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A Concurrent Design Facility Architecture for Education and Research in Multi-Disciplinary Systems Design

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the contents of this thesis is the result of work has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third part is acknowledge; and, ethics procedures and guidelines have been followed.

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List of Symbols (Greek)

α_t	Wing twist	degree
η_p	Propeller efficiency	
λ	Wing Taper Ratio	
λ_f	Fuselage fineness ratio ($\frac{L_f}{d_f}$)	
ρ_{fuel}	Fuel Density	$\frac{lbs}{ft.^3}$
ρ_{air}	Air Density	$\frac{slug}{ft.^3}$
Γ	Wing or Tail Dihedral or Anhedral Angle	degree

List of Symbols (Roman)

AR_h	Tail Aspect Ratio (Horizontal)	
AR_v	Tail Aspect Ratio (Vertical)	
b_w	Wing Span	ft.
b_{exp}	Wing Span exposed	ft.
b_{HT}	Tail Stabiliser Span (Horizontal)	ft.
b_{VT}	Tail Stabiliser Span (Vertical)	ft.
C	Wing Chord	ft.
C_{root}	Wing Root Chord	ft.
C_{tip}	Wing Tip Chord	ft.
C_h	Tail Chord (Horizontal)	ft.
C_v	Tail Chord (Vertical)	ft.
$tan\Delta_{LE}$	Leading edge sweep angle	degree
$\frac{\Delta_c}{4}$	Quarter Chord Sweep Angle	degree
$x\ c/4$	Wing Quarter Chord	inch
$\bar{C}$	Wing Mean Aerodynamic Chord (MAC)	ft.
xLE MAC	Leading edge Mean Aerodynamic Chord	inch
C_D	Drag Coefficient	
C_{D0}	Drag at zero Lift Coefficient	
C_{fe}	Skin friction Coefficient	
C_L	Lift Coefficient	
$C_{L_{max}}$	Maximum Lift Coefficient	
$\Delta C_{L_{HLD}}$	Change in High Lift Device of Lift Coefficient	
d_f	Fuselage external dimension	ft.
Dp	Propeller Diameter	ft.
e	Oswald efficiency factor	
H_{ig}	Landing Gear Height	inch
hp	Engine Horsepower	hp
$\frac{L_H}{L_f}$	Tail Moment Arm (Horizontal)	percentage

Symbol	Description	Unit
$\dfrac{L_V}{L_f}$	Tail Moment Arm (Vertical)	percentage
l_{fc}	Fuselage Cone length	inch
L_{engine}	Engine Length	inch
L_f	Fuselage Length	ft.
L_{fn}	Fuselage Nose Length	inch
L_H	Tail Stabiliser Length (Horizontal)	ft.
L_V	Tail Stabiliser Length (Vertical)	ft.
V_H	Tail Volume Coefficients (Horizontal)	
V_V	Tail Volume Coefficients (Vertical)	
i_w	Wing Incidence	degree
$\dfrac{W}{S}$	Wing Loading	$\dfrac{lbs}{ft^2}$
R_e	Reynolds numbers	
$tan\Delta_{LE}$	Leading edge sweep angle	degree
Δ_{LE}	Tail Leading-edge Sweep Angle (Horizontal) or Tail Sweep Angle (Vertical)	degree
S	Wing Reference Area	ft^2
S_f	Complete Flapped Area	ft^2
S_a	Complete Aileron Area	ft^2
S_e	Elevator Area	ft^2
S_r	Rudder Area	ft^2
S_{HT}	Tail Stabiliser Area (Horizontal)	ft^2
S_{VT}	Tail Stabiliser Area (Vertical)	ft^2
$\dfrac{S_f}{S}$	Flapped Area to Wing Area ratio	
$\dfrac{S_a}{S}$	Aileron Area to Wing Area ratio	
S_{exp}	Wing true-view exposed planform area	ft^2
S_{expth}	Horizontal Tail Surface Area	ft^2
S_{exptv}	Vertical Tail Stabiliser Area	ft^2
$S_{Wet_{th}}$	Horizontal Tail Wetted Area	ft^2
$S_{Wet_{tv}}$	Vertical Tail Wetted Area	ft^2
S_{Wet_w}	Wing Wetted Area	ft^2
S_{Wet_f}	Fuselage Wetted Area	ft^2
SM	Static Margin	Percentage MAC
TR_h	Tail Taper Ratio (Horizontal)	
TR_v	Tail Taper Ratio (Vertical)	
$\left(\dfrac{t}{c}\right)_{tip}$	Airfoil Thickness ratio (tip)	
$\left(\dfrac{t}{c}\right)_{root}$	Airfoil Thickness ratio (root)	
F_{vol}	Fuel Storage (volume) in Wing	ft^3
$V_{fuelwing}$	Wing Fuel Tank Volume	ft^3
W_{empty}	Empty weight	lbs
W_{engine}	Engine Weight	
W_{fuel}	Fuel Weight	lbs

W_f	Fuselage Weight	lbs
$W_{payload}$	Payload weight	lbs
W_{TO}	Initial gross take-off weight	lbs
w_{wing}	Wing Weight	lbs
$\bar{Y}$	Distance of MAC from Centreline of Fuselage	ft.
X_{ac_H}	Horizontal Tail Aerodynamic Centre location	Percentage MAC
$\bar{X}_{np}$	Aircraft Neutral PT: Aerodynamic Ctr.	Percentage MAC
$\bar{X}_{cg}$	Centre of Gravity location	Percentage MAC

List of Abbreviations

AGI STK	Analytical Graphic Incorporated System Tool Kit
AIAC2017	Australian International Aerospace Congress 2017
AMD	Advanced Micro Devices, Inc.
AOCS	Attitude & Orbit Control System
AR	Augmented Reality
ASDL	Aerospace Systems Design Laboratory
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CASA	Civil Aviation Safety Authority, Australia
CASR 1998	Civil Aviation Safety Regulations 1998
CD	Concurrent Design
CDC	Concept Design Centre
CDF	Concurrent Design Facility
CE	Concurrent Engineering
CEF	Concurrent Engineering Facility
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
CS	Case Study
CoA	Standard Certificate of Airworthiness
DES	Data Exchange Server
DLR	German Aerospace Centre (German: Deutsches Zentrum für Luft- und Raumfahrt e.V.)
EA	Engineers Australia
Export CoA	Export Certificate of Airworthiness
EPFL	Space Centre, École Polytechnique Fédérale de Lausanne, Switzerland
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
E-USOC	Spanish User Support, and Operations Centre
FAA	Federal Aviation Administration
FEM	Finite Element Method
FHD	Full-High Definition (1920 x 1080 display resolution)
FRDS	Fire Retardant Delivery System
GPU	Graphic Processing Unit
IACDT	Initial Aircraft Conceptual Design Tool
IDE	Integrated Design Environment
IP	Internet Protocol
ISU	International Space University
IT	Information Technology
JPL	Jet Propulsion Laboratory
LED	Light-Emitting Diode
MDE	Multi-Disciplinary Education
MDO	Multi-Disciplinary Optimisations
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
PBL	Project Based Learning

PC	Personal Computer
PDC	Project Design Centre
PM	Project Management
RAM	Read Only Memory
RMIT	Royal Melbourne Institute of Technology University
SE	System Engineering
SFP	Special Flight Permit
SRSD	Scalable Resolution Shared Displays
SSAL	Space Systems Analysis Laboratory
TE2017	International Conference on Transdisciplinary Engineering 2017
UIC	University-Industry Collaboration
UPM	Technical University of Madrid
USU	Utah State University
PDR	Preliminary design review
SAGE2	Scalable Amplified Group Environment (2.0)
SLS	Space launch system
SRSD	Scalable Resolution Shared Displays
UHD	Ultra-High Definition (4K: 3840 x 2160 display resolution)
URL	Uniform Resource Locator
VPN	Virtual Private Network
VR	Virtual Reality

A Concurrent Design Facility Architecture for Education and Research in Multi-Disciplinary Systems Design

Abstract

Engineering design processes applied in the industry focuses more towards a concurrent approach rather than traditional sequential design, because of its potential to improve lead-time, quality and reducing cost. In Concurrent Design (CD) or concurrent engineering (CE), all elements of the product life cycle are included and considered simultaneously during the design process. CE is also known as Collaborative Engineering.

Over the last two decades, industries have applied a dedicated CD environment, representing an infrastructure of integrated hardware and software, where multi-disciplinary design teams work together collaboratively on a specific project. Graduates moving into engineering design will become more involved in CD and the use of so-called Concurrent Design Facilities (CDF). Therefore, universities need to adopt their design curriculums and expose students to CD principles to make them work-ready for this new environment.

The objectives of this thesis are to investigate the design engineering education approaches in universities, with a focus on aerospace engineering, and to identify the requirements for a concurrent design facility specifically for design education and research. The thesis gives give special attentions to the design of concurrent design facility that are low-cost, adaptable, and easy to use and its role in the overall design curriculums.

1.   Introduction

Aerospace industry focuses more towards a concurrent approach rather than traditional sequential design. Specific-purpose concurrent design facility are being used, which improved the lead-time and cost [1]. This means shorter time to market as the concurrent design teams made far fewer changes before the product launch as compared to the over-the-wall teams. A Concurrent design facility (CDF) is a state-of-the-art facility equipped with computers, multimedia devices and software tools, allowing multi-disciplinary design teams to apply the Concurrent Engineering (CE), which is also be known as Collaborative Engineering methods to the design of space missions, including aircraft and other complex systems [2]. Concurrent design facility facilitates fast and effective interactions of all disciplines involved, ensuring consistent and high-quality results in much shorter time [3]. Research institutions, industries and universities adopting concurrent design (CD) have reported better results than the traditional methods for end-to-end space missions and space systems design projects [4-6].

Future graduates will become more involve in concurrent designs and use of concurrent design facilities. Therefore, universities should review their aerospace design curriculums, consider introducing students to concurrent design principles and make them workplace ready. Universities implementing a concurrent design facility must integrate it in the overall curriculums to have the best learning outcomes. This implementation must also meet other requirements, such as suitable for research, easy to use, adaptable, flexible and affordable.

The objectives of this thesis are to investigate the design engineering education approaches in universities, with a focus on aerospace engineering, and to identify the requirements for a concurrent design facility specifically for design education and research. The thesis gives special attention to the design of a concurrent design facility that is low-cost, adaptable, and easy to use and its role in the overall design curriculums.

1.1.   Current design practices in industry

Examples of organisations that have adopted the CD/CE approach are the Boeing Company USA, Jet Propulsion Laboratory USA and Airbus France.

The Boeing Company, Boeing Defence, Space & Security, Huntsville, Alabama, U.S.A. Dec. 21, 2012: Boeing and NASA have completed their Preliminary Design Review (PDR) for the Space Launch System (SLS) core stage and avionics. They have validated the rocket design for sending humans beyond low Earth orbit to the moon, asteroid and ultimately Mars. The design meets all system requirements within the acceptable risk constraints and establishes approval for proceeding with the detailed design. In 2017, the initial mission was an un-crewed loop around Earth's moon. Boeing has implemented the concurrent design and production planning to speed up the creation of a core stage preliminary design that integrates the heritage and new designs in less than a year from contract award. These are important elements of Boeing schedule management approach. Boeing runs ahead of schedule and uses the extra time to ensure a safe and affordable rocket [7].

Jet Propulsion Laboratory (JPL), California Institute of Technology: JPL concurrent engineering design centre, JPL's Project Design Centre (PDC) has been evolving concurrent engineering capability since 1994 to provide NASA faster, better, cheaper designs. JPL has been developing new capabilities for early mission concept formulation, and works toward the analysis capability to infuse new models, common database, providing a single source of truth, common infrastructure for concept formulation teams, and access to prior study results, allowing re-use [8]. The fundamental principal behind PDC was to improve the quality of space mission conceptual studies and proposals, while at the same time reducing their cost by using the integrated tools and concurrent engineering process. Two teams utilize the PDC

facility. The first team is Team X and is responsible for formulating proposals for new unmanned planetary exploration missions. The second team is Team I, is like Team X except that Team I develops space instruments concepts [4].

Airbus has started to design aircraft in 1969 using paper engineering drawings but has successfully applied CE to all their aircraft design: A380, A400M and A350 etc. since 1999. Airbus has also invested widely to develop and deploy their CE capabilities. The project called Airbus Concurrent Engineering (ACE), which commenced in the 1990s is now a key integrator and a strong vehicle of change management [9, 10].

Airbus reported that CE has:

- Been widely accepted concept to replace the traditional engineering process and aims at using CE to reduce times and costs through multi-disciplinary approach
- Led to their significant business benefits in terms of lead-time and reduction of effort in development. These benefits have now been made visible in developing the A340-500 and A340-600, and for the A380 [10].
- Concurrent process closes the gap between functional design and industrial design, providing the functional design with manufacturing information to facilitate 'Design for Manufacturing' and 'Design for Assembly'[11].

All three organisations (Boeing, JPL and Airbus) have reported benefits from their CD/CE practices. Boeing has implemented CD to speed up core stage preliminary design stage, which has been an important element to Boeing schedule management approach. JPL PDC has implemented CE to improve the quality of space mission conceptual studies and proposals, including the reduction in design times and costs. Airbus has also implemented CE to improve quality, reduce design times and costs, and manufacture their aircraft.

1.2. Supply shortage of aerospace engineers with relevant skills

With the industry adopting CD/CE practises together with a growing economy [12-14], which forces industry to improve their lead-time and costs in designing aircraft or spacecraft missions, it is important for universities to contribute by developing skilled human capital [15, 16].

However, there is a supply shortage of aerospace engineers since 2003. Some industry segments have 15% of the workforce eligible to retire 'now – i.e. 2003', with an additional 25% eligible to retire within 5 years, i.e. 2008 [17].

The U.S. alone, as one of the largest aerospace employers has projected a 6 % growth from 2016 to 2026 in the employment of aerospace engineers [18]. In 2015, 18 % of all U.S. aerospace engineers in the aerospace industry were eligible for retirement [19]. Boeing, for example, employs 14,000 workers over age 61, and 56 % of Boeing's engineers are 50 years old or older [19]. Therefore, it is challenging to employ aerospace engineers for these industries.

It is also critical to employ engineers with relevant skills useful to the industry. In 2003, there was already a skills shortage and unless action 'is taken now', (i.e. in 2003), 'this trend will create a systemic crisis in the future' [17]. Skills shortage includes technical capability and the lack of key systems integration thinking skills necessary for complex programs important to the industry. Such systems integration thinking skills relate to concurrent engineering methodologies. Though concurrent engineering facilities have already made their mark in the industry, university adoption has been somewhat limited. Two reasons are that, concurrent engineering centres is not a necessity (i.e. no requirement for fast, efficient end-to-end design environment) and its potential is not truly realised in the academic environment [4].

In 2009, the mismatch between the employers' expectations and universities curriculum provided a platform for academics to claim that aerospace engineering degree courses are producing graduates without the skills needed to work in the industry. The skills requiring more focus were aircraft operation and maintenance [20]. In 2014, the industrial focus group also indicated that the aerospace industries were reluctant to employ graduate students, as they perceive them to lack some industry-specific professional skills. This industrial focus group composed of industry leaders from the Consortium for Research and Innovation in Aerospace in Québec (CRIAQ) Academy [21]. This trend illustrates that the universities are behind in supplying aerospace engineers with relevant skills as early as 2003.

Table 1, Themes identified by students (X) and employers (black box) as relevant to employability [22].

Category	Sub-category	Engineering	Life sciences	Media and communications
Career development learning	Business acumen*		x	x■
	Career planning	x■	x	x
	Knowledge of industry and job market	x■	x	x■
	Networking	x■	x	x
	Passions and interests	x■	x	x■
	Professionalism*	■	x	x
	Recruitment processes preparation	x■	x	x■
Experience		x■	x■	x■
Degree subject knowledge, understanding and skills		x■	x■	x■
Generic skills	Adaptability	x	x■	x■
	Communication	x■	x■	x
	Critical thinking	■	■	x■
	Entrepreneurship	x		■
	Ethics*	x■	x	x
	Innovation and creativity	■	x	x
	Leadership*	x	x	
	Lifelong learning	x■	x■	x■
	Numeracy			
	Problem solving	x		x■
	Teamwork	x■	x■	x■
	Time management	x	x	x■
	Work ethic	x■	x	x
	Working under pressure	■	x■	x
Emotional intelligence	Self awareness	x■	■	x■
	Self management	x■	x■	x■
	Awareness of others	x	x■	■
	Managing others	x■	x	x■
	Motivation	x■		x

* Themes not explicitly included in the CareerEDGE framework.

In this light, a 2015 report produced by the Australian Government Office for Learning and Teaching, employability project has explored the perspective of stakeholders from 5 disciplines such as, engineering, information and computer technology, media and communications, life sciences and psychology [22]. The aims were to explore the perspectives on graduate employability and to identify areas of consensus, gaps and opportunities for development and collaborations.

The main issue presented in this 2015 report is the adequacy of employability frameworks at the time to drive curriculums renewal in Australia. Table 1 lists the employability themes identified as relevant by the study participants (employers and students),

which highlights themes not explicitly included in the CareerEDGE framework. CareerEDGE is a model of employability that can be used as a framework for working with students to develop their employability [23].

It is useful for universities to consider incorporating a CDF to address some of these themes (Table 1: blue boxes) such as 'Experience', 'Managing others' and 'Motivation'.

The 'Experience' refers to the relevant work experience, which has been ranked 3rd out of 10 in the engineering discipline [22]. This thesis proposed that the 'Experience' be gained through either industrial attachment (if feasible) and/or undertaking design project themes that have been jointly developed with the industry (if feasible). For the 'Managing others' and 'Motivation' themes, this thesis proposed for more focus on hands-on project management skills. This can be performed through more role-play case studies to improve students' confidence in interacting and leading team members, and adopting the right approach to manage and resolve problems in some different simulated industrial scenarios.

This is likely to help reduces the effects of mismatch between employer requirements and university graduate capabilities in some industry-specific professional skills [20, 21].

1.3. Concurrent design methodology

The first fully equipped CDF is the Project Design Centre (PDC), which started operations at Jet Propulsion Laboratory (JPL) in June 1994 [24]. In 1997, the Concept Design Centre (CDC) of Aerospace Corporation developed the Concurrent Engineering Methodology (CEM) for PDC. CEM is a collection of techniques, rules of thumb, lessons learned, algorithms, and relationships developed for conceptual space system design [25].

The European space industry has also adopted CE from the beginning of 1990s. An example is the Satellite Design Office at DASA/ Astrium in collaboration with the Technical University of Munich [26]. European Space Agency (ESA) CDF was established in November 1998 at the Research and Technology Centre (ESTEC) on an experimental basis. This event was under the sponsorship and initiative of the General Studies Program (GSP) to evaluate the use of CE to create an integrated design environment for assessing future missions. CDF is a state-of-the-art facility, which included computers, software tools and multimedia devices, allowing multi-disciplinary design team to apply CE methods for space mission designs.

CDF is used to provide technical and financial feasibility studies of future space missions. These included new spacecraft concepts and provide new mission concept assessments, space system trade-offs and options evaluations, and new technology validation at system mission level [6, 27]. Other uses of CDF include aircraft design and development and tertiary education and research [7, 28].

There are many definitions of CE. One such definition is "*Concurrent Engineering is a systematic approach to integrated product development that emphasises the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle.*" CDF is based on 5 key elements, namely [6, 27]:

- A process
- A multi-disciplinary team
- An integrated design models
- A facility
- A software infrastructure

The first key element is a design process as illustrated in Figure 1, with many interdependencies between components [6]. Each component may influence another, and any change will

propagate through the whole system. Therefore, early assessment of the changes is essential to ensure completion with an optimised solution. The design process begins with a design team follows by mission requirements refinements and formalisations to define the constraints, and resources estimations. The process is iterative in nature and conducted by all team members to address the system design components quickly and completely with the aim to minimise risk of incorrect or conflicting design assumptions through debates and agreements as a team.

The second key element is a multi-disciplinary team consisting of engineers working together in a collaborative environment. Each team member represents a domain discipline, and equipped with tools to design model, calculate and exchange data. These positions are project dependant. For instance, in space design project, these positions may consist of the systems, instruments, mission analysis, propulsion, attitude and orbit control, cost analysis, structures/ configuration, mechanisms/ pyros, thermal control, electrical power, command and data handling, communications, simulation, ground systems and operations, risk assessment and programmatics [6].
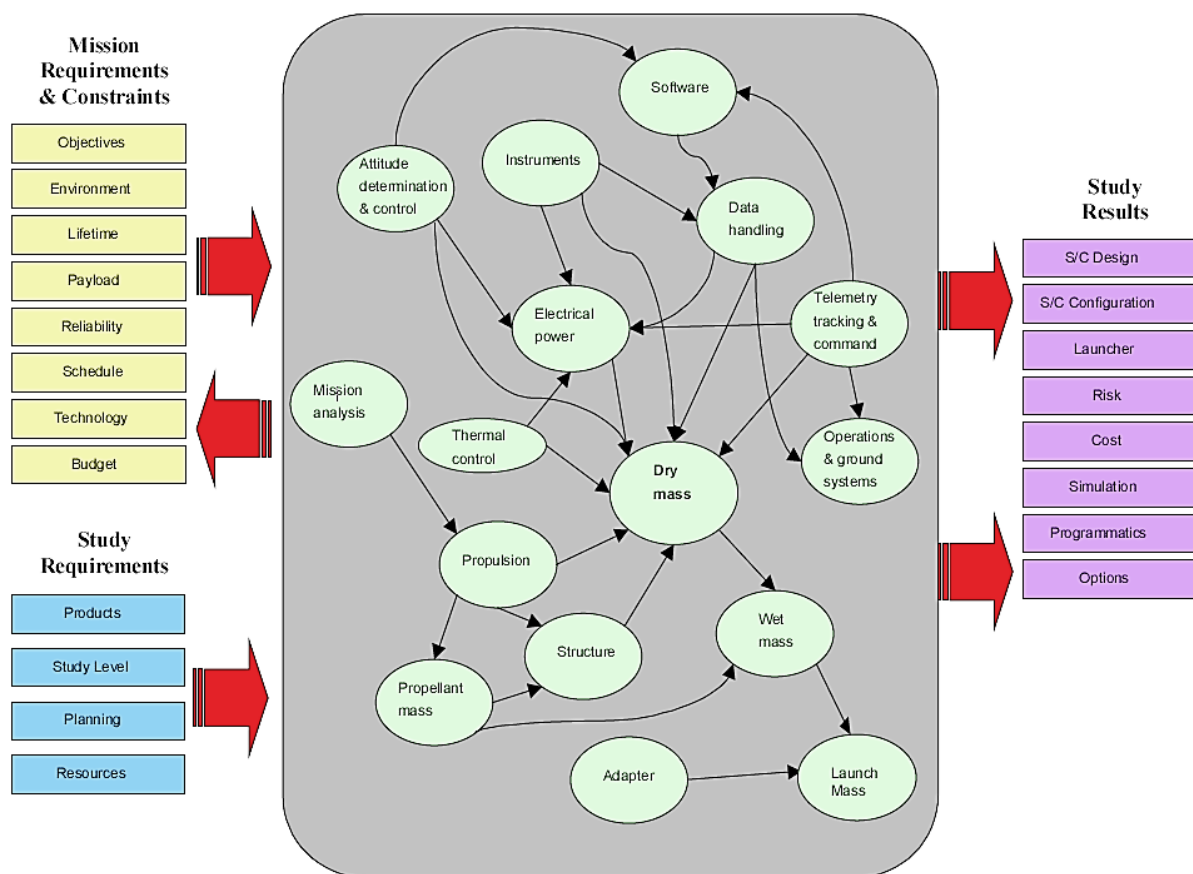
Figure 1, Mission Conceptual model and spacecraft design process [6].

The third key element is an integrated design model, where the design process is 'model-driven' using data derived from individual tools of each domain discipline [6]. These are parametric-based models (PBM). Uses of PBM enables generic models of various mission scenarios to be characterised for studies and supports fast modifications and analysis of new scenarios essential for real-time process. It acts to finalise the design ground rules and to formalise the responsibility boundaries of each domain. The established model refines the design and introduces further levels of details.

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Modelling process begins with acquiring the model suited to the mission scenario before performing the iterative design process of parameterisations. Each model includes an input, output, calculation and results area. Input and output areas are for exchanging parameters with the rest of the system such as the other internal and external tools and models. Calculations area includes equations and specifications data for different technologies to perform actual modelling process. Results area includes the numeric results summary used for presentations during the design process [6].

Figure 2 illustrates an example of the CDF Parametric-model-based Software Architecture, consisting of several specific domain disciplines (project dependant). Each Domain disciplines model's status can be consolidated through the CDF design process operation's spread sheet (spreadsheets/workbook containing Model Inputs, outputs, calculations and results) for the sub-systems and system progress reporting [6].
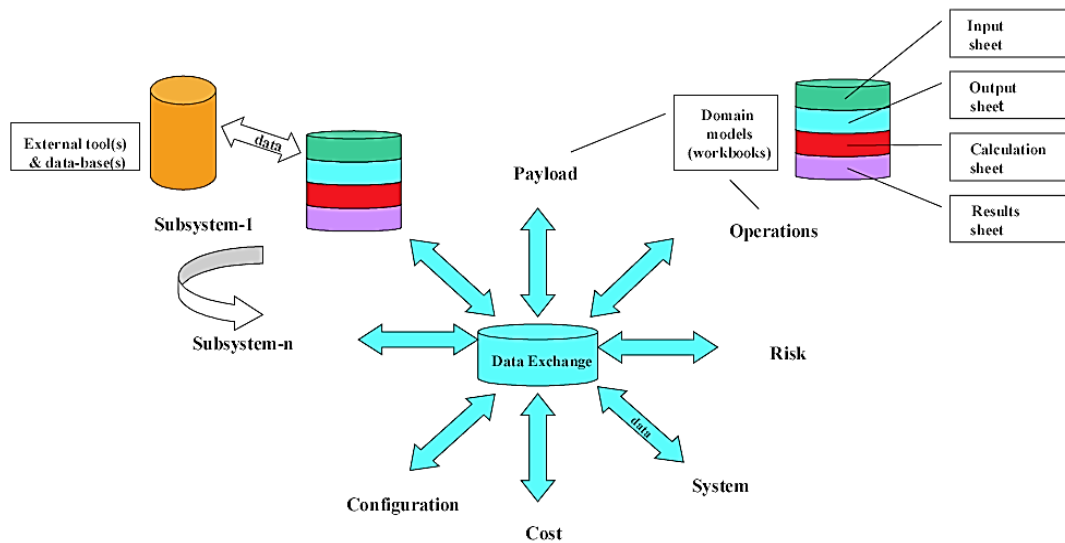
Figure 2, CDF Parametric-model-based Software Architecture [6].
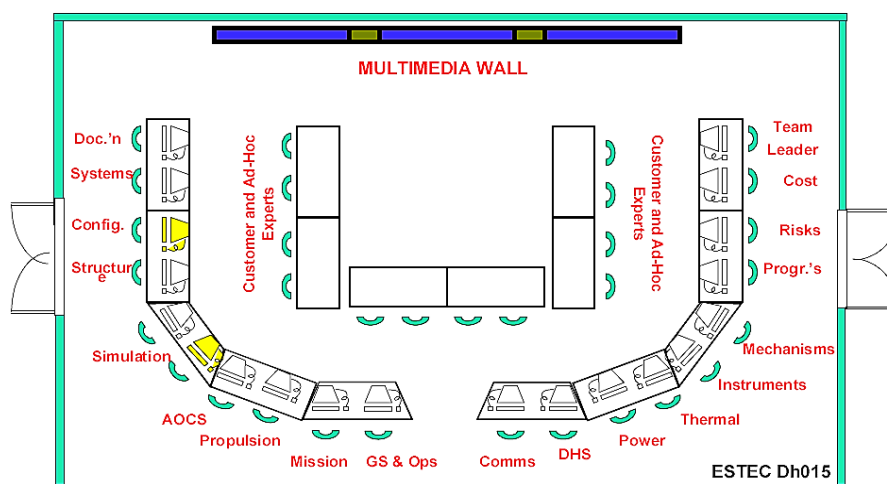
Figure 3, ESA Concurrent Design Facility room layout [6].

The fourth key element is a facility consisting a suite of rooms designed and equipped with relevant hardware and software tools to create a multi-disciplinary design environment. This aims to provide effective communications, data interchanges, engineering tools and databases to team members working concurrently. The main design room (e.g. Figure 3) may consists of a large projection screen for systems engineer to direct any of the team member computer (PC) screens directly to this screen and back, smart board, and a large number of design stations. Choice of design stations are project dependant, and may consist of the relevant domain disciplines suitable for the projects [6, 27].

The fifth key element is a software infrastructure to generate, integrate domain models, and propagates data between models concurrently, do sub-system and system level modelling and calculations. Some of the established CDFs, which have adopted the common design tools are illustrated in Appendix A, Table 23 [6, 28-32]. ESA CDF has become a reference point for other European partners to apply this approach to space mission designs. Industries and national space agencies are using the ESA CDF as a guide to create their own facilities and processes [27]. In the United States of America (U.S.A.), the JPL, which was established in 1994, is perhaps the most well-known of the concurrent engineering design centres [4]. Table 2 lists the timeline for some of the major worldwide CDF establishments.

Table 2, Timeline of some major concurrent design facility establishments [3].

Year starts	Name	Facility	Entity	Country
1994	**NASA - JPL Project Design Centre Team X [33]**	PDC	**Agency**	**U.S.A.**
1994	Georgia Technical Institute, Aerospace Systems Design Laboratory, CE & Integrated Product/ Process Development (IPPD) [34]	ASDL	University	U.S.A.
1996	TRW Integrated Concept Development Centre [4]	ICDC	Agency	U.S.A.
1997	NASA Goddard Space Flight Centre (Integrated Mission Design Centre) [4]	IMDC	Agency	U.S.A.
1997	Aerospace Corporation, Concept Design Centre [25]	CDC	Agency	U.S.A.
1998	**ESA CDF, Noordwijk was established at ESTEC - experimental basis** [3]	CDF	**Agency**	**Netherlands**
1999	EADS/ Astrium Satellite Design Office [35]	SDO	Industry	France
	EADS/Astrium, Friedrichshafen	SDO	Industry	Germany
	EADS/Astrium, Stevenage	SDO	Industry	U.K.
	Deutsche Aerospace AG (DASA)/ Astrium	SDO	Agency	Germany
1999	Laboratory for Spacecraft and Mission Design (LSMD) at California Institute of Technology [4]	PDC	University	U.S.A.
2000	Massachusetts Institute of Technology (MIT), Design Environment for Integrated Concurrent Engineering (DE-ICE) Project Design Centre [36]	PDC	University	U.S.A.
2004	Airbus, Airbus Concurrent Engineering (ACE) [37]	ACE	Industry	Netherlands
2004	Utah State University: Space Systems analysis Lab (SSAL) [4]	SSAL	University	U.S.A.
2005	Japan Aerospace Exploration Agency (JAXA) Mission Design Centre [38]	MDC	Agency	Japan
2005	CNES – CIC, Toulouse inauguration [3]	PASO	Agency	France
2006	Thales Alenia Space, Roma [39]	ISDEC	Industry	Italy
2007	China Academy of Space Technology (CAST) Shenzhou Institute (SZI) Concurrent Design Facility [2]	CDF	Agency	China
2007	Ecole Polytechnique Federal de Lausanne (EPFL), Lausanne [29]	CDF	University	Switzerland
2007	Thales Alenia Space, Torino (Collaborative System Engineering) [40]	COSE	Industry	Italy
2007	**Built a new ESA CDF**	CDF	**Agency**	**Netherlands**
2008	**Old ESA CDF knocked down**	CDF	**Agency**	**Netherlands**
2008	ASI CEF, Roma opened	CEF	Agency	Italy
2008	International Space University (ISU), Strasbourg [32] ISU CDF donated by ESA	CDF	University	France
2008	DLR (Bremen) inauguration [33]	CEF	Agency	Germany
2009	Technical University of Madrid (UPM) [28]	CDF	University	Spain
2015	University of Strathclyde, Glasgow (Concurrent & Collaborative Design Studio) [41]	CDF	University	U.K.
2017	Australian National Concurrent Design Facility (ANCDF). Funded by UNSW Canberra, ACT Government and supported by French Space Agency CNES (Centre National d'Etudes Spatiales) [42]	ANCDF	Agency	Australia

1.4. CDF applications and their effectiveness

This sub-chapter reviews the effectiveness of CDF for research institutions, and academia in collaborations with the industries.

Industry Research Institutions – operations of CDF

The European Space Agency (ESA) CDF has evolved from an experimental facility into a functional operation for mission assessment (since November 1998). It has obtained quality results for new missions in their early conceptual pre-phase-A level in shorter time than traditional methods and with minimum resources. ESA CDF teams were judged by customers to be more detailed and internally consistent than those using the classical approaches [6]. Benefits in performances for the typical pre-phase-A study includes shortening of study duration (design phase) from 6-9 months to 3-6 weeks; factor of 4 reduction in time; factor of 2 reduction in cost for customers; increased numbers of studies per year; improved quality, reduced risk and cost. The technical report becomes part of the specifications for subsequent industrial activity and capitalisation of corporate knowledge for further reusability [3].

　　Space Centre, École Polytechnique Fédérale de Lausanne (EPFL), Switzerland CDF is founded to foster, promote and federate space technology across education, science and industry at Swiss and international levels. EPFL CDF setup follows the approaches from ESA CDF and TeamX project at Jet Propulsion Laboratory and has close relationships with the industries. The benefits include faster design of new products, shorter times to market, overall quality improvements, knowledge re-usability and fast implementations of trade studies. However, the CDF development is mainly defined for improving the quality of education and providing a unique experience for EPFL students [43].

Industry-university collaboration – operations of university CDF

ESA-ISU collaboration: ESA donated their early CDF to the International Space University (ISU) with continuous supports and collaborations. During the 2 years of ISU CDF operations, students' assignments for the ISU MSc. in Space Studies (MSS) 2009/10 classes conducted have shown very encouraging results based on students' feedback and overall quality of the work produced by them [32].

　　E-USOC – UPM collaborations: Industry-university collaborations between the Technical University of Madrid (UPM), and Spanish User Support and Operations Centre (E-USOC) started from academic year 2009/10 on space education. ESA has assigned the E-USOC to support operations of scientific experiments on board the International Space Station (ISS). This collaboration incorporated the CDF approach and Project Based learning (PBL) training process, and has also shown good results where students' motivation and their results (technical and transversal skills) were improved [28].

1.5. Technologies available for CDF

A low-cost CDF suitable for engineering design education and for research is feasible. This is mainly due to the rapid advancement and lower cost in Information Technology hardware, software tools, and supporting IT infrastructure such as networking, video conferencing, cloud computing and storages and security [1].

　　Suppliers of Central Processing Unit (CPU) bring out new generation processors every year with improved performance-to-cost ratio (trend) [44]. Figure 4 illustrates the Intel CPU core i7 series performance improvement (trends) from 2nd to 8th generation. The corresponding

costs have been relatively flat from 4th to 6th generation and reduced in 7th and 8th generations. The CPU's performance is measured in term of CPU-mark value, which is a relative figure. The bigger the number the faster the CPU. For example, a PC with a CPU-mark value of 4000 can process roughly twice as much data as a PC with a result of 2000 [44].

Intel CPU Core i7: CPU-Mark vs. CPU-Generation
(Based on mainly highest specification from 3rd to 7th and currently available 8th generation Intel CPU)
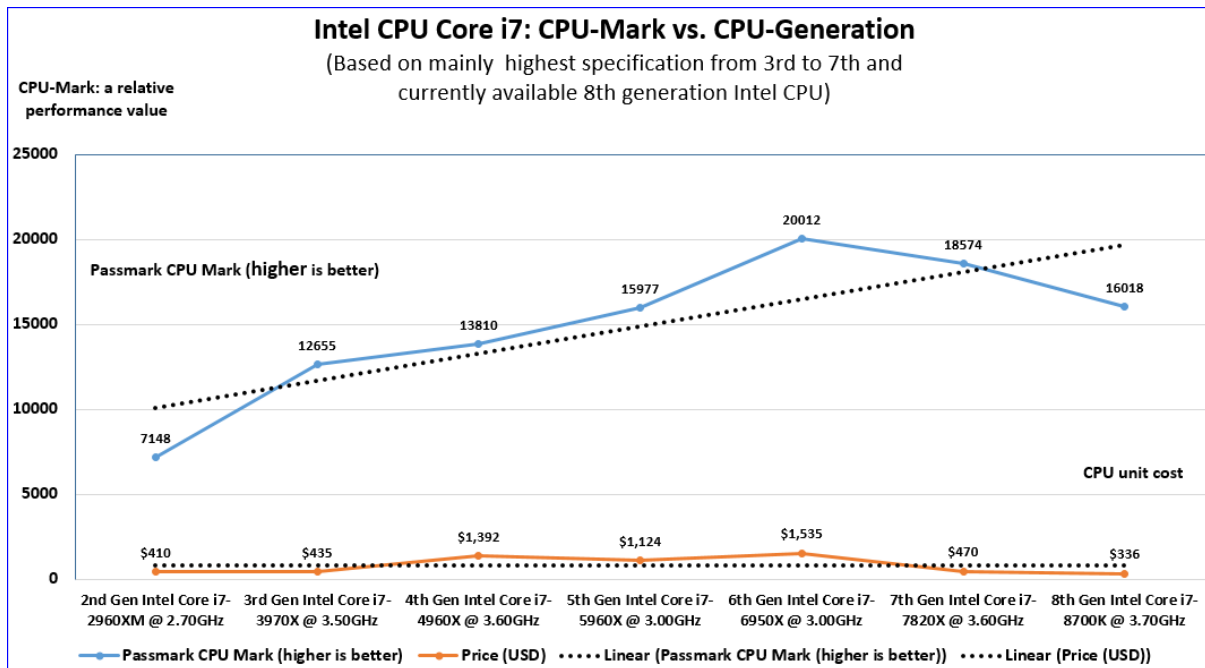
Figure 4, Intel CPU: Performance-to-Cost Ratio (trend, Q4 2011 to Q2 2017) [44].

Software suppliers, especially those with large user-base in industry and universities, offer students/academics educational licensing of their popular design tools universities.

For the Centralised Data Storage Server environment, universities may utilise their existing Information Technology (IT) infrastructure as alternative to purchasing new separate hardware and software if feasible. This should help to minimise the CDF setup cost.

The CDF facility is based on access to a multi-purpose room with high-speed networking and internet infrastructure. However, it is acknowledged that the availability of suitable infrastructure can be an issue. It may not be necessary to build a new building, but making modifications to a building, including furniture can still be costly.

1.6. Challenges to establish a CDF architecture for education and research

Literature shows that currently it is more affordable for many universities to setup a CDF for education and research [45]. However, universities still face challenges in operations and infrastructure when considering a CDF [28, 29, 46].

CDF in research institutions and industry are mainly engaged in commercial product development and design using experienced teams, while universities are mainly tied to their schedules and focus on Project Based Learning (PBL) [28]. In most cases, students starting their minor do not have the team experience required for project design in a group. These differences may limit the universities efforts to setup a suitable CDF [29].

Lecturers and students face a steep learning curve, project synchronisations with academic schedules, students' team changes and variations in students group size for each project [29, 46].

The purpose of setting up a CDF for education and research is mainly to address the relevant industry and agency needs. However, universities need to decide between implementing the CDF-based training course as an undergraduate core or elective course. If the initial CDF setup is offered as:

- A core course, relevant industry is likely to welcome the decision, since they can expect more future graduates to meet their requirements for employment. However:
  - o Potential students may be interested in other electives instead of CDF. As a result, they may not enrol in the aerospace program or may enrol at other universities with CDF as an elective.
  - o Universities may encounter resourcing issues such as academic, support staffing, and CDF room constraints.
- An elective course, industry may perceive that the universities are not moving fast enough to support them. However:

  - o Potential students will have more options to match their individual career needs.
  - o Universities will be given more times to fully implement the CDF in curriculum, including lower resourcing issue.
  - o Universities will be able to review the numbers of students opting for the CDF elective over times before deciding to remain as an elective or change to being a core course.

In this light, other university, such as Utah State University (USU) reviewed in this thesis (subsequent work) has an elective CDF course in their undergraduate program. USU Year-4 students need to select and complete the elective course: Spacecraft Systems Engineering before they can enrol in the Space System Design course [47]. The Space System Design Course is conducted in the USU Concurrent Engineering Facility (CEF), known as the Space systems Analysis Laboratory (SSAL) [4].

This is a challenging decision to be considered by the university management.

The Technical University of Madrid (UPM) and International Space University (ISU) reviewed in this thesis offer CDF training only in their Master programs.

1.7. Research questions and methodology

Literature reviews have shown the importance that universities need to embrace CD in their curriculums. Universities have considered implementing and did collaborate with the industries in setting up CDF in curriculums in view of the various challenges [48]. However, there appear to have minimal low-level focuses on what kinds of industry-university collaborations requirements are required to setup a low-cost long-term CDF architecture. These low-level focuses refer to the supporting elements such as the pre-requisites for attending CDF based training and post-CDF training requirements.

These are important gaps identified in this thesis because CD methodology and CDF is not just a single element implementation in the university. CDF setup will likely not work as well in isolation from the industries though it may have state-of-the-art setup (i.e. top-of-the-line IT infrastructure, hardware, CD software tools and facility). University CDF is just a part of a larger-scale-solution-package to allow the industries to address the associated problems due to economic growths [12-14]. Therefore, the university CDF is likely to work better and able to maintain its relevance through the continuous long-term industry-university collaborations as the economy and technology changes and progresses. Such collaborations should minimise the mismatch between employers' expectations and aerospace engineering

degree courses and, the reluctance of aerospace companies to hire graduate students, as they perceive them to lack some industry-specific professional skills [20, 21].

To this end, this thesis proposes a low-cost CDF be setup to enhance design teaching and research. This thesis has also identified and answered three research questions. These research questions are:

1. How is aerospace design currently taught at universities and to what extend are student graduate skills compatible with industry requirements?

2. What are the requirements for a Concurrent Design Facility suitable for design education and research at university level?

3. What CDF architecture would best meet the aforementioned requirements, including hardware, software, data management, infrastructure, etc., from an ease of use and cost perspective?

To answer research question-1, a comprehensive literature review was conducted in aerospace design teaching methodologies and Concurrent Design Facilities.

To answer research question-2, this thesis has identified the essential requirements for establishing a CDF suitable for design education and research, which covers broadly the following areas:

- Able to emulate industry design practices.
- Able to incorporate sufficient students training and preparation.
- Must be a low-cost ergonomic multi-disciplinary facility room with sufficient numbers of upgradable generic hardware and design/support software for an average size team.
- Must have secure data storage with ability to perform onsite/offsite content sharing and collaboration.
- Design tools are flexible and adaptable for multi-disciplinary research needs, and easy to learn and use.

To answer research question-3, the recommended CDF architecture and design environment that meets the requirements identified in research question-2 has been answered in detail.

1.8. Structure of this thesis

The structure of this thesis consists of five chapters. Chapter 1 introduces the main objectives of this thesis, followed by a comprehensive literature review with focus in the aerospace disciplines, identification of research questions and summary of contributions. The rest of this thesis is organised as follows:

- Chapter 2 reviews the aerospace design teaching methodologies, which includes a case study.
- Chapter 3 describes the development of the collaborative teaching tool to enhance design teaching.
- Chapter 4 investigates a low-cost CDF architecture for education and research.
- Chapter 5 concludes this thesis with discussions, concluding remarks and outlooks.

Brief descriptions of each of these chapters

Chapter 1: Introduction. This chapter introduces the main objectives of this thesis and focuses on a comprehensive literature reviews of the aerospace discipline. This includes industry practices, engineer skills, concurrent design methodologies and effectiveness, technologies available and challenges to setup CDF for education and research, and identification of research questions.

Chapter 2: Aerospace design teaching methodology. This chapter focuses on:

- Literature reviews of aerospace programs at selected universities that incorporate CDF or do not incorporate CDF.
- A case study that has been conducted for a typical capstone design course.

Chapter 3: Development of collaborative teaching tool to enhance pre-CDF multi-disciplinary design education.

- 'to enhance' refers to:
  - Allowing students to focus visually on the lectures and tutorials instead of having to spend extra times to learn new complex professional tools prior to completing their assignments.
  - The tool's workflow is similar to the popular ESA CDF approach.
  - The Real-time automatic interfacing between tool's workbook and 3D model, allowing students to perform iterative design cycle with system wide perspective.
- 'Pre-CDF' refers to education period prior to the actual use of a CDF.

This chapter introduces a collaborative teaching tool, which is called the Initial Aircraft Conceptual Design Tool (IACDT). This tool has been developed by closely referencing a typical Year-3 aircraft design course structure and aims at teaching students the interactions between multiple disciplines and self-discovery CD workflows. Appendix C provides the IACDT detail operations.

Chapter 4: Investigate a low-cost CDF architecture for education and research. The following research works have been conducted:

- Integration of a CDF in design curriculum with project-based learning, including remote collaboration with industries and universities.
- CDF architecture.

- Recommendations of IT hardware and software architecture (CDF for education and research).
- Minimum support facilities for CDF room (physical room layout).

A case study (simulation) has been conducted based on a sub-system component in another case study in this thesis: Year-4 final design course. The case study (simulation) has determined that the proposed multi-disciplinary optimisation tool, spreadsheet/workbook and computational simulation tool is able to interface with each other and function as a single cohesive design tool platform.

Chapter 5: Discussions, concluding remarks and outlooks. This chapter concludes a summary of research works conducted, answering the three research questions, which results in the proposal of a low-cost CDF for education and research before giving a brief outlook.

1.9. Contributions to this thesis

The contributions of this thesis are multi-folds:

- Conducted comprehensive relevant literatures reviews in the aerospace design teaching methodology and Concurrent Design Facility.

- Conducted a case study for a typical capstone design project.

- Developed original novel Collaborative Tool for pre-CDF education, known as the Initial Aircraft Conceptual Design Tool (IACDT).
  - The original novel elements come from combining into a single platform the:
    - Closely referencing a typical Year-3 aircraft design course structure, and
    - Real-time interfacing between the various spreadsheet (acting as MDO) within the tool and the 3D model.

- Proposed an original novel low-cost CDF architecture for education and research, which includes the integrated pre-requisites, post CDF-based supporting components and minimum support facilities to function as an overall single cohesive CDF platform as follows.

  - Pre-requisites:
    - Utilises the IACDT Collaborative Tool, developed in this thesis, to enhance the Year-3 aircraft design course as part of the pre-CDF education.
    - Maintain existing formal short courses as part of the overall integrated supporting components. This includes CAD/CAE, Computational Simulation, Multi-Disciplinary Optimisation and more focus on Project Management.
  - Maintaining existing post CDF-based training and industrial-university collaboration with more focus (if feasible) in:
    - Industrial attachment and final work experience reporting.
    - Industrial feedback.
    - Joint creation of design themes for realistic real-world scenarios.
  - IT hardware and software architecture.
  - Minimum support facilities for CDF room (physical room layout).

- Conducted a case study (simulation) successfully to integrate modeFRONTIER (multi-disciplinary optimisation), MS-Excel and MATLAB. This is to determine that the proposed design tools can interact with each other in a typical CDF environment. Lessons learned were:

  o Utilising a blank spreadsheet/workbook prepare a new design workflow for multi-disciplinary optimisation has taken longer time than the combination of 3 design tools.
  o Utilising the highly automatic modeFRONTIER, MS-Excel and MATLAB combination is more intuitive and required less preparation.
  o Optimisation results from modeFRONTIER combination are faster and more comprehensive.

- Conducted a case study, which has successfully determined that the proposed open-source parallel rendering middleware SAGE2 tool is able to function as intended in a typical CDF environment.

2.   Aerospace design teaching methodology

This chapter reviews the aerospace design teaching methodologies at different universities that are without CDF and with CDF incorporated in curriculums. The curriculum and design teaching methodology at a number of selected universities were investigated.

The descriptions of University of New South Wales (Sydney) (UNSW), the University of Queensland (UQ), RMIT University, University of Bristol (UB) and Utah State University (USU) programs in the following works were supported by Table 3, Table 4, Table 5, Table 7 and Table 8 program (courses listings) respectively. These tables are also relevant to the answering of research question 1 in chapter 5. This aims to identify each available course 'position' within the entire degree program-wide perspective better. Therefore, these tables are important in this work.

Design teaching methodologies (without CDF) in Australia

The aerospace design programs that are offered by the University of New South Wales (Sydney), the University of Queensland and RMIT University, which do not have CDF-based course in curriculum, were reviewed [49-51].

These three universities were selected for reviews due to their good ranking in Australia [52]. Another reason for selecting RMIT University is because this thesis included a case study based on the RMIT University's capstone design project and an Initial Aircraft Conceptual Design Tool was developed by closely referencing a RMIT University Year-3 aircraft design course structure.

All three universities are generally adopting similar 4-years curriculums structure and have a capstone design project.

There is no formal project management (PM) course in their honours programs, but PM elements are embedded in courses.

This thesis included a case study on a typical capstone design project course (without CDF) to investigate the course structures and attributes in more detail (Sub-Chapter 2.4).

Design teaching methodologies (without CDF) in United Kingdom

The aerospace design program that is offered by the University of Bristol (UB), which does not have CDF-based course in curriculum is also reviewed.

This university is selected for review due to its good ranking in U.K. [52].

The main difference between UB and UNSW (Sydney)/UQ/RMIT is that, although UB does not have a CDF at the university, UB has started to collaborate with external agency, Science and Technology Facilities Council's (STFC) RAL Space in 2017 to design UB's first CubeSat. UB student reported that working on a real-life mission was very motivating for them and a unique opportunity [53].

Design teaching methodologies (with CDF) in Spain, France and United States of America

The aerospace design teaching methodologies that are offered by the Technical University of Madrid (UPM), International Space University (ISU) and Utah State University (USU), which already have a CDF are reviewed [4, 28, 32].

UPM and ISU were selected for reviews because their CDF architecture is based on the ESA CDF. USU was selected for review because of its CDF architecture is based on that of the NASA JPL CDF. USU CDF is also known as the Space Systems Analysis Laboratory (SSAL).

UPM and ISU was also compared with the ESA/ESTEC CDF on domain disciplines implementations [6]. UPM, ISU and ESA/ESTEC CDF have adopted the six common domains disciplines: Mission, Power, Propulsion, Payload, Communication and Thermal.

UPM has integrated CD and PBL in their conceptual space mission design course, led by UPM and (industry) E-USOC staff.

ISU has adopted the ESA approach (ISU CDF donated by ESA) in their MSc design course, with internship and individual project in the final module of the course. Internship is defined as 'a period of time during which someone works for a company or organization in order to get experience of a particular type of work' [54].

USU undergraduate program included capstone courses in their Year-4 program, and an elective CDF course. USU Year-4 students need to select and complete a specific elective course before they can enrol in the CDF-based Space System Design course [47]. This course is conducted in the USU Concurrent Engineering Facility (CEF), known as the Space systems Analysis Laboratory (SSAL) [4].

UPM, ISU and USU have reported positive results from CDF-based training.

UPM Master in Space Systems students surveys results have shown that both Year-1 and -2 students were positive about CD concept and believed their skills have been improved due to CDF activities [55].

ISU MSS students' assignments involved generating different mission architectures and design options from a set of requirements. ISU Faculty plays the role of customer. Assignments for the ISU MSS 2009 and MSS 2010 classes results have been very encouraging, based on students' feedback and overall quality of the work by them produced.[32]

USU CDF-based course (space system design) is conducted at the USU Concurrent Engineering Facility (CEF). This course is mainly for teaching students on end-to-end design of a space system, including letting students perform their work in a CE setting. USU has reported that the use of CEF for teaching would be beneficial as the undergraduate space systems design course will be taught in a more practical and real-world applicable manner. USU has also reported that students have benefited in terms of better understanding of the complexity of modern aerospace systems and innovative approaches necessary to optimise these systems [4].

