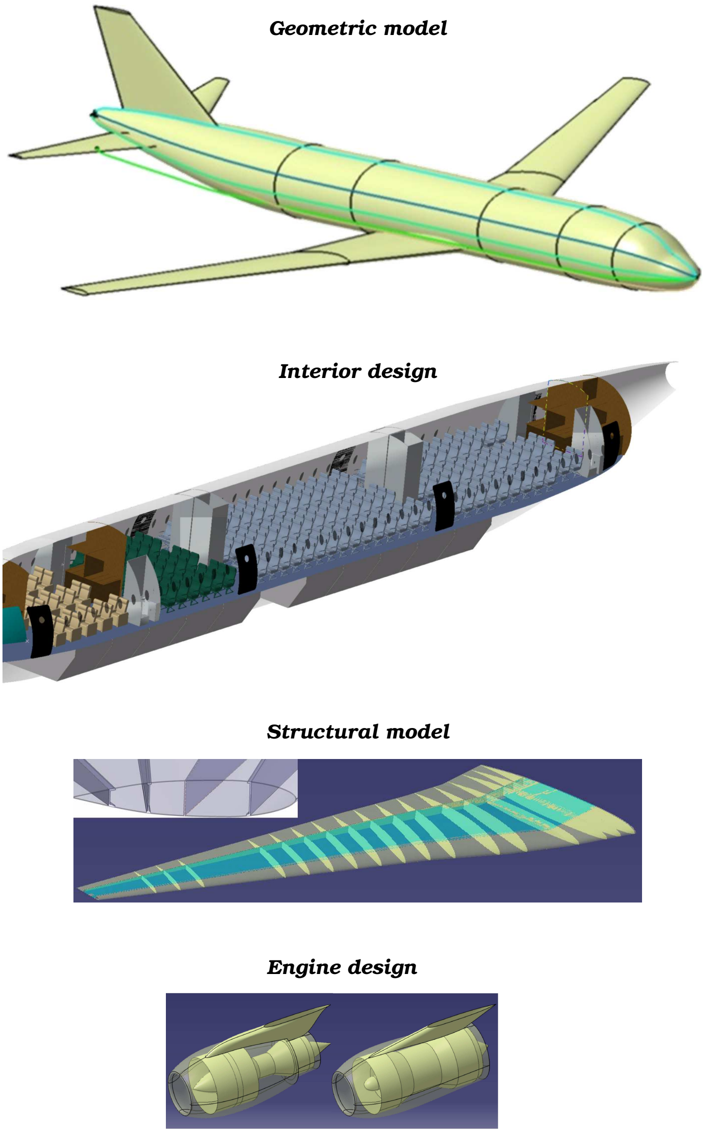


Figure 3.3 *`RAPID` overview - Initial KBE geometry layout [I; VII; XIII; XV; XVI].*

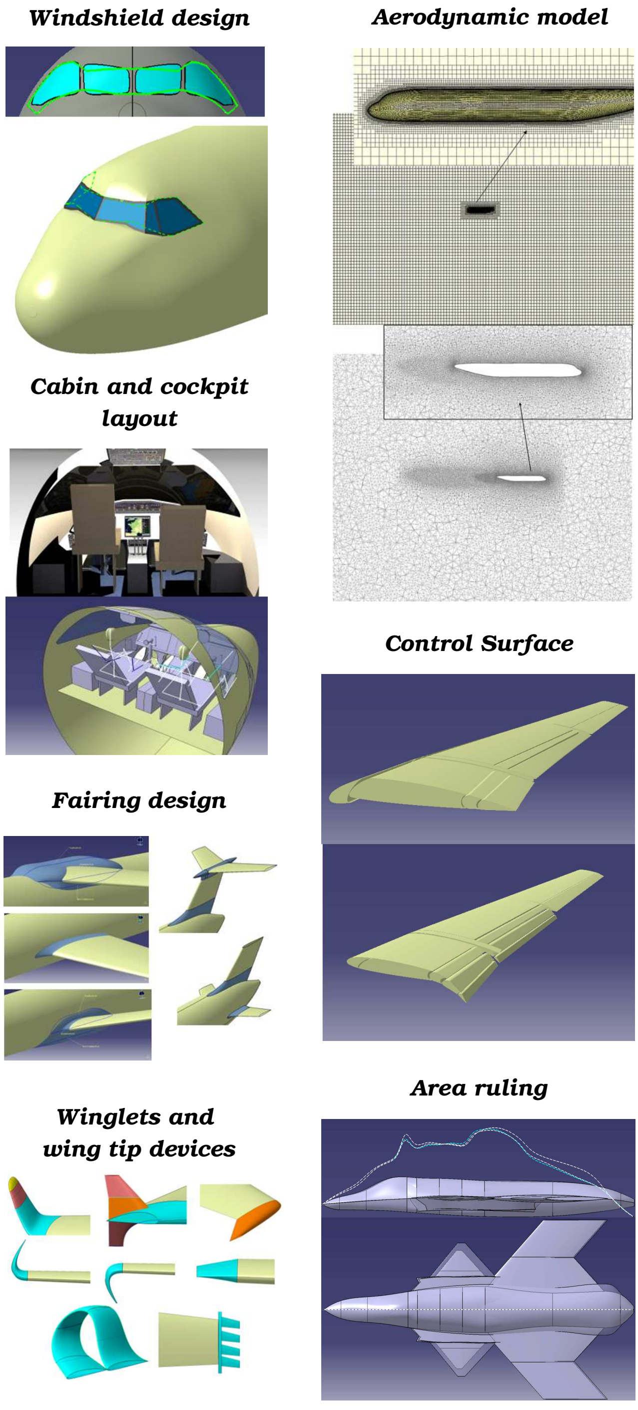


Figure 3.3 *`RAPID` overview - Geometry reuse and extensions [I; IV; V; VI; VII; VIII; IX; XIII; XV; XVI; XVII; XI].*

