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Aircraft Life Cycle Cost Analysis and Design Integration

A Knowledge Based Engineering Approach

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Aircraft Life Cycle Cost Analysis and Design Integration

A Knowledge Based Engineering Approach

AIRCRAFT LIFE CYCLE COST ANALYSIS AND DESIGN INTEGRATION

A KNOWLEDGE BASED ENGINEERING APPROACH

Proefschrift

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To my family

SUMMARY

From a design concept to a final product, the functional performance and economic properties of an aircraft are evaluated throughout the entire life cycle. Life Cycle Cost (LCC) plays a vital role in the decision-making process. LCC is not only influenced by the market status but also sensitive to technology developments in design concepts. More specifically, the geometric definition, the material choice, and the life cycle process execution all affect the aircraft's cost. There are four major types of cost considered in an aircraft's life cycle: Research, Development, Test & Evaluation (RDT&E) cost, Production cost, Operating & Maintenance (O&M) cost, and Disposal & Recycle (D&R) cost. Each type of cost in the life cycle possesses its own characteristics. Therefore, a method should be developed to associate the design concept with cost estimation. Moreover, since cost properties are performance indicators that apply over the whole life cycle, design optimizations should be established to consider product life cycle performance in terms of cost. This thesis proposes a scalable two-level LCC estimation method. It also focuses on the integration of aircraft LCC properties with the design concept, and the integration of cost analysis with design optimization, which incorporates Multidisciplinary Design and Optimization (MDO) studies supported by Knowledge Based Engineering (KBE) techniques. The study, therefore, has three facets: KBE, LCC, and MDO. All three are embedded in a cost integrated design and optimization framework with interactions among each other. The aircraft design process integrates cost analysis and optimization studies via the support of KBE techniques. LCC analysis employs design and life cycle process parameters to formulate the Cost Estimation Relationships (CER), and is utilized to support MDO. MDO is built upon the multi-disciplinary integration and cost involved optimization problem formulation, and is used to support design decision making.

KBE techniques are here employed to support design-cost integration and cost analysis by means of knowledge extraction, automation, and modularization. According to product master geometries and process meta-models, the process properties can be assigned to the product to generate disciplinary views. Disciplinary views are connected to corresponding cost estimations for the major cost types. In this way, the product geometry and cost estimation can be coupled. Furthermore, by introducing reusable Cost Primitives (CP), which are a suite of parametrical cost estimation blocks containing the relevant product, process, and CER data, a generically applicable and automated cost estimation capability has been developed. Moreover, by building a link between Product Breakdown Structure (PBS) and Cost Breakdown Structure (CBS), the integration of product, life cycle process, and cost is made explicit. Within cost analysis, KBE techniques enable a direct link between the product model and cost estimation through the disciplinary views containing the life cycle process derivation. This improves the accuracy of data extraction for cost analysis, and eliminates errors made via the more complicated manual approach. Relevant knowledge is invoked by Capability Modules (CM) from Knowledge Base (KB) to accomplish process automation. CMs are also responsible for pre- and post- processing activities. The integrated and auto-

mated cost analyses lead to reductions in the labour and time used to extract product and process information in a manual process.

The scalable two-level LCC estimation method is constructed using two levels of estimation: a high-level LCC estimation is built up based on a limited amount of available product and performance properties, while a detail-level LCC estimation is developed on a more detailed data set, including product, process, and performance properties. This addresses the issue of limited data availability for cost analysis within the aircraft design phase. According to the specific characteristics of each major cost type, cost driving parameters and CERs associated with cost elements in an LCC breakdown are developed. Within the high-level cost estimations, both the RDT&E and Production cost estimation employ top-down feature-based parametric methods using cost-time analysis techniques; the O&M cost estimation follows a top-down feature-based parametric method using regression analyses; and the D&R costing adopts a financial model using simple experiential factors. In the detail-level cost estimations, the RDT&E costing adopts a top-down process-based parametric method supported by data fitting techniques. The detail-level Production cost estimation employs a bottom-up process-based parametric method supported by KBE techniques. The detail-level O&M cost model uses a bottom-up process-based parametric method and process-based cost aggregation supported by KBE techniques. The detail-level D&R cost estimation follows a bottom up process-based cost aggregation. The life cycle process-step properties are the key to bridging the design concept and cost performance in the detail-level model. It was found that using two levels of cost estimation makes the cost information highly accessible during the overall life cycle. This inclusion of high-level and detail-level models using data sets and cost estimation methods in two levels of detail is here defined as scalable.

In order to optimize the design with the intention of reducing costs, an extended design structure matrix is built to construct the cost integrated design optimization solutions. Furthermore, to formulate the optimization objective functions, cost indicators such as Direct Operating Cost (DOC) and Surplus Value (SV) are developed based on estimates for the major cost types and the focus of different stakeholders. Structural and process constraints are extracted and applied on those cost indicators. Disciplinary analyses incorporated in the optimization studies contains weight, structure, life cycle process, and cost, which are utilized to either facilitate the objective function or to build necessary constraints.

According to the case studies applied on two typical aero-structures (a stiffened panel and a rudder), it was found that the proposed LCC analysis can be integrated into the design and optimization framework: Design and Engineering Engine (DEE). Relevant KBE techniques, especially the inference rules that enable the integration of the product, process, and cost analysis, facilitate the modularization and automation of the design and disciplinary analysis. Moreover, the proposed LCC method enables cost estimations during the design phase, while being less restricted by limited data availability. For both the stiffened panel case and the rudder case, the estimation results are validated between the high-level and detail-level models. By incorporating cost indicators into the design optimization, the influence of material, weight, process, and cost properties associated with the cost indicators are considered. The optimum design obtained from the cost integrated design optimization differs from the ones obtained from optimization using weight properties as objectives, providing a different referencing point for design decision making.

SAMENVATTING

Functionele prestaties en economische eigenschappen van vliegtuigen worden door de markt geëvalueerd voor en tijdens de hele levenscyclus, vanaf ontwerpconcept tot en met actueel product. Life Cycle Cost (LCC) analyse speelt een centrale rol in het beslissingsproces. LCC wordt niet alleen beïnvloed door de staat van de markt, maar is ook afhankelijk van technologieontwikkeling in ontwerpconcepten. Meer specifiek gezien beïnvloeden de geometrische definitie, materiaalkeuze en uitvoering van levenscyclusprocessen allen de kosten van een vliegtuig. Er worden vier primaire types kosten beschouwd tijdens de levenscyclus van een vliegtuig: onderzoeks-, ontwikkelings-, test- en evaluatiekosten (OOT&E), productiekosten, operatie- en onderhoudskosten (O&O), en afval- en recyclekosten (A&R). Elk type kosten heeft zijn eigen karakteristieken. Het is daarom nodig een methode te ontwikkelen welke een ontwerpconcept en kostenschatting kan koppelen. Daarnaast moet ontwerpoptimalisatie worden ontwikkeld waarbij prestaties in termen van kosten kunnen worden beschouwd, omdat kosteneigenschappen prestatie-indicatoren zijn die geldig zijn over de hele levenscyclus. In deze dissertatie wordt een schaalbare, data-afhankelijke LCC schattingsmethode voorgesteld. Daarnaast wordt gefocused op de integratie van vliegtuigeigenschappen betreffende LCC in het ontwerpconcept, en integratie van kostenanalyse in ontwerpoptimalisatie, wat tevens Multidisciplinary Design and Optimization (MDO) onderzoek ondersteund door Knowledge Based Engineering (KBE) technieken omhelst. Deze studie omvat dus in het kort drie facetten: KBE, LCC en MDO. Alle drie aspecten acteren en interacteren in een ontwerp- en optimalisatieraamwerk. Het vliegtuigontwerpproces integreert kostenanalyse en optimalisatie via ondersteuning van KBE technieken. LCC analyse maakt gebruik van ontwerp en levenscyclusprocessen en parameters om zogenaamde Cost Estimation Relationships (CER) te formuleren, en wordt gebruikt om MDO te ondersteunen. MDO is geconstrueerd op basis van disciplinaire integratie en formulering van een optimalisatieprobleem waarin kosten worden meegenomen, en wordt gebruikt om het beslissingsproces in ontwerp te ondersteunen.

KBE technieken worden gebruikt om de integratie van ontwerp en kosten te ondersteunen, alsmede kostenanalyse door middel van kennisextractie, automatisering en modularisatie. Proceseigenschappen kunnen op basis van productgeometrie en metamodellen van het proces kunnen toegewezen aan een product, wat het mogelijk maakt om disciplinaire perspectieven te genereren. Deze perspectieven zijn verbonden met corresponderende kostenschattingen voor de vier kostentypes. Op deze manier worden productgeometrie en kostenschatting met elkaar verbonden. Daarnaast is een generiek toepasbare en geautomatiseerde toepassing voor kostenschatting ontwikkeld door de introductie van herbruikbare Cost Primitives (CPs): een suite van parametrische modules voor kostenschatting welke de relevante product-, proces- en Cost Estimation Relationships (CER) data bevatten. Door het bouwen van een link tussen Product Breakdown Structure (PBS) en Cost Breakdown Structure (CBS) wordt de integratie van product, levenscyclusproces en kosten expliciet gemaakt.

KBE technieken maken een directe link tussen het productmodel en kostenschatting mogelijk via de disciplinaire perspectieven, welke de omschrijving van de levenscyclusprocessen bevatten. Dit verbetert de accuratesse van data-extractie voor kostenschatting, en elimineert fouten die worden gemaakt in de meer gecompliceerde handmatige benadering. Relevante kennis wordt door Capability Modules (CM) vanuit de Knowledge Base (KB) benaderd om procesautomatisering te bewerkstelligen. CMs worden ook gebruikt voor pre- en postprocessing activiteiten. Samen beschouwd leiden deze ontwikkelingen tot vermindering in benodigde mankracht en tijd door integratie en automatisering van kostenschatting in vergelijking met een handmatig proces.

De schaalbare data-afhankelijke schattingsmethode voor LCC bestaat uit twee niveaus van schatting: LCC schatting op hoog niveau gebaseerd op een beperkte hoeveelheid product- en prestatie-eigenschappen, en LCC schatting op gedetailleerd niveau gebaseerd op een meer gedetailleerde dataset, welke product-, proces- en prestatie-eigenschappen omvat. Deze benadering komt tegemoet aan het probleem van beperkte beschikbaarheid van data voor kostenschatting tijdens de vliegtuigontwerpfase. Naar gelang de specifieke karakteristieken van elk kostentype zijn kostenparameters en CERs ontwikkeld voor alle LCC kostenelementen. Voor de kostenschattingen op hoog niveau gebruiken de OOT&E en productie kostenschattingen top-down parametrische methoden op basis van product features en kosten-tijd analysetechnieken; O&O kostenschatting wordt uitgevoerd aan de hand van een top-down parametrische methode op basis van product features en regressieanalyse; en de A&R kostenschatting wordt gemaakt op basis van een financieel model dat eenvoudige ervaringsfactoren gebruikt. Voor de kostenschattingen op gedetailleerd niveau wordt voor OOT&E kostenschatting een top-down parametrische methode gebruikt op basis van procesrepresentatie en ondersteund door data fitting technieken. De gedetailleerde kostenschatting voor productie is gebaseerd op een bottom-up parametrische methode op basis van procesrepresentatie en ondersteund door KBE technieken. Het model voor O&O kostenschatting op detailniveau gebruikt tevens een bottom-up parametrische methode op basis van procesrepresentatie en kostenaggregatie, wederom ondersteund door KBE technieken. De gedetailleerde A&R kostenschatting wordt gemaakt met behulp van een bottom-up kostenaggregatie op basis van procesrepresentatie. De eigenschappen van processen en processtappen zijn de sleutel tot het overbruggen van het ontwerpconcept en kostenprestaties in het gedetailleerde model. Vastgesteld is dat het gebruik van twee niveaus van kostenschatting informatie over kosten zeer toegankelijk maakt tijdens de gehele levenscyclus.

Een uitgebreide 'design structure matrix' is ontwikkeld om ontwerpoptimalisatie met inachtname van kosten te bewerkstelligen, waarbij het ontwerp en het levenscyclusproces worden geoptimaliseerd met als doel kosten te reduceren. Om de doelfuncties van de optimalisatie te formuleren zijn kostenindicatoren zoals Direct Operating Cost (DOC) en Surplus Value (SV) ontwikkeld op basis van schattingen van de kostentypes en de belagen van verschillende belanghebbenden. Structurele en procesconstraints zijn ontwikkeld en toegepast met betrekking tot de genoemde kostenindicatoren. Disciplinaire analyses die zijn opgenomen in de optimalisatiestudies omvatten gewicht, structuur, levenscyclusprocessen en kosten. Deze analyses zijn gebruikt om formulering van de doelfunctie te ondersteunen of om de nodige constraints te definiëren.

Toepassing in case studies voor typische vliegtuigstructuren (verstijfd paneel en roer)

toont aan dat de voorgestelde LCC analyse geintegreerd kan worden in het Design Engineering Engine (DEE) ontwerp- en optimalisatieraamwerk. Relevante KBE technieken, in het bijzonder de inferentieregels welke de integratie van product, proces en kostenanalyse faciliteren, maken het mogelijk het ontwerp en disciplinaire analyses te modularizeren en automatiseren. De voorgestelde LCC methode maakt het tevens mogelijk kostenschattingen uit te voeren tijdens de ontwerpfase. In beide case studies zijn de resultaten gevalideerd voor zowel het kostenschattingsmodel op hoog niveau als op gedetailleerd niveau. Door het meenemen van kostenindicatoren in ontwerpoptimalisatie wordt een optimaal ontwerp gevonden dat anders is dan ontwerpen resulterend uit een traditionele ontwerpoptimalisatie. Dit zorgt voor een ander referentiepunt tijdens het beslissingsproces voor de betrokken belanghebbenden.

CONTENTS

Summary vii

Samenvatting ix

Nomenclature xvi

1 Introduction 1

1.1 The aviation industry and its evolution . . . 2
1.1.1 Aviation market . . . 2
1.1.2 Aviation economy . . . 4
1.1.3 Aviation technology development . . . 6
1.2 Aircraft life cycle . . . 8
1.3 The need for improvement on design process, cost estimation, and design optimization over the aircraft life cycle . . . 11
1.3.1 The need for improvement on the design process . . . 11
1.3.2 The need for life cycle cost analysis . . . 12
1.3.3 The need for multidisciplinary design optimization . . . 13
1.4 Research questions and objectives . . . 14
1.4.1 Research questions . . . 14
1.4.2 Objectives . . . 15
1.4.3 Hypotheses . . . 15
1.5 Overview of the thesis . . . 15

2 Literature Review and Thesis Originality 19

2.1 Relationships among the research domains . . . 20
2.2 Aircraft design and Knowledge Based Engineering (KBE) . . . 20
2.2.1 Aircraft design and disciplinary analysis processes . . . 20
2.2.2 The history of KBE development . . . 24
2.2.3 State-of-the-art . . . 25
2.3 Aircraft Life Cycle Cost (LCC) analysis . . . 28
2.3.1 Aircraft LCC . . . 28
2.3.2 Cost estimation methods . . . 31
2.3.3 The history of aircraft cost estimation . . . 34
2.3.4 State-of-the-art . . . 36
2.3.5 Aircraft design for LCC . . . 37

2.4 Aircraft Multidisciplinary Design Optimization (MDO) studies . . . 37
2.4.1 Aircraft MDO . . . 37
2.4.2 The history of aircraft MDO . . . 39
2.4.3 State-of-the-art . . . 43
2.4.4 KBE supported MDO. . . . 45
2.4.5 Cost integrated MDO . . . 45
2.4.6 Sensitivity analysis in MDO . . . 46
2.5 Synthesis and conclusions . . . 47
2.5.1 Challenges and opportunities . . . 47
2.5.2 Originality of the thesis research . . . 51
2.5.3 Conclusions . . . 54

3 Methodology of Knowledge Based Engineering Supported Design - Cost Integration 55
3.1 KBE supported cost analysis integrated design framework . . . 56
3.2 Life-cycle-process-specific view generation . . . 58
3.2.1 Research, Development, Test and Evaluation (RDT&E) view . . . 58
3.2.2 Production view . . . 61
3.2.3 Operating and Maintenance (O&M) view . . . 63
3.2.4 Disposal and Recycle (D&R) view . . . 64
3.3 KBE supported cost analysis . . . 67
3.3.1 Pre-processing . . . 67
3.3.2 Cost estimation . . . 67
3.3.3 Post-processing . . . 69
3.4 Implementation . . . 69
3.4.1 KBE supported cost analysis integrated design framework . . . 70
3.4.2 Life cycle process view generation . . . 72
3.4.3 KBE supported cost analysis . . . 73
3.5 Synthesis and conclusions . . . 75

4 Methodology of Aircraft Life Cycle Cost Analysis 79
4.1 Cost estimation framework and method generalization . . . 80
4.1.1 High-level model. . . . 83
4.1.2 Detail-level model . . . 84
4.1.3 General setup and conversion factors . . . 85
4.2 Cost estimation for major cost types . . . 87
4.2.1 RDT&E cost estimation . . . 87
4.2.2 Production cost estimation . . . 93
4.2.3 O&M cost estimation . . . 100
4.2.4 D&R cost estimation . . . 115
4.2.5 Miscellaneous cost estimation . . . 117
4.3 Implementation . . . 117
4.3.1 Knowledge Bases (KB) . . . 118
4.3.2 Capability Modules (CM) . . . 119
4.4 Synthesis and conclusions . . . 121

5 Methodology of Cost Integrated Design Optimization 123
5.1 Cost integrated MDO architecture . . . 124
5.2 Optimization problem . . . 126
5.2.1 Problem definition . . . 126
5.2.2 Optimization algorithm . . . 127
5.2.3 Cost indicators as optimization objectives . . . 127
5.2.4 Weight and process related analyses . . . 130
5.3 Disciplinary constraints . . . 130
5.3.1 Structural constraints . . . 130
5.3.2 Life cycle process related constraints . . . 135
5.4 Implementation . . . 135
5.4.1 Optimization workflow and CMs . . . 135
5.4.2 Sensitivity Analysis (SA) . . . 137
5.5 Synthesis and conclusions . . . 138

6 Case Study – Stiffened Panel 141
6.1 Study case implementation . . . 142
6.1.1 Stiffened panel product model . . . 142
6.1.2 Stiffened panel life-cycle-process-specific view . . . 143
6.1.3 KBE supported stiffened panel cost analysis . . . 145
6.2 Cost results . . . 149
6.2.1 Results of RDT&E cost analysis . . . 149
6.2.2 Results of production cost analysis . . . 163
6.3 Optimization results . . . 170
6.3.1 Optimization setup . . . 170
6.3.2 Results of optimization studies . . . 171
6.4 Synthesis and conclusions . . . 178
6.4.1 KBE perspective . . . 178
6.4.2 Costing perspective . . . 178
6.4.3 Optimization perspective . . . 179

7 Case Study – Rudder 181
7.1 Study case implementation . . . 182
7.1.1 Rudder product model . . . 182
7.1.2 Rudder life-cycle-process-specific views . . . 182
7.1.3 KBE supported rudder cost analysis . . . 185
7.2 Cost results . . . 185
7.2.1 Results of O&M cost analysis . . . 187
7.2.2 Results of D&R cost analysis . . . 196
7.3 Synthesis and conclusions . . . 196
7.3.1 KBE perspective . . . 197
7.3.2 Costing perspective . . . 197

8 Conclusions and Recommendations **199**
8.1 Conclusions. . . . 200
8.1.1 Addressing the research questions . . . 200
8.1.2 KBE perspective . . . 202
8.1.3 LCC perspective . . . 203
8.1.4 MDO perspective . . . 204
8.2 Contributions and novelty . . . 205
8.3 Limitations and recommendations . . . 206
8.3.1 KBE perspective . . . 206
8.3.2 LCC perspective . . . 207
8.3.3 MDO perspective . . . 208

Bibliography **209**

Appendices **233**

A Appendix Aviation Market Trend **235**

B Appendix Aviation Economy **239**

C Appendix Clarification for KBE Relevant Glossaries **243**

D Appendix Conventions of Terms Used and Their Relations **247**
D.1 Product related terms . . . 247
D.2 Cost related terms. . . . 247
D.3 Weight breakdown convention . . . 247

E Appendix Airframe Maintenance Cost Regression for Maturity Factor **251**

F Appendix The OMG's Unified Modeling Language^{TM} **(UML)** **253**

G Appendix Cost Estimation Excluding Fudge Factors **261**
G.1 RDT&E cost high-level and detail-level model . . . 261
G.1.1 High-level model. . . . 261
G.1.2 Detail-level model . . . 261
G.2 Production cost high-level model . . . 261

Acknowledgement **271**

List of Publications **273**

Curriculum Vitae **275**

NOMENCLATURE

List of Abbreviations

AAO	All-At-Once
AC	Aircraft
ACCEM	Aircraft Composite Cost Estimating Manual
AELS	Aircraft End of Life Solution
AFW	Airframe Weight
AI	Artificial Intelligence
AL	Airworthiness Limitations
API	Application Programming Interface
APSB	Aircraft Portfolio Strategy Board
APU	Auxiliary Power Unit
ASK	Available Seat Kilometres
ATAG	Air Transportation Action Group
ATC	Analytical Target Cascading
ATK	Available Tonne Kilometres
BES	Bombardier Aerospace Engineering System
BLISS	Bi-level Integrated Systems Synthesis
BOM	Bill of Material
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CASK	Operating Cost Available Seat Kilometres
CATK	Operating Cost Available Tonne Kilometres
CBS	Cost Breakdown Structure

CE	Concurrent Engineering
$cents/ASK$	Cents per Available Seat Kilometres
CER	Cost Estimation Relationship
CFD	Computational Fluid Dynamics
$CFRP$	Carbon Fibre Reinforced Plastic
$CFRP$	Carbon Fibre Reinforced Polymer
CM	Capability Modules
CMR	Certification Maintenance Requirement
CO	Collaborative Optimization
$COSTADE$	Cost Optimization Software for Transport Aircraft Design Evaluation
$COTS$	Commercial Off-The-Shelf
CP	Cost Primitive
CSD	Concurrent Subspace Design
$CSSO$	Concurrent Subspace Optimization
$D\&R$	Disposal and Recycle
$DAPCA$	Development and Procurement Cost of Aircraft
DEE	Design and Engineering Engine
DI	Detailed Inspection (or DET)
DMC	Direct Maintenance Cost
DOC	Direct Operating Cost
DS	Discard(or DIS)
EOF	End of Life
FC	Flight Cycle or Functional Check
FC/AC	Flight Cycle per aircraft
FC/IN^*	Functional Check/Inspection (or $^*/FNC$)
FEA	Finite Element Analysis
FEM	Finite Element Method

FH	Flight Hour
FH/AC	Flight Hour per aircraft
FY	Fiscal Year
FY_0	Reference Fiscal Year
GA	Genetic Algorithm
$GAGD$	Genetic Algorithm with Gradient Optimization
$GAPS$	Genetic Algorithm with Pattern Search
GD	Gradient Optimization
GDL	Genworks' General-purpose Declarative Language
GDP	Gross Domestic Product
$GFRP$	Glass Fibre Reinforced Polymer
GMF	Global Market Forecast
GV	General Visual Inspection/Inspection (or GVI)
$HLCP$	High Level Cost Primitive
HLP	High Level Primitive
$IATA$	International Air Transport Association
IDF	Individual Discipline Feasible
IMC	Indirect Maintenance Cost
IOC	Indirect Operating Cost
$IPPD$	Integrated Product and Process Development
ITP	Instruction To Proceed
KB	Knowledge Based
KBE	Knowledge Based Engineering
KBS	Knowledge Based System
KKT	Karush–Kuhn–Tucker
LCC	Life Cycle Cost
LOR	List Of Requirement

LU/*SV*	Lubrication/Servicing (or *LUB*/*SVC*)
M&A	Manufacturing and Assembly
MDF	Multidisciplinary Feasible
MDO	Multidisciplinary Design and Optimization
MMG	Multi-Model Generator
MML	MOKA Modelling Language
MOKA	Methodology and tools Oriented to Knowledge-based engineering Application
MPD	Maintenance Planning Document
MPMT	Mean Preventive Maintenance Time
MRB	Maintenance Review Board
MRBR	Maintenance Review Board Report
MTBF	Mean Time Between Failure
MTBF	Mean Time Between Failures
MTOW	Maximum Take Off Weight
MTTF	Mean Time To Failure
MTTF	Mean Time To Failures
MTTR	Mean Time To Repair
NAND	Nested Analysis and Design
NPV	Net Present Value
O&M	Operating and Maintenance
ODM	Original Design Manufacturer
OEM	Original Equipment Manufacturer
OOP	Object Oriented Programming
OP/*VS*	Operational Check/Visual Check (or *OPC*/*VCK*)
PBS	Product Breakdown Structure
PLM	Product Lifecycle Management

qty	Quantity
$RASK$	Operating Revenue Available Seat Kilometres
$RATK$	Operating Revenue Available Tonne Kilometres
$RDT\&E$	Research, Development, Test and Evaluation
$ROIC$	Return On Invested Capital
RPK	Revenue Passenger Kilometres
RR	Rate of Return
RS	Restoration(or RST)
RTK	Revenue Tonne Kilometres
$S-SHM$	Scheduled Structural Health Monitoring
SA	Sensitivity Analysis
$SAND$	Simultaneous Analysis and Design
SE	System Engineering
SI	Special Detailed Inspection (or SDI)
SME	Small and Medium sized Enterprises
$STEP$	Standard for the Exchange of Product Data
SV	Surplus Value
TES	Transonic Equivalent Strip
TXT	Text
UML	Unified Modelling Language
$WACC$	Weighted Average Cost of Capital
XML	Extensible Markup Language
XML	Object Oriented Programming

Subscripts

i	Life Cycle Cost major cost type: RDT&E, Production (or M&A), O&M, or D&R
j	Cost elements: labour, material, tooling&equipment, testing, energy consumption, or facility

l	flight operating process segment

List of Symbols

$(\Delta H_{climb})_l$	Segment time
α	Positive shape factor of the RDT&E cost profile
$\alpha_{maturity}$	Maturity curve intercept value
$\bar{W}$	Average weight
β	Positive shape factor of the RDT&E cost profile
$\beta_{maturity}$	Age coefficients
ΔH	The time difference between the start and the end of each life cycle process step
δt	time duration of a process step in the RDT&E phase
ΔW	The weight difference between the start and the end of each life cycle process step
γ_{FY}	Fiscal-year dummy variable
λ_k	Failure rate of a maintenance item
μ_{AC_type}	Aircraft-type dummy variable
v_0	Manufacturing/assembly process step steady state speed
ρ	Air density
τ_0	Manufacturing/assembly process step time constant
A	Coefficient of power law model
AGW	Aircraft Gross Weight
b	Exponent of power law model
b_f	Flange width
b_s	Stringer pitch
$BCAG$	Boeing Commercial Airplane Group
BH	Block Hour
C	Cost
C/W	Cost-weight ratio

$C/W_{analogy}$	Cost-weight ratio of an analogous aircraft
C_{D_0}	Zero-lift drag coefficient
$f()$	Function
f_k	Frequency of the task
$FH/trip$	Flight hour per trip
ft	Flight test
FTA	The number of Fly Test Aircraft
GS	Ground Speed
H	Labour hour
h	Altitude of the aircraft
h_s	Stringer height
H_{setup}	Setup time constant before manufacturing/assembly process step execution
hr	Hour
I	Inflation factor
IAS	Indicated Air Speed
$interval$	Maintenance task interval
K	Drag due to lift coefficient
K	Normalized constant of a RDT&E cost element
k	Life cycle process step
l	Skin length
LCC	Life Cycle Cost
MLW	Maximum Landing Weight
n	Number of times of performing a maintenance task
$n_{cabin-crew}$	Number of cabin crew
$n_{flight-crew}$	Number of flight crew
n_{seat}	Seat Capacity

OEW	Operational Empty Weight (mass)
P_{AC}	Aircraft price
$P_{residual}$	Aircraft residual price
Q	Production quantity
qc	Quality control
R	Labour rate
R	Range
r	Material/fuel/charge rate
R/C	Rate of Climb
r_f	Flange thickness
r_{CE}	Currency exchange rate
$r_{learning}$	Learning curve factor
$r_{maturity}$	Maturity factor
$r_{residual}$	Aircraft residual price rate
S	Wing reference area
SFC	Specification Fuel Consumption
T	Thrust
t	Skin thickness
t_0	Starting time of a process step in the RDT&E phase
t_1	End time of a process step in the RDT&E phase
t_w	Web thickness
$t_{depreciation}$	Depreciation period
$t_{normalized}$	Normalized time point during the RDT&E phase
$t_{RDT\&E}$	Time point during the RDT&E phase
$threshold$	Maintenance task threshold
TOC	Top of Climb
U	Aircraft yearly utilization

V	Velocity
V_∞	Velocity
W	Weight
w	Skin width
W_{fuel}	Fuel weight
x	Cost driving parameters
Y_{AC}	Aircraft age
YE	Year
z	Learning curve exponent

1

INTRODUCTION

This thesis will present research about the integration between aircraft design, Life Cycle Cost (LCC) analysis, and design optimization using Knowledge Based Engineering (KBE) techniques. From a concept in design to a product in the aviation market, the functional performance and economic properties of aircraft are evaluated by the market through the whole life cycle. As cost properties during the aircraft life cycle play a vital role in the aircraft evaluation process, a method should be developed for aircraft cost estimation and cost integrated design optimization. In this thesis, a comprehensive LCC analysis is proposed and integrated into the design process, in which Multidisciplinary Design and Optimization (MDO) studies supported by KBE techniques are involved. Therefore, research of the three domains is addressed: KBE, LCC, and MDO. Studies on integrating those three fields are presented. Efforts are made for the framework construction, methodology development, and application implementation. Integration and synthesis of all the three perspectives are emphasized. Later, case studies integrating all three perspectives are carried out to illustrate the implementation approach. The thesis ends with a discussion of the theoretical and practical contributions and future development of this research.