2.1. University of New South Wales (Sydney)

A typical 4-year undergraduate aerospace engineering (Honours) program at the University of New South Wales (Sydney) is listed in Table 3 [49]. Year-1 consists of eight core courses and one elective. Year-2 consists of eight core courses and one elective. Year-3 consists of six core courses (includes aerospace design course, introducing CATIA: a prerequisite for Year-4 design project (elective)), and three industrial training or exchange opportunity components (minimum 60 days Industrial Training): Year-3 mandatory. Year-4 consists of three (core) research thesis, two (core) courses, one aerospace design project and two discipline electives.

The Year-4 design project course consists of a capstone design project. Students design teams develop the aircraft preliminary design to satisfy the request for proposal in a holistic approach. Students need to review the requirements of several disciplines including conceptual designs, configurations, weights, sizing, payload, aerodynamics, propulsion, structures, systems, stability and control, performance, and cost. Subsequently, students will integrate these elements into a single aircraft design through teamwork, report writing, and presentation skills, which is a focus to develop important professional skills for the industry. Students use the school resources such as the computer aided design and manufacturing, wind tunnels, simulation and test facilities. Team meetings with staff and lectures on advanced project design

support the projects. The school and external experts give lecture in specific areas, which include structural design, aerodynamic, engine integration and system design. This program does not have a CDF-based training, nor a formal PM course.

Table 3, University of New South Wales (Sydney) aerospace engineering (Hon) program [49].

University of New South Wales (Sydney): Aerospace Engineering (Honours) [assess date: 28 Aug 2018]			
Year-1	Year-2	Year-3	Year-4
Engineering Design and Innovation	Discipline (Elective)	Aerospace Structures	Dynamics of Aerospace Vehicles
Computing for Engineers or Computing 1A or Introduction to Programming	Engineering Mathematics 2E	Aerodynamics	General Education
Maths 1A or Higher Maths 1A	Thermodynamics	Flight Performance, Propulsion	Research Thesis (1/3)
Engineering (Elective)	General Education	Aerospace Design	**Aerospace Design Project A (capstone/teamwork)**
Maths 1B or Higher Maths 1B	Numerical Methods and Stats	Professional Engineering and Communication	Discipline (Elective)
Physics 1A or Higher Physics 1A	Engineering Mechanics 2	Linear Systems and Control	Research Thesis (2/3)
Electrical and Telecommunications Engineering	Engineering Design 2	Industrial Training or Exchange Opportunity (Mandatory: minimum 60 days)	Discipline Elective
Engineering Mechanics	Mechanics of Solids 1		Discipline Elective
Design and Manufacturing	Fluid Mechanics		Research Thesis (3/3)

Australian National Concurrent Design Facility (ANCDF) located at UNSW Canberra Space

While UNSW (Sydney)'s BEng Aerospace Engineering (Honours) program does not have a CDF-based program, a new Australian National Concurrent Design Facility (ANCDF) is opened in November 2017 at UNSW Canberra Space. ANCDF is also known as the Australia's National Space Agency (ANSA), which is jointly funded by UNSW (Canberra), the ACT Government and supported through a partnership with the French Space Agency CNES, who are providing software and training. Since the opening of ANCDF in November 2017, staff and academic training at the ANCDF are conducted by the French Space Agency CNES (Centre National d'Etudes Spatiales) [42].

2.2. University of Queensland

A typical 4-year undergraduate Bachelor of Engineering (Hon) Mechanical and Aerospace Engineering Dual Major, such as the one at The University of Queensland, is listed in Table 4 [50]. Students must complete 64 units comprising 56 units, being all courses from part A - compulsory; and 4 units from part B4 - advanced electives; and four units' introductory electives from part B1. The Year-4 design project course consists any one of the four options:

- Professional Engineering Project (I) or
- Engineering Thesis (II), or
- Engineering Thesis (III) or
- Major Design Project (IV) – (capstone design course)

Option (I) is a major investigation, research project or a significant design task, as part of a Centre of Excellence for Environmental Decisions (CEED) project taken in conjunction with industry.

Option (II) and (III) involve a thesis project on an approved topic that integrates engineering skills acquired through the engineering program.

Option (IV) involves multidisciplinary topics for group design project sponsored by the industry in research, academic and commercial organisations to complete detailed design calculations to the sponsor's specifications.

- The 'Major Design Project (option IV)' course is a capstone course for senior students of Mechanical, Mechanical and Aerospace, and Mechanical and Materials Engineering, and requires in depth project-based application of knowledge from a wide range of preceding courses.
- Students must also conduct and demonstrate the ability to independently study and research relevant materials as required to complete their assigned designs. This includes the formulations of technical specifications through a process of negotiation with the course coordinator, project supervisor, and to complete the designs with a high level of scientific and engineering rigor.
- Students manage the projects, and coordinate the group workloads in documentations, formal public presentations, demonstrations of teamwork for satisfactory completions. Students' final submitted reports are marked based on the standards of professional consulting engineers.

Table 4, The University of Queensland mechanical aerospace engineering (Hon) program [50].

The University of Queensland: Mechanical Aerospace Engineering (Honours) [assess date: 28 Aug 2018]			
Year-1	Year-2	Year-3	Year-4
Engineering Design, and	Calculus & Linear Algebra II	Analysis of Ordinary Differential Equations	Aero Design and Manufacturing
Engineering Modelling & Problem Solving	Advanced Calculus and Linear Algebra II	Finite Element Method & Fracture Mechanics	Aerospace Propulsion
Or Engineering Design, Modelling & Problem Solving	Structures & Materials	Thermodynamics & Heat Transfer	Professional Practice and the Business Environment
Calculus & Linear Algebra and Advanced Multivariate Calculus & Ordinary Differential Equations	Introduction to Engineering Design and Manufacturing	Engineering Management & Communication	Control Engineering 1
Or Advanced Calculus & Linear Algebra I and	Fundamentals of Fluid Mechanics	Analysis of Engineering & Scientific Data	1 **elective** from: Professional Engineering Project or Engineering Thesis or **Major Design Project (capstone/collaborative)**
Multivariate Calculus & Ordinary Differential Equations	Machine Element Design	Mechanical Systems Design	B1 – 2 Introductory elective from: Chemistry 1, Introduction to Software Engineering, Introduction to Research Practices - The Big Issues or Electromagnetism and Modern Physics
Engineering Mechanics: Statics & Dynamics	Intermediate Mechanical & Space Dynamics	Advanced Dynamics & Vibrations	B4 – 2 advanced elective from: Flight Mechanics & Avionics, Aerospace Composites, Hypersonic & Rarefied Gas Dynamics, Space Engineering or Computational Fluid Dynamics
Engineering Thermodynamics	Engineering Analysis I	Fluid Mechanics	
Introduction to Electrical Systems		Engineering Analysis II	

2.3. RMIT University

A typical 4-year undergraduate (BEng) aerospace engineering (Hon) program such as the one at RMIT University is listed in Table 5, which includes a typical capstone design project course [51].

Year-1 consists of eight core courses. Year-2 consists of seven core courses and one University elective. Year-3 consists of 7 core courses and 1 Program elective (includes aerospace design principles course, which covers project plan, CAE, aircraft sizing and

configuration) and 1 elective course. Year-4 consists of five core courses, Program 2 electives and one University elective.

Year-1 and -2 devote to understanding of engineering such as maths and mechanics of materials.

Year-3 deepens student knowledge in aerospace engineering including one program elective tailored to suit students' areas of interest and enhance career opportunities.

Year-4 focuses on putting theory into practice through a major professional research project. Students plan their research project, conduct relevant literature review, complete the research project and report findings. This capstone research design project will develop and reinforce students' skills and knowledge as defined by Engineers Australia. This program does not have a CDF, nor formal project management course.

The Year-4 'International Industry Experience 2' (IIE) and 'Industrial Placement Program' (IPP) courses are available. However, IIE enrolment depends on the course coordinator's confirmation of placement with an international host organisation. Beside this, the eligibility is based on both academic performance and a successful interview. The IPP enrolment must be pre-approved by the course coordinator.

Table 5, RMIT aerospace engineering (Hon) program [51].

RMIT: BEng (Aerospace Engineering) (Honours) (assess date: 12 Oct 2018)			
Year-1	Year-2	Year-3	Year-4
Introduction to Professional Engineering Practice	Mechanics and Materials 2	Aerospace Dynamics and Control	**Engineering capstone Project Part A (team work)**
Introduction to Aircraft	Dynamics	Advanced Aerodynamics	Aerospace Design Project
Engineering Mathematics C	Math & Stats for Aero, Mech. & Auto.	Aerospace Propulsion	Aerospace Finite Element Methods
Mechanics and Materials 1	Principles of Aerodynamics	Computational Engineering Analysis	Program elective
Applied Thermodynamics	Systems Engineering	Aerospace Structures	**Engineering capstone Project Part B (team work)**
Fluid Mechanics of Mechanical Systems	Flight Mechanics	Research Methods for Engineers	Advanced Aerospace Structures
Computer Aided Design	Design for Manufacture and Assembly	Aerospace Design Principles	Program elective
Further Engineering Mathematics C	University elective	Program elective (12pt) International Industry Experience 1: *a. Required placement confirmation. b. Eligibility based on academic performance and successful interview.*	Program elective (24pt) International Industry Experience 2: *a. Required placement confirmation. b. Eligibility based on academic performance and successful interview.* or, Industrial Placement Program: *a. Required pre-approval to enrol by course coordinator.* And, 1 university elective.

Figure 5 illustrates a typical capstone design project course structure, which is based on the Honours program in Table 5 [51, 56]. Students team work together to develop concept solutions of real-world problem requirements through PBL. Student group selections begin when the course commences. Students receive the design project themes to aid group selections and formations.

These themes may come from academic staff and the course coordinator for development into the product requirements document (PRD). Students also receive the project schedules and academic advisor's mentor throughout the lectures, tutorials, reviews and

presentations. The design process aims to deliver a peer learnings process and guide students toward a properly managed group project to train students in design skills.

A supporting Year-3 course precedes the Year-4 design course. This Year-3 course covers the aerospace design principle, where students learn what design is, the steps in a typical design process, available resources and multi-disciplinary design, etc. The course includes assignments involving research of a design related topic, estimating the initial aircraft weight and aircraft sizing. The combined Year-3 and -4 courses aim to consolidate the learning of individual supporting aerospace courses from Year-1 to -4 and apply this combined knowledge to design complex multi-disciplinary systems (i.e. baseline engineering practice).
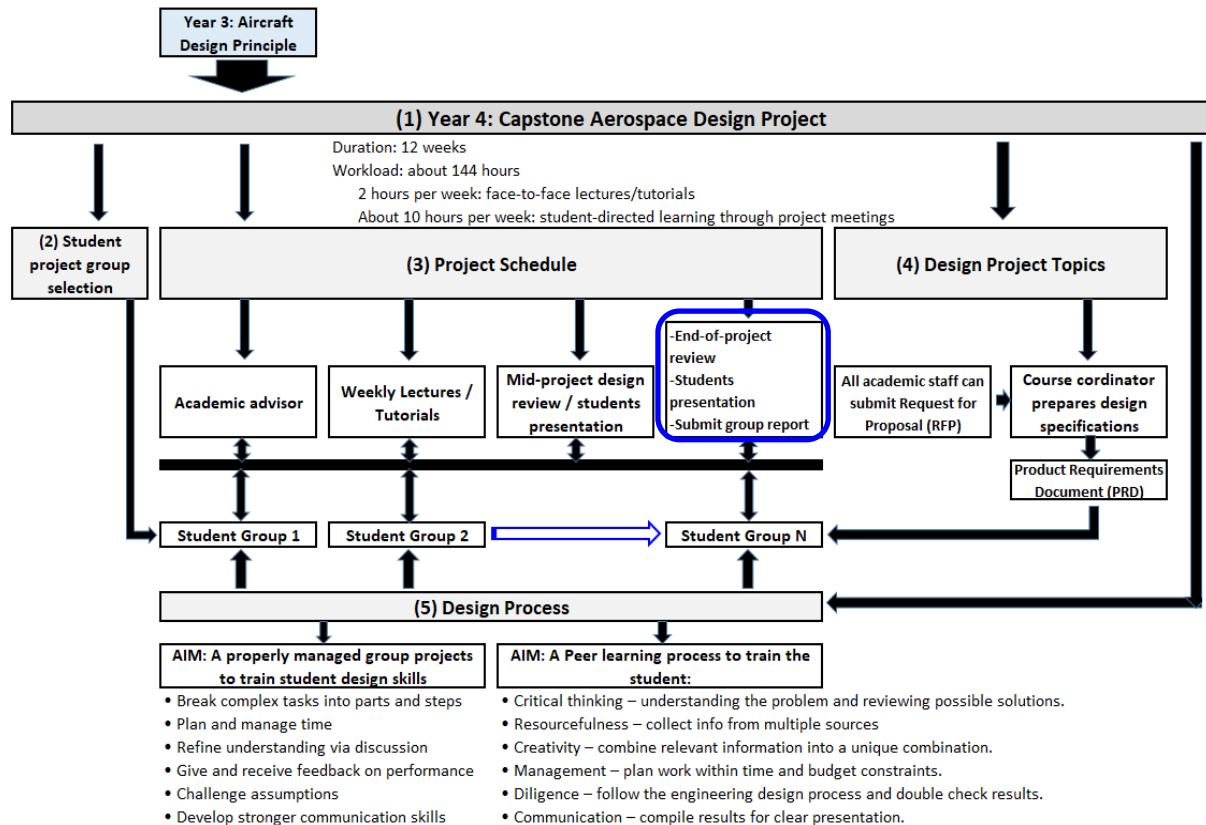
Figure 5, A typical capstone design course structure.

Overall, this program appears to meet the aerospace discipline components required by the industries in light of some challenges in conducting the Year-4 aerospace design course [22]. From a course coordinator's perspectives, such challenges include the managing of these groups, and determining a transparent and fair assessment scheme. The project finishes with the submission of a consolidated design report. Although this report reflects the outcome of the group efforts in Figure 5 – blue box, it does not reflect the contributions of individual students, nor how each has contributed to the design process. University policy requires the assessments of individual student contributions, and their involvements in the design process is a challenge in project-based learning [56].

2.4. Case study: A typical Year 4 aerospace design course, RMIT

The preceding sub-chapter reviews four typical university aerospace undergraduate programs that are without CDF. This sub-chapter evaluates a typical Year-4 aerospace design course structure and attributes in Figure 5 through a case study.

2.4.1. Capstone design project course

The Year-4 design project course includes a duration of 12 workweeks at about 10 hours per week per student. Face-to-face learning mode is 11 workweeks, teachers guided hours are 36 hours per semester and learner directed hours is 84 hours per semester. The primary learning mode consists of lectures and facilitated project-based group design sessions for students to tackle complex tasks, aim at generating credible conceptual design solutions. The course coordinator and tutor meet face-to-face with students twice a week. Students are also able to assess to the course coordinator through the University student course 'blackboard' website and emails. Students may meet on their own group or part of a group during the week in the University study areas or computer laboratories for additional discussions in-between lectures and tutorials.

Students receive the design briefs to generate, evaluate and select suitable the design concepts to meet these requirements. Each students group averaging at seven students work on the same design brief. Workweek 1 to 10 allocates an hour of lecture each week. Eight tutorials are available with tutorial one starting on workweek 3 after lecture 3. Tutorial is a non-teaching or counselling class conducted by teaching staff in a tutoring role to assist, facilitate and encourage 1 or small group of students to feel competent in their learning process to achieving their educational goal [57]. Workweek 11 and 12 has no lecture or tutorial, but in workweek 11, the student groups do their final presentations. The judging panel consists of the course coordinator, tutor, internal lecturer and an external aviation industry person. Students group submit their final group reports in workweek 12.

2.4.2. Project workflows structure

The Year-4 design project course commenced with lecture1, also known as workweek1 (wwk1) and lecture2 in wwk2. Tutorial 1 commenced in wwk3 as illustrated in Table 6 timeline.

Table 6, Case study: Capstone Design Project Course – Timeline

Case study: Capstone Design Project Course – Timeline (average 7 students per design project group)													
wwk1	wwk2	wwk3	wwk4	wwk5	wwk6	wwk7	Public Holiday wk	Public Holiday wk	wwk8	wwk9	wwk10	wwk11	wwk12
Lecture 1 (1 hour)	Lecture 2 (1 hour)	Lecture 3 (1 hour)	Lecture 4 (1 hour)	Lecture 5 (1 hour)	Lecture 6 (1 hour)	Lecture 7 (1 hour)			Lecture 8 (1 hour)				
		Tutorial 1 Supervised (45 min)	Tutorial 2 supervised (45 min)	Tutorial 3 supervised (45 min)	Tutorial 4 supervised (45 min)	Tutorial 5 supervised (45 min)			Tutorial 6 supervised (45 min)	Tutorial 7 supervised (45 min)	Tutorial 8 supervised (45 min)		
		I was present (wwk4 to wwk7)							I was present (wwk8 to wwk10)				
		I download off-line data from students google drive (From wwk4 to wwk12, including 2 Public Holiday wks.)											

Course coordinator and tutor activities

From tutorial 2 to 6, the course coordinator and tutor each:

- Supervised different groups at around 45 minutes each group, and
- Exchange groups in the following wwk.

The author was in the tutor's supervised groups from tutorial 2 to 6 and able to observe more students' groups as the course coordinator and tutor exchange groups each wwk.

In tutorial 7 and 8 (last tutorial), the course coordinator gathered the groups with similar design brief to discuss their progress. This included:

- What went wrong in their research approach in selecting concepts and options?
- What they have not touches on, and critically analysed a few possible concepts?

Subsequently, a suitable concept with justifications is determined for the students final reporting and presentations in the last two wwks.

Author's activities

Observations have been conducted through the below activities as illustrated in Table 6.

- Being present at each tutorial group discussions supervised by the course coordinator and tutor from workweek (wwk) 3/tutorial 1 to workweek (wwk) 10/tutorial 8.
- Downloading the off-line data collections stored in the students' group google drives (permissions given by students) from workweek (wwk) 4/tutorial 2 to workweek (wwk) 12.

In each tutorial session, the observations involved the following:

- Recorded the main collaboration activities using notebooks, and
- Summarised into short pointers (MS-Word) as part of the data collections.
- Did not directly contributes to the discussions, but
- Did request for clarifications if unclear and did provide some minimal personal views.

2.4.3. Adopted design process, software and hardware tools

Design process was observed to consist the applications of iterative cycles from concepts generation to evaluations, and finally to concepts selections. Students need to have a minimum of two concepts generations stages in wwk3 and wwk7, be prepared for final group presentations in wwk11 and final group report submissions in wwk12. Each students group has at least one member who is able to use CAD to create conceptual diagrams for final reporting. Tools used were mainly MS-Word, MS-Excel, MS-PowerPoint, Email, Google drive, MATLAB and CATIA. These were running in non-CD mode though for example, MS-Excel has such a feature. For hardware, students were able to book the university desktop computers in any available computer laboratory or use their own laptops.

2.4.4. Off-line data collections

The students group setup their shared google drives in wwk3 and wwk4 to function as their primary data exchange and storage server environment, but each group have setup their design document folders structures differently though they may have similar design briefs. Off-line data have been collected from wwk4/tutorial2 to wwk12 by downloading the design documents from the assessable students group google drives each week.

Off-line data collections were analysed and consolidated into a chart as illustrated in Figure 6. The chart shows the trends for the numbers of design documents changes for three students' groups with similar design brief from wwk4 to wwk12. These data were further analysed regarding their collaborations levels, where data downloaded each week were analysed for its file folder names, filenames, file dates, and compared with the preceding week's downloads. The aims were to determine whether the documents were deleted, newly added files (new filenames), modified files (same filenames but different dates) or similar files (same filenames and dates) Examples:

- File1 added in wwk1 equal 1 change/increase in collaboration level (CL).
- File1 modified in wwk2 (file date change) equal 1 change/increase in CL.
- File1 deleted in wwk3 equal 1 change/increase in CL.
- File1 not changed in wwk4 (file date not changed) equal No change in CL.
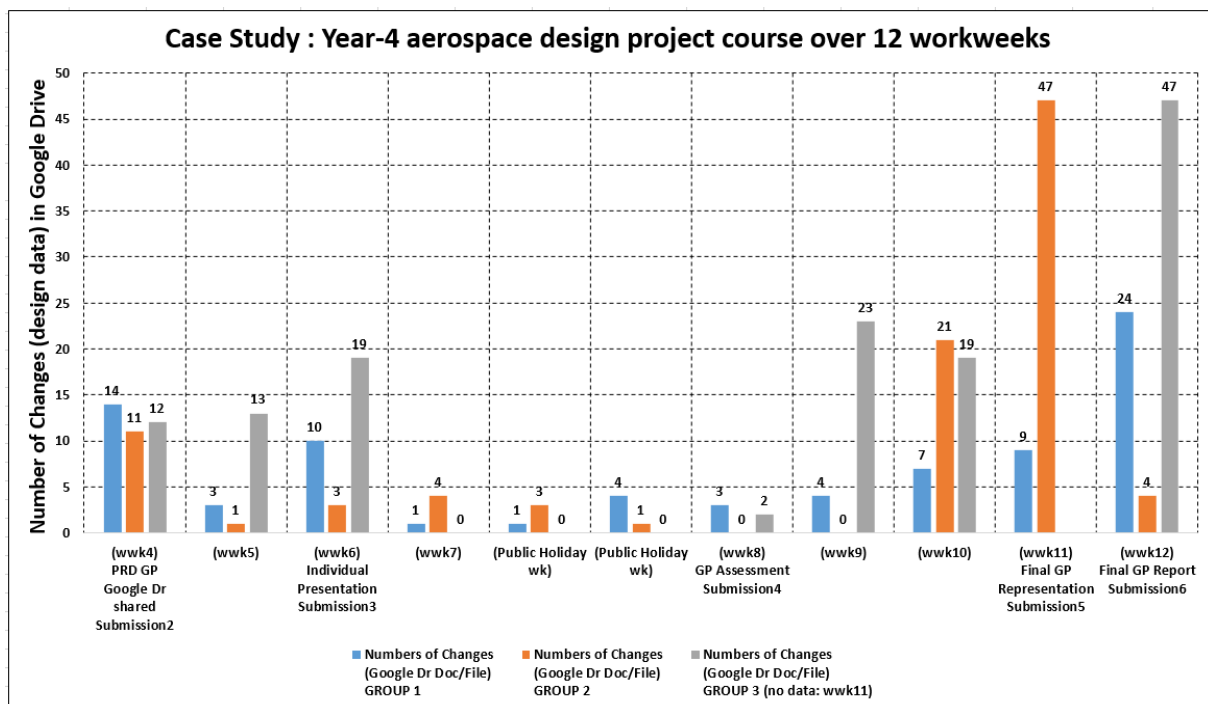
Figure 6, Number of Changes (vertical axis) in Google Drive 'data server' over Timeline.

Collaborations levels observed have shown that the offline google drive activities in Figure 6 has similar trend, with higher documents change levels near to the submissions periods for assignments and presentations 2, 3, 4, 5, 6). During wwk7, wwk8 and the two Public Holidays in between these two wwks, these collaborations levels have shown a downward trend. All three Groups activities levels also seem to synchronise with the curriculums timeline and not based on the needs to achieve the optimal numbers of iterative cycles.

2.4.5.   Student group tutorial sessions

Observations on student group tutorial sessions started from tutorial1 (wwk3) to tutorial 8 (wwk10, last tutorial). Each group discussions usually take place after tutorials. Some groups have arranged their follow-up discussions in the same lecture room after the tutorials, while others meet during the week, to consolidate individual works before next tutorials. Generally, the design workflows were non-concurrent as students usually do their own research.

In tutorial 1, 2 and 3, the course coordinator and tutor led each group at around 45min per group to determine their design status, encouraged them to select a team leader to manage the group activities, and proactively participate in the discussions. In tutorial 1, 2 and 3, individual member presents their own idea with the aid of notebook drawn by hand.

In tutorial 2 (wwk4), the course coordinator formed student groups with an average of 7 students per group having similar design theme. In tutorial 1 and 2, student groups were required to determine 10 product design requirements (PDR). In tutorial 3, 4 and 5, students were asked to determine the concept options, select one for presentation. The tutor and course coordinator provided feedbacks during the student presentations.

In tutorial 7 and 8 (wwk10, last tutorial), students were in the process of selecting and finalising one concept for final group presentation (wwk11) and final group report submission (wwk12). In wwk11, student final group presentation taken place. In wwk12, students submitted their final group reports to the course coordinator. Overall, the general interests and enthusiasms of the students were good.

2.4.6.   Analysis and discussions design group observations

The analysis and discussions of the preceding case study includes Collaboration level ('data storage server' activities levels), Collaboration level (team communications level), Tools (software and Hardware), Design facility, Design Process/ workflow/ iterative cycle and Project management and control. These were the essential elements observed in the capstone design course, which provided a 'window' into its design approach and effectiveness.

Design process chart in Figure 6 shows high collaboration levels in the data storage server and team communications occurring at the initial design cycle but this reduced mid cycle. The highest collaborations levels occurred near to the final stage of the design cycle.

This could be due to students aligning their design activities with the course curriculums (Submission 2 due: wwk4, submission 3 due: wwk6, final group presentation/ submission 5 due: wwk11, and final submission 6 due: wwk12) and not based on the actual design project requirements. In general, students tend to focus on their own project works, especially around the mid cycle, resulting in less than expected communication level between team members. Students may meet for discussions 2 to 3 times per week during the design timeline. This could be before and after each tutorial and maybe another two to three times during mid-week in the university study areas or laboratories.

Design activities are highest when near to the end of design timeline. From the engineering standpoint, there is not enough iterative cycles executed resulting in some missing options and considerations as highlighted in the preceding discussions.

Tools used included MS-Word (with EndNote), MS-Excel, Power Point, Email, Google Drive (shared), MATLAB and CATIA. These tools were running in non-CD mode though e.g. MS-Excel has such a feature. Students skills in 3D CAD modelling are also limited (learning mode), which were reflected in some student's final group reports. Some students also found themselves having to learn CAD instead of focusing on the design project. For hardware, students could book the typical personal computer (PC) 'standard hardware configurations' in the university laboratories or use their own laptops.

Design facility is an important aspect of the whole design process. Generally, there were at least 2 to 4 student group discussions amongst students before and after each lecture and tutorials, either in the computer laboratories, tutorial rooms or at the allocated study areas within the University. Real-time collaborations appeared to be minimum especially when there was no lecture or tutorial. Students usually do own research works when not discussing in groups. Therefore, the students worked in a combination of centralised and de-centralised (mainly) design environment.

The design project adopted an iterative cycle approach, but bended towards the sequential or 'over-the-wall' workflows. Design activities levels were higher when getting near to each task's assignment submissions periods with highest levels near to the final group presentation and report submission period. The overall design workflows were more aligned with course curriculums and do not allow sufficient iterative cycles.

Project management (PM) and control were generally present though not as tight. This was likely due to the student team leader lacking in PM hands-on experience in leading, motivating the team members, and time managements on the group.

Student group sizes seem to vary between institutions. Some believe it is ideal to have between 3 to 6 students in a group tutorial (mainly general curriculums), another (aerospace design project) have between 6 to 7 students [28, 57]. Yet, other (aerospace design project) may have a team of 4 students [29]. In tutorial sessions 1 to 6, there was an average of seven students, which are like other institutions.

2.4.7. Lessons learned from case study results

The CS has shown the 'waterfall' and 'over-the-wall' approaches resulting in reduced iterative cycles and lower project completeness. However, the presence of these findings have to also be looked at in the context, that a typical aircraft design project takes about 5 years or more and will involve engineers, scientists and managers from a wide range of disciplines [56].

Universities should help the industries by aligning its curriculums closer to the CDF attributes (benefits) described in this thesis despite constraints in the curriculums timelines and costs. This is in-line with many case studies that have demonstrated savings in time and cost compared to traditional processes for systems design, and aerospace engineering education should adopt CDF for design teaching and research [48].

The CS has also shown a general lack in concurrent enabled software tools used, CAD skills and project management hands-on skills from students. This could have further contributed to lower project completeness. Universities should consider adopting the CDF platform, along with CD enabled software platforms and with more focus on project management (PM) hands-on skills as pre-requisites in order to realise the full potential of CDF implementation.

This work has also developed a Year-3 aerospace conceptual design project tool (closely referencing a typical Year-3 aircraft design course structure) aims at enhancing the design teaching so that Year-3 students could have better appreciation and improve their preparedness for their Year-4 aircraft design curriculums.

PM is a crucial component of effective Project-Based Learning (PBL), which offers a wealth of opportunities to build the essential 21st Century competencies, which enhance the PM skills that will be extremely valuable to students as they enter the workforce [58]. David Woerner, chief engineer, NASA pointed out that; there are difference in PM process in the 1990s and today. In the 1990s, (Mars Pathfinder (launched in 1996): risk was not really an area of focus, where one person on Pathfinder working on risk, and did have a short list of risks that were transformed into requests for funds. Today, risk analyses are done in a meticulous approach (e.g. every subsystem (Mars Science Laboratory, launched in 2011)) and every engineer had baskets of risk. These information are consolidated at project level, and the team could see how project risk evolved over time [59]. Therefore, it will likely be a challenge for students to enrol in the Year-4 design course without more focus in PM.

2.5. University of Bristol (UB), United Kingdom

In the U.K., it is common for universities to offers 3 years undergraduate (BEng) and 4 years undergraduate (MEng) study, such as the University of Sheffield and the University of Bristol.

The University of Bristol offers 2 undergraduate study, the 3 years BEng Aerospace Engineering (H405) and the 4 years integrated Masters (MEng) Aerospace Engineering (H410) [53]. The BEng study does not have research or capstone design project and is course works based.

The first 2 years of the MEng course follows the same structure as the BEng in Aerospace Engineering. The curriculums focus on teaching students the solid understanding of engineering studies such as Mathematics, and Mechanics etc.

In Year-3 and -4, greater flexibility is available for the students to pursue options that interest them. A typical 4-year undergraduate (MEng) aerospace engineering program such as the one at UB is shown in Table 7. The Year-4 Group Design Project involves capstone activity, where the students will exercise and consolidate their design, aeronautical engineering and management skills in the context of a complete aerospace vehicle design study. Project Management learning is embedded within the course.

Table 7, University of Bristol, undergraduate study: 4 Years Integrated Master in Aerospace [53].

University of Bristol, undergraduate study: 4 Years Integrated Master in Aerospace			
Year-1	Year-2	Year-3	Year-4
Fluids 1	Aerodynamics	Aerodynamics 3	AVDASI 4 – Group Design Project (capstone/team collaboration)
Thermodynamics 1	Structures and Materials 2	Aircraft Propulsion	Final Year Research Project (PM skills)
Structures and Materials 1	Flight Dynamics & Control 2	AVDASI 3	
Aeronautics and Mechanics	Vibrations 2	Structures and Materials 3	
Design and Computing	Aerospace Vehicle Design and Systems Integration 2	Individual Exploratory Project	
Application of Electronics	Space Systems	Sensors, Signals and Control	
Engineering Mathematics 1	Engineering Mathematics 2	Professional Studies B – Professional Awareness	
AVDASI 1 – Aerospace Vehicle Systems Introduction	Professional Engineering		
1 course (Optional)		2 courses (Optional)	5 courses (Optional)

The aerospace design program that is offered by the University of Bristol (UB) does not have a CDF-based course, nor an Industrial Placement Program in curriculum. However, UB has started to collaborate with external agency, namely, the CDF at the Science and Technology Facilities Council's (STFC) RAL Space in 2017 to design UB's first CubeSat. UB student reported that working on a real-life mission is very motivating for them and it's a unique opportunity [53].

2.6. Spanish User Support and Operations Centre – Technical University of Madrid collaborations (with CDF)

The space education program (since academic year 2009/10) at the Technical University of Madrid (UPM), which is also known as Polytechnic University of Mardrid, is a good example to illustrate the benefits of industry-university collaboration. This was in collaboration with the Spanish User Support and Operations Centre (E-USOC), the centre assigned by ESA to support

the International Space Station operations of scientific experiments [28]. E-USOC is located at UPM technology campus in Madrid and is a centre of Polytechnic University of Madrid (UPM) [60].

These activities have been integrated within the last semester of the UPM Aerospace Engineering degree, which included a laboratory created for students to validate and integrate the subsystems of a microsatellite using demonstrator satellites [28]. In parallel, students were also involved in a Project Based Learning (PBL) to work in groups of (6 – 7) to develop the conceptual design of a space mission. One student in each group is given the role and responsible for the design of one of the satellite subsystems (SS) such as the project manager, mission design engineer, mechanical engineer (SS), electrical engineer (SS), propulsion engineer (SS), orbit and attitude control engineer (SS) and payloads engineer (SS).

The incorporation of PBL allows students to do a similar works as in different companies and space agencies. This is where multi-disciplinary experts work together for a limited time to develop a feasible space mission.

The results of the student surveys and lecturers' perceptions show that PBL encourages student motivation and improves their results. They acquired better technical training and improved transversal skills. However, this methodology also requires more lecturer involvement than the traditional methods [28].

Final-year degree students, led by lecturers and E-USOC staff, developed the project topic and schedules, which was very challenging, because such projects require high student's participations, but their program schedule is not always compatible with the project schedule and milestones. Only very high motivation and commitment with the project make it possible [28].

Since the IDR/UPM Institute (Instituto Universitario de Microgravedad 'Ignacio da Riva') established a CDF for space mission design in 2011, the CDF has been mainly used for academic purposes within the:

- UPM Master in Space Systems, MUSE (Master Universitario en Sistemas Espaciales) incorporating PBL [55, 61].
- This was besides the PBL related surveys activities in academic years 2012/2013 and 2013/2014 [28].

First year MUSE students cooperate with their more experiences second year students to enable comprehensive and resource-effective use of the CDF. MUSE student surveys results show that students [55]:

- Have a positive point of view about the CD concept.
- Suggest that more activities would be beneficial for the learning.
- Think that their skills have been improved due to CDF activities, where progress has been higher for Year-1 students.
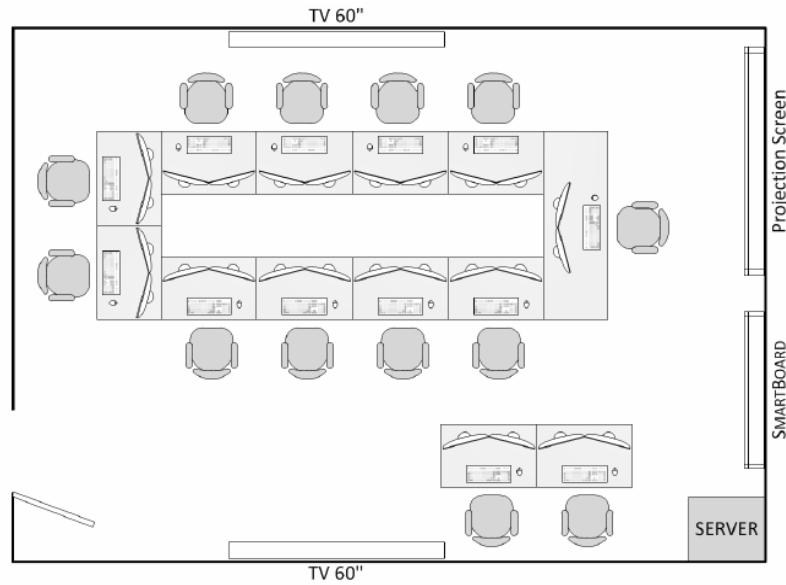
Figure 7, IDR/UPM CDF layout established since 2011 [61].

The layout of IDR/UPM CDF is illustrated in Figure 7 [61]. This CDF is based on a smaller scale ESA/ESTEC CDF approach, with 13 workstations in a round table distribution, audio-visual distribution system and videoconference system.

2.7. European Space Agency - International Space University collaborations (with CDF)

Another good example is the ESA – ISU collaboration. The ISU CDF shown in Figure 8 was donated by ESA research centre ESTEC after 10 years of operations, with wide portfolio of future missions studied and several concept designs analysed. A new and more advanced CDF installation was established at ESA [32].

Figure 8, Panoramic view of the ISU CDF (courtesy of Remy Chalex, ESA) [32].

The ISU offers two graduate degrees:

- Master of Science (MSc.) in Space Studies (MSS)
- Master of Science (MSc.) in Space Management (MSM)

Both courses include CE-based activities in each of these degrees, run for a full academic year and divides into five separate modules as shown in Figure 9. Module 1 (7 weeks) core

curriculums is common to both programs Module 2 (9 weeks) and Module 3 (9 weeks) covers a specialised curriculum for each program separately. Module 4 (8 weeks) includes team projects by students from both programs. Module 5 (12 weeks + 1 week presentations) includes internship and an individual project.
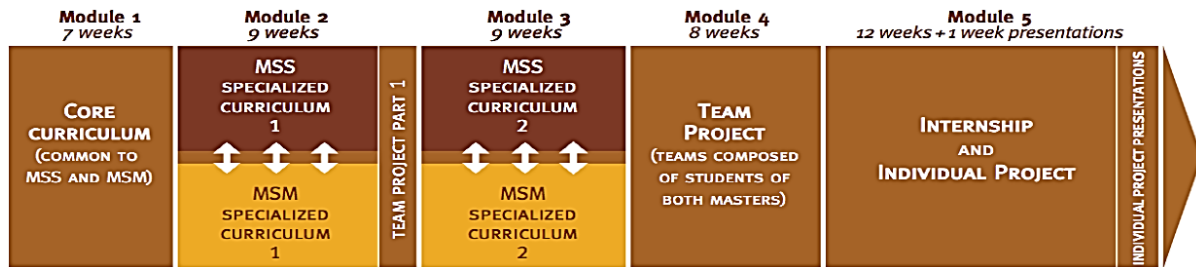
Figure 9, ISU Master of Science Course Structure [32].

The ISU CE approach follows the one defined by ESA, which states that for the successful and effective application of CE, the five key elements must be present as reviewed in Sub-Chapter 1.3 [6, 32].

For the preliminary design, ISU CDF has adopted 10 mission study domains such as the System, Attitude Determination and Control, Power, Structures, Communications, Propulsion, Thermal, Payload, Mission and Cost. Although these are not enough to complete and accurately model a spacecraft, this breakdown structure is acceptable for design teaching purposes. The ISU CDF Integrated Design Environment (IDE), which is based on the architecture employed at ESA is given in Figure 10 [6]. This IDE has been fully implemented in Spreadsheet/Workbook, which was also based on the internal Spreadsheet/Workbook functions and Visual Basic macros.

ISU Master of Space Studies (MSS) students' assignments involved generating different mission architectures and design options from a set of requirements. ISU Faculty plays the role of customer. Assignments for the ISU MSS 2009 and MSS 2010 classes results have been very encouraging, based on students' feedback and overall quality of the work by them produced [32].
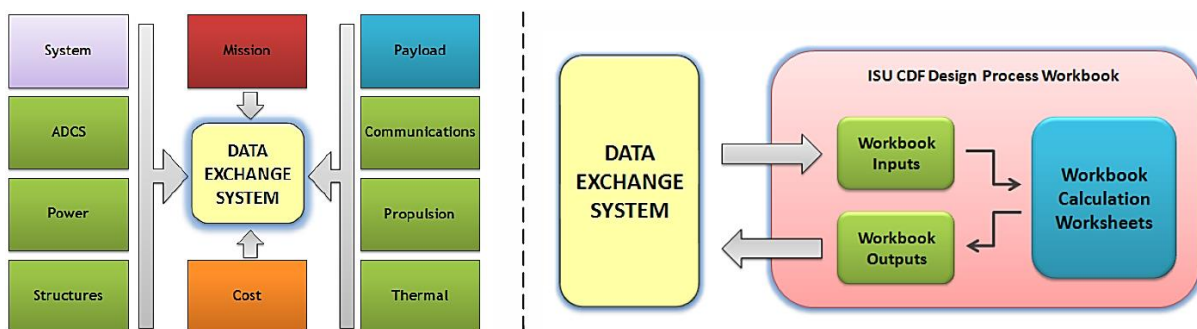
Figure 10, ISU CDF Integrated Design Environment (left.). Design Process Workbook structure (right) [32].

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2.8. Utah State University (USU) (with CDF)

Utah State University (U.S.A.) offers a Bachelor of Science in Mechanical Engineering with Aerospace Emphasis Program.
In the Space System Design Course, students work in teams to perform a space system design involving all aspects, including technical, cost, and schedule. It is conducted in the USU Concurrent Engineering Facility (CEF), known as the Space systems Analysis Laboratory (SSAL) [4].

Table 8, Bachelor Science, Mechanical Engineering: Aerospace Emphasis Program [47]

Year-1: Pre-Professional Program (* : require for admission to the Professional Engineering Program)					
Fall Semester	**Credits**	**Notes**	**Spring Semester**	**Credits**	**Notes**
CHEM 1210: Principles of Chemistry 1*	4		MAE 1200: Engineering Graphics*	2	
CHEM 1215: Chemical Principles Lab 1*	1		MATH 1220: Calculus 2 (QL)*	4	
MATH 1210: Calculus 1 (QL)*	4		PHYS 2210: Physics for Scientists & Engineers 1 (BPS/QI)*	4	
MAE 1010: Intro to Mechanical Engineering*	3		PHYS 2215: Physics for Scientists & Engineers Lab 1*	1	
Breadth American Institutions (BAI)	3	Pick course	Breadth Creative Arts (BCA)	3	Pick course
Year-2: Pre-Professional Program (* : require for admission to the Professional Engineering Program)					
ENGL 2010: Intermediate Writing: Research Writing in a Persuasive Mode (CL2) *	3		MAE 2160: Material Science *	3	
ENGR 2010: Engineering Mechanics Statics *	3		MAE 2165: Material Science Laboratory *	1	
ENGR 2210: Fundamental Electronics for Engineers *	3		MAE 2300: Thermodynamics I *	3	
MATH 2210: Multivariable Calculus (QI) *	3		MATH 2250: Linear Algebra and Differential Equations (QI) *	4	
PHYS 2220: Physics for Scientists and Engineers II (BPS/QI) *	4		ENGR 2030: Engineering Mechanics Dynamics *	3	
PHYS 2225: Physics for Scientists and Engineers Lab II *	1		ENGR 2140: Mechanics of Materials *	3	
Year-3: Professional Engineering Program					
CS 1400: Introduction to Computer Science--CS 1	4		MAE 3210: Engineering Numerical Methods	3	
MAE 3600: Engineering Professionalism and Ethics	1		MAE 3340: Instrumentation and Measurements	3	
ENGR 3080: Technical Communication for Engineers (CI)	3		MAE 3440: Heat Transfer (QI)	3	
MAE 3040: Mechanics of Solids	3		MAE 4300: Machine Design	3	
MAE 5360: Advanced Dynamics	3		Breadth Life Sciences (BLS	3	Pick course
MAE 3420: Fluid Mechanics	3				
Year-4: Professional Engineering Program					
MAE 4400: Fluids/Thermal Laboratory (CI)	2		**MAE 4810: capstone Design II**	3	
MAE 4800: capstone Design I (CI) (Team Work)	3		*Mechanical Engineering Technical Electives- Aerospace*	*3*	*ECE 5230 - Spacecraft Systems Engineering*
MAE 5500: Aerodynamics OR MAE 5560: Dynamics of Space Flight	3		Mechanical Engineering Technical Electives- Aerospace	3	Pick course
Mechanical Engineering Technical Electives- Aerospace	3		Depth Humanities and Creative Arts (DHA)	3	Pick course
Breadth Humanities (BHU)	3	Pick course	Depth Social Sciences (DSS)	3	Pick course
Breadth Social Sciences (BSS)	3	Pick course			

This course is mainly for teaching students on end-to-end design of a space system, including students performing their work in a CE setting. The use of CEF for teaching is beneficial as space systems design courses are taught in a more practical and real-world

applicable manner. Students also benefited in terms of better understanding of the complexity of modern aerospace systems and innovative approaches necessary to optimise these systems [62].

USU Concurrent Engineering Facility has adopted similar approach to NASA Jet Propulsion Laboratory (JPL), Godard Space Flight Centre and The Aerospace Corporation. USU reported that their Concurrent Engineering Facility is suited for teaching a space systems design, with nine PCs networked together with file sharing server. Each PC is installed with tools for space systems design. The PCs are laid out in a U-configuration to allow easy interaction among team members as shown in Figure 11 [4]. An LCD projector in front of the room can display content from any PC as shown.

This undergraduate program consists of 4 years. Year-1 and -2 are known as the pre-professional program and Year-3 and -4 are known as the professional engineering program. In Year-4, there are 2 capstone courses as shown in Table 8 [47].
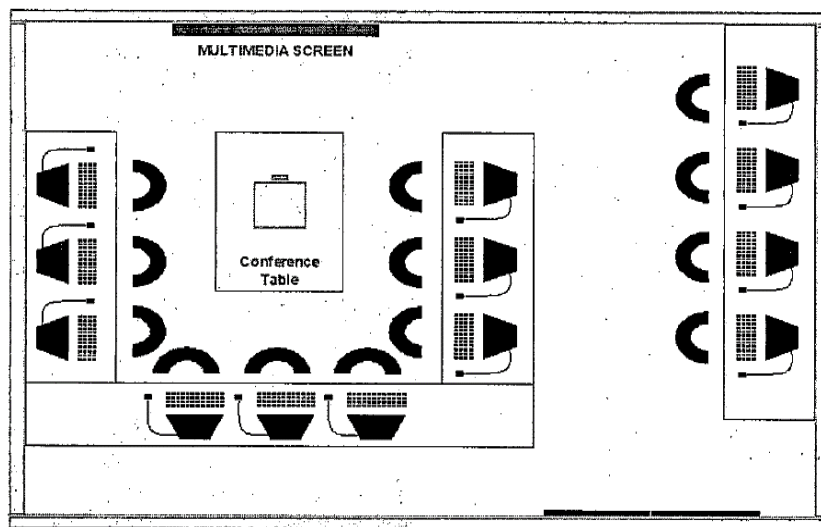
Figure 11, USU SSAL CEF layout [4].

2.9. Lessons learned from (E-USOC)-UPM, ESA-ISU collaboration, and USU

In comparison to UPM and ISU, the ESA/ESTEC CDF uses more domain disciplines for their full-scale mission studies [6]. However, all three CDFs have adopted the six common domains disciplines: Mission, Power, Propulsion, Payload, Communication and Thermal.

UPM has adopted the ESA CDF approach, and integrated CD and PBL in their conceptual space mission design course, led by UPM lecturers and (industry) E-USOC staff. UPM challenges are that, the students attending other courses are not always compatible with the project schedule and its fixed milestones. Since the PBL/CDF related surveys activities in academic years 2012/2013 and 2013/2014 for UPM aerospace engineering degree course, the UPM CDF has been mainly used for academic purposes within the UPM Master in Space Systems (MUSE) incorporating PBL [28, 55, 61].

ISU has adopted the ESA approach (ISU CDF donated by ESA) in their MSc. design course, with internship and individual project in the final module of the course. USU has incorporated capstone courses and CDF based training in their under-graduate and graduate program. All three universities have reported positive results from the CDF based training [4, 28, 32].

2.10. Summary comparisons of employability themes and aerospace design teaching (without and with CDF)

Table 9 provides the summary comparisons of the employability themes identified by the 2015 report with the referenced aerospace design teaching methodologies (without and with CDF) [22]. The comparison shows that current curriculums (without and with CDF) reviewed meet most of the identified employability themes except industrial 'business acumen' and 'experience'. The main difference between curriculums without and with CDF is listed in the last 3 rows (highlighted in grey) of Table 9. The curriculums with CDF incorporate the CDF facility and CD workflows in designs training, but not available to curriculums without CDF.

Table 10 provides a comparison of the referenced aerospace design programs, which is also based on some similar sub-categories (denoted by #), from Table 1, as follows:

- Current programs as referenced that incorporate or do not incorporate a CDF.
- A proposed curriculum: CDF integrated with pre-requisites and industry collaboration (subsequent research works). (*) denotes assessments given in this thesis.

Literature reviews of the 7 universities (UNSW (Sydney), UQ, RMIT, UB, UPM, ISU and USU), including the case study results have shown that there should be more focus in the sub-categories as listed in Table 10 [28, 32, 47, 49-51, 53]. This includes project management, pre-CDF multi-disciplinary education (e.g. via IACDT incorporating MDO), CAD, CAE, computational engineering simulations, joint industrial-university design theme creations, more focus on industrial attachments and individual final project reporting.

Table 9, Comparison of employability themes and aerospace design teaching (without and with CDF) [22]. Category, Sub-category and Engineering disciplines listings were taken from Table 1,

Category	Sub-category	Engineering disciplines	UNSW [49], UQ [50], RMIT [51], UB [53]. Design teaching curriculums (without CDF)	UPM [28], ISU [32], USU [4]. Design teaching curriculums (with CDF)
Career development learning	Business acumen	X,O	No	No
	Career planning	X,O	Yes	Yes
	Knowledge of industry and job market	X,O	Yes	Yes
	Networking	X,O	Yes	Yes
	Passions and interests	X,O	Yes	Yes
	Professionalism	O	Yes	Yes
	Recruitment processes preparation	X,O	Yes	Yes
Experience		X,O	No	No
Degree subject knowledge, understanding and skills		X,O	Yes	Yes
Generic skills	Adaptability	X	Yes	Yes
	Communication	X,O	Yes	Yes
	Critical thinking	O	Yes	Yes
	Entrepreneurship	X	No	No
	Ethics	X,O	Yes	Yes
	Innovation and creativity	O	Yes	Yes
	Leadership	X	Yes	Yes
	Lifelong learning	X,O	Yes	Yes
	Numeracy		Yes	Yes
	Problem solving	X	Yes	Yes
	Teamwork	X,O	Yes	Yes
	Time management	X	Yes	Yes
	Work ethic	X,O	Yes	Yes
	Working under pressure	O	Yes	Yes
Emotional intelligence	Self-awareness	X,O	Yes	Yes
	Self-management	X,O	Yes	Yes
	Awareness of others	X	Yes (PBL)	Yes (CDF, PBL)
	Managing others	X,O	Yes (PBL)	Yes (CDF, PBL)
	Motivation	X,O	Yes (PBL)	Yes (CDF, PBL)

Table 10, Comparison of Design teaching methodology (with and without CDF), and CDF integrated with pre-requisites and industry collaborations.

Category	Sub-category (# = sub-categories similar to Table 1)	Design teaching curriculums (without CDF) UNSW [49], UQ [50], RMIT [51], UB [53].	Design teaching curriculums (with CDF) UPM [28], ISU [32], USU [4].	CDF integrated with pre-requisites and industry collaboration (*) denotes assessment in this thesis
Specialised skills	**Project Management (with more focus)** *(# Leadership, Communication, Awareness of others, Managing others, Motivation, Teamwork, Time management)*	PM: Yes (PBL), but need more focus	PM: Yes (CDF, PBL), but need more focus	PM: Yes (CDF, PBL)
	Year-3 Aerospace (Aircraft) Design formal course, with pre-CDF multi-disciplinary education (MDE via IACDT tool)	Yes, but also need pre-CDF MDE	Yes, but also need pre-CDF MDE	Yes
	Project Based Learning (PBL), capstone project and group report	Yes	Yes	Yes
	CAD, CAE formal short course	Yes	Yes	Yes
	Computational engineering simulation tools formal short course	No	No	Yes *
	Multi-disciplinary Optimisation formal short course	No	No	Yes *
	Concurrent Design Facility environment formal short course	No	No	Yes *
	Year-4 design themes from joint industrial-university collaborations	No	Yes	Yes
	More focus on industrial attachment and individual report *(# Work experience, Adaptability, Networking, Professionalism)*	Yes, but need more focus	Yes	Yes

3. Development of a collaborative teaching tool to enhance multi-disciplinary design education

This chapter introduced an original novel collaborative teaching tool to enhance multi-disciplinary education prior to students enrolling in the capstone design course.