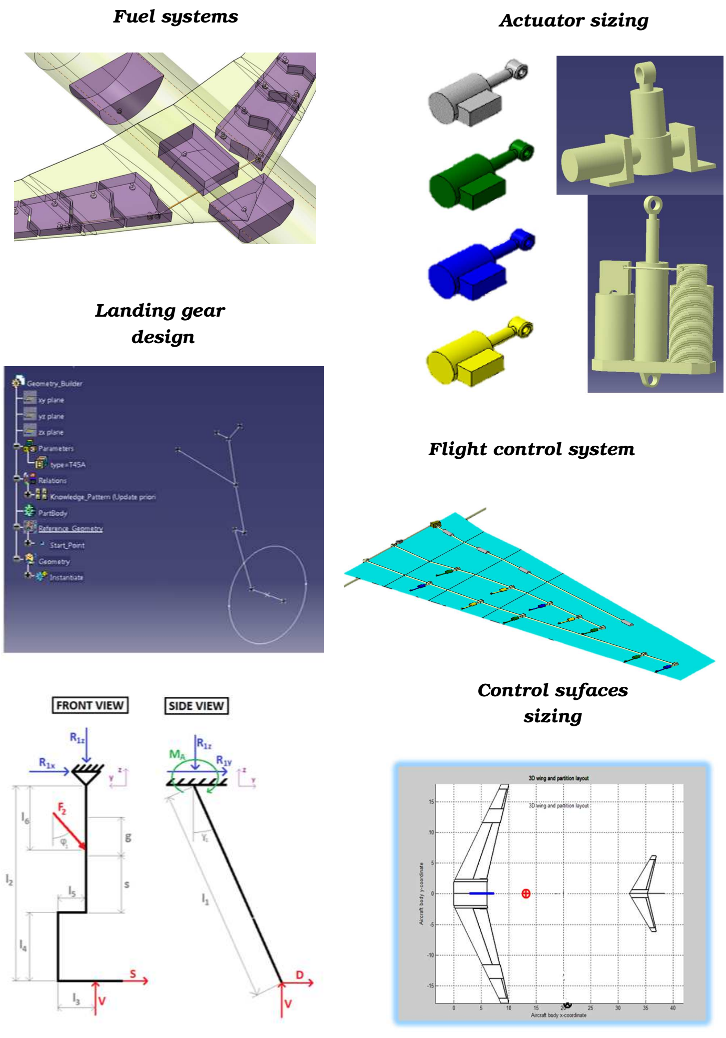


Figure 3.3 *`RAPID` overview - Systems integration [I; II; III; X; XI; XII].*

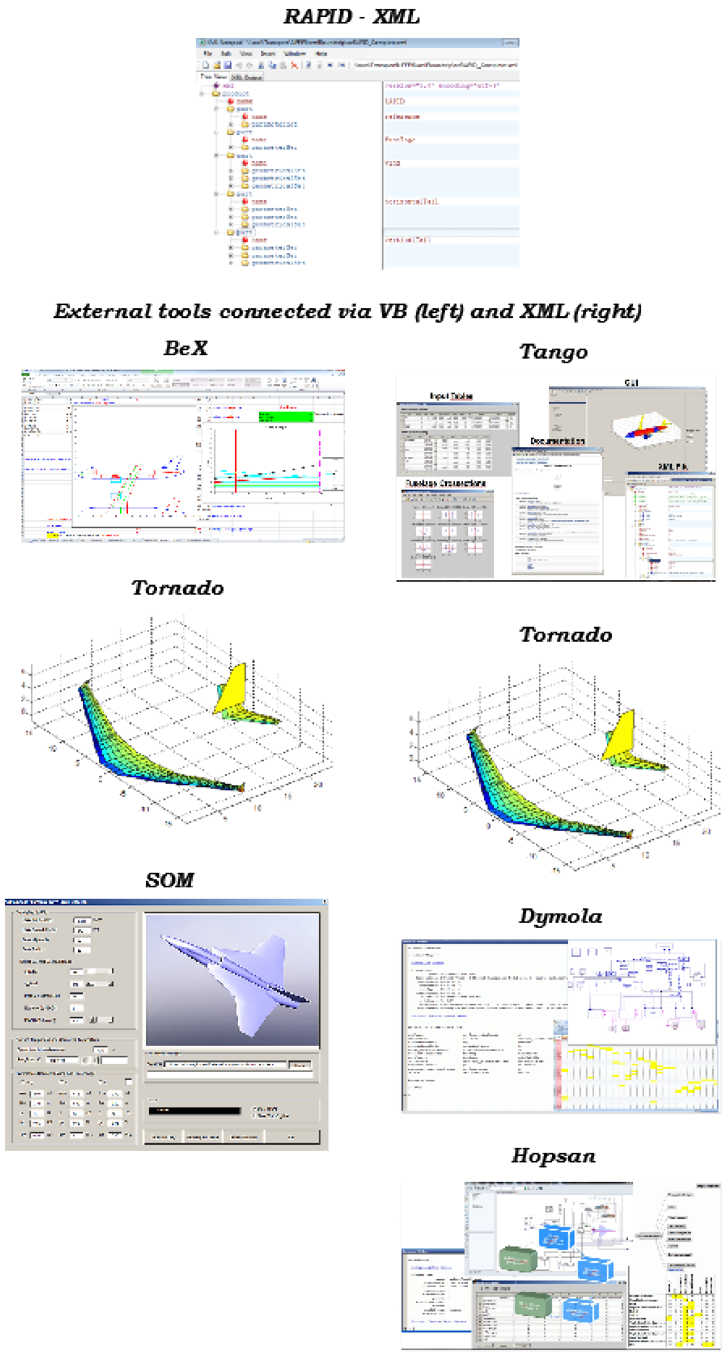


Figure 3.3 *RAPID overview - Data management and collaborative network [I] till [XIX].*

3.1 RAPID - Robust Aircraft Parametric Interactive Design

RAPID (Figure 3.4 is a geometry oriented design tool used in the framework of aircraft conceptual design. Using CATIA® allows the geometry propagation from conceptual design to preliminary design. KP and VB embedded in CATIA® are used for automation at necessary stages. There are three ways the user can design the aircraft in RAPID [XIV]:

- By modifying the existing model after loading from the XML data library.
- By updating the model from the Sizing Excel (BeX).
- By a bottom-up design approach.

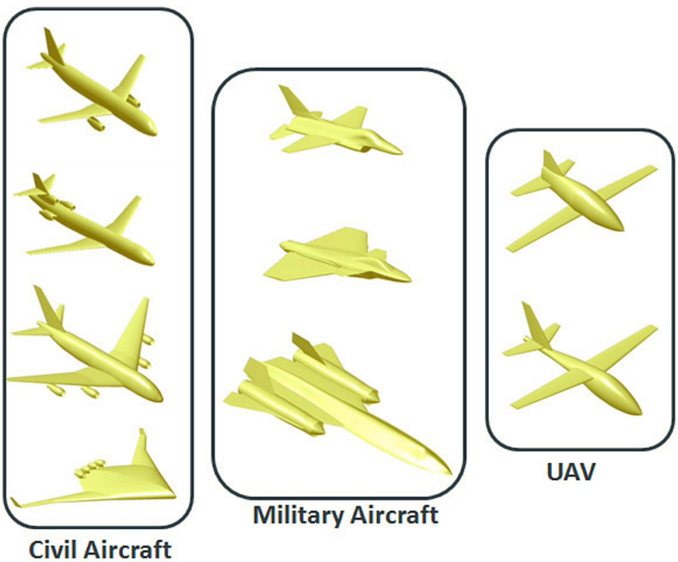


Figure 3.4 *Different aircraft configurations of a geometry model in RAPID.*

Users can design from scratch or can load the existing aircraft model from the XML data library using the bottom-up design approach in RAPID. The user begins by modifying the fuselage curves according to design requirements and later adapting the wing. Depending on the given fuselage parameters and wing parameters, the empennage is automatically sized. The adaptability of the model helps different aircraft configurations to be obtained. [XIV]

A more detailed geometry can be developed after the initial setup of the wireframe model of the aircraft (Figure 5.1). Depending on the requirement, the user chooses the number of frustums needed for the fuselage and the number of partitions needed for the wings, empennage and canard. [XIV]

3.2 Data Management

The flow of data between each discipline in a multidisciplinary design environment (Figure 3.5) is coupled and saved in XML format [Lin et al., 2004; Lee et al., 2009]. The database definition (including several component libraries like functional assemblies) is parametrically defined in such a manner that a data refinement over time alongside the project is possible. [XIV]

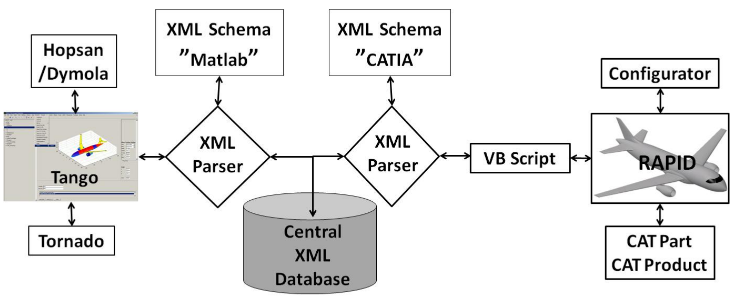


Figure 3.5 *XML data flow between RAPID and Tango with the help of XSD and XSLT.*

Information is represented in XML using markup tags and data. An XML forms a tree structure which makes it easy to retrieve data and find relationships between different information. Transformation of XML documents is performed using XSLT. XSLT uses XPath language to navigate in XML documents. It can serve for complex translations such as element and attribute editing (add, remove, replace), rearrangement, sorting, performing tests and making decisions [XML and DOM Objects, 2016]. [XIV]

The functional approach is different in RAPID and Tango as the fundamental design approach varies in CAD and technical computing/programming language. Data is translated between the programs using the

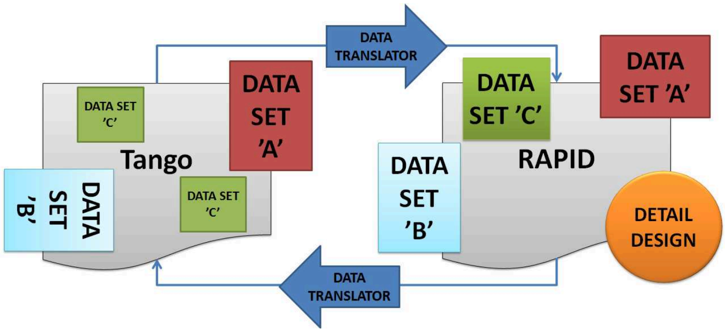


Figure 3.6 *Data communication with different subsets of geometry.*

data translator. In Figure 3.6 dataset 'A' of the initial geometry representation is available in both programs. Later, dataset 'B' is added in `Tango` and is updated in `RAPID`, e.g. a canard is added to the existing configuration. It is to be noted that dataset 'C' created in `RAPID` is split into two subsets in `Tango`; for example:- wing and the engine housing are in the same geometrical product in `RAPID` but this is split up into a geometrical and functional subset in `Tango`. This results in different local product/`XML` tree structures in `RAPID` and `Tango` respectively. The internal parameters used with in `RAPID` (e.g. parameters used with in a template) are not stored in the common database. Detail design or design add-ons to the geometry are not updated in `Tango`. [XIV]

3.3 Design space, Robustness, and Flexibility

Information is congregated in the product from the conceptual design to detail design; in this case the `RAPID`/`Tango` model saves a lot of data about the aircraft. The initial design defined by the skeleton is a design point in the design space obtained from the initial requirements. [XIV]

The three measures that makeup a good parameterization are conciseness, robustness, and flexibility, as proposed by [Sóbester and Forrester, 2014]. The following section explains the definitions along with implementation examples. Conciseness is stated as from several possible parametric geometries choosing the one with the smallest number of design variables, all other features being equal. The design space increases with the number of parameters/design variables involved in the design and optimization of the product under consideration, so the geometry needs to be as concise as is feasible. To address the conciseness of the model, the number of parameters is limited/reduced to a minimum by the use of relational design. Further description of the model's relational design is elaborated in the *Results and discussion* section.