1

1.1. THE AVIATION INDUSTRY AND ITS EVOLUTION

The world of civil aviation has a significant impact on the world economy. It plays a vital role in fostering trade and making the world quickly accessible and connected. In this chapter, the historical evolution of the world aviation industry is summarized. The stimuli of aviation industrial development are focused on market growth, world economic development, and the application of new technologies. The progress of the aviation industry shows that many effective and beneficial engineering practices are improvements on the current aircraft design process and the aircraft concepts while taking their life cycle performance into consideration. This leads to a focus on advances in supporting techniques for design processes, life cycle cost analyses, and design optimizations, which are also the three domains surrounding this research.

The aviation industry started in the early 19th century, with the first heavier-than-air human flight made by the Wright brothers in 1903 and the first commercial flight made by the St. Petersburg – Tampa Airboat Line in 1914 [1]. It is officially regulated based on the establishment of the Convention on International Civil Aviation (also called the "Chicago Convention") [2]. Over 100 years of evolution, huge improvements have been made to this industry. On the one hand, brand new aircraft types have been continuously introduced into the market. In 2007, Airbus delivered its first A380 to Singapore Airline two years after its maiden flight in 2005. All Nippon Airways received the first Boeing 787 Dreamliner in 2011, while the first flight was made in 2009. In early 2015, Qatar Airways received the first A350XWB from Airbus after its successful flight in 2013. On the other hand, airlines have grown dramatically in strengthening their fleets, flight routes and networks. At present, there are 1397 commercial airlines in operation, 3864 airports running scheduled commercial flights in the world, 173 air navigation providers, 49871 flight routes opened up and 25332 commercial aircraft in service [3]. A variety of business models and systematic management strategies are used by the airlines. In addition, research projects considering next generation aircraft concepts and next generation air transport system have also progressed significantly [4][5][6][7]. The history and the future trend of the aviation industry, it suggests that there will be significant growth over the next 20 years [3].

1.1.1. AVIATION MARKET

The aviation market connects aircraft productions with air transport operations, which enables an accessible world and an efficient global trade market. According to the analysis of the Air Transportation Action Group (ATAG), in 2012 there was an average of 8.6 million passengers, 99700 flights, and $17.5 billion worth of goods transported by air transport each day [3]. Statistically, 2.97 billion passengers were carried by airlines, while 49.2 million tonnes of freight worth $6.4 trillion were handled in 2012 [3].

The market trend of aviation can be seen in the commercial aircraft yearly order and production numbers shown in Figure 1.1. Compared with 1981, both the aircraft orders and the units of production have been largely increasing. Recently, driven by the growth of passenger travel demand in Asia and Middle East, commercial aircraft production is in a prolonged upcycle. Moreover, the innovation in industry technology, such as the new engine development of Airbus 320NEO and Boeing 737MAX, as fuel-efficient aircraft, also generates significant product demand. It is forecast that an increasing number of yearly order and production

units will be seen in the next 20 years, while as seen from history, economic intervention is also unavoidable. In total, more than thirty thousand commercial aircraft are expected to be demanded over the next 20 years [8][9].

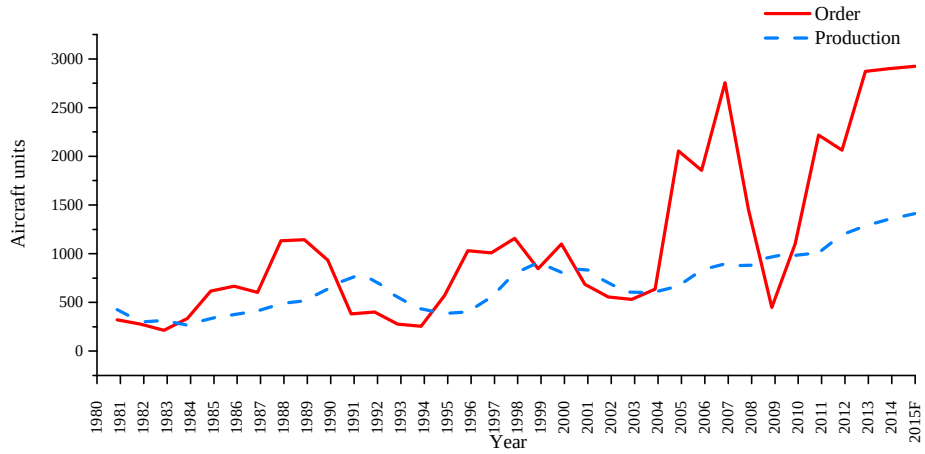


Figure 1.1: History and forecast for large commercial aircraft orders and production (1981 - 2015F, yearly value)[1], adapted from Deloitte [10]

Other indicators of the aviation market are the Revenue Passenger Kilometres (RPK) / Revenue Tonne Kilometres (RTK) and the Available Seat Kilometres (ASK)/Available Tonne Kilometres (ATK) of the airliners/freighters. The former displays the passenger/cargo transported on the basis of the market demand. The latter indicates the capacity of the commercial and cargo transportation that can be provided by the market. Figure 1.2 shows estimates of yearly RPK and RTK including the Global Market Forecast (GMF) till 2034 [9][11]. The air passenger traffic in 2014 grew 85% compared with that of 15 years ago, and is shown to be resilient to economic crises [9]. This is due to the stable air travel market caused by both family and business travel [11]. Airbus figures suggest that RPK doubles every 15 years [11]. Air cargo growth is closely related to world trade volume, which is more sensitive to the financial crisis than the Gross Domestic Product (GDP) [8][11]. Appendix A provides deeper insights into the demand and capacity interactions supporting the market trend analysis.

In general, there are positive expectations of market growth in the aviation industry by Original Equipment Manufacturers (OEM), airlines and other aviation organizations. All stakeholders are working on aircraft design techniques, operating strategies, and economic performance to improve aviation market development. Essentially, those are all related to the functional and economic performance of the aircraft concepts over the life cycles.

[1] Data sources: DTTL Global Manufacturing Industry group analysis of the following data: The Boeing Company, "Order and deliveries," accessed in January 2015 http://active.boeing.com/commercial/orders/index.cfm; Airbus Group, Orders and deliveries," accessed in January 2015, http://www.airbus.com/company/market/orders-deliveries/; UBS, US Aerospace and Defense Playbook, 17 October 2014; and Credit Suisse, Global Aerospace and Defense, 17 October 2014

[2] Data source: ICAO (RPK total traffic), Airbus (RPK GMF, RTK total traffic/GMF), Seabury (RTK total traffic/GMF)

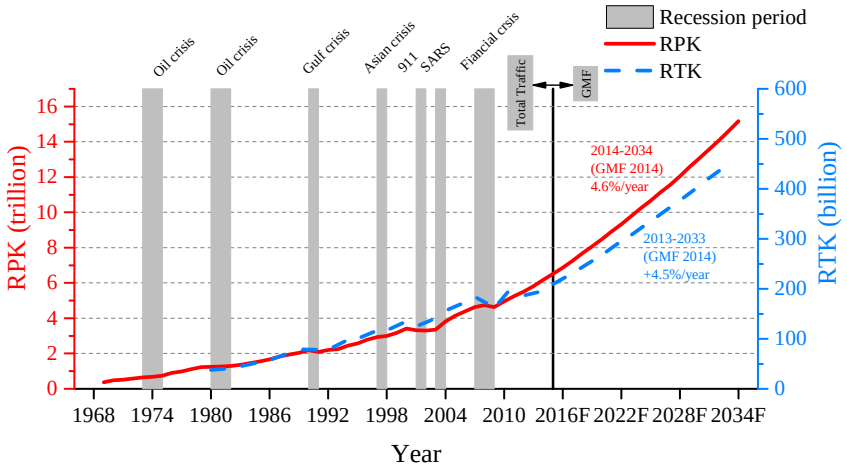


Figure 1.2: History and forecast for world annual traffic and cargo (1969 – 2034F, yearly value)[2], adapted from [8][9][11]

1.1.2. AVIATION ECONOMY

The aviation market fluctuates along with changes in the global economy; conversely, the growth of air transportation demand and capacity stimulate world economic growth. The factors that influence the aviation economy are further analysed in Appendix B. In particular, the revenue and cost performances of the aviation industry driven by market condition and world economic indicators are demonstrated in Figure 1.3. A similar trend appears for both revenue and cost indicators. In the 15-year averages, non-fuel cost represents 75% of the total cost, while the other 25% is contributed by the fuel cost. The profit in the aviation industry is rather small, according to the differences illustrated between the revenues and the costs. This implies that the change in the costs passed onto the revenue, so that consumers seem to be more beneficial than investors in such a competitive industry [12]. It can also be seen that the gap between revenues and costs has gradually widened in recent years, which shows the effect of introducing new aircraft with higher performance in fuel efficiency, capacity, utilization and operations [13]. By eliminating the influence of the capacity (ATK/ASK) change, the operating Revenue per ATK (RATK)/Revenue per ASK (RASK) and the operating Cost per ATK (CATK)/Cost per ASK (CASK) are shown an alleviated variation compared to the actual revenue and cost changes.

Using the cost and revenue figures, aviation profits can be estimated. The profits and profit margins (the profit as a percentage of the revenue) generated by the world commercial airline during the last 15 years are shown in Figure 1.4. It is forecast that the aviation industry will generate $29.3 billion net profits in 2015, which represents an operating margin

[3] IATA economics, www.iata.org/economics

[4] Data source: ICAO, IATA economics, www.iata.org/economics. Operating profit is the same as the Earnings Before Interest and Taxes (EBIT). Net profit refers to net post-tax profit, Operating profit margin, also called the EBIT margin, is the operating profit as a percentage of the revenue. Net profit margin, also called net post-tax profit margin, is the net profit as a percentage of the revenue

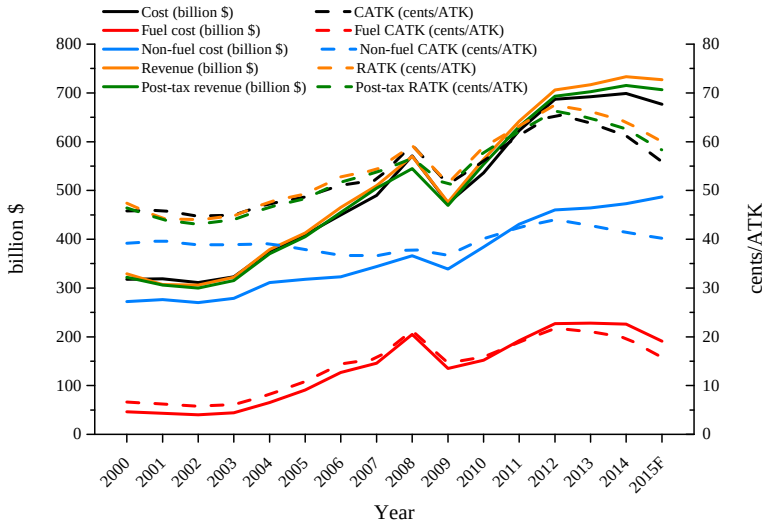


Figure 1.3: Annual cost and revenue properties (2000-2015F)[3]

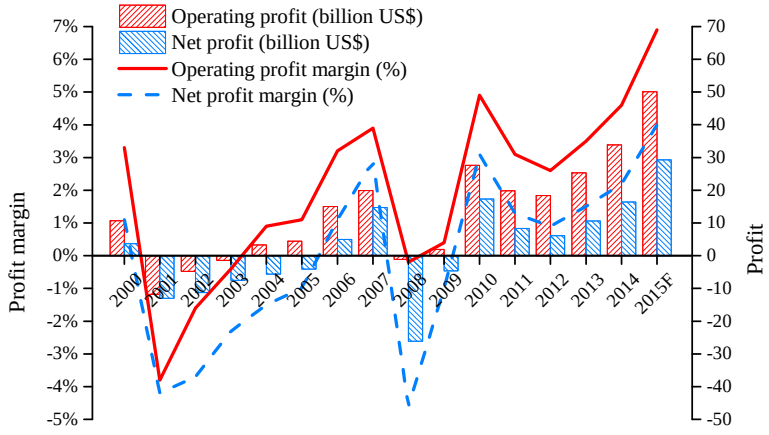


Figure 1.4: Annual global commercial airline profitability (2000-2015F)[4],adapted from [11][13]

of around 6.9%, and $8.3 per departing passenger [12]. In that sense, the world commercial airlines are able to pay for its cost including fees, tax, new aircraft (fleet), service and debts, but they still cannot afford the risk taken by the airline investors [13]. In fact, airlines have been among the least profitable of all industries for decades [13]. This results in various societal costs. For example, it can lead to a reduction in operating quality and reliability such as delays and/or difficult reservation. That, in turn, constrains capacity growth and load factor increases. Moreover, it can also cause a financial burden on both government and employees. The low profitability is associated with the industry fragmentation, which causes more congestion, high operational costs and greater environmental impact [13].

Since the airlines' profitability is interrelated with societal costs, which should be concerns of all industry stakeholders, improving airline profitability would be very beneficial. However, there is little awareness of the public on the low profitability of airlines, and airlines have less market power of airlines than other industries to raise profitability [12]. By focusing on reducing costs and airline consolidation with the support of government policies, greater value creation can be expected compared to redistribution within the aviation industry, which will improve profitability [12]. Other strategies would be to introduce new technologies to reduce the cost of aircraft during their life cycle. Therefore, an integration of economic analysis and aircraft design should be conducted, in which the life cycle cost performance plays a vital role.

1.1.3. AVIATION TECHNOLOGY DEVELOPMENT

In its century of development, the aviation industry has shown a strong correlation with technological innovation [14]. Examples of industry innovations that improve aviation development include: the development of the variable pitch propeller that improved take-off and climb in the 1930s; the use of aluminium alloys for the DC-3 and the employment of hydraulics for its landing gears in the same period; the pressurizing of the aircraft cabin for B-29 towards a higher comfort level during the Second World War; the introduction of jet aircraft commercially in the 1950s; the design and production of bigger jets (B737) and wide-body jumbo jets (B747) in the 1960s; the fly-by-wire technology of Airbus A320 for improving flight control and weight in 1980s; global airline alliances and low cost carriers that improved the business model of air travelling in the 1990s; the use of composite material for the Boeing 787 and Airbus A350; and the recent use of renewable energy. [1]. Industrial innovations are not limited to the aircraft concept itself, but also applied to its whole life cycle process, including the Research, Development, Test and Evaluation (RDT&E) phase, Production (also called Manufacturing and Assembly (M&A)) phase, Operating and Maintenance (O&M) phase, and Disposal and Recycle (D&R) phase.

Some of those technologies have not only improved the aircraft performance but also reduced the unit cost during the operation. Examples can be seen from the development of energy intensity and the use of composite materials. According to Figure 1.5, the improvement in fuel efficiency of large aircraft results in a considerable saving of fuel cost [15][16]. Figure 1.6 shows the growth in the use of composite materials in recent aircraft types, which substantially reduces the airframe weight, and results in improved fuel efficiency and reduced cost.

[5] The range of the point for each aircraft reflects varying configurations; connected dots show estimated trends for

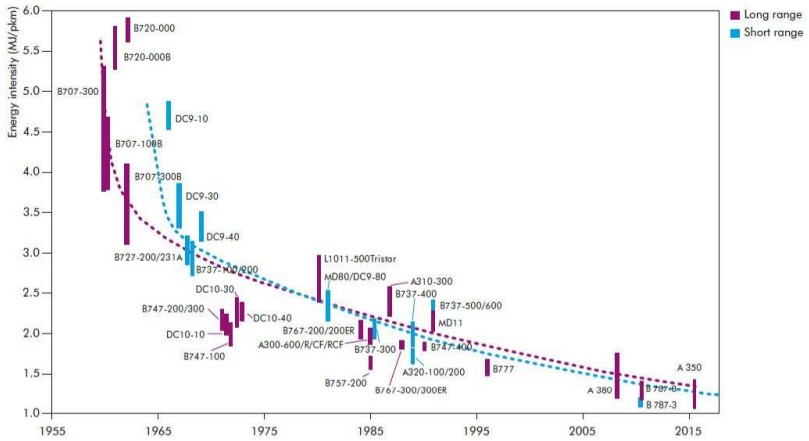


Figure 1.5: Trends in transport aircraft fuel efficiency[5],adapted from [15][16]

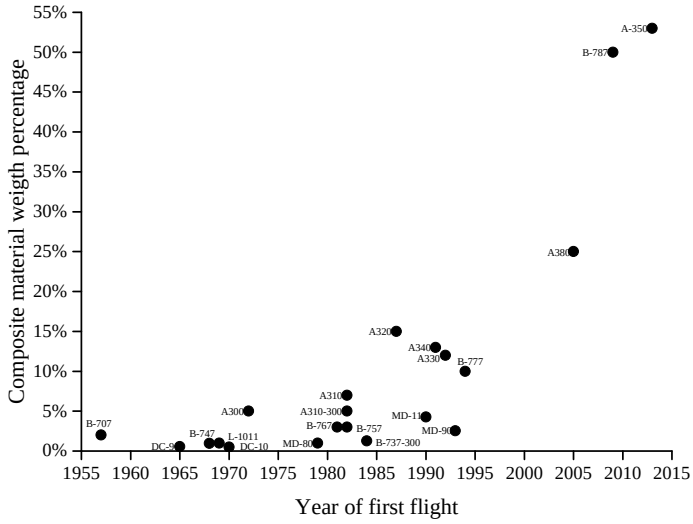


Figure 1.6: Percentage of composite material structural weight of total airframe weight[6],adapted from [17]

Future innovations in the aviation industry are ones that potentially reduce aircraft production and operating costs, increase aircraft speed and capacity, mitigate environmental impacts, and improve airline operating flexibility [13]. Although there are uncertainties in which property takes the priority over others, benefits can be foreseen from changes in the following aspects: airframe configuration, engine efficiency and architecture, alternative fuel, new materials usage, cabin interior, sustainability improvement in terms of noise and emissions, and information sharing for aircraft operating improvement [13]. Nevertheless, the costs and benefits of those technological developments over the aircraft life cycle ought to be considered in order to maintain a sustainable industrial development [18].

1.2. AIRCRAFT LIFE CYCLE

The development of the aviation industry, including the aspects of market, economy and technology, depends on both the aircraft in the market and the related activities conducted by the main stakeholders. For each aircraft concept, all stakeholders are linked with a common design while various activities are conducted by different stakeholders during the aircraft life cycle. Therefore, analytical capabilities are desired in the early design stage to obtain the relevant life cycle performance. The categorization of an aircraft life cycle and the activities are shown in Figure 1.7. Correspondingly, different groups of participants and relevant entities are presented in Table 1.1.

At the early phase of the life cycle, the RDT&E phase starts with identifying the current market needs and opportunities [22]. Standards and design requirements are then established based on a List Of Requirement (LOR). Then, designers can generate promising aircraft concepts, accompanied by a series of feasibility studies. The actual design exercise starts from the conceptual design phase. According to the performance goals, the designers are required to generate possible competing concepts, after which iterations on performance evaluation and optimization are performed, leading to the selection of a baseline configuration. The output of the conceptual design is a three views' drawing of the baseline design associated with performance indicators. Subsequently, the concept is further developed via parametric sizing studies in the preliminary design phase. The size of the baseline concept is refined while the aircraft level configuration is frozen, while modest changes on components are still possible. The main deliverable of the preliminary design is a 3-D drawing of the aircraft concept with sized components. Finally, detailed design is taken place by involving design iterations from the whole aircraft to each of the parts. The final outputs are the detailed production drawings, finalized aircraft specifications and performance properties. When the preliminary and detailed design activities are conducted, the design of the manufacturing and assembly process is carried out concurrently. The entities involved in the research and development phase are the design group from the Original Design Manufactures (ODM) or the OEMs, research institutions including aerospace research laboratories,

short- and long-range aircraft, data source: Lee et al., 2001, IEA updates

[6] Data sources: GAO analysis data from FAA, NASA, Boeing company, Jane's All the World's Aircraft, and Jane's Aircraft upgrades

[7] Photo sources: Flight global website www.flightglobal.com/; Airbus website, www.airbus.com/galleries/photo-gallery/, up left photos © AIRBUS S.A.S. 2011, by e.m company / H.GOUSSE and P. POGEYRE

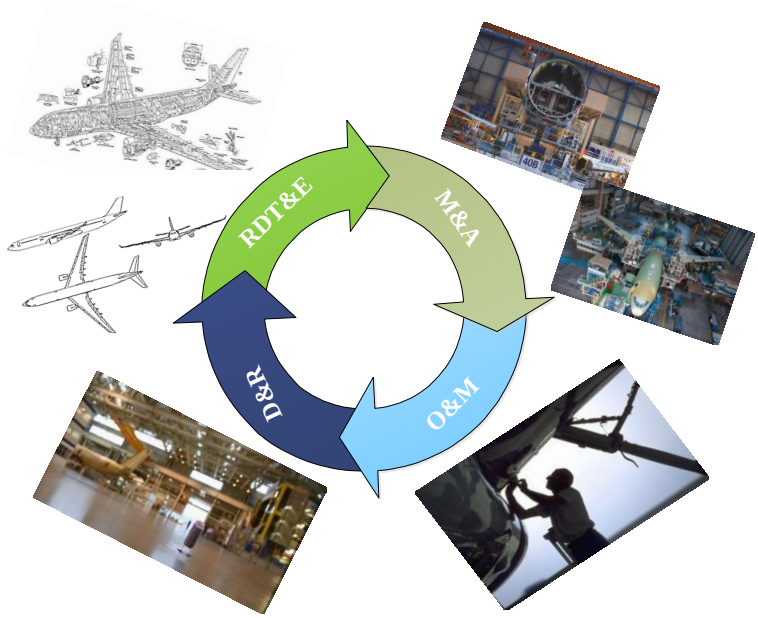


Figure 1.7: Aircraft life cycle[7] ,adapted from [19][20][21]

and universities. According to the engineering practices in Airbus and Boeing companies, the timescale for a design project from start to first flight is around 5 to 10 years; and the time from first flight to mass production is an average of about 2 years [6][18][23].

Designers and manufacturers work closely during the M&A phase, also called the production phase. Parts manufacturing is initiated first, followed by sub-assemblies for manufactured parts and components, and then final assembly. The testing of components and systems are conducted during the whole production. And once the ground tests are completed, the multiple prototypes are prepared for the first flight and a series of subsequent flight tests. When the aircraft is found to have achieved all the standard specifications, an airworthiness certificate can be issued by the regulatory authorities. Then mass production will be launched based on the aircraft orders received from various airlines. In addition, the aircraft needs to achieve a certain level of operational readiness. The OEMs/ODMs invest significantly in manufacturing capabilities (such as lean and automated production) for the whole production process. Other entities such as suppliers and outsourcing manufacturing companies play a major role in the extended enterprise, and the OEMs become more of designers and integrators. Additionally, there are also inputs from the regulatory authorities. Depending on the distribution of the manufacturing and assembly facilities and the efficiency of the production runs needed by the OEMs, the time scale for producing an aircraft is from days to months. For instances, the production of the A330 was around 9 per month in 2015 [24], and Airbus is expects 46 A320s to be produced per month by 2016 [25]. The overall production of each aircraft type lasts several years (spreads over 5 to more than

Table 1.1: Aircraft life cycle activities, personnel and relevant entities

Aircraft life cycle phase	RDT&E	Production	O&M	D&R
Activity	• Market analysis • Conceptual design • Preliminary design • Detail design • Type certification	• Part manufacturing • Subassembly fabrication • Final assembly • Aircraft certification	• Flight operating • Scheduled maintenance • Unscheduled maintenance • Air transportation operations • Aviation training • Air navigation • Airport services • Regulatory functions	• Storing • Disassembling • Parts management • Dismantling • Reuse • Recycle • Destruction
Personnel	• Designer	•Manufacturer • Regulator	• Crew • Passenger • Ticket staff • Air traffic controller • Maintenance technician • Regulator • Other ground staff	• Airline staff • Disposal & Recycle technician
Relevant entity	• ODM • Research institution	• OEM \ODM • Supplier • Regulatory authority	• Airline • Airport outsourced maintenance company • Regulatory authority	• Airline • Aircraft disposal company

20 years) according to the market demand and the world economic conditions. The A340-600 was produced from 2002 until 2011 [26], while the A330 family has been produced since 1994, and the A330neo is currently in development and will be produced in 2017 [27].

Activities in the O&M phase starts when the aircraft enters into service. Associated activities include air transportation operations, aviation training, air navigation, maintenance services, airport services, and regulatory functions. The activities of the O&M phase are performed simultaneously and recursively. Moreover, the detailed operations of an aircraft, a

fleet, an airline or an airport are distinct. For instance, the focus of operating an aircraft is constrained by a flight profile, while the attention of operating a fleet would involve the fleet flight routes and networks. Besides airlines, other entities are maintenance companies, who constantly provide maintenance checks and overhaul activities to keep the aircraft in an airworthy state as aircraft ages. Other stakeholders during this life cycle phase include the passengers, airline crews and tickets staff, air traffic controllers responsible for flight and ground control, and regulatory authorities responsible for the continued airworthiness of each aircraft. Generally, the calendar life of a commercial aircraft is around 20 to 30 years for passenger aircraft and 30 to 40 years for freight aircraft. The time when the aircraft reaches its economic operating limit (its economic life) is more than 15 years on average [28].

Ageing aircraft get retired, sold-out or disposed according to the airlines' fleet management strategy. Based on an aircraft's service condition and End-of-Life (EOF) solution, the disposal process can be defined, and normally involves being 'parked' in a dry desert graveyard or being disassembled so that the dismantled parts can be recycled or sold to outsourcing companies. The time period for D&R lasts months to years. For example, a company disassembled and dismantled a KLM Boeing 737-400 between April and May 2006 in a few days [29], while a freighter Boeing 747-200 stopped operation in 2008 and was parked till 2014 for disassembly and dismantling [30].

1.3. THE NEED FOR IMPROVEMENT ON DESIGN PROCESS, COST ESTIMATION, AND DESIGN OPTIMIZATION OVER THE AIRCRAFT LIFE CYCLE

1.3.1. THE NEED FOR IMPROVEMENT ON THE DESIGN PROCESS

It is desired to have a measure of the impact of design decisions on the product life cycle, even on their market and economic performances. Therefore, it is necessary to develop an integrated design process that can respond to design decisions and is capable of anticipating the life cycle performances of the aircraft and its components.

The conceptual/preliminary design process is normally performed in a short time period, while more detailed and higher fidelity analyses are required in the early design stage along with the improvement of the computation capability. The more accuracy the conceptual design achieves, the fewer the design decisions and performance analyses are needed. In this way, the cost effectiveness of the whole life cycle can be improved [22]. Knowledge reuse and process automation are also encouraged in the whole design process. This is to realize the reduction of time and cost expenditure for both the design process and other life cycle phases [31]. Besides, an emerging research area is in the coupling of product geometry with multi-disciplinary analyses, which even triggers the change of the design environment. For example, a group of experts and design resources is gathered together for one design project in a collaborative design environment, which can facilitate the real-time data exchange and high-efficiency design processes [32]. Additionally, design optimization coupled with a central design geometry and a unified data management system has proven to be a feasible and beneficial approach during the design process, where advanced techniques of data exchange and computation speed acceleration are intensively adopted [33][34]. The

combination of those research interests leads to the possibility of developing an integrated design and analysis process, which is built in a systematic fashion and fulfils a fast and accurate paradigm. Techniques, such as System Engineering (SE) [35][36][37][38], Concurrent Engineering (CE) [39][40][41][42], Knowledge Based Engineering (KBE) [31][43], Integrated Product and Process Development (IPPD) [44][45], Process Integration and Design Optimization (PIDO) [46][47], Product Lifecycle Management (PLM) [48][49], *etc.*, can be adopted to support and facilitate the advanced design process. In this research, a large amount of knowledge extraction, knowledge reuse and process automation are foreseen to be utilized for integrating cost analyses into the design process. Therefore, a focus is placed on KBE techniques among the other design supporting techniques.

1.3.2. THE NEED FOR LIFE CYCLE COST ANALYSIS

Cost performance is concerned within every aspect of an aircraft life cycle. Therefore, Life Cycle Cost (LCC) properties of each aircraft and its components are key indicators demonstrating the overall performance in a life cycle. Furthermore, cost and safety are the fundamental driving elements in the transportation market. All industry activities associated with the aircraft are assessed and even enabled by effective cost performance. From another perspective, all disciplines and parameters for an aircraft in air transportation are highly interrelated and mutually influential [50]. The aircraft concept or the component design can only be allowed within the cost constraints in each stage of an aircraft life cycle. Accordingly, the development of LCC analysis is necessary.