The original novelty elements come from the development of the Real-Time Integration of spreadsheets/workbook (acting as MDO) and CAD 3D model, and closely referencing the typical Year-3 aircraft design course structure. This integration allows any change in any of the sub-system to propagate in real-time to all others relevant sub-systems and the dynamically linked 3D aircraft model.

Learning to use this tool is aimed at enhancing the Year-3 aircraft design course with CE workflows. Therefore, this tool functioned as a pre-requisite to prepare students for enrolment in CDF-based capstone design project. Subsequently, students enrolling in the future CDF-based (capstone/PBL) design project will be able to focus more on the design projects, instead of spending their times during the project design to learn the CD attributes and workflows.

This tool has also provided answers to research question 3 in later work (Chapter 5) on one of the essential requirement (ER 12) established in Sub-chapter 4.1.1, Table 11.

This collaborative teaching tool is called the 'Initial Aircraft Conceptual Design Tool' (IACDT). It is dynamically linked to CAD for real-time geometry updates of the 3D model. IACDT development involved closely referencing a typical Year-3 aircraft design course structure. The 'collaborative' element comes from the spreadsheet/workbook built-in 'sharing' function, which allows the same spreadsheet/s/workbook to be opened by multiple users to view, edit and save their entries simultaneously. Therefore, a team of 10 students can use this tool concurrently to change their individual sub-system spreadsheet, and review the corresponding change/s to other sub-system spreadsheet within the same workbook for a system wide perspective, which is useful in trade-off studies.

The limitation of this collaborative tool is that, it is 'hardwired' only to the FAR 23 general aviation 2-seaters propeller aircraft. Future enhancement may include FAR 25 commercial aircraft, and the removal of the current limitations. The Chapter Structure is:

Figure 12 illustrates the structure of this chapter with the five sub-chapters as follows:

- Objective of IACDT
- Benefits of the IACDT
- A typical university aerospace design principle curriculum
- Closely referencing a typical Year-3 aircraft design course structure.
- Operations of the IACDT: Detail operations (equations/workflows) are in Appendix C.

The detail operations for the following sub-components are described in Appendix C:

- IACDT design process demonstration/ colour codes, aircraft mission requirements (spreadsheet (TAB1)),
- Weight estimation (spreadsheet (TAB2))
- Matching chart (spreadsheet (TAB3))

Aircraft Configurations:

- Fuselage (spreadsheet (TAB4))
- Propulsion (spreadsheet (TAB5))
- Wing (spreadsheet (TAB6))

- Tail (spreadsheet (TAB7))
- Weight and balance (spreadsheet (TAB8))
- Drag polar (spreadsheet (TAB9))
- Preliminary 3 view of the aircraft concept (3D solid model).
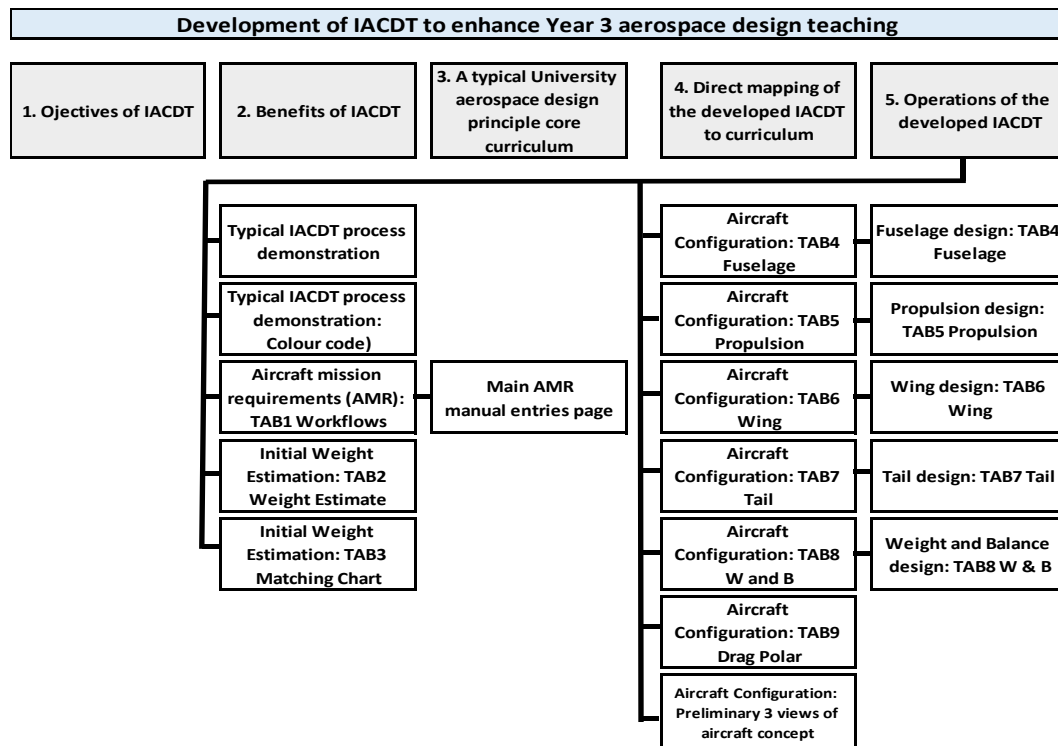
Figure 12, Sub-chapter structure of IACDT development.

3.1. Objective of IACDT tool

The objective of IACDT is to enhance aircraft design teachings by including an iterative CD environment. This tool demonstrates the iterative design workflows for sizing of an aircraft design concept with focus on CD, which include:

- Concept evaluation, weight estimation, sizing, configuration and optimisations.
- IACDT development references [6, 63-66], real-time automatic linking computation results between the relevant sub-system components.
- Adopt an approach similar to ESA CDF status reporting by using workbooks to consolidate all domain model data [6]. This workbook is also a multi-disciplinary optimisation (MDO) platform. Computational results are automatically and dynamically linked to the CAD 3D model (aircraft concept).
- The IACDT Concurrent Design (multiple access) functions come from the followings:
  - o Setup the linking (cells/equations) between all relevant sub-system spreadsheets in the same workbook.
  - o Activating the 'shared' function built into Excel allows all spreadsheets in the same workbook to be opened and shared by multiple students at the same time (real-time).
  - o Multiple students can review and edit concurrently on their individually assigned sub-system spreadsheet (i.e. assigned role). This provides a system wide perspective to multiple students at the same time.

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Limitation:
Multi-disciplinary optimisation function is still sequential, where each iteration of optimisation is performed through each parameter change within any of the sub-system.

The lecturer conducts the course on a large screen and in parallel using this tool to demonstrate in real-time how the initial aircraft design process can be sped up. Students will be better equipped to complete their assignments by following the workflow of the tool. Students will also be able to understand the links between the CD benefits and their learning in initial weight sizing, matching chart to aircraft configuration and optimisation. The real-time and semi-automated changes (the tool) in various aspects of the initial sizing and configurations, including automatically and dynamically updating of the CAD 3D model via the framework of this tool, will allow students to understand the iterative system wide perspective better and appreciate the benefits of CD that could help in their capstone design projects.

3.2. Benefits of IACDT tool

IACDT development involves interfacing between spreadsheets/workbooks and CAD, which provides benefits over the full feature professional tools as follows:

- IACDT closely referenced a typical Year-3 aircraft design course structure allowing students to focus visually on the lectures and tutorials instead of spending extra times to learn new professional full-features complex tool/s. This included the IACDT workflows and equations auto calculations and linkages between sub-system components.
- The disadvantages of professional tools are that, students will require extra times to evaluate the entire tool options and understand the tools to some reasonable extend before they could filter out only the features relevant to their project. This could side track students and delay their assignments completion. If students are to explore professional tool/s, they will still need to figure out their own unique workflows/ approach to their assignments from the beginning.
- IACDT adopts a similar approach to the ESA CDF status reporting. This approach uses a workbook to consolidate all the domain model data to calculate and produce the results instantly for further analysis and progress reporting [6]. This allows students to acquire the CD knowledge (via demonstrations during lectures), which includes the team members and leader's collaboration process.
- Real-time 3D model automatic updating (interfaced between IACDT and CAD) allows students to review visually the 3D model changes to certain aircraft components parameters (e.g. Initial take-off gross weight (converged – from weight sizing). Students will learn and appreciate the benefits of such CD integration (system wide perspective), make them aware of any error in their IACDT formulas/ equations, and enables students to submit more accurate assignments.

3.3. Typical aerospace design core curriculum

The Year-3 aerospace/aircraft design course in a typical 4-year (BEng) aerospace engineering (Hon) program spreads over 12 weeks of lectures, tutorials and assignments and teaches sizing of an aircraft design concept [51]. This includes weight estimation, sizing, configuration, and optimisation. Project management elements are covered, as part of developing a plan for an aerospace project, which includes professional ethics and communication skills.

3.4. IACDT closely referenced a typical Year-3 aircraft design course structure

IACDT development involves closely referencing a typical Year-3 aircraft design course structure, e.g. aircraft initial weight estimation and aircraft configuration sizing, etc. Students are taught how to step through the first conceptual design phase, focusing on the preliminary sizing (weight estimation and matching chart) and configuration design (fuselage, propulsion, wing, tail, weight and balance, and drag polar). From the configuration freeze phase onwards to detail design, fabrication and support phases making up the complete aircraft design cycle are not included in the IACDT workflows.

The IACDT workflows consist of three main components as shown in Figure 13, namely, the aircraft mission requirements, conceptual design phase: Preliminary Sizing (weight estimation and matching chart) and Preliminary Configuration (fuselage, propulsion, wing, tail, weight and balance, and drag polar).

Since the objective is mainly to demonstrate the user-friendliness and benefits of CDF environment (as a teaching tool), this version of the tool is deemed sufficient with the limitation to a single engine, 1 pilot, 1 PAX, FAR 23 only, and variation in mission requirements as given in the tool. Future works will expand this tool into the FAR 25 commercial aircraft category, and not limited to 2-seaters propeller aircraft.
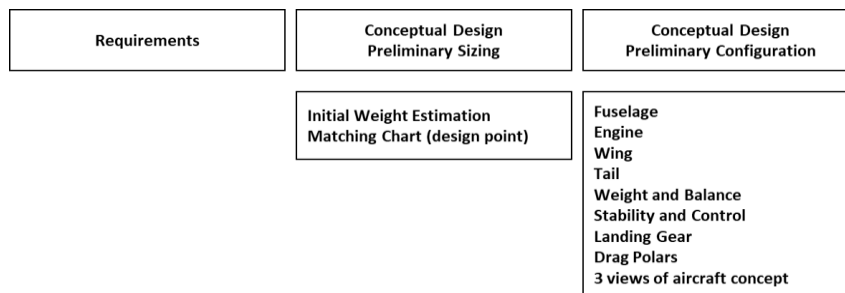
Figure 13, Aircraft Conceptual Design Phases adopted by IACDT.

3.5. IACDT tool operations

The IACDT main workbook consists of a number of spreadsheet (TAPs). Each spreadsheet is assigned from (TAB1: manual entries of mission requirement, summary of design workflows and summary of calculated overall design results) to (TAB2 to TAB9: for various aircraft components) as illustrated in Figure 14. The detail IACDT operations (with equations and workflows) are given in Appendix C, and the main source of references are as follows:

- Raymer 1992: Aircraft design: a conceptual approach [67].
- Roskam 1997: Airplane aerodynamics and performance [68].
- Sadraey 2013: Aircraft Design: A Systems Engineering Approach [69].
- Snorri Gudmundsson, 2013: General Aviation Aircraft Design: Applied Methods and Procedures [64].

Each IACDT worksheet in Figure 14 is layout to closely match the workflows of the core curriculums (e.g. lecture notes/slides and tutorial slides for assignments) to allow students to visually relate better between what they learned and how they could translate the knowledge into completed assignments.
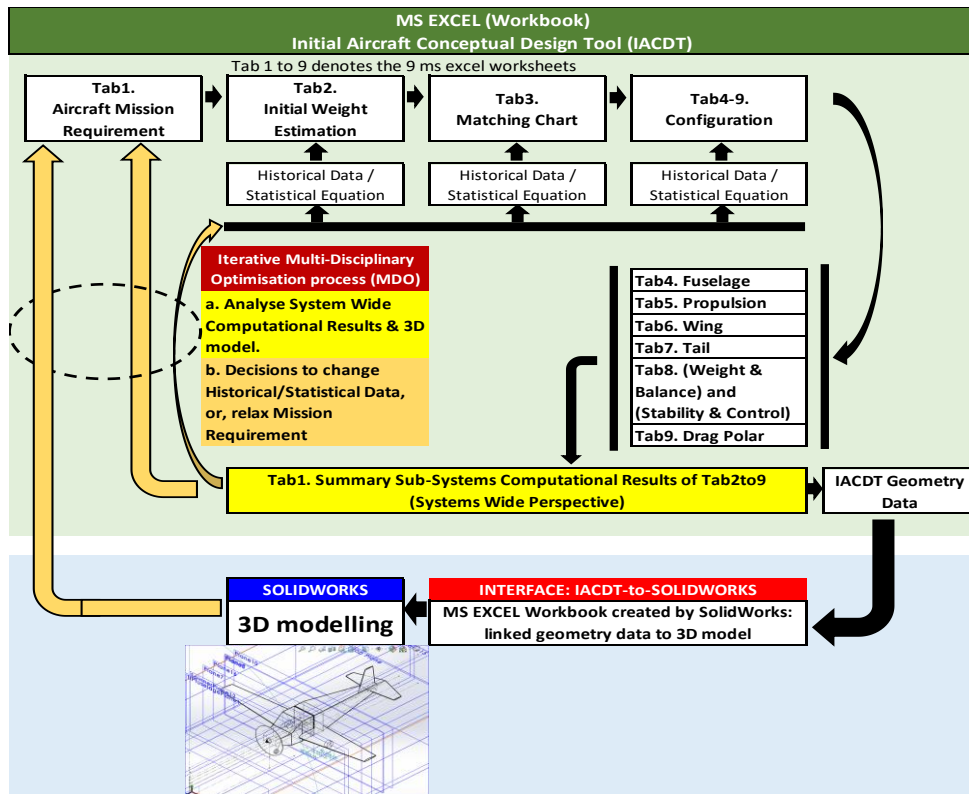
Figure 14, IACDT Workflow Structure from 9 * TABs: system (worksheet).

The IACDT workflows begin with manual entry of the aircraft mission requirements in spreadsheet (TAB1), including various constraints and historical data/ statistical equations in Tab 2 – 9. Subsequently, both initial weight estimation (Tab 2: Initial Take-off Gross Weight, Empty Weight, Fuel Weight, and assumed Coefficient: CLmaxclean, CLmaxTO and CLmaxL)) and Matching Chart (Tab 3: Power Loading (W/hp: lbs/hp) vs. Wing Loading (W/S: $lbs/_{ft.^2}$), S and hp (propeller aircraft)) will be computed. Design point/s may be selected manually from the Matching Chart, which is updated automatically when any relevant parameter value changes (Tab 3).

With the design point selected, the other configuration computation results (Tab 4 – 9), could be reviewed and the relevant parameters could be fine-tuned (an iterative process). These include fuselage, propulsion, wing, tail, weight and balance, and stability and control, and drag polar. The relevant geometries linked with the CAD model will also be changed when the relevant parameter/s change. This is an iterative process, where the change continues until the spreadsheet results and CAD model is perceived as optimised by the team. The results can be re-computed automatically upon modifications. This iterative process will continue until all relevant disciplines converge.

The CD elements come from the combination of linking between all relevant sub-system spreadsheets and the collaborative 'shared' function built into the spreadsheet. Therefore, multiple students can review and edit concurrently. This provides a system wide perspective to multiple students at the same time.

Limitation:

The IACDT tool optimisation function is performed at every change in at least one-parameter value in any of the sub-system spreadsheet. However, it is still not a full-featured commercial grade automatic optimisation tool.

4. Investigate a low-cost CDF architecture for education and research

This chapter investigate a low-cost CDF architecture for education and research, which includes:

- Integration of a CDF in design curriculums with project-based learning, including remote collaboration with industry and other universities.
- Simulations of a proposed CDF architecture based on a case study and using standard hardware and software.
- Recommendations of IT hardware and software architecture (CDF) for teaching and research in engineering design in a university environment.
- Minimum support facilities for CDF room (physical room layout).

4.1. Integration of a CDF in design curriculums with project-based learning, including remote collaboration with industries and universities

This thesis focuses directly on the specific described gaps that appeared to have little attention from the literature reviews. The final CDF setup for education and research will mainly be based on the evaluations of existing industry CDF setup components, the existing typical undergraduate aerospace curriculums, and taking advantages of the current low-cost advances in IT technology.

4.1.1. Essential requirements of a CDF for education and research

The objective to establish a CDF for education and research is to meet the needs of the relevant industries. Therefore, a set of rationale and its essential requirements that are relevant to these industries must be established as given in Table 11.

Table 11, The rationales and its respective essential requirements of a CDF for education and research

No.	Rationales	No.	Essential requirements (ER)
1	It is important to expect industry to employ graduates with relevant skills. This is also to minimise the effects of mismatch between employer requirements and university graduate capabilities in some industry-specific professional skills [20, 21].	ER1	The architecture must emulate industry design practices to expose the students to concurrent design workflows, skills and collaborations, which are critical to industry setting.
2	Although a CDF in industry and university has common elements such as a multi-disciplinary design team, where the team work together in the same room, both do have different priorities. Industry is more focus in deliverable commercial project design, but university is more focus in teaching students how to apply CD methodology [28]. Therefore, it is reasonable for this thesis to recommend a smaller size design team to be administratively more manageable at university level. In this light, the team size can be expanded when the needs arise.	ER2	The architecture should include sufficient specific domain disciplines PCs to accommodate an average size design team.
3	It is important to teach students not only to work together in the same room, but also learn to interact with others of different cultures and like-minded students who are in other countries.	ER3	The CDF should be capable of offsite contents sharing to enable concurrent collaborations between universities, industries and agencies, such as multi-disciplinary design projects and competitions.
4	It is important to have affordability as it will allows more university to embrace CDF.	ER4	The CDF should be low-cost in terms of IT hardware, software tools and IT infrastructure.
5	It is important that university will not likely have to spend more time and cost whenever new tools are required due to new research requirements. This can be disruptive to the overall university programs and staff scheduling.	ER5	The architecture should be flexible and adaptable to research needs through ease of installing low cost new commercial and internally developed tools.
6	It is important that university will not likely have to spend more time and cost to change or upgrade hardware whenever new area of research is required. This can disrupt the university programs scheduling.	ER6	Generic hardware configuration needs to be selected for multi-disciplinary complex design studies.
7	It is important to have scalability to minimize maintenance cost over long-term. The time taken to scale installed hardware is likely to be shorter and lower cost than purchasing new hardware to install and uninstalling existing hardware.	ER7	The CDF architecture should be scalable such as hardware configuration can be extended or upgraded when new technologies are available.
8	It is important especially for projects that are confidential, patent and defense in nature to have secure collaboration.	ER8	The CDF should include secure data storage to keep design data internally and/or in the Cloud.
9	The whole purpose of CDF training is to teach students how to apply these methodology to be work-ready. Therefore, intuitive and easy to learn and use is an important priority for education.	ER9	The facility must be capable of Design Optimization and Sensitivity Analysis, which is intuitive and easy to learn and use, and effective for multi-disciplinary design projects.
10	It is important that students learn how to apply CD methodology, the ability to share content onsite or offsite intuitively and effectively becomes an integral part of the whole learning experience.	ER10	The Data processing and Visualization must be available through shared projection of contents between local and off-sites (distributed concurrent design process) simultaneously and seamlessly.
11	It is important to the well-being of the students and staff to be able to work in a conducive environment. This will allow them to be more productive as well.	ER11	The CDF room must meet ergonomic and safety standards.
12	Project design timeline is usually relatively short. It is important that students should spend more quality time to design project instead of learning the pre-requisite/s. In a group environment, this may also potentially delay the group progress.	ER12	The curriculums incorporating CDF must include sufficient student training and preparation.

4.1.2.   Approaches for Universities-Industries collaborations

Aerospace industries are likely to have their own unique design workflows and tools, and often with rapid changes and upgrades. Therefore, universities should collaborate with the industry to maintain an up-to-date environment similar to the two industry-university collaborations examples as reviewed. Both UPM and ISU have shown encouraging results [28, 32]. Lessons learned from (E-USOC)-UPM and ESA-ISU collaborations did highlight their different objectives. These differences are not always compatible in terms of each entity's priorities. For example, a university may have a lesser number of specific domain disciplines in the CDF based program than industry [32]. Despite of these differences, the collaborations has significant benefits [15]. The key mechanism to bridge the gaps is:

- Creating joint industry-university design themes and
- More focus on student industrial attachment (internship) post CDF/PBL based training.

This allows students to apply what they have learned, while the industry could assess the students' performances for feedback to the university (i.e. closing the gaps). The internship enables students to experience the real industry environment in advance before graduation and excite them to study harder, which is good [70].

With the importance of industrial-university collaborations to help minimise the mismatch between employers' expectations and aerospace engineering degree courses and, minimise the reluctance of aerospace companies to hire graduate students, this thesis proposes a general collaborations workflow as part of the overall CDF architecture for educations and research [20, 21].

Figure 15 illustrates a proposed industry-university collaboration workflow. The existing industry CDF elements may consist of the mission/product design workflows, software design tools, hardware and the facility. The existing curriculums consist of the undergraduate supporting core courses from Year-1 to -4, Year-3 design principle core course and Year-4 final design project course (elective).

The additional curriculums are the modifications to the existing Year1 to -4 curriculums in order to embed the relevant software tools with the existing formal short course to prepare students for the Year-4 final design project, with more PM focus as a pre-requisite prior to enrolling in the Year-4 final design project course. Post-CDF-based training is to be followed by industrial attachment (whenever feasible). Finally, there should be a continuous industry-university collaboration whenever feasible, with joint efforts on creating the design project themes relevant to the industry. These built-in supporting elements, which 'wrapped' around the defined CDF architecture aims to maintain a long-term suitable CDF for education and research.

As part of closing the identified gaps, this thesis has introduced a pre-CDF multi-disciplinary education component. This aims to enhance design teaching in preparation (as a pre-requisite) for the capstone/PBL design project course within a CDF setting.
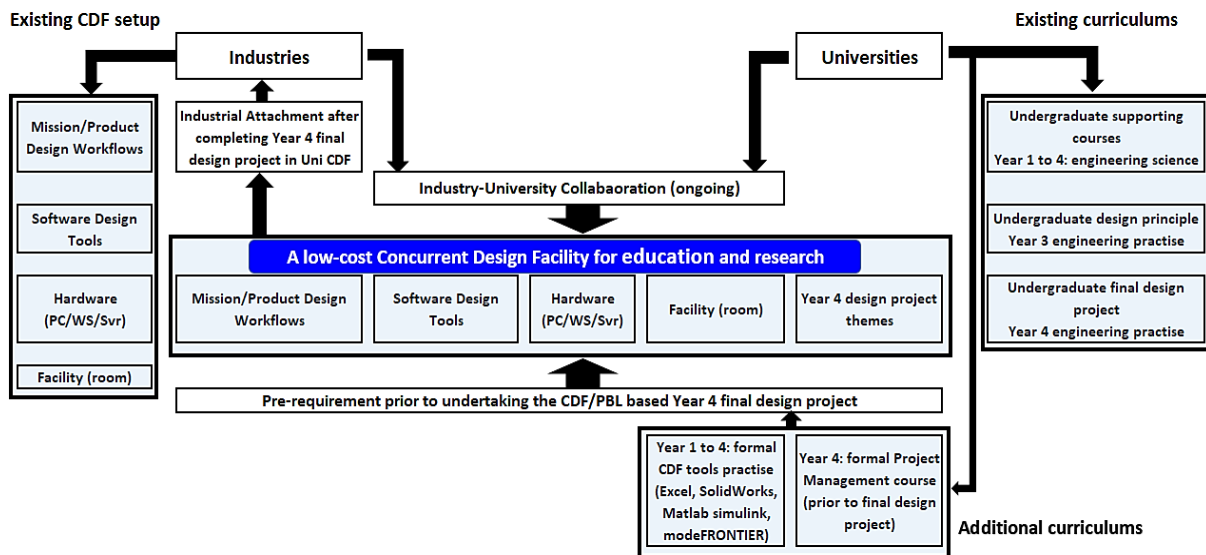
Figure 15, A relevant CDF setup for universities requires suitable supporting elements.

4.2. CDF architecture

The objectives of this thesis are to investigate the design engineering education approaches in universities, with a focus on *aerospace engineering*, and to identify the requirements for a concurrent design facility specifically for design education and research. In this light, industries and national space agencies have been using the ESA CDF established in 1998 as a guide to creating their own facilities and processes [6, 27].

Since the focus of this thesis is on aerospace engineering, it is reasonable to identify the ESA CDF design stations/domain disciplines, as a reference guide for the typical university initial CDF setup. ESA CDF adopted 19 design stations/disciplines for their full-scale preliminary studies as illustrated in Appendix B, Table 24.

This thesis has selected up to 10 such stations/disciplines and the corresponding tools. These are also the same tools adopted by other established CDFs in the industries and universities.

Adoption of the 10 disciplines stations for initial setup is because lessons learned in literatures have shown that universities with CDF have implemented a maximum of 10 or less disciplines workstations. Besides this, case study in this thesis and literatures have shown that universities with non-CDF/PBL and CDF/PBL combination has an average of 7 and 6 – 7 students in a group respectively [28]. The CDF architecture can expand beyond 10 relevant disciplines workstations in the future when the needs arise.

Finally, a case study has been conducted in this thesis to simulate the interfacing between some of these tools (project dependant).

4.2.1. Design tools adopted by industries, educational and research institutions, and proposal for initial CDF setup

A short list of industries and universities adopting the CDF platform with their choices of tools adoptions is shown in Appendix A, Table 23. From the 3 CDFs (ESA, UPM and ISU) reviewed, all 3 have adopted the 6 common domain disciplines as in Table 12 – List A [6, 28, 32]. ISU adopts additional disciplines and tools similar to ESA as listed in Table 12 - list B [32].

Table 12, List A: 6 common disciplines used by ESA, UPM and ISU. List B: disciplines used by ESA and ISU.

List A: adopted by ESA, UPM and ISU	Corresponding Tools adopted
Mission (analysis)	**AGI STK** - (4D modelling, simulation, and analysis of objects from land, sea, air, and space. This aims to evaluate system performance in real or simulated-time) [71]
Power	**AGI STK**
Propulsion	**MATLAB** - (Stateflow/Simulink Aerospace Blockset to model and simulate aircraft, spacecraft, rocket, propulsion systems and unmanned airborne vehicles [72]), Turbofan Engine System Block, and Programming codes. **SolidWorks** (CAD/CAE)
Payload	**MATLAB** - (requires programming codes), **CATIA** (CAD)
Communication	**AGI STK** – (4D modelling, simulation, and analysis of objects from land, sea, air, and space. This aims to evaluate system performance in real or simulated-time)
Thermal	**ESARAD/ESATAN**, **MATLAB Simulink** - (Simscape/Fluids Block: Thermal and programming codes).
List B: adopted by ESA and ISU	**Corresponding Tools adopted**
Team Leader/ System Engineer	**MS-Excel** - (proposed to combine with System Engineer)
Cost (Analysis)	**AGI STK**, **Small Satellite Cost Model 2014**
Attitude Determination & Control/ Simulation (Mission: spacecraft. motion)	**MATLAB Simulink**
Structures	**CATIA**, **SolidWorks** - (CAD/CAE, SIMULIA Structural Simulation/Finite Element Analysis)

Since the objective is to familiarise students with the common domain disciplines adopted by the industries and industry-university collaboration, this thesis proposes to adopt the same 10 domain disciplines/stations as listed in Table 12 – List A and B. The Team Leader and System Engineer disciplines can be combined into one station.

List A and B, are combined in Table 13, based on design tools allocations to its corresponding domain disciplines.

Table 13, Proposed CDF tools used for specific disciplines in space engineering designs.

Proposed CDF Tools	Domain Disciplines			
MS-Excel	Team Leader	Systems		
AGI STK	Mission (analysis)	Power	Communication	Cost (analysis)
MATLAB/Simulink	Propulsion	Payload	Thermal	Attitude Determination & Control/ Simulation (Mission: spacecraft motion) (Aerospace Blockset add-on for Simulink to model and simulate aircraft, spacecraft, rocket, propulsion systems and unmanned airborne vehicles [72]). Payload needs programming code. MATLAB Simulink (Simscape Block: Thermal and programming codes).
SolidWorks	Propulsion	Structures		
CATIA	Payload	Structures		
ESARAD/ ESATAN	Thermal			
Small Satellite Cost Model 2014	Cost (analysis)			

The proposed CDF tools are multi-industries and multi-disciplines (described in this subsequent works), which include MS-Excel, MATLAB, SolidWorks, AGI STK and modeFRONTIER. Figure 16 shows the five proposed tools for the 10 specific domain disciplines after the following design tools consolidation. This aims to minimise students' learning curve.

- CATIA can be installed as an alternative when future needs arise, but is initially excluded to minimise learning curve of 2 CAD tools as:
  - Payload discipline can be allocated to MATLAB programming coding environment (or alternatively to SolidWorks).
  - Structures discipline can be allocated to SolidWorks (3D CAD, FEA, CFD, Kinematics, CAM, Electrical, Sustainability, Plastics mold filling)
- For Thermal, instead of using ESARAD/ESATAN (No interface to MDO, modeFRONTIER), MATLAB (Simscape/Fluids Block: Thermal and programming coding) can be used instead.
- For Cost (analysis), instead of using Small Satellite Cost Model 2014 (No interface to modeFRONTIER), AGI STK (Free license under AGI STK Educational Alliance program) can be used for:
  - 4D modelling, simulation, and analysis of objects from land, sea, air, and space
  - All aspects of space mission design:
    - Oribit, power/fuel budget, payload performance, attitude modelling, communication modelling, space weather, trade analyses/optimisation/maneuver planning and rendezvous/proximity operation.
  - Aircraft and UAV design at mission level:
    - Aircraft flight modelling, formation flying, navigational precision, test/evaluation support, radar/detection modelling, dense traffic safety of flight analysis, pre-flight planning, real-time visulaisation, post-flight reconstruction, terrain effects and RE communications.
    - Aircraft systems design cost analysis.
  - Missile systems design and model end-to-end complex missile defense systems.
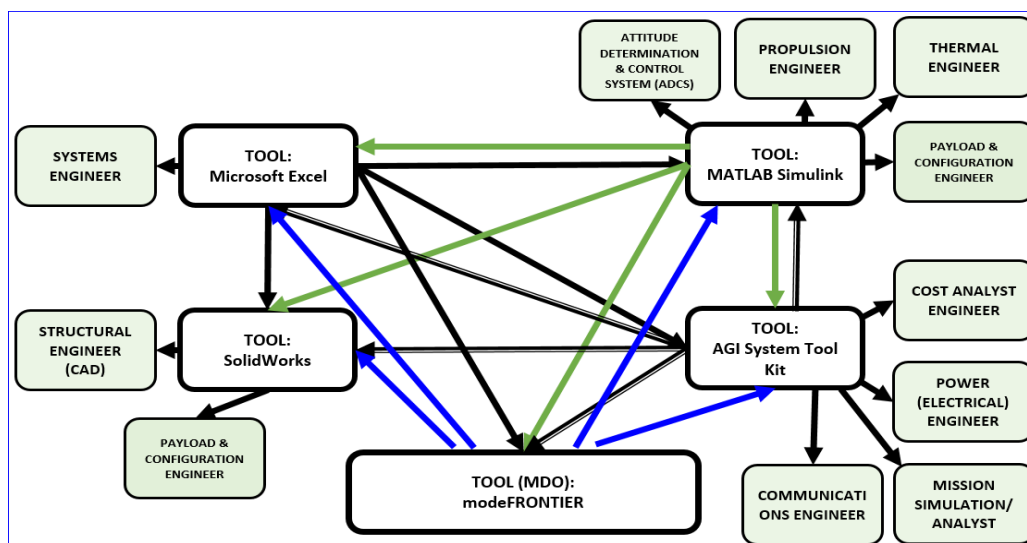
Figure 16, The 5 proposed design tools with abilities to interface with each other for spacecraft and aircraft conceptual design.

4.2.2. The proposed design tools are multi-disciplines

Although the initial selections of the following domain specific and general design tools, are focused toward the aerospace discipline. These tools are multi-disciplines and applicable to different industry as illustrated in Table 14 (by industry) and Table 15 (by functions). Therefore, the proposed design tools are ready for these other disciplines as well.

Domain specific tools:

- SolidWorks (Pricing not publicly available)
- MATLAB/Simulink (Each education license: AU$775/AU$775)
- STK (Free education license)

General tools:

- MS Excel (Free education license)
- modeFRONTIER (MDO) (Each education license (yearly): Euro $1,200 teaching/research, $240 PhD student and $120 student)

Table 14, Multi-disciplinary design tools (Industry application)

Multi-disciplinary design tools (Industry application)				
Domain specific tools			General tools	
SolidWorks [73]	MATLAB [72]	AGI STK [71]	MS Excel [74]	modeFRONTIER [75] www.esteco.com (assess date: 28Nov2018)
Aerospace & Defense	Aerospace & Defense	Aerospace (space, aircraft, UAV, missile design)	MS Excel can be used in most industries that require automatic numerical computation simulations.	Aerospace
Automotive	Automotive			Automotive
Electronic	Electronics / Semiconductors			Electronics
Industrial Equipment – Packaging Machinery Mold, Tool & Die Heavy Equipment	Industrial Automation & Machinery / Railway Systems			Industrial equipment
Architecture, Engineering & Construction (AEC)	Software & Internet			Architecture Engineering & Construction
Transportation & Mobility	Biotech and Pharmaceutical / Medical devices / Neuroscience			Biotech & Pharmaceutical
Marine & Offshore	Energy Production			Marine & Off-Shore
Energy, Process & Utilities	Chemicals and Petrochemicals			Energy & Environment
Consumer Goods & Retail	Metals, Materials and Mining			Consumer Goods

Table 15, Multi-disciplinary design tool's functions

Multi-disciplinary Design tool's functions				
SolidWorks [73]	**MATLAB** [72]	**AGI STK** [71]	**MS Excel** [74]	**modeFRONTIER** [75] (list aircraft, automotive design only)
3D CAD	Embedded Systems Control Systems Digital Signal Processing Wireless Communications Image Processing and Computer Vision Internet of Things FPGA Design and Co-design Mechatronics Test and Measurement Computational Biology Computational Finance Robotics Data Analytics Predictive Maintenance Power Electronics Control Design Deep Learning Enterprise and IT Systems	4D modelling	The list is too long to be included in this table for automatic numerical computational simulations.	**Aircraft design** Wing design Aero-elastic systems Fuselage shape Aircraft structural components Composite materials Metal sheet thermal forming Turbine blades Acoustic emissions Mission design Impact damage prediction
Simulation: (FEA) Finite element analysis		Simulation, and analysis of objects from land, sea, air, and space		
Simulation: (CFD) Computational fluid dynamics				
Motion (kinematics Analysis)				
Plastics (Part & Mold filling Analysis)		**All aspects of space mission design:** Orbit, power/fuel budget, payload performance, attitude modelling, communication modelling, space weather, trade analyses/optimisation/maneuver planning and rendezvous/proximity operation.		**Automotive design** Chassis structural analysis Vehicle multi-body dynamics Transmission and powertrain systems Noise, Vibration, and Harshness (NVH) Handling and comfort Engine cooling system Engine optimization, calibration and tuning Hybrid and fuel cell engine Thermodynamics Drag minimization Racecar aerodynamics Train aerodynamics Crashworthiness optimization Restraint systems ABS control ADAS systems Electronic Control Valves HVAC component optimization
Sustainability (environmental impact)		**Aircraft and UAV design at mission level:** Aircraft flight modelling, formation flying, navigational precision, test/evaluation support, radar/detection modelling, dense traffic safety of flight analysis, pre-flight planning, real-time visualisation, post-flight reconstruction, terrain effects and RE communications.		
Electrical systems design				
Model Base Definition				
Composer (technical documentation)		**Missile systems design** and model end-to-end complex missile defense systems.		
Visualisation				
CAM Computer Aided Manufacturing				

4.2.3. Justification to MDO into the CDF platform

This sub-chapter discusses the justifications to integrate modeFRONTIER as the MDO tool in the proposed CDF platform.

Lessons learned from literature shows that ESA, (E-USOC)-UPM and ESA-ISU collaborations and the IACDT tool presented in this thesis has one common element in their workflows. This is the multi-disciplinary optimisation (MDO) function within the design process of the ESA CDF inspired Integrated Design Model (IDM) using the spreadsheets/workbook. This is a 'must-have' function due to the iterative nature of the whole design process to provide improved quality.

Using spreadsheets/workbook as the main CDF data exchange and session management tool inspired by the ESTEC's CDF-IDM is fast and easy for development and deployment. However, it requires lots of maintenance once the projects grew in scopes and numbers. This means it has reached the limit of what spreadsheets/workbook can reasonably do for software maintenance and integration with other tools [29, 76].

For instance, in workbook, a typical new design workflow will need to be manually created from a blank spreadsheet. Intuitively, this is a lengthy manual process with a certain amount of debugging/testing before the first meaningful data can be entered.

On the other hand, commercial MDO tool such as ModeFRONTIER and iSIGHT, etc. offer system integration from CAD/CAE to optimisation, visualisation, statistical analysis and full product data management (PDM) integration [77-79]. ModeFRONTIER provides intuitive workflows creations based on simple Drag-and-Drop of functional and application built-in interface icons into its workflow space. This is a relatively short process before the first meaningful data can be entered.

In this light, this thesis has utilised the MS-Excel (IACDT development) and modeFRONTIER (case study) and has been able to determine that the modeFRONTIER is more intuitive and efficient than its spreadsheets/workbook counterpart.

When selecting MDO tools, it is important to consider commercial MDO tools over free MDO tools, though the free tools usually supports provided in terms of User Group Forums. This is because:

- Open source software is generally perceived as not as well supported as proprietary software and there are considerations for Warranties and Liability Indemnity Matters [80].
- It is difficult to make open-source developers liable for their code due to the open-source software development environment. Developers share code around the community, responsibility is collective. "Potentially there's no way to enforce liability" [81].
- With the preceding 2 points and with students having short durations in design curriculums, logically, it's better for them to spend their time learning such complex design tools that are, not only well established and supported by large numbers of well establish industries and institutions, but also have developer's accountability and liability. This is especially important, when a design project have urgent critical quality and safely issues to resolve.

Two of such open source MDO tools are the NASA OpenMDAO and ESA OCDT.

OpenMDAO developed at the NASA Glenn Research

OpenMDAO is an open source engineering analysis framework, written in Python. This tool is hosted at the site: (http://openmdao.org/ assess date: 21 Aug 2018) and is used for analysing and solving Multi-Disciplinary Analysis and Optimization (MDAO) problems [82]. The environment requires coding to function, which includes interfacing plug-ins.

Open Concurrent Design Tool (OCDT) developed at ESA

OCDT is released by ESA in 2016 to replace the previous ESA CDF IDM implemented in spreadsheets/workbook [76]. OCDT keep the good points of IDM and lessons learned which is extendible to multi-site distributed design sessions. It has the following attributes:

- Restricted in OCDT Software Licences. Membership of the community requires that the persons work in a ESA member state or cooperating state.
- Australia is not listed as 1 of the 22 ESA member states or a cooperating state. Therefore, Australian industries and universities are not able to consider the ESA OCDT.

ESTECO modeFRONTIER (Justification of the Proposal)

This thesis proposes to integrate the commercially available MDO Tool, modeFRONTIER, into the proposed CDF design tool platform, and the justifications as follows:

- Proposed over other commercial tools such as iSIGHT and ModelCenter is because of its large optimisation algorithm library and powerful post-processing capability [83].
- Implemented in recent time, by the industries, universities as well as research institutes for teaching and research proposes around the world [84].
  - One reason for its popularity is the way it uses the available resources in an efficient and integrated manner and providing multi-dimensional post-processing tools.
  - It is also user-friendly, which integrates with major CAE codes and commercial numerical analysis tools.
- A case study (simulations) has been conducted successfully in the thesis using modeFRONTIER, MS-Excel and MATLAB to interface with each other and function as a single design unit.
- Other baseline benefits:
  - Suitable for Aerospace, Automotive and Electronics disciplines.
  - Include integration Interfaces to the proposed design tools [85, 86].

4.2.4. Case study simulations to evaluate the proposed software tools.

The set of design tools listed in Table 13 are evaluated for its suitability for incorporations into the proposed CDF platform. The evaluations focused mainly on the interfacing functions between tools by using simple examples and a case study (simulation).

Tools evaluations by simple examples

A number of evaluations of the proposed tools by using simple examples shown in Table 16 have been performed successfully. The evaluations include tools setup, interfacing testing status between tools, and developer information for tools integration supports. Some corresponding details are illustrated in the Appendix section.

Table 16, Proposed CDF design tool interfacing with each other.

Interfaces illustrated through setup and/or simple examples			
2 applications interfacing with each other		Setup status	Interface tested status
MS-EXCEL [87] with MATLAB Simulink	**Appendix D**	Completed	Ok
MS-EXCEL with SolidWorks		Completed	Ok (shown in IACDT development)
MS-EXCEL with AGI System Tool Kit (STK)	**Appendix E**	Completed	see (I)
MS-EXCEL with modeFRONTIER	**Appendix F**	Completed	Ok
MATLAB Simulink [88] with SolidWorks	**Appendix G**	Completed	Ok
MATLAB Simulink with AGI System Tool Kit (STK)		see (II)	see (II)
MATLAB Simulink with modeFRONTIER	**Appendix H**	Completed	Ok
AGI STK [89] with SolidWorks	**Appendix I**	Completed	Ok
AGI STK with modeFRONTIER		see (III)	see (III)
SolidWorks [90] with modeFRONTIER		see (IV)	see (IV)
No	**Developer's information: integrations between (below) tools are supported (last assess: May 2018)**		
(I)	Integrating STK with Excel	http://help.agi.com/stk/index.htm#training/StartExcel.htm [assess date: 21Aug2018]	
(II)	Integrating STK with MATLAB	http://help.agi.com/stk/index.htm#training/StartMatlab.htm%3FT.ocPath%3DTraining%7CLevel%25202%2520-%2520Advanced%2520Training%7C 9) and MATLAB Interface: http://help.agi.com/stk/index.htm#matlab/matlab.htm%3FT.ocPath%3DIntegrating%2520with%2520STK%7C 4 [assess date: 21Aug2018]	
(III)	Integrating STK with modeFRONTIER	https://www.esteco.com/modefrontier/multiobjective-aerospace-mission-performance-optimisation-systems-tool-kit-stk-and-mode (require registering and login) [assess date: 21Aug2018]	
(IV)	Integrating SolidWorks with modeFRONTIER	https://mydesktop.rmit.edu.au/Citrix/StoreWeb/clients/HTML5Client/src/SessionWindow.html?launchid=1527578124649 (require license, lecturer/student login) [assess date: 21Aug2018]	

Tools evaluations by case study (Simulations)

Evaluation by a case study (simulations) has been conducted to:

- Determine whether the proposed design tools could interface with each other as a single unit in the proposed CDF setting.
- Lessons learned from the evaluation were:

  o Utilising a typical blank spreadsheet/workbook as a basis to manually prepare a new design workflow for multi-disciplinary optimisation has taken longer time than the combination of 3 design tools. The manual approach also required more debugging/testing before the first meaningful data can be entered.
  o Utilising the highly automatic modeFRONTIER, MS-Excel and MATLAB combination is more intuitive and required less preparation before the first meaningful data can be entered.
  o Optimisation results from the modeFRONTIER combination are faster and more comprehensive due to its built-in optimisation options. The manual method requires lots of hands-on preparation to change between optimisation workflow due to the need to prepare each new optimisation option workflow.
  o It is apparent that a sufficiently complex design project will need the highly automatic modeFRONTIER combination tools instead of the manual method. This will allows the design team to focus on the project instead of spending time to prepare the workflow.

This case study is based on the preceding capstone design project case study, and focused on the power configuration and management sub-system of the design theme: Fire Retardant Delivery System (FRDS), Appendix J.

The case study evaluated one parameter requiring three of the five proposed tools (study dependence). This is deemed sufficient to illustrate the interfacing capability between these tools to function as a single unit. The tools used are MS-Excel, MATLAB, and modeFRONTIER.

The case study (Simulations) estimates the maximum copper cable length allowable for the required operations, at a particular cable size (circular cross-section area), continuous rated current and fixed power supply voltage. Figure 17 illustrates the case study design and interfacing workflow.
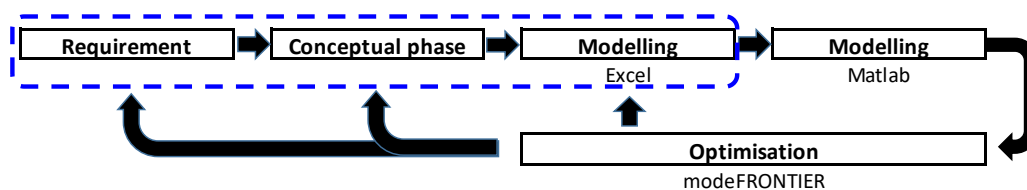
Figure 17, Case study to determine interfacing function between design tools: MS-Excel, MATLAB and modeFRONTIER (MDO).

The detail descriptions of the case study assumed configuration, and following Case Studies are given in Appendix J:

- Case study – Evaluation approach by Manual Calculations
- Case study - Evaluation approach by the proposed CDF design tools
  - Simulation: modeFRONTIER interfaces with MS-Excel (built-in application node)
  - Simulation: modeFRONTIER interfaces with MATLAB (built-in application node)
  - Simulations: modeFRONTIER interfaces with MS-Excel and MATLAB (built-in application node)

In summary, the preceding evaluations results by Simulations using modeFRONTIER interfaces with MS-Excel and MATLAB (built-in application node) have shown that these tools is able to function as a single unit in the CDF environment.

4.3. Recommendations of IT hardware and software architecture (CDF for education and research)

Figure 16 lists the proposed software design tools and Table 17 lists the proposed design tool's operating systems. The next step is to identify the IT hardware to install these tools, which include:

- Hardware configuration, costs and supports for the design software tools: Personal Computer Brands, CPU, GPU, memory, hard disk and display (initial cost, annual maintenance cost and upgradability).

Table 17: Evaluations and selections of the proposed design tools operating systems.

Design tool	Comparison	Results	Conclusion
MS- Excel	Comparison between Windows and MAC operating system by Microsoft for its MS-Excel application [91].	Windows version has more features than its MAC counterpart	MS-EXCEL 2013 for Windows proposed over MAC.
MathWorks MATLAB	Comparison between Windows, MAC and Linux operating system by MathWorks for its MATLAB and Add-On applications [92].	Windows version has more Add-On application availabilities than its MAC or Linux counterpart.	MATLAB 2018a for Windows proposed over MAC and Linux.
Dassault Systems SolidWorks	SolidWorks is only available in Windows but not MAC or Linux operating system: by Dassault Systèmes SolidWorks Corporation, for its SolidWorks CAD application [93].	SolidWorks CAD applications are available for Windows and support MS-Excel and MS-Word, but not for MAC.	SolidWorks for Windows proposed.
Analytical Graphic, Inc. System Tool Kit (STK)	n.a.	n.a.	AGI STK available only for Windows [94] and is proposed.
ESTECO modeFRONTIER	n.a.	n.a.	ModeFRONTIER [85, 86] for Windows proposed as other proposed tools (MS-Excel, MATLAB, SolidWorks and STK) are to be in Windows platform.

4.3.1. Hardware Cost: Personal Computers, Video Wall and Smart Board

The evaluations is conducted to determine the recommended Personal Computer Brands, CPU, GPU, memory, hard disk/solid state disk and display, which includes the initial cost, annual maintenance cost and upgradability.

- Table 20 provides the summary proposal in unit costs.
- Table 21 Summary of hardware and annual maintenance costs.

The hardware configuration justifications are based on the software tool's minimum and recommended system installation requirements with subsequent considerations of pricing. The focus is not on the brand of the hardware.

The Justification – Personal Computers

The proposed PC configurations has the latest Intel 8th generation CPU, NVIDIA 1070 series graphic accelerator (GPU) and solid-state drive (SSD) storage in 'C' drive installed with Windows 10 pro and essential applications/tools. Therefore, these are powerful PCs and with its upgradability, it is a cost-effective solution. Since, the aim is to setup a CDF at lowest possible cost, this same hardware configuration is proposed for the individual domain discipline stations, workstations and servers.
Table 18 lists the minimum and recommended systems requirements for installing the proposed design tools. Table 20 lists the proposed hardware system specifications, which well exceeds the recommended systems requirements.

Table 18, Minimum and recommended systems requirements for installing the proposed design tools.

Software Tools	Operating Systems	CPU, Processors	Disk Space	RAM	GPU, Graphics
MS-Excel [74]	Windows 10, 8.1, 7 SP1 (64bit)	Intel, 1.6 GHz or faster, 2-core. 2.0 GHz or greater recommended for Skype for Business.	4 GB	4 GB	128 MB graphics memory
MathWorks Matlab Release 2018a [95]	Windows 10, 8.1, 7 SP1 (64bit)	Minimum Any Intel or AMD x86-64 processor Recommended Any Intel or AMD x86-64 processor with 4 logical cores.	Minimum 2 GB HDD for MATLAB only, 4-6 GB typical Installation Recommendations SSD recommended Full install: all MathWorks products may use up to 22GB space.	Minimum 4 GB Recommended 8 GB For Polyspace, 4 GB per core is recommended	No specific graphics Card is required. Hardware accelerated graphics card, OpenGL 3.3 with 1GB GPU memory is recommended
Dassault Systems SolidWorks 2018 [73]	Windows 10, 8.1, 7 SP1 (64bit)	3.3 Ghz or higher	10 GB or more 50 GB or more for server function	16 GB or more.	Not specified
Analytical Graphic, Inc. System Tool Kit (STK) [96]	Windows 10, 8.1, 7 SP1 (64bit) or higher	2+ Ghz, Intel Core Duo, SSE2 (minimum). Pentium 4 or Xeon Processors	136 GB (includes supplemental STK Modules)	3 + GB	High-end OpenGL-2.0+ compatible graphics card (512+ MB memory)
ESTECO modeFRONTIER [75, 97]	Windows 10, 8.1, 7 SP1 (64bit)	Intel, Core i5 2.4G, 8MB for mF. Intel, Pentium 2 266Mhz processor for Java 8.0.	500 MB	128 MB – same as Java 8.0.	Not specified

The Justification – Video Wall

The justification for the proposed video wall is based on the minimum and maximum recommended viewing distances limits taken from the ergonomics considerations of the proposed CDF layout described in the subsequent works.

Table 19, Specifications comparisons between 2 different video walls.