Robustness is the ability to produce sensible shapes both geometrically and physically in a given design space and *flexibility* is the number of shapes the parametric geometry is capable of generating. The robustness and flexibility of the design are considered to be measurement factors in this study. Flexibility and robustness of geometry have a direct impact on the efficiency of a CAD-centric MDO framework. They are therefore indirectly considered to be a metric to measure the robustness of an MDO framework. The robustness and flexibility of the CAD model are calculated using Equations 3.1, 3.2, and 3.3. For more information, see [Amadori, 2012; Amadori et al., 2012].

$$MeanDesignSpace = \overline{V_{S}}_c = \prod_{i=1}^{n} \left(\frac{x_i^{max} - x_i^{min}}{x_i^{ref}} \right) \tag{3.1}$$

$$x_i^{ref} = ReferenceValue$$
$$x_i^{max} = MaximumValue$$
$$x_i^{min} = MinimumValue$$

$$Robustness = R_{S_c} = \frac{SuccessfulDesigns}{TotalDesigns} = \frac{S_C}{S} \tag{3.2}$$

$$Flexibility = F_{S_c} = \overline{V_{S}}_c * R_{S_c} \tag{3.3}$$

3.3.1 Aircraft Wing

The kinked wing has two-sections: inner wing and outer wing. The sweep of these two-sections are changes independent of each other (Figure 3.7). To measure the robustness and flexibility of the geometry, three tests were conducted on the same kinked wing of a civil aircraft (Figure 5.1(a)). `modeFRONTIER`® [modeFRONTIER 4.5.2, 2016] was used to compute different designs. [XIV]

Design of experiments was created using Latin Hypercube sampling to obtain values that are relatively uniformly distributed for each input parameter, as shown in Table 3.2. Robustness and flexibility of the design are also computed [Amadori et al., 2012], as shown in Table 3.3. In "Wing Test 2" the designs have failed because the kink position is placed

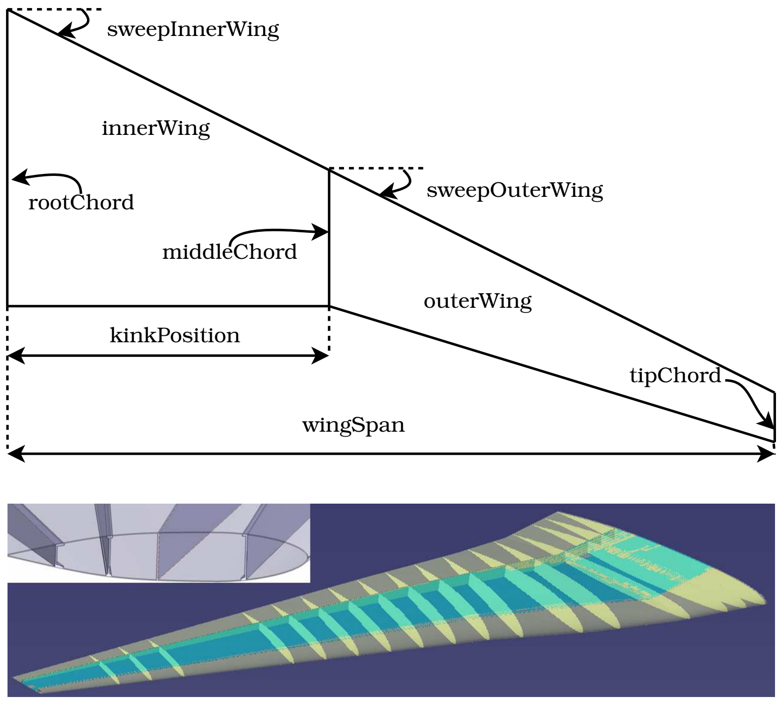


Figure 3.7 *Aircraft kinked wing used for analysis.*

outside the wing for minimum values of aspectRatio and wingArea (Table 3.2). The robustness in “Wing Test 2” is affected by poor parameterization of the kinkPosition. To improve the robustness of the model, the kink position could be given as a ratio of the span of the wing. “Wing Test 3” was conducted with the same span of the wing as in “Wing Test 2” so that the design space is the same. It can be seen from Table 3.3 that for “Wing Test 3” the flexibility and robustness of the model have increased. There were only 31 of 2000 designs that failed in this case. It has been observed that the failure of these designs occurred for values of sweepInnerWing and sweepOuterWing, at angles closer to 85 degrees and above. The robustness of the model increase considerably by having the kink position as a ratio of the span [XIV]. The “Wing Test 1” can be compared to DS1, “Wing Test 2” to PS1 and “Wing Test 3” to DS2 as presented by [Blessing et al., 2009] in Figure 1.4 in Section 1.6.2.

Design space in Table 3.3 is affected by the number of design parameters involved in the process; it would become very large once all the parameters in Table 3.1 are used to compute the design space. The

Table 3.1 *Number of parameters for aircrafts in Figure 5.1.*

	Number of Parameters		Total number of Parameters	
CAD Parts	**Wireframe**	**Surfaces**	**Civil Aircraft**	**Military Aircraft**
Fuselage	93	108	201	201
Wing	93	108	201	201
Horizontal Tail	18	46	64	64
Vertical Tail	18	46	64	64
Canard	18	46	-	64
Engine Civil	11	34	45	-
Engine Military	11	50	-	66
Total number of parameters			464	549

Table 3.2 *Wing test case setup.*

		Wing Test 1		Wing Test 2		Wing Test 3	
Design Parameter	**Ref**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
aspectRatio	9.71	4.71	14.71	0.7147	18.71	0.7147	18.71
TROuterWing	0.14	0.09	0.19	0.04	0.24	0.04	0.24
TRInnerWing	0.53	0.13	0.93	0.03	1.03	0.03	1.03
kinkPosition (mm)	6407 (0.3812)	5907	6907	5407	7407	0.3212	0.4407
wingArea (m^2)	116.32	66.32	166.32	16.32	216.32	16.32	216.32
sweepInnerWing (deg)	21.43	-28.57	71.43	-43.57	86.43	-43.57	86.43
sweepOuterWing (deg)	21.43	28.57	71.43	-43.57	86.43	-43.57	86.43

normalized sensitivity matrix is shown in Table 3.4, wingArea and aspectRatio are the two parameters that mainly affect the system characteristics or output parameters of the wing. [XIV]

In `RAPID`, as the user has different reference area methods, this might be difficult to pick the correct method. A number of parameters are accessible for the user in order to obtain various configurations. This might lead to a geometry that is over-defined or has a lot of parameters to play with. [XIV]

Table 3.3 *Robustness and flexibility for a kinked wing.*

	Number of Designs	Number of Parameters	Design Space	Robustness	Flexibility
Wing Test 1	1000	7	13.59	1	13.59
Wing Test 2	2000	7	19.33	0.751	14.52
Wing Test 3	2000	7	19.33	0.985	19.04

Table 3.4 *Normalized sensitivity Matrix.*

	Design Parameters				
System Characteristics	**aspectRatio**	**TROuterWing**	**TRInnerWing**	**kinkPosition**	**wingArea**
middleChord	-0.24	-0.10	0.00	-0.37	0.61
rootChord	-0.24	-0.10	-1.01	-0.38	0.61
tipChord	-0.50	0.88	0.00	0.00	0.50

3.3.2 Tidal Power Plant Turbine

For the tidal power plant (Figure 3.8), to obtain uniformly distributed values for each parameter shown in Table 3.5, uniform Latin hypercube sampling with 1000 DOEs is created for the study. With respect to reference value, "Test 1" and "Test 2" are changed 10% and 20% except for stator angle for all the test cases. In accordance with the research methodology presented by [Blessing et al., 2009] in Figure 1.4 in Section 1.6.2, the following have been defined, and tested against the measures of robustness and flexibility.

Table 3.5 *Parameters and limits for the design space of the parametric model.*

		Test 1		Test 2	
Parameters	References	Min	Max	Min	Max
Stator angle (deg)	8.5	6	11	6	11
Stator root chord (cm)	5.350 (0.275)	4.290 (0.255)	6.435 (0.365)	4.815 (0.2825)	5.885 (0.3375)
Rotor angle (deg)	27.50	19.25	35.75	22.50	32.50
Rotor root chord (cm)	6.050 (0.310)	4.840 (0.248)	7.260 (0.372)	5.445 (0.279)	6.655 (0.341)
Rotor diameter (cm)	25.50	20.40	30.60	22.95	28.05

Table 3.6 *Mean design space, robustness and flexibility of the parametric model.*

Approach		Number of Designs	Number of parameters	Mean Design Space	Robustness	Flexibility
Non-Relational	Test 1	1000	5	0.0226	0.223	0.0050
Design (NRD)	Test 2	1000	5	0.0017	0.435	0.0007
Relational	Test 1	1000	5	0.0226	0.334	0.0075
Design 1 (RD1)	Test 2	1000	5	0.0017	0.467	0.0008
Relational	Test 1	1000	5	0.0226	0.797	0.0180
Design 2 (RD2)	Test 2	1000	5	0.0017	0.981	0.0017
Relational	Test 1	1000	3	0.1412	0.821	0.1159
Design 3 (RD3)	Test 2	1000	3	1.6667	0.99	1.6500

- **Non-Relational Design (NRD)** – The parameters do not have any relationship to each other (DS1).
- **Relational Design 1 (RD1)** – Stator root chord and Rotor root chord are given as a variable ratio of the Rotor diameter (PS1).
- **Relational Design 2 (RD2)** – Stator root chord and Rotor root chord are given as a variable ratio of Rotor length and Rotor length is moreover a fixed ratio (0.765) of Rotor diameter (DS2).
- **Relational Design 3 (RD3)** – Compared to RD2, the ratios of both Stator root chord and Rotor root chord are fixed in relation to Rotor length. As the values of Rotor diameter are changed, it indirectly changes the value of the chords at a constant ratio at all times. This ensures that the overall lengths of all the components are always scaled with the defined ratios.