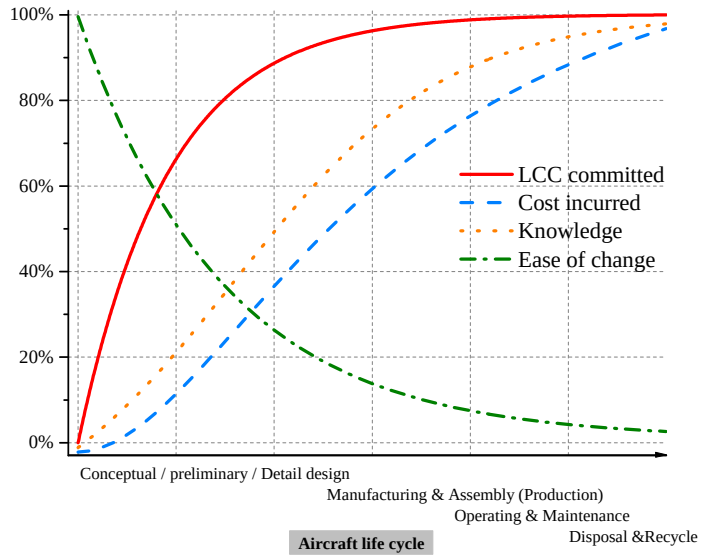


Figure 1.8: The relation of cost, knowledge and aircraft life cycle (adapted from [31][51][52]).

There is a lack of an analytical process to obtain the cost indicators from a component to an aircraft, to the whole fleet, and even to the overall aviation industry. An overview of the

direct driving parameters to cost, revenue and profit are not clear. This suggests a possible research direction of linking LCC analysis to an aircraft or to its component via the product attributes, so that the cost properties can be controlled during the early stage of a life cycle. 85% of the LCC is determined at the end of the preliminary design stage, 95% of the LCC is locked at the end of the detailed design [51]. This is shown in Figure 1.8, where most of the LCC is fixed due to the decisions made during design and development although less cost is induced within those stages. Moreover, the cost committed in the RDT&E and M&A phases are tightly related to the acquisition cost of the product, which is further linked to its operating and maintenance cost, and even disposal & recycle expenses. Therefore, it is crucial to lowering the LCC as early as possible.

1.3.3. THE NEED FOR MULTIDISCIPLINARY DESIGN OPTIMIZATION

Although a radical product innovation is encouraged under the circumstances of good economic and market condition, optimization studies are always needed to assure a steady improvement of either a conventional product or an innovative one. Based on systematic considerations, the optimum is potentially obtained by trade-off balancing multiple disciplines such as aerodynamic, structural, weight, cost, reliability, sustainability, *etc.* In particular, one of the objectives of the aviation industry is to reduce the aircraft cost while still achieving the technical and operating requirements in its life cycle. It leads to cost related Multidisciplinary Design Optimization (MDO).

In more detail, the reason for employing MDO is elaborated. *First*, aviation systems, such as aircraft contain interactions among disciplines, and conflicts between technical and economic requirements. Support from MDO is needed to construct the interactions and balance the conflicts by taking those requirements into consideration for a common objective in a systematic fashion [53]. *Second*, 'what-if' questions need to be tested by tuning relevant design variables to investigate the cost change in a multi-disciplinary environment during the early design phase. Together with trade-off studies and sensitivity analyses, a system optimum towards the final decision-making can be formulated [54]. Incorporating LCC in the environment facilitated by MDO increases the objectiveness of a design to some extent. *Third*, improving the design process and considering the life cycle performance in a design require the flexible deployment of disciplinary analyses for the need of the moment. For this reason, the design tool should be tailored by inserting selected simulation capabilities as the design progresses [54]. This is related to the 'adaptive' property of MDO. Since the interactions among disciplines are built within the application, it avoids manual changes of a single disciplinary analysis caused by the influence of other disciplines. By treating each discipline as a black box, it also promotes the use of Commercial Off-The-Shelf (COTS) software for disciplinary analysis. *Last but not least*, LCC, as one discipline among the others during the design process, is desired to be handled efficiently in terms of reducing the development cost. The simultaneous property of MDO fits this need. It considers relevant disciplines through concurrent engineering processes such as parallel computing, which speeds up system level analysis. Therefore, MDO accelerates the prototyping of new designs and reduces the time-to-market of new products under the control of their quality requirements [55]. The integration of economic indicators, obtained via LCC estimation and the surrounding studies, makes the life cycle performance quantitatively measurable and explicitly available for

design optimizations. Furthermore, optimization involving the LCC analysis would open up a new design space where the economic goals and the traditional design objectives are combined. This also adds another dimension to the multidisciplinary analyses and brings the potential for optimizing the overall life cycle performance. In summary, the integration of LCC analysis and design should be applied through MDOs.

1.4. RESEARCH QUESTIONS AND OBJECTIVES

Given the necessity to improve the design process, cost estimation and design optimization considering the aircraft life cycle, the following research domains are covered: the integration and development of KBE assisted design process, aircraft LCC analysis, and design optimization studies considering cost performance. More specifically, within the conceptual and preliminary design phase, cost engineers in a design team often encounter a missing link between the design process and the cost analysis. During this stage, the cost analysis is often performed qualitatively due to a lack of data and analytical costing method. Therefore, it also leads to a lack of consideration about the influence of LCC on the design decision making. By combining the literature review in Chapter 2, the research questions and the definition of the objectives and hypotheses are generated. Although the identification of the research problem and the literature survey is an iterative process, which is conducted in tandem with the literature review, the former is presented first in this chapter for readers to have a direct access.

1.4.1. RESEARCH QUESTIONS

Given the need for involving LCC to improve the aircraft design process and the design decision making, and the potential of using KBE as a supporting technique, the main research question is formulated: **Is it possible to conduct LCC analysis and integrate the relevant cost indicators into the aircraft design process effectively and efficiently by using KBE techniques?** This leads to the following three groups of sub-research questions:

- Design process:
  What is a generalized and modularized aircraft design process? How can LCC estimation be integrated into the aircraft design process? How can KBE techniques support the design-cost integration?

- LCC analysis:
  How can the LCC be estimated within the aircraft design phase when limited data is available? What is a general, modular, and fast LCC estimation process? What are the driving parameters and the relationships between the driving parameters and the cost? How can KBE be used to support aircraft LCC estimation process?

- Design optimization:
  What framework can integrate optimization into the aircraft design process? What is the optimum design concept in terms of the minimum cost that still satisfies the constraints from other disciplines such as structural restrictions?

1.4.2. OBJECTIVES

Corresponding to the proposed research questions, the high-level objective of this thesis is defined: **In order to include life cycle considerations into the aircraft design process, the research is aimed at incorporating LCC analysis and optimization capabilities into the early design phase via the support of KBE techniques**. It contains sub-objectives from three related aspects:

- To develop a KBE supported design process that integrates LCC analysis and optimization;
- To develop a method for LCC analysis;
- To develop an optimization study to involve lifecycle consideration in terms of aircraft/aircraft component cost performance.

1.4.3. HYPOTHESES

In addition to the research questions and objectives, challenges are identified respectively in KBE, LCC, and MDO through an extensive literature review illustrated in Chapter 2. By zooming into selected challenges closely related to this study, methods have been proposed and developed in Chapters 3 to 5. In other words, in order to address the lack of modularized design-cost integration approach, analytical LCC estimation method, and generalized cost-integrated design optimization strategy, it proposes KBE supported design-cost integration and KBE supported cost analysis (Chapter 3), scalable two-level LCC analysis (Chapter 4), and LCC-related cost indicator for design decision making (Chapter 5). Therefore, hypotheses have been proposed to be tested by cost engineers during the conceptual and preliminary design phases: If the LCC analysis can be integrated into the aircraft design process via the support of KBE techniques and optimization capabilities, then

- The use of KBE techniques in LCC analysis within the design process will lead to a more modularized and efficient integration of cost that can be optimized computationally over the life cycle;
- The scalable two-level LCC analysis will lead to an adaptable, comprehensive, consistent, and design-driven costing approach;
- The inclusion of life cycle related cost indicators in design optimization will reduce LCC through a better trade-off with other performance factors such as weight.

1.5. OVERVIEW OF THE THESIS

In order to realize the objective and sub-objectives, this thesis provides a comprehensive study of the proposed research questions. This research is carried out using the following approach: Firstly, an extensive literature survey is conducted in respective research domains: KBE, LCC, and MDO. The relationships among those domains and their current status of development are analysed. A broad set of challenges and opportunities are identified. Next, by combining the challenges with the scope of the research, it zooms into the specific originality

of this research. Furthermore, the method of design - cost integration using KBE techniques, the method of LCC analysis employing two levels of cost models, and the method of design optimization integrating cost performance are developed. The synthesis of those methods composes the overall research development. In order to illustrate the application of the proposed method, two study cases - the stiffened panel case and the rudder case - are carried out. The stiffened panel case is utilized to demonstrate the RDT&E cost analysis, the production cost analysis, and the design optimization studies. The rudder case is employed to illustrate the O&M cost and the disposal cost analyses. The former is a typical structural component used to compose the aircraft wings and fuselage, the latter represents a movable-type component of an aircraft. Those two cases are complex enough to demonstrate the proposed method in a sufficient level of detail. Assumptions considering the geometry sizes, material type, and manufacturing method are made for the stiffened panel case, while the operating condition and maintenance plan have been planned for the rudder case. Data for the case studies is extracted from engineering practice and from literature. More complicated applications such as the whole aircraft can also be achieved by using the same approach conducted for those two cases. The capability of the proposed method is shown by investigating the results obtained for the study cases. It leads to the discussion in the conclusions, in which the novelty and the recommendations are highlighted.

Therefore, the structure of the thesis is generated, see Figure 1.9. In Chapter 1, aviation industry developments are evaluated from the market, economy, and technology perspectives. The research interest and research objectives are presented. Chapter 2 focuses on the current aircraft design process, cost analysis, optimization strategies, and the application of KBE techniques. Contributions of this research distinguished from the current status of development are addressed. It is noted that the research questions, objectives and hypotheses have been presented before literature review although it is an iterative process while setting up research objectives and reviewing the relevant literature. In this way, a direct access to the research field is made available. Research carried out on the three main foundations are elaborated in the following chapters. Chapter 3 contains the overall workflow, and it emphasizes the methodology development of KBE assisted design process. Chapter 4 presents the detailed life cycle cost analysis methodology. The cost integrated optimization methods are developed in Chapter 5. Chapters 3 to 5 construct the main development of this research. Each of them contains its own framework, the detailed method and the method implementation, and a discussion of its synthesis approach within the overall work flow. Two case studies are presented in Chapters 6 and 7, and the results are shown as a validation of the methodology. Finally, Chapter 8 concludes with the main findings and recommendations from this research.

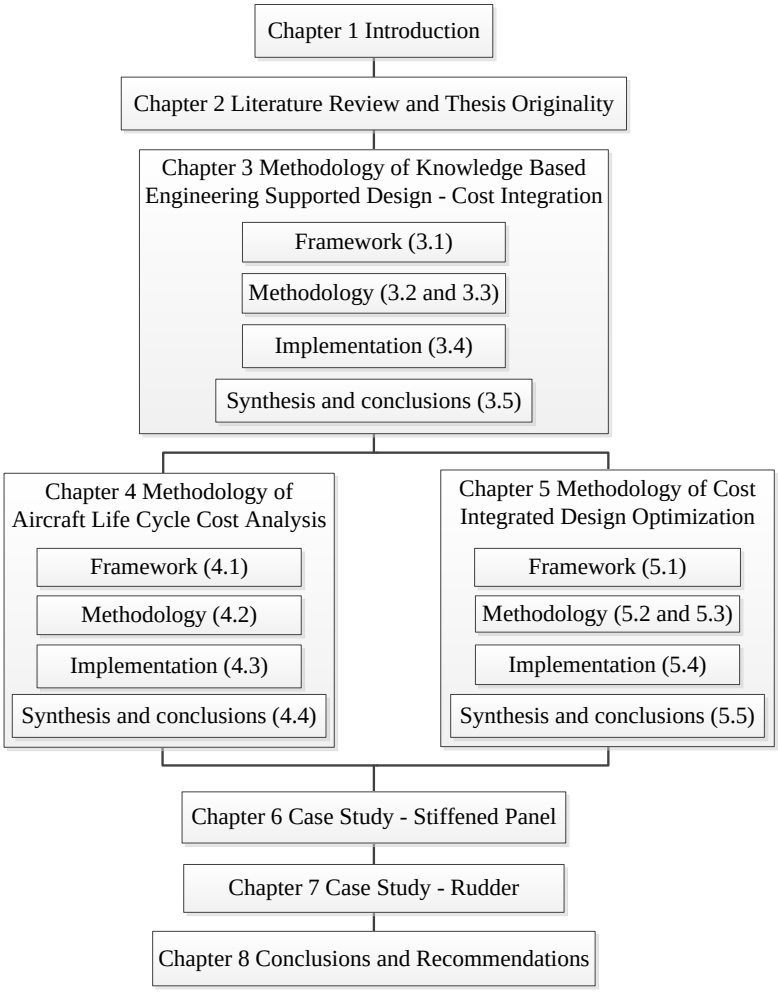


Figure 1.9: Thesis structure

2

LITERATURE REVIEW AND THESIS ORIGINALITY

The literature is grouped into three categories: the KBE-assisted aircraft design process, LCC analysis, and MDO development. The review includes an overview of the current status of research approaches and research trends from diverse research groups in both academia and industry. First, selected literature is evaluated chronologically and distinguished by research groups/leaders over more than five decades from 1960 until 2015. Next, the trend of the historical development is identified, tracing recent updates from relevant research groups and extracting the research focus, theoretical foundations, methodologies, results, and conclusions from existing studies. Then the state-of-the-art in those research fields is illustrated by highlighting the advanced techniques and challenges. Finally, by emphasizing the challenges and opportunities within current developments, the contributions and improvements of this thesis are highlighted.

2.1. RELATIONSHIPS AMONG THE RESEARCH DOMAINS

Figure 2.1 depicts the relationships among the three main research domains: KBE-assisted aircraft design process, LCC, and MDO. Firstly, they are all embodied in a cost integrated design and optimization framework. The aircraft design process involves cost analyses and optimization studies, while KBE techniques can support automatic and modularized cost analyses and optimization studies within the design process. The methodology and the implementation of the LCC analysis are focused, and it is also an element to be integrated into the MDO framework. MDO is built upon the disciplinary integration and the support of KBE, and is used for the design decision making. Design iterations are represented by the MDO framework, which can be applied to the design process. By involving design knowledge and automation into MDO using KBE, the analysis becomes more efficient and its fidelity can be pushed forward. An elaborative discussion of KBE, LCC and MDO and their interactions are illustrated in Sections 2.2, 2.3, and 2.4 respectively.

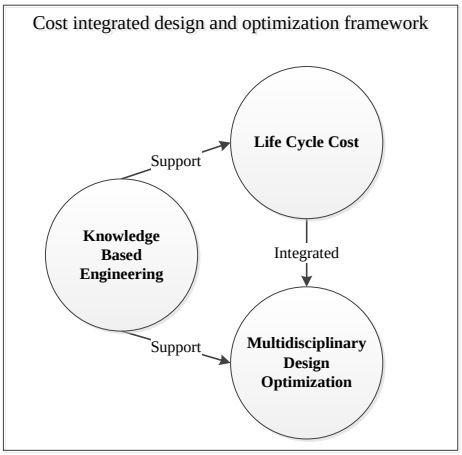


Figure 2.1: Relationships among KBE, LCC and MDO

2.2. AIRCRAFT DESIGN AND KNOWLEDGE BASED ENGINEERING (KBE)

2.2.1. AIRCRAFT DESIGN AND DISCIPLINARY ANALYSIS PROCESSES

In order to establish the potential improvements on the design process from a KBE perspective, modern design and disciplinary analysis processes are investigated. Current design processes are developed on the basis of SE technology and follow the 'V' model throughout the project life cycle (Figure 2.2). The 'V' model illustrates the logic of design development and implementation. First, the product is developed from the system to the detailed system element, containing the system decomposition, concept definition, and baseline design. Then it is implemented from the level of the system elements to the level of the system, involving

the fabrication and integration from the detailed component and subassemblies to the system. Verification is involved in the process as the maturity of the baseline design is shifted from left to right along with the V process. On the basis of the V model, OEMs/ODMs develop their own design processes.

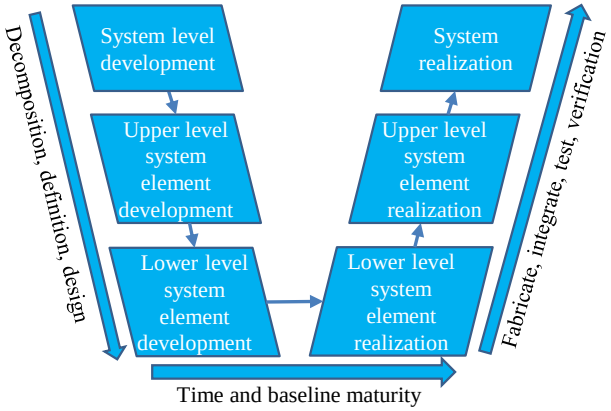


Figure 2.2: System engineering V model (Adapted from [56][57][58][59])

The design process used by Airbus is depicted in Figure 2.3. Five phases are distinguished: feasibility, concept, definition, development and series. Each phase is elaborated in a group of activities. Milestones identified for the first three phases are the points at which the decisions are made from both technical and managerial perspectives, while for the development phase, the milestones are the dates on which the objective is achieved for the stage. When the concept is selected, the conceptual design process is moved forward to preliminary design which includes higher fidelity performance analyses and optimizations. Baseline configurations are produced and validated to support the decision of the Instruction To Proceed (ITP). Thereafter, the design process focuses more detail on component level detail until the 'go ahead' (component design is completed); then resources are collected and arranged for manufacturing development. In a product life cycle, once the aircraft is ready for operation, the main design process is completed, Series Production takes place in the series phase.

In Bombardier, an MDO deployed aircraft design process is conducted via the Bombardier Aerospace Engineering System (BES) [20]. Figure 2.4 is adapted according to Piperni et al. [20], so that it can be compared with the Airbus design process. First, the new design is prepared through market analysis to obtain a basic product definition in the Aircraft Portfolio Strategy Board (APSB). Design activities are controlled by a series of deliverables recorded in review reports. In order to strengthen the efficiency and fidelity in various design phases, the multilevel MDO capability is incorporated by employing design teams with different tools at appropriate levels of detail to execute design processes.

It can be seen that the aircraft design process generally conforms to a schema that includes conceptual, preliminary, and detail design phases, while OEMs have developed more

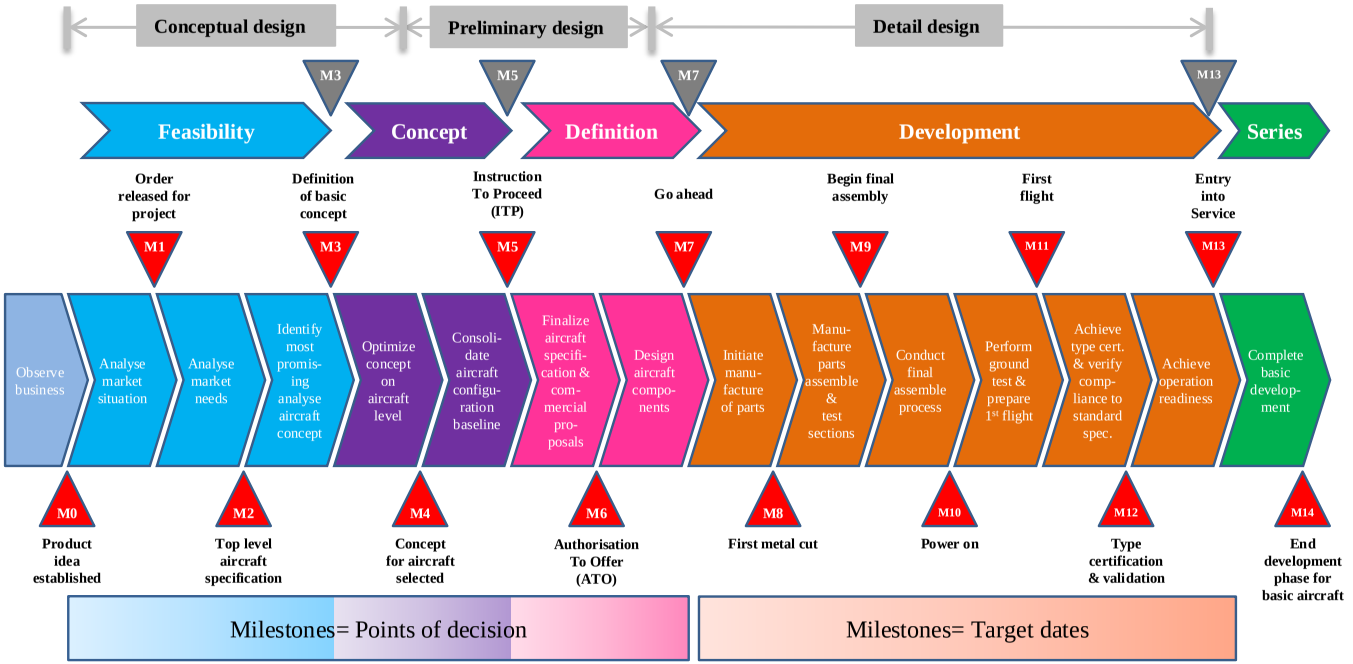


Figure 2.3: Aircraft development milestones in the product lifecycle of Airbus [20]

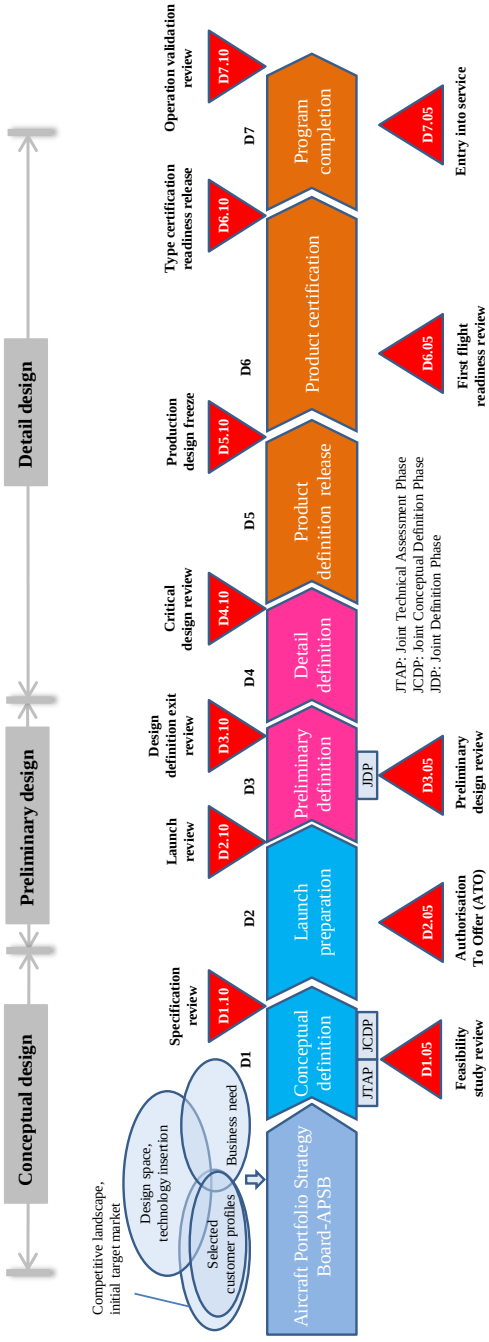


Figure 2.4: MDO deployed aircraft design process of Bombardier [56]

detailed processes according to their own design practices. The boundary between the conceptual design phase and the preliminary design phase is slightly more ambiguous than the boundary between the preliminary design phase and the detail design phase. A trend of improvement is to push analyses from the preliminary design phase forward to the conceptual design phase. In this way, more comprehensive evaluations can be obtained in early phases to avoid rework in later stages. Techniques for knowledge management and process automation are required to reduce repetitive work while increasing the time for creative solutions. To this end, KBE, multidisciplinary engineering, process synchronization, and system integration have been recommended [20][56]. Given the potential use of KBE to support the design process while involving LCC analysis, investigations of the development of KBE techniques are emphasized in the following sections.

2.2.2. THE HISTORY OF KBE DEVELOPMENT

KBE followed from the development of the ICAD system in the 1980s, and became quite popular in the 1990s [60]. The technology evolved based on the development of Artificial Intelligence (AI), Computer Aided Design (CAD), and computer programming [61]. In particular, it is the combination of Knowledge Based System (KBS), the parameterized geometry model and Object Oriented Programming (OOP), rooted in the aforementioned three fields.

A commonly used definition of KBE emphasizes 'the capture and systematic reuse of the product and process engineering knowledge' to automate 'repetitive and non-creative design tasks' and to support 'multidisciplinary design optimization in all phases of the design process [62]. KBE is employed as an assistant to 'realize an efficient and economic product development process'. The concept of KBE was introduced after the integration of Expert Systems and CAD in the middle 1980s [21][31][63][64]. A more systematic approach to KBE system development was developed in the European project MOKA (Methodology and tools Oriented to Knowledge-based engineering Applications), resulting in the initial version of the KBE System Lifecycle and MOKA methodology as proposed by Oldham and Sainter [43][65][66] around the year 2000. A comprehensive report of the MOKA project is recorded by Stokes [67], which among other things illustrates necessary knowledge representation and management techniques, KBE life cycle identification, and automatic code generation methodologies. Simultaneously, Brimble et al. were involved in the development of UML-based Knowledge representation [68]. Cooper identified the opportunity to introduce KBE into the industry using a general practice guideline during the same period [69]. KBE applications integrated into product design and development were generated by Whitney et al. as well as Chapman and Pinfold [70][71]. Negnevitsky pointed out that OOP and inference mechanisms are often employed in expert systems [72]. Van Der Laan and La Rocca further developed KBE techniques applied to aircraft design tool development [73]. In particular, they worked on automated design applications. La Rocca and Van Tooren focused on aircraft geometric model parameterization and automatic generation, not only for product representation but also for multidisciplinary analyses [62]. KBE applications including aircraft cost analysis appeared briefly in researches conducted by Choi et al. and Van der Laan and Van Tooren separately [74][75]. Furthermore, those applications were extended to support the product design and optimization process, to which end a dedicated KBE assisted MDO framework was presented and extended by various authors [64][76][77].

2.2.3. STATE-OF-THE-ART

Although a number of studies have elaborated practical KBE techniques employed to support design and analysis, the generalized procedure of developing a KBE application has not been specified. Based on an overview of KBE technology and practices, a guideline for aircraft or aircraft component KBE application development can be summarized as follows: after checking KBE applicability for the application case and determining the policies of KBE application development in the company (OEMs/ODMs and Small and Medium sized Enterprises (SMEs)) and/or in the research group, technical steps are taken during the KBE life cycle [43]. First, a domain Knowledge Base (KB) should be developed by capturing and modelling the product and process knowledge in a Unified Modelling Language (UML) or a UML-based visual modelling language such as the MOKA Modelling Language (MML). Second, a KB management tool is needed to store, analyse, publish, and maintain the product and process knowledge. The KB management tool can be separated from a design and analysis tool, but it can also be integrated within an application for simplification purposes. Third, a step of mapping the knowledge from the KB to the design process is necessary. This involves the knowledge transmission from the KB management platform to the design platform, or from knowledge storage to the design process in the same application. The fourth step is to identify the design and analysis tasks and to automate the process using mapped knowledge. The KBE techniques employed in this step for performance design integration and disciplinary performance analysis are summarized in the following sub-sections. Once the KBE application is developed, final deployment to end users can be accomplished.

2.2.3.1. KBE SUPPORTED DISCIPLINE AND DESIGN INTEGRATION

In order to fulfil the disciplinary requirements for a design, analyses are carried out during the conceptual design phase. In this context, design mainly refers to the generation of suitable product geometry and relevant attributes satisfying the performance requirements. Using a modern design and optimization framework, called the Design and Engineering Engine (DEE) [78], which is schematically illustrated in Figure 2.5, an optimized geometric representation and disciplinary performances can be obtained through iterative simulations of disciplinary analyses based on a central product model.