Specifications	Barco UniSee	NEC
	https://www.barco.com/en/product/barco-unisee#modal-1 (assess date: 1 Oct 2018)	https://www.necdisplay.com/p/displays/un551s-tmx9p (assess date: 1 Oct 2018)
LCD technology	PA-VA	S-IPS (P-DID)
Resolution	Full HD (1920 X 1080 pixel)	Full HD (1920 X 1080 pixel)
Backlight	Direct LED	LED Direct-lit
Aspect ratio	16:9	16:9
Luminance	800 cd/m^2 (TYPICAL)	700 cd/m² max.
Contrast	4000:1 (TYPICAL)	1200:1 (500,000:1 Dynamic)
Pixel Pitch	Not specified	0.63 mm
Viewing Angle (typical)	Not specified	178° Vert., 178° Hor.
Refresh Rate	Not specified	60Hz
Response Time (Gray to Gray)	< 8 ms	8 ms
Active Screen Area	1212.5 x 682 mm | 47.7" x 26.8"	1209.6 x 680.4mm / 47.6 x 26.8 in.
Bezel Width:Left/Right,Top/Bottom	NA (bezel-less)	0.9mm inactive border along all display sides
Dimensions (WxHxD)	1213.5 x 683 x 94.9 mm | 47.8" x 26.9" x 3.74"	47.7 x 26.9 x 3.9 in. / 1211.4 x 682.2 x 98.8
Operating Temperature	0°C - 40°C	41-104°F / 5-40°C
Operating Humidity	Min. 20% | Max. 70% for T < =30°C or 115%-(1.5% x T/°C) for T=30°C to 40°C (non-condensing)	20-80%
Limited Warranty (parts & labour)	Not specified	3 years

This justification is also taken in conjunctions with the secondary considerations of the Barco and NEC video wall specification in Table 19, which is quite similar though the Barco model has more contrast. The estimated prices for the nine FHD panels making up a 3 x 3 tiled video wall in Table 20 have shown that the NEC is more cost effective.

Table 20: Proposed CDF hardware with unit costs.

Hardware	Descriptions	Estimated Cost (per unit)	Remarks
Personal Computer (PC)	DELL (XPS Tower): Intel CPU, 8th generation i7-8700 (6 core, up to 4.6Hz) Windows 10 pro 64bit Memory (System): 16GB, upgrade: 32GB Storage: 'C' drive: SSD 256GB, upgrade 1TB 1TB, 'D' Hard Drive: 2TB, upgrade 4TB Price: AUD$2,6000 Graphic Accelerator (GPU): NVIDIA 1070: 7680x4320@60Hz (Max resolution) (upgradeable to dual NVIDIA 1080) Display (Monitor): 31.5 in 4K (UHD) (upgradeable to large screen size); Dell UP3216Q - UltraSharp 32 Ultra HD 4K Monitor with PremierColor AUD$2,199.00	$4,800 AUD	www.dell.com.au (date assessed: 31 Oct 2018) *Note:* Total 13 x PC required: 10 x PC: specific domain disciplines 1 x PC: Gateway, VPN, Cloud 1 x PC: SAGE2(admin) to drive Video Wall 1 x PC: Data Exchange Server Design data to be back up nightly into the University central Server to save cost on Data Exchange Server (DES) hardware. SAGE2-server PC is used to drive the daisy-chained video wall (total 9 * 55" (3x3 tile) 1920x1080 FHD each = 5760x3240 resolution). Nvidia GPU max.7680x4320@60Hz should be able to drive the 9 panels that are daisy-chained using DisplayPort. This GPU is upgradable to dual GPU cards running in parallel.
Video Wall	NEC 55" Ultra Narrow Bezel S-IPS 3x3 Video Wall Solution: Model: un551s-tmx9p LCD TileMatrix™ (1920 x 1080) Dimensions (WxHxD) each of the 9 display: Without stand: 47.7 x 26.9 x 3.9 in. / 1211.4 x 682.2 x 98.8 mm OR, Barco UniSee Video Wall 55" Display size, Full HD (1920 x 1080), Bezel-less design Unit price USD: $8,500 List / $7,600 (offer)	$46,999 USD converted to $65,050 AUD $68,400 USD (offer x 9 panel) converted to $94,670 AUD	https://www.necdisplay.com/p/displays/un551s-tmx9p (assess date: 21Aug2018) *Viewing Angle (typical): 178° Vert., 178° Hor. Expanded daisy chain options with UHD pass through via DisplayPort enables UHD resolution across the entire wall. (55" Ultra-Narrow Bezel, S-IPS Video Wall Display@$4,449.00 each)* http://www.barco.com (assess date: 31 Oct 2018) https://www.electronicwhiteboardswarehouse.com/barco-unisee-video-wall-display.html (assess date: 31 Oct 2018) for pricing.
Smart Board	84" Microsoft Surface Hub (smart board) Size: 46.12" x 86.7" x 4.15" (1171.5mm x 2202.9mm x 105.4mm) Resolution: 3840 x 2160 @ 120Hz	assess date: 21Aug2018 $34,099 AUD, 84 in assess date: 08Oct2018 start from: $22,000 est: $34,099 AUD with accessories e.g. rolling stand etc)	https://www.theaustralian.com.au/business/technology/microsoft.-surface-hub-offers-walltowall-conference-possibilities/news-story/ab03c84ec247009d69ebfa13974b20f7 (assess date: 21Aug2018) https://www.microsoft.com/en-us/surface/business/surface-hub/tech-specs (assess date: 08Oct2018)

Table 21, Summary of hardware and annual maintenance costs.

Hardware description	Unit Price	Quality required	Total cost
Personal Computer (PC)	$ 4,800 AUD	13	$ 62,400 AUD
Video Wall (3 x 3) 55"	$ 65,050 AUD	1	$ 65,050 AUD
Smart Board 84"	$ 34,100 AUD	1	$ 34,100 AUD
Networking platform	$ 5,000 AUD	1	$ 6,000 AUD (estimated)
Annual Maintenance (10%) hardware cost	$16,755 AUD	1	$ 16,755 AUD (estimated)
Exclude setup cost			**$ 184,305 AUD (estimated)**

4.4. Minimum support facilities for CDF room (physical room layout)

For the CDF facility, it is based on functionality, and a room with high-speed networking and internet infrastructures can be selected to be multipurpose.

However, the thesis acknowledges that the availability of suitable infrastructure could be an issue. It may not be necessary to build a new building, but making changes to a building, including furniture is still costly.

The physical room layout will include 10 computers and desks configured in a 'U' shape in front of a video wall and a movable smart board. This is to facilitate efficient collaboration amongst the team and unobstructed view of the video wall.
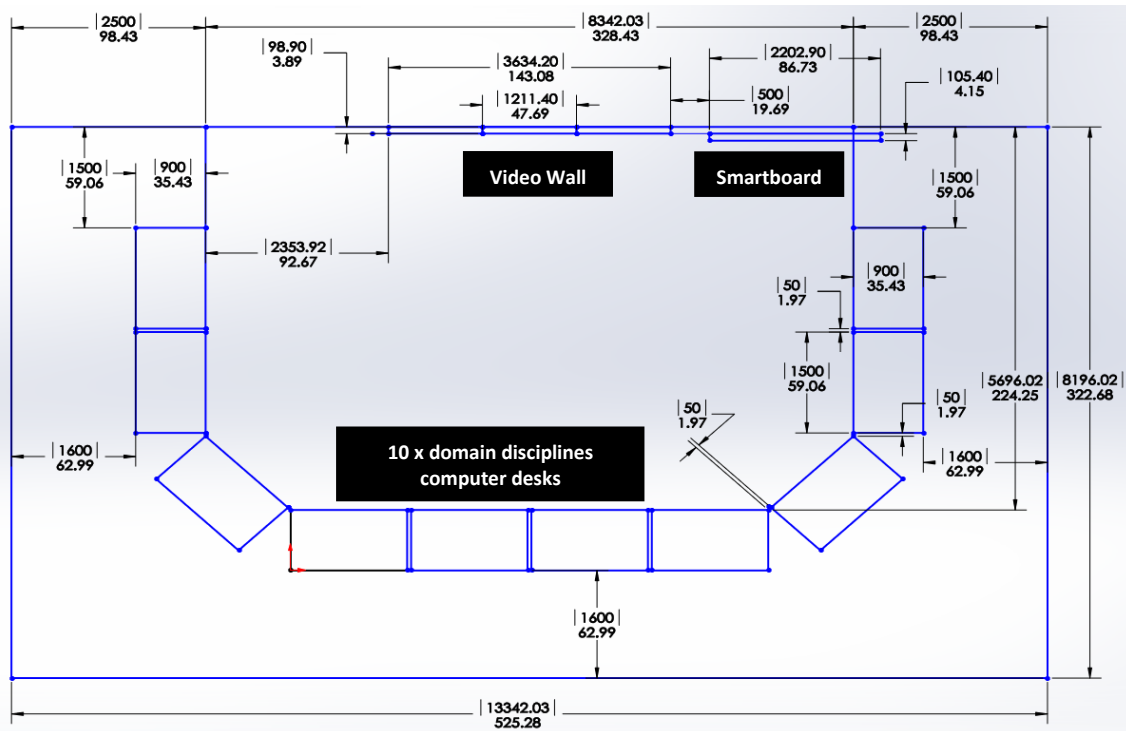
Figure 18, Proposed CDF layout for engineering education and research. Dimensions: mm (top), inch (bottom).

4.4.1. CDF Integrated Design Environment and design/supporting software tools

CDF Integrated Design Environment (IDE) architecture

This thesis proposes a CDF Integrated Design Environment (IDE) as illustrated in Figure 19. The CDF IDE consists of up to 10 domain disciplines linked to the central data exchange system (DES) servers, which is similar in approach to the IDE adopted by the ESA CDF and ISU CDF [6, 32]. These domain disciplines may include the Team Lead/System Design Engineer, Systems, Cost, Mission, Propulsion, Attitude Determination and Control/Simulation, Communications, Structures, Thermal, and Power and Payload. However, the specific tools utilisation is also project dependent.

The domain model design status can be consolidated from the DES by the CDF design process workbook for progress reporting [6]. The MDO enhancement is through the workbook (previously, used as the main MDO), which is to be embedded within the proposed commercial MDO tool environment. The embedded spreadsheet/workbook will host all the required parameters for inputs into MDO tool highly automated MDO workflows. The 'Model-Driven'

design process uses data derived from the collections and integrations of the design tools used by each specialist for his/her domain. During in-session discussions, the video wall displays the sub-systems and system model's data for the entire team. Offsite collaboration is through the Virtual Private Network and/or cloud services, which depends on the project confidentiality level.
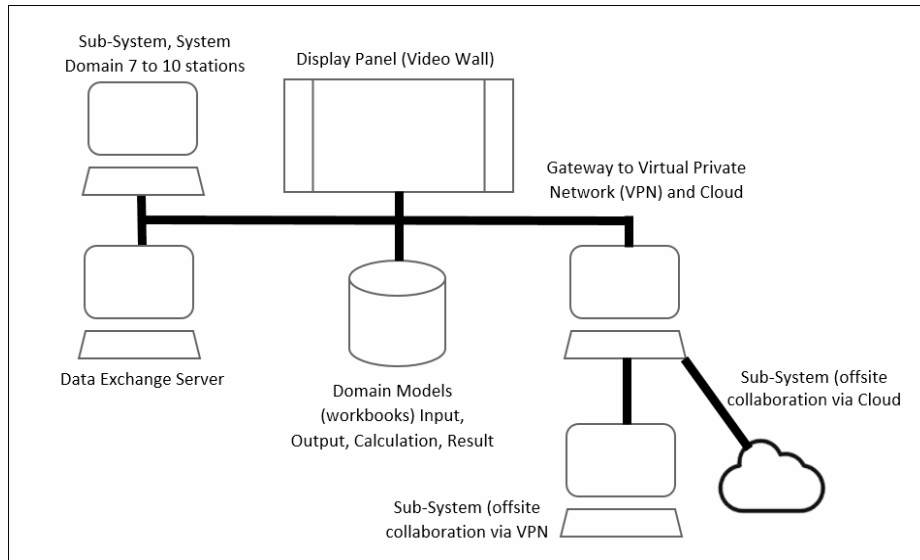
Figure 19, Proposed CDF IDE architecture for engineering education and research.

The proposed VPN will be suitable for design projects undertaken in the proposed CDF architecture that are confidential, with patent/copyright, and defence in nature.

The proposed Cloud services alongside with the VPN will provide easily implementation and low cost, though less safe than VPN. This is in terms of hosting and delivering services over the internet, allowing sharing of software, data and services over internet from any location [98, 99].

Though the Cloud computing is less safe than VPN, it has been considered among the top 10 most important technologies [100]. Researchers estimated that from 2011 to 2016, 12% of software market will move toward cloud computing and cloud computing market will reach $95 billion [101]. Emerging new paradigm in cloud computing such as public cloud computing servers from Google Drive, SkyDrive, Dropbox, Mendeley may be used in CDF for education to save investment on hardware [16].

CDF Design/Support Software tools

The thesis proposes using generic hardware with minimal use of domain specific software. The summaries of proposed tools are given as follows:

Design tools (domain disciplines)

- MS-Excel (for Systems Analysis)
- MATLAB Simulink (for Attitude Determination and Control, Propulsion, Thermal, and Payload and Configuration).
- SolidWorks (for Structural/Mechanical CAD modelling, Payload and Configuration)

- AGI System Tool Kit (for Cost Analysis, Power, Mission Simulation/Analysis, and Communications).
- ModeFRONTIER (MDO) (for highly automated iterative optimisation and interfacing with other proposed tools to work as a single unit platform concurrently).
  - It is also able to interface with other design tools and disciplines, such as the automotive and electronic/electrical industries.

Support tools (general)

- Microsoft (MS): MS-Word - report writing, MS-Excel - computational, MS-Outlooks or Windows Mails – emailing and communications/collaborations, and MS-PowerPoint – Presentations.
- MS-Skype - video conferencing and communications/collaborations.
- MS-Windows security and cloud storage.

Support tools (video wall and computers collaborations)

The proposed CDF workflow includes a large video wall and 10 disciplines personal computers for team member's collaborations, which requires seven essential functions as listed in Table 22. This table also compares the various tools that enable collaborations. SAGE2 facilitates data intensive co-located and remote collaboration by using a Scalable Resolution Shared Displays (SRSD), is the most feature-rich amongst the tools compared [102].

Table 22, Comparison of systems that enable collaboration [102]

	Simultaneous Multi-user Interaction	Windowing Environment for Multiple Applications	Extensible 2D and 3D Applications	Off-the-shelf Application Support	Multi-site Remote Collaboration	Supports Content with Unlimited Resolution	Leverages Cloud-based Infrastructure
Google Hangouts	X				X		X
Skype, WebEx					X		X
Binary Meetings					X		X
DiCoDEv					X		X
CollaBoard	X			X	X		X
OmegaLib	X		X			X	
Equalizer			X			X	
CGLX	X		X	X		X	
Liveboard				X	X		
Impromptu	X	X		X			
CubIT	X	X				X	
Mezzanine	X	X			X		
Montage		X				X	X
Display Custer	X	X	X	X		X	
SAGE	X	X	X	X	X	X	
SAGE2	X	X	X	X	X	X	X

Therefore, the thesis proposes to adopt SAGE2 tool. This is an Open-source parallel rendering middleware SAGE2 (Scalable Amplified Group Environment) web-based collaboration tool. The National Science Foundation funded the SAGE2 and that it was developed by Electronic Visualization Laboratory at the University of Illinois, and Laboratory for Advanced Visualization and Applications at the University of Hawaii [102, 103].

SAGE2 is a cloud-based customised web server with clients accessed through visiting a uniform resource locator (URL) in a web browser to facilitate data intensive co-located and remote collaborations using a Scalable Resolution Shared Displays (SRSD) [104].

The only 2 prerequisites for running SAGE2 are the cross-platform Node.js JavaScript runtime that is built on Chrome's V8 JavaScript engine https://nodejs.org/en/ (assess date: 17 Oct 2018), is installed on the computer that hosts the Web Server, and up-to-date (Google Chrome) web browsers are installed on any computer running a client [102]. In this light, there

is no requirement for a separate Audio/Video Switcher desktop unit such as the AMX Control System Processor Unit (https://www.amx.com/en-US (assess date: 31 Oct 2018).

SAGE2 allows the CDF design team members to mirror any number of computer screens or application windows to share their individual screen contents. Such contents may include PDFs, videos, images, 2D and 3D custom and off-the-shelf applications on the large video wall.

Figure 20, Ranges of Scalable Resolution Shared Displays (SRSD) configurations [102].

SAGE2 SRSD can run using one or multiple computers with each connected to one or multiple monitors. Figure 20 illustrates a range of SRSD configurations. Picture A shows 1 x 4K monitor connected to one computer running SAGE2. Picture B shows eight monitors connected to two GPUs on one computer running SAGE2. Picture C shows a cylindrical tiled wall with 72 x displays connected to a 36-computer cluster, with the SAGE2 Server running on the head node. Picture D shows a tiled wall with 18 x displays connected to a 6-computer cluster, with the SAGE 2 Server running on the head node.

A SAGE2 session can starts at one site and mirrors the SRSD to all other sites by simply visiting the same URL. All contents uploaded to the SAGE 2 Server are displayed on each site's SRSD. Any SAGE2 components (e.g. server, audio client, display clients, interaction clients and input clients) can run on the same computers or distributed across a cluster of computers. The SAGE2 Display Clients are web browser's instances, which connect to the SAGE2 Server by visiting a URL. The Audio-Client runs in a web-browser and initialised by

connecting to the SAGE2-Server by visiting a URL. Once a video file is loaded into SAGE2 space, the Audio Client will output the sound and synchronize the Display Clients' video with its audio.

SAGE2 operations – A simple case study (simulation)

A simple case study (simulations) has been successfully conducted in the thesis to illustrate the SAGE2 setup and collaborations workflows. The 1st step is to register with the SAGE2 website and download the open source code http://sage2.sagecommons.org/sources/ (assess date: 17 Oct 2018) [103]. The computer used to install and setup SAGE2 host web server is connected to two monitors (a desktop monitor and a large 'simulated' video wall).

After SAGE2 is setup and running, the simulated 'large video wall' is active without content. On-site (in CDF room) or off-site team members may connect to the CDF video wall's SAGE2 host web server through the client connections by visiting the server website address (i.e. IP: port - Internet Protocol to communicate over a network).
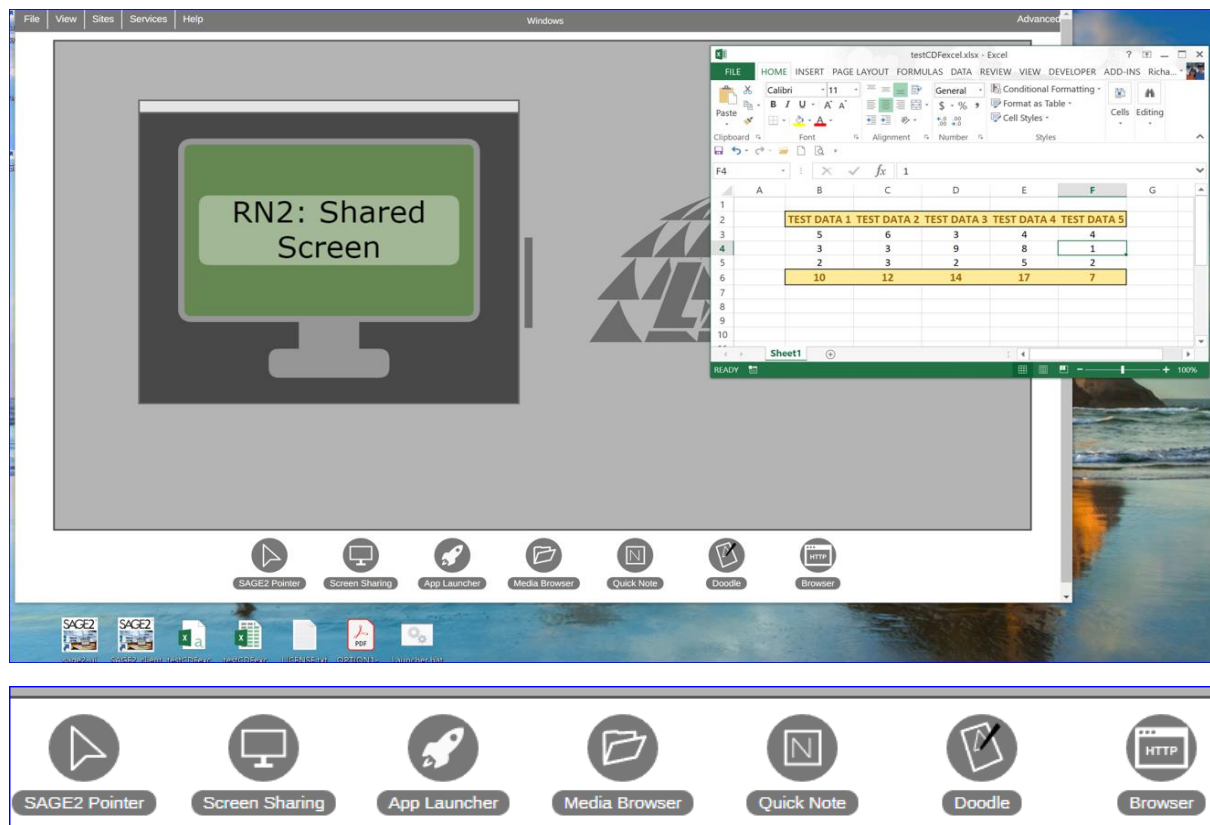
Figure 21, Simulation of a Client SAGE2 screen (an instance of domain discipline) connected to SAGE2 server (top), with 'Screen Sharing' option (bottom) activated to share spreadsheet Data on the video wall.

Figure 21 (top), illustrates the simulations of a Client SAGE2 screen (an instance of specific domain discipline) connected to SAGE2 server. The 'Screen Sharing' option (bottom) is activated to share the spreadsheet Data on the simulated video wall in Figure 22. Upon clicking on the 'Screen Sharing', followed by the 'Application Window' and the opened spreadsheet to share, the selected spreadsheet will be displayed on the video wall and all connected client's screens. The spreadsheet data may be changed directly at the video wall (using client SAGE2 pointer in Figure 21 bottom, or from the Client screen that shared the spreadsheet data). Since

the same SAGE2 host web server has two displays (monitor and video wall), the monitor screen in Figure 23 may also run the 'client' service that can be doubled up as one of the 10 disciplines station PC. However, this is not recommended as it may potential slowdown the video wall responsiveness to support other clients connected to the server.
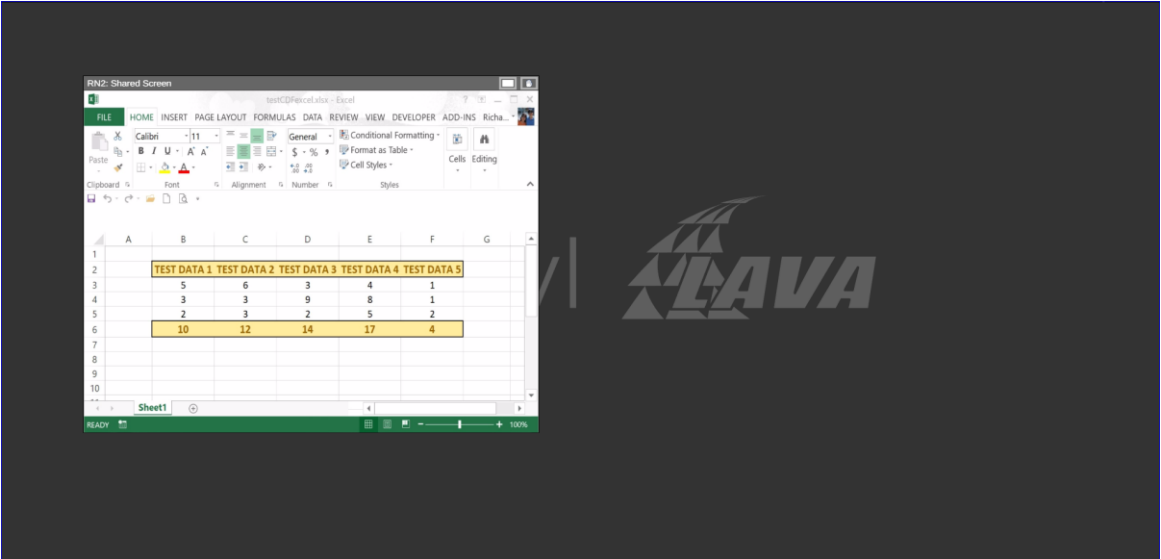
Figure 22, Simulated video wall displaying spreadsheet upon the Client sharing the spreadsheet. Spreadsheet data may be changed directly at the video wall (using client SAGE2 pointer or from the Client screen).
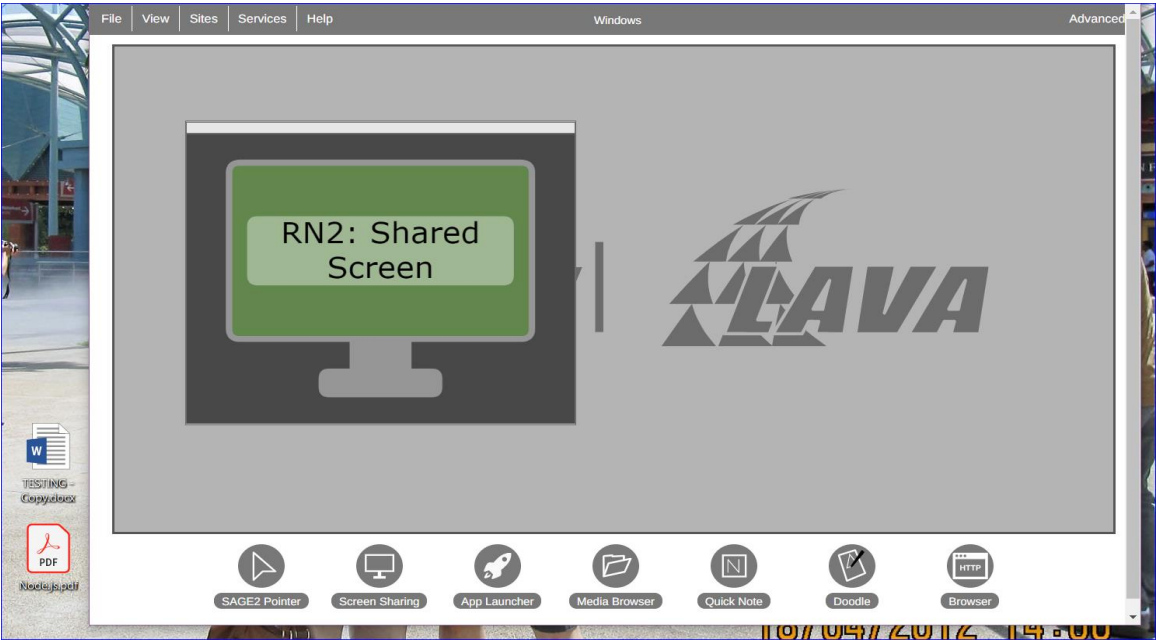
Figure 23, Simulation of the 'client' monitor screen running on the same SAGE2 web server.

4.4.2. Proposed CDF physical layout

The proposed CDF facility consists of up to 10 disciplines personal computers (PC). This is deemed sufficient for the purpose of education and research [28]. A Local Area Network (LAN) connects the 10 discipline PCs, Data Exchange Server and Gateway PC. Each discipline PC will be installed with the relevant tools for executing various domain discipline workloads, e.g. for satellite design. The 10 discipline PCs are not restricted to any discipline and may change discipline when the needs arise.

Data such as CAD models, graphs, tables, CFD/FEM results, etc. can be presented on a large tiled video wall with the support of an open-source SAGE2 parallel rendering middleware [102]. The PCs will be laid out in a U-shape configuration to enable efficient interaction between the team members and for viewing the video wall. This layout is similar in concept to the ESA CDF layout [6, 105].

The team leader/system engineer can create status reports using a workbook, which consolidate all the domain model's data for computation, produce the results for further analysis and progress reporting. Since, a typical new project may require each team member to use a blank spreadsheet to populate data, the team leader needs to discuss and agree on the data formats with the team members.

Offsite collaboration will be through the Gateway using Virtual Private Network (VPN) or Cloud services. The thesis acknowledged that the bandwidth issue is a challenge as there are uncontrollable elements due to potential limitation from different country national broadband infrastructure.

Ergonomics considerations of the proposed CDF layout

The proposed CDF layout is similar in concept to the ESA CDF, which uses a 'U' shape layout for the stations to facilitate the project design process [6]. The ergonomics aspects is also taken into consideration. The sizing for aisles and walkways at minimum of 1,500mm has exceeded the requirements from the Code of Practice, Managing the work environment and facilities requirements, Safe Work Australia. The Code states that the Aisles and walkways should be at least 600 mm wide and kept free of furniture or other obstructions at all times [106]. The proposed computer desks at minimum of 1500 * 900 mm have also meet the requirements from the University of Adelaide Health Safety and Wellbeing (HSW) Handbook [107].

Horizontal video wall and smart board viewing considerations

Based on the proposed 55-inch (3 x 3 = 9 panels) video wall, the 10 x 'U' shape domain disciplines desks configurations have been evaluated to have suitable minimum and maximum viewing distances from the video wall. The video wall with nine panels has a size of 3,634.2mm (W) x 2,046.6mm (H) x 98.9mm (T) mounted at the centre-front wall without gap as illustrated in Figure 24 and Figure 25.

Team members sitting at 'EYE 1 Position' and 'EYE 2 Position' locations in Figure 24 with a viewing angle range of 14.53 degree and 27.08 degree respectively is within the horizontal normal viewing field limits of 50 degree. The members eyes viewing angle range of 50 degree occupying the full view of the computer monitor has also meet this same requirement, Figure 26 [108].

In relations to the eye-to-monitor distance, the proposed distance of 450mm + 300mm = 750mm (e.g. EYE 2) illustrated in Figure 24 does meet the recommended requirements of a minimum 15.7 inch (398.78mm) and about one arm length away or slightly further as a general guide [109, 110].

The average viewing distances from 'EYE 1 position' and 'EYE 2 position' to the centre of the video wall in Figure 24 at 5,785.76mm and 7,183.76mm respectively is also within the recommended limits. This is based on the followings:

- A fixed-frame projection screen size of 3,632mm (W) x 2,108mm (H) is recommended to have a maximum viewing distance of 12.6 meters [111].
- A LED video wall size of 4,000mm (W) x 2,500mm (H) with 1920 x 1080 (FHD) and Pixel Pitch of 1.9mm (per FHD panel) is recommended to have a maximum and minimum viewing distances (1000 * Pixel Pitch) of 12.3 meters and 2 meters respectively [111].
- In general, a text height of 1 inch (25 mm) displayed at 15 feet (4.5 m) of viewing distance will ensure legibility, and a text height of 2 inch (50mm) improves legibility at 30 feet (9m) as illustrated in Figure 27 [112].
- The proposed 3x3 panel video wall has the following specifications [113]:
  o Total 3x3=9 FHD panel has a total size: 3,634mm (W) x 2,046mm (H)
  o Total combined resolution: 5,760 x 3,240 (better than 4K: 3,840 x 2,160 pixels).
  o Viewing angles of (typical) 178° Vertical and 178° Horizontal
  o Pixel Pitch of 0.63 mm, the minimum viewing distance may be reduced further to 1000 * 0.63 = 630mm [111].

Figure 24, Proposed CDF detail layout for education and research, with horizontal dimensions. Dimensions: mm (top), inch (bottom).

The moveable 84 inch smart board with a 100 degree horizontal field of view and a size of 1,171.5mm (H) x 2,202.9mm (W) x 105.4mm (T) as in Figure 24, is recommended with a maximum viewing distance of 6.3 meters [111, 114]. Therefore, in most situations, both the moveable smart board and team members located outside its field of view will have to move and angle within the field of view if the smart board is required for discussions.

Vertical video wall and smart board viewing considerations

The proposed CDF layout does consider the vertical fields of views and distances beside the horizontal aspects as illustrated in Figure 25. The desk top height of 700mm (average) and monitor height-to-eye level of 40mm (maximum recommended) meets the guidelines, and the male common sitting posture measurement for eye height of 1,336.04mm meets [107, 110].

Based on these guidelines for the layout and the vertical normal viewing field limits of 60-degree, Figure 26, team members at 'EYE 3 position' should have unobstructed views of the whole video wall [108]. However, team members at 'EYE 1 position' or similar positions will have the bottom 188.91mm (H) of display content obstructed. This is mainly due to the height of the monitor in front of the eye level and the average viewing distances for EYE 2 is longer than EYE 1 position by an average of 1,398mm (i.e. avg. 7,183.76 – 5,785.76) to the video wall centre. However, this may not be a problem as it is assumed that usually, most of the content does not occupy the entire video wall. Note: the video wall be may raise by an estimated 254mm (10 inches) if the ceiling could accommodate the additional height in order that EYE 1 could have full view of the video wall.
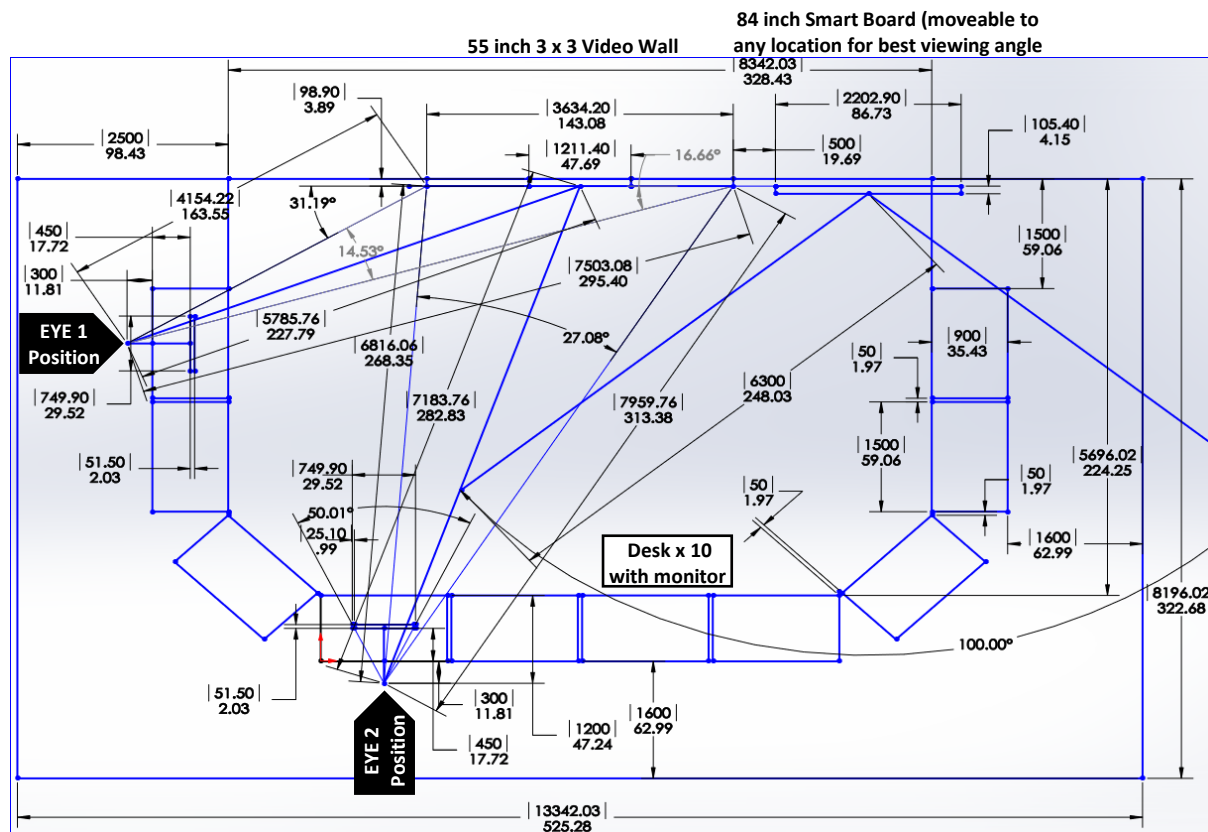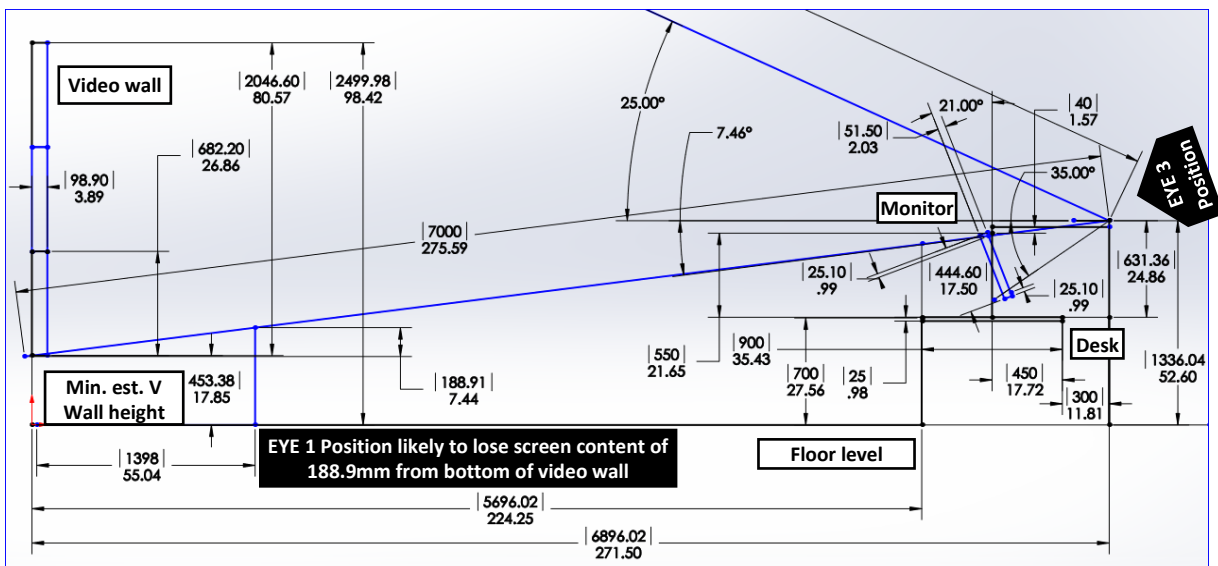

Figure 25, Proposed CDF layout for education and research, with vertical dimensions. Dimensions: mm (top), inch (bottom).
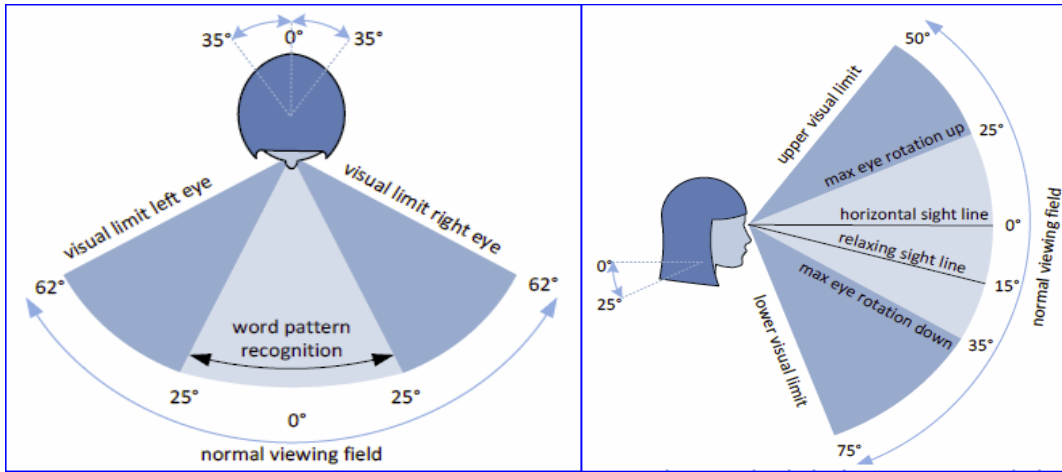
Figure 26, Eye's field of views, A: left, horizontal and B: right, vertical viewing fields [108].
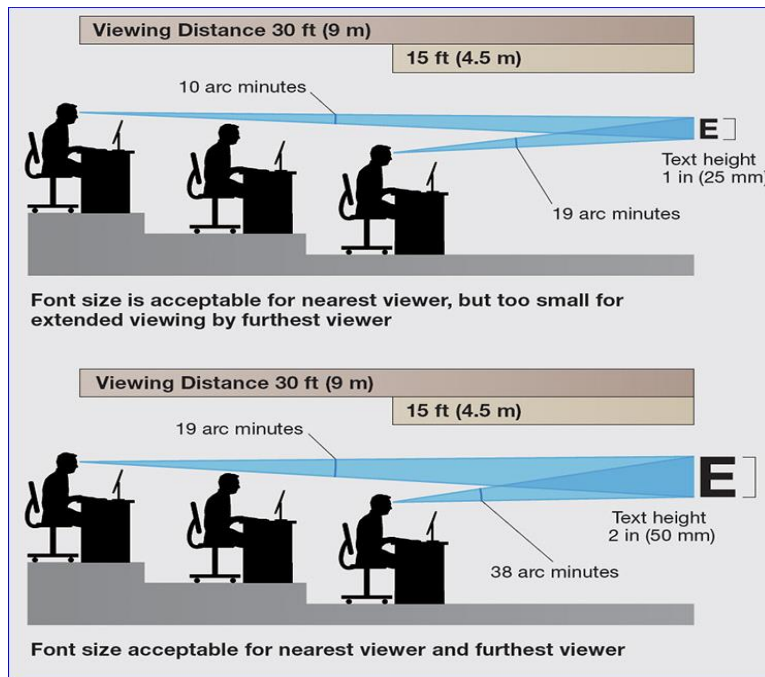

Figure 27, Font size vs. viewing distance [112]

5. Discussions, concluding remarks and outlooks

Concurrent Engineering (CE) design practices and processes are increasingly used in industry. However, there is a shortage of aerospace engineers with relevant skills. There is a lack of exposure to Concurrent Design (CD) at university since Concurrent Design Facilities (CDF) are perceived to be expensive and are not available since there is no requirement for learning and teaching practices based on fast, efficient end-to-end design environment. As a result, CE design practice potential is not truly realised in the academic environment.

Best practices show that a CDF can shorten design time, reduce cost, and improve quality. There are also evidences that CDF applications are effective in the industries and research institutions, and albeit limited, there have been successful implementations of CDF at university and examples of industry-university collaborations based on CE.

It is important that higher education institutions embrace concurrent design CD/CE methodology in their curriculum. With technologies such as computer hardware continues to improve its costs-to-performance ratios, and its corresponding costs remain relatively flat, it becomes more affordable for many universities to setup an initial low-cost CDF.

There are cases where universities have collaborated with industry to setup CDF and pushed CE practices in the curriculum, however, these attempts have often lower-level focus in directing to specific CDF supporting elements addressing pre- and post-CDF-based training requirements.

The pre-CDF requirements include the proposed pre-requisites such as using the IACDT collaborative tool to enhance Year-3 teaching and maintaining various formal short courses prior to attending the CDF-based training. The post-CDF requirements include the proposed Industrial-University Collaborations and joint-creations of design themes (whenever feasible) and focus on enabling more students to attend the Industrial Placement Programs.

These are important gaps being identified. CD methodologies and CDF require the implementation of a multi-disciplinary solution. The CDF may have state-of-the-art, top-of-the-line IT infrastructure, hardware, CD software tools and facility. However, the CDF implemented at a university should be linked to industry, and students entering CE courses should have the proper pre-requisites for the CDF-based training. If not, students are likely to spend a lot of their times learning the pre-requisites instead of focusing in the core design projects in a relatively short timeline.

Research Question 1: How is aerospace design currently taught at universities and to what extend are student graduate skills compatible with industry requirements?

Four universities were investigated, where three offers undergraduate (BEng) degree in aerospace engineering and one offer undergraduate (BEng) degree with Dual Major in Mechanical and Aerospace Engineering. All four universities programs have a capstone design project, but do not have a CDF integrated in their curriculums. All four universities use a similar teaching philosophy, and with some differences in their overall design teaching methodology in general.

- Students are taught the essential core engineering science and practice courses.
- Industries are linked to the program, usually through the university school of engineering industry advisory or similar role committee, where the industries provide comments and advices on the contents of these programs.
- Students are taught specialist skills such as analysis, design and operation of complex aerospace hardware and software.

- Year-1 to -2 of the curriculums focus on teaching students to understand the core engineering fundamentals including Mathematics, Physics and Mechanics. Out of the four, one university has a CAD course in Year-1.
- Year-2 to -3 curriculums focus on specialist aerospace related courses to deepen the students acknowledge in aerospace engineering, such as Aerospace Structures and Aerodynamics etc.
  - Elective studies allow students to tailor the program to suit their areas of interests and enhance their career opportunities.
- Year-4 curriculums consolidate the students' Year-1 to -3 learning, and put it into practice through engineering research thesis, or capstone design projects with elements of Project Management (PM) or Team Works or Team Collaborations.
  - The capstone design project is either industry-based or simulates an industrial situation.
  - The capstone design project develops and reinforce the skills and knowledge of students. In Australia, this is as defined by the professional body *Engineers Australia* enabling them to commence their professional engineering career upon graduation [115].
  - Year-4 continue to enable the selections of aerospace engineering electives.
- Two universities have industrial training or placement and 2 do not have.
  - University of New South Wales (UNSW Sydney) – Year-3 Industrial Training or Exchange Opportunity (at least 60 days): Mandatory.
  - Royal Melbourne Institute of Technology University (RMIT) – Year-4 Industrial Placement program (at least 6 months full time): Elective.
  - University of Queensland (UQ) - Does not have an Industrial Placement Program.
  - University of Bristol (UB) – Does not have an Industrial Placement Program.

In this light, the observation through a case study on a typical capstone design course in the thesis has shown that there is a:

- Presence of 'waterfall' and over-the-wall' approaches resulting in reduced iterative cycles and lower project completeness as shown in the students' final group reports.
- A general lack of CD enabled software tools that allow concurrent collaborations with each other through compatible interfaces.
- A general lack of students' CD, CAD and project management skills, which were reflected in their tutorial 'in-session' group collaborations/discussions and final group reports.

These results are also in-sync with the studies conducted by the Professional Engineering Magazine (U.K.), Industrial Focus Group (Canada), University World News and OpenEdition Freemium for Journals [20, 21, 116, 117].

These three preceding misalignments observed in the case study are related to the applications of engineering practice in the capstone design project. The design project's workflows and tools used are not in line with the concurrent design approach applied in many industries. Universities should consider establishing a CDF architecture along with CD enabled software tools, maintaining the CAD/CAE formal short courses, with more focus on project management as pre-requisites, and post-CDF based training if feasible (i.e. work-integrated-learning with placement at industry or with industry participation) to realise the full potential of CDF implementations.

The CAD/CAE formal short course is not course embedded in another engineering course. This is because, a dedicated separate CAD/CAE formal short course can focus more

directly on the tool's main features, whereas, an embedded 'course' is just a by-product of another engineering course.

Lessons learned in literatures were that, some universities have already implemented a CDF and offer CDF-based aerospace courses at BSc. and MSc. Degree levels. Two universities placed their CDF-based trainings in their Master programs, and 1 university in their Bachelor and Master programs.

The CDF-based Bachelor program has two capstone design project courses, and one elective (Space System Engineering course) in the Year-4. Following the completion of these three courses, students can proceed to the Space System Design Course, which is conducted in the USU Concurrent Engineering Facility (CEF). Whereas, the Master program from this same university, started the CDF-based course from Year-1 to -2.

The CDF-based Master programs conducted by the two universities in close collaborations with ESA, also conduct their Year-1 to -2 courses within the CDF.

The thesis acknowledged that it is an issue to decide which course need to be removed or changed to accommodate the CDF-based training course.

The Concurrent Design Facility (CDF) at Technical University of Madrid (UPM, Spain), and International Space University (ISU, France: donated by European Space Agency) conformed to the best practise and approach of European Space Agency (ESA CDF), while USU CDF conformed to the National Aeronautics and Space Administration Jet Propulsion Laboratory (NASA JPL) best practise and approach. All three universities also collaborated closely with their agencies in design projects, educations and research. Therefore, the students are trained by the same ESA or JPL CDF approaches.

Since the ESA CDF and NASA JPL CDF approaches have been used as guidelines and adopted by many industries in Europe, North America and worldwide, it is logical and reasonable to believe that graduates from UPM, ISU and USU and the likes, will have a better chance to be more work-ready and perform better in their Industrial Placement Programs (IPP). This is especially true for students who are performing their IPP in organisations that use CDF based on the ESA or JPL CE solutions.

Research Question 2: What are the requirements for a Concurrent Design Facility suitable for design education and research at university level?

The requirements for establishing a Concurrent Design Facility suitable for design education and research at university level must meet the needs of the relevant industries. Therefore, a set of rationales and its essential requirements that are relevant to these industries have been established as given in Sub-chapter 4.1.1, Table 11.

Research Question 3: What CDF architecture would best meet the aforementioned requirements, including hardware, software, data management, infrastructure, etc., from an ease of use and cost perspective?

The recommended CDF architecture and design environment that meets the essential requirements (ER) identified in Research Question-2 (Sub-chapter 4.1.1, Table 11) are given as follows:

- For ER1:
  - The recommended CDF architecture incorporate the ESA CDF 5 key CE elements in literatures, which has largely become a reference point for other European partners to apply this approach to space mission designs.

Industries and national space agencies are using the ESA CDF as a guide to create their own facilities and processes, such as the French Space Agency CNES, which also partner with the Australian National Concurrent Design Facility opened at UNSW (Canberra) in Nov 2017.

- For ER2:
  o The recommended CDF architecture consists of 10 workstations (PC).
    - Universities with the best practices in the CDF have implemented a maximum of 10 or less disciplines workstations. Furthermore, universities with non-CDF/PBL and CDF/PBL combination have an average of 7 students in a group.
    - The CDF architecture can be expanded beyond 10 relevant disciplines workstations when the needs arise.

- For ER3:
  o The recommended CDF architecture implemented a custom webserver/client based collaborative content-sharing tool, which is capable of:
    - Connecting any authorized Internet-enabled offsite discipline workstations (running a client and web-browser) to the onsite networked CDF workstations (running a custom webserver) for multi-disciplinary contents sharing simultaneously. The offsite/onsite clients disciplines workstations access the webserver, which is hard-wired to the video wall, by visiting the webserver's uniform resource locator (URL) address.

- For ER4:
  o The recommended CDF architecture consists of generic upgradable IT hardware, off-the-shelf design and support software tools, and Cloud Computing.
    - This low-cost implementation is possible due to the advancements of computer hardware, Information and Communications Technology (ICT) infrastructure, and educational software licensing.

- For ER5:
  o The recommended CDF architecture consists of a proposed Multi-Disciplinary Optimization (MDO) Collaborative tool to support the CDF core iterative design process workflows. This MDO tool is also capable to support easy installation and integration of:
    - A large variety of 3rd party popular commercial design tools (low cost education licensing) using its ready-made built-in interfaces.
    - In-house developed tools with its built-in custom-made interface wizard-style tool.
    - A case study (simulation) conducted in the thesis has demonstrated the seamless integrations of the proposed MDO tool with the spreadsheets/workbook and computational simulation tools.

- For ER6:
  o The recommended CDF architecture consists of generic hardware, which can easily be used to install many different disciplines software tools without or in rare scenarios, with minimum restrictions, which may be resolved with upgrade (e.g. more ram).
    - Different installed disciplines software tools can be used in the CDF generic hardware at any given times, depending on the project types and disciplines.

- For ER7:
    o The recommended CDF architecture consists of low cost and yet, powerful upgradable hardware as requirement arise. For examples:
        ▪ PC: upgradable components (new technology) includes: display, hard-drive and/or solid-state-drive capacity, Central-Processing-Unit (CPU), Graphic-Processing-Unit (GPU) etc.
        ▪ Video Wall: add new display panel, by tiling using daisy-chain/display-port connections.

- For ER8:
    o The recommended CDF architecture includes secure data storage of 2 types:
        ▪ Cloud Computing Services: design data kept in the pubic cloud service.
        ▪ Virtual Private Networks (VPN): design data kept in the internal CDF data exchange server.