As shown in Table 3.6, the robustness and flexibility have increased. The design space for NRD, RD1, and RD2 is unchanged. The values of Stator root chord and Rotor root chord are specified as ratios of Rotor diameter in RD1 and Rotor length in RD2 and RD3. In RD1, the flexibility and robustness have not improved. The designs failed for higher values of Stator or Rotor chords and when the Rotor diameter is greater than Rotor length, the failures have increased. To make the parametric model more concise, the Rotor length is given as a ratio of Rotor diameter in RD2 and RD3. As a result, the robustness and flexibility have increased, the parameters are reduced in RD3 and this, in turn, reduced the design space. The robustness and flexibility are improved in RD3 compared to the other approaches.

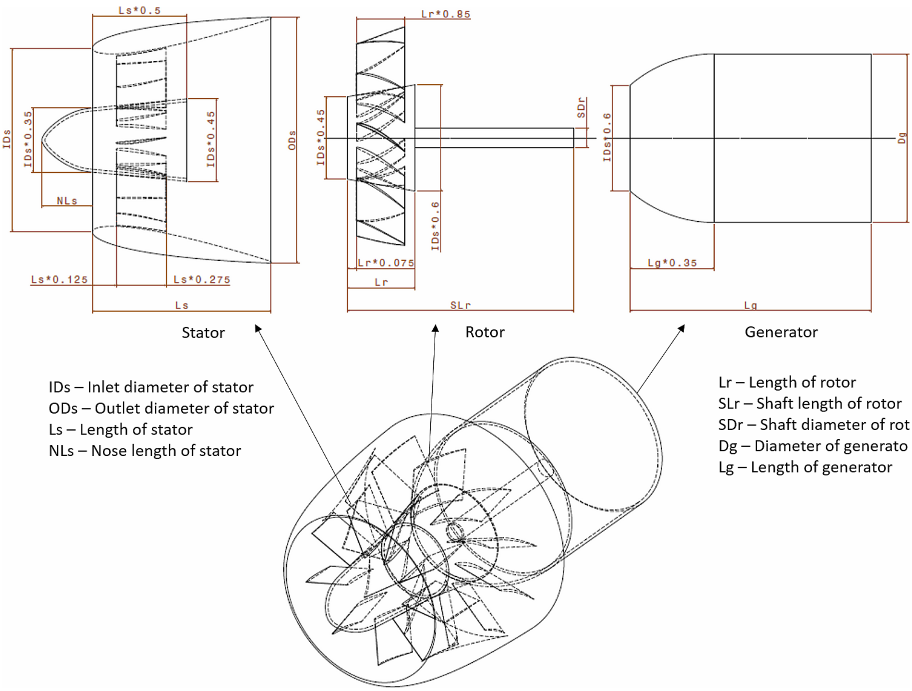


Figure 3.8 *Relational parameters involved in the design of the tidal power plant turbine.*

The proportional and sensible designs reduced the CFD failures and increased the MDO's flexibility (see [Sóbester and Forrester, 2014]). Another option is to use Singular Value Decomposition (SVD). [Krus, 2016] presents models based on SVD and demonstrates that complex systems can be represented with fewer of parameters.

"We can't solve problems by using the same kind of thinking we used when we created them." - Albert Einstein

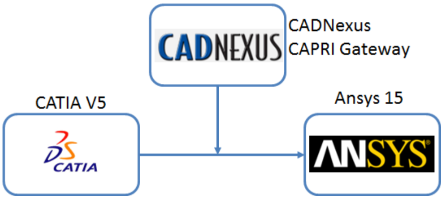
4 Geometry Analysis Features

The various levels of fidelity as shown in Figure 2.7 can be used for analysis. The empirical calculations provide faster weight estimation, sizing, etc. The vortex lattice method provides quick lift, drag and other coefficients. The weight penalty method coupled with high-fidelity geometry provides more accurate weights. The high-fidelity geometry is streamlined with CFD and FEA. The 3-D systems' integration coupled with systems simulation provides a better estimation of the components.

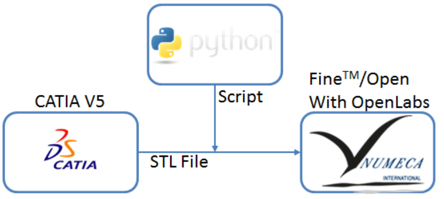
4.1 Mesh Generation

The automated CFD methods using the adaptive-fidelity approach presented by [Tomac, 2014], proposes automatically generated grids for RANS. "Surface meshing for CAD geometry" proposed by [Tomac, 2014] is also worth investigating for future meshing of design-automated geometry. The primary reason to use CAD software to create an aircraft model is to have the geometry propagation from conceptual to preliminary design, thereby reducing the time for the overall design process. The three ways meshing can be performed using `ANSYS`® [Ansys, 2016] or `Fine`^{TM}`/Open with OpenLabs` [FINE^{TM}/Open, 2017] are by means of a native CAD geometry (no geometry update), parametric geometry for meshing or scripts for meshing with updated geometry. One needs no introduction to native CAD format; it is the default setup that is used in most of the software for performing different analyses such as CFD, FEA etc. More details are given in the following sections.

4.1.1 Using Parametric Geometry for Analysis

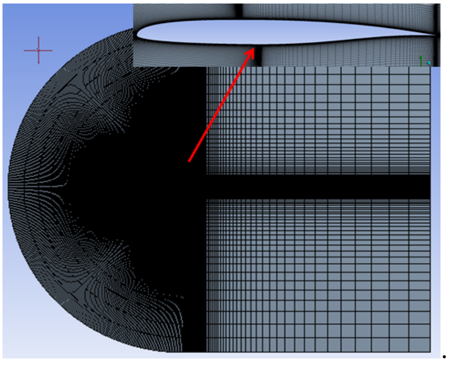


(a) Methodology involving ANSYS® for analysis.

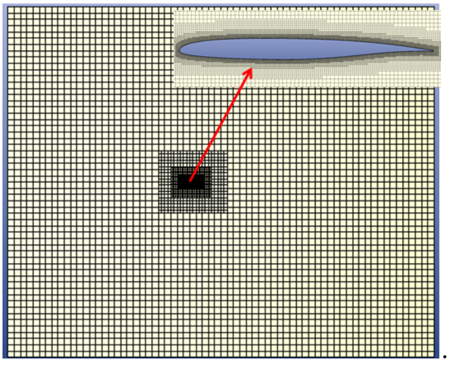


(b) Methodology with Fine^{TM}/Open with OpenLabs for Analysis.

Figure 4.1 *Proposed Methodologies for parametric geometry.*



(a) Automated mesh in ANSYS®



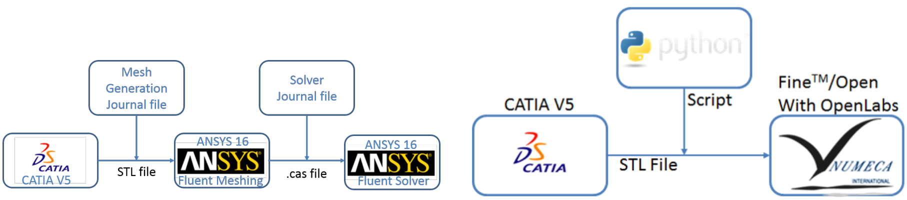
(b) Automated mesh in Fine^{TM}/Open with OpenLabs

Figure 4.2 *2-Dimensional airfoil mesh for parametric geometry.*

CADNexus CAPRI CAE Gateway [CADNexus, 2016] is used to establish live integration between CATIA® and ANSYS®. CADNexus is a third-party software that is used for geometry propagation from most of the commercially available software to ANSYS®. Figure 4.1(a) shows the method employed for aerodynamic analysis of airfoil and wing and structural analysis of the wing. Aerodynamic analysis is performed to obtain the lift coefficient (C_L) and drag coefficient (C_D) for each updated design of airfoil. For each satisfactory design, an aero-structural analysis and an initial aerodynamic and structural analysis for the wing are performed during the global optimization (see Paper [XIII] and Section 4.2.1 for optimization results).