This framework not only illustrates a concurrent design and optimization process but also includes the assistance of KBE techniques. According to La Rocca [22], DEE contains a geometry-centric model generator as well as disciplinary analysis modules. It starts with an initiator, which represents a product instance with initial input values. The core of the DEE is a Multi-Model Generator (MMG), which refers to a parametric product model, including a product model generation module and one or more disciplinary views generation modules. The product model generation is realized by instantiating the master geometry composed by High Level Primitives (HLP), while the disciplinary views generation are implemented by Capability Modules (CM). HLPs are defined as basic design elements of a geometric model. Those design elements are common parts or components extracted from different aircraft configurations, like the wing, fuselage, connection-elements and engine, and they are distinguished from low level primitives of a CAD system such as points, lines, shells and solids. In addition, each HLP is packaged with specific product knowledge that is not shared by other HLPs. CMs are the operators of engineering rules and procedural knowledge so that

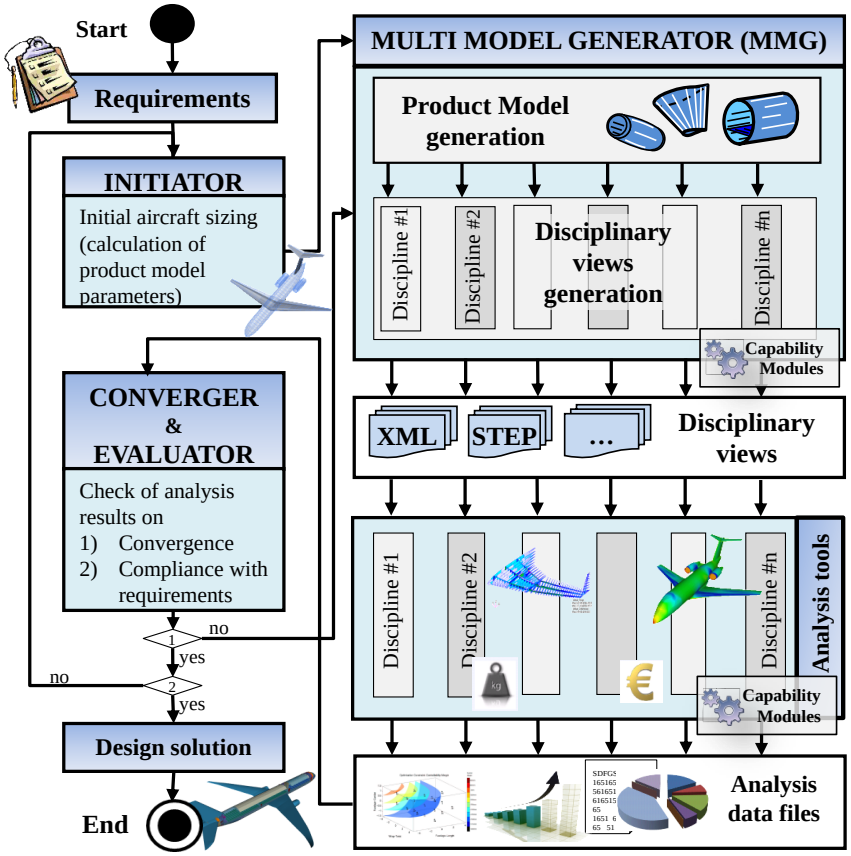


Figure 2.5: Design and Engineering Engine [22]

disciplinary product representations can be generated automatically. Disciplinary product representations are also known as disciplinary views, which collect geometric segmentations and attributes in certain formats for disciplinary analyses. The MMG is connected to analysis tools via formatted data files such as XML (Extensible Markup Language), STEP (Standard for the Exchange of Product Data), and TXT (text) files. Analysis tools are outsourced or in-house developed applications employed by disciplinary analyses. Analysis data files are produced for optimization or output reports. Extra CMs are developed as Application Programming Interface (API) managing software communications and writing reports. The convergence of the performance analysis and/or optimization algorithm are checked in the Converger & Evaluator (Optimizer) by evaluating if the automatic generated analysis results meet the requirements and/or the objectives.

The implementation of KBE techniques within the DEE is often realized by an object-oriented application. Classes and objects constitute parameterized building blocks incorporating knowledge for generative modelling. These are applied to represent HLPs and their in-

stances. KBE techniques are also utilized to develop the correspondent KB and to automate the design process. In more detail, KBE engineers extract explicit and implicit rules from repetitive design activities, then apply them as functions in CMs. In summary, the KBE techniques of knowledge reuse, automation, and analysis significantly rely on KBE rules. There are five types of rules summarized [22]: logic rules, math rules, geometry handling rules, topology rules and communication rules. Based on the practice of KBE applications development, the KBE rules normally used for design-discipline integration are listed as follows:

- Product master geometry generation using geometry handling rules and topology rules;
- Geometry pre-processing for disciplinary analyses using logic rules, geometry handling rules and topology rules;
- Optimization using math rules;
- Optimization results post processing for output reporting using communication rules;
- Product master geometry updating based on optimization results using geometric handling rules and communication rules.

2.2.3.2. KBE SUPPORTED DISCIPLINARY PERFORMANCE ANALYSIS

Disciplinary performance mainly includes aerodynamics, structure, weight and cost in the aircraft design field. Two options are available for disciplinary analysis within a KBE application: COTS disciplinary analysis software and in-house developed disciplinary analysis tools. The KBE assistance for COTS disciplinary analysis mainly enables the automation of the analysis loop using logic rules and communication rules. For example, if the Finite Element Analysis (FEA) modelling software MSC Patran/Nastran is employed for structural analysis, a control mechanism in the KBE application would automate the analysis process in MSC Patran/Nastran from structural meshing to stress analysis without manual intervention. The KBE support for in-house developed disciplinary analysis not only enables process automation but also performs actual analysis calculation. Detailed rules associated with domain knowledge vary depending on the specific discipline to be analysed. The list below shows the KBE rules used for an in-house developed cost analysis:

- Parameter transmission from pre-processed geometry to disciplinary analysis using communication rules;
- Disciplinary analysis modelling and disciplinary analysis process control using logic rules, math rules and communication rules;
- Disciplinary analysis results post-processing for optimization or output report using logic rules;
- Optimization results post processing for output report using communication rules;
- Post-processed results transmission from disciplinary analysis to optimization or output report using communication rules.

2.3. AIRCRAFT LIFE CYCLE COST (LCC) ANALYSIS

2.3.1. AIRCRAFT LCC

Aircraft LCC refers to the total cost induced during a product life cycle. For civil aircraft, it involves the cost components generated during the aircraft's lifetime, from the start of design to the end of disposal. The LCC breakdown is illustrated in Figure 2.6. The categorized cost elements, also called the Cost Breakdown Structure (CBS), are divided comprehensively. Two cost streams related to two main stakeholders: the manufacturer and the operator. Miscellaneous costs, such as tooling and equipment depreciation cost, insurance, interest, tax, and the overheads, which mainly depend on the company's strategy, are categorized and quantified as wrap-up factors. Some companies assign percentages to the estimates representing those cost impacts, while others assign a fixed amount to quantify their influences on the LCC. Furthermore, a more detailed cost breakdown is built up separately for the RDT&E, production (or M&A), O&M and D&R cost types. RDT&E cost refers to the cost of the aircraft design process, involving research, development, test and evaluation. Production cost indicates the cost of manufacturing and assembly processes. O&M cost is the cost spent on aircraft operating and maintenance. D&R cost is generated when the aircraft is no longer effective or economic, including the cost of dismantling and recycling [79][80]. The cost elements under each cost type vary based on the various LCC characteristics. For example, the recurring cost and nonrecurring cost are defined specifically for the production cost, while the direct cost and indirect cost are established for the O&M cost. There are also general cost elements such as labour cost, material cost, tooling & equipment cost, energy consumption, and facility cost which appear in all cost categories. Labour cost is generally time dependent and material cost is product dependent, while the other cost elements are often related to the company policies. Additionally, economic indicators, regarding cost, revenue, and profit associated with different LCC cost types, are considered (Table 2.1). The LCC distribution varies based on the actual RDT&E investment, the production strategy, the O&M condition, and the disposal approach. In general, a composition of 20-40% of RDT&E and production costs, and a 60-80% O&M and D&R costs are presented [81]. Along the aircraft life cycle, the production cost and the O&M cost would be the main contributors of the LCC. While according to the learning curve effect, the production cost per each aircraft will go down. The fuel cost within the O&M cost will keep increasing. Due to the ageing effect of the aircraft, the scheduled maintenance cost will remain relatively stable while the unscheduled maintenance cost will increase.

The significance of the various LCC elements to stakeholders participating each stage of the life cycle is different. This is driven by their controllability on the major cost types for each life cycle stage and their profitability linked to the cost elements. For **designers**, the most beneficial design would be a high performance aircraft using advanced technology while at an acceptable development budget and low product expenses. Therefore, designers care about the balance between the aircraft price and the performance. For the current **ODMs**, the design team is normally a department of the company, where the RDT&E cost and the production cost are rigorously controlled. The production cost needs to be evaluated in detail also for product pricing. In addition, operating cost is one of the main factors for aircraft bidding [83]. In order to improve product competitiveness, low production and O&M

Table 2.1: LCC related economic indicators

LCC major cost type	Cost	Revenue	Profit	Other
RDT&E cost	• First cost • Investment cost	- -	- -	• Fixed cost • Variable cost • Direct cost • Indirect cost • Recurring cost • Non-recurring cost • Sunk cost • Future cost • Rate of Return (RR) • Surplus Value (SV) • Net Present Value (NPV)
Production cost	• Unit cost • Total cost	• Price • Acquisition cost • Procurement cost	- -	
Operating & Maintenance cost	• Weighted Average Cost of Capital (WACC) • Direct Operating Cost (DOC) • Indirect Operating Cost (IOC) • Direct Maintenance Cost (DMC) • Indirect Maintenance Cost (IMC) • CATK/CASK • Yield • Opportunity cost of Capital • Payroll cost	• Revenue • RATK/RASK	• Operating profit • Net profit • Operating profit margin • Net profit margin • Return On Invested Capital (ROIC)	
Disposal & Recycle cost	• Residual value	• Salvage value	- -	

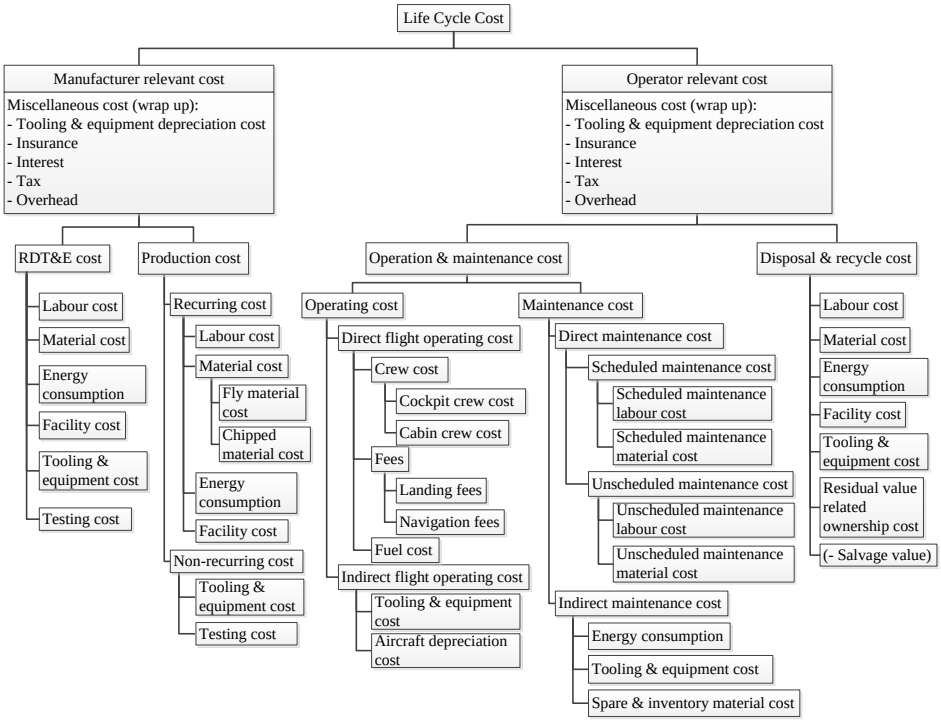


Figure 2.6: Life Cycle Cost composition [19][82]

cost are desired. Favourably, it is better to have economic EOF solutions. The counterpart of production cost for **airlines** is the acquisition cost, while it not only includes the production cost, but also the profit made by the ODM. Airlines are the stakeholders who mostly care about the operating cost. By choosing economic aircraft types and developing various operating strategies, a low operating cost is expected; low acquisition and disposal cost with high operating and disposal profit are also needed. Last, disposal companies purchase retired aircraft to make a profit by using economic and efficient dismantling and recycling techniques. Table 2.2 shows the focuses of aircraft stakeholder with respect to each LCC major cost type. The number of '•' qualitatively expresses the significance of each major cost type to the corresponding stakeholder. In summary, from the designer's perspective, the main interest is the design and development cost (if it is cost efficient to design) and the life cycle cost (if the target manufacturer can produce it at a reasonable production cost and if the airline would invest in the design) [84]. From the manufacturers' perspective, the main interest is the production cost (if it is cheap to produce), the price and the O&M cost (if the airline would invest the aircraft). From the airlines' perspective, an aircraft fleet with low acquisition cost (if it is affordable) and economic operating expenses (if it is operationally cost effective) are essential to a successful business [85]. To conclude, costs in an aircraft life cycle are of significant importance for decision makings related to design, choice of resources, and operating.

Table 2.2: Stakeholders' focuses in terms of LCC major cost types

LCC major cost type	Designer	Manufacturer	Airline	Disposal company
RDT&E cost	• • •	• • ○	• ○ ○	○ ○ ○
Production cost	• • •	• • •	• • ○	• ○ ○
Operating & Maintenance cost	• • ○	• • ○	• • •	• ○ ○
Disposal & Recycle cost	• ○ ○	• ○ ○	• • ○	• • •

2.3.2. COST ESTIMATION METHODS

The main task of cost estimation is to collect the values of the driving parameters and to define the mathematical relationships between the parameters and the cost. By reviewing methods and techniques for cost estimation [82][86][87], four necessary elements for composing a complete cost estimation can be distinguished: the estimation process, estimation model, calculation method, and assistant techniques, as shown in Table 2.3.

An **estimation process** specifies the sequence of performing cost estimation activities along with the Product Breakdown Structure (PBS) and CBS. According to the specific properties of each life cycle phase, distinct PBSes and CBSes are needed for the estimation of different costs. Using the production cost as an example, a bottom-up process [88][89] follows the hierarchy which conducts the analysis from a part to a component till the final product assembly in a PBS, and from material/labour cost to recurring/non-recurring cost until production cost in a CBS. In contrast, a top-down process [88] goes from the product level to the part level, and from the total cost to more detailed cost elements. The cost estimation may follow a bottom-up process for the PBS and a top-down process for the CBS based on available data and the actual estimation models. While within the PBS and CBS respectively, only one process route should be taken for each.

A **cost estimation** model defines the fundamental hypotheses, indicating the relationships between independent parameters (e.g. geometry, material, production process) and the dependent parameter (cost). It emphasizes the cost driving parameters. Examples of estimation models are feature-based, activity-based, case-based, operation-based, genetic-causal, tolerance-based, uncertainty-based, financial, and value-based models. Feature-based models assume that the product attributes, mainly shape properties like a circle pocket, and geometric sizes such as length and width, are the main drivers for the product cost [90]. CAD and Computer Aided Engineering (CAE) techniques are adopted for this type of model. Activity-based models emphasize that cost is driven by the production activity chain [91][92][93][94] while case-based models determine cost from historical comparable cases [95][96]. Process-based models evaluate cost based on the time taken for each process [97][98]. Operation -based models obtain the cost from the estimation of operation process time, non-productive process time and setup process time. While the Cost Estimation Relationships (CERs) are based on the manufacturing process features [99]. Genetic-causal models are based on causality between the driving parameters and their induced cost in the same part

families [82]. Tolerance-based models relate the impact of the design tolerance to the product cost [100][101]. Uncertainty involved models predict the cost using stochastic analysis [102]. Financial models estimate cost based on existing cost data using accounting method [103]. Value-based model takes cost as a composition of a value, which also includes other non-cost factors [95][96][104].

A **cost calculation model** specifies the mathematical relationships between the independent and dependent parameters. Existing approaches can be grouped into parametric, analogous, fuzzy logic, neural networks, and accounting methods. CERs are mainly built by the parametric method using predefined mathematical relationships such as the power law, first order law and hyperbolic function, or regression parametrization techniques based on statistics [105][106]. The analogous method typically utilizes a matching algorithm and data available on existing similar cases to establish cost functions [107][108]. The fuzzy logic method adopts fuzzy rules to construct the mapping from the cost drivers to the final cost [109]. Neural networks are employed to push the estimated cost to the target cost by iteratively correcting the weight factors of the driving parameters, so that a mathematical relationship is built through training/learning algorithms [110][111][112].The accounting method aggregates cost based on statistical analysis. Note that although both the estimation model and the calculation method can define the relationships between the independent parameters and the dependent parameters, they are distinct elements in a cost estimation. The estimation model emphasizes the logic between the driving parameters and the evaluated cost, especially the philosophy of choosing driving parameters, whereas, the calculation method focuses on the mathematical formulation, which indicates the arithmetic relationship between the driving parameters and the evaluated cost. In general, the driving parameters would be defined based on the same philosophy once the estimation model is selected, while different calculation methods can be adopted for the estimation model. For example, if the cost estimation adopts the process-based estimation model, the driving parameters are related to processes, while either the parametric method or analogous method can be selected for the actual mathematical calculation.

Finally, specific **assistant techniques** are employed to support the estimation model and mathematical relationship development. Some techniques are embedded in certain estimation models and calculation methods, while some techniques are generally applicable to any cost estimations. The former contains techniques such as activity-chain analysis, case-based reasoning and cost-time analysis. The latter includes techniques like data mining [113][114][115], KBE and statistical analysis [116], which deal with effective data collection, design cost integration and data analysis respectively. Some specific techniques have been associated with the introduction to the estimation process, the estimation model and calculation model.

At least one item from each of the four elements should be selected. The items are then combined to build up a cost estimate. Items from one element can also be mixed to form a hybrid approach. For instance, the operation-based model can be regarded as a mix of the feature-based model and process-based model. Research referencing each item is summarized in Table 2.3.

Table 2.3: Refined classification for elements of a cost estimation method

Estimation process	Estimation model	Calculation model	Assistant techniques
• Bottom-up process [88][89] • Top-down process [88]	• Feature-based model[90] • Activity-based model [91], [94] • Case-based model • Process-based model [97][98] • Operation-based model [87][99] • Genetic-causal model [82] • Tolerance-based model [100][101] • Uncertainty involved model [102] • Financial model [103] • Value-based model [96][104][95]	• Parametric method [117] [118] • Analogous method [107][108] • Fuzzy logic method [109] • Neural networks method [110][111][112] • Accounting method	• Cost estimation model specific techniques - CAD and CAE techniques [90] - Activity chain analysis [119][94] - Case-based reasoning techniques - Production process time analysis [97][98] - Operation process time, non-productive time, setup time analysis [87][99] - Causal relationship analysis [82] - Cost tolerance relationship analysis [100][101] - Cost-benefit analysis - Stochastic analysis • Cost calculation method specific techniques - Regression parameterization techniques [117] - Cost time analysis techniques [117][120] - Matching algorithms [107][108] - Training/learning algorithm [111]

2.3.3. THE HISTORY OF AIRCRAFT COST ESTIMATION

LCC analysis was initiated in the early 1970s by the US Department of Defense [121][122] [123][124]. It is aimed at providing guidelines for equipment/system procurement. Gradually, life cycle costing was employed to support decision making. In response to a growing interest in aircraft life cycles, research into LCC estimation has progressed significantly. Some cost estimations have been applied to an entire aircraft, while others have focused on individual aircraft components. Furthermore, most of the research has highlighted the development of one or two cost types in the LCC CBS, while some have investigated the complete LCC estimation. Some literature has mentioned all the elements composing a cost estimation method summarized in the previous section, while a few have emphasized only certain cost element(s). The following review divides the literature from the aircraft level to the component level in a chronological order. The major cost type(s) estimated and the cost element(s) evaluated through these analyses are summarized. At the end, applications of cost estimations incorporated in early design phases are discussed.

On the aircraft level, the RAND Corporation carried out a large amount of research on aircraft cost estimations beginning in 1967. The Development and Procurement Cost of Aircraft III (DAPCAIII) model was developed for the entire airframe, including engine cost, using parameterized cost estimation [125][126]. DAPCAIV updated the representative CERs in DAPCAIII in the early 1980s [117]. A modified DAPCAIV model was built based on the performance parameters such as take-off gross weight, cruise velocity and production quantity [61]. Another LCC model was developed by Roskam [127], which is similar to DAPCAIV, but with altered parameter types. The aforementioned LCC models are the main ones for the evaluation of all cost categories an aircraft. Others have focused on one or two cost types of the LCC. For example, Liebeck [84], who focused on DOC, established a method based on ground rules and a parameterized modelling technique using airframe weight, engine thrust and trip time as driving parameters. According to Dhillon [128], the maintenance cost can be estimated through the reliability of the components. Tirovolis and Serghides [83] have developed a design-oriented unit cost (acquisition cost) estimation method for large commercial jet aircraft employing top down aircraft component breakdown and regression cost estimations. By using a parametric and analogous estimation method, Roy et al. [129] conducted a case study on an automotive powertrain containing intensive new technologies. In addition, valuation as an engineering technique is introduced into aircraft cost analysis in order to incorporate the cost analysis into MDO. The interpretations of value is varied in the form of, for example, program value [130] and SV [95][96]. The former is developed based on the integration of commercial aircraft performance, cost and revenue on a system level. The latter utilizes the value concepts to strengthen the cost analysis by adding the market profit into the model.

In general, cost estimation on the aircraft component level often requires more detailed information. In this sense, costing methods related to detailed processes are also included in cost estimation. Gutowski et al. [105] have proposed a first-order calculation model that can simulate composite fabrication process cost. Then the cost of each process is aggregated to the final cost. Marx et al. [131] established a hierarchical LCC analysis framework using bottom-up PBS and top-down CBS for the complete LCC estimation of a wing component. Later, a cost/time analysis technique was implemented for LCC prediction [120]. An accu-

rate cost model was established for the manufacturing and assembly processes of composite materials productions. Haffner [106] has implemented a cost analysis for each typical manufacturing process specific to aircraft composite component production. In this research, a hyperbolic function is proposed to perform cost estimation related to labour hours. The component production cost has been studied by Castagne et al. [132] who have investigated cost models for skin, stiffener and skin-stiffener assembly. Curran et al. [82] have reviewed the state of the art in aerospace cost modelling. They suggest that cost engineers follow a genetic-causal approach to model cost using causal variables rather than purely adopting financial cost estimation based on accounting techniques. They also discussed the necessity of integrating cost analysis into the design environment. Curran et al. [133] also suggest that the fundamental nature of cost estimation for aircraft structure should be on a genetic-causal basis. Newnes et al. [134] have linked a CAD package with an on-line automated computer system to estimate injection moulding cost. The analysed the cost estimation approaches applicable to different stages of a product's life.

In addition, in order to cope with the competitive market, product cost information should be made available early in the design phase. A trend in aerospace engineering is to integrate the design concepts and cost analyses into a single synthetic framework, in which the material, manufacturing, and cost properties can be considered simultaneously in the conceptual design stage. Moreover, design and optimization studies including cost influence can also be performed within the integrated framework. Kassapoglou [135][136][137] has applied design optimization studies on composite stiffened panels with various stiffener types as well as fuselage frames by simultaneously minimizing cost and weight under structural constraints. Apostolppoulos and Kassapoglou [138] have focused on recurring cost optimization including learning curve effect. Recently, by considering the influence of implementing structure modularity design, the cost-weight trade-off study has been carried out by van Gent and Kassapoglou [139]. A group of researchers, including Kundu et al. [140], Price et al. [141], Curran et al. [59], Castagne et al. [132], and Early et al. [142], has promoted a generic cost estimation tool development by integrating cost into design, multidisciplinary optimization and system engineering. Van der Laan et al.[143] have integrated friction stir welding into a multidisciplinary aerospace framework, DEE, building a process-based cost model to compare the costs of the friction stir welding and the riveting process. Another cost estimation tool has been developed by Scanlan et al. [144], who emphasized cost estimation utilising modular library elements and the integration of CAD representation, cost estimation, and automation of design optimization. An architecture of a KBE application has been proposed by Choi et al. [74], who discuss the interaction between the KB and the cost/weight estimation are discussed. Kaufmann et al. [145] have investigated cost/weight optimization adopting commercial software packages: SEER for cost estimation and ABAQUS for structural and weight analysis. Hollingsworth and Patel[146] evaluated a value model from Collopy [147], in which an SV parameter is developed for commercial aircraft design optimization . An approach to optimize cost on components by means of integrating cost analysis into the design process was suggested by Kassapoglou [137], Curran et al.[148] and Kaufman et al. [149].

2.3.4. STATE-OF-THE-ART

The aforementioned research has all contributed to the development of LCC analysis. Those contributions are made explicit through the reviews on its purposes, frameworks, cost estimation models, applications and the pros and cons. The trend of LCC analysis is then extracted.

Sherif and Kolarik [150] have inspected models and applications with the evolvement of the scope and concept of LCC. They categorised literature into groups such as LCC guidelines, models and applications. The LCC models are classified into conceptual, analytical and heuristic types based on their formalities, the use of mathematical relations and rules on the system level. Concurrently, in order to fill the gap of a comprehensive and up to date introduction to the life cycle costing in the 1980s, Dhillon [151] has outlined its historical development, basic techniques, and models in engineering fields including its applications in aviation industries. Later, Fabrycky and Blandchard [19] summarized the fundamentals of LCC analysis on the basis of a generalized LCC CBS. They also investigated methods for decision makings and LCC optimizations for alternative designs. Woodward [152] outlined the costing procedure, the LCC cost types, the life of assets, the uncertainty and sensitivity considerations. Information acquisition strategies are underlined by proposing an integrated database. Asiedu and Gu [86] have analysed cost calculation models (parametric, analogous and detailed models) and compared existing LCC tools with the discussion of estimation accuracy, reliability, etc. Durairaj et al. [153] have reviewed the frameworks of LCC analyses in the 90s. They compared the modelling approaches according to features such as objective, available cost profiles, cost drivers, etc. Korpi and Ala-Risku [154] have identified the current status of LCC use cases and found that those cases cover only a few LCC cost types, have low estimation detail, depend on expert opinion, and mainly use pure deterministic analyses. They propose the use of comprehensive, detail, statistical, sensitivity-involved methods in LCC applications. In 2009, by extending the previous work, Dhillon illustrated the basic LCC formulations in various engineering domains [155]. He shows that the LCC models differ because of different CBSs are adopted and various cost estimation methods are used.

In summary, a general **purpose** of LCC analysis is to achieve a minimum and balanced LCC by conducting trade-offs among the major cost types, not an optimization for a single cost element. This encourages a long-term outlook rather than short-term decision making for a product design and investment [152]. According to Asiedu and Gu [86], it is necessary to develop a generalized LCC **framework** that considers costs over the aircraft life cycle. The framework should require the fewest inputs that still providing sufficient cost information for decision making. Moreover, the framework can be utilized to explore design decisions based on the main cost drivers and to analyse alternative designs. In addition, it should contain breakeven, risk and sensitivity analyses [153]. **An LCC estimation method** is built upon general cost estimation methods while taking the properties of the LCC major cost types for a specific product into consideration. Furthermore, it should have a clear definition of the cost-driving parameters and the corresponding cost indicators according to the availability of the information [154]. LCC estimations should follow a formal procedure, and comprehensive method description. The **applications** normally cover only one or two major cost types in LCC. This is often caused by the lack of cost estimation knowledge including data and rules. In addition, the cost results in some applications are not realistic while can be ap-

plied only to compare alternative solutions evaluated by the same approach [86]. Therefore, **design-support tool** using LCC analysis is needed to provide quick and accurate financial reaction to the decisions of designers or operators [86][154]. This would improve communications between stakeholders such as manufacturers and airlines about cost information such as the O&M cost [154]. Besides cost analysis tools such as Piano, SEER and PRICE at a low level of detail, it is pointed out by Price et al. and Nickol that a gap still exists in medium/high-level cost analysis tools [141]. In addition, Woodward [152] has also pointed out the need for optimizing the LCC, which also requires accurate, relevant, and rapid LCC estimation. In conclusion, the LCC analysis for aircraft design needs to develop accurate engineering simulations by modelling product and relevant processes, identifying cost compositions, evaluating cost driving parameters, and establishing analytical relationships for cost indicators in an efficient paradigm.

2.3.5. AIRCRAFT DESIGN FOR LCC

In the aerospace industry, cost estimation should be taken seriously right from the conceptual design stage onwards, and be considered throughout its life cycle. When combining the statistics shown in Figure 1.8, the design influence on the LCC is evident. Asiedu and Gu [86] have indicated that the LCC could be substantially reduced by designers based on their decisions on the design concepts, the budget and the design decisions amongst the alternatives. According to Dhillon [155], the share of operating & maintenance cost can even exceed the procurement cost. The aircraft LCC drivers are properties such as structure, material, manufacturing process, speed, payload, and range, which are all design related [155].

The LCC performance is an important factor in design competitiveness in the air transportation market. LCC analysis in the design stage plays a significant role for trade-off studies and MDO analyses. Moreover, the operating decisions made by airlines are largely dependent on their operating strategies as well as the aircraft performance of a specific type. Therefore, an understanding of the LCC in the conceptual/preliminary design phase is critical to designers and/or airlines. The design can be changed with a certain freedom, although not much knowledge is available during the RDT&E phase [19][156][157]. Therefore, an LCC analysis on the basis of the data availability during the design process is critical.