VPN is proposed for design projects that are confidential, patent and defense in nature, because VPN can provide highly secure data networking connections between the onsite CDF (internal) data exchange storage server and authorized offsite disciplines workstations. VPN can be setup in software (e.g. Window 10 Operating System built-in feature), with no additional hardware requirement.

Onsite students/researchers/staff will need to be trained to back up their design project data to the CDF internal data exchange server only, which 'sit' behind a firewall. Offsite/international students/researchers/commercial partners will also need to be trained to back up their design project data to the onsite CDF internal data exchange server using VPN connections only.

On the other hand, Cloud Computing Services data storage, though less safe than VPN, is also proposed, mainly due to its ease of implementation and low cost (i.e. not required to purchase separate internal data storage server, including annual maintenance cost). Therefore, Cloud data storage services is proposed for design projects that are not confidential, not patent/copyright and not defense in nature. Such design projects may be based on design themes that simulate industrial scenarios or design competitions etc.

For minimum internet speeds requirements, a broad estimate of standard resolution video streaming is at 3Mbit/s, HD at 5Mbit/s and UHD at 25Mbit/s. Assuming a typical design session may have 1 ongoing HD video streaming, including some other uploading/downloading taking place in parallel, intuitively, a 50 - 100Mb internet speed at the onsite and offsite discipline stations is sufficient for seamless and simultaneous collaborations.

- For ER9:
    o The recommended CDF architecture consists of a proposed off-the-self commercial collaborative design tool that are capable of:
        ▪ Performing system integration from CAD/CAE/numerical-computation to optimization, visualization, statistical and sensitivity analysis, and full product data management integration.
        ▪ Performing intuitive workflows creations based on simple Drag-and-Drop of functional and application built-in interface icons into its workflow space. This is a relatively short process before the first meaningful data is entered.
        ▪ Research works in the thesis has utilised the proposed MDO tool to integrate with the spreadsheet/workbook and computational simulation tools to conduct a case study (simulation). The case study is able to successfully determine that this MDO tool is intuitive, easy to learn and use, and efficient.

- Performing in multi-disciplinary environments, such as Aerospace, Automotive, Electronics, and Architectural and Construction disciplines for design projects.

- For ER10:
  - The recommended CDF architecture consists of:
    - Powerful low-cost generic computer hardware, a large video wall, smart board, and supporting Networking/ICT infrastructure for concurrent seamless Data processing.
    - CDF room physical layout, with the 'U' configurations of the 10 PCs/disciplines and front large video wall, including ergonomics considerations to provide suitable visualisations.
    - Media contents are shared seamlessly and simultaneously with the proposed support tool to display between the video wall and the 10 connected PC on-site and any authorised off-site PC.
    This function has been successfully demonstrated through a case study (simulation) in the thesis.

- For ER11:
  - The recommended CDF architecture meets the ergonomic and safety standards in Australia:
    - Safe Work Australia: Code of Practice: Managing the work environment and facilities, Dec 2011. This is an Australian Government statutory agency.
    - The University of Adelaide: Health, Safety and Welfare (HSW) Handbook: Workstation Ergonomic Guidelines, Oct 2015.

    The relevant standards and guidelines include:
    - Lighting will be sufficient to allow the design teams to function safely and effectively. There will be minimum glare and reflection to avoid straining the eyes.
    - Ambient air temperature range, humidity and air movement will be comfortable.
    - Workstation ergonomic ideal setup.
    - Ambient air temperature range and humidity will be within equipment operating range such as video wall.

- For ER12:
  - The recommended CDF architecture includes a set of integrated Pre-CDF components, aiming to provide sufficient training and preparation to students prior to their progression to the subsequent year for the actual CDF-based training. These proposals include:
    - Utilising the Aircraft Design Collaborative (IACDT) Tool developed in the thesis to enhance the Year-3 aircraft design course with CE workflows.
    - The various separate formal short courses for: CAD/CAE, Computational Simulations, Multi-Disciplinary Optimisations, and more focus on Project Management.
  Note:
  The term 'Pre-CDF' usually refers to time-dependency element. Example, before a CDF has been installed. However, in the thesis, it refers to the students being trained in the CDF related curriculums, before they progress to the subsequent year to utilize the CDF that is already installed.

Future works

Future works may include Prototyping and Visualisations enhancements evaluations capabilities in the overall CDF-based design project course. Such enhanced extensions may be through various methods, such as 3-Dimensions printing, and virtual/augmented reality (VR/AR) that are becoming popular in the industries.

These are interesting future directions because the initial CDF only allows for visualisations of 3D model in 2D screen. However, with 3D Printing or VR/AR, students' exposure to the system engineering will be enhanced in terms of depth and breath. Just like using the 2D screen for reviewing/inspecting the 3D model, in the 3D printing or VR/AR situations, students may export the same 3D models file into any of the following:

- A 3D Printer to print the scale-down physical prototype with multiple parts making up the complete model, or
- A VR/AR environment where students can digitally visualise the 3D model from different point of views.

For the prototype with multi-sub-parts, it will allow students to separate the parts to conduct close-up hands-on physical inspections/reviews, which is far more detail than reviewing on a 2D screen. While, in a VR/AR environment (using a headset and hand-held device), students will also be able to 'move around' in a virtual environment to look, and 'touch and assess' the 3D model from different perspectives.

Both of these technologies are more engaging and effective in identifying issues in the early design stage. By implementing this technology, students may remain motivated to produce the 3D model quickly and keeping them interested in the projects.

References

[1] C. Bil and P. Marzocca, "Concurrent design facility for aerospace education," presented at the 9th Annual International Conference on Education and New Learning Technologies, Barcelona, 2017.

[2] L. Yang and X. Yongquan, "Application of Concurrent Engineering in Satellite Design," in *Computer Science & Education (ICCSE) 2010 5th International Conference*, 2010, pp. 292-295.

[3] A. Pickering. (2017, 22 Aug 2018). *The ESA Concurrent Design Facility Concurrent Engineering Applied to space mission assessments*. Available: https://esamultimedia.esa.int/docs/cdf/CDF_infopack_2017.pdf

[4] T. J. Mosher and J. Kwong, "The Space Systems Analysis Laboratory: Utah State University's new concurrent engineering facility," in *Aerospace Conference, 2004. Proceedings. 2004 IEEE*, 2004, pp. 3866-3872.

[5] RAL Space - Science & Technology Facilities Council U.K. and D. Griffin. (2016, 02 Oct 2018). *Science & Technology Facilities Council, The RAL Space Concurrent Design Facility (CDF)*. Available: http://www.ralspace.stfc.ac.uk/RALSpace/Facilities/35656.aspx

[6] M. Bandecchi, B. Melton, B. Gardini, and F. Ongaro, "The ESA/ESTEC concurrent design facility," *Proceedings of EuSEC,* vol. 9, p. 2000, 2000.

[7] P. Soloveichik. (2012, 22 Aug 2018). *Boeing Completes Preliminary Design Review for Space Launch System Core Stage*. Available: http://boeing.mediaroom.com/2012-12-21-Boeing-Completes-Preliminary-Design-Review-for-Space-Launch-System-Core-Stage

[8] J. Z. Kelley Case, Bjorn Cole, James Chase, and Michael Kolar "Cohesion, Power, Flexibility: JPL Formulation MBSE Vision," Jet Propulsion Laboratory, California Institute of Technology2014.

[9] F. Mas, J. L. Menéndez, M. Oliva, and J. Ríos, "Collaborative Engineering: An Airbus Case Study," *Procedia Engineering,* vol. 63, pp. 336-345, 2013.

[10] T. Pardessus, "Concurrent Engineering development and practices for aircraft design at Airbus," presented at the 24th International Congress of the Aeronautical Sciences, Yokohama, 2004.

[11] F. Mas, J. L. Menéndez, M. Oliva, A. Gómez, and J. Ríos, "Collaborative Engineering Paradigm Applied to the Aerospace Industry," in *Product Lifecycle Management for Society*, Berlin, Heidelberg, 2013, pp. 675-684.

[12] International Monetary Fund (IMF). (2018, 22 Aug 2018). *World Economic Outlook Update*. Available: http://www.imf.org/en/Publications/WEO/Issues/2018/01/11/world-economic-outlook-update-january-2018

[13] General Aviation Manufacturers Association, "General Aviation Manufacturers Association 2017 ANNUAL REPORT," U.S. HEADQUARTERS 1400 K Street, NW, Suite 801 Washington, DC 200052017.

[14] T. Captain and A. Hussain, "2017 Global aerospace and defense sector outlook - Growth prospects remain upbeat," Deloitte, New York - National Office 30 Rockefeller Plaza, 41st Floor New York, NY United States, 10112-00152017.

[15] M.-H. Huang and D.-Z. Chen, "How can academic innovation performance in university–industry collaboration be improved?," *Technological Forecasting and Social Change,* vol. 123, pp. 210-215, 10// 2017.

[16] D. Xu, C. Bil, and G. Cai, "Framework of concurrent design facility for aerospace engineering education based on cloud computing," *IOS Press (Netherlands),* 2014.

[17]   R. Stephens and E. V Scott, "ENSURING WORKFORCE SKILLS OF THE FUTURE: THE BIRTH TO WORK PIPELINE," presented at the AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Y, Dayton, Ohio, 2003.

[18]   Bureau of Labor Statistics - U.S. Department of Labor. (2018, 20 Aug 2018). *Occupational Outlook Handbook, Aerospace Engineers Job Outlook*. Available: https://www.bls.gov/ooh/architecture-and-engineering/aerospace-engineers.htm#tab-6

[19]   Aerospace Industries Association, "The Defining Workforce Challenge in U.S. Aerospace & Defense STEM EDUCATION, TRAINING, RECRUITMENT & RETENTION," Aerospace Industries Association,, 1000 Wilson Boulevard, Suite 1700 Arlington, Va 22209-3928 703.358.10002016.

[20]   Professional Engineering. (08 July 2009) Aerospace courses are failing to meet employers' needs. *Professional Engineering Magazine* [News]. Available: http://imeche.summon.serialssolutions.com/?q=aerospace%20course%202009#!/searc h?ho=t&fvf=ContentType,Magazine%20Article,f&l=en&q=mismatch%20between% 20aerospace%20courses%20and%20employers'%20need%202009

[21]   C. Fortin, J.-P. Lemarquis, S. Yue, Y. F. Zhao, M. Kokkolaras, and K. Packwood, "A NEW CDIO-BASED TRAINING PROGRAM FOR ADVANCED DEGREES IN AEROSPACE," presented at the Proceedings of the 10th International CDIO Conference, Universitat Politècnica de Catalunya, Barcelona, Spain, June 16-19, 2014., Barcelona, Spain, 2014.

[22]   M. Jollands, "A framework for graduate employability adapted for discipline differences," presented at the HERDSA 2015 conference proceedings, 2015.

[23]   L. Dacre Pool and P. Sewell, "The key to employability: developing a practical model of graduate employability," *Education + Training,* vol. 49, pp. 277-289, 2007.

[24]   J. Smith, "Concurrent Engineering in the Jet Propulsion Laboratory Project Design Center," presented at the Aerospace Manufacturing Technology Conference & Exposition, U.S.A., 1998.

[25]   J. A Aguilar, A. B Dawdy, and G. W Law, "The Aerospace Corporation's Concept Design Center," in *INCOSE International Symposium*, 1998, pp. pp.776-782.

[26]   D. Xu, C. Bil, and G. Cai, "Overview on the development of concurrent design facility," in *20th ISPE International Conference on Concurrent Engineering: Proceedings*, 2013, p. 551.

[27]   European Space Agency. (2012, 22 Aug 2018). *ESA: Concurrent Design Facility*. Available: http://www.esa.int/Our_Activities/Space_Engineering_Technology/CDF/What_is_the _CDF

[28]   J. Rodríguez, A. Laverón-Simavilla, J. M. del Cura, J. M. Ezquerro, V. Lapuerta, and M. Cordero-Gracia, "Project Based Learning experiences in the space engineering education at Technical University of Madrid," *Advances in Space Research,* vol. 56, pp. 1319-1330, 2015.

[29]   A. B. Ivanov, L. Masson, and F. Belloni, "Operation of a Concurrent Design Facility for university projects," in *2016 IEEE Aerospace Conference*, 2016, pp. 1-9.

[30]   A. Braukhane. (2011, 01 July 2018). *The DLR Concurrent Engineering Facility (CEF), A presentation*. Available: https://www.dlr.de/irs/Portaldata/46/Resources/dokumente/sara/CEF_presentation_20 11_v1.pdf

[31]   A. B. Ivanov, V. Gass, M. Richard, S. Rossi, and F. Belloni, "Concurrent design facility in an academic environment," in *64th International Astronautical Congress 2013, IAC 2013*, Beijing, 2013, pp. 9590-9594.

[32] P. Esteves and E. Detsis. (2010, 01 July 2018). *Concurrent Engineering at the International Space University*. Available: https://www.researchgate.net/publication/268290037_Concurrent_Engineering_at_the_International_Space_University

[33] O. Romberg, A. Braukhane, and H. Schumann, "Status of the Concurrent Engineering Facility at DLR Bremen," presented at the DGLR-Congress, Bremen, Germany, 2008.

[34] Georgia Technical Institute. (1994, 03 Oct 2018). *Aerospace Systems Design Laboratory generic concurrent engineering, Georgia Tech*. Available: https://www.asdl.gatech.edu/History.html

[35] S. Finkel and M. Burazanis, "2.3.3 A Transparent Way for Process Guidance in Satellite Design," *INCOSE International Symposium,* vol. 14, pp. 312-326, 2004.

[36] R. Shishko, "The Proliferation of PDC-Type Environments in Industry and Universities," presented at the European Systems Engineering Conference Munich, Germany, 2000.

[37] F. Mas, J. L. Menéndez, M. Oliva, and J. Ríos, "Collaborative Engineering: An Airbus Case Study," *Procedia Engineering,* vol. 63, pp. 336-345, 2013.

[38] S. A. Bendoukha, K.-I. Okuyama, S. Bianca, and M. Nishio, "Control System Design of an Ultra-small Deep Space Probe," *Energy Procedia,* vol. 100, pp. 537-550, 2016.

[39] S. Cresto Aleina, N. Viola, F. Stesina, M. A. Viscio, and S. Ferraris, "Reusable space tug concept and mission," *Acta Astronautica,* vol. 128, pp. 21-32, 2016.

[40] L. Piovano, M. Brunello, L. Rocci, and V. Basso, "Representing planetary terrains into a virtual reality environment for space exploration," *Pattern Recognition and Image Analysis,* vol. 21, pp. 549-552, 2011.

[41] ICELAB UK. (2015, 02 Oct 2018). *Concurrent and Collaborative Design Studio at TIC of University of Strathclyde UK*. Available: http://icelab.uk/resources/ccds/

[42] G. Quinlan. (2017, 30 Oct 2018). *Australia's first space mission design facility opens in Canberra*. Available: https://the-riotact.com/australias-first-space-mission-design-facility-opens-in-canberra/224757

[43] A. Ivanov, M. Noca, M. Borgeaud, F. Belloni, E. Guzman, A. Flueglistaler*, et al.*, "Concurrent design facility at the Space Center EPFL," presented at the SECESA 2010 - 4th International Workshop on System & Concurrent Engineering for Space Applications, Netherlands, 2010.

[44] PassMark Software Pty Ltd. (2018, 20Aug2018). *About PassMark Software*. Available: https://www.passmark.com/about/index.htm

[45] D. Xu, C. Bil, and G. Cai, "A low cost CDF framework for aerospace engineering education based on cloud computing," ed: Amsterdam, Netherlands: IOS Press, 2013, pp. 561-568.

[46] V. G. Anton B. Ivanov, Muriel Richard, Luzius Kronig, Federico Belloni, "Concurrent Design Facility in an Academic Environment," *SECESA 2012, Lisbon,* 2012.

[47] Utah State University. (2018, 02 Nov 2018). *Mechanical Engineering - Aerospace Emphasis - BS*. Available: http://catalog.usu.edu//preview_program.php?catoid=12&poid=10403

[48] D. Xu, C. Bil, and G. Cai, "A CDF framework for aerospace engineering education " *Journal of Aerospace Operations,* vol. 4, pp. 67-84, 6 April 2016 2016.

[49] University of New South Wales. (2018, 28 Aug 2018). *Aerospace Engineering (Honours)*. Available: https://www.engineering.unsw.edu.au/study-with-us/undergraduate-degrees/aerospace-engineering#outlines

[50] The University of Queensland. (2018, 28 Aug 2018). *Course list for the Mechanical and Aerospace Engineering Dual Major*. Available: https://my.uq.edu.au/programs-courses/plan_display.html?acad_plan=MEAERW2342

[51]   Royal Melbourne Institute of Technology (RMIT) University. (2018, 12 Oct 2018). *Bachelor of Engineering (Aerospace Engineering)(Honours)*. Available: https://www.rmit.edu.au/study-with-us/levels-of-study/undergraduate-study/honours-degrees/bachelor-of-engineering-aerospace-engineering-honours-bh078

[52]   Times Higher Education. (2018, 08 Nov 2018). *Best universities in Australia and World Ranking 2019*. Available: https://www.timeshighereducation.com/student/best-universities/best-universities-australia

[53]   University of BRISTOL. (2018, 05 Nov 2018). *Aersopace Engineering (BEng/MEng)*. Available:
http://www.bristol.ac.uk/engineering/departments/aerospace/courses/undergraduate/

[54]   Cambridge Dictionary. (2018, 30 Oct 2018). *Meaning of "internship" in the English Dictionary*. Available: https://dictionary.cambridge.org/dictionary/english/internship

[55]   J. Bermejo, J. M. Álvarez, P. Arcenillas, E. Roibas-Millan, J. Cubas Cano, and S. Pindado Carrion, "CDF as a tool for space engineering master's student collaboration and concurrent design learning," presented at the 8th International Systems & Concurrent Engineering for Space Applications Conference. SECESA 2018, Glasgow, 2018.

[56]   C. Bil and G. Dorrington, "Student assessment in team project-based learning: Challenges and experiences," presented at the 9th Annual International Conference on Education and New Learning Technologies Barcelona, Spain 2017.

[57]   Clarkson College. (2017, 21 Aug 2018). *Role of the Tutor*. Available: http://www.clarksoncollege.edu/student-life/campus-services/student-success/tutors/become-a-tutor/role-of-the-tutor/

[58]   Project Management Institute Educational Foundation, "Bringing project management into the school transformation conversation," Project Management Institute Educational Foundation2014.

[59]   B. a. Harpham, *Project managers at work*. Berkeley, CA: Apress : Imprint: Apress, 2018.

[60]   E-USOC. (2018, 27 Nov 2018). *Spanish User Support and Operations Centre*. Available: https://www.eusoc.upm.es/

[61]   I. T. Germán Fernández Rico, Gustavo Alonso, Isabel Pérez Grande, Alejandro Martínez Muelas, "INTEGRATION OF THE CONCURRENT DESIGN FACILITY IN THE RESEARCH AND EDUCATIONAL ACTIVITIES AT IDR/UPM," *5th International Workshop on Systems & Concurrent Engineering for Space Applications Lisbon,* 2012.

[62]   T. J. Mosher and J. Kwong, "The Space Systems Analysis Laboratory: Utah State University's new concurrent engineering facility," vol. 6, ed. USA, 2004, pp. 3866-3872.

[63]   M. H. Sadraey, *Aircraft Design, A systems engineering approach*: John Wiley & Sons Ltd, U.K., 2013.

[64]   S. Gudmundsson, *General Aviation Aircraft Design : Applied Methods and Procedures*. Saint Louis, UNITED STATES: Elsevier Science, 2013.

[65]   J. Roskam, *Airplane Design: Part II: Preliminary Configuration Design and Intergration of the Propulsion System*. Lawrence, Kansas [USA]: DAR Corporation, 2004.

[66]   D. P. Raymer, "Aircraft Design: A Conceptual Approach," *American Institute of Aeronautics and Astronautics, Inc. Washington D.C. 20024,* 1992.

[67]   D. P. Raymer, *Aircraft design : a conceptual approach*, 2nd ed. ed. Washington, D.C: American Institute of Aeronautics and Astronautics, 1992.

[68]   J. Roskam and C. E. Lan, *Airplane aerodynamics and performance*, [Rev. ed.] ed. Lawrence, Kan.: DARcorporation, 1997.

[69]   M. H. Sadraey, *Aircraft Design A Systems Engineering Approach*. Chichester, West Sussex, U.K.: Wiley, 2013.

[70]   Y.-S. Shin, K.-W. Lee, J.-S. Ahn, and J.-W. Jung, "Development of Internship & Capstone Design Integrated Program for University-industry Collaboration," *Procedia - Social and Behavioral Sciences,* vol. 102, pp. 386-391, 2013.

[71]   Analytical Graphics Inc. (2018, 04 Nov 2018). *AGI Engineering Tool: Systems Tool Kit (STK)*. Available: http://www.agi.com/products/engineering-tools

[72]   MathWorks. (2018, 30 Oct 2018). *MathWorks, Mathlab Aerospace Blockset to model, simulate, and analyse aerospace vehicle dynamics*. Available: https://au.mathworks.com/products/aeroblks.html

[73]   Dassault Systèmes SolidWorks Corporation. (2018, 31 Oct 2018). *SOLIDWORKS and SW PDM System Requirements*. Available: https://www.solidworks.com/sw/support/SystemRequirements.html

[74]   Microsoft. (2018, 31 Oct 2018). *System requirements for Office*. Available: https://products.office.com/en-au/office-system-requirements

[75]   ESTECO. (2018, 31 Oct 2018). *modeFRONTIER User Guide: Minimum System Requirements*. Available: https://mydesktop.rmit.edu.au/Citrix/StoreWeb/clients/HTML5Client/src/SessionWindow.html?launchid=1540957334925

[76]   H. P. d. Koning, S. Gerene, I. Ferreira, A. Pickering, F. Beyer, and J. Vennekens. (2014, 31 Oct 2018). *ESA Open Concurrent Design Tool ESA Community Open Source Ready to Go!* . Available: http://old.esaconferencebureau.com/docs/default-source/14c08_docs/open-concurrent-design-tool---esa-community-open-source-ready-to-go!.pdf?sfvrsn=0

[77]   M. Frenzel, D. Heiserer, D. Keller, M. Schemat, V. Balabanov, R. Dreisbach*, et al.*, "Multidisciplinary optimization and integration requirements for large-scale automotive and aerospace design work," presented at the 11th World Congress on Structural and Multidisciplinary Optimisation 07th -12th, June 2015, Sydney Australia, 2015.

[78]   Dassault Systemes. (2018, 04 Nov 2018). *Isight & the SIMULIA Execution Engine. Process automation and design exploration*. Available: https://www.3ds.com/products-services/simulia/products/isight-simulia-execution-engine

[79]   ESTECO. (2018, 04 Nov 2018). *modeFRONTIER. Process automation and optimisation in the engineering design process*. Available: https://www.esteco.com/modefrontier

[80]   P. Rubens. (2014, 17 Sep 2018). *CIO: 7 Reasons Not to Use Open Source Software*. Available: https://www.cio.com/article/2378859/open-source-tools/7-reasons-not-to-use-open-source-software.html

[81]   G. Moody. (2009, 31 Oct 2018). *Should Software Developers Be Liable for their Code?* Available: https://www.linuxjournal.com/content/should-software-developers-be-liable-their-code

[82]   R. M. Coroneos and S. S. Pai, "Deterministic Design Optimization of Structures in OpenMDAO Framework - NASA/TM-2012-217433," ed: Sponsoring Organization: NASA Glenn Research Center, 2012.

[83]   X. Shi, "Design optimization of insulation usage and space conditioning load using energy simulation and genetic algorithm," *Energy,* vol. 36, pp. 1659-1667, 2011.

[84]   A. Mosavi, R. Rituraj, and A. R. Varkonyi-Koczy, "Review on the usage of the multiobjective optimization package of modeFrontier in the energy sector," vol. 660, ed, 2018, pp. 217-224.

[85]   ESTECO. (2018, 21 Aug 2018). *ModeFRONTIER Integration nodes*. Available: https://www.esteco.com/technology/integration-nodes

[86]   ESTECO. (2018, 21 Aug 2018). *Multiobjective Aerospace mission performance optimisation with Systems Tool Kit (STK) and modeFRONTIER*. Available: https://www.esteco.com/modefrontier/multiobjective-aerospace-mission-performance-optimization-systems-tool-kit-stk-and-mode

[87]   Microsoft. (2018, 21 Aug 2018). *Microsoft - Microsoft Office Product Page*. Available: https://products.office.com/en-au/home

[88]   MathWorks. (2018, 21 Aug 2018). *MathWorks - MATLAB for Deep Learning*. Available: https://au.mathworks.com/

[89]   Analytical Graphics Inc. (2018, 21 Aug 2018). *Analytical Graphics, Inc - Mapping Space and Time - Yesterday. Today. Tomorrow*. Available: http://www.agi.com/home

[90]   Dassault Systèmes SolidWorks Corporation. (2018, 21 Aug 2018). *SOLIDERWORKS Office Site - SOLIDWORKS 2018 | Accelerate Innovation*. Available: https://www.solidworks.com/

[91]   Microsoft. (2018, 21 Aug 2018). *Compare Excel 2016 for Mac with Excel 2013 for Windows, Applies To: Excel for Office 365 for Mac Excel 2016 for Mac*. Available: https://support.office.com/en-us/article/Compare-Excel-2016-for-Mac-with-Excel-2013-for-Windows-1b24f293-739c-4120-b884-893b6687e0d0

[92]   MathWorks. (2018, 21 Aug 2018). *MathWorks: System Requirements & Platform Availability*. Available: https://au.mathworks.com/products/availability.html

[93]   SolidWorks Dassault Systemes. (2018, 21 Aug 2018). *SOLIDWORKS System Requirements*. Available: https://www.solidworks.com/sw/support/SystemRequirements.html

[94]   Analytical Graphics Inc. (2018, 21 Aug 2018). *Analytical Graphics, Inc - Mapping Space and Time, yesterday, today, tomorrow*. Available: http://www.agi.com/resources

[95]   MathWorks. (2018, 31 Oct 2018). *System Requirements - Release 2018a*. Available: https://www.mathworks.com/content/dam/mathworks/mathworks-dot-com/support/sysreq/files/SystemRequirements-Release2018a_Windows.pdf

[96]   Analytical Graphics Inc. (31 Oct 2018). *STK recommended system requirements*. Available: http://help.agi.com/stk/index.htm#install/sysreq.htm

[97]   Oracle Corporation. (31 Oct 2018). *Java: What are the system requirements for Java?* Available: https://www.java.com/en/download/help/sysreq.xml

[98]   N. H. Hussein and A. Khalid, "A survey of Cloud Computing Security challenges & solutions," *International Journal of Computer Science & Information Security,* vol. 14, p. 52, 2016.

[99]   I. Ştefan and I. Alina Anabela, "CLOUD COMPUTING SECURITY," *Fiabilitate şi Durabilitate,* vol. 1-suppl, pp. 206-212, 2016.

[100]   K. Hashizume, D. G. Rosado, E. Fernández-Medina, and E. B. Fernandez, "An analysis of security issues for cloud computing," *Journal of Internet Services and Applications,* vol. 4, p. 1, 2013.

[101]   S. Subashini and V. Kavitha, "A survey on security issues in service delivery models of cloud computing," *Journal of network and computer applications,* vol. 34, pp. 1-11, 2011.

[102]   T. Marrinan, J. Aurisano, A. Nishimoto, K. Bharadwaj, V. Mateevitsi, L. Renambot, *et al.*, "SAGE2: A new approach for data intensive collaboration using Scalable

Resolution Shared Displays," in *10th IEEE International Conference on Collaborative Computing: Networking, Applications and Worksharing*, 2014, pp. 177-186.

[103] SAGE2. (2018, 18 Oct 2018). *SAGE2: Scalable Amplified Group Environment.* Available: http://sage2.sagecommons.org/

[104] Node js Foundation - Joyent Incorporation. (2018, 18 Oct 2018). *Node.js is a JavaScript runtime built on Chrome's V8 JavaScript engine.* Available: https://nodejs.org/en/

[105] European Space Agency. (2017, 21 Aug 2018). *Concurrent Design Facility Design Stations 1 to 19.* Available: http://www.esa.int/Our_Activities/Space_Engineering_Technology/CDF/Design_Stations_1_2

[106] Safe Work Australia, "Code of Practice, Managing the work environment and facilities," ed. Australia: Safe Work Australia, 2011.

[107] Assoc. Director HR Compliance and Improvement Services Australia. (2015, 22 Aug 2018). *HSW Handbook: Manual Handling and Ergonomics, Workstation Ergonomic Guidelines.* Available: https://www.adelaide.edu.au/hr/hsw/docs/haz-man-task-ergo-guide.pdf

[108] i. A. H. W. P. Van Der Zanden. (2014, 02 Nov 2018). *Readability in Classrooms.* Available: http://homepage.tudelft.nl/9c41c/Readability_in_classrooms.pdf

[109] Workplace Health and Safety Queensland and Department of Justice and Attorney-General, "Ergonomic guide to computer based workstations," Workplace Health and Safety Queensland2012.

[110] S. Openshaw and E. Taylor, "Ergonomics and Design: A Reference Guide," ed. U.S.A.: Allsteel Inc., 2006.

[111] J. Higton, "Information Systems: AV Design Requirements - Display Screens," NOTTINGHAM Trent University, 50 Shakespeare Street, Nottingham, U.K.2017.

[112] Extron Electronics. (2018, 17 Oct 2018). *Font Size and Legibility for Videowall Content.* Available: https://www.extron.com/company/article.aspx?id=videowallfontsize&tab=technology

[113] NEC. (2018, 17 Oct 2018). *55" Ultra Narrow Bezel S-IPS 3x3 Video Wall Solution, Model: un551s-tmx9p* Available: https://www.necdisplay.com/p/displays/un551s-tmx9p

[114] Microsoft. (2018, 18 Oct 2018). *84 inches Microsoft Surface Hub (smart board).* Available: https://c.s-microsoft.com/en-us/CMSFiles/Tech_specs.pdf?version=be175007-9a11-e4fd-b6fb-5ee0c4351b64

[115] Engineers Australia. (2018, 10 Nov 2018). *The Institution of Engineers Australia (IEAust).* Available: https://www.engineersaustralia.org.au/About-Us

[116] M. Mourshed, T. Isherwood, A. Jaffer, C. Lim, B. Cardoso, S. Fennell, *et al.*, "Policy Debate | Education and Employment Mismatch, International Development Policy | Revue internationale de politique de développement," *OpenEdition Freemium for Journals,* 2014.

[117] Y. Sharma. (2014, 12 Nov 2018). *Around the World, the 'Skills Mismatch' Between Graduates and Jobs Is Growing.* Available: https://www.chronicle.com/article/Around-the-World-the/148735

[118] V. J. d. S. Pereira. (2009, 01 July 2018). *Development of a concurrent design facility based on ESA CDF: Application to aircraft design.* Available: https://fenix.tecnico.ulisboa.pt/downloadFile/395138023051/Vasco%20Pereira%20-%20CDF-IST_ARTIGO_Final.pdf

[119] Massachusetts Institute of Technology. (2018, 01 Sep 2018). *MIT Space Systems Laboratory.* Available: http://ssl.mit.edu/newsite/about/partners.php

[120] S. Makarov, R. Ludwig, and S. Bitar, *Practical electrical engineering*. Cham: Springer International Publishing : Imprint: Springer, 2016.

[121] Wikipedia the free encyclopedia. (2018, 21 Aug 2018). *Wikipedia: American wire gauge*. Available: https://en.wikipedia.org/wiki/American_wire_gauge

[122] Department of Transportation Federal Aviation Administration, "Maintenance of Electrical Power and Control Cables, February 8, 1978, FAA," vol. Initiated by: AAC-1010, distribution: FAF-0(Wide), RAF-3, ZAF-607, ZAC-328, ed. Federal Aviation Administration, USA: Federal Aviation Administration, USA, 1978.

[123] Adams Electric Cooperative. (2018, 21 Aug 2018). *Voltage Drop*. Available: http://www.adamselectric.coop/wp-content/uploads/2015/02/Voltage-Drop.pdf

[124] PowerStream Technology. (2018, 22 Aug 2018). *PowerStream 6000VA 3-phase Inverters*. Available: http://www.powerstream.com/inverter-3-phase-24vdc-208vac-6000w.htm

Appendices

Appendix A, Listing of Concurrent Design Facility Design Tools adopted in Industries and Industry-University Collaboration

Table 23, Listing of CDF design tools adopted in Industry and Industry-University Collaboration (1. ESA [6], 2. DLR [30], 3. SSC [31], 4. IST [118], 5. ISU [32], 6. UPM [28] and 7. MIT [119].

ESA/ESTEC CDF includes 18 desktop computers and 2 workstations http://www.esa.int/Our_Activities/Space_Engineering_Technology/CDF/Design_Stations_1_2	(1) European Space Agency (ESA)/ESTEC CDF — Tools	(2) Deutche Luft und Raumfahrt (DLR), the German Space Agency DLR CDF — Tools	(3) Swiss Space Center CDF in an academic environment — Tools	(4) Aerospace Laboratory of Instituto Superior Técnico, IST-CDF, Portugal 2009 — Tools	(5) International Space University (ISU) CDF, France — Tools	(6) Technical University of Madrid (UPM) CDF — Tools	(7) MIT, undergraduate education (CD) — Tools
1. Desktop computer (for system level): 5							
Team Leader	Not specified					Project Mgr: Not specified	
Systems	GT: MS Excel			GT: MS Excel	GT: MS Excel		Not specified
Programmatic and AIV: Assm integrate/ Verify	GT: MS Project			GT: MS Project			
Risk assessment	Not specified						
Cost Analysis	DST: ECOM Cost/ Technical Database & Small Satellite Cost Model	DST: Small Satellite Cost Model 2007 (development & production cost est)	DST: AGI STK	Not specified	Not specified		
2. Desktop computer (for sub-system level): 13							
Mission Analysis	DST: IMAT, AGI STK, ORION, Swing-by-Calculator	DST: STK	DST: AGI STK	DST: AGI STK	DST: AGI STK	DST: AGI STK	
Mechanisms & Pyrotechnics	Not specified		GT: CATIA, SolidWorks				Not specified
Power	Not specified		DST: AGI STK		Not specified	Electrical: Not specified	Not specified
Propulsion	Not specified				Not specified	Not specified	
AOCS (Attitude & Orbit Control System)	DST: Matrix X GT: MATLAB		GT: MATLAB	GT: MATLAB		Not specified	GT: MATLAB Simulink
Payload	Not specified		GT: MATLAB		Not specified	Not specified	
Documentation	GT: MS Word	GT: MS Office 2003		GT: MS Word	GT: MS Word GT: MS PowerPoint - presentation		
Structural Engineering	GT: CATIA		GT: CATIA, SolidWorks	GT: SolidWorks	GT: CATIA, AutoCAD	Mechanical: Not specified	DST: NASTRAN (analysis) GT: CATIA (design)
Ground System & Operation	Not specified						
Communication	DST: AGI STK		Not specified DST: AGI STK	DST: AGI STK	Not specified		DST: AGI STK
Data Handling	Not specified		DST: AGI STK				
Thermal control	Not specified		DST: ESARAD/ESATAN or GT: MATLAB Simulink		Not specified	DST: ESARAD/ESATAN	Not specified
Instruments	GT: MathCAD			Not specified			
Avionics & Software							Not specified
3. Workstation (for sub-system level): 2							
Configuration	GT: CATIA	DST: CATIA		GT: SolidWorks	GT: CATIA, AutoCAD		
Simulation	DST: EUROSIM	GT: MATLAB/Simulink	DST: AGI STK	DST: AGI STK	GT: MATLAB for sim - attitude Determination & control		
General Back-office systems (University)							
Storage area for all data files	GT: NT file server			WS1 Hard disk			
Documentation storage & archive	GT: Lotus Notes data base			WS1 Hard disk			

Appendix B, Listing of Domain Disciplines design stations in industry (ESA)

Table 24, Listing of Domain Disciplines design stations in Industry (ESA). Design stations 1 to 9 (top table) and 10 to 19 (bottom table) [105].

European Space Agency 19 Concurrent Design Stations descriptions (from station 1 to 9) [105]			
Date	No	Design Station	Descriptions
Design Stations 1of2, Last update: 25 September 2017	1	Team Leader	1. Responsible for managing the study. 2. Work with customer to define scope of study and mission objectives for study analysis. 3. Work with CDF Manager to select internal and external team members. 4. Organises design sessions, supervises team members works. 5. Works with systems engineers to complete the design at the shortest possible timeline. 6. At study conclusion, oversees compilation of final report, along with technical author.
	2	Systems	1. Team leader supervise the Systems engineer to conduct most of the systems level analysis. 2. In charge of budgets, which include mass and Power, and checks whether the design satisfies mission requirements. 3. Coordinates with the various disciplines and conduct design sessions in the absence of the team leader.

	3	Mission Analysis	1. Mission analyst defines the spacecraft operational environment with team leader and system engineer throughout its mission. This includes
			   1.1. Launch profile, orbital analysis, & trajectory definition.
			   1.2. 1.1. - Critical preliminary study phase, support mission definition requirements and development of a mission profile.
			2. Updates and optimises the mission profile as the spacecraft design progresses.

	4	CDF PC station for Ground Systems & Operations	1. GS&O engineer analyses resources required to support the spacecraft from a ground station & operational point of view & calculate cost of operating mission throughout its lifecycle. 2. Work with communications engineer to select ground station(s) to be used 3. Work with cost engineer to include costing for supporting workforce and equipment within the overall cost estimate. 4. Assesses overall mission operational complexity work with Systems engineer to optimise operational complexity versus cost constraints.

	5	Programmatic & AIV (assembly integration & verification)	1. Programmatic & AIV engineer develops plan for the development, fabrication, testing and integrating the spacecraft aimed at launching on time.
			2. This involves
			   2.1. Analysing the time for development work & procurement.
			   2.2. Defining the test models and testing procedures.
			   2.3. Advising the other disciplines whether the design can be easily tested & integrated.

	6	Technical Risk Assessment	1. Risk engineer analyses the preliminary spacecraft design and identifies risks during the mission, which is based on the designs from other disciplines, such as the:
			   1.1. Definition of a risk management policy.
			   1.2. Assessment of risks.
			   1.3. Communicate these risks to team leader.
			2. Overall goal - use this data to mitigate risk to improve chances of meeting goals.

	7	Cost Analyst	1. Responsible to:
			   1.1. Prepare the preliminary design industrial cost estimates.
			   1.2. Provide a cost-guided approach to the overall system design throughout study.

	8	Simulation	1. Simulation engineer is responsible to create the mission simulation.
			   1.1. To analyse the spacecraft motion at any time during mission.
			   1.2. To ensure that the simulation accurately reflects the latest design and mission profile data.

	9	Configuration	Configuration engineer is responsible for:
			1. The spacecraft components arrangement and fitting within their allocated spaces.
			   2. Working with structural engineer to generate CAD file to represent the assembled spacecraft.
			   3. Working with Programmatic / AIV engineer to analyse manufacturability and ease of assembly of the design.

			European Space Agency 19 Concurrent Design Stations descriptions (from station 10 to 19) [105]
Date	**No**	**Design Station**	**Descriptions**

Design Stations 2of2, Last update: 28 April 2014	10	Structural Engineering	1. Structural engineer designs the spacecraft supporting structure, which includes
			    1.1. Analysing the launch and operational environment to ensure that all components are
			        1.1.1. Properly supported.
			        1.1.2. Can survive the structural loads.
			    1.2. Creating CAD models for components and assembles it in a master file that represents the geometry of the entire spacecraft.

	11	Attitude & Orbit Control System (AOCS)	AOCS engineer: 1. Is responsible for the system that enables the spacecraft to determine, control its position and orientation throughout the mission. 2. Design sensors to measure attitude & actuators to change attitude, to ensure that the craft always points in the desired direction. 3. Works with propulsion engineer to ensure the spacecraft can perform all required manoeuvres.
	12	Propulsion	Propulsion engineer is responsible for Engine design, which involved: 1. Selecting and calculating the propellant required for mission. 2. Selecting a tank to hold the propellant. 3. Creating a preliminary design for the pumps, valves and pipes to supply the engines.
	13	Communication	Communications engineer is responsible for: 1. Designing a system to allow the spacecraft to communicate with Earth. 2. Interfaces with many disciplines in the study, which are involved in handling, transmitting, & receiving data to size the antenna and supporting hardware.
	14	Data Handling	CDF data handling engineer is responsible for: 1. The on-board system for collecting, interpreting and recording of data. 2. Analysing mission objectives, determines the required data processing and storage capability of the spacecraft, prior to sending data to Earth. 3. Specifies the required components and data bus to interface other subsystems to the central processor.
	15	Power	Electrical engineer is responsible for: 1. Designing the spacecraft power systems. 2. Analysing the power requirements for each subsystem and determines the overall power consumption profile. 3. Selecting and sizing the power generation system (solar arrays, primary cells). 4. Calculating the required battery capacity. 5. Generating specifications for the power handling system.
	16	Thermal Control	Thermal engineer is responsible for: 1. Ensuring that the spacecraft components are within the operating temperature ranges. 2. Analysing the mission profile to determine effect of the spacecraft operational environment. 3. Designing active and/or passive units to control temperatures throughout the spacecraft.
	17	Mechanisms & Pyrotechnics	Mechanical engineer is responsible for designing all spacecraft mechanical components to: 1. Provide options for moveable parts required for (e.g. an antenna pointing mechanism).
	18	Instruments	Instruments engineer is responsible for: 1. All spacecraft science instruments. 2. Defining the interface between instruments and spacecraft. 3. Interacting with the systems engineer and other disciplines to ensure that requirements relating to the instrument are satisfied.

	19	Technical Author, YGTs & Stagiaires	1. Technical author works with the team leader, customer and system engineer throughout the whole study. Tasks include
			    1.1. Minuting the design session discussions and results.
			    1.2. Production and edit all the final study documentation.
			    1.3. Production and edit all technical documentation related to the CDF and its utilisation, such as various technical domain-workbook user manuals, or the CDF user manual.
			    1.4. Assist in all the studies as assistant system engineers.
			    1.5. Support to the CDF activities such as rapid prototyping, model preparation, software management etc.

Appendix C, Operating the Initial Aircraft Conceptual Design Tool

IACDT is a collaborative tool originally developed in the thesis to demonstrate the concurrent design workflows and aims to enhance the pre-CDF multi-disciplinary optimisation education.

This appendix describes the detail operation of the collaborative tool called the Initial Aircraft Conceptual Design Tool (IACDT).

A typical IACDT process demonstration: begins with the following steps

- Step1: Create a new directory/folder in C drive (C:\IACDT) – only once during installing
- Step2: Copy the following files into the '*C:\IACDT directory/folder*' – only once during installing
  - File1: '*Workbook Concurrent Design - Conceptual Aircraft Design 1.xlsx*'
    - This is the main excel initial IACD source file
  - File2: '*ConcurrentDesignBasedTool - Conceptual Aircraft Design 1.SLDPRT*'
    - This is the main SolidWorks2017 data file, containing the 3D aircraft concept
  - File3: '*Worksheet in ConcurrentDesignBasedTool - Conceptual Aircraft Design 1.xlsx*'
    - This is SolidWorks2017 excel data file (with dimensions for 3D model) created within SolidWorks2017 dynamically linking dimensions of the aircraft conceptual design 3D model.
    - File3 can be opened within SolidWorks2017
- Step3: Launch IACDT by opening (double click) the preceding 3 files in below sequence:
  - 1st – open MS Excel File1
  - 2nd – open SolidWorks2017 File2
  - 3rd – open MS Excel File3 (in SolidWorks: '*Configurations-> Table-> Edit Table in New Window*')

At this point, MS-Excel File1 (with relevant dimensions for 3D model) is linked to MS-Excel File3 within SolidWorks2017, linking the 3D model. Any change in the relevant linked dimensions in MS-Excel File1 will also change the MS-Excel File3 and 3D model. This happens upon saving or closing File3.

IACDT process Colour code descriptions

On launching IACDT, the main MS-Excel workbook (File1) comprising of nine worksheets TABs will dynamically link to each other. Each of these TABs contains the design workflows and computations of specific sub-system component. Within some of TABs in File1, colour codes are provided in the relevant cells to represent the following functions:

15000	Denote manual entry values
4	Denote auto-calculated and/or linked values
400	Denote linked values
162.18	Denote values linked between SolidWorks2017 3D model's File3, and main MS-Excel

IACDT File1. Any change in File 1 automatically updates the model in SolidWorks.

Aircraft mission requirements (AMR), TAB: '1.IACDT-WORKFLOWS':

The main functions of this spreadsheet are to:

2. Provide Main Aircraft Mission Requirements (AMR), FAR23 by manual entries.
3. Highlight High-level IACDT process workflows (iterative)
4. Summary results (automatic updating computational results from TAB: 2 to 9 in Figure 14.

Main Aircraft Mission Requirements (AMR), FAR23 will be entered manually.

The main AMR includes aircraft conceptual design mission requirement values for FAR 23 as listed in Table 25 and Table 26. These are the:

- Range (R = nm)
- Endurance or loiter time (E = minutes)
- Take-Off ground roll at sea level (S = feet), which may be varied (demonstration purpose) for each unique design scenario during lecture session.

Figure 28 illustrates the actual manual data entries cells (blue values)/area for the AMR.

Table 25, Aircraft mission requirements

Requirements

(1) Mission Specification & Variant Requirements (Manual Entries)
- Payload (1 pilot + XX (variant, PAX) passenger
- Mission (R, E, 2R)
- Altitude
- Cruise speed
- Takeoff (distance (S) + temperature)
- Landing (distance (S/2) + temperature)
- Climb
- Service Ceiling
- Stall speed
- Certification: FAR 23

Table 26, Aircraft mission requirements: e.g. possible values (Left) & Variant values: R, E and S (Right) for FAR23 General Aviation, 1 engine, 1 pilot, 1 PAX aircraft IACD.

Mission Specification B

A single engine aircraft for private use has the following requirements:

Payload:	1 pilot and at least *PAX* passengers
Mission:	2 consecutive sets of cruise at least *R* nm and loiter at least *E* min, then return trip at least 2*R* nm
Altitude:	at least 15,000 ft for design mission
Cruise speed:	at least 120 kts
Takeoff:	ground roll at most *S* ft, at sea level and 120°F
Landing:	ground roll at most *S/2* ft, at sea level and 120°F
Climb:	climb to 15,000 ft in at least 20 min
Service ceiling:	at least 20,000 ft
Stall speed:	at most 48 kts
Certification:	FAR 23

Variant	1	2	3	4	5	6	7	8	9	10
PAX	1	1	1	1	1	1	1	1	1	1
R	80	80	100	100	125	80	80	100	100	125
E	40	45	20	40	20	40	45	30	30	30
S	750	750	750	750	750	900	900	900	900	900

Figure 28, TAB1: Manual Entries area (colour coded cells: blue values) for main mission requirements in IACDT (FAR23, 1 engine, 1 pilot, 1 PAX general aviation aircraft only).

Initial Weight Estimation (IWE), initial sizing – TAB '2.IACDT-Weight Estimate':

The main functions of this spreadsheet are to determine:
- Initial Gross Take-off Weight ($WTO_{convergence}$).
- Empty Weight (W_{empty}).
- Fuel Weight (W_{fuel}).

The computations' assumptions are based on the following historical data (Lift Coefficient):
- $C_{L_{maxClean}}$
- $C_{L_{maxTO}}$
- $C_{L_{maxLanding}}$

The computed results are subsequently applied to the relevant sub-system components (other linked spreadsheets) for further estimation as shown in Table 27.

Limitation of IACDT

IACDT is currently 'hard-wired' for FAR23, single engine, 1 PAX General Aviation (G.A.) aircraft only. Therefore, the historical data, statistical equations and assumptions used for computations are mainly for FAR23 G.A. aircraft. This is deemed sufficient for demonstration of the initial aircraft conceptual design within the CD environment. Future development may include FAR25 aircraft.

Table 27, Expected results: Initial Weight Estimation & Matching Chart (design points).

Conceptual Design Preliminary Sizing
Initial Weight Estimation (IWE) **IWE Result:** WTOconverge, Wempty, Wfuel **Historic Data:** CLmaxClean, CLmaxTO, CLmaxL
Matching Chart (MC) **MC Result: (manual select design pt)** T/W jet, W/hp propeller, W/S **IWE/MC Results:** Wing S (WTOconv/(W/S)), hp (WTOconv/(W/hp)) *Want lowest T/W and highest W/S* *Want highest W/hp and highest W/S* **Historic Data:** Wing AR

The complete Initial Weight Estimation (IWE) workflows are given as:

- Step1 (auto-calc.) – Determine Payload from Mission Requirements (Crew + PAX + Luggage and Cargo (excludes Fuel).
- Step2 (manual entry) – Reference Payload Weight (from step1) to research comparative aircraft's Initial Gross Take-off Weight (WTO_{guess}) with similar payload weight.
- Step3 (manual entry) – Select comparative aircraft with similar Payload weight and guess the initial gross take-off weight (WTO_{guess}).
- Step4 (auto-calc.) – Determine all Mission Segment Weight Fractions based on mission requirements.
- Step5 (auto-calc.) – Determine Fuel Weight Fraction ($\frac{Wfuel}{WTO}$) from Overall Mission Segment Weight Fraction ($\frac{Wlast}{WTO}$) of step4.
- Step6 (auto-calc.) – Determine Initial Gross Take-off Weight ($WTO_{convergence}$), by solving equation iteratively until no change in WTO (i.e. after convergence) in lbs.
- Step7 (auto-calc.) – Determine Empty Weight (W_{empty}) in lbs.
- Step8 (auto-calc.) – Determine Fuel Weight) (W_{fuel}) in lbs.

Matching Chart, sizing to performance – TAB '3.IACDT-Matching Chart': design points selection:

The main functions of this spreadsheet are to compute the Matching Chart (Power Loading vs. Wing Loading) for sizing to performance.
- Power Loading ($\frac{W}{hp}$) (lbs/hp) for propeller aircraft
- Wing Loading ($\frac{W}{S}$) (lbs/ft^2)

Once the Power Loading and Wing Loading have been computed for the sizing to Stall, Take-off, Landing, Cruise, Rate of Climb and Service Ceiling, the Matching Chart can be utilised to manually select 2 suitable possible design points. Subsequently, the following 2 values are automatically computed based on the 2 selected design points.
- Wing surface area (*S*)
- Maximum Take-off Engine horsepower (*hp*)

The complete Matching Chart workflows for sizing to performance are given as:

- Step1 (auto-calc.) – Sizing to Stall (Wing Loading $(\frac{W}{S})$ stall at assumed stall speed (V_{stall}) in kts.

- Step2 (auto-calc.) – Sizing to Take-off (Wing Loading (Power Loading $(\frac{W}{hp})TO$ in lbs/hp vs. $(\frac{W}{S})$ in lbs/$ft.^2$).

- Step3 (auto-calc.) - Sizing to Landing (Wing Loading $(\frac{W}{S})$ landing in lbs/$ft.^2$.

- Step4 (auto-calc.) – Sizing to Cruise (Power Loading $(\frac{W}{hp})cr$ in lbs/hp vs. $(\frac{W}{S})$ in lbs/$ft.^2$).

- Step5 (auto-calc.) – Sizing to Rate of Climb (ROC) $(\frac{W}{hp})roc$ in lbs/hp vs. $(\frac{W}{S})$ in lbs/$ft.^2$).

- Step6 (auto-calc.) – Sizing to Service Ceiling $(\frac{W}{hp})ceil$ in lbs/hp vs. $(\frac{W}{S})$ in lbs/$ft.^2$).