4.1.2 Automated Meshing Methodology for a Design-Automated Geometry

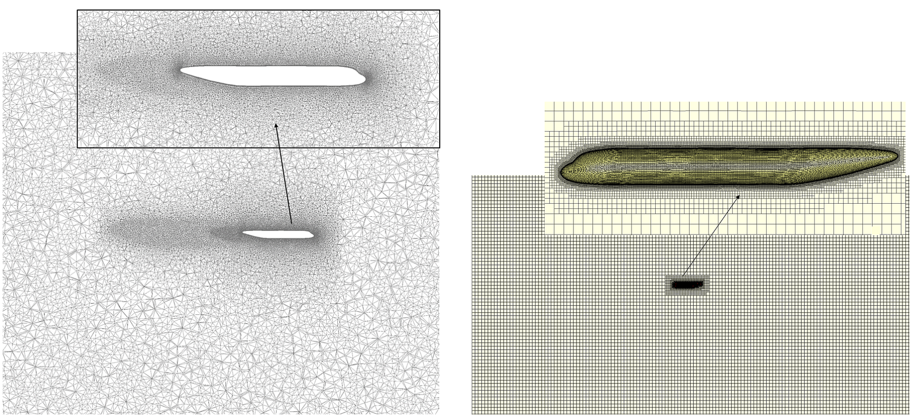
The number of surfaces remains the same at all times in a parametric geometry, whereas they increase or decrease in a design automation during the processes. The surfaces are named and remembered by the `CADNexus` program for a parametric geometry but the same does not apply in design-automated geometry as the surfaces are renamed for every update. The following section presents the design methodology implemented for a design-automated geometry.



(a) Methodology involving `ANSYS`® for analysis.

(b) Methodology using `Fine`^{TM}`/Open with OpenLabs`.

Figure 4.3 *Methodology for Design-Automated Geometry.*



(a) 3-D mesh model with `ANSYS`®.

(b) 3-D mesh model with `Fine`^{TM}`/Open with OpenLabs`.

Figure 4.4 *3-Dimensional fuselage Mesh.*

Two automatic meshing methodologies are presented. The first case, `ANSYS`® creates the automated meshing by using two journal files (Figure 4.3 (a)). The imported geometry is in STEP file format. The first file includes mesh settings and it creates a case file (.cas file extension) to be run for simulation. The second file has the solve settings and takes the case file for simulation. The ASCII file stores the results and these results are examined in modeFRONTIER® [modeFRONTIER 4.5.2, 2016] during the optimization process. In the second case, Fine^{TM}/Open with OpenLabs creates the mesh automatically using Python script (Figure 4.3 (b)). The imported geometry is in STL file format and both mesh and solver settings are saved in the script. The outputs' lift and drag are saved in an ASCII file (with .mf extension) and these values are later used by modeFRONTIER® in the optimization process.

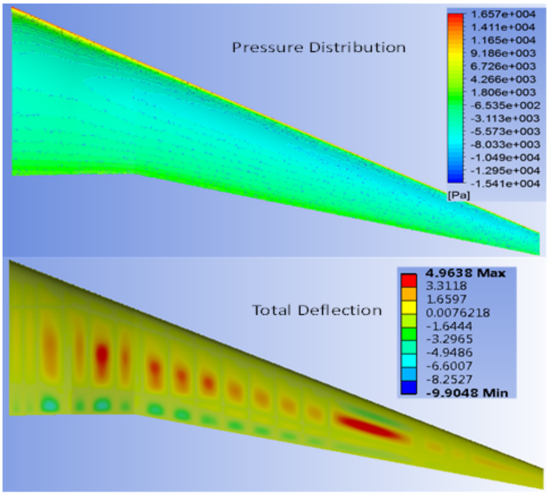
The mesh created in Fluent is based on the STEP-model and in HEXPRESS™, it is based on STL-model. Both models are exported directly from CATIA®. The computational domain consisted in this case is of a rectangular block. Fluent meshes with tetrahedral elements in Figure 4.4 (a) with refinements in the region around the fuselage and in the wake, while HEXPRESS™ meshes with hexahedral unstructured elements in Figure 4.4 (b). To ensure adequate boundary layer resolution along the fuselage, 30 layers of prism elements are inserted at surface and the thickness of the first layer is adjusted so that non-dimensional wall distance y+ stays below unity. See Paper [VIII] for more information on the optimization of windshield involving the 3-D fuselage.

4.2 Multi-fidelity Analysis

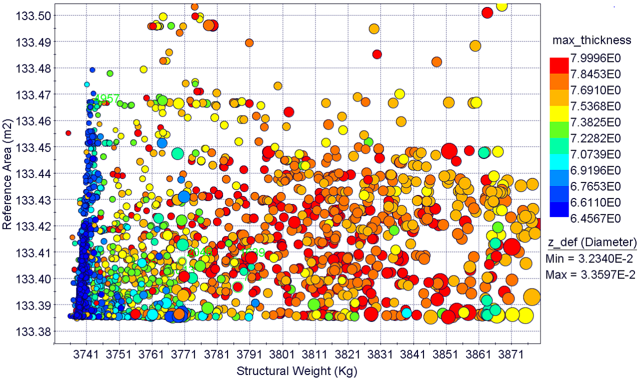
The section presents the two optimization framework examples that are implemented in this work. [Martins et al., 2013] presents several available MDO approaches for integrating efficiently in an optimization. [Perez et al., 2004] concludes that Multidisciplinary Design Feasible (MDF) is the best method by comparing five MDO approaches with examples and a comprehensive summary. The complexity of the optimization also reduces the efficiency of the framework. In all the optimization work that is presented in this thesis MDF is used with modeFRONTIER® as solver.

4.2.1 Wing Optimization

A multidisciplinary optimization framework connecting the geometric model, aerodynamic model and structural model, is proposed for both parametric and design automated geometry. Two methods are employed for the global optimization : first, utilizing `Fine`^{TM}`/Open with OpenLabs` for Aero analysis and `CATIA`® for structural analysis. This method uses design-automated geometry as explained in Section 4.1.2. Second method is performing the investigation in `ANSYS`® using parametric wing in `CATIA`® which is seamlessly integrated with `ANSYS`®. In this case, the number of airfoils and ribs remains constant, as explained in Section 4.1.1.



(a) Pressure distributions (top) and total deformation. (bottom)



(b) Pareto Frontier for proposed framework.

Figure 4.5 *Results from aero-structural analysis and modeFRONTIER.*

The global optimization involves RAPID, BeX and Tornado with a low-fidelity model, which is later connected to high-fidelity local optimization of the airfoil at each station. Finally, the satisfactory airfoils are implemented in the high-fidelity aerodynamic model both in ANSYS® and Fine^{TM}/Open with OpenLabs. The aero-loads are transferred to the structural analysis in ANSYS® or CATIA®. For simplicity during optimization, the number of partitions is kept constant (four) and the airfoils are optimized for variable thickness. The optimization [Tribes et al., 2005; Zhang et al., 2012; Goldberg, 1989] is performed on a wing shape with predefined loads on the wing.

Surrogate models using Anisotropic Kriging are created for airfoil and wing and utilized during the optimization for aerodynamic and structural analysis of the wing. Surrogate models are estimated models which are numerically efficient and can impersonate the conduct of a recreated model. It is not necessary to create any surrogate models for the optimization connecting BeX-RAPID-Tornado as the time taken for each simulation is less than a minute. For global optimization, MOGA is used and for local optimization Simplex Algorithm is used as the design variables are continuous.

The model represents the core of the framework and features extensive use of automation methodologies that ensure solution for the optimization problems and minimize design cycle time. The design automation methods permit vast design spaces to be explored and detailed optimized design solutions be obtained from the conceptual design phase and the borderline between conceptual and preliminary design be merged. Weight estimation is performed by combining the weight penalty method with the automatically generated geometry and thus providing a closer weight approximation of the model. See the result in Figure 4.5 and Paper [XIII] for optimization framework.

4.2.2 Supersonic Aircraft Optimization

The optimization processes connecting several disciplines such as geometric model, aerodynamic model, structural model, wave drag model and the simulation model. The first estimate of control surfaces size is performed using BeX, Tornado and HURRICANE-CS. SOM and RAPID work together in a local optimization loop to optimize each cross-section of the geometry.

Area distribution is performed in different ways; the capture area is

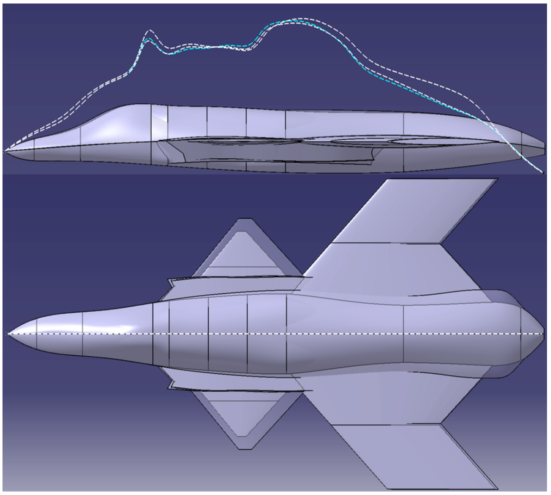


Figure 4.6 *Area distribution of initial, intermediate and optimized geometry (top); Optimized FX5 (bottom - initial geometry in light gray and optimized geometry in dark gray)*

deducted from all the cross-section areas for the calculations. Figure 4.6 illustrates the deduced capture area from the maximum cross-section area. The geometry is first minimized manually at the engine location to reduce the drag and start with a design closer to the solution. The optimization is performed using NSGA-II with 40 individuals and 50 generations. The figure shows the area distribution for initial, intermediate and one of the optimized geometries for the design Mach number of 1.3.