2.4. AIRCRAFT MULTIDISCIPLINARY DESIGN OPTIMIZATION (MDO) STUDIES

2.4.1. AIRCRAFT MDO

MDO originated from the integration of disciplines into optimization studies for engineering design in the1960s, particularly in the field of aircraft structural optimization [158][159][160]. The MDO concept continues to evolve. A recent definition from Martins and Lambe [161] is: 'MDO is a field of engineering that focuses on the use of numerical optimization for the design of systems that involve a number of disciplines or subsystems'. Over the past four decades, MDO has evolved in various aspects, ranging from the overall architecture to application development. Extracting and reorganizing the MDO elements summarized by Sobieszczanski-Sobieski [162], four aspects comprising MDO have been identified by Giesing and Barthelemy [163]: architecture, evaluation, application and management, as shown in

Figure 2.7. Architecture is the core component of MDO. The concept of architecture relates to following aspects: How the objective and constraints are formulated, how the disciplines are coupled and analysed and how the optimization algorithm is applied. It contains the following elements: problem formulation, disciplinary analysis and optimization algorithm. Evaluation of within MDO, referring to performance measurement, includes the accuracy, computation cost, level of fidelity, verification and validation. Application development, which converts the architectures into the computer simulation programmes, includes the consideration of applicability, knowledge management and engineering (processing/storage/standardization), parametric geometric modelling, design space visualization and software platform. Management factors connect the application with the actual industry, where human factors are involved. Associating the application with achievable cost and benefit, properly defined organizational structure, operation process and training strategies, reduces resistance during the MDO application.

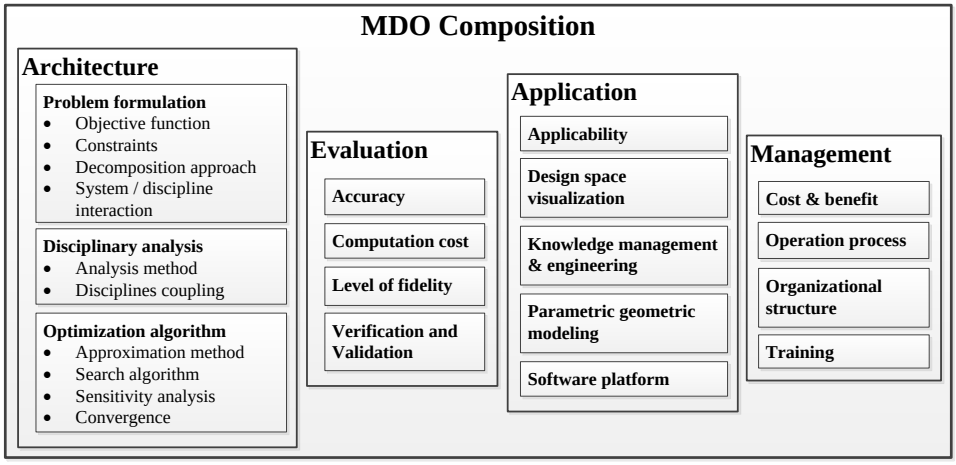


Figure 2.7: MDO composition [163]

In order to distinguish MDO from the other engineering analyses, distinctions among (mono-)discipline, multidiscipline, interdiscipline and transdiscipline have been made [164]. The classification is made on the basis of the following characteristics: What disciplines are considered, if the boundaries among the disciplines involved are clearly defined, if the design results produced are constrained within each of the disciplines and if it is within a fixed (or dynamic) system. (Mono-)disciplinary analyses involve one specific discipline within a clear boundary. The results generated are the discipline-related properties for a fixed system [165]. Multidisciplinary analyses use a collection of disciplines within identified boundaries for a fixed system. The results remain within a pre-defined scope [166]. Interdisciplinary analyses emphasize disciplinary integration. Disciplines interact more collaboratively. A new theory or method will be produced to solve the problem of a fixed system. The integration of disciplines are limited within their own theories and methods, but share design and analysis variables [167]. Generally, the boundary between multidisciplinary analysis and interdis-

ciplinary analysis is not well defined. The two are sometimes interchangeable. Transdisciplinary analyses handle diverse disciplines crossing boundaries for a dynamic and adaptive system. The solutions produced extend beyond traditional boundaries [168][169]. This thesis aims at integrating engineering cost analysis, weight analysis and structure analysis within a fixed design system for design optimization studies. It is, therefore, MDO focused. In the following sections, the history and current state of MDO development, the inclusion of cost as a discipline distinguished from traditional design and sensitivity analysis are discussed in more detail.

2.4.2. THE HISTORY OF AIRCRAFT MDO

By reviewing selected literature from multiple facets of MDO in aviation, a general route of MDO evolution can be specified. In the first two decades (the 1960s to 1980s), the development was mainly in the interaction among different disciplines in the problem formulation and sensitivity analysis. The disciplines were mostly structure, control, and aerodynamic. Along with the maturing of MDO architecture formulations, optimization algorithms began to be explored, particularly in the use of gradient-based optimization techniques. Later, computation efficiency and disciplinary fidelity were emphasized. The objectives and disciplines involved were then extended to other domains, such as aircraft performance for the best mission profile, design for the minimum recurring cost, structural/manufacturing interactions, and structural/acoustic interactions [170]. The optimization algorithms tended to include gradient-free methods such as genetic algorithm, simulated annealing, particle swarming, integer programming, and stochastic programming. In recent years, more comprehensive architecture categorization was developed, and multilevel optimization and multi-objective optimization have now become hot spots for MDO.

Studies on MDO have been conducted continuously since the 1960s. Sobieszczaztski-Sobieski [171] developed an analytical structural optimization on a stringer-skin aircraft fuselage using optimality criteria. Venkayya [172] reviewed developments ins structural optimization concerning loading types (static loads, dynamic loads and aeroelastic loads) and optimization algorithms mathematical programming, optimality criteria, optimal control theory, and dynamic programming). In particular, the viability of optimality criteria methods on wing structure optimization was demonstrated. Later, a multi-level structural optimization approach was promoted by Sobieszczaztski-Sobieski [173] illustrating three-level decomposition on an assembled structure. Since top-down decomposition is limited to hierarchic systems, an optimization approach was developed for non-hierarchic system decomposition [174]. Grossman et al. [175] implemented an integration of aerodynamic-structural design optimization. The computation burden problem emerged and was alleviated by the global sensitivity equation technique and a sequential approximate optimization technique. Studies also conducted on applying mathematical optimization to physical problems. They focus on problem formulations and optimization algorithms in the structural design domain. Complex system decomposition and computation issues also began to appear.

During the decade 1990-2000, a vast amount of research was concentrated on reducing computational cost. Haftka [176] improved effectiveness by using perturbation methods for sensitivity calculation and using approximate optimization techniques. He reviewed MDO architectures and computation costs of available techniques in 1992, and focused on

the trade-offs in the use of MDO architecture [177]. The effect of the topology of the interaction among disciplines is a key factor in the choice of analysis, sensitivity and optimization methods. In the same year, Consoli [178] proposed a system sensitivity analysis and a decomposition for non-hierarchic MDO problem for the same purpose. A year later, Sobieszczanski-Sobieski [166] specified seven components that form the MDO: Design-oriented analysis, approximation concept, system mathematical modelling, decomposition, design space search, optimization procedure, human interface. For MDO problem formulations, Cramer et al. [179] identified three main groups: All-At-Once (AAO), Individual Discipline Feasible (IDF), and Multidisciplinary Feasible (MDF). The influences of discipline/multi-discipline feasibility for various formulations were addressed. Depending on the problem formulation, proper single-level optimization algorithms were discussed. Later, Kroo [180] provided an overview of monolithic and distributed architectures demonstrated with analysis structures and collaborative decompositions. The terms 'monolithic and distributed' are the same as 'single and multi-level'. Kroo's study is included in the proceedings edited by Alexandrov and Hussaini
[181] on MDO progress up to date in the early 90s. The proceedings have also collected analyses from Alexandrov for multilevel architectures [182]. That same year in 1995, Wakayama and Kroo [183] presented an application on a wing planform in minimizing drag while satisfying structural weight and aerodynamic lift constraints. Balling and Sobieszczanski-Sobieski categorized six problem formulations being applied on non-hierarchically coupled systems, for which the disciplinary analyses are directly coupled with each other without the interference of the parent disciplines. Both single-level approaches versus multi-level approaches and Simultaneous Analysis and Design (SAND) versus Nested Analysis and Design (NAND) are considered [184]. Both Cramer et al., Balling and Sobieszczanski-Sobieski have mentioned the consideration of computation cost relevant to each type of problem formulations [184]. The former mainly focused on single level approaches, while the latter covered both single and multi-level approaches. Sobiesczanski-Sobieski and Haftka have investigated the recent development of MDO from the perspective of the seven MDO components [166]. They emphasized the decomposition approaches for MDO involving Concurrent Subspace Optimization (CSSO)and Collaborative Optimization (CO) [180][185][186][187][188][189][190]. In 1998, on the basis of the seven MDO components from Sobiesczanski-Sobieski [166] and Haftka [160], Giesing and Barthelemy [54] proposed four categories of the MDO elements. They are Design Formulations & Solutions, Analysis Capabilities & Approximations, Information Management & Processing, Management & Cultural Implementation. The needs of MDO from industry are emphasized in each category. In addition to the general surveys and classifications, Zang and Green [191] identified the lack of summary in MDO techniques for fluid dynamics research. Therefore, They provided a comprehensive review of MDO elements especially for studies of aerodynamic discipline integrated MDO. They have also critically addressed issues and strategies for application development. Various decomposition approaches were mentioned, the Bi-level Integrated Systems Synthesis (BLISS) was added to most of the aforementioned ones.

The MDO framework continues to evolve. Batill et al. have focused on response surfaces approximations using neural network [192][193] to fulfil the system target and system constraints [194]. This approach is referred to Concurrent Subspace Design (CSD), which

is an extension of SAND. Kroo and Manning have reviewed CO architectures and identified problems about large scale problems, low dimensionality coupling, special disciplinary optimization, and practical applications [195]. Alexandrov and Lewis have proposed a modular approach, referring to an autonomous sensitivity calculation, for MDO problem formulations [196]. During this most recent period, various problem formulations have been developed. The understanding and classification of the problem formulation have become more comprehensive. Applications in aerodynamic and structural optimization as well as structures and control optimization are being extensively exercised. Besides the continuous challenge on computation expenses, the level of fidelity has become another research interest. For instance, Chen et al. [197] have improved Computational Fluid Dynamics (CFD) using an integrated Transonic Equivalent Strip (TES) method with modal-based aerodynamic-influence-coefficient, which is then integrated with Finite Element Method (FEM) analysis for MDO. This has been proved to be computationally efficient compared to the usual CFD.

Carrying on previous research directions, recent developments in MDO have been focused on the following: problem formulation, optimization algorithms, computational efficiency, analysis fidelity, and engineering applications. Problem complexity and computation burden have greatly increased due to the integration of more disciplines and higher fidelity analyses. In 2004, Piperni et al. [198] have integrated in-house developed aerodynamic, structure, weight, en route fuel burn prediction, and static aeroelastic deformation analyses for conceptual and preliminary wing design optimization. Both low- and high- fidelity aerodynamic and structure models are included in the overall optimization loop. Lin [199] enhanced CO by replacing consistency equality constraints to avoid the convergence difficulties caused by Lagrange multipliers in the Karush–Kuhn–Tucker (KKT) necessary conditions. A review from Arora and Wang [200] focused on problem formulations in structural and control system. The mathematical formulations and gradient evaluations are studied. Weck et al. [201] and Agte et al. [202] extracted individuals specialized in MDO theory, architecture, applications, companies, and projects from 2006 European-US MDO Colloquium. They outlined the timeline of MDO relevant developments, compared four decomposition architectures (BLISS, CO, Analytical Target Cascading (ATC), and CSSO), and listed an overview of software tools. Groups of industry applications were also summarized, which lead to the identification of MDO limitations concerning the analysis composite component, the minimization of manufacturing cost and the optimization of life cycle performance. In addition, they suggested future developments to include educational evolution, concurrent computing, and horizontal/vertical growth. Similar to the reviews in the 1990s, Tosserams [203][204] surveyed available decomposition methods and classified them into nested and alternating formulations. Kang et al. [205] reviewed structural optimization under dynamic loads. They discussed three aspects: the treatment of time-dependent constraints (direct method and transformation method), sensitivity calculation (direct differentiation and adjoint variable method) and problem approximation (equivalent static load). Araújo et al. [206] proposed a dynamic optimization approach to maximize modal loss factor in a passive damping sandwich plate. The approach proved well performed and more efficient than the ABAQUS finite element model associated with genetic algorithm approach. In order to improve MDO applications, Balachandran and Guenov [207] adopted process management knowledge to support an initiative that can dynamically derive an effective and efficient computational

workflow for complex system optimization. Guo and Du [208] observed the existence of both random and interval variables in a multidisciplinary system; they proposed a framework to deal with probabilistic and interval analyses for those variables sequentially and effectively.

In 2011, Mastroddi et al. [209] built an intermediate approach by mixing the use of a high-fidelity numerical model for structures, aerodynamics disciplines, and a low-fidelity analytical model for aero elasticity analysis to reduce the computational burden. This approach was applied on a wing structure design case. It addressed the need for computational efficiency and coupled high-fidelity analysis. Neufeld [210] improved the reliability of general MDO by evaluating the discrepancies associated with low-fidelity analyses based on historical data, so that the solution is more reliable to be used in further high fidelity analyses. At the same time, Urscache et al. [211] constructed an adaptive structure for morphing configurations that aims to enhance roll while minimizing drag via multi-objective optimization using a surrogate model. Henderson et al. [212] considered aircraft environment impact by minimizing CO2 emissions, a function of fuel burn and landing-take-off NOx. Augmented Lagrangian particle swarm optimization was used for the single objective optimization of DOC, mission fuel burn and landing-takeoff NOx emission respectively, while the genetic algorithm is employed for multi-objective optimization of DOC and mission fuel burn. Smith et al. [213] applied multi-objective optimization to a morphing wing system using a conventional commercial passenger jet as a baseline, where both the ranking and sorting Pareto frontier and game theory methods were employed. In 2013, Piperni et al. [20] provided an overview of MDO development in industry after more than ten years' research. In particular, they focused on the multilevel framework. Similar to the process of product design, they divided MDO analyses into increased fidelity levels, which are plugged into the conceptual and preliminary design respectively. The emphasized the economic aspect in optimization studies. Martins and Lambe [161] supplied a comprehensive review of MDO. The assumed that the objective and constraints are differentiable, which assures that the KKT optimality conditions (necessary conditions) are satisfied. They categorized architecture in two main classes: monolithic and distributed. The former composes various disciplinary models into a single optimization problem, while the latter decomposes the overall optimization problem into sub-problems with interdependent data transmission.

Recent MDO research has a diverse orientation. There are reviews from specific domains. Deaton and Grandhi [214] conducted a survey on structural and multidisciplinary topology optimization. They classified four types of topology optimization for continuum structures: density-based methods, hard-kill methods, boundary variation methods, and biology-inspired methods. Viana et al. [215] reviewed the evolution of the metamodel technique in MDO using multi-fidelity approximation and design space exploration/visualization. Some research focuses on dynamic systems. An example is Allison and Heber [216], who addressed MDO for engineering systems with variable system status. They discussed four elements, including multidisciplinary analysis, optimal physical design, optimal control, and integrated methods are discussed. They proposed synergized physical- and control- system analyses for system optimal design to overcome the organizational and technical issues during integration. Some keep reducing computational cost. Mariens et al. [217] developed a quasi-three-dimensional aerodynamic solver including a local and a global optimization method. It is validated with accurate results under low computational cost. Hoburg and Abbeel [218] used

geometric programming to solve a specialized type of convex optimization problem. This method is restricted to specific problem formulations, but is extremely powerful on computational efficiency and robust global solution. Paiva et al. [219] produced an architecture for wing design employing a Kriging surrogate model for robustness/reliability optimization. It takes probability constraints into consideration while retaining reasonable computational time. Some research has focused on multi-fidelity, multi-phase, and multi-objective optimizations. Elham et al. [220] decomposed wing-planform optimization and wing-aerofoil shapes optimization into top level and sub level separately, where the top-level optimizer controls the consistency of design variables and the sub level embraces a series of optimizations in accordance with the aerofoil shapes in various span wise positions. This bi-level optimization allows the use of simple and fast two-dimensional analyses. Shirley et al. [221] conducted the trade-off studies for the weight and lift/drag ratio of a cantilever, strut-braced and truss-braced wing aircraft illustrated by pseudo-Pareto fronts.

2.4.3. STATE-OF-THE-ART

In this section, a general review of current MDO is introduced from the four proposed aspects, viz., architecture, disciplinary analysis, optimization algorithms, and evaluations and benchmarks. Most recent literature is grouped to shape the up-to-date status, which also unveils the trend of the development.

Recently, Martin and Lambe [161] summarized a broad range of MDO **architecture** for single objective continuous optimization problems. A comprehensive classification, which contains monolithic and distributed architectures, is presented in a unified format (see Figure 2.8). This categorization can be traced back to the division of single and multi-level approaches as well as hierarchic and non-hierarchic systems [162]. It is summarized on the other reviews of MDO development up to that date [20][166][190][196], elaborations of specific problem formulations [184][204], and summaries from practices such as structural optimization [168], fluid dynamics [191], and preliminary design [180]. Multi-objective optimization has become a booming area of research, since it provides a set of feasible solutions for multi-conflict objectives while the decision maker determines the optimum based on one's preferences [186][211][221]. Similarly, multi-level, multi-fidelity optimization and/or optimization considering performance at multi-stages/phases/points are stimulated by their capability of considering system level optimization [220][222]. In addition, reliability involved optimizations are increasingly studied, since it improved the confidence in the optimum by providing relevant probabilities [208][210][215][219]. In terms of **disciplinary analysis**, the involvement of more disciplines is encouraged. Brackett et al. [170] have proposed structural and acoustical involved optimization, while Anderson et al. [212] have considered the inclusion of emissions in aircraft MDO. Except structure, aerodynamic, weight and aeroelastic, subjects such as fuel burn, manufacturing, emission, acoustic and cost have been addressed in the literature. In particular, Section 2.4.5 emphasizes the inclusion of cost as a discipline in MDO. A comprehensive summary of optimization algorithms can be found in Rao [223], and Wright and Robinson [224]. The former focuses on the numerical algorithm for optimization. The latter includes both gradient-based methods and gradient-free methods for engineering optimization. Advanced approximation techniques, such as the Kriging model [215][225] and response surface/surrogate model [226][227], are developed

to achieve computational effectiveness, In addition to continuously refined sensitivity analysis, which is discussed in Section 2.4.6, derivative-free optimization algorithms have been increasingly adopted due to their advantages, such as to provide a global optimum and to optimize problems with discrete design parameters. Some of the well-known methods are trust region, pattern search, genetic and evolutionary algorithm [228], particle swarm optimization [229],and simulated annealing [230][231]. The algorithms and available optimization solvers have been summarized and categorized by Rios and Sahinidis [232], who benchmarked and compared the search pattern, computational effectiveness and optimization result of each solver on six test problems in various scales.

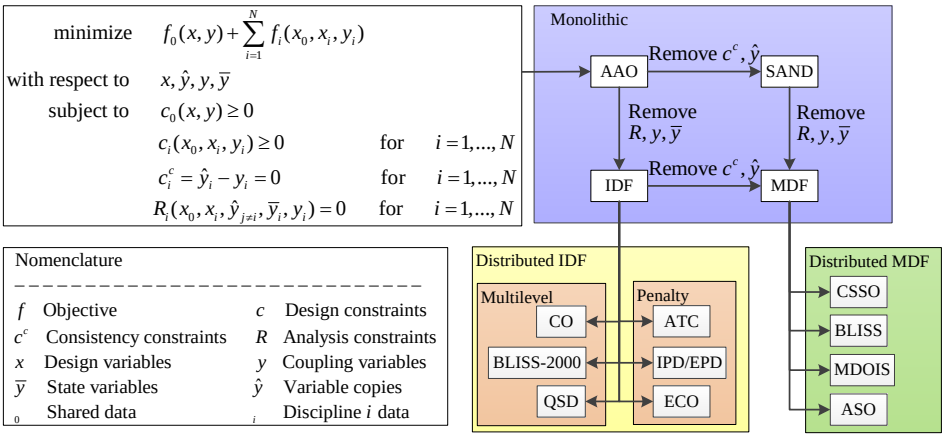


Figure 2.8: Classification of MDO architectures [161]

There is always a need to provide a guidance on choosing a proper architecture for a practical problem. Accordingly, several **evaluations and benchmarks** are available: Alexandrov and Kodiyalam [187][190] presented the initial results of MDO evaluations. Rois and Sahinidis [232][233] have focused on the comparison of derive-free optimizations. Castellini et al. [233] have developed a method to assess MDO model accuracy on the system level for launch vehicle design. Methods are proposed to quantitatively evaluate the performance of MDO architectures. Tedford and Martins [234] have made an effort to compare the available MDO architectures via PyACDT, which is a software framework developed in Python. A suit of four problems is solved by MDF, IDF, SAND, CO, and CSSO respectively, where their performances are compared in the following perspectives: computational performances of sensitivity calculations, errors in optimal design variables and convergence histories. As one of the key performance indicators, the computational cost is constantly stressed.

Applications tend to favour aerodynamic shape optimizations [235][236][237] and new aircraft concept optimizations [222][238][239]. The applicability of the methods is illustrated by Roy et al. [240]. Additionally, techniques of data mining and KBE have been adopted to improve data storage, process automation and decision making in MDO applications [207][221][241][242]. The adoption of KBE techniques is further illustrated in Section 2.4.4.

Managerial improvements are mainly made by integrating the established MDO archi-

tecture and traditional design process with the support of both project coordinators and disciplinary experts [20][167][207].

2.4.4. KBE SUPPORTED MDO

Price et al. [242] have proposed a variable control method that employs an expert system with rule base and data mining capability to manage the bounds on a common design variable vector. Chiba et al. [243] have recommended a design informatics approach combining multi-objective optimization and data mining. Bombardier has employed KBE based tools on the low fidelity level to provide a reference for new configurations, that has proved to be time-efficient [141]. A way of using KBE tools supporting new concept development is proposed: the reference concept provided by KBE tools is used as a baseline. Any new design deviated from the historical KB can then be measured after assuring those deviations are understood and validated in terms of underlying physical mechanisms. Therefore, it enables the exploration of future concepts while improved the traceability [141]. Berends and Van Tooren [241] have proposed a multi-agent task environment framework, which models the MDO application based on agents, humans, and the collaborations among them.

Current MDO tends to encourage the involvement of AI techniques, such as expert systems, KBE, and agent-based modelling. KBE assisted MDO specifically addresses process automation, and considers the MDO organizational arrangement as well as the combined design, analysis and optimization process.

2.4.5. COST INTEGRATED MDO

Cost optimization studies, which regard aircraft component cost as an optimization objective or as a part of an optimization objective, have been documented in recent research. Giesing [163] has emphasized that the quantification of manufacturing and maintenance cost is not only based on weight but also associated with the part count and complexity. Castagne [95] has proposed a method to optimize the aircraft design concept considering the SV parameter. This parameter is derived according to the value of flight revenue, flight operating cost, aircraft production cost and development cost. The optimum design can be obtained when the SV parameter approaches its maximum. Comparing this method with the conventional optimization methods, which only focus on minimizing the aircraft weight, the SV value involves both the impacts of aircraft cost and profit [96]. Curran et al. [148] have developed a method to optimize the DOC for an aircraft fuselage skin panel. A similar approach was implemented by Kaufman[244], who has combined manufacturing cost and weight penalty into the calculation of the DOC . The integrated DOC function is then formulated as the objective. An optimal design point, which differs from the aforementioned one, is achieved when the DOC reached its minimum. This method integrates the influence of aircraft cost and weight. Similarly, Gantois and Morris [245] have established an optimization tool for a large civil airliner wing. They used weight, cost and drag information to evaluate the aircraft DOC. An optimum design was shifted again compared with the results according to weight optimization [132][245]. The optimization process was adopted through a hierarchical system in which DOC comprised the top level. In summary, the optimum changes within the design space by considering different aspects of design problems. It provides designers with more economical design options by emphasizing cost performances as the

optimization objectives. Johnson [246] is perhaps the earliest among the others who have interests in optimizing LCC. A comparison has been made between the results of MTOGW, fuel-burn weight, acquisition cost and DOC. Giesing and Wakayama [247] have developed a DOC objective function included the influence of structural area in a normalized form, which is then utilized for a coupled aerodynamic and structural optimization of a 225 passenger medium range aircraft. Price et al. [242] set the system level objective as DOC measured via the drag, lift, weight with penalty coefficient and the annual capital. Methods involve expert system are benchmarked with traditional MDO architectures such as MDF, CO, and BLISS. It is claimed the rule-based approach is advanced in organizational integration, while is not guaranteed for convergence.

Examples of MDO integrating independent analysis and design activities to improve engineering system performance and reduce development time and costs are illustrated [54][166] [202][248][249]. Some papers address the importance autonomous and semiautonomous dynamic systems across several domains, including manufacturing and its impact on economic competitiveness [250][251].

In summary, the optimum changes within the design space according to different objective functions involving cost. It provides designers with more economical design options by considering cost into the optimizing objective function.

2.4.6. SENSITIVITY ANALYSIS IN MDO

The design factors are highly inter-connected, while in what degree the design factors influence the output is often neglected. Sensitivity Analysis (SA) is applied to enable this capability. Instead of focusing on all factors, the cost driving parameters are identified.

The sensitivity analysis method can be traced back to research conducted by Sobiezanski-Sobieski et al. [252][253][254][255]. They have proposed sensitivity equations derived from Lagrange multiplier equations or from an extreme condition of the penalty function. The derivatives obtained are the optimal objective function/design variables with respect to the constant design parameters. They are applicable to direct search method and sequential unconstraint optimization algorithm. This method can avoid computation cost and accuracy issues caused by finite difference approximation approach. Later, two sensitivity methods, based on implicit function theorem acting on residuals of governing equations and local sensitivity derivatives of each part in the system respectively, are developed. The sensitivity derivatives are the internally coupled system with respect to independent variables, so-called global sensitivity analysis, which addresses the answer of 'what if' design questions. Then they have summarized the quantitative evaluation of sensitivity would be the derivative of the state variable with respect to the input variables [162]. Similarly, other than focusing on finite-difference approximation, Cramer et al. [55] have summarised two alternative approaches to obtaining derivatives: automatic differentiation; analytical approaches using sensitivity equations, implicit differentiation and adjoint equation. They discussed the derivative required for MDO in terms of problem formulations such as MDF, IDF and AAO up to that state. In 1994, Tortorelli and Michaleris [256] summarized first- and second-order sensitivities in the early 90s with a simple example of the two-degree-of-freedom spring system.

Among those methods, many have been applied in aerospace applications. Newman [257]

have reviewed sensitivity analysis in steady aerodynamic shape optimization. Abdel-Khalik [258] have presented an adjoint-based sensitivity analysis which can determine the minimum number of adjoint evaluations and treat each component as a black-box. Martins and Hwang [259] have summarized derivative computing methods in a multidisciplinary system.

In summary, properties of common SA approaches are shown. The computation cost of finite differentiation method grows linearly with the number of design variables. The accuracy is influenced by the magnitude of the design perturbation (Δx). The result is influenced by truncation error if the design perturbation is too large; while it is affected by the round-off error if the design perturbation is too small. If the analysis is iterative, finite differentiation executed at a nominal situation may produce meaningless results [256][260][261]. A Quasi-analytical approach based on Implicit Function Theorem normally benefits from effective computations. It has two versions: direct sensitivity derivatives of all the analysis unknowns, which is also called automatic differentiation, and adjoint method derivatives of a subset of the unknowns [262][263]. Automatic differentiation avoids new coding because they do not need additional matrix assemblies and decompositions while under reasonable computation effort [256][264]. Since it follows the chain rule of derivative, the results are exact. The adjoint method solves the adjoint problem for each state variables. Normally, the number of state variables are less than the number of design variables, therefore, the sensitivity can be effectively computed with exact results [256].

2.5. SYNTHESIS AND CONCLUSIONS

As the competition between aircraft types is closely related to the LCC performance. Any design alternation will potentially lead to LCC changes. Correspondingly, and any variation of the LCC major cost types will also influence the decision making. Therefore, it is essential to involve LCC estimation and optimization as a dedicated analysis module embedded in a design and optimization framework, which employs the support of KBE techniques to improve the implementation efficiency and achieve product cost reduction. However, challenges remain in terms of the inclusion of LCC estimation into the design process, the LCC analysis itself and the involvement of LCC in MDO analysis. In this section, those challenges are identified, which also leads to a clear positioning of the originality of the thesis.