- Step7 (auto-calc. & Plot Matching Chart) $(\frac{W}{hp})$ in lbs/hp vs. $(\frac{W}{S})$ in lbs/$ft.^2$).

- Step8 (manual/visual determine) min. 2 Design Points from Matching Chart: $(\frac{W}{hp})$ and$(\frac{W}{S})$.

- Step9 (auto-calc.) – Wing Reference Area (S) in $ft.^2$, and Engine horsepower (hp) in hp from manual/visual determined 2 x Design Points.
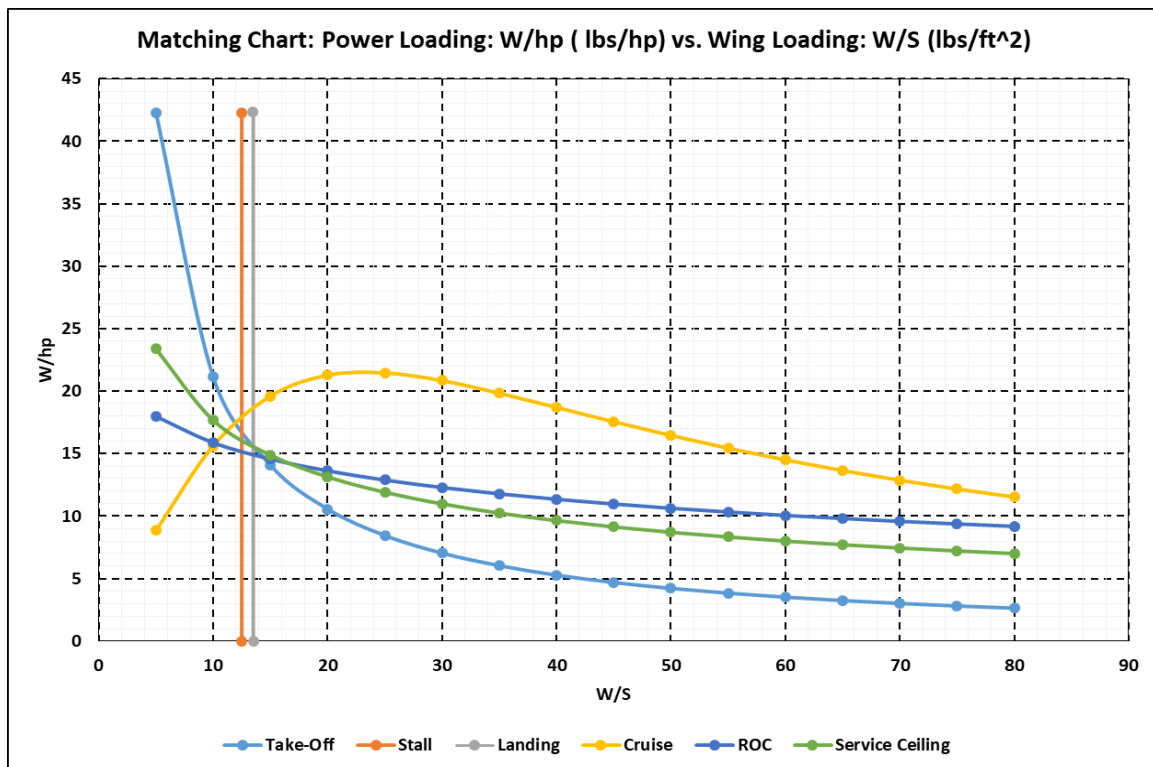

Figure 29, E.g. of Matching Chart Plot at Configurations phase: Power Loading vs. Wing Loading, to allow manual selections of Design Points.

Table 28, E.g. Manual selection of 2 suitable Design Points. Wing Ref. Area & Engine Power are auto-calc.

Possible Design Points					Manual Entry (Visual Est. fm Matching Chart)		
	WTO converge	Wempty	Wfuel	S	W/hp	w/s	hp
	lbs	lbs	lbs	ft^2	lbs/hp	lbs/ft^2	hp
Design Point 1	1633.88	1018.01	215.87	130.71	15.00	12.50	108.93
Design Point 2	1633.88	1018.01	215.87	162.58	16.50	10.05	99.02

- Step10 (manual selection) – 2 suitable Design Points from Matching Chart in Figure 29.
  - Table 28 illustrates the manual selections of 2 suitable Design Points, DP $(\frac{W}{hp})$, $(\frac{W}{S})$.
  - Wing Ref. Area (S) and Engine Power (hp) are auto-calc.
  - Colour codes:
    - 1 DP is manually selected (dark blue) from the 2 suitable DP (light blue)
    - S and hp are auto-calc. (yellow) and linked to WTO, W_{empty}, W_{fuel} (light grey)
  - Preference:
    - Highest Power Loading $(\frac{W}{hp})$: Propeller Aircraft or
    - Lowest Trust-to-Weight ratio $(\frac{T}{W})$: Jet Aircraft and
    - Highest Wing Loading – smaller size and lower weight wing
- Step11 (Proceed to Aircraft Configurations) upon computing all the results as in Table 28.

Aircraft Configuration – TAB '4.IACDT-Config FUSELAGE'

This section describes Aircraft Configuration phase to estimates the fuselage Width, Height, Length and Internal Cabin dimensions. Fuselage design will consider the Payload, Flight Crew, System, Low Drag Shape and Low Structural Weight.

Fuselage design – TAB '4.IACDT-Config FUSELAGE'

The main functions of this spreadsheet are to commence the Preliminary Configuration Design Process upon computing all the results as illustrated in Table 29. These are the design summary results, which include:

- Initial Weight Estimation (initial Sizing)
- Matching Chart (Sizing to Performance)
- Historical Data assumption.

This process will commence with the Fuselage. The additional parameters are also required:

- Fuselage Length and Diameter can be computed based on following taken from Aircraft Mission Requirements [66]:
  - Number of passengers, pilots and seats-across
- Fuselage Nose Length can be computed based on:
  - Engine Model specification, which in-turn, is based on the Power Loading derived from Initial Weight Estimation and Matching Chart

Table 29, Design Summary from Initial Weight Estimation, Matching Chart and Historical Data used as preliminary configuration to begin design process.

	Sizing Description	Abbreviation	Unit	Originate from	Remark
1	Initial Gross Take-Off Weight	$WTOconverge$	lbs	Initial Weight Estimation	
2	Empty Weight	$Wempty$	lbs	Initial Weight Estimation	
3	Fuel Weight	$Wfuel$	lbs	Initial Weight Estimation	
4	Power Loading (Propeller AC)	$(\frac{W}{hp})$	$\frac{lbs}{hp}$	Matching Chart: sizing to performance	FAR23
5	Or Trust-to-Weight Ratio	$(\frac{T}{W})$	$\frac{lbf}{lbs}$	Matching Chart: sizing to performance	FAR25
6	Wing Loading	$(\frac{W}{S})$	$\frac{lbs}{ft^2}$	Matching Chart: sizing to performance	
7	Wing Reference Area	S	ft^2	$(\frac{WTOconverge}{(\frac{W}{S})})$	
8	Engine Horse Power	hp	hp	$(\frac{WTOconverge}{(\frac{W}{hp})})$	
9	Wing Aspect Ratio	AR		Historical Data	[67]
10	Max. Lift. Coefficient	$Clmaxclean$		Historical Data	[68]
11	Max. Lift. Coefficient	$ClmaxTO$		Historical Data	[68]
12	Max. Lift. Coefficient	$ClmaxL$		Historical Data	[68]

The complete Fuselage design workflows are given as:

- Step1 (manual entry): Fuselage internal Width, Height & Structural Wall Thickness assumption
  - Fuselage internal Width dimensions ($d_{fw_{internal}}$), assumption 2+18+8+18+2 = 48 inch [64, 67].
  - Fuselage structural thickness ($d_{fs_{thickness}}$): 1.5 in. [67].
  - Fuselage internal height ($d_{fh_{internal}}$): 49 in. [64].
  - Fuselage Door
- Step2 (manual entry): Historical Data for equation used for Fuselage Length estimation [67]:
  - a = 4.37 and c = 0.23
- Step3 (manual entry): Historical Data for equation (Roskam Part 2 2004) used for Fuselage Length estimation
  - Fuselage length and fuselage dim ext. width ratio($\frac{l_f}{d_f}$).
  - Fuselage Cone length and fuselage dim ext. width ratio($\frac{l_{fc}}{d_f}$).
  - Fuselage Tip Back Angle(θ_{fc}).
- Step4 (auto-link) from TAB '5.IACDT-Config PROPULSION' – Engine Length (L_{engine})
  - Engine Length (L_{engine}), $X = a(bhp)^b$ (lb or in.), table 10.4 [67].
    Note: Step4 (auto-link) true result cannot be computed until:
    - A suitable Design Point is selected
    - Subsequent (auto-calc) of Engine Horsepower in TAB '3.CDF-Matching Chart'
    - Historical Data are manually entered in TAB '5.IACDT-Config PROPULSION' [67].
  - Engine Length, La = 3.86 and Engine Length, Lb = 0.42
- Step5 (manual entry): Historical Data for Propeller Spinner Length & Engine + Firewall Buffer Length (L_{engine}).
  - Propeller Spinner Length, L_{ps} – Assumption
  - Propeller Spinner Diameter, D_{ps} - Assumption

- o Engine/Firewall Buffer Length [64].
- Step6 (auto-calc.): Fuselage external Width, Height, Length & Cone Length
  - o Fuselage external width dimension $(d_{fw_{external}}) - (d_{fw_{internal}} + (d_{fs_{thickness}} * 2))$
  - o Fuselage external height dimension $(d_{fh_{external}}) - (d_{fh_{internal}} + (d_{fs_{thickness}} * 2))$
  - o *Fuselage Length (based on Step2 data, equation & $WTO_{convergence}$), $l_f = aW_{TO}^c$
  - o **Fuselage Length (based on Step3 data & equation): $d_{fexternal}(\frac{l_f}{d_f})$.
  - o Fuselage Cone length (l_{fc}) (based on Step3 & equation) : $((\frac{l_{fc}}{d_f})d_f)$.

    Note: The results from step 6* and 6** should be quite similar. The $(\frac{l_f}{d_f})$ ratio should be within Roskam's recommended range [68].
- Step7 (auto-calc.): Fuselage Nose Length (from spinner tip to firewall)
  - o Fuselage Nose Length (L_{fn}): *Sum* (L_{engine} + L_{ps} +L_{buffer}).
- Step8 (manual entry): Historical Data for Fuselage Cockpit Length [64].
- Step9 (auto-calc.): *Luggage Length = Fuselage total Length – Nose Length – Cockpit Length – Cone Length – Row2PAXseatLength* (if applicable).

Aircraft Configuration – TAB '5.IACDT-Config PROPULSION'

The main functions of this spreadsheet are to commence the Preliminary Configuration Design for the Propulsion System. The tasks performed will include the estimation of the Engine Length, Width, Height, Weight (Un-installed stage) and (Installed in fuselage), including the Propeller Length (2 blades) by referencing the historical data.

Propulsion design – TAB '5.IACDT-Config PROPULSION'

Once the Engine horsepower has been estimated based on the manually selected design point in the Matching Chart, the preliminary configuration design process for the Propulsion System can begin.

Note: Fuselage design requires the Propulsion System results prior to completion.

The complete Propulsion system design workflows are given as:

- Step1 (auto-link) - Engine Horsepower (*hp*) from TAB '*3.IACDT-Matching Chart*' (auto-calc. from selected design point: $(\frac{WTOconverge}{(\frac{W}{hp})})$
- Step2 (manual entry) – Historical Data for Engine Width, Height, and Equations to calc. Engine Weight and Length [67].
  - o Weight, *Wa* = 5.47 and *Wb* = 0.78
  - o Length, *La* = 3.86 and *Lb* = 0.42
  - o Width = 34 in (range 32 to 34 in)
  - o Height = 25 in (range 22 to 25 in)
- Step3 (manual entry) – Historical Data (assumption) for Propeller Weight (est. 20 lbs, 2 blade)
- Step4 (auto-calculation) – Engine Weight (Not installed), (Installed with Prop + Spinner), Engine Length & Propeller Length (using 2 blades equation) [67].
  - o Engine Weight, $X = a(bhp)^b$ (*lb or in.*), table 10.4.

- o Engine Length (Not installed and installed results)
- o Propeller Length equation (diameter, *d*), (10.23), (10.24) respectively:

$$2\text{-blade: } d = 22\sqrt[4]{Hp} \qquad \text{Equation 1}$$

$$3\text{-blade: } d = 18\sqrt[4]{Hp} \qquad \text{Equation 2}$$

Aircraft Configuration – TAB '6.IACDT-Config WING'

The main functions of this spreadsheet are to commence the Preliminary Configuration Design for Wing. The tasks performed include the estimation of the Wing Parameters such as the Dimensions, Aerofoil selection, High Lift. Device (single slotted flap), Control Surfaces (Flap and Aileron) and Fuel Storage (volume) in Wing (need to reference the historical data).

Wing design – TAB '6.IACDT-Config WING'

Wing design can begin once the following parameters have been computed or assumed:
- Engine Wing Loading ($\frac{W}{S}$)
- Wing Reference Area (*S*) from Initial Weight Estimation and Matching Chart (selected design point: ($\frac{W}{hp}$) vs. ($\frac{W}{S}$))
- Historical Data required:
  - o Wing Aspect Ratio (*AR* = 7.6, [67].
  - o Lift Coefficient ($C_{L_{maxClean}}$ = 1.6, $C_{L_{maxTO}}$ = 1.8 (Est. 80% L), $C_{L_{maxLanding}}$ = 2.3) [68].

The complete Wing design workflows are given as:

- Step1 (auto-links): Historical Data and auto-calc. results
  - o Wing Aspect Ratio (*A* or *AR*) = 7.6 (Linked from Initial Weight Estimation) [67].
  - o Wing Reference Area (S) in $ft.^2$ (from Matching auto-calc. - selected Chart, design point)
- Step2 (manual entry): Historical Data
  - o Wing Taper Ratio (λ) = 0.45
  - o Wing Twist Angle = -3 degree (C_{tip}) lower angle of incidence than (C_{root}) to reshape lift. distribution)
  - o Wing Dihedral or Anhedral (low wing) (Γ) = 5 degree [67].
  - o Quarter Chord Sweep Angle (($\frac{\Lambda_c}{4}$)= 0 degree (0 degree reduce cost) [69].
  - o Wing Incidence: (i_w) = 2 degree [67].
- Step3 (auto-calc.): Wing Span, Root Chord, Tip Chord, Y: distance of MAC from Centreline, Mean Aerodynamic Chord, Leading edge sweep angle
  - o Wing Span (*b*, in ft.): Table 4.1*: *A*=aspect ratio, *S*=wing & canard area [67]:

$$b = \sqrt{AS} \qquad \text{Equation 3}$$

  - o Wing Root Chord (cruise), (C_{root}, in ft.) [67]:

$$(C_{root} = \frac{2S}{b(1+\lambda)}) \qquad \text{Equation 4}$$

  - o Wing Tip Chord (cruise), (C_{tip}, in ft.) [67]:

$$(C_{tip} = \lambda C_{root}) \qquad \text{Equation 5}$$

- Wing, Y is distance of *MAC* from Centreline of Fuselage [67]:

$$\bar{Y} = \frac{b}{6}\left[\frac{(1+2\lambda)}{(1+\lambda)}\right]$$ *Equation 6*

- Wing Mean Aerodynamic Chord (MAC, $\bar{C}$, in ft.) [67]:

$$\bar{C} = \left(\frac{2}{3}\right)C_{root}\frac{(1+\lambda+\lambda^2)}{(1+\lambda)}$$ *Equation 7*

- Leading edge sweep angle (due to taper, in degree) [67]:

$$tan\Delta_{LE} = tan\Delta_{C/4} + \left[\frac{(1-\lambda)}{AR(1+\lambda)}\right]$$ *Equation 8*

- Step4 (auto-link): Historical Data and auto-calc. results
  - Wing Loading, from Selected Design Point (Matching Chart), $\left(\frac{W}{S}\right)$ in $\frac{lbs}{ft.^2}$
  - Air Density at 15,000 ft. (ρ) in 0.001498 $\frac{slug}{ft.^3}$ (Mission Requirement)
  - Velocity at Cruise, (Vcr) in kts, converted to ft./s (Mission Requirement)
  - Weight (average) estimation at cruise, est. *0.9 * WTO* [69].

$$W_{avg} = \frac{1}{2}(W_i + W_f)$$ *Equation 9*

  - Maximum Lift Coefficient (clean), ($C_{L_{max}}$) from Initial Weight Estimation [68].

- Step5 (auto-calc.): Wing Aerofoil selection, where design Lift Coefficient, $C_{L_{design}}$ should be around $C_{L_{cruise}}$ for efficiency during high-altitude cruise.

Wing Airfoil Ideal Lift Coefficient [69].

- Aircraft ideal Lift Coefficient (cruise) needed for Aerofoil Design, ($C_{L_{icr}}$):

$$C_{L_c} = \frac{2W_{ave}}{\rho V_c^2 S}$$ *Equation 10*

- Wing Ideal Lift Coefficient (cruise), excludes the rest of aircraft ($C_{L_{C_w}}$):

$$C_{L_{C_w}} = \frac{C_{L_c}}{0.95}$$ *Equation 11*

- Wing Airfoil Ideal Lift Coefficient ($C_{L_{i_{airfoil}}}$):

$$C_{L_i} = \frac{C_{L_{C_w}}}{0.9}$$ *Equation 12*

Wing Airfoil Gross Maximum Lift Coefficient [69].

- Maximum WING Lift Coefficient ($C_{L\,max\_w}$):

$$C_{L\,max\_w} = \frac{C_{L_{max}}}{0.95}$$ *Equation 13*

- Gross Maximum AIRFOIL Lift Coefficient, with High Lift Device ($C_{L\,max\_airfoilgross}$):

$$C_{L\,max\_gross} = \frac{C_{L_{max\_w}}}{0.9}$$ *Equation 14*

Note: Results of the example mission requirements have shown that the HLD (flap):
- Is more than sufficient for TO ($C_{L_{maxTO}}$) range: 1.3 to 1.9, assumed 1.8), but
  - Not sufficient for LANDING ($C_{L_{maxL}}$) range: 1.6 to 2.3, assumed 2.3) [68].

- Referring to the Chart: Maximum Lift Coefficient vs. Ideal Lift Coefficient of preceding example results - for NACA Airfoil selections, the possible Airfoil are: NACA 4412, 4415, 64-412 [69].

- Step6 (manual entry): History Data [69].
  - Change in High Lift Device (for TO and Landing) fully extended to 60 degree, slotted flap:

$$\Delta C_{L_{HLD}} = (1.3 * \frac{c_f}{c})$$ *Equation 15*

  - General Aviation 2 seats aircraft (avg. Flap-to-Chord ratio, $(\frac{c_f}{c})$), est. = 0.30.
- Step7 (auto-calc.): change in C_L in HLD, & NETT Max. Airfoil C_L without HLD
  - Change in C_L (single slotted HLD flap) when fully extended:

$$\Delta C_{L_{HLD\_f}} = (1.3 * \frac{c_f}{c})$$ *Equation 16*

  - NETT Max. Airfoil Lift Coefficient (without *HLD*):

$$C_{L\,max} = (C_{L\,max\_gross} - \Delta C_{L\,HLD})$$ *Equation 17*

- Step8 (auto-link & manual entry): for calc. Reynolds numbers Airfoil Croot and Ctip
  - Air density at cruise attitude: 15,000 ft. (requirement) - ρ
  - Cruise velocity (requirement) - *V*
  - Wing airfoil C_{root} (calc.) - *L*
  - Wing airfoil C_{tip} (calc.) - *L*
  - Dynamic Viscosity of fluid (Historical data) - μ.
- Step9 (auto-calc.): Reynolds numbers at Airfoil C_{root} and C_{tip} that meet Mission Requirements (cruise attitude: 15000 ft., cruise velocity):

$$R_e = \frac{\rho V L}{\mu}$$ *Equation 18*

Note: Reynolds is a dimensionless value that measures ratio of Inertial Forces to Viscous Forces and describes the degree of Laminar or Turbulent Flow.

- Step10 (manual selection): Airfoil selection uses Sadraey chart that meets the calc. ideal lift coefficient vs. max. Lift coefficient (no HLD) as calculated [69].
  - Reynolds number C_{root} is 5,000,066, which is estimated to be close to the Chart with data at Re = 6,000,000.
  - Airfoil selected is NACA 4415 (Airfoil thickness, max. camber location & max. camber).
- Step11 (auto-link) – Check the Wing C_L value to see whether ideal C_L calculated is ok.
  - Ideal Lift Coefficient (C_{L_i})
  - $\frac{W}{S}$ (wing loading)
  - Air density at 15,000 ft.
  - Cruise Velocity at 15,000 ft.
- Step12 (auto-calc.): *q cr* (dynamic pressure) and Lift coefficient *cr* (design) and check (C_{L_i}) *vs.* ($C_{L_{des}}$) is within 10%
  - *q cr* (dynamic pressure):

$$q = \frac{\rho V^2}{2}$$ *Equation 19*

- o Design Lift Coefficient:

$$C_L = \frac{W}{S} * \frac{1}{0.5 \rho_c V_c^2} \qquad\qquad \textit{Equation 20}$$

- o Check (C_{L_i}) (Step5.c) vs. $(C_{L_{des}})$ (@ Step12.b) is within 10% or not.
- Step13 (auto-link): Wing control surfaces (Flap and Aileron)
  - o External diameter, in ft. (fuselage) $(d_{f_{external}})$ – from TAB '*4.IACDT-Config FUSELAGE*'
  - o Wing Span, in ft. (*b*) , SQRT(Wing Aspect Ratio * Wing Reference Area) [67].
  - o Wing Root Chord, Croot (cruise, in ft.):

$$C_{root} = \frac{2S}{b(1+\lambda)} \qquad\qquad \textit{Equation 21}$$

  - o Wing Tip Chord, C_{tip} (cruise, in ft.):

$$C_{tip} = \lambda C_{root} \qquad\qquad \textit{Equation 22}$$

  - o Wing Reference Area, S (in ft.) – from TAP '*3.IACDT-Matching Chart*', selected design point's derivation.
- Step14 (manual entry): Wing control surfaces (Flap and Aileron)
  - o Flap, outer $(\frac{C_f}{C})$, (η)
  - o Aileron, inner, outer, $(\frac{C_a}{C})$, (η)
- Step14 (auto-calc.): Wing control surfaces (Flap and Aileron)
  - o Flap, inner: η, y ft., c ft.
  - o Flap, outer: y ft., c ft.
  - o Complete Flapped Area, (S_f), in $ft.^2$
  - o Flapped Area to Wing Area ratio : $(\frac{S_f}{S})$
  - o Aileron, inner: y ft., c ft.
  - o Aileron, outer: y ft., c ft.
  - o Complete Aileron Area, (S_a), in $ft.^2$
  - o Aileron Area to Wing Area ratio : $(\frac{S_a}{S})$
- Step15 (auto-link): Fuel Weight, from Initial Weight Estimation
  - o Fuel Weight, W_{fuel}, in lbs
- Step16 (manual entry): Fuel Storage (volume) in Wing, Historical Data
  - o Fuel Density (assumption), (ρ) fuel, in lbs/$ft.^3$
  - o Step17 (auto-calc.): Fuel Storage (volume) in Wing required for mission, Fuel Volume Check, (F_{vol}) in $ft.^3$:

$$F_{vol} = \frac{W_{fuel}}{\rho_{fuel}} \qquad\qquad \textit{Equation 23}$$

- Step18 (auto-link): Check Fuel Volume requirement vs. Wing Fuel Tank Volume capacity (check ok or not)
  - o Wing Reference Area, (S), in $ft.^2$
  - o Wing Span, (b), in ft.
  - o Taper Ratio, λ , Historical Data [67].
  - o Wing Root Chord (cruise), C_{root}, in ft.
  - o Wing Tip Chord (cruise), C_{tip}, in ft.
  - o Dihedral or Anhedral (low wing), Γ, in degree [67].

- Step19 (manual entry): Check Fuel Volume requirement vs. Wing Fuel Tank Volume capacity (check ok or not)
- Manually selected Airfoil : NACA 4415:
  - Maximum thickness 15% at 30.9% chord
  - Maximum camber 4% at 40.2% chord
- Airfoil Thickness ratio (tip), $(\frac{t}{c})_{tip}$.
- Airfoil Thickness ratio (root), $(\frac{t}{c})_{root}$.
- Step20 (auto-calc.): Check Fuel Volume requirement vs. Wing Fuel Tank Volume capacity (check ok or not)
  - Wing Fuel Tank Volume, in $ft.^3$:

$$\Gamma = \frac{(\frac{t}{c})_{tip}}{(\frac{t}{c})_{root}} \qquad \qquad Equation\ 24$$

$$V_{fuelwing} = 0.54(\frac{S^2}{b})(\frac{t}{c})_{root}\frac{(1+\lambda\sqrt{\tau}+\lambda^2\tau)}{(1+\lambda)^2}V_{fuelwing} \qquad Equation\ 25$$

  - Wing Fuel Volume Check whether mission requirement is sufficient vs. fuel tank capacity in wing

Aircraft Configuration – TAB '7.IACDT-Config TAIL'

The main functions of this spreadsheet are to commence the Preliminary Configuration Design for the Tail. The tasks performed include the estimation of Tail parameters such as the Dimensions, Aerofoil selection, thickness ratio, sweep angle, taper ratio, incidence, twist dihedral, Control Surfaces and historical data.

Tail design – TAB '7.IACDT-Config TAIL'

The Tail surface area is directly proportional to Wing area, therefore:
- Tail area cannot be selected until the initial weight estimation of aircraft $WTO_{convergance}$ has been completed.
- Initial estimation of tail area will be made using the Tail Volume Coefficient method [67].

Tail design process can begin after the following parameters have been determined:
- Wing Chord (*C*) ft.
- Wing Span (*b*) ft.
- Wing Area (*S*) ft.^{2}

The complete Tail design workflows are given as:
- Step1 (auto-link) – Wing Chord, Wing Span, Wing Area & Fuselage length
  - Wing Chord (*C*) in ft. (from Wing design)
  - Wing Span (*b*) in ft. (from Wing design)
  - Wing Area (*S*) in $ft.^2$ (from Matching Chart selected design point's derivation)
  - Fuselage Length (L_f) in ft. (from Fuselage design)
- Step2 (manual entry) – Historical Data
  - Tail Aspect Ratio (Horizontal, (AR_h)) [67].
  - Tail Aspect Ratio (Vertical, (AR_v)) [67].

- o Tail Taper Ratio (Horizontal, (TR_h)) [67].
- o Tail Taper Ratio (Vertical, (TR_v)) [67].
- o Tail Leading-edge Sweep Angle (Horizontal, (Δ_{LE})) in degree [67].
- o Tail Sweep Angle (Vertical, (Δ_{LE})) in degree [67].
- o Tail Airfoil Thickness Ratio, horizontal (similar to Wing), $(\frac{t}{c})_h$ [67].
- o Tail Airfoil Thickness Ratio, vertical (similar to Wing), $(\frac{t}{c})_v$ [67].
- o Tail Dihedral Angle, horizontal, Γ, in degree [67].
- o Tail Dihedral Angle, Vertical, Γ, in degree [67]. (not applicable in example)
- o Tail Volume Coefficients (Horizontal, C_{HT} (V_H)) [67].
- o Tail Volume Coefficients (Vertical, C_{VT} (V_V)) [67].
- o Tail Moment Arm (Horizontal, $(\frac{L_H}{L_f})$), est. 60% of Lf [67].
- o Tail Moment Arm (Vertical, $(\frac{L_V}{L_f})$), est. 60% of Lf [67].
- o Tail Airfoil selection, NACA 0012 (Horizontal and Vertical)
- Step3 (auto-calc.) – Tail Stabiliser Length
  - o Tail Stabiliser Length (Horizontal, L_H, in ft.) = (Tail Moment Arm, $(\frac{L_H}{L_f})$ in %) * (Fuselage Length) [67].
  - o Tail Stabiliser Length (Vertical, L_V, in ft.) = (Tail Moment Arm, $(\frac{L_V}{L_f})$ in %) * (Fuselage Length) [67].
- Step4 (auto-calc.) - Tail Stabiliser (Horizontal) Area, Span, Root Chord, Tip Chord, Chord
  - o Tail Stabiliser Area (Horizontal, S_{HT}, in $ft.^2$) [67].

$$S_{HT} = \frac{C_{HT}\bar{C}_W S_W}{L_{HT}} \qquad \qquad Equation\ 26$$

  - o Tail Stabiliser Span (Horizontal, b_{HT}, in ft.)
  - o Tail Root Chord (Horizontal, C_{root_h}, in ft.)
  - o Tail Tip Chord (Horizontal, C_{tip_h}, in ft.) – convert to inches as well
  - o Tail Chord (Horizontal, c h, Y h, x c/4 h, in ft.)
- Step5 (auto-calc.) - Tail Stabiliser (Vertical) Area, Span, Root Chord, Tip Chord, Chord
  - o Tail Stabiliser Area (Vertical, S_{VT}, in $ft.^2$) [67].

$$S_{VT} = \frac{C_{VT} b_W S_W}{L_{VT}} \qquad \qquad Equation\ 27$$

  - o Tail Stabiliser Span (Vertical, b_{VT}, in ft.)
  - o Tail Root Chord (Vertical, C_{root_v}, in ft.)
  - o Tail Tip Chord (Vertical, C_{tip_v}, in ft.) – convert to inches as well
  - o Tail Chord (Vertical, C_v, Y_v, $X_{c/4_v}$, in ft.)
- Step6 (manual entry) – Tail Control Surface (Elevator)
  - o inner, $\eta = 0$
  - o outer $= 0.90$ (%) [67].
  - o $\left(\frac{C_e}{C_h}\right) = 0.45$ (control surface chord to tail chord elevator ratio)
- Step7 (auto-calc.) – Tail Control Surface (Elevator)
  - o Inner, y ft. and c ft.
  - o Outer, y ft. and c ft.
  - o Elevator Area (S_e, in $ft.^2$)
  - o Elevator Area to H Tail Area Ratio$(\frac{S_e}{S_H})$.

- Step8 (manual entry) – Tail Control Surface (Rudder)
  - inner, $\eta = 0$
  - outer $= 0.90$ (%) [67].
  - cr / cv = 0.40 (control surface chord to tail chord elevator ratio)
- Step9 (auto-calc.) – Tail Control Surface (Rudder)
  - Inner, y ft. and c ft.
  - Outer, y ft. and c ft.
  - Rudder Area (S_r, in $ft.^2$)
  - Rudder Area to V Tail Area Ratio($\frac{S_r}{S_V}$).

Aircraft Configuration – TAB '8.IACDT-Config W and B'

The Aircraft Configuration phase to estimate the Weight and Balance Parameters are aimed at designing a balanced and stable aircraft that is controllable within the designed flight envelope.

For example, a tail-heavy aircraft is unstable, but a nose-heavy aircraft may be overly stable, which may also reduce its controllability.

This stage of design workflows estimates the initial weight distribution, C.G. grouping components positions and travel range of the aircraft concept (airframe structure & systems). These also include the fuselage, horizontal tail, vertical tail, landing gear (nose and main), system (others), wing, propulsion, empty weight, fuel weight, useful payload (pilot + PAX + luggage).

Weight and Balance design – TAB '8.IACDT-Config W and B'

The main functions of this spreadsheet are to commence the Preliminary Configuration Design Process for the Weight and Balance of the aircraft. The W & B Design process begins after the following conceptual workflows have been completed:

- Initial weight estimation (WTO, W_{empty}, W_{fuel}),
- Matching Chart (selected Design Point: $(\frac{W}{hp})$, $(\frac{W}{S})$, *S, hp*) and the relevant historical data such as: $C_{L_{max}}$, $C_{L_{maxTO}}$, $C_{L_{maxL}}$.
- Fuselage, Propulsion, Wing and Tail (horizontal and vertical).

The complete Weight and Balance design workflows are given as:

Summary listing of W & B related parameters:

- WTO_{conv}, W_{empty}, W_{fuel}, $W_{payload}$.
- WING Parameters
- HORIZONTAL TAIL Parameters
- VERTICAL TAIL Parameters
- FUSELAGE Parameters
- LANDING GEAR (Weight) Parameters
- ENGINE Parameters
- LANDING GEAR (Tricycle) Requirement/Parameters
- STATIC MARGIN: longitudinal stability & control Parameters
- MAIN DESIGN VALUES (this sheet: '*8.IACDT-Config W and B*') Parameters
- C.G. GROUPING Parameters

- LANDING GEAR Parameters

  Note: values in **red colour** denote that it is directly exported for dimensioning the SolidWorks 3D model (aircraft concept).

- Step1 (auto-link): WTOconv, Wempty, Wfuel, Wpayloadt
  - Initial take-off gross weight ($WTO_{convergence}$) – from Initial Weight Estimation
  - Empty Weight (W_{empty}) – from Initial Weight Estimation)
  - Fuel Weight (W_{fuel}) – from Initial Weight Estimation)
  - Total useful Payload (Pilot, PAX, Luggage), ($W_{payload}$) – from Initial Weight Estimation
- Step2 (manual entry)
  - Approximate Empty Weight Build-up Historical Data (General Aviation, $\frac{lb}{ft^2}$), Table 15.2 – for approximating Group Weights [67]. This includes C.G. estimate via statistical data + approximate locations of components C.G.
    - Wing = 2.5
    - H_{tail} = 1.9 (given = 2)
    - V_{tail} = 1.9 (given = 2)
    - Fuselage = 1.3 (given = 1.4)
    - L_{gear} = 0.057
    - Engine (installed) = 1.4
    - Others = 0.1
  - X C.G. coordinates measured from datum 200" in front of nose (x offset = 200 in)
  - Z C.G. coordinates measured from datum 30" below ground level (z offset = 30 in)
- Step3 (auto-link): WING Parameters
  - Wing Flap inner, c ft. (c at fus) - from WING design
  - Wing Tip Chord (cruise, C_{tip}, in ft., convert to in) – from WING design
  - Mean Aerodynamic Chord (MAC) – from WING design
  - Y: distance of MAC from Centreline (Y) – from WING design
  - Leading Edge MAC – from WING design
  - $tan\Delta_{LE}$, Leading edge sweep angle due to taper (Δ_{LE}) – from WING design
  - Wing Root Chord (cruise, C_{root}, in ft.) – from WING design
  - Wing Airfoil Thickness-to-Chord Ratio ($(\frac{t}{c})_{root}$) – from WING design
  - Wing Airfoil Thickness-to-Chord Ratio ($(\frac{t}{c})_{tip}$) – from WING design
  - Wing Span (b, in ft.) convert to inch – from WING design
  - Wing Dihedral Angle, Γ in degree – from WING design [67].
- Step4 (auto-calc.): WING Parameters
  - Wing Span exposed (b_{exp}, in ft.)
  - Wing true-view exposed planform area (S_{exp}, in $ft.^2$)
  - Wing Weight (w_{wing}, in lbs)
  - Wing Quarter Chord (x c/4, in inch)
  - Location point Reference Wing (x C_{root}, in inch)
  - Airfoil thickness-to-chord ratio MAC ($(\frac{t}{c})$ MAC)
  - WingCtipSweepLengthLocation based on Sweep Angle, in Inch
- Step5 (auto-link): HORIZONTAL TAIL Parameters
  - Horizontal Tail Surface Area (S_{expth}, in $ft.^2$), from TAIL design

- o Horizontal Tail Stabiliser length (LH (LHT) previous – from TAIL design
  - o Tail mean Chord (Horizontal) (c mean, in ft.) – from TAIL design
  - o Tail root Chord (Horizontal) (c root, in ft.) – from TAIL design
  - o TAILhSweep (deg) – from TAIL design
  - o Horizontal Tail Span (b, in ft.), convert to inch and divide by $2 = b/2$
- Step6 (auto-calc.): HORIZONTAL TAIL Parameters
  - o Horizontal Tail Weight (W_{th}, in lbs)
  - o Horizontal Tail Stabiliser Length (LH (LHT), in ft.)
  - o Horizontal Tail Leading Edge (x LE h, in ft.)
  - o (CtipLEstartPt based on sweep angle+TAILhCrootLE), in inch
- Step7 (auto-link): VERTICAL TAIL Parameters
  - o Vertical Tail Stabiliser Area (S_{exp}, in $ft.^2$) – from TAIL design
  - o Vertical Tail Stabiliser length (LV (LVT) previous, in ft. – from TAIL design
  - o Chord mean (Vertical) (c mean, in ft.) – from TAIL design
  - o Chord root (Vertical) (c root, in ft.) – from TAIL design
  - o Chord tip (Vertical) (c tip, in ft.) - from TAIL design
  - o Vertical Tail Leading Edge (x LE v, in ft.) - from TAIL design
  - o Vertical Tail Span (b, in ft.) from TAIL design, and convert to inch
  - o Vertical Tail Sweep Angle (Δ_{LE}, in degree) [67].
- Step8 (auto-calc.): VERTICAL TAIL Parameters
  - o Vertical Tail Weight (W_{tv}, in lbs)
  - o Vertical Tail Stabiliser length (LV (LVT), in ft.)
  - o (CtipLEstartPt based on sweep angle+TAILvCrootLE) in inch
- Step9 (auto-link): FUSELAGE Parameters
  - o Fuselage length (L_f, in ft.) – from FUSELAGE design
- Step10 (auto-calc.): FUSELAGE Parameters
  - o Fuselage external dimension (d_f, in ft., width) – from FUSELAGE design (in) convert to ft.
  - o Fuselage fineness ration [67].

$$\lambda_f = (\frac{L_f}{d_f}) \qquad\qquad Equation\ 28$$

  - o Fuselage Wetted Area (S_{wet}, in $ft.^2$)
  - o Fuselage Weight (W_f, in lbs)
- Step11 (auto-link): LANDING GEAR (Weight) Parameters
  - o Initial Take-off gross weight ($WTO_{convergence}$, in lbs) – from Weight
- Step12 (auto-calc.) – LANDING GEAR (Weight) Parameters
  - o Nose Landing Gear Weight (15% of $WTO_{convergence}$ * 0.057, table 15.2) [67].
  - o Main Landing Gear Weight (85% of $WTO_{convergence}$ * 0.057, table 15.2) [67].
- Step13 (auto-link): ENGINE Parameters
  - o Engine Weight (W_{engine}, in lbs) – from PROPULSION design
  - o Engine Weight (installed with Propeller + Spinner) – from PROPULSION design
  - o Propeller Diameter (Dp, in ft.) – convert to inch (FAR 23) – from PROPULSION design
  - o Engine Length, not install (x L_{engine}, in) – from PROPULSION design
- Step14 (manual entry): ENGINE Parameters
  - o Engine – *y* coordinate location, in ft.
- Step15 (auto-calc.): ENGINE Parameters
  - o Engine Length + Engine an Firewall buffer, (x $L_{engineInst}$, in: $L_{engine} + L_{buffer}$)

- o WTO (include other system weight (W_{others}, in lbs: $WTO_{convergence}$ * *ApproxEmptyWeightBuildup*) [67].
- Step16 (auto-link): LANDING GEAR (Tricycle) Requirement/Parameters
  - o Landing Gear Height (H_{ig}, in: baseline fuselage to ground level)
- Step17 (manual entry): LANDING GEAR (Tricycle) Requirement/Parameters
  - o Propeller Tips Clearance from ground level (FAR 23.925)
  - o Main Landing Gear carry: 80% to 90% Aircraft loads, assumption [67].
  - o Front Landing Gear carry: 10% to 20% Aircraft loads, assumption [67].
  - o Main Landing Gear Rotation (TO, Landing) $R ngTOL$, deg., assumption [67].
- Step18 (auto-link): STATIC MARGIN: longitudinal stability & control Parameters
  Note:
  Static Margin is used to determine the longitudinal stability and controllability.
  - Neutral point is located in front of most aft.-CG. I.e. static margin = 0.
  - Neutral Point = CG neutral stability = Static Margin is 0.
  - Static margin is about 4-10% for propeller aircraft [67].

  - o Wing Aspect Ratio (AR_w) – from MATCHING CHART
  - o Wing Taper Ratio (λ) – from WING design
  - o ($\frac{\Delta_c}{2}$): assume $tan\Delta_{LE}$(Wing leading edge sweep angle due to taper) – fm WING design
  - o Fuselage external width dimension (d_f, in ft.) – from FUSELAGE design
  - o Wing Span (b_w, in ft.) – from WING design
  - o Tail Aspect Ratio, Horizontal (AR_{th}) from TAIL design
  - o ($\frac{\Delta_c}{2}$): assume Δ_{LE} Leading-edge sweep (Horizontal TAIL) – from TAIL design
  - o Horizontal Tail Stabiliser length (L_H (L_{HT}), in ft. – from TAIL design
  - o Quarter Chord Sweep Angle (($\frac{\Delta_c}{4}$) in degree) from WING design [69].
  - o Horizontal Tail Stabiliser Area (S_H (S_{HT}), in $ft.^2$ – from TAIL design
  - o Wing Reference Surface Area (S, in $ft.^2$) – from WING design
- Step19 (manual entry): STATIC MARGIN: longitudinal stability & control Parameters
  - o Wing Power off calculations (M)
  - o Wing η (0.95 if unknown)
  - o Horizontal Tail Power off calculations (M)
  - o Horizontal Tail η
  - o ($\frac{C_L}{C_L}$):

$$\frac{(C_{L_{\alpha_w}})at\ M}{(C_{L_{\alpha_w}})at\ M=0} \qquad \textit{Equation 29}$$

  - o Tail to free Stream Dynamic Pressure Ratio (ηH)
- Step20 (auto-calc.): STATIC MARGIN: longitudinal stability and control Parameters
  - o Xacwf (Xacw: location of wing/fuselage aerodynamic center)
  - o Wing β:

$$\beta = \sqrt{1 - M^2} \qquad \textit{Equation 30}$$

  - o ($C_{L_{\alpha_w}}$) - for ($C_{L_{\alpha_w}}$) and ($C_{L_{\alpha_H}}$) , use:

$$C_{L_\alpha} = \frac{2\pi AR}{2+\sqrt{4+\frac{AR^2\beta^2}{\eta^2}(1+\frac{tan^2\Delta c/_2}{\beta^2})}} \qquad \textit{Equation 31}$$

- (K_{wf}), buckling coefficient wing/fuselage:

$$K_{wf} = 1 + 0.025 \left(\frac{d_f}{b}\right) - 0.25(\frac{d_f}{b})^2 \qquad \text{Equation 32}$$

- $(C_{L_{\alpha_{wf}}})$:

$$C_{L_{\alpha_{wf}}} = (C_{L_{\alpha_w}} K_{wf}) \qquad \text{Equation 33}$$

- Horizontal Tail β:

$$\beta = \sqrt{1 - M^2} \qquad \text{Equation 34}$$

- $C_{L_{\alpha_h}}$ (per rad) Horizontal Tail Lift Curve Slope:
- $(C_{L_{\alpha_h}})$ - for $(C_{L_{\alpha_w}})$ and $(C_{L_{\alpha_H}})$ use:

$$C_{L_\alpha} = \frac{2\pi AR}{2 + \sqrt{4 + \frac{AR^2 \beta^2}{\eta^2}(1 + \frac{\tan^2 \Delta_{c/2}}{\beta^2})}} \qquad \text{Equation 35}$$

- K_{AR}:

$$K_{AR} = \frac{1}{AR} - \frac{1}{1 + AR^{1.7}} \qquad \text{Equation 36}$$

- K_λ:

$$K_\lambda = \frac{(10 - 3\lambda)}{7} \qquad \text{Equation 37}$$

- K_H:

$$K_H = \frac{\frac{1 - h_H}{b}}{(\frac{2L_H}{b})^{1/3}} \qquad \text{Equation 38}$$

- $\frac{\partial \varepsilon_H}{\partial \alpha}$:

$$\frac{\partial \varepsilon_H}{\partial \alpha} = 4.44[(K_{AR} K_\lambda K_H (\cos\Delta_{c/4})^{1/2})^{1.19}] \frac{(C_{L_{\alpha_w}})_{at\ M}}{(C_{L_{\alpha_w}})_{at\ M=0}} \qquad \text{Equation 39}$$

- X_{ac_H}, (% MAC) Horizontal Tail Aerodynamic Centre location ($Tail\_H\_moment\_arm * MAC$)
- C_{L_α}:

$$C_{L_\alpha} = C_{L_{\alpha_{wf}}} + C_{L_{\alpha_H}} \eta_H (\frac{S_H}{S})(1 - \frac{\partial \varepsilon_H}{\partial \alpha}) \qquad \text{Equation 40}$$

- $\bar{X}_{np}$, Aircraft Neutral PT: Aerodynamic Ctr. (% MAC):

$$\bar{X}_{np} = \bar{X}_{\alpha\ wf} \frac{C_{L_{\alpha_{wf}}}}{C_{L_\alpha}} + \eta_H \frac{C_{L_{\alpha_H}}}{C_{L_\alpha}}(1 - \frac{\partial \varepsilon_H}{\partial \alpha})(\frac{S_H}{S})\bar{X}_{\alpha\ H} \qquad \text{Equation 41}$$

Note:
The Length in equations can be expressed as a fraction of WING MEAN CHORD: C, where a bar denotes this fractional length. So, e.g. $\bar{X}_{cg}$ represents $\frac{\bar{X}_{cg}}{C}$.

- $\bar{X}_{cg}$, Centre of Gravity location (% MAC)
- Static Margin (SM, %MAC) is the Distance in % MAC from Neutral Point to C.G. (aircraft neutral point - aircraft centre of gravity). Therefore, SM [67, 69]:

$$SM = \frac{X_{np} - X_{cg}}{\bar{C}} \qquad \text{Equation 42}$$

- Step21 (auto-link): MAIN DESIGN VALUES (sheet: '*8.IACDT-Config W and B*') Parameters
  - xLE MAC (Leading edge Mean Aerodynamic Chord), height in inch
- Step22 (manual entry): MAIN DESIGN VALUES (sheet: '*8.IACDT-Config W and B*') Parameters
  - *h* ground (from fuselage bottom surface to ground) - to meet FAA FAR23.925
  - *x* nose wheel (estimate from comparative aircraft specification)
  - *x* main wheel (CG_{aft} to *m* gear: need to re-calc. manually this value if CG_{aft} changes each time)
  - Wheel Track (estimate from comparative aircraft specification)
- Step23 (auto-calc.): MAIN DESIGN VALUES (sheet: '*8.IACDT-Config W and B*') Parameters
  - XoffsetANDCGaft.ANDCGaft.TOWheelMainLoc@Sketch41 (solidworks model), in inch
  - 'WheelNoseLocation@Sketch43 (solidworks model), in inch
- Step24 (auto-link, manual entry and auto-calc.): C.G. GROUPING Parameters
  The MS-Excel Table 30, Table 31, Table 32 and Table 33 illustrate the C.G. grouping, including: Airframe structure + system (others), Propulsion and components weights.

These tables include calc. values for interfacing inputs linking with SolidWorks 3D model (aircraft concept). Any change in this workbook on the relevant linked values, the 3D model will also auto update. This provides a CD like environment while working through the core design curriculums. Colour Codes are: ____50____ for auto-link; ___0___ for manual entry; __72.41__ for auto-calc.; __79.50__ for auto-calc. + link to SolidWorks 3D model

Table 30, Centre of Gravity Grouping.

C.G. Grouping	Weight	X	WX	XI	XO	Z
	(lbs)	moment arm (in)	Weight * moment arm (lbs.in)	Starting X location of component (in)	Ending X location of component (in)	Height (in)
Airframe Structure + system (others)						
fuselage	345	315	108677	200.00	487.54	79.50
h tail	55	482	26666	468.84	512.36	79.50
v tail	23	479	10984	443.24	487.54	82.94
l gear ng	14	228	3185			34.95
l gear mg	79	314	24826			38.24
others	98	315	30882			79.50
wing	268	286	76720	261.02	329.66	65.14
Propulsion						
engine (Installed)	275.00	234.21	64406.45	210.00	244.21	77.50
Wempty	1157.64					
Wempty (Prev: init Weight Est)	1018.01	1.14				
Fuel (Wing) init Weight Est)	215.87	286.00	61738.39			
Useful Payload						
Pilot + 1 PAX	350	296	103600			
PAX (row 2)	0	332	0			
Luggage	50	355	17768			

Table 31, Centre of Gravity Grouping.

		Weight (lb)	X	WX	We	pilot	aft pax	fuel only	fuel + pax	cargo	Z
	Wfuel (init Weight Est)	216	286	61738	0	0	0	216	216	0	65.14
cockpit	pilot + 1 PAX	350	296	103600	0	350	0	0	350	0	79.50
Cabin n.a.	PAX (row 2)	0	332	0	0	0	0	0	0	0	79.50
cargo	luggage	50	355	17768	0	0	0	0	0	50	79.50
	WTO	1774			1158	1508	1158	1374	1724	1208	
	WTO prev (init Weight Est)	1634	1.085461		299	307	299	299	306	287	

Table 32, Centre of Gravity Grouping.

	X	Z	X/c	
CG	299	73.12	0.64	c
CG We	299	72.41		
CG fuel	286	65.14		
CG payload	303	79.50		
XLE MAC	265.14	65.14		
Xac	278	65.14		
Xnp	299	65.14	5.74	% MAC
Xcg	299	65.14	5.72	% MAC

Table 33, Centre of Gravity Grouping.

CG Envelope - Aircraft Compon	X axis (In)	Weight (lb)		
Wcargo	287	1208	0.420605	c
Wempty	299	1158	0.657523	c
pilot only	307	1508	0.803422	c
aft pax only	299	1158	0.657523	c
fuel only	299	1374	0.647189	c
fuel + front pax	306	1724	0.776912	c
WTO	299	1774	0.640346	c

- Step25 (auto-calc.) – Determine Forward and Aft. C.G. Limits Parameters
  o CG, forward limit, in inch
  o CG, aft. limit, in inch
  o CG travel (range between fore and aft. CG limits)
- Step26 (auto-link): LANDING GEAR Parameters
  o h ground (fm fuselage bottom surface to ground), in inch
  o x nose (l gear ng - exclude x offset), in inch
  o x main (l gear mg - exclude x offset), in inch
  o main D main (Main Wheel Diameter), d (wheel), in inch
  o D nose (Nose Wheel Diameter) ,(wheel) in inch
  o X CG aft. (CG Aft. Limit), in inch
  o X CG fwd (CG Forward Limit), in inch
  o X main (l gear mg, with x offset), in inch
  o X nose (l gear ng, with x offset), in inch
  o Wheel Track, in inch

- Step27 (manual entry): LANDING GEAR Parameters
  - N struts m
  - N struts n
  - Safety
  - Growth allowance in MTOW [67].
  - $(\frac{D_n}{D_m})$ (Ratio: Diameter Nose Wheel / Diameter Main Wheel) [67].
- Step28 (auto-calc.): LANDING GEAR Parameters
  - CG_aft. to m_gear, in inch
  - HCG (Height of I gear, CG to Gnd), in inch
  - HCG + Z_offset, in inch
  - Angle (Tip Over Longitude est. 15 degree)

Lateral Tip-Over Values, main gear

  - **Wheel Track (TrackW/2, in inch)**
  - a, in degree
  - d, in inch
  - Angle (Tip Over Lateral >25 and < 63 degree) [67, 69].
  - X fcone, in inch
  - a (Rotation Longitude), in degree
  - htip, in inch
  - xtip-mg, in inch
  - a, in degree
  - h_{engine}, in inch
  - xeng-mg, in inch
  - a (Rotation Laterial est. 5 degree)
  - B (Wheel Base Length, in inch)
  - I_m (Length fm CG_fwd to main_gear, in inch)
  - **(from fuselage TIP to Nose Gear at fuselage underside (firewall buffer), in inch**
  - **NoseWheelGearHeight@Sketch54 (SolidWorks model), in inch**
  - I_n (Length fm CG aft. to Nose Gear) in inch

Tire Selection (W_W = load per tire (wheel)

  - $W_{w\,m}$(Max load on main wheel, in lbs):

$$W = \frac{l_n}{Bn_{struts_m}} \qquad \qquad Equation\ 43$$

  - $W_{w\,n}$ (Max load on nose wheel, in lbs):

$$W = \frac{l_m}{Bn_{struts_n}} \qquad \qquad Equation\ 44$$

  - $\frac{W_n}{WTO}$:

  With Growth allowance in MTOW

  - $W_{w\,m}$ (Max Load on Main Wheel) : with Growth allowance in MTOW assumption
  - $W_{w\,n}$ (Max Load on Nose Wheel) : with Growth allowance in MTOW assumption

  Main and Nose Wheel Diameter and Width

  - D main (Main Wheel Diameter), in AW_w^B inch and **convert to Radius** [67].