A smooth area distribution reduces the supersonic drag of the aircraft. The region between the two peaks in Figure 4.6 are smoothed for minimizing the wave drag. The optimization has reduced the wave drag of the aircraft considerably. The first peak occurs at the start of the inlet and the second peak at the beginning of the wing. These geometries add up to total volume and are not avoidable. Therefore, the optimization smooths the region between the peaks by adding extra volume to hold additional entities. More details of the design and optimization can be found in papers [IV; V].

"Eventually everything connects - people, ideas, objects. The quality of the connections is the key to quality per se." - Charles Eames

5 Applications

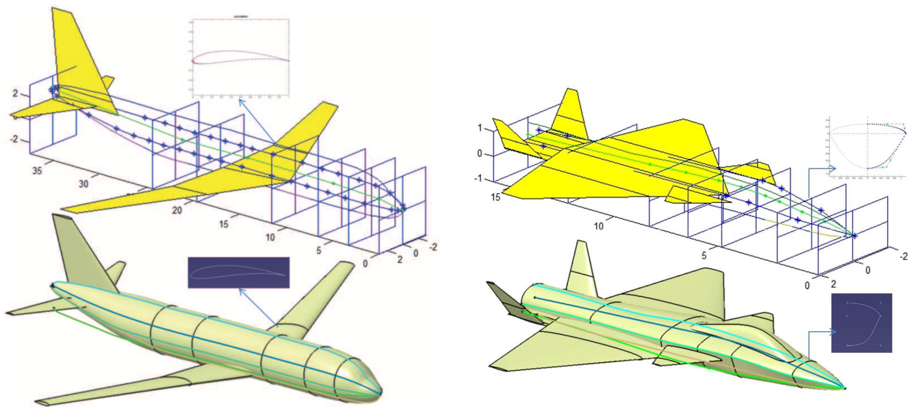
The flow of data between each discipline in a multidisciplinary design environment is coupled and saved in XML format [Lin et al., 2004] [Lee et al., 2009]. The database definition (including several component libraries like functional assemblies) is parametrically defined in such a manner that a data refinement over time alongside the project is possible.[XIV]

5.1 Data Translation RAPID/Tango Implementation

This section describes the application examples of the framework, showing the data build up and data translation between RAPID and Tango and vice versa. Two examples have been tested to investigate the data flow processed in the correct approach. In RAPID, as the user has different reference area options, it might be difficult to pick the correct method. A number of parameters are accessible for the user in order to obtain various configurations. This might lead to a geometry that is over-defined or has a lot of parameters to play with.[XIV]

5.1.1 Civil Aircraft Example

In this example, the double delta reference method is used (see Figure 5.1(a)). The fuselage cross-sections range from a circle to an ellipse. The data was successfully exchanged in both ways. The robustness and flexibility of this aircraft's wing are presented in Section 3.3.1 and optimization in Section 4.2.1. [XIV]



(a) Civil aircraft example. (b) Military aircraft example.

Figure 5.1 *Aircraft geometry in `Tango` (top) and `RAPID` (bottom).*

5.1.2 Military Aircraft Example

A more complicated fighter aircraft was selected to test as shown in Figure 5.1(b). Data exchange showed promising results. It is to be noticed that the data structure in the background of both examples is similar with modified parameters with an added lifting surface "canard" in the fighter example.[XIV]

5.2 Concept Generation

To obtain an overall analysis of the framework presented in Chapter 3, the F-16 design case is studied and the FX5 concept is designed and analyzed.

5.2.1 Existing Concept Evaluation

The framework presented in Chapter 3 is used to showcase the ideas and capabilities of multi-fidelity models. The aircraft geometry is built up from the 2-D sketch of the F-16 and data is exchanged between the tools in the framework using a centralized `XML` database. A KBE system simulation is performed with low-fidelity aerodynamic analysis (vortex lattice method). The framework benchmarks the aircraft performance analysis, capability, model management, and data structure efficiency (see Paper [IX] for more details).

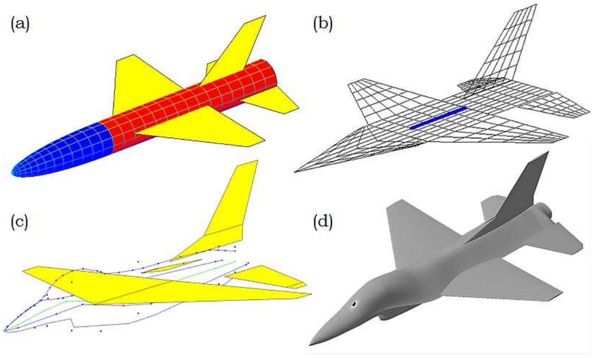


Figure 5.2 *Aircraft geometry representation: (a)* `Tango` *low-fidelity model, (b)* `Tornado` *model, (c) CAD model in* `Tango`*, and (d)* `RAPID` *model.*

5.2.2 New Concept Design and Development

A future combat aircraft for deployment in 2030 is designed and studied; a lot of development would have taken place in terms of materials, engines, systems, etc. The aircraft could be both unmanned and manned with a stealthy design and super-cruise capabilities. For the tailless aircraft, thrust vectoring helps to achieve high maneuverability with reduced radar signature, drag, high angle-of-attack landings [Jouannet and Krus, 2005], quick rotation, and short take-off and landing capabilities. A differential canard with differential/split elevons as shown in Fig. 5.3 provide yaw control at low speeds. More details of the design and optimization can be found in Papers [IV; V].

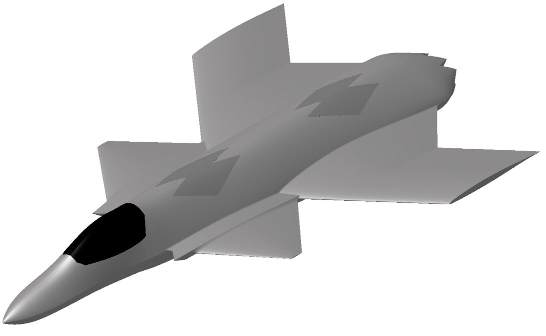


Figure 5.3 *Baseline design for a combat aircraft without vertical tail design.*

5.3 Academic Implimentation

This section shows the application examples of the `RAPID` implementation in academia in several courses at Linköping University.

5.3.1 The Jet Family Project

In the course "Aircraft Conceptual Design", the assignment was to design a family of turbofan-powered aircraft according to FAR 25. The aircraft family has three members (see Figure 5.4). The number of seats ranges from 75 to 110 (design payload), at 32-inch pitch, but high density versions had to allow two more rows of seats and a seat pitch of 28 inches. In addition to this, a two-class internal layout had to be studied. The two classes were business and economy. 15% of the passengers in each version had to be seated in business class and the rest in economy. The seat pitch in business class was 34 inches and in economy class 30 inches. The family of aircraft had to be equipped with one and the same wing. The assignment also includes a study of how an optimal aircraft should be designed (for each family member) and the lost weight and efficiency by keeping the wing unchanged. Interior design for this assignment was very important (as for all designs) as it leads to the length of the cabin. It includes a study of the number of doors and the sizes required for different family members. [XIV]

It is also important to provide the required space at the emergency exits for evacuation. Number of toilets, galleys and cabin crew required for the different family members also need to be figured out. Where to put and access passenger luggage and cargo on the aircraft needs to be addressed. All kinds of ground handling while on the ground, i.e. the possibility to service the aircraft by means of different vehicles during a ground stop also need to be considered. [XIV]

- Mdes: 0.82 at 35000 ft for all family members
- Range: 2500 NM at design payload for in-between member of the family
- Reserves : 200nm + 30 min holding
- T-off field length (SL, ISA +20) max: 1900 m for all members
- Landing field length (SL, ISA +15) max: 1500m for all members