2.5.1. CHALLENGES AND OPPORTUNITIES

2.5.1.1. CHALLENGES AND OPPORTUNITIES FOR DESIGN AND KBE

By evaluating the current aircraft design process and the involvement of disciplinary analyses, KBE techniques have been extensively developed in building the product geometries and enabling the automation between design geometry and performance analyses. It is promising for application with the performance analyses in the conceptual and preliminary design phase, especially on LCC analysis. A number of attempts have been made to develop an integrated design, however, challenges still exist in the design process, design-discipline integration and disciplinary analysis, specifically in the costing involved design and analysis process.

During the **design process**, the analyses needed can be different based on various functions of aircraft components. This indicates a need for a generalized yet flexible design

framework that can be customized by plugging in/out necessary analysis modules. Moreover, a design process includes both routine and creative activities. Routine activities can be extracted and automated, while creative activities need human intervention. However, it is challenging to convert the routine activities into design automation. In addition, although the design application based on the supportive techniques such as KBE is specialized for its accuracy and efficiency, a proper qualitative evaluation should be established and validated to provide a strong justification.

In order to explore the design space when the design freedom is still high, the level of detail of the analyses is moving forward to the early design phase. This means that more disciplines, higher computation capacities as well as longer time range need to be analysed in conceptual / preliminary design stage. However, **the KBE assisted design-cost integration**, which is one of the key enablers, still lacks focus. Firstly, A central product model, comprising a 3D representation and the product attributes, need to be developed in an integrated design environment. It should have the capability of being extended and adapted for disciplinary analyses. However, because of lack of process automation, the design and costing modules are uncoupled. In particular, the disconnection between product geometries and cost estimations often leads to complicated and troublesome costing process. Secondly, some models incorporate fixed production processes for cost estimation. When considering alternative design concepts, e.g., for changes of geometric sizes and material types, the production process will be updated correspondingly. In such cases, the cost estimation model may not be applicable anymore. Therefore, the reusability of the cost estimation is limited when the design varies. Thirdly, the link between cost breakdown and product breakdown, which constitutes the core relation between cost and design, is typically not clearly defined and implemented [265]. Consequently, it is not able to distribute the estimated costs on specific product structures. Therefore, due to the vague connection between a product and the evaluated cost, the traceability of the cost estimation is low. Fourth, a large amount of the design automation is facilitated by knowledge stored in the design system. Therefore, it requires a knowledge management strategy corresponding to the design process. While in cost involved design process, those knowledge is still very little, let along the formalization and organization of them.

LCC has been considered in SE, CE, and value driven design. However, it is mainly a qualitative approach used for project management purpose other than an analytical approach employed for design and performance analysis in practice. SE is driven by requirement analysis, and not really addresses the practical approach and method for integration and analysis. The LCC considered in SE practice is often highly conceptual [37][38][41]. Some analysis only provides estimation methods for one or two cost types of the life cycle cost [121][265]. Some analysis only provides high-level cost aggregation other than analytical cost estimation [19][131]. Many of them have not really linked the life cycle cost estimation with the causal parameters including geometric sizes, material types and life cycle process steps in an analytical way [151][152]. This indicates a lack of analytical method which identifies the product properties as the cost driving parameters. Although there is research which has developed analytical cost estimation, while only one cost type is often addressed [265][125], e.g. manufacturing cost or operating cost, a consistent method evaluating all cost types of the LCC is missing. By reviewing the definitions related to the cost, effectiveness and cost-

effectiveness in SE [266], there is a lack of consistency in cost integration. For different systems, the cost-effectiveness is different; even for the same system, distinct cost-effectiveness can be introduced. Before addressing the challenge of integrating the cost-effectiveness of the sub-system level and the system level. An objective proposal of the cost-effectiveness should be evaluated first, however, SE does not provide a guideline on this. In terms of KBE assisted cost analysis, one of the challenges is the loose geometry-cost coupling, which leads to rough estimates. Cost estimations using parametric calculation methods often employ geometric attributes as the cost driving parameters, which requires a tight connection between geometry and cost to improve the accuracy. Another challenge is caused by the labour intensive and time consuming cost estimation processes. Data and calculations used for cost analysis are mostly stored in extensive spreadsheets; often, a macro programming language is used to facilitate cost calculations [144]. In this way, a significant amount of data needs to be imported manually and the knowledge of calculation is only available for the cost engineers who have developed the spreadsheets [267].

2.5.1.2. CHALLENGES AND OPPORTUNITIES FOR LCC ANALYSIS

After reviewing the aircraft LCC analysis, more systematic LCC estimation framework is necessary. Accordingly, it also requires an LCC application corresponding to the framework with a proper and consistent cost estimation method and fidelity level. In addition, the cost driving parameters for the whole LCC as well as for LCC items should be clearly defined. Moreover, due to little consideration on the interaction between product design, i.e., the product configuration, material type, and process steps (with innovative technology), and its cost properties in a life cycle. Challenges arise when conducting design optimization studies. In more detail, challenges in both the LCC estimation and the LCC optimization are elaborated.

It is found that LCC estimation **frameworks** are rarely generalized and presented in the literature. Mostly because they are case-specific and non-reusable. An integrated and systematic architecture for LCC analysis is still missing.

Furthermore, challenges in estimation methods are considered. First, LCC estimation methods are mostly developed specifically for certain LCC types such as production cost and/or O&M cost. However, there is a lack of complete LCC **estimation methods**. Second, categorizations of cost estimation methods are normally based on one aspect of the methods and it can only provide a rough guideline for cost estimation applications. For example, if the analytical method is chosen from the classification of conceptual, analytical and heuristic types, it only indicates a general calculation method, while the estimation process, the logic of the model and the assistant techniques are still too vague for the cost engineers. Third, statistical analyses cannot unveil the relation between the aircraft design properties and the costs since it is based on historical data, which can be used to predict a general trend of revenue and expenses but cannot illustrate the link between the cost drivers and cost values. Fourth, due to the availability of the input parameters and their levels of detail, different cost estimation methods suitable for different cost types vary on the basis data availability. It would often cause obstacles if the detailed estimation method is chosen for evaluating s specific cost type while only limited data is available.

In addition, it is challenging to develop an **LCC application as a design/decision support tool**. From one aspect, most cost estimation tools are independent of the design environ-

ment. Cost properties are critical for trade-off studies of for a design decision making, which includes the selection of design concept (e.g. geometric configuration, structure) and for resources (e.g. materials, manufacturing techniques) chosen. However, a cost estimation tool independent to design and optimization would have the limited capability on those studies. From another aspect, the fidelity level of the LCC estimation is restricted by specific design phases: On the conceptual design stage, limited data are available for cost estimation. Besides, In addition to the lack of communication among cost engineers, manufacturing engineers and design engineers in practice. Therefore, the fidelity level of the analysis is lowered. Besides, many costing tools are developed for accounting purpose, which is only available for project manager rather than the designers, airlines and cost engineers who are relevant to the whole life cycle process. Subsequently, this introduces barriers for cost control.

2.5.1.3. CHALLENGES AND OPPORTUNITIES FOR MDO

Based on the extensive review, challenges are found from the four aspects of MDO. In particular, challenges for cost involved MDO are stressed. Firstly, since the complex problem with sophisticated optimization algorithms is to avoid the counter-productive problem or over simplification [172], it is ought to solve complex problems using integrated and hybrid architecture with efficient communication techniques. Problems involve multi-fidelities, multi-objectives (or multi-points), and multi-phases (or multi-stages) which need to be recognized and optimized. In addition, the influence of problem scale and/or system dynamics need to be addressed explicitly, which requires innovative solutions [172][216]. Disciplines should be extended to include not only physic disciplines but also non-physic disciplines such as environment, economy, and operational service issues. Existing disciplinary analysis software/applications are preferred in the MDO architectures and to be treated as black boxes [263]. Interactions between system and discipline(s) need to be emphasized in order to clearly define the variables which are output from one discipline analysis while also input (or transition data) to other discipline analysis. This clearly defines the interdependence between variables and dependent variables in both objective and constraints functions within each discipline [263][268]. It is still a challenging to develop optimization algorithms which achieve global optima for problems with a large number of design variables and constraints [20]. Accordingly, efficient global sensitivity analysis is recommended. In addition, the discrete optimization algorithm has the possibility to be integrated into a system for discipline flexibility [53].

Secondly, challenges exist in two aspects specific to **evaluation**. On the one hand, the MDO committee is continuously working on improving the optimization performance such as computation cost reduction and accuracy enhancement. The MDO time can consume much more than the sum of that for the single discipline analyses and optimizations [166]. There is always a trade-off between computation cost and accuracy (the level of fidelity). It is recommended to either condense data exchange by unifying or merging analysis modules or to combine low/high-fidelity analysis in a system [53]. On the other hand, it encourages MDO engineers to develop comprehensive methodologies to evaluate and benchmark optimization architectures. Unified numerical evaluation is wanted to assess formulas and parameters of a suite of standard test problems with sufficient fidelity and complexity and/or to determine the most suitable and efficient architecture for a given problem or a class of

problems [53] [161][172][234].This capability should also be able to be applied to a new architecture.

Thirdly, the MDO application ought to be improved, where automation, design space visualization and knowledge management are often addressed. Automated analysis and optimization are enhanced by using engineering techniques like KBE, data mining and decision making, etc. Those engineering design processes are then needed for the integration of current computing technologies [194]. Besides, considering current engineering organization, it is necessary to establish a collaborative working environment for specialists with disparate expertise. The improvement of the product development process with human participation should also be incorporated in the MDO application, so that the innovation for a new design would not be negatively affected [20]. Corresponding to the growth of MDO problem dimension, difficulties emerge in design-space sampling and visualization strategy [215].

Last, from the **management** perspective, it is challenged to consider human interference in organizing the MDO system, and effective organizational structure is required. It should involve human factors, data exchange, code synthesis, etc. [161][166][241].

Particularly for MDO cost performance, there are few applications that show this improvement on the component level of detail. The main issue is the lack of cost analysis for components because limited data for parts and assemblies is available in the conceptual design phase. Moreover, when detailed data on component variables for cost-oriented MDO is available, the optimization computation is normally intensive and requires substantial computation cost, even for a limited set of components let alone the bottom-up analysis for a whole aircraft.

2.5.2. ORIGINALITY OF THE THESIS RESEARCH

In general, the research emphasizes the integration of KBE, LCC, and optimization in a unified design and optimization framework. It suggests to push the conceptual/preliminary design in more detail and to be more proactive and long-sighted, especially to bring LCC analysis into the early design stage; in another word, to add life cycle analysis into the conceptual/preliminary design phase to better access the concept in its lifespan. This would provide a strong foundation for decision making. It would improve the analysis efficiency by strategically applying KBE for the aircraft life cycle analysis, and it encourages the application of KBE not only in the conceptual design stage but also in the preliminary design and detailed design phase.

Innovative strategies are employed to connect the design and performance analysis including optimizations. Originality is also highlighted over the three aspects. By adopting KBE techniques, Cost Primitives (CPs) can be developed for LCC analysis. The product geometry (design) is transformed to be fed into cost estimations of LCC major cost types including RDT&E, production, O&M, and D&R costs. For LCC estimation, for the first time the link is built directly between design parameters and maintenance cost. In addition, the LCC analysis is applied on the level of component detail. From an optimization perspective, it realises the integration of structure analysis and LCC major cost types into an MDO framework.

2.5.2.1. ORIGINALITY FOR AIRCRAFT DESIGN AND KBE

In accordance with the challenges identified in the previous section, the following improvements have been made to integrate LCC into the design process and to implement KBE techniques for the LCC analysis.

In order to demonstrate an integrated **design process**, the DEE framework is adopted to be the framework controlling the design system. This is a standardized yet customizable framework involving repetitive activities in the design process while still providing the design freedom for designers. Furthermore, the transfer from the extraction of the routine knowledge to the use of design automation is covered by the KBE techniques embedded in the DEE. Additionally, a qualitative evaluation has been applied on the KBE application developed. It is found that the proposed approach accelerates the integrated design and analysis process when the KB is ready to use. Practices in industry for the cost estimation of a complex component need weeks to finish, while when the KB is available, this approach is immediate.

Responding to issues on **KBE assisted design-cost integration**, the LCC analysis is integrated into the MDO framework by considering both high-level and detail-level cost estimations. The supportive capabilities of KBE techniques in terms of the design-cost integration and cost analysis are addressed. First, the product geometry and property needed for each of the life cycle processes and further for LCC analysis are defined. This refers to the development of a standard description for an aircraft or aircraft component model and the development of transforming functions for model conversions from the general product model to disciplinary model geometry, so that the LCC estimation based on the disciplinary model properties can be automatically performed. Second, to enable the repeatability and generalization, CPs are created to integrate part families with desired cost type and corresponding CERs work as building blocks for the total cost. They are recognized as basic elements of cost-related views and are applicable to any products associated with the same CPs. Each CP is approachable and reproducible. Third, in order to improve the traceability of the cost evaluation process, the PBS and CBS are generated and integrated. This approach constructs the topology of the cost distribution. In addition to data laid in each CP, it clearly records the causality between a product and its cost. Specifically, the cost estimation should be integrated into the design stage and the cost indicator is ought to be utilized for design optimizations. Fourthly, the data and their relations for the design-cost integration have been extracted, formalized, stored and utilized.

In regard to the challenges in **KBE assisted cost analysis**,a disciplinary view for different cost analysis in a life cycle is developed to establish the coupling between the product geometry and the cost estimation. For example, a production view is generated for production cost analysis. The geometric segmentation in the production view is transformed by applying geometry handling rules on the master geometry. In this way, the product and process properties required for cost estimation are stored in the production view, which is directly connected to product model so that reduces error induced by the manual process. Another challenge is addressed by the cost integration and estimation process to reduce labour and time for cost estimation. To realize the automation, CMs utilizing KB with inference mechanisms are constructed. This generates input parameters, estimation equations and output reports based on a series of operations within the analysis process, so that the effort of extracting corresponding modules from an extensive spreadsheet will be greatly reduced.

2.5.2.2. ORIGINALITY FOR LCC ANALYSIS

A scalable two-level LCC estimation methodology is built on the basis of both high-level and detail-level costing methods. The emphasis is also laid on the integration of the cost module with the aircraft geometry and life cycle processes. A method to analyse LCC using an automated modular paradigm is proposed. A cost analysis tool is developed and integrated into the design process. In summary, the main contributions of the LCC research are as follows.

An aircraft LCC **framework** is developed which contains modularized LCC cost types, transitions from high-level estimation to detail-level estimation and links between cost and the other modules. In this way, it provides a generalized framework for various study cases. Furthermore, challenges in **estimation methods** are addressed. Firstly, a complete LCC estimation method is developed. It contains the costing of RDT&E, M&A, O&M and D&R costs and the stakeholder relevant miscellaneous costs. It aims to link design and process parameters with the cost properties so that cost can be accurately and effectively evaluated. Secondly, a refined cost estimation classification is proposed. It provides a clear guideline to constructing a cost estimation using the fundamental elements from each of the following categories: the estimation process, estimation model, calculation method and assistant techniques. Thirdly, in order to reveal the relations between cost drivers and the cost values, the aircraft life cycle process is analysed. Possible cost driving parameters related to product and process steps are identified. Fourthly, a two-level cost estimation approach is proposed, which identifies separate data sets for high- level and detail-level estimations for each cost type. Preferably the cost estimation would remain at the same level of detail for each LCC major cost type. In case that a gap in detailed level cost estimation occurs for one of the four life cycle phases, an adjustment would be performed by switching to the high-level estimation, while the rest of the analysis remains at the detailed level. In this way, it bridges cost analysis between the high- level estimations and detail-level estimations.

To address the challenges in developing the **LCC application as a design/decision support tool**, the proposed aircraft LCC estimation application is incorporated into a design and optimization framework so that during design process the LCC properties could be analysed as a discipline in the MDO studies. Besides, by extracting design, material, and production knowledge, the cost estimation fidelity is improved. To provide the capability of high-fidelity cost estimation within the conceptual design phase, data and rules for detailed cost estimation are extracted and stored in the KB. It includes data and their logic relations ranging from design and production to operating from historical applications or from current implementations. Additionally, based on the level of detail the estimation method is designed for, different sets of essential cost driving parameters and CERs are identified to facilitate the cost estimations.

2.5.2.3. ORIGINALITY FOR MDO

By integrating the developed LCC analysis and analytical structural analysis into the MDO framework, the progress can be made in this research is addressed corresponding to the four facets of MDO.

First, this research employs DEE, which is a highly synthesized MDO **architecture**. It contains the central geometric model, the capability modules for disciplinary model conversion/knowledge transition, disciplinary analysis, and optimization capabilities. Within

DEE, the high-level and detail-level LCC estimations open up the possibility for multi-fidelity problem formulation, while the optimization problem can be formulated when considering various cost indicators as objectives. By involving cost properties throughout the life cycle, it adds another dimension for disciplinary analysis. Different optimization algorithms are also utilised. Second, in terms of the improvement on MDO **evaluation**. The proposed LCC methodology has considered both high-level and detail-level cost estimations. The detail-level models are established on the essential links between cost and design/process parameters, while the high-level model is mostly weight based cost estimations. The LCC can adopt both high-level and detail-level analysis for different LCC elements, so assuring the time for the optimization while trying to achieve high accuracy. However, the evaluation of the accuracy and efficiency still need more quantitative analyses. Third, using the DEE framework with the support of KBE techniques, the MDO **application** is improved by the modularization and automation mechanisms. In addition, the 'master geometry' concept encourages professionals to work collaboratively on a common product. It offers a virtual collaborative working environment. However,improvement of the MDO process human intervention and the design space visualization are not considered in this research. Fourth, since the **management** perspective of MDO is often related to top level considerations, which is not the main focus of this thesis. Only the data exchange problem is considered. Finally, cost indicators of a component can be calculated based on the proposed LCC estimation method and can be used for optimization studies.Although those indicators for a specific component might not represent physical significance, but they are eligible for cost-integrated optimizations representing the economic measures. By developing cost indicators, some of the issues on computation cost and the influence of the design/process properties are resolved.

2.5.3. CONCLUSIONS

In summary, this research focuses on the integration of LCC and design optimization with the support of KBE techniques to establish the link between the design process and the cost analysis, to construct analytical costing method based on limited data set during conceptual and preliminary design phase, and to utilize the cost estimation method to serve a generalized design optimization study where the life cycle cost is considered. From the aircraft design perspective, the LCC consideration enables the link between the aircraft design properties and cost performance. From the economic perspective, the analyses can establish the connections between aircraft cost performance and its life cycle performance in the aviation market. In this chapter, the three fundamental elements of the thesis work are reviewed. Previous finding and experiences are extracted by tracing back to the development of KBE, LCC and MDO in recent years. Then the current status and development trends are discussed, so that challenges of the three elements are analysed to identify possible contributions. Last, originality of the research is highlighted, which also contributed to the research hypothesis introduced in Chapter 1. The main contribution of this research is the integration of LCC estimation into the design and optimization framework. In design, the support of KBE techniques and LCC estimation methods are studied in detail. Less attention has been given to the evaluation of the speed of the method and the integration of human intervention into the design process.

3

METHODOLOGY OF KNOWLEDGE BASED ENGINEERING SUPPORTED DESIGN - COST INTEGRATION

In response to the aforementioned challenges in the current design process, design-cost integration, and cost analysis, this chapter proposes a comprehensive method which integrates aircraft component life cycle costing into aircraft design process using KBE techniques. According to the process meta model, the process properties can be assigned to the product. By building the link between PBS and CBS, the integration of product, process and cost is made explicit. By introducing a suite of parametrical cost estimation blocks, a generically applicable and automated cost estimation capability has been developed. This chapter is arranged as follows: based on the theory and principles of KBE-assisted design and discipline analysis introduced in Chapter 2, the assistance of KBE is extended from design to cost analysis and further to cost integrated design optimizations. The methodology and implementation of the framework integration are outlined. This is concluded by highlighting the contributions of the proposed method. The performance of this method is further verified and validated by case studies in Chapters 6 and 7.

Based on the highlighted issues existing in the design-cost integration and the engineering costing domain, a KBE-assisted method is proposed to facilitate the design-cost integration and the performance analysis and optimization concerning aircraft LCC. The integration refers to the synthesis of the design process, cost analysis and cost optimization. In Section 3.1, a generalized product–process–cost procedure is illustrated to specify when the cost analysis ought to be performed within a design process. Besides, the synthesis of design and cost is introduced. It highlights the key development of PBS and CBS integration within the DEE framework. Finally, the life cycle process view generation, which is an indispensable operation providing a discipline-specific geometry for the synthesis, is discussed with the main focus on 'integration'. In Section 3.3, the focus shifts to the cost estimation methodology development with the support of KBE techniques. The definition of cost building blocks is addressed. Three modules including pre-processing, cost estimation and post-processing are elaborated. The relevant KBE terms can be referenced by Appendix E.

3.1. KBE SUPPORTED COST ANALYSIS INTEGRATED DESIGN FRAMEWORK

A design solution should contain not only the geometric description of an optimized product but also attributes including the cost predictions. This motivates the integration of cost analysis and design process. The position where the production cost analysis is located in a design process is firstly identified. Cost analysis is bound to follow a product-process-cost procedure, as shown in Figure 3.1. This is a general procedure when a product life cycle or each of the life cycle phases is considered. It can be seen that the cost evaluation occurs after the process is scheduled, regardless of whether RDT&E cost, production cost, O&M cost or D&R cost is considered. The term 'process' can point to the design routines, production plan, operation and maintenance programme and dismantling and recycling procedure for each cost type. Moreover, a process is tightly related to the product configuration and relevant attributes. In order to provide sufficient detail for different cost estimates, the product representations may vary in terms of the geometric simplifications. Inference mechanisms are included in the process to translate the product representation into the process representation. Furthermore, the process representation also needs to be converted to a cost representation, which contains the actual cost estimations.

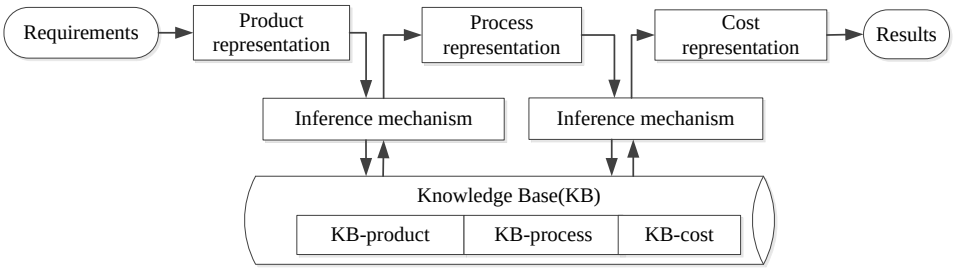


Figure 3.1: Product-process-cost procedure.

By embedding the product-process-cost procedure into the DEE framework, the design cost integration is established (as shown in Figure 3.2). Relative to production cost estimation, the following approach applies. Based on a product model (i.e., a master geometry or a product view), a parametrised manufacturable product representation is generated. This is facilitated by operations related to production geometry segmentation. As the production segmentation is produced, a PBS is generated specially for production. Subsequently, process representation including manufacturing and assembly process plans as well as relevant attributes are derived. Based on the specific product geometry, the material use and the generalized process model, detailed production process plans can be deduced from the rules and constraints of the production factory. The product representation and production process representation compose the production view. Similarly, specific views can be defined respectively for the use of RDT&E, O&M and D&R cost estimations.

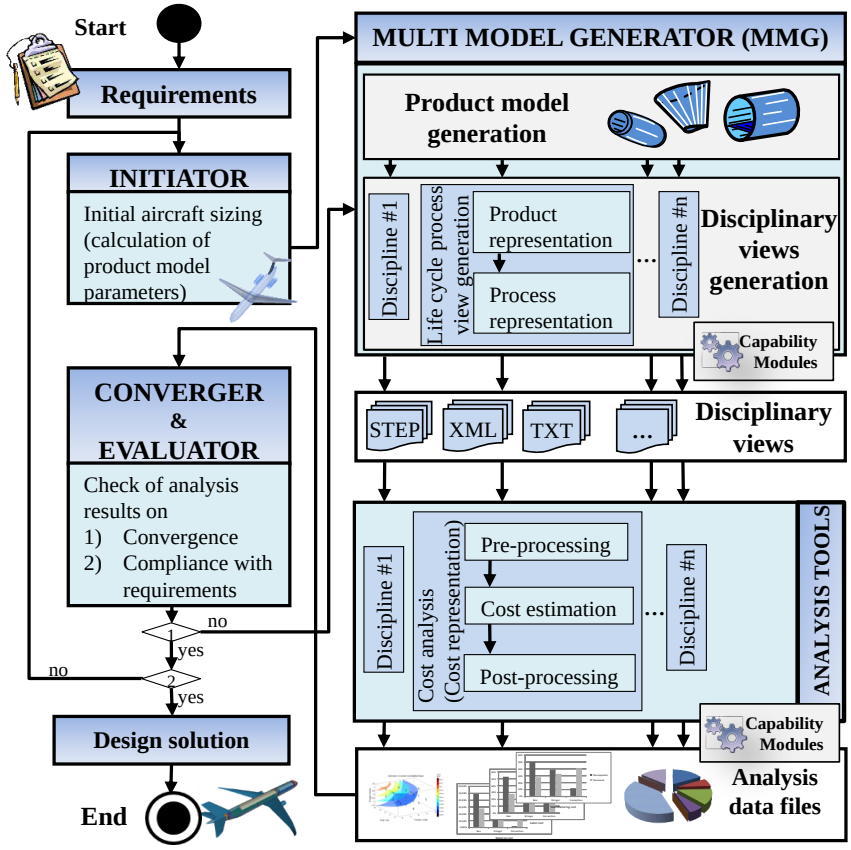


Figure 3.2: Cost integrated Design and Engineering Engine, adapted from [64]

3.2. LIFE-CYCLE-PROCESS-SPECIFIC VIEW GENERATION

The RDT&E view, production view, O&M view and D&R view all belong to the module of life cycle process view. According to the cost type needed for the LCC analysis, corresponding views are generated. The combination of the master geometry and the life cycle views formulate the MMG. The life cycle views generated from MMG are stored in a formatted data report. The data report is then provided to an in-house developed cost analysis tool, where the cost representation is produced. The cost representation refers to the cost analysis including pre-processing, cost estimation and post-processing. It is obtained by assigning attributes of each PBS object to a CBS in cost estimation. The first step produces data and rules used for cost calculation. The last step provides the formatted cost results prepared for the analysis data file. There are also data exchanges between cost analysis, weight analysis and structural analysis. Data relevant to product, process and cost are stored in the three representations. The inference mechanisms and KBs are highly intertwined within the CMs.

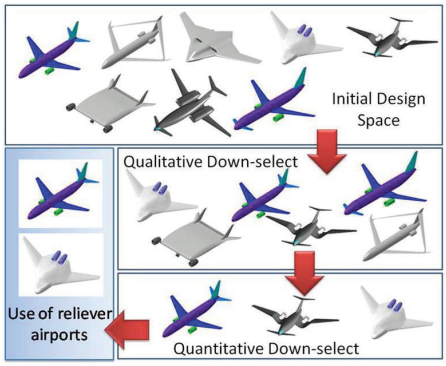
The life cycle process views, referring to the geometric representations and/or the data inputs needed for the associated cost analysis, should be generated. They are derived from the original product model but differs according to the rules and data for distinct cost types. The definition of 'view' is not only limited to an explicit geometry, but also contains the geometric, material, process and performance attributes. In order to perform the cost analysis for an aircraft life cycle, information from specific geometric segmentation other than the original master geometry is needed. In particular, the product geometry segmentation for manufacturing actually differs from that for maintenance activities. Moreover, data needed for each life cycle phase is shown clear differences. For example, the material information is needed for choosing the manufacturing method, while the aircraft cruise speed is necessary for defining the time of a flight operation. Although there are cost types which are less geometric dependent, while the process operating parameters stored in the life cycle process view are still necessary to facilitate the cost estimation capabilities at later stages.

3.2.1. RESEARCH, DEVELOPMENT, TEST AND EVALUATION (RDT&E) VIEW

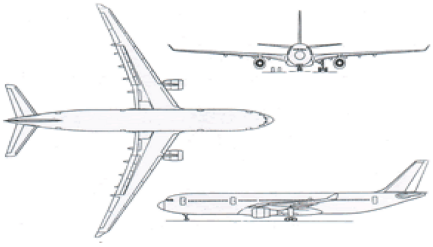
The main tasks of the RDT&E view generation are to produce the product representation and process representation of the whole design project, viz., to define the geometric control parameters, to generate the master geometries, to identify the complexity of the product, to evaluate the readiness level of the technological maturities and to allocate the time needed for delivering each milestones.

3.2.1.1. PRODUCT REPRESENTATION

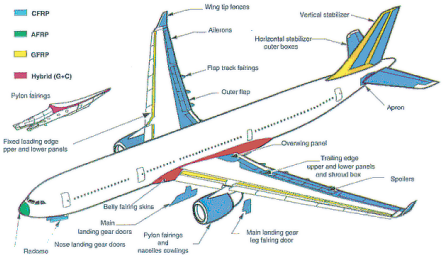
Since RDT&E is the process defining and producing the product geometry, therefore, the RDT&E product representation directly adopts the product model. Figure 3.3 illustrates the product modelling at various design stages in the aircraft design process with different design parameters available within each stage. Accordingly, the geometric control parameters, the PBS, the structural layout and the component materials are also employed.