- o **w main (Main Wheel Width), in inch**
- o D nose (Nose Wheel Diameter), in inch: 60-100% $W_{w\,m}$ and **convert to Radius** [67].
- o **w nose (Nose Wheel Width), in inch**

Aircraft Configuration: TAB '9.IACDT-Config DRAG POLAR'

The main functions of this spreadsheet are to commence the Preliminary Configuration Design is to estimate the Drag Polar Parameters.

Aerodynamic Coefficient vs. Drag Polar (C_L vs C_D) is the relationship between Lift, Drag and Angle of Attack. It can be calculated once the following parameters have been computed:
- Weight and Balance:
  - o Weight distributions
  - o C.G. and
  - o Locations of components (includes locations and dimensions for SolidWorks 3D model) related parameters has been determined.

The complete Drag Polar workflows are given as:

- Determine Wetted Areas of: Wing, Vertical Tail, Horizontal Tail and Fuselage
- Determine Drag at zero Lift. (cruise), C_{D0}
- Determine Lift. to Drag Ratio, $(\frac{L}{D})$ (TO and Landing)
- Determine Drag Coefficient, C_D (cruise, TO and Landing)

- Step1 Determine Wetted Area: Wing, Vertical Tail, Horizontal Tail & Fuselage, Table 34.

Table 34, Wetted Areas: Wing, Vertical Tail, Horizontal Tail & Fuselage.

		wing	v tail	h tail
True-View Exposed Planform Area (Sexposed)	S exp ft2	107.30	11.46	27.66
Airfoil Thickness Ratio (root)	t/c root	0.15	0.15	0.15
Airfoil Thickness Ratio (tip)	t/c tip	0.15	0.15	0.15
dihedral	τ	1	1	1
Taper Ratio (Historical)	λ	0.45	0.45	0.45
Wing, Vtail, Htail Wetted Area (total exposed surface area: external parts of AC get wet if dipped in water)	S wet ft2	222.65	23.78	57.39
fuselage (Wetted Area)	Swet	246.42	ft2	

The nacelle is a housing, separate from the fuselage, that holds engines, fuel, or equipment on an aircraft.

nacelles	**0**	ft2	**Manual Entry**	(Note: ignored for this G.A. aircraft)

Total Wetted Area: Wing, V Tail, H Tail, Fuselage	Swet total	550.24	ft2

$$\tau = \frac{(\frac{t}{c})_{root}}{(\frac{t}{c})_{tip}} \qquad\qquad Equation\ 45$$

$$\lambda = \frac{C_{tip}}{C_{root}} \qquad\qquad Equation\ 46$$

$$S_{wet} = 2S_{exposed}\left(1 + \frac{0.25\left(\frac{t}{c}\right)_{root}(1+\tau\lambda)}{(1+\lambda)}\right) \qquad\qquad Equation\ 47$$

- Step2 Determine: Drag at zero Lift (cruise), C_{D0}, Table 35.

Table 35, Drag at zero lift (cruise), C_{D0}.

skin friction co-efficient	Cfe	0.0055	Historical	**Manual Entry**
Drag at zero Lift (cruise)	CD0	0.023153		
Wing Aspect Ratio	AR	7.60	Raymer 1992	

$$C_{D0} = C_{fe} \frac{S_{wet}}{S_{ref}} \qquad \textit{Equation 48}$$

- Step3 Determine Lift to Drag Ratio, $(\frac{L}{D})$ (TO and Landing), Table 36.

Table 36, Lift-to-Drag Ratio, (TO and Landing).

	cruise		takeoff		landing	
Drag at zero Lift	CD0	0.02	ΔCD0	0.03	ΔCD0	0.07
Oswald efficiency factor (e), (assumed 0.8, Roskam)	e	0.80	CD0	0.05	CD0	0.09
Lift induced Drag Constant (K)	K	0.05	e, Roskam	0.75	e, Roskam	0.70
Lift to Drag Ratio	L/D	14.36	K	0.06	K	0.06
	LD assume	10.00	L/D	9.18	L/D	6.70

$$K = \frac{1}{\pi A R e} \qquad \textit{Equation 49}$$

$$\left(\frac{L}{D}\right)_{best\ range\ prop} = \left(\frac{L}{D}\right)_{max} \qquad \textit{Equation 50}$$

$$\left(\frac{L}{D}\right)_{max} = \frac{1}{2\sqrt{C_{D0}K}} \qquad \textit{Equation 51}$$

- Step4 Determine: Drag Coefficient, C_D (cruise, TO and Landing), Table 37.

Table 37, Drag Coefficient, CD (cruise, TO and Landing).

Total Drag Coefficient		C_D =	CD0	+	K		CL	
Total Cruise Drag Coefficient	cruise	C_D =	0.02	+	0.05	C_L^2	0.39	Calc
Total Takeoff Drag Coefficient	takeoff	C_D =	0.05	+	0.06	C_L^2	1.80	Roskam
Total Landing Drag Coefficient	landing	C_D =	0.09	+	0.06	C_L^2	2.30	Roskam

$$C_D = C_{D0} + K C_L^2 \qquad \textit{Equation 52}$$

Aircraft Configuration – Preliminary: 3-view of aircraft concept

The Aircraft Configuration phase includes the automatic (real-time) updating of the 3D model when the relevant dimensions in the IACDT workbook changes.

When the SolidWorks 3D model as illustrated in Figure 30 opened, the relevant dimensions within the IACDT spreadsheets (sub-system components) will be automatically linked to the 3D model. Any change (linked dimensions) in the 3D model or individual IACDT spreadsheet will automatically change the other linked dimensions in the relevant spreadsheets and the 3D model.

Therefore, this tool can provide a system-wide perspective for example, the trade-off analysis between sub-system components in a real-time environment.
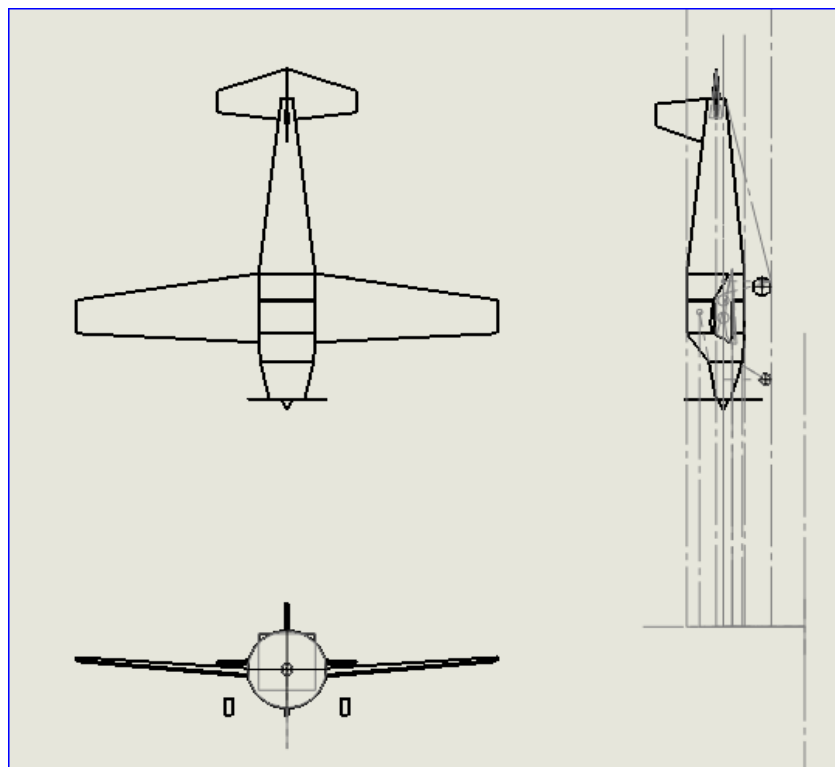
Figure 30, SolidWorks 3D model dynamically linked with Initial Aircraft Conceptual Design Tool.

Appendix D, Interfacing MS-Excel with MATLAB Simulink

This appendix includes an example on how MS-Excel has been interfaced with MATLAB Simulink for the specific purpose to carry out the research. The reader should refer to Table 16.

Setup MS-Excel connection with MATLAB (from within MS-Excel)

The setup procedure includes the following steps:

- Start the MS-Excel application
- Click 'FILE' tab
- Click 'Options' ('Excel Options' dialogue box appear)
- Click 'Add-ins'
- Click 'Go…' button for Manage: 'Excel Add-ins' drop-down list (Add-ins' dialogue box appears)
- Select option 'Spreadsheet Link 3.2.5 for use with MATLAB and Excel'
- Click 'OK' button ('Add-ins' dialogue box closes)
- Click 'HOME' tab (MATLAB function lists appear. Spreadsheet Link 3.2.5 for use with MATLAB and Excel as illustrated in Figure 31. MS-EXCEL spreadsheet link is ready for use.
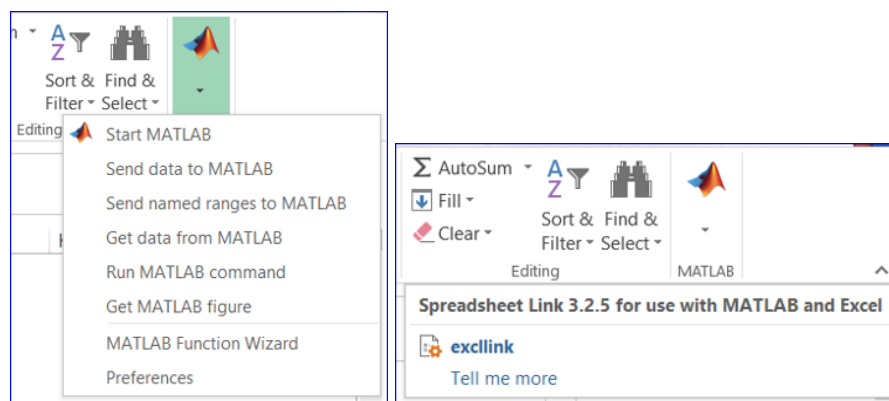
Figure 31, MATLAB function lists appear in EXCEL after MATLAB link setup completion.

Procedures to Write a Matrix array from MATLAB into MS-Excel file

A matrix array can be written using one of the four MATLAB functions as shown below with different options.
- xlswrite(filename,A)
- xlswrite(filename,A,sheet)
- xlswrite(filename,A,xlRange)
- xlswrite(filename,A,sheet,xlRange)

The steps to write an example matrix array from MATLAB into MS-Excel are as follows:
- At the Command-Window and next to the prompt '>>', enter:
  - \>\> testdataarray1 = {'dataA' 1 2 3; 'dataB' 4 5 6; 'dataC' 7 8 9}acknow and click 'Enter' key.

- A 3x4 cell matrix array is displayed as illustrated in Figure 32.

Note: There is no requirement for a MS-Excel spreadsheet to exist prior to transferring the preceding array. The MATLAB 'xlswrite' command can be setup to write the array into a certain file directory and new filename, including what cell to write.

- At the Command-Window and next to the prompt '>>', enter:
  - >> a = xlswrite ('D:\MATLAB EXCEL LINK\matlabExcel', testdataarray1,2,'F5');
    - Figure 33 illustrates that the matrix array have been transferred into MS-EXCEL's worksheet 2 and populated at cell 'F5".

```
>> testdataarray1 = {'dataA' 1 2 3; 'dataB' 4 5 6; 'dataC' 7 8 9}

testdataarray1 =

  3×4 cell array

    'dataA'    [1]    [2]    [3]
    'dataB'    [4]    [5]    [6]
    'dataC'    [7]    [8]    [9]

>> a = xlswrite ('D:\MATLAB EXCEL LINK\matlabExcel',testdataarray1,2,'F5');
```

Figure 32, In MATLAB, showing functions to create an array & follow by transferring to MS-EXCEL.

	A	B	C	D	E	F	G	H	I
1									
2									
3									
4									
5						dataA	1	2	3
6						dataB	4	5	6
7						dataC	7	8	9
8									

Sheet1 **Sheet2** Sheet3 ⊕

Figure 33, In MS-EXCEL showing an array populated from cell 'F5" as defined in MATLAB.

Procedures to Read a Matrix array from MS-Excel into MATLAB within MATLAB

Figure 34 illustrates the execution of MATLAB command 'xlsread' to read an matrix array from the MS-Excel file in certain directory, worksheet and cell ranges into the MATLAB Command-Window.

```
>> a = xlsread('D:\MATLAB EXCEL LINK\matlabexcel',2,'G5:I7')

a =

    1    2    3
    4    5    6
    7    8    11

fx >>
```

Figure 34, MATLAB 'xlsread' function to read an array from MS-EXCEL file, worksheet 2 & cell range: G5:I7 into MATLAB.

Appendix E, Interfacing MS-Excel with AGI System Tool Kit (STK)

This appendix includes an example on how MS-Excel has been interfaced with AGI STK for the specific purpose to carry out the research. The reader should refer to Table 16.

Setting up MS-Excel to interface with AGI STK

The steps to setup MS-Excel to interface with AGI STK are as follows:

- Step1: Download the STKExcelAdd-in1100.zip file from AGI website
  http://help.agi.com/stk/index.htm#gettingstarted/excelAddin.htm?Highlight=excel
  (assess date: 01 Sep 2018)
  o At the AGI website, download the 'STK Excel Add-in' by clicking on the 'Resources' and select the 'Other tab'.
  o The 'STK Excel Add-in' creates a custom toolbar in MS-Excel. This is to enable the transferring of data between MS-Excel spreadsheets and STK scenarios.
- Step2: Unzip the downloaded .zip file into a new directory and run the setup.exe file.
  o This will automatically install the Excel-STK 'Stk Add-in 11' and 'Stk Add-in 11 X64' for AGI STK version 11 into Excel application.
- Step3: Activate the installed 'STK Add-in' feature within the Excel application with the following sub-steps.
  o Click on the DEVELOPER Tab
  o Click on the 'Add-Ins' box to display the 'Add-Ins' dialogue box as illustrated in Figure 35.
  o Check on both the 'STK Add-Ins 11' and 'STK ADD-In 11 X64' box (for Windows 8/10 64bit version) if unsure which version is installed.
  o Once this is completed, MS-Excel is ready for interfacing with AGI STK.
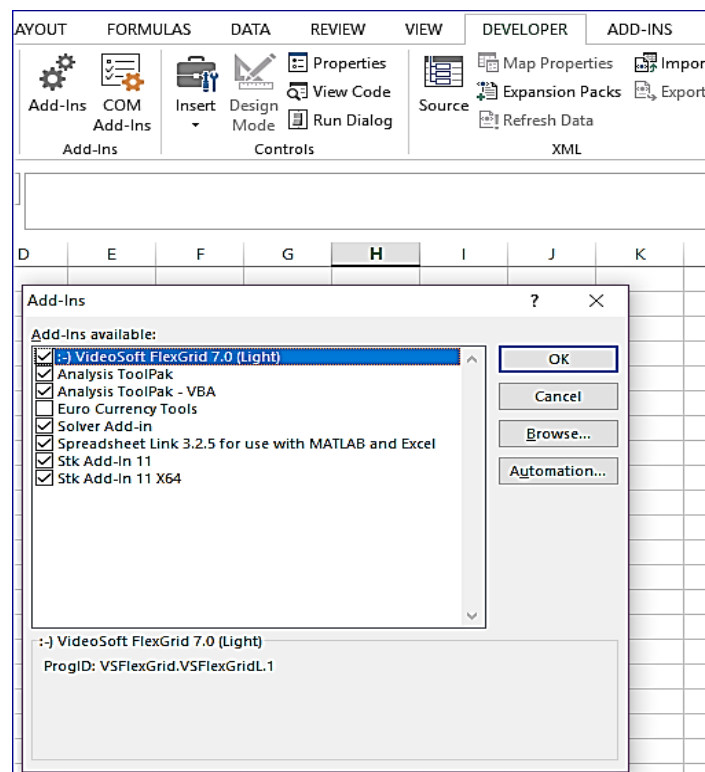
Figure 35, Activating STK Add-in feature within Excel application.

Appendix F, Interfacing MS-Excel with modeFRONTIER

This appendix includes an example on how MS-Excel has been interfaced with modeFRONTIER for the specific purpose to carry out the research. The reader should refer to Table 16.

ModeFRONTIER built-in features support different versions of MS-Excel [85].

The supported versions of MS-Excel application are listed in Table 38, where:
- 'T' = Tested and Supported
- 'E' = Expected to Work
- 'Empty cell' = Not Supported

Table 38, ModeFRONTIER 3rd part integration application – MS-Excel.

Microsoft Excel										
Software Version	**Windows**							**Linux**		**UNIX**
	Vista		**7**		**8**		**10**	**i586**	**64bit**	
	32bit	**64bit**	**32bit**	**64bit**	**32bit**	**64bit**	**64bit**			
2003	E	E	-	-	-	-	-	-	-	-
2007	T	T	E	E	-	-	-	-	-	-
2010*	E	E	E	T	E	T	T	-	-	-
2013	E	E	E	T	E	E	T†	-	-	-
2016	-	-	E‡	E‡	E	E	T	-	-	-

* Only applicable to Excel 2010 32bit. Excel 2010 64bit is not supported.
† Only 32bit version
‡ Only Windows 7 SP1

Excel direct integration node

This appendix describes the use and setup of Excel2010 (32bit) Direct Integration Node interface, which is built into modeFRONTIER.

The MS-Excel application must be setup prior to interfacing with modeFRONTIER for the following purposes:

- Utilising the Excel2010 (32-bit) Direct Application Integration Node of modeFRONTIER to perform design evaluation or
- Editing the MS-Excel workbook from within modeFRONTIER prior to performing the optimisation.

Setup of MS-Excel application to interface with modeFRONTIER

The steps to setup the MS-Excel's VB Project component are as follows:

- Click on File
- Click on menu
- Click on Options
- Click on Trust centre
- Click on Trust Centre Settings
- Click on Macro Settings.
- Check Trust Access to the VBA project model.

- Close all instances of Excel.
- Double-click on the MS-Excel Node in modeFRONTIER workflow to open 'Excel Workbook Properties' dialog box as illustrated in Figure 37 for further setup.
    - Assumption: The MS-Excel Node has already been dragged into workflow space as illustrated in Figure 36.
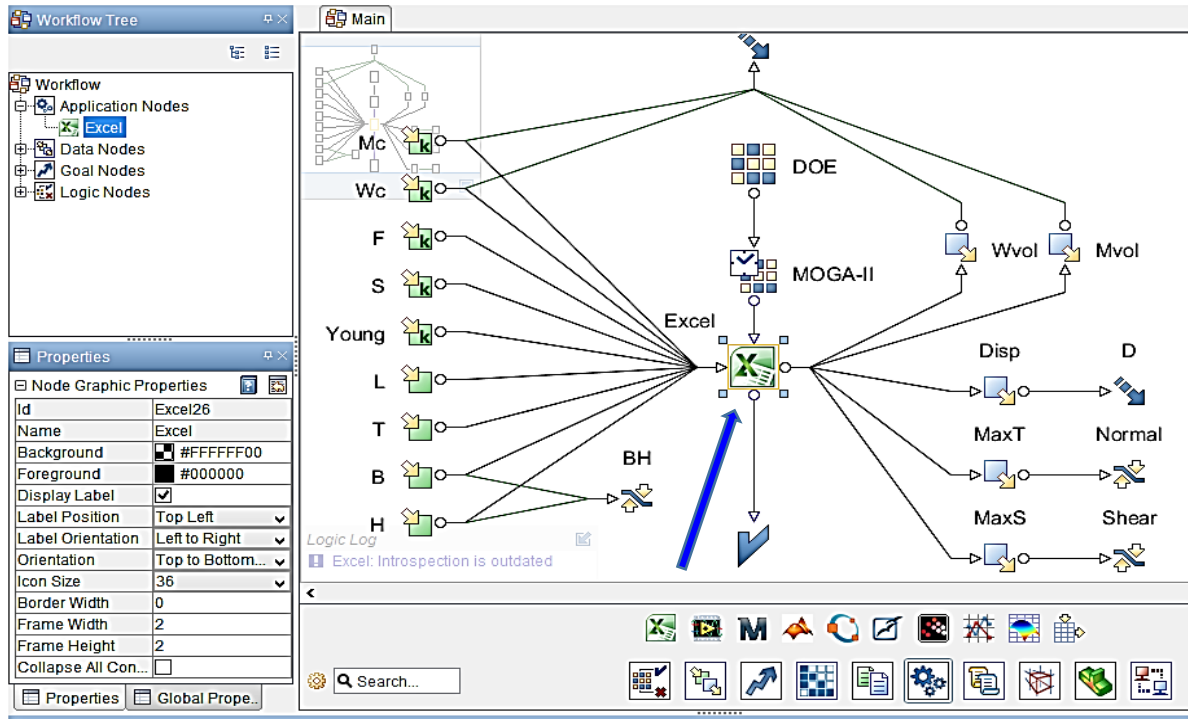
Figure 36, Excel application integration node dragged from tool bar into Workflow.

Setup 'Excel Workbook Properties' using Tutorial: modeFRONTIER project and MS-Excel file

The setup steps for modeFRONTIER 'Excel Workbook Properties' are as follows:

- At the 'Workbook' field as in Figure 37, select the 'excelfile.xls' file (c:\Program Files\ESTECO\modeFRONTIER2017r2\tutorials\prj\Excel_Node\Weldbeam.xls).
    - This file will be subjected to introspection to detect the input and output parameters set within. ModeFRONTIER will optimise these parameters during evaluation process.
    - The MS-Excel workbook performs the design evaluation within modeFRONTIER using the Excel formula applied to the output cells.
- Click on the 'Edit Excel Workbook' button in the Toolbar. This will open the MS-Excel workbook directly from modeFRONTIER.
    - Once opened, the worksheet shows the Input, Output data and formulas as illustrated in Figure 38.
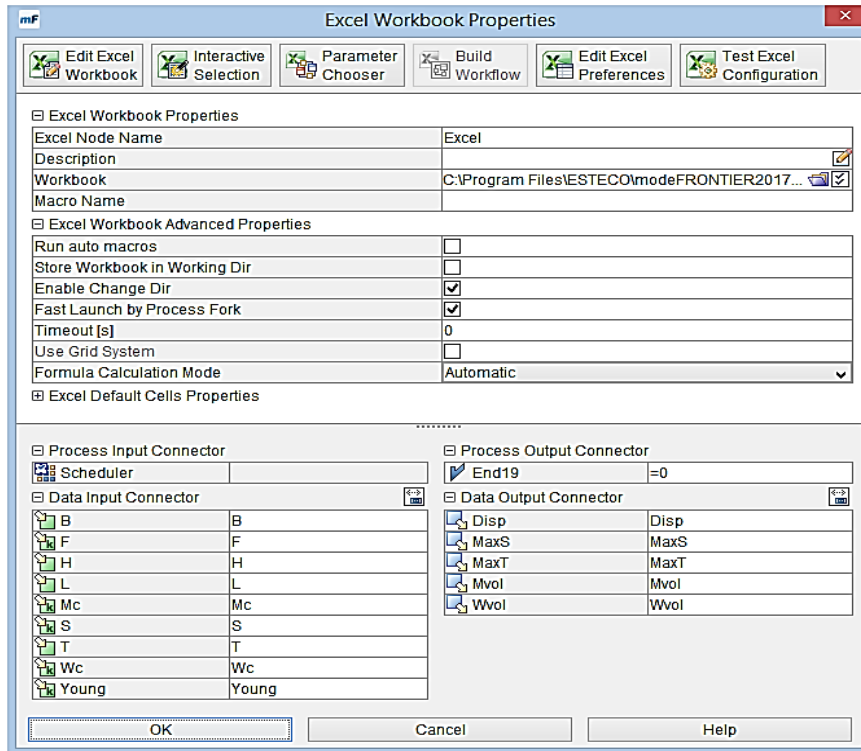
Figure 37, Double-click on Excel node in modeFRONTIER to display Excel Properties dialog box.

Figure 38, Double-click Edit Excel Workbook button in the dialog box to open Excel application.

Problem Definition (an example)

The aims of this problem definition are to optimise a rectangular section beam, welded at one end and loaded at the other end.

There are four parameters defining its geometry, while load conditions, the young modulus of the material, the weld and material costs (per unit volume) are fixed.

- The 4 Input Variable Parameters as illustrated in Figure 39 are:
  - L: Weld Length, H: Weld Thickness, B: Beam Width and T: Beam Thickness.
- The 5 Constant Parameters are:
  - Young: Young Modulus; WC: Welding Cost; MC: Material Cost; F: Applied Load; S: Beam Length

- The Output Data are:
  - Displacement at the end of Beam (Disp)
  - Max Shear Stress (MaxS)
  - Max Normal Stress (MaxT)
  - Material Volume (Mvol)
  - Weld Volume (Wvol)
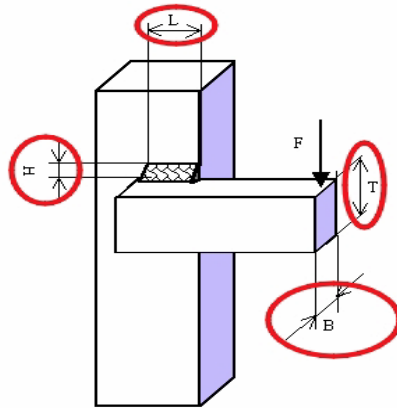
Figure 39, Weldbeam showing various parameters.

Workflow Description

The workflow consists of a main application chain, starting from Design of Experiment (DOE), Scheduler Nodes and ending with the Complete Logic Node. ME-Excel is the only Direct Application Node, in use to run the specified MS-Excel model for each configuration proposed for the optimisation, updating input variables and extracting output values, until the set objectives are achieved.

Parameters Setup for the example problem definition (link Excel file cells/ranges with modeFRONTIER variables)

The next step is to link the parameter values set in Excel file cells or cell ranges with the modeFRONTIER variables via Interactive Selection, or Parameter Chooser.

Both methods are accessible from the Actions Toolbar and all established connections are shown in the lower part of the Properties panel. Interactive Selection button launches the Excel application and loads the specified workbook, which enable the linking of modeFRONTIER variables to Excel parameters. Before using this feature, the desired input and output variable nodes must be inserted in the workflow and link to the MS-Excel node.

Optimisation Run – modeFRONTIER with Excel

When the project is ready to run, the following must be performed:

- Create a DOE table using a Random DOE sequence of 24 points and
- Use MOGA-II of 20 generations as optimisation algorithm in the Scheduler node.
- Save the project
- Click on the green arrow (top toolbar) to run the optimisation.

- o The optimisation run can be monitored real-time from the Run Analysis environment by using different gadgets. E.g.
  - Project Info gadget (1) shows the general project run log (index.html)
  - Scatter/Bubble gadget (2) enables to check how the data is dispersed, whether the variables are correlated and whether any anomalies are present
  - Engine Table gadget (3) shows in a tree format all ongoing processes, i.e. IDs of designs currently evaluated and application nodes performing the evaluation
  - Multi-History gadget (4) shows the progress of the optimisation.
  - Clicking on a single design in the Design List (5), the Info Design panel (6) opens a tree view of the log and process directories of the selected design and allows for the direct access to the relevant files, which are thus opened in a new gadget.
  - It also indicates the design ID number, type (feasible/unfeasible, real/virtual, error, etc.) and completeness. It reflects a single design selected in a gadget or the Design List.

The example optimisation run uses the 'Excel_tutorial.prj' file with a run duration of about 2 ½ hours and can be stopped manually. The modeFRONTIER and MS-Excel configurations are as follows:

- ModeFRONTIER2017 and Excel2010 installed in RMIT server (operating system: Windows Server 2012 R2).
- Workbook: c:\Program Files\ESTECO\modeFRONTIER2017r2\tutorials\prj\Excel_Node\Weldbeam.xls
- Installation Dir: C:\Program Files\MATLAB\R2017a
- Java (SDK/JRE) Version: 1.8.0_60; Java Home: C:\Program Files\ESTECO\modelFRONTIER2017R2\jre

The Design Analysis (after the optimisation run) is illustrated in Figure 40, where the 'Evaluated designs' was 99, Real-Feasible was 95 and Real-Unfeasible was 4.
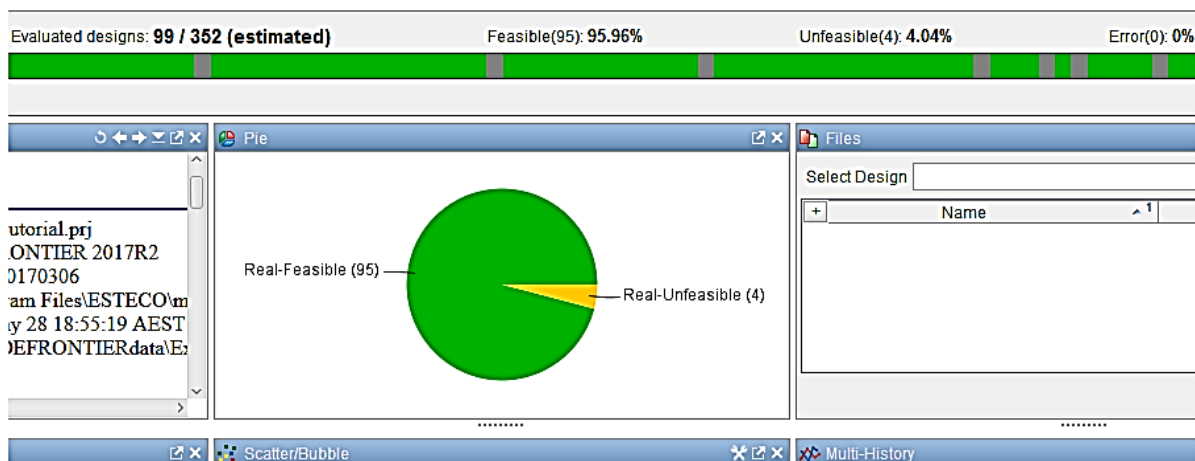
Figure 40, ModeFRONTIER analytical results: stopped manually after 99 evaluated designs inabout 2 1/2 hours.

Appendix G, Interfacing MATLAB Simulink (Simscape) with SolidWorks

This appendix includes an example on how MATLAB Simulink (Simscape) has been interfaced with SolidWorks for the specific purpose to carry out the research. The reader should refer to Table 16.

This appendix describes the MATLAB functions to allow SolidWorks 3D models to be exported to MATLAB Simulink (Simscape Multibody) environment. This function provides:

- A multibody simulation for 3D mechanical systems, such as the aircraft landing gear.
- The Import function allows a complete CAD assemblies model, which includes all masses, inertias, joints, constraints, and 3D geometry.
- Automatic generation of 3D animation to enable visualising the system dynamic.

Simscape Multibody Link is a CAD plug-in that:
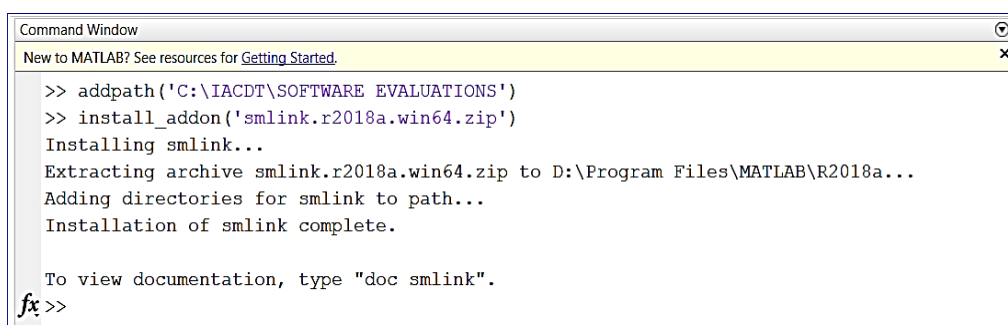
- Allows installation of CAD application such as SolidWorks to export CAD assembly models from SolidWorks into MATLAB Simulink (Simscape) environment.
- Generates the files that need to import the model into the Simscape Multibody environment (using the 'smimport' function).

Setup MATLAB Simulink (Simscape Multibody) connection with SolidWorks

The installation steps for the Simscape Multibody Link Plug-In are taken from the MathWorks website: https://au.mathworks.com/help/physmod/smlink/ug/installing-and-linking-simmechanics-link-software.html (assess date: 01 July 2018). The Simscape™ Multibody™ Link plug-in provides the primary interface for exporting CAD assemblies into Simscape Multibody software.

Step 1: Download the Simscape Multibody Link installation files:
- Go to Simscape Multibody Link download page.
- Follow the download page prompts.
- Save the zip archive and MATLAB file in a convenient folder.
- Select the file versions, which matches the installed MATLAB release no. and system architecture—e.g., release R2015b and Win64 architecture.
  - smlink.r2018a.win64.zip (Do not extract the zip archive)
  - install_addon.m

```
Command Window
New to MATLAB? See resources for Getting Started.                          ✕
>> addpath('C:\IACDT\SOFTWARE EVALUATIONS')
>> install_addon('smlink.r2018a.win64.zip')
Installing smlink...
Extracting archive smlink.r2018a.win64.zip to D:\Program Files\MATLAB\R2018a...
Adding directories for smlink to path...
Installation of smlink complete.

To view documentation, type "doc smlink".
fx >>
```
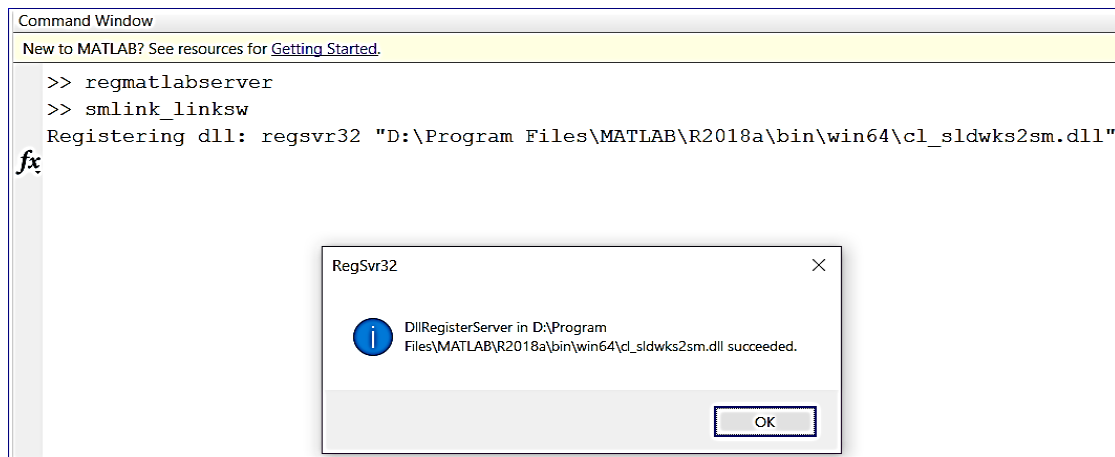
Figure 41, Setup MATLAB Simulink (Simscape Multibody) connection with SolidWorks – In MATLAB: step2, run installation function.

Step 2: Run the installation function:
- Run MATLAB as administrator.

- Add the saved installation files to the MATLAB path by entering addpath ('foldername') at the MATLAB command prompt as illustrated in Figure 41.
- Replace foldername with foldername of the saved installation files—e.g., C:\Temp.
- Enter install_addon ('zipname') at the MATLAB command prompt.
- Replace 'zipname' with the name of the zip archive—e.g., smlink.r2015b.win64.zip.

Step 3: Register MATLAB as an Automation Server each time to export a CAD assembly model.
- Simscape Multibody Link plug-in will attempts to connect to MATLAB.
- For the connection to occur, MATLAB must be registered as an automation server as follows:
  o In a MATLAB session, run in administrator mode: at the command prompt, enter regMATLABserver as illustrated in Figure 42.
  o In MS-DOS window run in administrator mode: at command prompt, enter MATLAB -regserver.
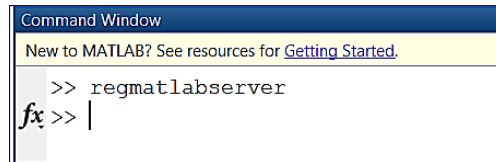
Figure 42, Setup MATLAB Simulink (Simscape Multibody) connection with SolidWorks – In MATLAB: step3, register MATLAB as an automation server.

Figure 43, Setup MATLAB Simulink (Simscape Multibody) connection with SolidWorks – In MATLAB: step4, enable simscape multibody link plug-in.

Step 4: Enable the Simscape Multibody Link Plug-In:
- At MATLAB® command prompt, enter smlink_linksw as illustrated in Figure 43.
- Start SolidWorks.
- In the SolidWorks Tools menu, select Add-Ins as illustrated in Figure 44.
- In the SolidWorks Add-Ins dialog box, select Simscape Multibody Link check box.
  o A Simscape Multibody Link menu appears in the SolidWorks menu bar when user starts or opens a CAD assembly.

o Once, the 'Simscape Multibody' box has been clicked, the file will be saved in .xml file format in any selected directory.
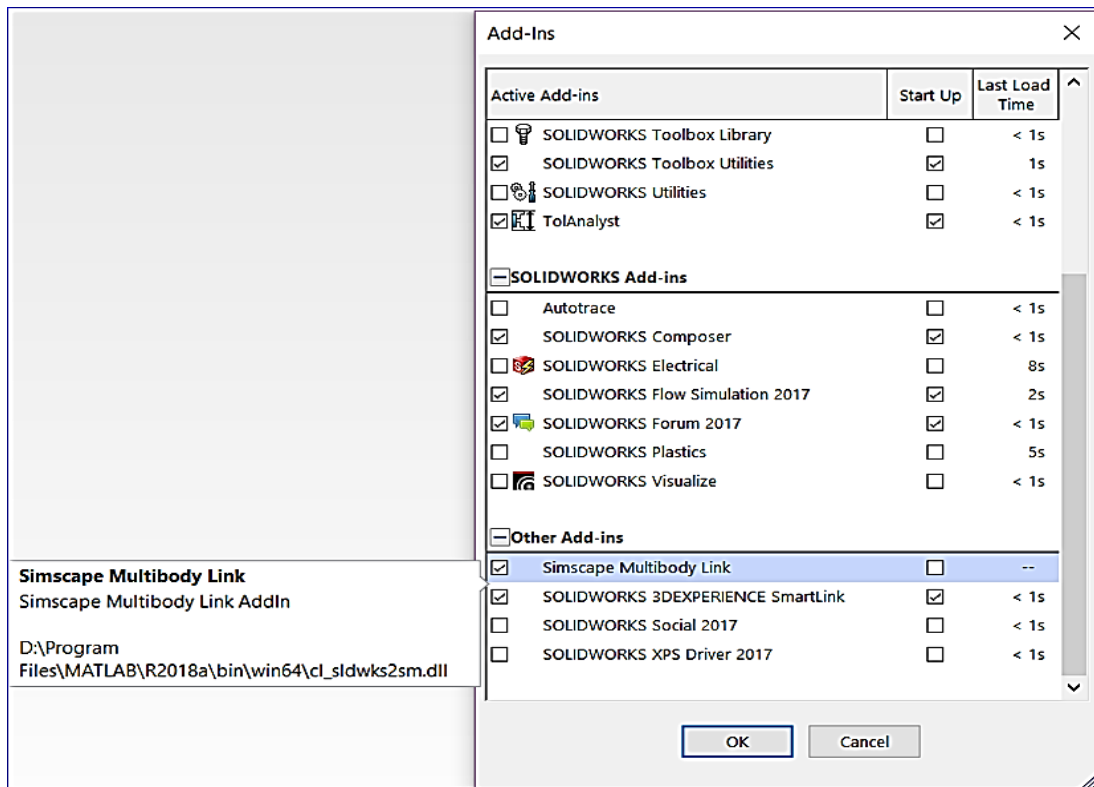

Figure 44, Setup MATLAB Simulink (Simscape Multibody) connection with SolidWorks – In SolidWorks: check simscape multibody link.

Exporting a CAD assembly from SolidWorks into MATLAB Simulink: Simcape

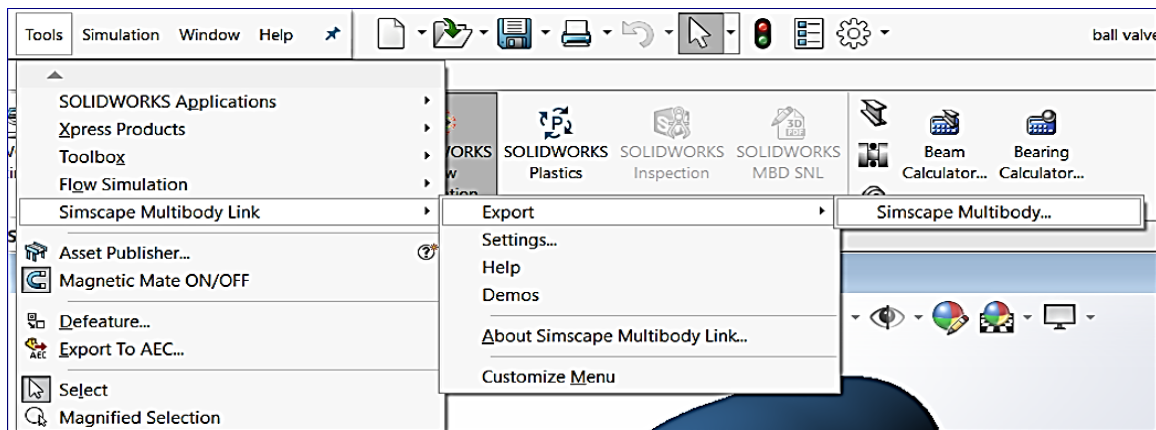A CAD assembly from SolidWorks that has been saved in .xml file format can be exported into the MATLAB Simulink: Simcape environment as illustrated in Figure 45.

Figure 45, Setup MATLAB Simulink (Simscape Multibody) connection with SolidWorks – In SolidWorks: export CAD assembly to .xml file compatible for simscape import.

After saving the example ballvalve.xml, the MATLAB can be started and followed by typing
>> smimport ('C:\IACDT\ballvalve.xml') in the Command-Window. Simscape will import the
CAD file and transform to simscape simulation model. The simulation could be run by click
the play button.
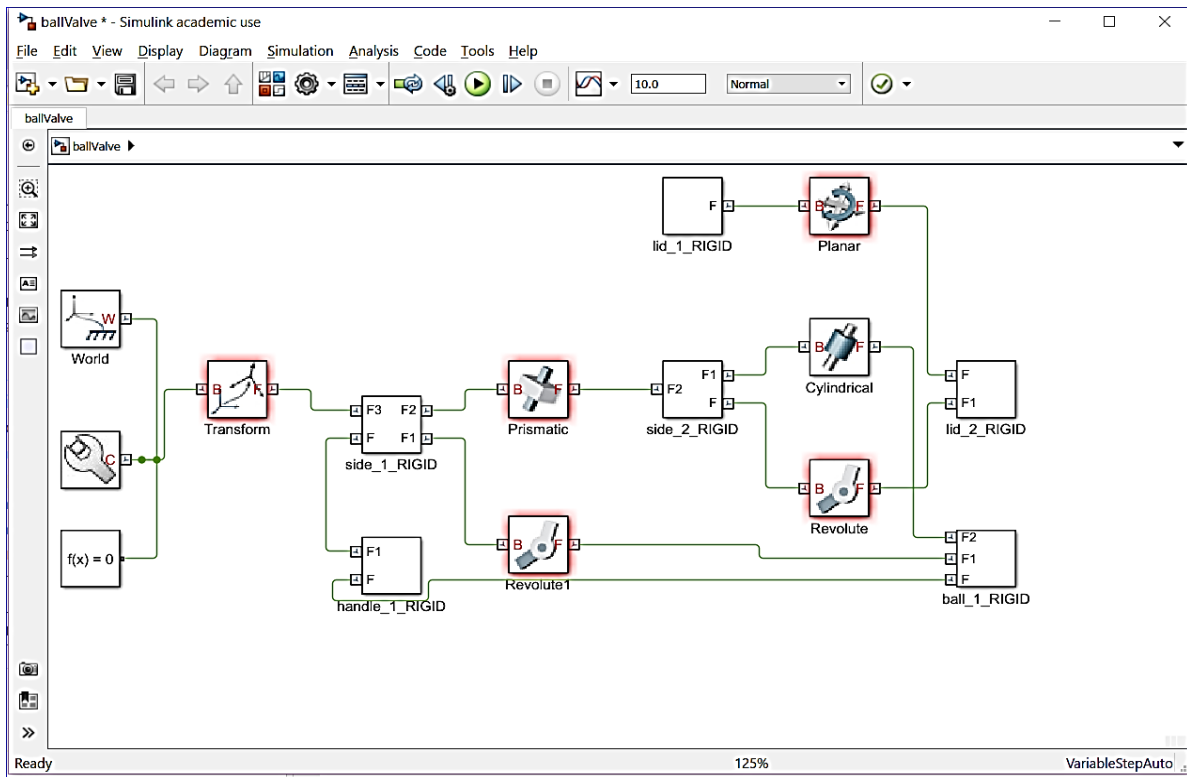
Figure 46, Setup: MATLAB Simulink (Simscape Multibody) connection with SolidWorks – Simscape: .xml file
has been imported and converted to Simscape block, ready for simulation.

Appendix H, Interfacing MATLAB with modeFRONTIER

This appendix includes an example on how MATLAB has been interfaced with modeFRONTIER for the specific purpose to carry out the research. The reader should refer to Table 16.

The supported versions of MATLAB application are listed in Table 39, where [85]:

- 'T' = Tested & Supported
- 'E' = Expected to Work
- 'Empty cell = Not Supported'

Table 39, ModeFRONTIER 3rd part integration application – MATLAB.

MATLAB

| Software Version | Windows | | | | | | | Linux | | UNIX |
| | Vista | | 7 | | 8 | | 10 | i586 | 64bit | |
	32bit	64bit	32bit	64bit	32bit	64bit	64bit			
6.5x	E	E	-	-	-	-	-	E	E	-
7.x.x*	E	E	E	E	-	-	-	T	T	-
2010a	E	E	E	E	E	T	E	E	T	-
2011	E	E	E	E	E	E	E	E	T	-
2012	E	E	E	T	E	E	E	E	E	-
2013	E	E	E	T	E	E	E	E	T	-
2014	E	E	E	T	E	E	E	E	T	-
2015	E	E	E	T	E	E	E	E	T	-
2016	E	E	E	E	E	E	E	E	T	-

* To check your MATLAB version, please refer to http://www.mathworks.com/help/matlab/ref/version.html

MATLAB Application Integration Node

The MATLAB Application Integration Node can be dragged from the tool bar directly into the workflow space as illustrated in Figure 47. After that, the 'MATLAB properties' dialog box can be opened by double-clicking on the MATLAB Node as illustrated in Figure 48.
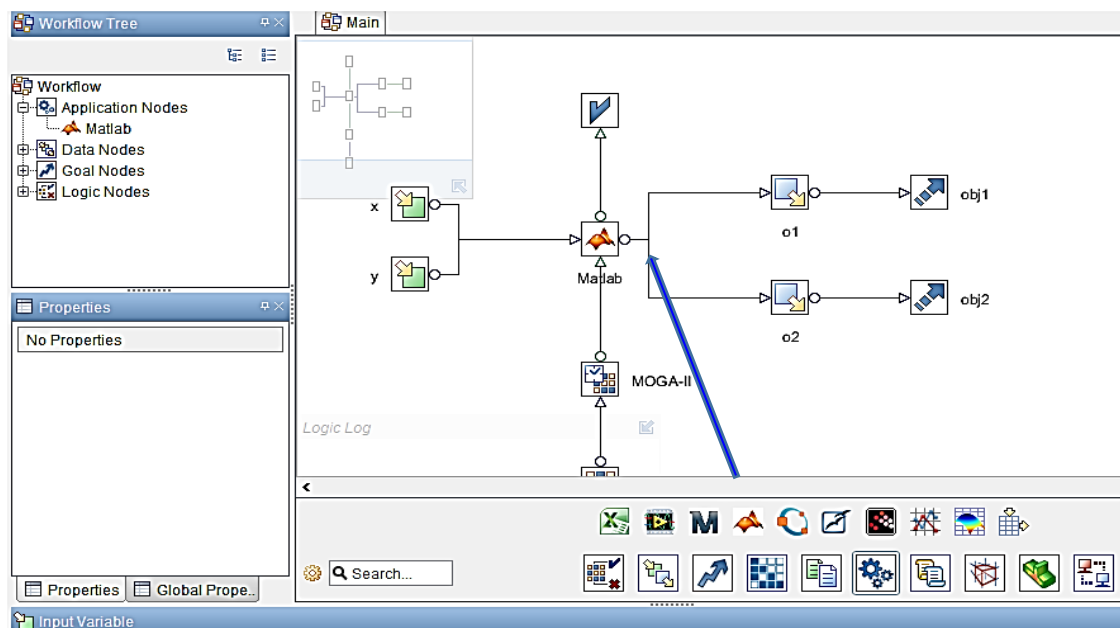

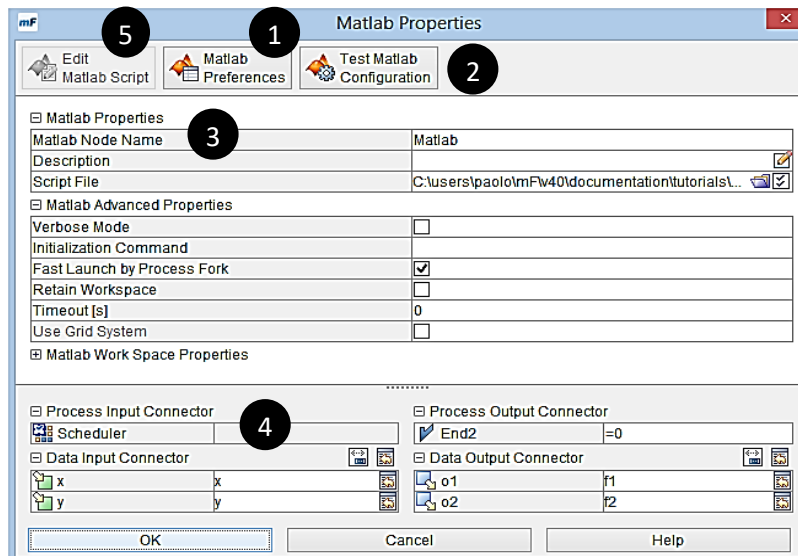Figure 47, MATLAB app. integration node dragged from modeFRONTIER tool bar into workflow.

Figure 48, MATLAB property dialog box opened in modeFRONTIER by double-clicking MATLAB node.

Problem description (an example)

In this example modeFRONTIER tutorial problem: Matlab_Tutorial.prj, 2 functions in x and y are to be optimised.

- The 1st function (F1) is a complicated sum of sines and cosines.
- The 2nd function (F2) is a 2nd order polynomial.
- Input data consists of 2 parameters:
  - x: [-3.14; 3.14]
  - y: [-3.14; 3.14].
- Output data consists of 2 objectives:
  - Maximum value of function F1 and F2 in the domain of definition.