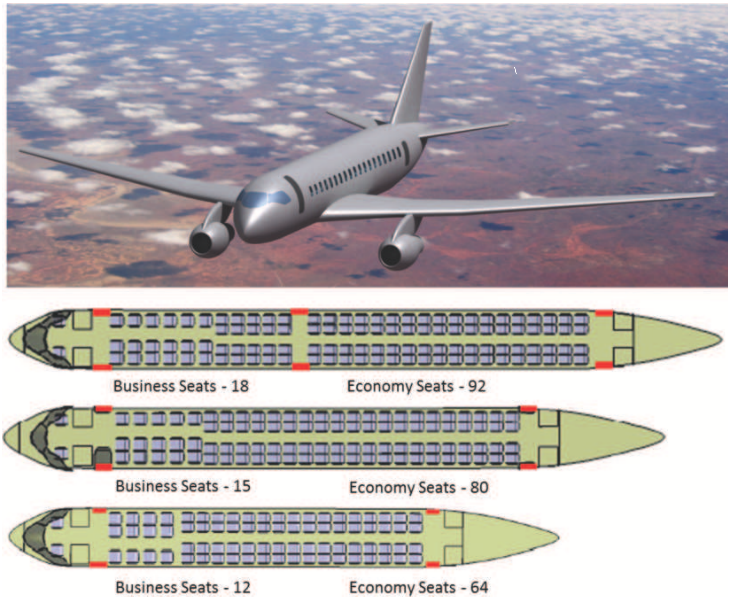


Figure 5.4 *One of the students' aircraft and interiors with two-class seating configurations and an artistic view of the aircraft.*

- Individual passenger weight (including luggage): 110 kg
- Pilots including personal luggage: 104 kg each
- Attendants (including personal luggage): 100 kg each

5.3.2 Very Light Jets (VLJs)

Figure 5.5 *Students aircraft from VLJ project.*

The VLJs project was to design a two-seater and a four-seater aircraft. Both aircraft were to be designed around the DGEN-380 engine. The aircrafts should be flown by normal, average skilled pilots, e.g. flying club members. The flight altitude was below 20000 ft and the cabins were not pressurized. The main design solutions were presented including seating arrangement, structural layout, entrance door placements and design, engine placement, fuel placement, baggage and basic landing gear design. Weight and general performance of the aircraft were evaluated along with center of gravity range, stability, and trimmability. The artistic view of the aircraft designed in RAPID by the students are shown in Figure 5.5. [XIV]

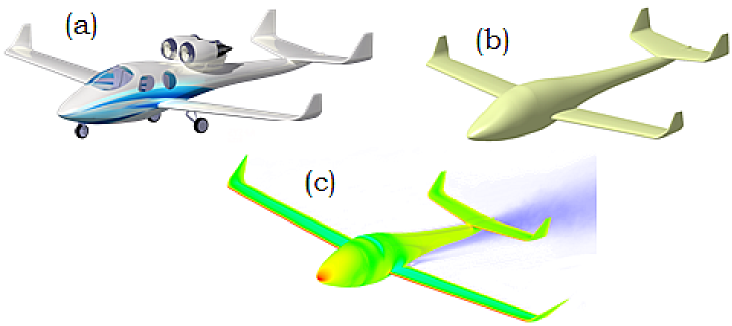


Figure 5.6 *VLJ optimization: (a) initial geometry, (b) updated geometry for optimization, (c) aerodynamic optimization result.*

One of the VLJ aircraft was further used in the "Aircraft Aerodynamics" project course. The geometry was updated, checked for failures, and provided to the students for optimization. The Figure 5.6 shows students' aircraft geometry, updated geometry for aerodynamic analysis and the optimized aircraft.

5.4 Concept Demonstration

A scaled demonstrator is a means to test the concept feasibility in aircraft conceptual design at low cost [Lundström, 2012; Jouannet, Berry, et al., 2012]: it is an alternative means without risking full-scale manned vehicles. This section presents two concepts, a dorsal intake fighter and a personal jet, that were designed in RAPID (Section 3.1) and prototypes were built to validate the concepts.

5.4.1 The Mid-Jet Aircraft Project

The Mid-Jet project (Figure 5.7) was to build an aerobatic, aesthetic, striking, and overwhelming single-seat sport jet. To test and demonstrate the flight performance and characteristics, a scaled model was built. As a first part of the project, a study was conducted on the existing single-seat sport jets and the teams later came up with different concepts. Many different concepts were studied from each team in the group and finally one concept was chosen for further studies. A conceptual design had been performed for a full-scale version. The initial model was built in RAPID. Later on, many different features had been added during the detail design process. A demonstrator was built and tested with a scaled down version. [XIV]

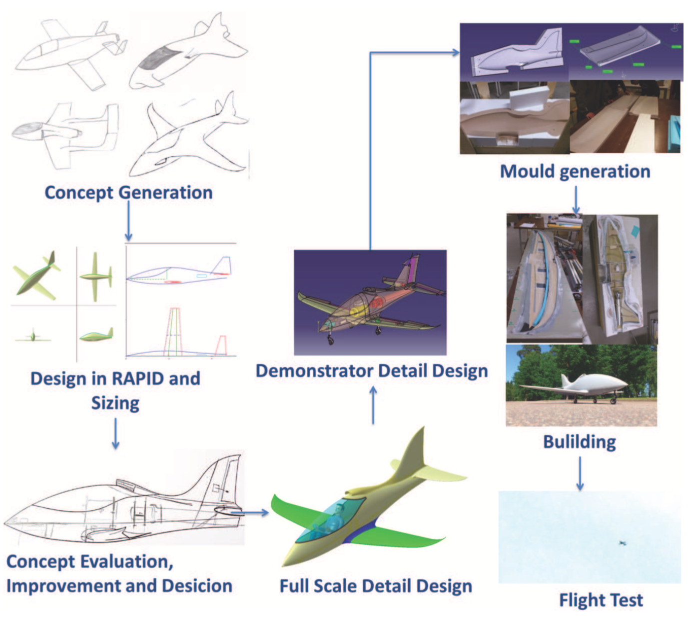


Figure 5.7 *Mid-Jet aircraft project process.*

5.4.2 Dorsal Intake Fighter

To analyze the aerodynamic characteristics of the fighter aircraft operating at high incidence angles, wind tunnel tests were conducted (Figure 5.8). The Initial model was designed and built at the Aircraft Design Group of the Aeronautical Engineering Department of EESC-USP. The initial geometry is updated in `RAPID` with dorsal intake, a 3-D printed part of the dorsal intake was fitted to the existing model, and the test was conducted in a wind tunnel. The wind tunnel has a 1.30 m X 1.70 m X 3.0 m working section with turbulence level of 0.2% and max speed at 45 m/s. The model's wingspan is 1.2 m. The model is attached to a sting balance with 6 degrees-of-freedom. The test conditions were set at 40 m/s with the model -5 to 23 degrees of incidences, with the canard incidence varying from -25 to 25 degrees for each model incidence angle (see Paper [XIX] for more information).

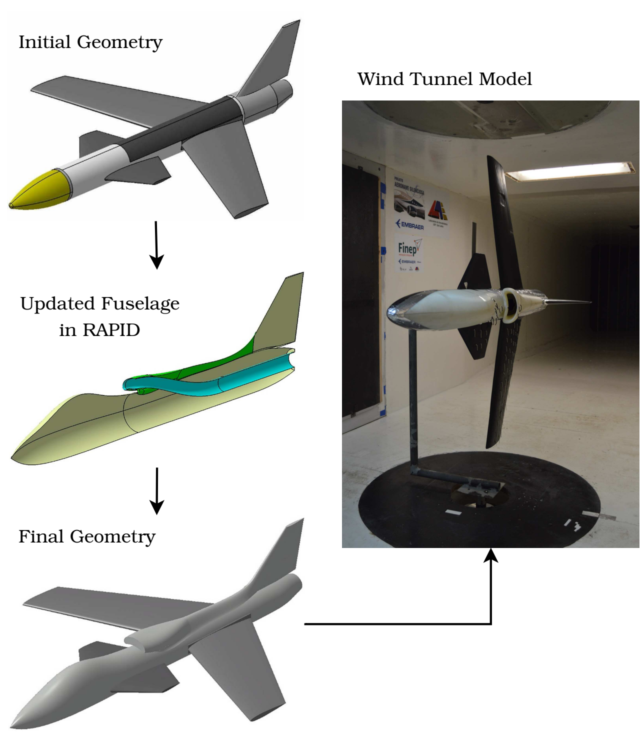


Figure 5.8 *Dorsal intake fighter.*

"The true method of knowledge is experiment." - William Blake

6 Conclusions

Aircraft Conceptual Design is an iterative process. The designer needs to gain an overview of the aircraft geometry and the design changes that occur during the design process. The geometry plays a major role in the design process and is usually represented in a CAD environment to be carried forward to the next level. The geometry created during the processes is desired to change rapidly and the changes to the geometry need to be realized immediately with less effort. KBE methods implemented in early design phases will assist in a wide range of studies that can be conducted with the design. It also helps in the rapid realization of a concept generated during the design process.

To enable reuse of geometry and bridge the gap between conceptual and preliminary design, a KBE approach is employed in aircraft conceptual design. Fast geometry creation helps create a broad range of aircraft configurations. Further studies can be conducted to obtain a better understanding of aircraft concepts. To enhances the geometry construction, effective parameterization is implemented. As the geometry is built in layers, different fidelity models of the geometry can be used at the respective stages depending on need and purpose. Watertight models are obtained from the created geometry and provide better success in meshing for CFD and FEA.