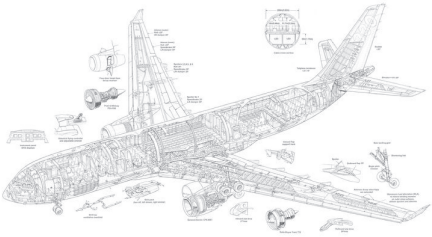
(a)



(b)



(c)



(d)

Figure 3.3: Product representation for RDT&E process:(a) Aircraft concept down selection; (b) Aircraft three perspective views; (c) Aircraft material distribution; (d)Aircraft structural configuration.(figures sources: NASA [269], Airbus [270], Flight global websites [271])

3.2.1.2. PROCESS REPRESENTATION

Next, the RDT&E process model is generated based on the generalized RDT&E procedure while the specific product properties and the particular ODM work flow are also considered. The product properties, such as the complexity, are also extracted for the use of cost analysis. The RDT&E view is then constructed by involving both the product model and RDT&E process model. A complete RDT&E model, shown in Figure 3.4, contains activities and iterations in a very detailed work flow. It starts with identifying the need and opportunities in current market situations. Standards and design requirements are then established. The actual design exercise starts from the conceptual design phase. Based on an LOR, designers propose promising aircraft concepts, followed by a series of feasibility verification. According to the performance goals, the designers are required to generate potential competing concepts, iterations of disciplinary analysis, performance evaluation and trade-off studies for those promising concepts are performed, a baseline configuration is chosen. The output of the conceptual design is a three views' drawing of the baseline aircraft design with performance indices. Next, the concept is brought to preliminary disciplinary analysis, evaluation and optimization studies. The deliverable of the preliminary design is a 3-D drawing of the current

concept with sized components. The size of the baseline concept is refined while the aircraft level configuration is frozen at the end of the preliminary design stage. Only a few changes on the components are still possible. Later, the detailed design phase involves the analysis and optimization iterations from the global level of the whole aircraft to the local level of each part. Systems are also developed. The output is the detailed production drawings, finalized aircraft specifications and performance properties. Afterwards, the initial production of the prototype is conducted. Tests for components and systems are conducted along with the prototype production. Once the ground tests are completed, the prototype begins to be prepared for the 1st flight and a series of flight tests. When the aircraft is validated to achieve all the standard specifications, an airworthiness certificate can be issued by the regulatory authorities.

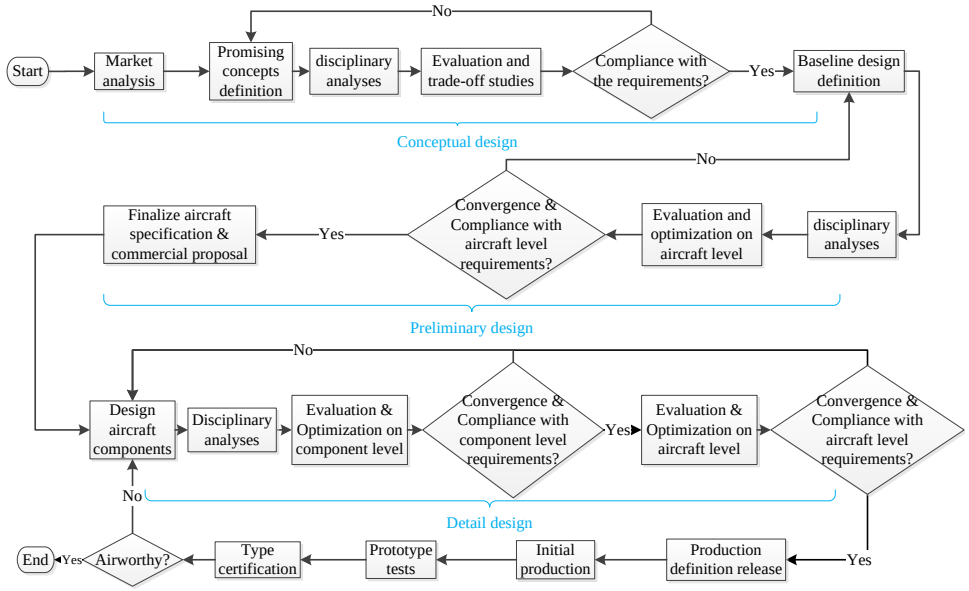


Figure 3.4: Complete Research, Development, Test & Evaluation process model

By investigating the complete RDT&E model, it is found that the core of the design activities is repetitive for conceptual, preliminary and detail design stages while the level of fidelity is gradually deepened along with the process. It can be summarized as Figure 3.5. The product definition varies from the promising concept definition to the baseline definition as a commercial proposal until the detailed component design with a production definition for each of the three stages. The design solution also varies from baseline definition to the aircraft commercial proposal till the production definition with prototypes. The design solution of the previous stage is just the product definition of the next design stage until the product is built and certified as for the final delivery. Not coincidentally, the design phases of this process model conform with the design process embedded in the DEE.

The output of the RDT&E view is a structured data list. It is generated by collecting prod-

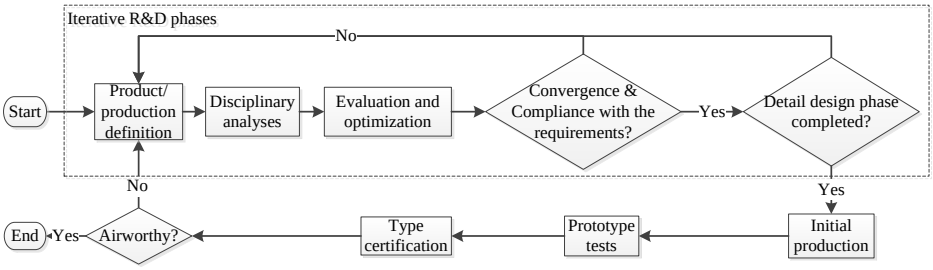


Figure 3.5: Research, Development, Test & Evaluation process model

uct data such as part complexity and symmetric part counts, and design process data such as the number of software licences and the technical drawing speed.

3.2.2. PRODUCTION VIEW

The main tasks of the production view generation are to produce the product representation and process representation particularly for manufacturer use, i.e. to segment parts and assembly connection interfaces out of the final assembly, and to plan the production processes [272]. In the meantime, additional materials are predicted, assembly types and assembled parts reference are assigned specially for assembly connections (see Figures 3.12 to 3.14).

3.2.2.1. PRODUCT REPRESENTATION

The product geometry for production process needs segmentation on the manufacturing edges for parts, sub-assemblies and final assemblies. Figure 3.6 shows examples of product model needed for manufacturing and assembly processes. The production geometry is segmented based on the geometries of the functional parts and their material types. When a single solid geometry is detected, then it is detected as a manufacturable part. When an interface between two solids is detected, then it is recognized as an assembly connection interface. When a group of geometries is found, it is treated as sub-assembly, which will be further divided into the manufacturable part(s) and connection interface(s). This involves geometric operations such as merge, intersect, separate, etc.

3.2.2.2. PROCESS REPRESENTATION

The production process is defined according to part functional types and their corresponding material types. It includes both manufacturing processes of the parts and assembly processes of the assembly connection interfaces. In particular, each aircraft assembly component is a composition of manufacturable parts. Those assembled parts need to be firstly referenced by an assembly. This referencing is done by assigning assembled part IDs, part types and their material types to the assembly component. In addition, assembly components are categorized into two types: sub-assembly and final-assembly. Then the referencing part properties and the assembly type are used to predict applicable assembly processes and additional materials. Specific examples are illustrated in case studies (Chapters 6 and 7).

Manufacturers and designers are working closely during the production process. Part



(a)



(b)



(c)

Figure 3.6: Product representation for production process: (a) part manufacturing; (b) subassembly; (c) final assembly. (figure sources: Airbus website [270])

manufacturing is initiated firstly, followed by sub-assembly fabrications. After which the final assembly process is carried out for the integration of the manufactured parts and sub-assembled components. The mass production is followed on the basis of the orders received and the production lots planned. In addition, the aircraft needs to achieve the operation readiness through aircraft certification before its delivery. Similar with the generalization of the RDT&E process, the production process model is generalized as Figure 3.7.

The output of the production view is an extended Bill of Material (BOM). It is generated by traversing all the manufacturable parts and assemblies in the production view and obtaining a list of relevant attributes for each. Those attributes include the part ID (a designated number), qty (quantity), geometric sizes, part type, material, production process(es), weight, and etc.

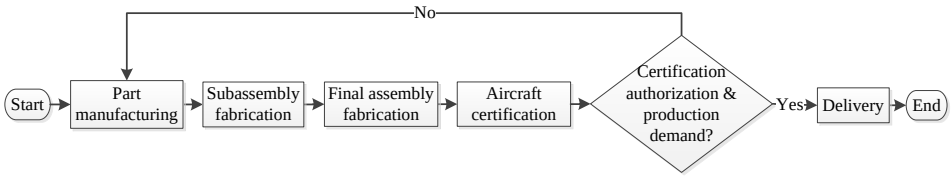


Figure 3.7: Production process model

3.2.3. OPERATING AND MAINTENANCE (O&M) VIEW

The O&M view generation is to produce the product model (also referred as product representation) and process representation specifically for operating processes and maintenance programmes, i.e. to supply aircraft performance properties for the flight operating cost evaluation and to segment aircraft zones, structural components and functional systems for maintenance cost analysis.

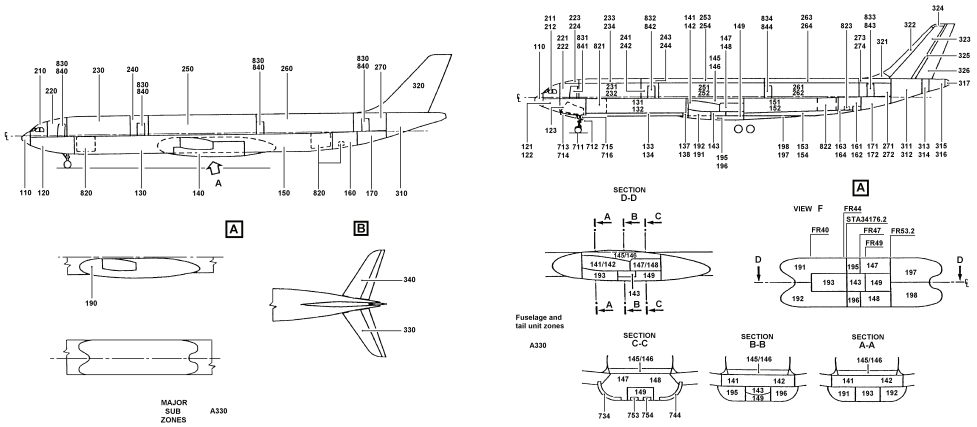
3.2.3.1. PRODUCT REPRESENTATION

The product representation needed for the O&M costing is generated according to the tasks conducted during the process. For operating tasks, the aircraft level geometric attributes and performance properties are collected. Moreover, the flight mission profile is determined. For maintenance tasks, the geometric representation is generated based on the maintenance programme, which considers the aircraft division of system, Auxiliary Power Unit (APU), powerplant, structure and zones. In this research, the maintenance of a system, APU and powerplant are not taken into consideration, only the airframe is considered. The product view is then divided to various zones covering structure and system for maintenance operations. The example of zonal divisions of an aircraft is illustrated in Figure 3.8. M&O representation is particularly for designer's prediction and airline use, i.e. to segment aircraft operating profile phases for flight operation, to zones for maintenance tasks.

3.2.3.2. PROCESS REPRESENTATION

Operation and maintenance activities comprise the major part of the life cycle once the aircraft enters into service. Activities including air transportation, aviation training, air navigation service, maintenance and overhaul, airport service and regulatory functions are conducted. The activities of the operation and maintenance process are performed simultaneously and recursively. Detailed processes for flight operating and maintenance procedure are defined separately. A flight operating process is generally visualized by a flight mission profile, which includes all flight stages from aircraft setup till approaching & landing, where the reserve mission is planned to cope with possible congestion or emergencies during flight. In detail, the flight stages are aircraft warm up, taxi out & take-off, climb, cruise, descent and approaching, landing & taxi-in. Scheduled maintenance is performed directly after landing at gate and/or in hanger depending on tasks. When unexpected failure is detected, unscheduled maintenance has to be performed. Both operation and maintenance interact with each other until the aircraft reaches its life expectancy.

Considering a flight trip, the detailed operation & maintenance process is shown in Fig-



(a) (b)

Figure 3.8: Product representation for maintenance process:(a) Aircraft major and sub zones; (b) Fuselage and tail zonal division. (figure sources: Airbus MRBR [273])

ure 3.9. It involves flight segments from aircraft set up to landing, where the maintenance schedule is performed. If a failure is detected and the aircraft is not authorized for the next flight, unscheduled maintenance will be performed until it is cleared for flight again. If the aircraft reaches its life limits, it is transferred to the next life cycle phase.

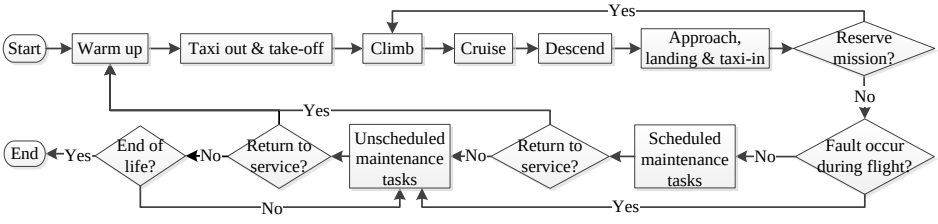


Figure 3.9: Operation & maintenance process model

3.2.4. DISPOSAL AND RECYCLE (D&R) VIEW

The activities conducted by the D&R view generation are to produce the product model and process representation for disposal and recycle procedures, viz. to identify reusable parts, to sort out dismantled parts by geometric sizes and material properties, to determine the recycle process according to material properties. This way, the cost and salvage of D&R process can be estimated.

3.2.4.1. PRODUCT REPRESENTATION

An aircraft is retired if it reaches its calendar life. Other conditions which lead to aircraft disposal are the aircraft is beyond economic repair due to an accident, the aircraft is grounded due to a technical defect and the aircraft is grounded due to the bankruptcy of the owner [274]. The product geometry segmentation for dismantling will be defined in advance, see Figure 3.10. The segmented product model contains the components and systems removed first from the aircraft, the airframe pieces dismantled according to the pre-defined cut lines and later the final product pieces sorted out by their shapes and material types for the final recycle and disposal. The product representation in D&R phase will also include the data of aircraft materials, the reusable components, the recyclable materials and so on.



Figure 3.10: Product representation for R&D process (figure sources: AELS (Aircraft End of Life Solution) company website [275])

3.2.4.2. PROCESS REPRESENTATION

A generalized process flow is shown in Figure 3.11. The D&R process is determined based on the status of the aircraft and the customer requirements specifically for recycle and reuse [276]. Some are stored in the aircraft boneyard, some are reconditioned and repainted for exhibitions, some are processed as recovered materials to be supplied to other products.

During the storing phase, the aircraft is transported, parked with or without performing maintenance activities. If the maintenance is necessary mainly depends on the aircraft current condition and its future usage. After deciding not to park the retired aircraft, it can either be reconditioned and recertified for resale to be reused as passenger or freighter aircraft, or be disposed of via a series of process steps. When disposing of an aircraft, it is firstly disassembled to get all the valuable components removed and will be reused on the other aircraft or for alternative reuse. For a component to be reused on the other aircraft and engine, the component needs to be recertified first. If it is used alternatively such as for product exhibition, it might need to be reconditioned. The airframe is dismantled by removing and scrapping hazardous materials, and it is cut and shredded into pieces. Material sorting and separating are often performed manually immediately after the dismantling process. Depending on the material properties, the scrapped materials are used for secondary recycling,

which is distinguished with the primary recycling for materials scrapped during the aircraft manufacturing processes. In general, the metal parts, glass parts, plastic parts, and composite parts are distinguished. Based on their sizes, different materials are supplied for respective recycling processes. Metal parts are firstly grouped by sizes. Then they can be melted to be reformed to new parts. The composite parts such as Carbon Fibre Reinforced Plastic (CFRP) material can be decomposed and the pure carbon fibres can be extracted. Those carbon fibres can then be reused as recovered materials for new components. Those new components are often non-structural parts inside the aircraft or parts for automotive components and for electronic instruments. Two types of the secondary recycling process are divided in terms of the quality of the recovered materials. Some are recycled without losing the material quality. Some are recycled containing paint/glue or recycled by the immature recycling techniques, accordingly, lower quality materials are obtained, which is also called down-cycling. If the material cannot be recycled but can be burnt as wastes, the burning process will then converts the burning energy to heat or electricity, so-called energy recovery. In an ecological hierarchy, the last level of the end-of-life solution would be land filling when the part/component material cannot be reused, recycled or used for energy recovery.

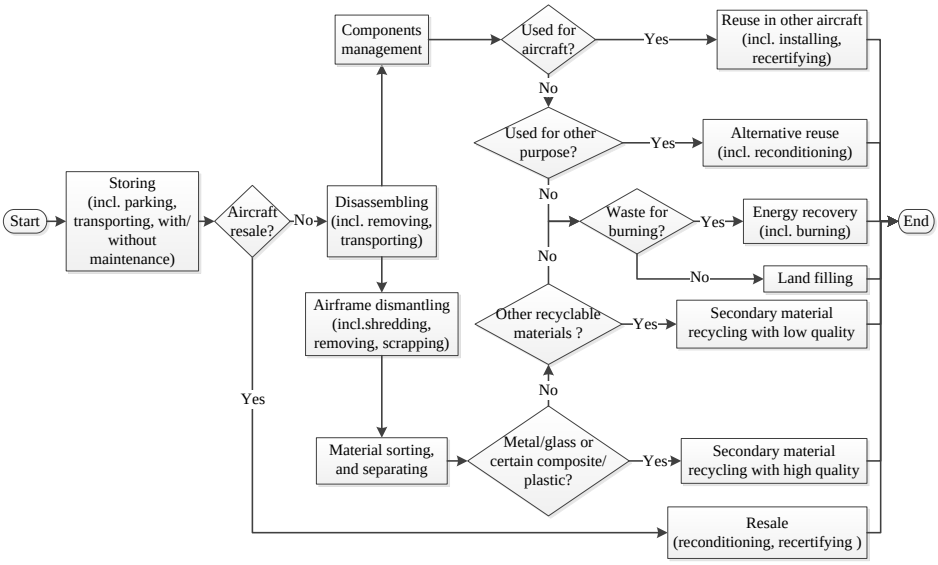


Figure 3.11: Disposal & recycling process model (adapted from [276] and [277])

Taking a B737 D&R project as an example, the following process flow can be constructed: The aircraft is purchased and transported to the disposal site; then the systems such as air conditioning, auto flight, and electrical power are removed, the engine and landing gear are also removed; some systems and engine parts are reconditioned, recertified and reused for the other aircraft; the landing gear is scrapped; the airframe is shredded and the materials are sorted to be further recycled as recovered material. For a DC-9 aircraft project, the nose

section, the engine cowl and the landing gear are going to be used for exhibition. The following process can be proposed: The aircraft is firstly purchased and transported to the disposal site; the engine cowl and the landing gear are removed, reconditioned, painted and transported to the exhibition site; then a D&R process similar to the previous one is conducted for the rest of the aircraft. Those two examples are constructed by referencing two D&R projects conducted by AELS company [275], while the constructed process steps are conceptual for demonstration purpose and not necessarily the same as they were actually conducted.

3.3. KBE SUPPORTED COST ANALYSIS

According to the life cycle process views, respective geometry representations and process representations are encapsulated to correspondent data lists. They are then transmitted to analysis modules for cost evaluations. Considering that pre- and post-processing for cost analysis are dominated by rule-based operations, these activities can be automated to reduce intricate yet repetitive work. Since similar approaches apply to all four cost types in an aircraft life cycle, the method of developing production cost analysis is elaborated in the following sections. Different techniques applied in the analysis of the other three cost types are also pointed out. The main activities in production cost analysis module (as also shown in Figure 3.15 and Figure 3.17) are further detailed below.

3.3.1. PRE-PROCESSING

Cost analysis pre-processing will import the extended BOM by loading the formatted data file to the cost analysis module. By using the BOM inputs and referencing to both the PBS and CBS hierarchy, an integrated PBS and CBS is formulated. This is detailed and exemplified in case studies of Chapter 6 and Chapter 7. For the other cost types, respective structured data lists, PBS(es) and CBS(es), generated from the associated life cycle process views, are adopted instead of the extended BOM, manufacturable PBS and production CBS.

3.3.2. COST ESTIMATION

Before conducting cost estimation activities, KBE techniques adopted to support the automation and the development of the cost estimation should be identified. Moreover, a cost estimation method should be constructed. To realize those considerations within a consistent cost estimation module, two aspects are developed: definition of cost primitives and formulation of CMs, determination of the cost estimation method.

3.3.2.1. DEFINE COST PRIMITIVES (CP) AND FORMULATE CAPABILITY MODULES (CM)

After importing the extended BOM into the cost analysis module, the properties of PBS objects are supplied to their corresponding CBS objects, which are then treated as building blocks of the cost estimation. They contain parameterized cost calculations among different configurations. Instances of a cost primitive have similar attributes such as the part ID, qty, geometry sizes, material(s), production process(es), cost driving parameters, CERs, and the cost (value). Not only the attributes from BOM are assigned, but also the cost properties are included. By extending the application of part primitives in the DEE module of product model generation, a suite of parametrical cost estimation blocks are defined as Cost Primi-

tives (CP). A CP in the production cost estimation domain is:

- a manufacturable geometric aircraft part, an assembly connection interface or an assembly component;
- with specific material(s);
- with specific production process(es);
- which can represent a typical group of aircraft parts/assemblies;
- which has specific cost driving parameters and parameterized CERs not shared/reusable by other primitives.

Similarly, referring to the definition of HLPs in DEE, an HLP should be a necessary parametric building block in a specific domain and can be reused and manipulated during analysis. Accordingly, a High Level Cost Primitive (HLCP) is defined as either cost-assembly or cost-part. The CPs related to sub-assemblies and final assemblies are instances of the cost-assembly. Based on the definition of two modularised HLCPs, it is possible to assemble the total cost for various configurations of aircraft components. Note that this definition only applies to production cost, while it needs justifications to be applied to RDT&E cost, O&M cost and D&R cost. The justifications are mainly addressed on the items related to the geometry and process. For RDT&E cost, the CPs are the geometric model developed during a particular design process. The CPs are the overall aircraft geometry for operating cost and they are the zonal segmented airframe structure and system models for maintenance cost. For R&D cost, the CPs are the reusable parts, the recyclable parts/components and the discards. Accordingly, the HLCPs for the other costs are also defined differently. The HLCPs for RDT&E cost would be the same as those for MMG including wing, fuselage, engine and the connection element. Whereas the HLCPs are the aircraft model and zones for the two cost types in O&M cost, they are reusable parts, recyclable parts and discards for D&R cost respectively.

CMs, which are analogous to those in MMG, are developed in cost estimation module for automation purpose. They contain procedural knowledge such as CERs and rules of selecting CERs under various material and manufacturing conditions. The CMs are applied to CPs, so that the geometry and attributes of CPs can be processed to obtain relevant costs.

3.3.2.2. DETERMINE COST ESTIMATION METHOD

Cost estimation methods are determined on the basis of the costing requirement and the four elements summarized in Chapter 2. According to the characteristics of the LCC types, cost estimation methods are determined respectively. Moreover, depends on the availability of the cost input data for LCC estimation, it develops two levels of estimation methods. For high-level production cost estimations, the analysis is conducted from the cost of the overall aircraft to the components. It is estimated on the basis of weight features of the aircraft using parametric calculation method and KBE techniques. Therefore, it is a top-down feature-based parametric cost estimation assisted by KBE techniques. For detailed level production cost estimation, the analysis is conducted from part and assembly connection interface to final assembly, and from material cost and labour cost to production cost. As such, a

bottom-up process is performed. A process-based model is built as the manufacturing and assembly processes are predicted by rule-based techniques, which are utilized to define appropriate CERs. The CERs are collected from industry as well as academic literature, and comply with a parametric calculation method. This process-based model is also combined with the genetic-causal model philosophy since cost driving parameters are employed as the causes of the incurred costs. Supporting techniques, such as KBE techniques, are employed in particular. In summary, detail-level production cost estimation research adopts a bottom-up process-based parametric cost estimation method using KBE techniques. Similar cost estimation methods on both levels are also applied to other LCC types.

3.3.3. POST-PROCESSING

Cost analysis post-processing retrieves and analysis cost results, followed by generating the cost report. Once the cost values have been calculated, they are collected and categorised into various cost categories to generate cost distributions of the product on parts/assemblies and material compositions. A cost report is generated in a formatted data file, which can be used for trade-off studies. At the meantime, it is prepared for optimizations, which utilise the data file as an intermediate data exchange (Figure 3.15). Corresponding capability functions are developed to cover data transmissions via application program interfaces such as those from Genworks' General-purpose Declarative Language (GDL) [278] to analysis tools such as Microsoft Excel or MATLAB. In addition, The updated product geometry achieved after each loop of the design optimization will be fed back to the MMG, so that the product model is also updated during the optimization process.

3.4. IMPLEMENTATION

Following the method developed for design-cost integration with the support of KBE techniques, the implementation of the method, specifically the use of the CPs and CMs are addressed and exemplified. In Section 3.4.1, the PBS and CBS integration is explained in detail. Moreover, activities for the life cycle process view generation are highlighted through the CMs, which also facilitate the integration. In Section 3.4.3, the cost estimation application utilizes the CPs and CMs are developed. Activities conducted within the estimation analysis are emphasized. It has also addressed the automation approaches adopting inference mechanisms in the application. In Section 3.4.3, the intention is to develop CMs for cost integrated design optimization including the transmission of the optimization data and the connection between the cost analysis tool and the optimization solver. The implementation of the production cost analysis is highlighted in this section. The analysis of the other cost types follows a similar implementation procedure, while the PBS, CBS and some of the CMs needed for each differ from those of the production cost analysis. Some of the differences have been addressed, while some of them will be explained along with the introduction of cost estimation method (Chapter 4) and the case studies (Chapter 6 and Chapter 7). The relevant UML diagram indication can be seen from Appendix F.

3.4.1. KBE SUPPORTED COST ANALYSIS INTEGRATED DESIGN FRAMEWORK

According to the Product-Process-Cost procedure, the actual integration happens when the PBS based on respective life cycle phase product representation and the CBS of the cost type to be evaluated are coupled. PBS contains the product hierarchical classification in different levels of detail.

A PBS meta UML model in the production domain is shown in Figure 3.12. The final product is seen as a final assembly, which consists of the part, assembly connection interface and subassembly classes. A part represents the smallest manufacturable unit without assembly operations. Apart from basic parts such as skin, spar, rib, stiffener, etc., additional materials used during the assembly process, like fastener, shim, hinge bearing and so on, are also categorized into the different part classes. Assembly connection interface stands for the interface between two or more parts where an assembly operation takes place. Subassembly refers to a component of the final product, which can also include parts, assembly connection interfaces and other subassemblies. The production representation is an object instance of the PBS meta model. The number of elements in a production PBS instance depends on the design itself and the manufacturing/assembly capability. Note that the PBSs for R&D, production, operating and disposal processes are not identical but all based on the initial PBS of the master product geometry.

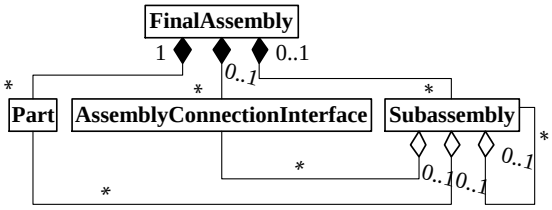


Figure 3.12: Product Breakdown Structure meta model for production

Similarly, the production cost is also categorized hierarchically, which forms the CBS. Figure 3.13 depicts a CBS meta UML model. The production cost adopts the classification of recurring cost and non-recurring cost. Recurring cost refers to the cost occurring through the production process which is repetitively incurred with every production run, while non-recurring cost is the expenditure before the first production and is spent once in the whole production process [279]. Therefore, the former mainly contains the costs on labour usage, material consumption (including fly material cost and chipped material cost), energy consumption and facility cost; whereas the tooling and testing compose the latter category. There are also miscellaneous costs for both recurring and non-recurring costs. The recurring miscellaneous costs are the recurring overhead expenses, and nonrecurring miscellaneous costs are those from the depreciation, insurance, interest and nonrecurring overhead expenses. The miscellaneous costs for production together with those for the RDT&E are paid by the manufacturer, and is wrapped up after the lump-sum based on the LCC CBS. Depending on the data availability and the focus of the analysis, specific costs allocation within a CBS can vary. In this research, only recurring labour and material costs are addressed. Furthermore, not only production cost but also R&D cost, operating cost and disposal cost

correspond to their own CBSes. The number of elements of a CBS instance is determined by the number of the PBS elements and the cost types.