The MATLAB Direct Application Integration Node is used to run the specified MATLAB model for each configuration proposed during the optimisation, updating the input variables and extracting the output values, until the set objectives are achieved.

Setup - MATLAB node and preferences (1)

The setup steps are as follows:
- Open MATLAB Preferences dialog box, Figure 49.
- Enter path to MATLAB installation directory, which is required for opening the loaded MATLAB script directly from modeFRONTIER, Figure 49.
- Select the correct MATLAB version from the drop-down list, which must correspond to the version registered using the MATLAB automation server (the mismatch between this parameter and the actual version used, may cause error in design evaluation).
- If several MATLAB versions are installed, verify the current MATLAB automation server.
  - For example, if MATLAB version x.y.z is to be used in Windows, the automation server must be manually registered with the following command:
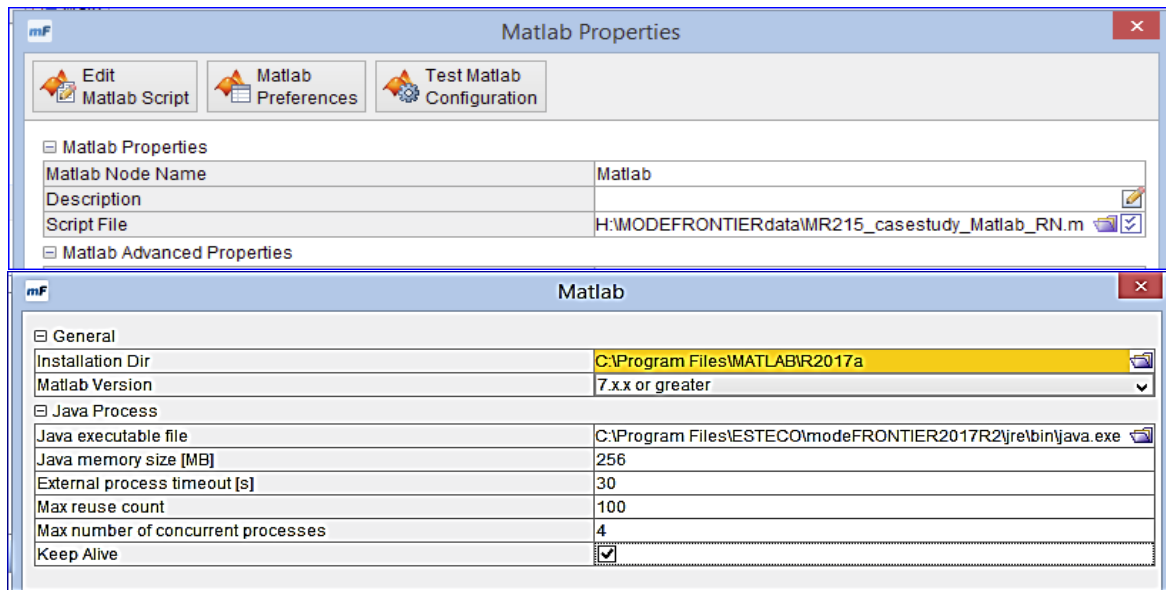   'C:\Programs\MatlabXY\bin\win32\MATLAB.exe/regserver'

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Figure 49, MATLAB direct application node: properties, preferences button.

Setup - Test MATLAB Configuration (2)

The 'Test Matlab Configuration' button as illustrated in Figure 48 (2) can be used to verify whether:

- All installation requirements have been respected
- ModeFRONTIER is able to access Matlab, modify the inputs and extract the outputs by using an internal test model without executing the user script as illustrated in Figure 50.
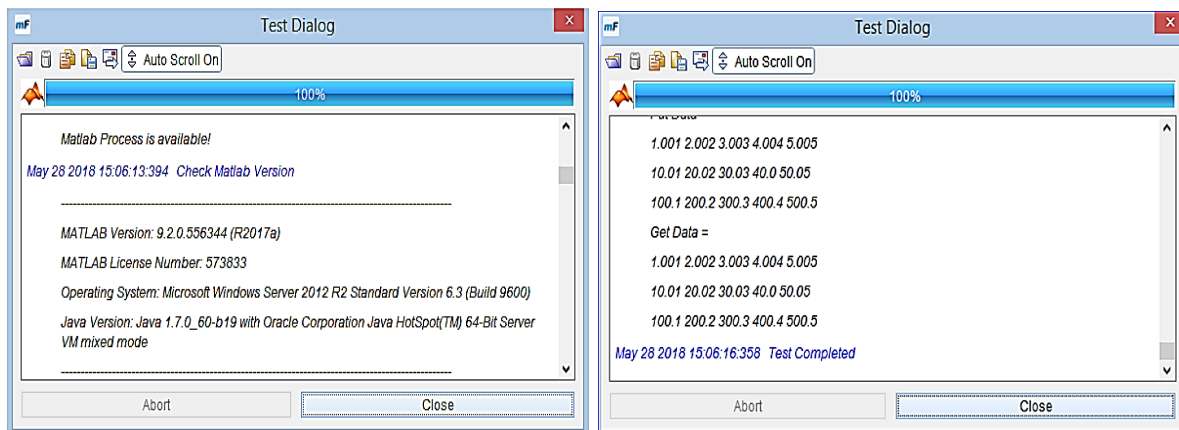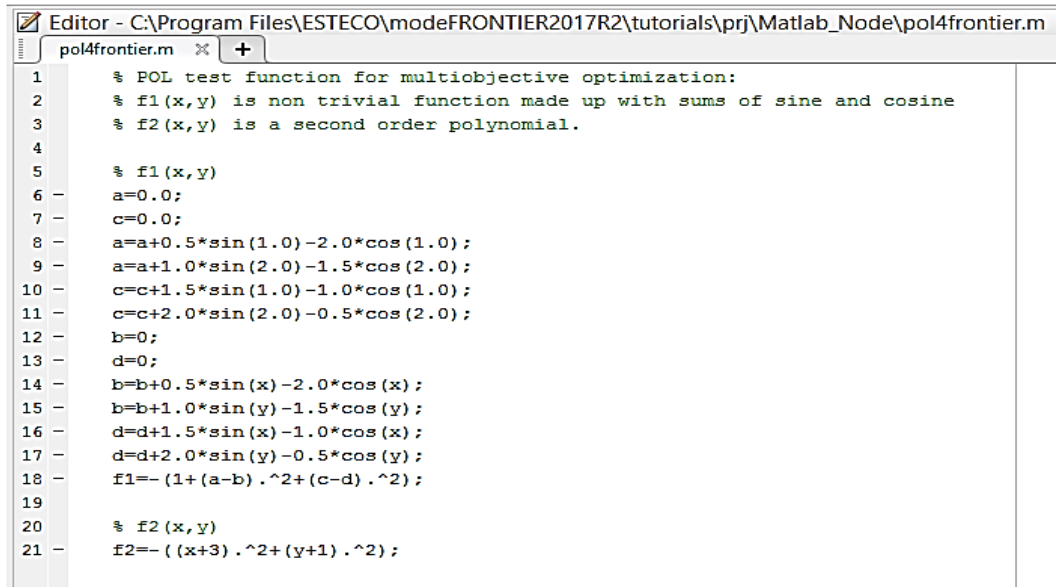

Figure 50, Testing MATLAB configuration.

Setup - MATLAB Properties (3)

The Script File field can be used to select the example 'pol4frontier.m' file from the file system.

- This file will be subject to introspection to detect the input and output parameters set within, which will be subsequently optimised by modeFRONTIER.
- Clicking on 'Edit Matlab Script' button, Figure 48 (5) will open MATLAB2017a application in modeFRONTIER as illustrates in Figure 51.

```
Editor - C:\Program Files\ESTECO\modeFRONTIER2017R2\tutorials\prj\Matlab_Node\pol4frontier.m
pol4frontier.m  ✕  +
1      % POL test function for multiobjective optimization:
2      % f1(x,y) is non trivial function made up with sums of sine and cosine
3      % f2(x,y) is a second order polynomial.
4
5      % f1(x,y)
6 -    a=0.0;
7 -    c=0.0;
8 -    a=a+0.5*sin(1.0)-2.0*cos(1.0);
9 -    a=a+1.0*sin(2.0)-1.5*cos(2.0);
10 -   c=c+1.5*sin(1.0)-1.0*cos(1.0);
11 -   c=c+2.0*sin(2.0)-0.5*cos(2.0);
12 -   b=0;
13 -   d=0;
14 -   b=b+0.5*sin(x)-2.0*cos(x);
15 -   b=b+1.0*sin(y)-1.5*cos(y);
16 -   d=d+1.5*sin(x)-1.0*cos(x);
17 -   d=d+2.0*sin(y)-0.5*cos(y);
18 -   f1=-(1+(a-b).^2+(c-d).^2);
19
20     % f2(x,y)
21 -   f2=-((x+3).^2+(y+1).^2);
```

Figure 51, MATLAB script file used to run design Model.

Setup - Linking modeFRONTIER variables with MATLAB parameters (4)

The Input and output variable nodes in modeFRONTIER must be inserted in the workflow and connected to the Matlab node before linking them to the Matlab parameters. Once the insertion and connection are completed, the variable nodes will appear in the Data Input Connector/Data Output Connector panels in the bottom part of the 'Matlab Properties' dialog as illustrated in Figure 48 (4). In this example:
- Link only those parameters whose values will be evaluated with modeFRONTIER.
- All others parameters can be ignored and kept at their fixed values.
- In order to do this, it is sufficient to write the correct variable name (as in the Matlab script) in the field next to the corresponding modeFRONTIER variable.

In any given moment, the Matlab script can be opened directly from modeFRONTIER:
- By clicking on the 'Edit Matlab Script' button (5) in the Toolbar.
- When finished, press OK to exit the Properties dialog.

Optimisation Run – modeFRONTIER with MATLAB

When the project is ready to run, the following actions must be performed:
- Create a DOE table using a Sobol DOE sequence of 24 points
- Utilise MOGA-II of 24 generations as optimisation algorithm in the Scheduler node.
- Save the project and click on the green arrow in the top toolbar to run the optimisation as illustrated in Figure 52.
  - The optimisation run can be monitored real-time from the Run Analysis environment by using different gadgets, such as:
    - Project Info gadget (1) shows the general project run log (index.html)
    - Scatter/Bubble gadget (2) enables to check how the data is dispersed, whether the variables are correlated and whether any anomalies are present

- Engine Table gadget (3) shows in a tree format all ongoing processes, i.e. IDs of designs currently evaluated and application nodes performing the evaluation
- Multi-History gadget (4) shows the progress of the optimisation.
- By clicking on a single design in the Design List (5),
  o Info Design panel (6) opens a tree view of the log and process directories of the selected design and
  o Allows for the direct access to the relevant files, which are thus opened in a new gadget.
  o It also indicates the design ID number, type (feasible/unfeasible, real/virtual, error, etc.) and completeness.
  o It reflects a single design selected in a gadget or the Design List.
  o Remember to set the option Clear Design Dir on Exit in the Scheduler node Properties on Never to keep all designs' log files.
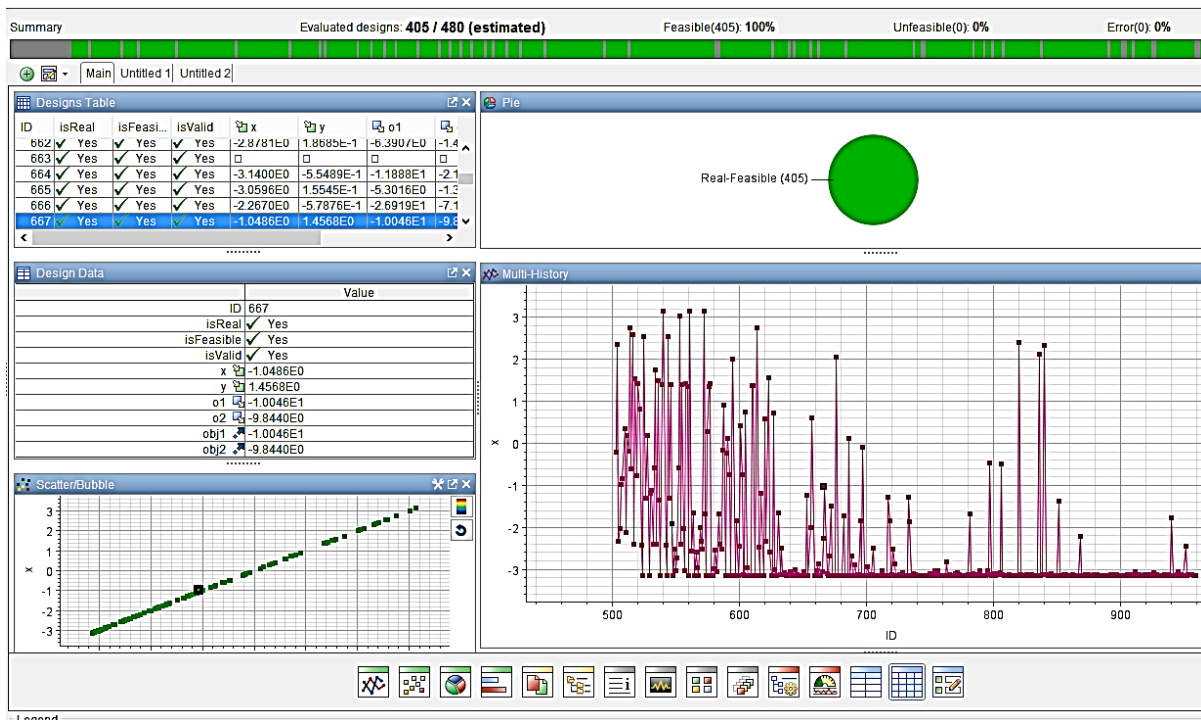
Figure 52, Design Analysis (after optimisation run).

The example optimisation run uses the 'Matlab_tutorial.prj' file with a Run duration of about 2 hours. The modeFRONTIER and MATLAB configurations are:
- ModeFRONTIER2017 and MATLAB2017a are installed in RMIT server (Windows Server 2012 R2).
- Script File: C:\Program Files\ESTECO\modelFRONTIER2017R2\tutorials\prj\Matlab_Node\pol4frontier.m
- Installation Dir: C:\Program Files\MATLAB\R2017a
- Java executable file: C:\Program Files\Java\jdk1.8.0_131\bin\java.exe

Design Analysis (after the optimisation run) is illustrated in Figure 52:
- Evaluated designs: 405. Real-Feasible: 405 – all feasible
- Design Point ID: 667 have been highlighted.

Appendix I, Interfacing AGI System Tool Kit (STK) with SolidWorks

This appendix includes an example on how AGI STK has been interfaced with SolidWorks for the specific purpose to carry out the research. The reader should refer to Table 16.

Using 3D Models in STK

The AGI STK can use 3D models to represent scenario objects and aid in analysing and visualising the relationships among the objects. STK contains detailed 3D models representing objects such as ground stations, aircraft, airstrips, satellites, aircraft carriers and helicopters.
Once a model is specified to represent an object, it is graphically displayed in its correct position and orientation, as defined in the objects. Basic properties, Position and orientation can vary over time and can be manually adjusted within the objects 3D Graphics properties. Models used in the STK 3D graphics windows can be imported into STK in:

- COLLADA (.dae) file format
- MDL (.mdl) file format.

Once a model is available in COLLADA or MDL, functionality such as Ancillary features consist of articulations (moveable components), attach points, pointable elements, and solar panel groups, and could be added. After loading the models (.dae or .mdl) into STK the model may be scaled to adjust the position of the model articulations.

A simplified case study - method to convert SolidWorks (.sldprt, .sldasm) into Collada (.dae) file format prior to importing into AGI STK

Step#1: Create a 3D model in SolidWorks and save as (.sldprt, .sldasm), Figure 53.
Step#2: Import SolidWorks 3D model (.sldprt, .sldasm) into Autodesk 3dsMax2018, Figure 54.
Step#3: Export the 3dsMax2018 3D model into Autodesk Collada file format (.dae), Figure 55.
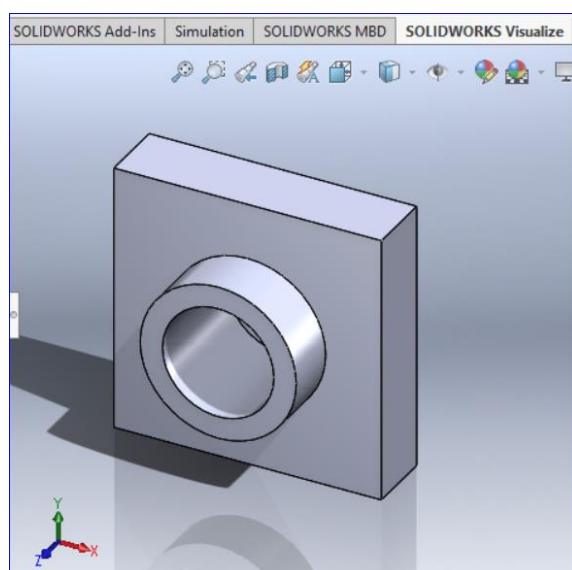Step#4: Import the 3D model in file format (.dae) into AGI STK, Figure 56.

Figure 53, Step#1: create a 3D model in SolidWorks and save in file format (.sldprt, .sldasm).
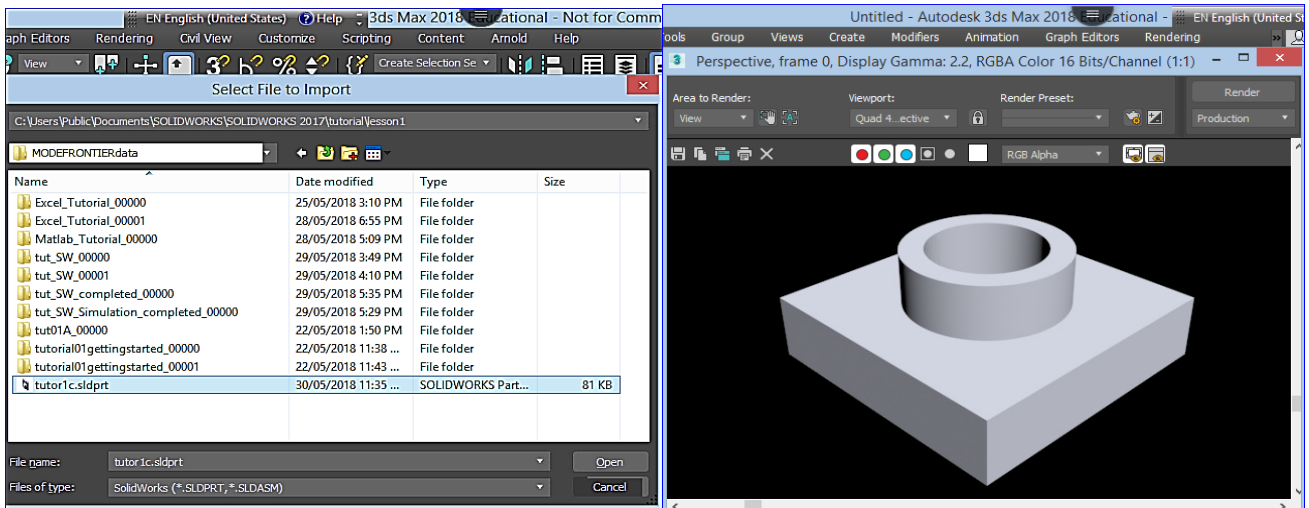
Figure 54, Step#2: import SolidWorks 3D model (.sldprt, .sldasm) into Autodesk 3ds Max2018.
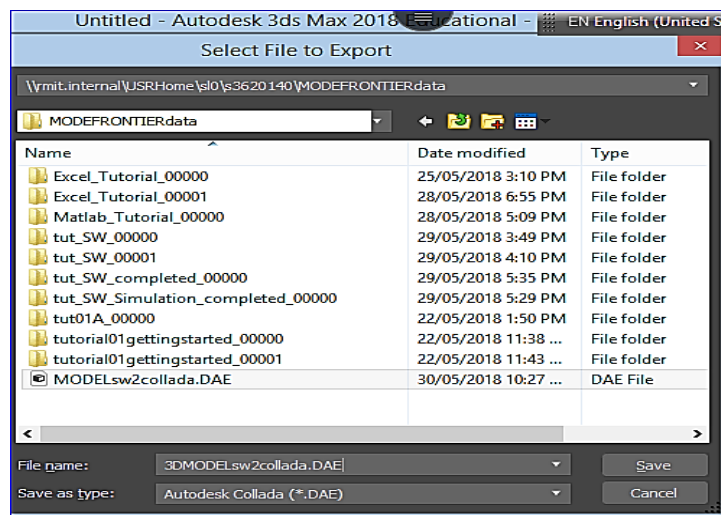

Figure 55, Step#3: export 3ds Max2018 3D model into Autodesk Collada file format (.dae).
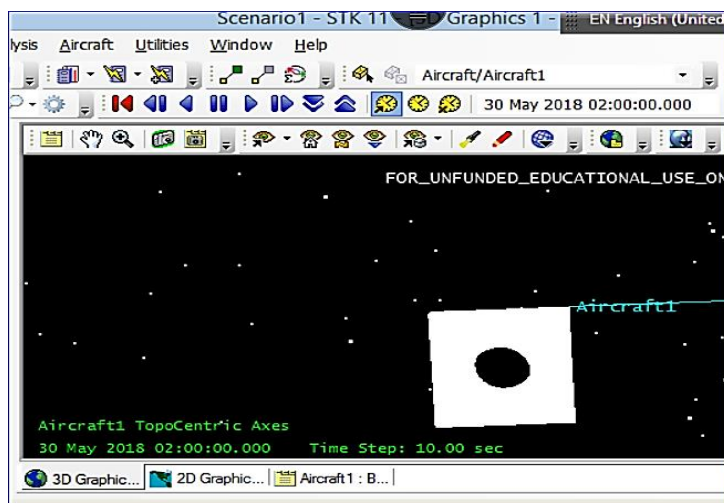

Figure 56, Step#4: import 3D model in file format (.dae) into AGI STK environment.

Appendix J, Case studies by manual calculations and simulations by modeFRONTIER, MS-Excel and MATLAB

This appendix includes the Case Studies on how modeFRONTIER has been interfaced with MS-Excel and MATLAB for the specific purpose to carry out the research.

Case study (simulations) assumed configuration

The mission requirement for the FRDS system is to expel 5,000 litre per second of retardant from a 28,000-litre reservoir through the door of the A400M aircraft Figure 57 (top). https://www.airbus.com (assess date: 26 Oct 2018).
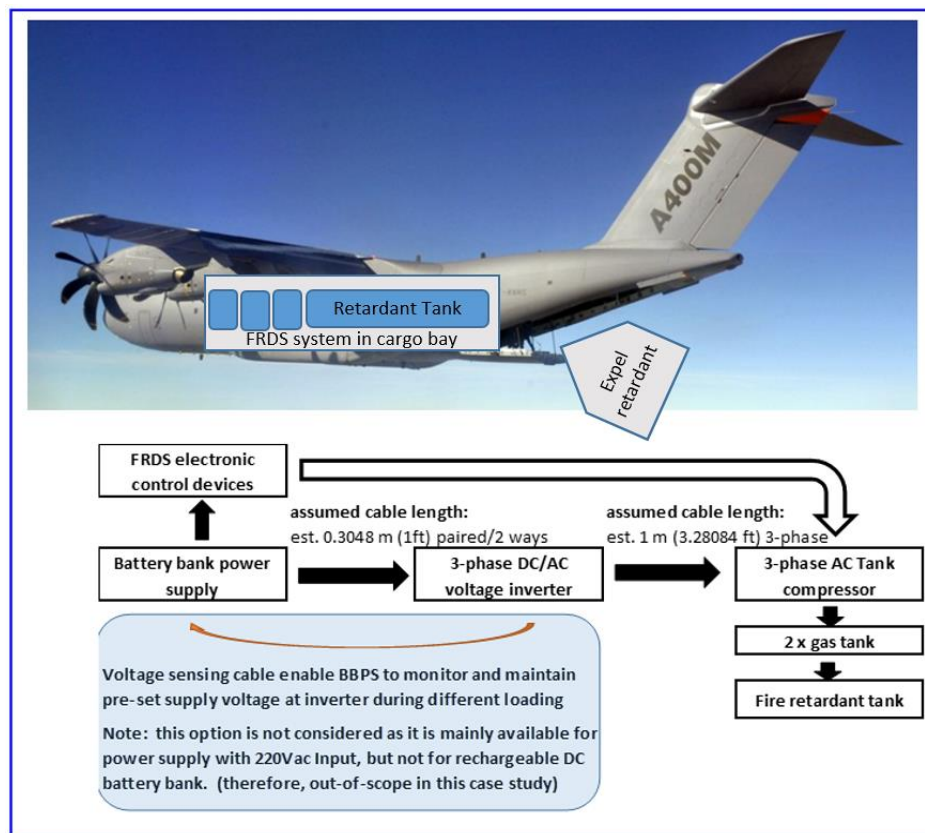
Figure 57, Airbus A400M aircraft (top). Configuration used for evaluations (bottom).

The assumed configuration utilised for evaluation as illustrated in Figure 57 consists of the following components:

- 1 fire retardant tank (28,000 litre, max)
- 1 high pressure compressor
- 2 gas tanks (Pressure needed in the $2 * 1m^3$ gas tank is estimated at 4.28MPa (+ 20% loss, estimated at 5.13MPa, Mega Pascal)) to expel gas into the retardant tank
- 1 battery bank power supply (bbps) coupled with a DC-to-AC 3-phase voltage inverter to power the compressor.

- Battery bank and DC-to-AC 3-phase voltage inverter are allocated underneath the compressor with short power cabling to minimise excessive voltage drop in order to be able to operate within a typical limit of 5% supply voltage tolerance.
- The assumed FRDS system operation requires an estimated 55kwh.

Battery bank output is assumed at 48V, 1500Ah (72kwh, max) connected to the 3-phase pure sine wave DC-to-AC inverter (Input at 48V nominal, Output at 415VAC, 3-phase, 50Hz pure since wave), which in turn connects to the high-pressure compressor (Specification at max, power consumption 27kw, pressure 85bar/1230psig, 1700 l/min F.A.D., free air delivery).

With an estimated 5.13MPa = 51.3bar (Pressure: 1 Mega pascal = 10 bar) required from the maximum 85bar capacity of the compressor, the continuous power consumption could be estimated at $\left(\frac{51.3}{85}\right) * 27kw = 16.3kw$. This means a continuous flow of current estimated at 339 ampere (Ampere = Power/Voltage [120], chapter 1, page 1-16) is expected from the battery bank at 48V output to the inverter via a 1foot copper cable.

Based on the assumed power supply Vdc = 48V, continuous drawn Idc = 339amp and copper cable length = 1 foot (P.S. to Inverter), the cmil (cross-section area) value is estimated as at least 31.89 mm^2. The wire size: 31.89 mm^2 taken from the wire size conversion chart is therefore based on next higher value: 33.61 mm^2, with the corresponding values: 6.54 mm diameter; American Wire Gauge (AWG) 2 and 0.2576 inch diameter [121, 122]. AWG 2 = 66350 (circular mils, cmil) [122, 123].

Case study – Evaluation approach by Manual Calculations

The configuration: For total Vdc dropped across cable run of paired copper conductors from 1 foot (0.3048 m) to 32.8 feet (10 m) at constant 24 Vdc and 339 Amp connecting from battery bank to inverter.

The first step is to calculate the voltage dropped across a 1 foot copper cable run of paired copper conductors (L) could be calculated based on following equation [122, 123]:

Voltage drop (2-wire DC or AC 1-phase (inductance negligible@60Hz)) ([122], chapter 2, page 13 and 14) is given as:

$$V_{drop2wire} = \frac{(2*K*I*L)}{cmil} \qquad \textit{Equation 53}$$

Where,
Resistivity of conductor (a constant): K = ohms-cmil per ft. (or 1ft. = 0.3048m)
K_copper = 12.9ohms-cmil/ft.; K_aluminum = 21.2 ohms-cmil/ft. (estimated)
I = current (or amperes) in conductor
L = one-way length of paired circuit cable run (feet)
cmil = circular mil area (cross sectional area size) of conductor
Where, $(wire\ diameter\ in\ decimal\ inches * 1000)^2$ (1inch = 25.4 mm)

Therefore, Vdc dropped across a 1 foot (L) copper cable run of paired copper conductors (0.3048 meter) copper cable is $\frac{(2*12.9*339*1)}{66350} = 0.13v$ [122, 123].

Subsequently, the remaining supply voltage available to drop across the load, i.e. supply to inverter = 48V – 0.13V, resulting in 47.87V. This result is within the typical 5% tolerance, i.e. 2.4V. This calculation is based on the voltage divider principle (i.e. Supply Voltage (Vsource: 48V) = VacrossCable (in pair): 0.13V + VacrossInverter: 47.87V connected in series [122]. Some 3-phase inverters may have input voltage tolerance up to -15% + 12.5% [124].

The second step is to calculate Vdc dropped across the changing cable run of paired copper conductor from 1 foot (0.3048 m) to 32.8 feet (10 m) at the same constant 24 Vdc and 339 Amp connecting from the battery bank to inverter, and plot a chart as in Figure 58. For example, voltage dropped across the cable run of paired copper conductor is calculated at 2.42V and 18.3 feet respectively. This means the actual cable length run (L in equation) of the paired copper conductor from the battery bank to the inverter location is 18.3 feet.

With the increases in voltage dropped across the cable run as its length increases, and typically, the supply voltage should be kept within 5% tolerance (i.e. 2.4v of 48v) at the inverter contact terminals (i.e. load), the maximum cable run of the paired copper conductor should be estimated at around 16.4 feet or 5 meters and not exceeding 18 feet.

Longer cable run is only possible with supply voltage still within tolerance at the inverter contact terminal, if the power supply unit incorporate a voltage feedback sensing cable connecting the inverter contact terminals. This is to continuously monitor and maintain the supply voltage at 48Vdc (within 5% tolerance) by automatically increasing the voltage upwards at the power-supply contact terminals when the cable length is increased.

However, such DC power supply is mainly available with 220Vac Input, and not as a rechargeable battery bank, and is out-of-scope in this case study. Note: The sensing cable feature of the DC power supply (if available) is also suitable for maintaining supply voltage at the target unit (i.e. inverter) contact terminals for different current load conditions, such as during initial power up and down of the compressor. With voltage dropped across the cable continues to change as the load changes, the supply voltage at the power supply terminals will continue to be higher than at the contact terminals of the inverter.
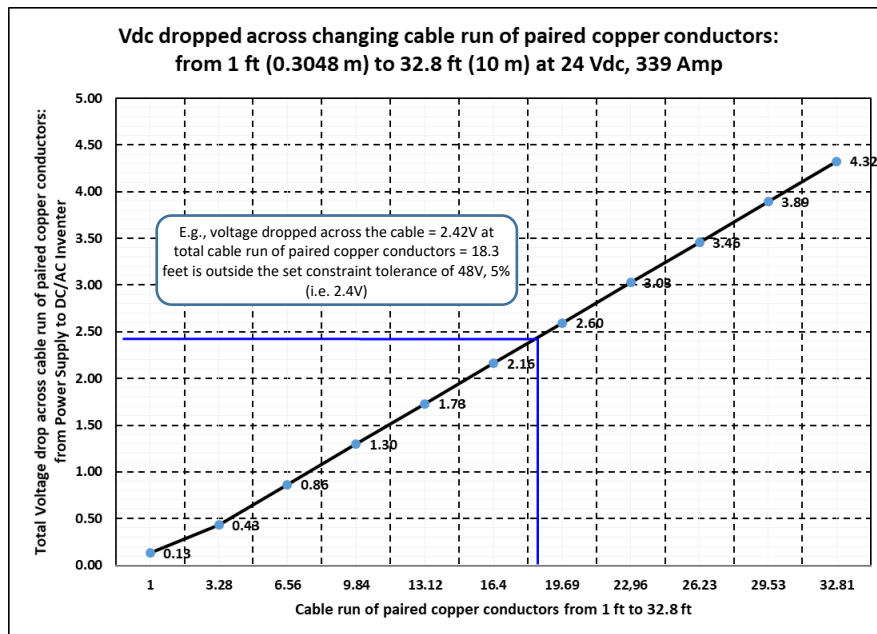

Figure 58, Vdc dropped across changing cable run of paired copper conductors at rated 339Amp and 48Vdc.

Case study - Evaluation approach by the proposed CDF design tools

The configuration: For Vdc dropped across cable run of paired copper conductor from 1 foot (0.3048 m) to 32.8 feet (10 m) at constant 24 Vdc and 339 Amp.

The evaluation (simulation) estimates the <u>maximum (i.e. optimal) cable run of paired copper conductor allowable for normal operation,</u> at a particular cable size (circular cross-section area) and with a continuous rated current flowing from a battery bank through the copper cable to the load (inverter) at fixed power supply voltage for the FRDS system in a A400M aircraft. The evaluation does not include computation at the initial compressor power up (with max current drawn: voltage should drop due to surge current), during operation (with rated current drawn) and power down stage. Once the range of changes voltage drop levels at different cable run of pair copper conductor is known, these values will be used to estimate the maximum allowable cable length connecting the battery bank and the inverter. Further assumptions and expectations are:

- Battery bank power supply (bbps) does not have a voltage-sensing cable connected to the DC-to-AC 3-phases voltage inverter's contact terminals to monitor the voltage to be within the pre-set level (i.e. within specification of power supply, e.g. typical 5% tolerance).
- The voltage at the bbps contact terminals was always higher than the voltage at the inverter contact terminals due to the voltage drop across the cables connecting both.
- The cable run of paired copper conductors connecting between the bbps and inverter will be varied to observe the level of voltage dropped. (I.e. shorter cable run will have lower voltage drop).

The simulation: modeFRONTIER interfaces with Excel (built-in application node)

The simulation runs were 51 of the 320 random iterative evaluation design cycle available (estimated). Feasible cycle is 86.27% (44 cycles) and unfeasible is 13.73% (7 cycles). From the 51 cycles completed, at cycle ID 304, the voltage dropped across the cable = 2.42V at cable run of paired copper conductor at 18.3 feet, is outside the set constraint tolerance of 48V, 5% (i.e. 2.4V), and recorded as unfeasible condition in Figure 59 and Figure 60. Therefore, the cable run of paired copper conductor should not exceed an estimated of 18 feet for the supply voltage, 48V (at the target inverter contact terminals) to be within 5% tolerance (i.e. 2.4V). This also means that the battery bank should be within 18 feet from the DC/AC inverter.
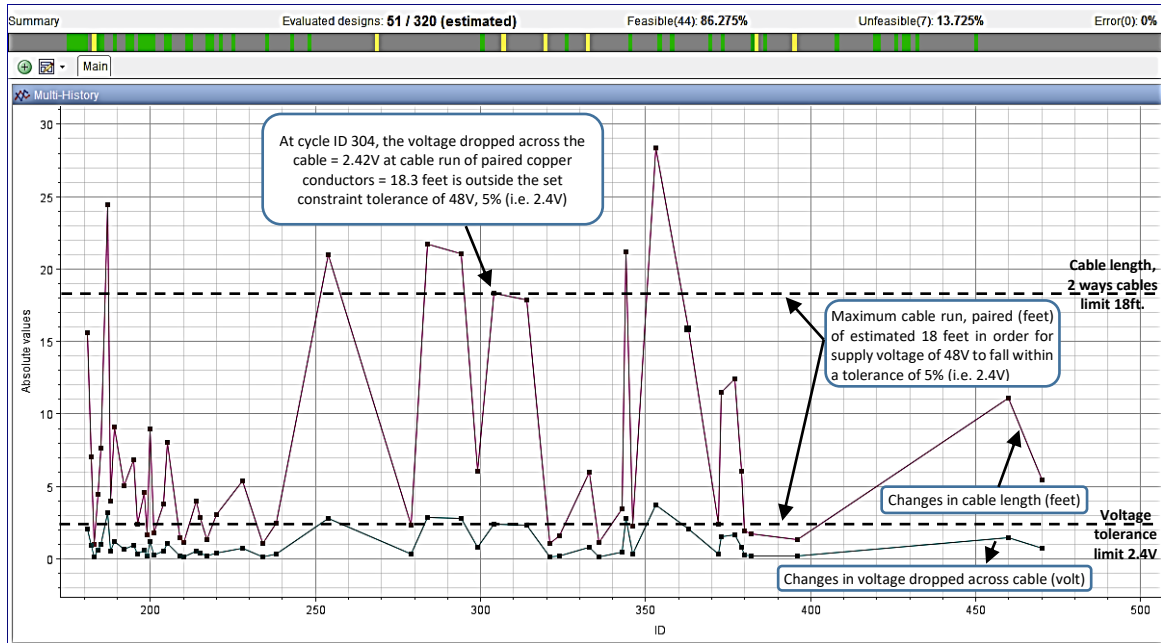
Figure 59, 51 of 320 estimated random evaluation cycles completed. Feasible cycles: 86.27% (44 cycles). Unfeasible: 13.73% (7 cycles).
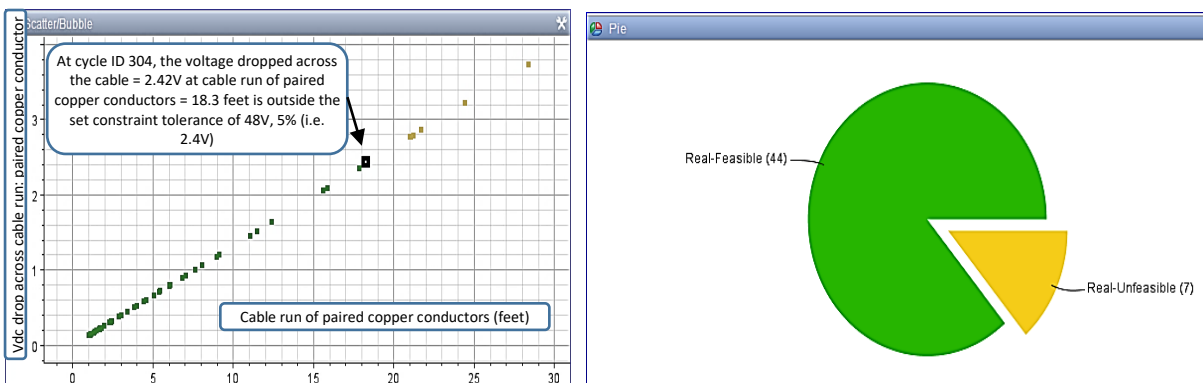

Figure 60, Completed 51 random evaluation cycles. Left: Scatter/Bubble graph. Right: Pie chart. Green dot/area = Feasible. Yellow dot/area = Unfeasible condition.

The simulation: modeFRONTIER interfaces with MATLAB (built-in application node)

The simulation runs were 54 of the 200 random iterative evaluation design cycle available (estimated). Feasible cycle is 70.37% (38 cycles), unfeasible is 27.78% (15 cycles) and 1 cycle recorded due to error when executing the stop cycle (i.e. disregarded). From the 54 cycles completed, at cycle ID 584, the voltage dropped across the cable = 2.44V at cable length = 18.5 feet, is outside the set constraint tolerance of 48V, 5% (i.e. 2.4V), and recorded as unfeasible condition in Figure 61 and Figure 62. Therefore, the cable run of paired copper conductor should not exceed an estimated of 18 feet for the supply voltage, 48V (at the target inverter contact terminals) to be within 5% tolerance (i.e. 2.4V). This also means that the battery bank should be within 18 feet from the DC/AC inverter.
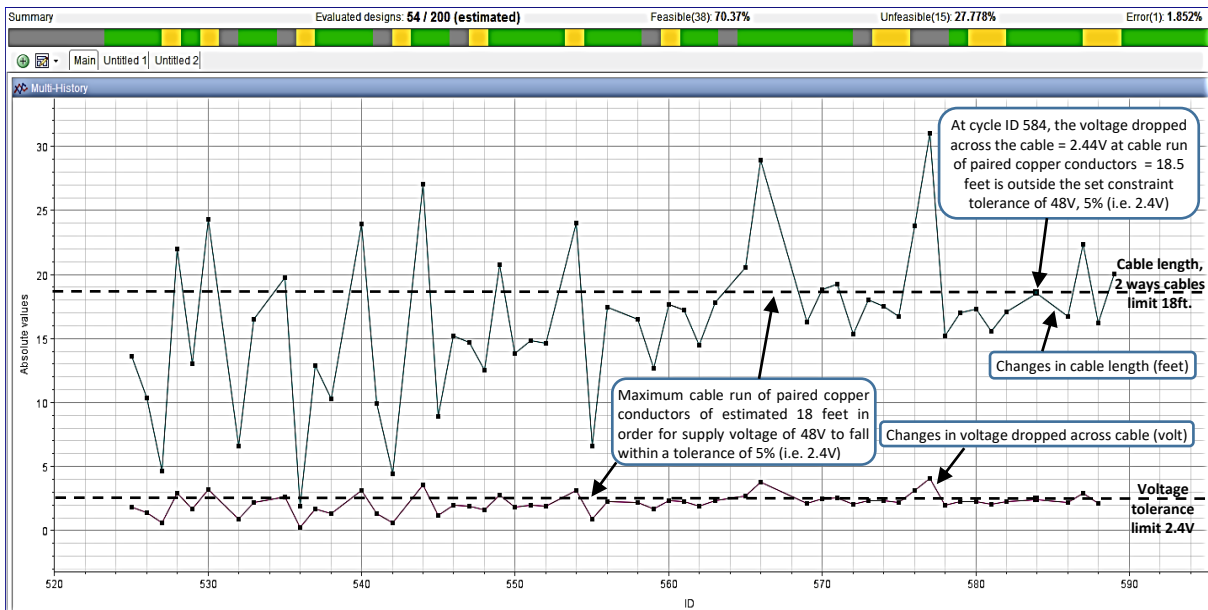
Figure 61, 54 of the 200 estimated random evaluation cycles completed. Feasible cycle: 70.37% (38 cycles), unfeasible: 27.78% (15 cycles) and 1 cycle due to error when executing stop cycle.
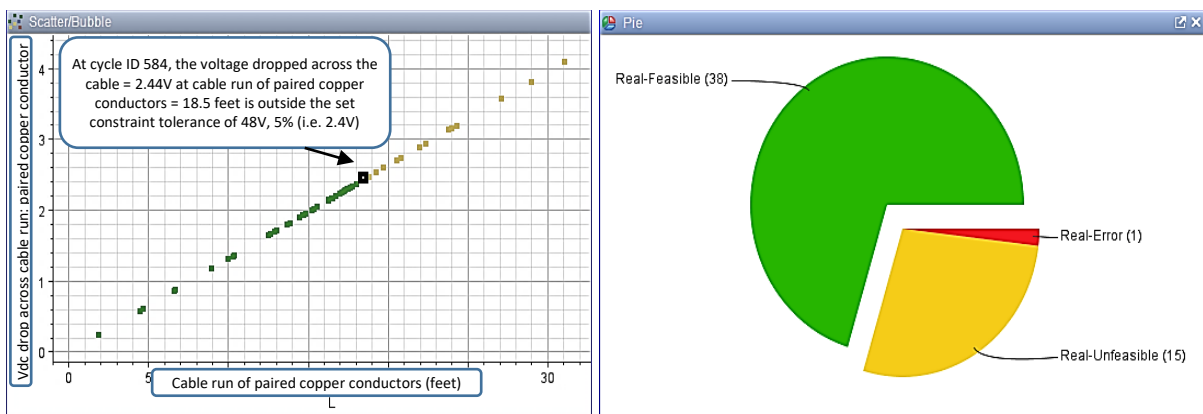

Figure 62, Completed 54 random evaluation cycles. Left: Scatter/Bubble graph. Right: Pie chart. Green dot/area = Feasible. Yellow dot/area = Unfeasible condition. Red area = error due to executing stop cycle.

Simulations – modeFRONTIER interfaces with Excel and MATLAB (built-in application node)

This last part of the case study combined both Excel and MATLAB application nodes together within modeFRONTIER to illustrate the ability of the 3 applications to work as a single unit in a concurrent design environment. The modeFRONTIER workflow is illustrated in Figure 63, where the required mission parameters are input into Excel node for modelling (Equation 1 [122], chapter 2, page 13 and 14) to produce the output results, and subsequently fed into MATLAB node (acting as a pass-through buffer). Outputs from MATLAB is in turns fed into the constraint node to determine which results value is feasible (meeting the defined limits) or not feasible.
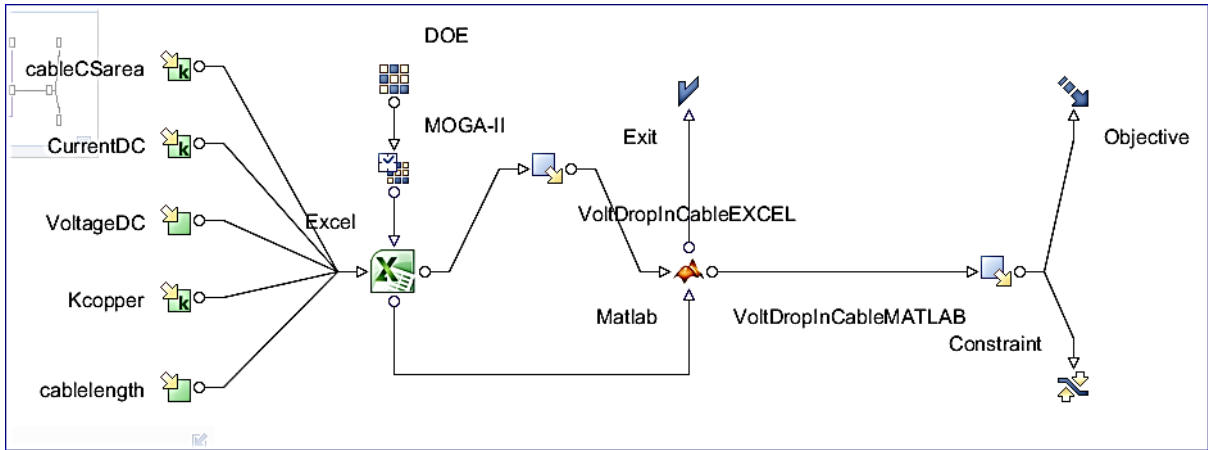
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Figure 63, Simulations, modeFRONTIER interfaces with Excel and MATLAB.

The simulation runs were 65 of the 320 random iterative evaluation design cycle available (estimated). Feasible cycle is 86.15% (56 cycles) and unfeasible is 13.85% (9 cycles). From the 65 cycles completed, at cycle ID 437, the voltage dropped across the cable = 2.28V at cable length = 17.3 feet, is just inside the set constraint tolerance of 48V, 5% (i.e. 2.4V), and recorded as unfeasible condition in Figure 64 and Figure 65. Therefore, the cable run of paired copper conductor should not exceed an estimated of 18 feet for the supply voltage, 48V (at the target inverter contact terminals) to be within 5% tolerance (i.e. 2.4V). This also means that the battery bank should be within 18 feet from the DC/AC inverter.
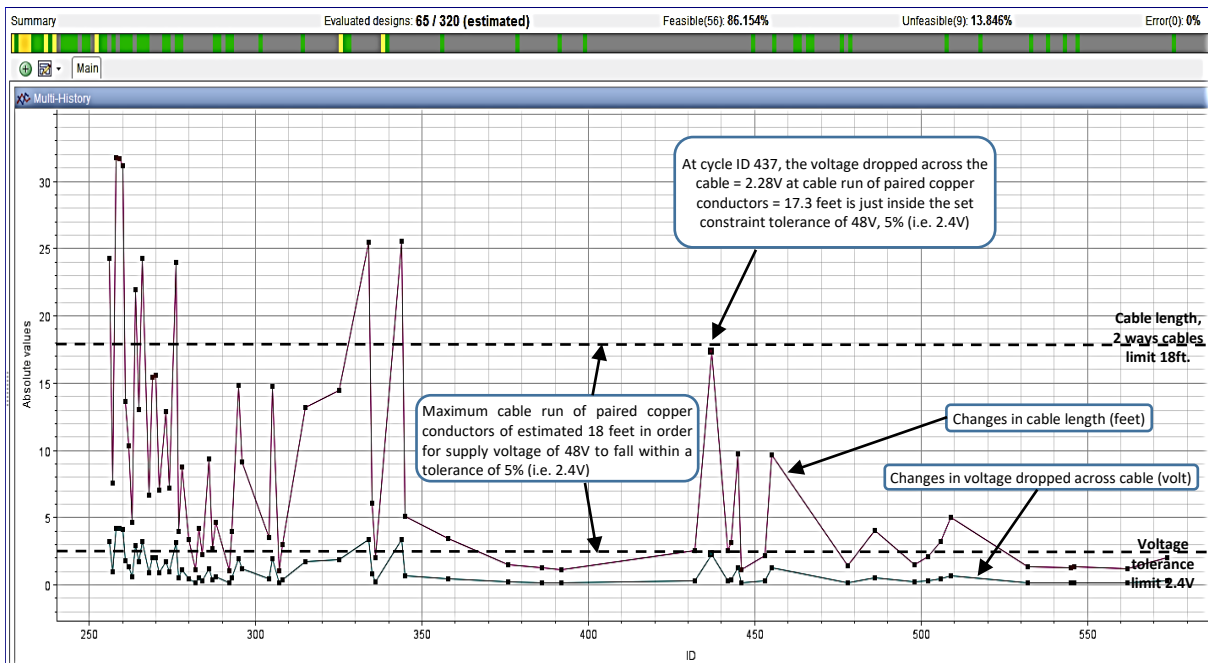

Figure 64, Estimated 65 of the 320 random iterative evaluation design cycles completed. Feasible cycle is 86.27% (44 cycles) and unfeasible is 13.73% (7 cycles).
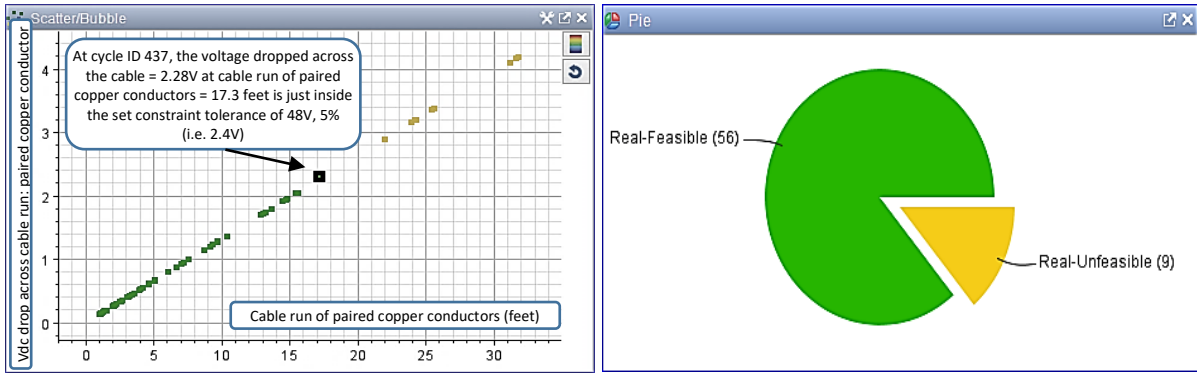
Figure 65, Completed 65 random evaluation cycles. Left: Scatter/Bubble graph. Right: Pie chart. Green dot/area = Feasible. Yellow dot/area = Unfeasible condition.

In summary, the preceding evaluations results by Simulation using modeFRONTIER to interface with ME-Excel and MATLAB (built-in application node) have shown that these tools are capable to function as a single unit in the CDF environment. ModeFRONTIER user interface is intuitive and preparation stage is relatively fast as compared to the manual method based on a workbook. Changing from 1 optimisation option to another can also be performed with ease with its built-in library of optimisation options.