A geometry created in CAD environments encloses a great deal of data, e.g. design concept layout, geometrical parameters, etc. The amount of data increases as the design builds up. To save the data and to have better communication with different disciplines, an `XML` database is used. This method allows for direct access to geometry for other tools, a geometry optimization outside the CAD environment. Simulation models can also be generated out of the description in `XML` data. Geometrical data has been successfully implemented between `RAPID` and `Tango` [I].

Different optimization frameworks have been reflected (see Papers [I; II; III; IV; V; VI]), each framework being different from the others in method and implementation. Different disciplines for the optimization are unified using customized scripts. An enhancement is made by means of commercial software for optimization with meta-models. The use of meta-models for optimization has reduced the time required for optimization and the different experiments can be conducted on the same geometry. A framework using the `XML` data setup is presented that supports sharing the data with other tools for greater collaboration. One tool vs. one database has been discussed and the one-database concept is proven to be more effective as each tool is specialized in a specific domain.

6.1 Answers to Research Questions

The research question mentioned in Section 1.2 are briefly answered to avoid repetition by referencing the published papers and chapters in the thesis.

- **RQ1**: How can a KBE approach satisfy conceptual design needs with various fidelity levels?

The geometry is built in three layers, with the possibility to create a solid model if necessary. A low-fidelity model is the 2-D boundary of the aircraft, such as the outer shape of the fuselage or the wing. A medium-fidelity model is developed from the previous one, consisting of a wire-frame design of the aircraft; a 3-D skeleton is generated. Finally, the high-fidelity model is generated by adding surfaces to the example shown in Figure 2.9. All the above is made possible with the use of KBE and implimented in `RAPID` [I]. Using KBE increases the knowledge of the concept (see Papers [I; II; IV; V]). KBE enables design automation, thereby reducing design cost, time, adding value, and increasing product design capabilities. With the use of design automation, the geometry is standardized and reused. The risk of error is marginal. The proposed parametrization methodology is implemented in this work (see Section 2.2.4). The use of KBE in conceptual design with various fidelity levels is presented in Papers [IV; V]. Further, the KBE-enabled systems definition is coupled to systems simulation presented in Papers [II; III].

- **RQ2**: Which systematic approach enables KBE/parametric modeling for an efficient MDO?

The geometry needs to be flexible to handle all the design changes and update quickly to realize the design intent. A quantitative approach that provides qualitative results for flexibility and robustness is presented in Papers [I; VI] and in Section 3.3. Using the proposed parameterization, the design space is increased and more designs are evaluated, enabling an efficient MDO (see Papers [V; VI]). The fineness of the parameterization allows minimum failure in the design update. The results from the qualitative approach are concise, clear, and understandable. The effective parameterization enhances the MDO and is implemented for concept generation in all the work presented in this thesis (see Papers [I; II; III; IV; V; VI]).

- **RQ3**: In what way can different aspects of aircraft conceptual design be integrated?

Integrated centralized data that is transparent and easy to understand helps bring together different disciples as one entity. This integrates more disciplines than is possible in standalone models. All tools utilize the design data stored in `XML` format for further analysis (see Papers [I; II; IV; V] and Section 3.2). The obtained geometry is automated for further analysis to reduce the routine work (see Papers [I; II; III; V; VI]. The various aspects of aircraft conceptual design are integrated with the multi-disciplinary multi-fidelity approach. This enables faster simulation and analysis by combining several disciplines and various fidelity models for systems simulation, CFD, FEA, and MDO.

"Start where you are. Use what you have. Do what you can." - –Arthur Ashe

7 Outlook

The different methodologies, frameworks, and outcomes of this thesis are implemented in academia in different courses; nevertheless, the framework is partially validated in industry. Further work needs to be done to effectively distribute the complete KBE geometry for different disciplines such as aerodynamics, structures, systems simulation etc. Improvements in the existing structural and aerodynamic models to update the mesh automatically will enhance the optimization framework. More aircraft systems need to be coupled to a complete systems overview of model-based systems engineering, for example, to obtain a system approach to the landing gear design, system simulation with 2-D and 3-D FEA integration for faster simulation, analysis, and better understanding. Implementation of automatic routing for systems integration would also help the design process.

The current buzzwords are Virtual Reality (VR), cloud (computing, storage, integration), and AI or machine learning. VR helps visualize, cloud contributes storage and decreases the computing time with the use of multiple-cores, and AI deepens understanding of the concept. As a pedagogical aspect, VR could help understand the design by simulating the designed aircraft directly in a flight simulator and to visualize the interior layout of the designed aircraft. This could complement the concept demonstration that is done by building and testing the prototypes. The software are moving more towards cloud-based services/application ([Onshape, 2017; 3DEXPERIENCE, 2017]). We need to wait and see the integration process with several disciplines. Most CAD vendors are moving toward a one-tool concept and trying to integrate all the disciplines under one roof. This increases the cost to purchase the tools for

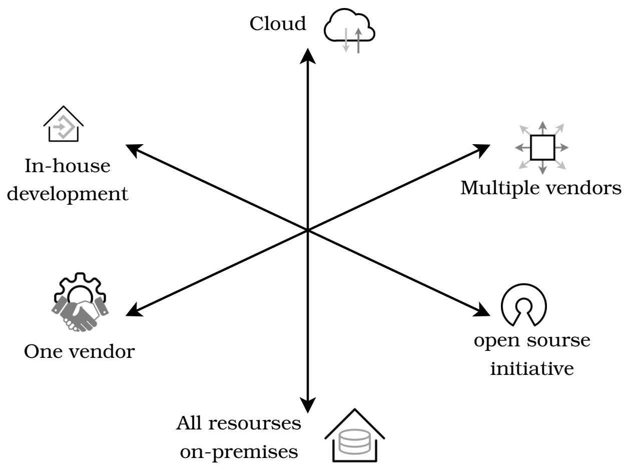


Figure 7.1 *Future tools, needs, and requirements.*

industrial/academic purposes. Open-source software could hold the key but industry/research institutes nevertheless need to put some resources into developing and utilizing the software. Automation is necessary but human-in-the-loop helps analyze and understand the results. Academic or research institutes use all the services in Figure 7.1 except one vendor while the industry is open to all services except cloud as it has to deal with more propitiatory/defense material.

"Knowledge is not simply another commodity. On the contrary, knowledge is never used up. It increases by diffusion and grows by dispersion." - Daniel J. Boorstin

8
Review of Papers

This section presents a short summery of the appended Papers ([I] , [II], [III], [IV], [V], till [VI]) in this thesis.

Paper I

A knowledge-based integrated aircraft conceptual design framework

A conceptual aircraft design laboratory - `CADLab` framework with the knowledge-based aircraft conceptual design applications `RAPID` and `Tango` is presented. The one-database approach enables a parametric data definition in a centralized `XML` database. This helps an efficient and flexible integration of several disciplines in a multidisciplinary environment for conceptual design. It describes the KBE methodology of `RAPID` and data processing between `RAPID` and `Tango`. The examples show the implementation in academia and data processed by the applications.

Paper II

Knowledge-based aircraft fuel system integration

This paper describes a knowledge-based approach to fuel systems in conceptual design. Methodology and software tools Oriented to Knowledge based engineering Applications (MOKA) methodology used to build the system. This provides an opportunity to optimize the fuel systems to predict a better center of gravity of the aircraft. The components used are only symbolic; nevertheless, the real components can be updated in detail design. The geometry helps better estimation of weight, range, and sizing. An initial estimation of most of the components can be obtained. Several alternatives can be visualized with the use of KBE and by coupling with systems simulation; the handling qualities of the aircraft are obtained.

Paper III

Analytical weight estimation of landing gear designs

Landing gears are designed and the weight is computed by combining analytical methods with the 3-D parametric geometry. As an initial baseline, the procedure by Kraus and Wille is used. Four landing gears along with their derived equations are presented. These geometries can be altered to obtain new designs. It provides a lot of freedom to the user to test and modify the design to estimate the weight of the same.

Paper IV

Knowledge-based design for future combat aircraft concepts

The paper presents the FX5 fighter aircraft. It demonstrates the KBE capabilities along with design, sizing, and analysis for both aerodynamic and system simulation of the aircraft. The engine diameter is a direct influence on the maximum cross-section area, thrust, fuel consumptions, and wetted area for supersonic flight. The supersonic segment and the mission are optimized and present the capabilities implemented using KBE.

Paper V

Knowledge-based future combat aircraft optimization

The future combat aircraft FX5 aircraft presented in the above paper is optimized with the `CADLab` framework and the sonic optimization module (SOM). Fuel consumption, military performance, and mission fulfillment are the requirements to be satisfied for the aircraft. The simulation models proved to be reliable for an unproven concept, as statistical data is absent.

Paper VI

A comprehensive computational MDO approach for a tidal power plant turbine

The effect of relational and non-relational parameterization is studied on an underwater tidal power plant turbine along with the robustness and flexibility of the model in MDO. Several disciplines such as CAD, CFD, FEA, and a dynamic model were used in the optimization. The parameterization technique proved effective in MDO with increased design space, robustness and flexibility. Benchmarking is also performed for the relational and non-relational parameterization.

"High achievement always takes place in the framework of high expectation" - Charles Kettering

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