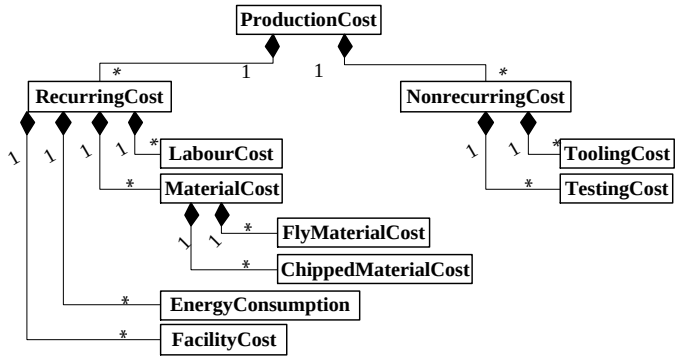


Figure 3.13: Production Cost Breakdown Structure meta model

The costs are estimated when a CBS is connected with each item in PBS. To couple PBS and CBS, an extended BOM is generated as the production view data file and to be provided to the cost analysis module. An extended BOM is a collection of all levels of PBS objects' geometry, material and production process properties. It contains data lists using a unified data structure. The extended BOM still follows the hierarchy of the PBS implicitly by storing topology reference data in each data list. A data list is regarded as a BOM item, and corresponds to an object from the PBS. Afterwards, a BOM item is supplied to instantiate a cost building block. Each cost building block contains a CBS, which is a hierarchical tree structure of cost types. Every cost type embodies cost driving parameters and CERs, which are collected from KB by CMs. As such, the PBS and CBS are integrated (Figure 3.14). Thereafter, cost estimates can be obtained for every PBS element.

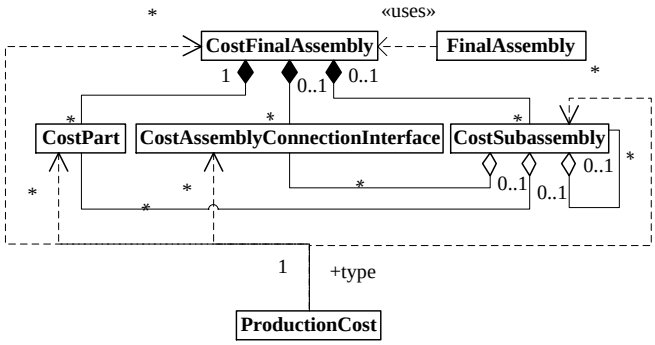


Figure 3.14: Product Breakdown Structure and Cost Breakdown Structure coupling for production

Accordingly, a production cost estimation application is developed. It includes three

modules displayed in Figure 3.2, viz., product model generation, production view generation and cost analysis. The activity diagram of the overall cost design integration is given in Figure 3.15. The zoom-in fork, at the side of the activity-'production cost estimation', is further explained via Figure 3.17. Following the logic of Figure 3.17, the product model generation mainly intends to produce the master geometry based on the input parameters and the initial PBS. The production view generation capability is further discussed, followed by the elaboration of cost analysis module. All the functional steps are automatically linked together without interventions by the end users.

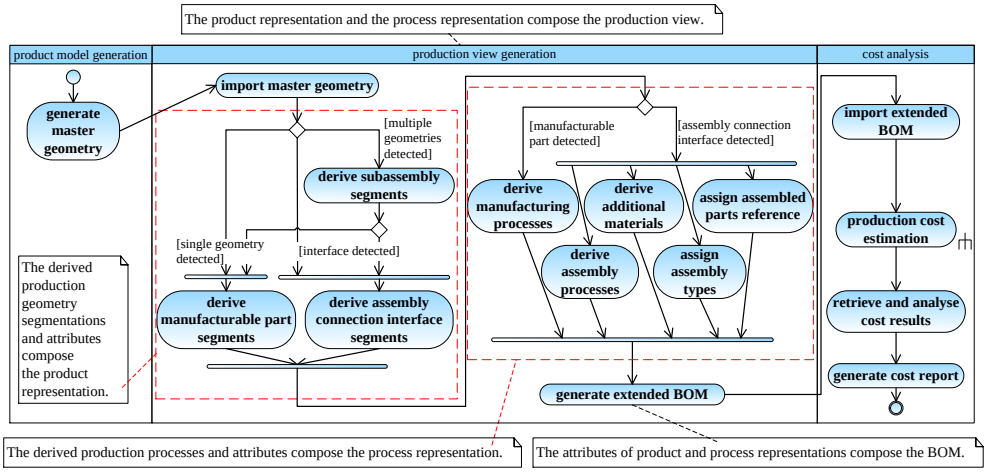


Figure 3.15: Activity diagram of the cost analysis tool

3.4.2. LIFE CYCLE PROCESS VIEW GENERATION

In this module, two main activities are conducted: To generate the product geometry and to extract parameters needed for the cost analysis of a certain process. The RDT&E cost requires aircraft and the design process properties. For production cost analysis, the product definition ready for manufacturing and assembly needs to be extracted. It is then utilized for generating production procedure. For O&M cost estimation, it is necessary to allocate the trip operating plan to the aircraft, to determine the scheduled maintenance and to consider the unscheduled maintenance tasks. The D&R cost depends on the retired aircraft condition and the process plan made by the airline and the disposal company. Since the planning of those processes is mostly rule-based activities from engineering practice, therefore, product-specific LCC plan can be made by applying the rules on the general LCC process model defined in this research. In this way, routine life cycle process can already be made automatically in the design phase. Besides extracting the geometric properties for the life cycle process view, the emphasis is also drawn on the process planning.

The swim lane in the middle of Figure 3.15 shows the activities conducted for production view generation. By detecting the singularity of the segmented geometry and/or interface,

parts, connection interfaces and subassemblies are identified and structured hierarchically. Next, the manufacturing process and the assembly process are determined separately. The manufacturing process is decided based on the material property of a part, while the assembly process is derived based on the materials of the parts involved in the assembly. Meanwhile, the additional materials used for the assembly process, and the assembly types specifying the connection between which parts, are also interpreted in the process view model. Later, an extended BOM is attained to be supplied to the cost analysis module.

3.4.3. KBE SUPPORTED COST ANALYSIS

To realize those considerations within a consistent cost estimation module, two aspects are developed: implementation of cost primitives and implementation of the estimation functionalities.

3.4.3.1. PRE-PROCESSING

In the right swim lane in Figure 3.15 before the actual cost estimation, the pre-processing for cost estimation is defined. It is mainly to import the extended BOM. Depends on the platform used for the integrated design-cost process and the software employed for the cost analysis, the implementation of this step varies. If both the DEE and the cost analysis are developed in the same development system, the importing process would be an internal data transfer. If they are developed via distinct software, e.g., the DEE is developed in GDL while the cost analysis is developed in MATLAB, a cross-platform data transition is needed for importing. In this research, the cross-platform data transition is developed for general usage.

3.4.3.2. COST ESTIMATION

- **Cost Primitive implementations**

For production cost analysis, the examples of CPs (cost assembly connection interface, cost subassembly, cost final assembly and cost part) and the HLCPs (cost assembly, cost part) are shown in Figure 3.16 with their relations. The CP instances differ according to the final product and cost type. Using a multi-rib wing production cost as an example, the CPs include skin-stringer connection production cost, spar-rib connection production cost, leading edge labour cost, torsion box labour cost, skin material cost, stringer material cost, etc.

- **Cost estimation implementation**

Figure 3.17 details the activity of 'production cost estimation' in Figure 3.11, where the involved operations are embedded in HLCPs. The PBS for production view and the CBS are integrated by passing the attributes from BOMs to HLCPs, it the meantime, the CPs are also instantiated. Production cost estimation in this implementation mainly refers to production recurring cost, meaning material and labour cost. The cost driving parameters for production cost are geometric sizes (e.g. length, area), material types (e.g. density, unit price), weight (e.g. fly-weight, chipped-weight) and part numbers. Some of them are served as parameters to evaluate the labour times, which can be converted to the labour cost. The geometry sizes and material density will be used to calculate the product mass in order to derive

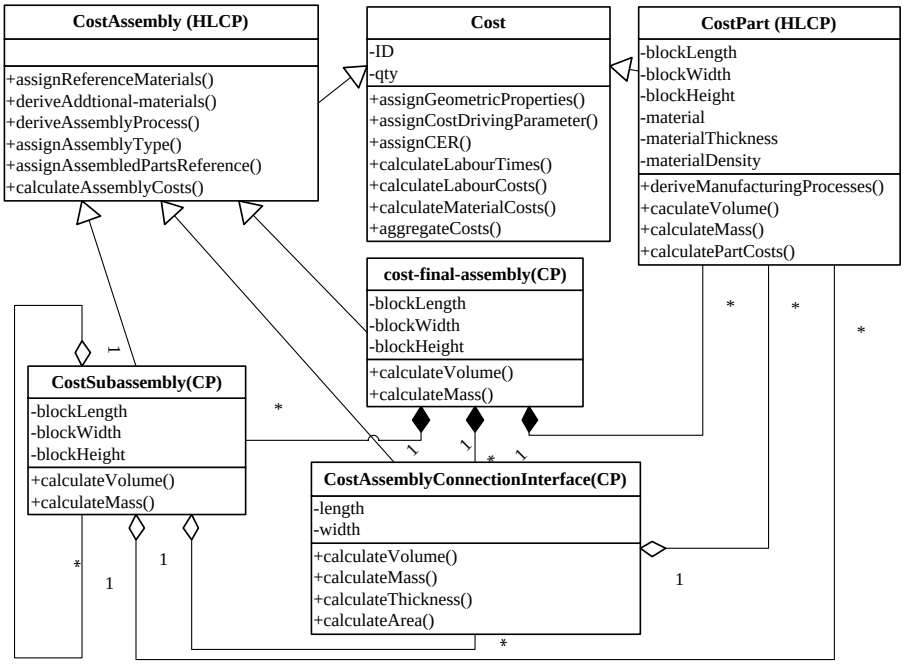


Figure 3.16: Static structure diagram of the Cost Primitives (CPs) and High Level Cost Primitives (HLCPs)

the material cost. Those parameterized relationships, so-called CERs, are assigned to the CPs. The cost will be evaluated instantly when the calculation is performed. The value of the total cost is then aggregated.

3.4.3.3. POST-PROCESSING

In the right swim lane in Figure 3.15 after the actual cost estimation, the post-processing for cost estimation is summarized as 'to retrieve and analyse cost results and to generate a cost report'. Those activities involve the organization and formalization of the cost information. For instance: to extract cost by part and/or connection interface, to collect costs by cost types such as recurring and non-recurring costs. Furthermore, extracted costs need to be analysed to produce cost distribution figures, cost tables and so on. Additionally, the cost data also needs to be provided as inputs for cost involved design optimization. Those can be facilitated by building connections and automation between analysis software and data processing software. Similar with the pre-processing, connections and automation have been built between Genworks GDL and MATLAB as well as Genworks GDL and Microsoft Excel to facilitate the post-processing in this research.

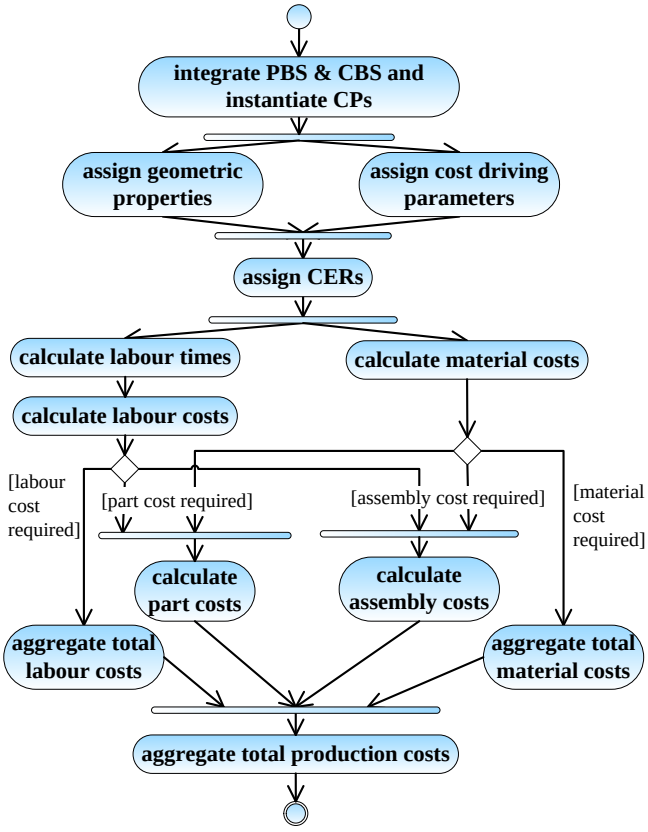


Figure 3.17: Activity diagram of the cost estimation module within cost analysis tool

3.5. SYNTHESIS AND CONCLUSIONS

To synthesize the method developed and implemented for design-cost integration and the aircraft LCC analysis, the interactions between the system and the stakeholders are investigated. Figure 3.18 shows the Use Case diagram of the cost integrated design and optimization application. The responsibilities of the designer, manufacturer, airline (incl. maintenance engineer), disposal personnel and cost engineer are identified. The designer initiates the design with the parametrized master geometry and corresponding geometric presentation suitable for the life cycle process analysis. From the other perspective, the manufacturer, airline and the disposal personnel are developing general process procedures and properties relevant to the cost analysis. By combining the product representation and the process procedure & properties, the process-specific product views are generated. This step basically completes the functioning of MMG in DEE, corresponding to the method development and implementation introduced in Sections 3.1 and 3.2. Later, the cost analysis methods are developed mainly by cost engineers. Next, those methods are extended to LCC indicator

evaluations which use parameters from the corresponding views to feed to the estimation. This step is accomplished by the analysis module illustrated in Section 3.3. This is then connected with the optimization studies. Within the application, it needs knowledge from the engineers within the life cycle process. Moreover, it requires interactions between the engineers during the design process for information update and exchange. After the cost analysis and optimization, not only cost engineers but also the other stakeholders will obtain the insights of the product LCC performance. In summary, by integrating the cost analysis into the design and optimization framework, another dimension is added into the DEE. The key of synthesizing the whole architecture is the utilization of KBE techniques.

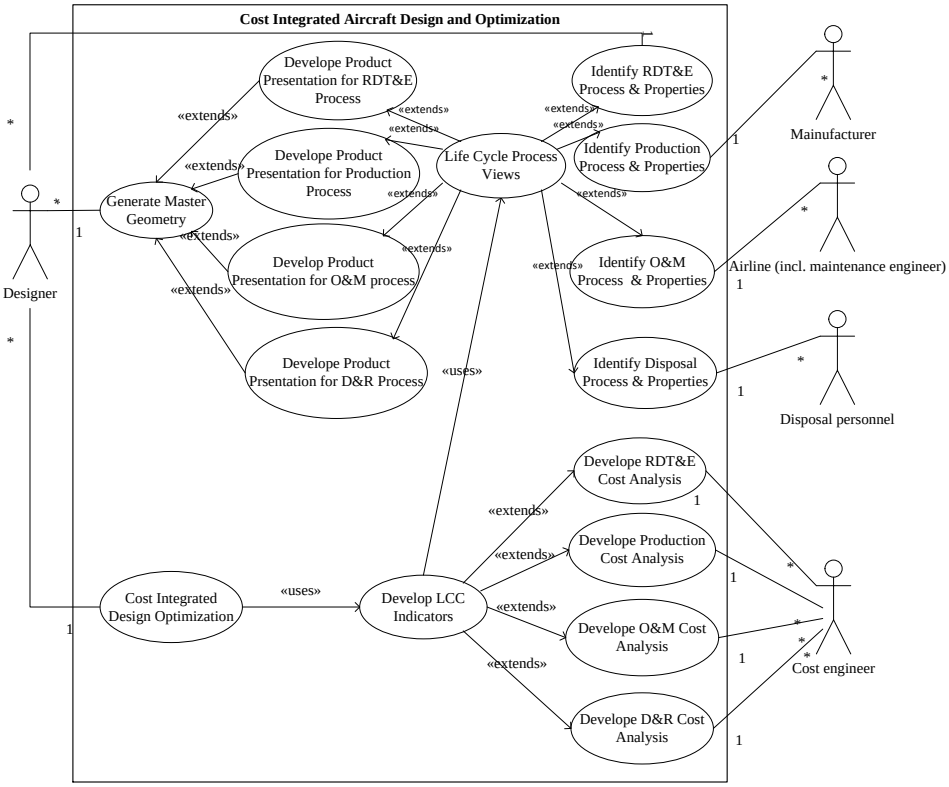


Figure 3.18: Use Case Diagram for cost integrated aircraft design and optimization

In summary, this chapter focused on the integration of the aircraft design process and the LCC analysis. The integration not only refers to involve cost evaluation into design and optimization but also the integration of the LCC analysis itself. KBE techniques are employed intensively to facilitate this integration. Firstly, the methodological development is stressed containing the extraction of the Product-Process-Cost procedures, the development of the life cycle process models, the invention of Cost Primitive and the standardization of the cost

analysis method selection. Those are then implemented by applying KBE techniques, so that it is able to integrate the aircraft LCC analysis into its design and optimization process by knowledge extraction and reuse. Moreover, by implementing corresponding CPs and CMs specifically for cost analysis, KBE techniques including geometric modelling and knowledge-based inference mechanisms can also improve the LCC analysis itself in an efficient and modularized manner. Those techniques are originated from AI, Object Oriented Programming and Computer Aided Design respectively. During the research implementation, the techniques employed are mainly knowledge extraction/inference, programming languages such as Common Lisp embedded in Genworks GDL and parameterized geometric modelling such as the use of the NURBS-based geometry kernel empowered by Genworks GDL. On the basis of the integration, the LCC analysis and optimization studies can then be developed in-depth within their respective modules. This solves the main problem of the objective which is to realize the inclusion of life cycle consideration into aircraft design process. As one of the three areas in this research, the integration part provides a fundamental platform to facilitate the process where the repetitive procedure and reusable knowledge are valued. Although the knowledge is extensively distributed over the life cycle and not understandable by all stake-holders, the integration encourages their collaboration and facilitates the analysis of their common concerns - the LCC, which in turn also benefits themselves for a more comprehensive view of the design and its cost performance.

4

METHODOLOGY OF AIRCRAFT LIFE CYCLE COST ANALYSIS

LCC analysis not only affects the final design and its life cycle but also supports the cost reduction by evaluating the driving parameters and the induced cost variation. It is essential to develop an LCC analysis method and an analysis tool to simulate the aircraft cost performance within its life cycle, which can reveal the design influences and facilitate the design optimizations. On the basis of the generalized cost estimation method classification and the reference costing methods, improvements have been made to the current LCC estimation method. In this chapter, a complete LCC analysis framework is proposed. The framework is oriented by two levels of estimation, the high-level LCC estimation and the detail-level LCC estimation. The transition between the LCC estimations on both levels is extracted. Both the LCC estimation method and the model implementation are investigated in detail. The specific cost driving parameters and the CERs detailed to the cost elements in the LCC breakdown such as the labour cost and the material cost estimations are analysed.

According to the review in the field of cost analysis, there is a lack of a systematic LCC estimation framework. Moreover, no explicit distinction has been made about cost estimation method for aircraft and aircraft component respectively. To this end, this section deals with the cost analysis methods in terms of all major cost types in an aircraft life cycle in both high-level model and detail-level models. Those two levels are utilized based on the level of detail that the data resources are available as well as the level of detail that the cost results are required to be estimated. In Section 4.1, the architecture of the LCC estimation method and the generalized method description are depicted. In particular, the CERs developed and/or adapted for the cost items in each major cost type are stressed in Section 4.2.

4.1. COST ESTIMATION FRAMEWORK AND METHOD GENERALIZATION

The main purpose of the LCC framework developed in this research is to improve the design competitiveness and support long-term planning and budgeting. The RDT&E cost and disposal cost are not only influenced by the design itself but also the process. The production cost is determined by the product geometry as well as the production plan. For operating and maintenance cost analysis, the logic relies on the product properties and the operating process planning. Therefore, it aims at hiring design and process factors as cost driving parameters to facilitate cost estimation in the early design stage, in this way, a direct link between product design and its cost can be built. It also deals with the availability of the parameters for aircraft costing and component costing respectively.

Accordingly, a scalable two-level LCC estimation framework is built on the basis of both high-level and detail-level costing methods. The high-level cost estimation employs aircraft weight properties as the main cost driving parameters to evaluate major cost types in an aircraft life cycle, The major cost types refers to the miscellaneous cost, RDT&E cost, Production cost, O&M cost, D&R cost and LCC indicators. The detail-level cost estimation considers the direct cost drivers from design and process properties. Besides obtaining the values of the major cost types from the detailed cost elements under each of the major cost type, it also investigates the cost contribution from the actual process steps to the cost elements. While the high-level cost estimation requires less cost driving parameters than those needed for the detail-level cost estimation, so that it contains less uncertainty in the cost results. The framework takes advantages of both estimations. This inclusion of the high-level and detail-level models using data sets and cost estimation methods in two levels of detail is here defined as scalable.

According to the LCC CBS, the LCC model is modularized in several building blocks based on major cost types. The framework measures each of the cost types, further to the total LCC. It also contains the flexibility of evaluating a singular cost indicator so that it can respond to the stakeholder who is interested in a specific cost aspect. In the meantime, it predicts life cycle process information according to the product design properties so that it compensates for data shortages in the detailed cost estimation. However, it can still happen that some data are not predictable and the cost estimation for certain cost type cannot be conducted on the detailed level, in which case the high-level cost estimation is then applied. Note that the mixture of the high-level and the detail-level cost estimations is among the major cost

types. The estimations for cost elements belonging to each major cost type is restricted to stay at the same level of detail. In this way, it does not violate the consistency of the calculation when combining both the high-level and the detail-level cost estimations in a framework. The parameters needed are recommended to be categorised in two groups: design parameters and process parameters. Figure 4.1 shows the framework of the cost analysis, it conforms to the product-process-cost procedures established in Chapter 3, while it details each costing procedure and provides the route of conducting the cost analysis on both high- and detail- levels. The functional blocks are aligned with the DEE counterparts. A label tag of each module can be referenced back to the DEE framework. The cost analysis module is emphasized in this Chapter. It also elaborates the calculation methods for each cost type.

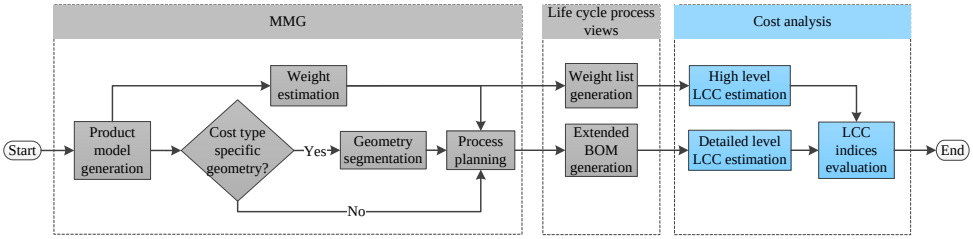


Figure 4.1: Scalable two-level LCC estimation framework

An N2 chart is provided to show the interactions and data transmissions among those modules, see Figure 4.2. The inputs for each module are extracted from KBs. The product sizes and the materials are supplied by the product-KB, while the weight, process and cost relevant properties and rules are stored in their corresponding KBs. The outputs generated from product model geometry, the weight estimation and the process analysis are all fed forward to the cost module. The output cost indicators are provided to the cost report generator and/or to the optimization solver for further operations. Note that the emphasis of this chapter is cost analysis, while the parametric geometry model and the process analysis have been introduced in Chapter 3, and the weight analysis adopts class I method and class II/class II&1/2 method for detail-level model respectively [280].

Referring back to the LCC CBS summarized in Chapter 2, the major cost types are highlighted in Figure 4.3 in grey blocks. The orange block refers to the cost aggregated in the LCC analysis. The cost elements estimated in this model are labelled in blue blocks in the CBS of the specific cost type, shown in Figure 4.4, 4.8, 4.11 and 4.17. The white blocks are the cost elements which are not thoroughly investigated. In general, due to the labour and material costs are two of the most significant cost elements of each cost type and are less dependent on the company strategies, their estimation methods are detailed in this research. Whereas the tooling & equipment cost, energy consumption and facility cost are mostly determined by factory conditions and company policies, and they are neglected for simplification purpose.

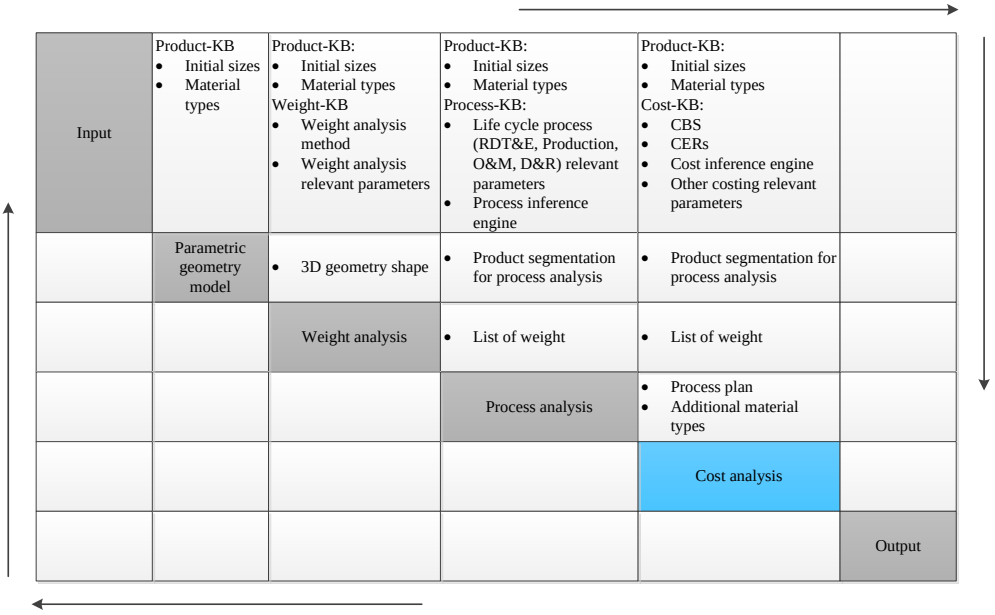


Figure 4.2: N2 Chart for LCC estimation

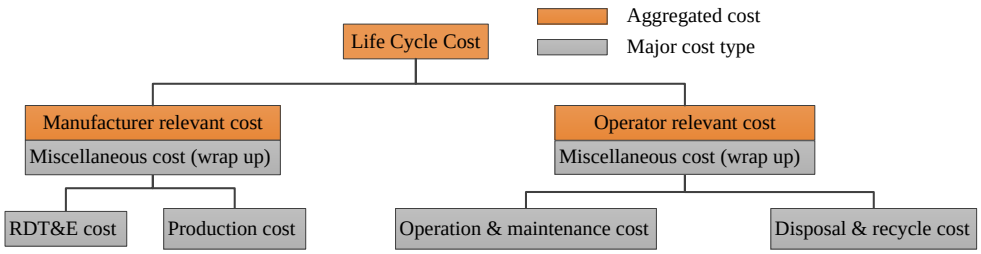


Figure 4.3: Highlight of investigated cost elements in the LCC CBS

4.1.1. HIGH-LEVEL MODEL

High-level cost models adopt weight/mass as cost driving parameters. It is built on the basis of the product breakdown and the cost breakdown, while due to the limited available knowledge, the process plan is not considered on this level comparing with the detail-level cost estimation. The estimations are generalized in Eqs. 4.1-4.5.

$$H_{i,j} = f_{i,j}(W) \quad \text{(when } j \text{ refers to labour cost)} \tag{4.1}$$

$$C_{i,j} = H_{i,j} R_{i,j} \quad \text{(when } j \text{ refers to labour cost)} \tag{4.2}$$

$$C_{i,j} = r_{i,j} W \quad \text{(when } j \text{ refers to material/fuel cost)} \tag{4.3}$$

$$C_i = \sum_j C_{i,j} \tag{4.4}$$

$$LCC = \sum_i C_i = C_{RDT\&E} + C_{Production} + C_{M\&O} + C_{D\&R} \tag{4.5}$$

where the costs (C) of each LCC phase are estimated on the basis of the aircraft weight properties. Generally, the labour cost is obtained through the evaluation of labour hours (H) and the labour rates (R) conducted on the level of each life cycle phase. The expression of the labour hours is obtained from statistical data analyses based on aircraft weight (W) using power law models or polynomial regressions represented by f. The material cost is also based on aircraft weight and the unit price (r) in $\$/kg$. Depending on the data extracted for formulating the parametric relationships, various weight types are utilized. The categorization of different weight types are illustrated in Appendix D as a clarification. i symbolizes one of the four major LCC types, j is the cost element such as the labour cost and the material cost shown within the CBS under each LCC cost type. Therefore, C_i refers to $C_{RDT\&E}$, $C_{Production}$, $C_{O\&M}$ or $C_{D\&R}$. The key of the high-level cost estimation is to obtain the $C_{i,j}$, which is also the focus of the following sections.

The high-level cost analysis can be conducted from aircraft to part in PBS once the weight values are available, therefore, top-down process is adopted. The cost value is always aggregated from material cost and labour cost to the higher level cost types. As such, a bottom-up process is performed in CBS. Since it mainly uses weight and other high-level parameters such as the aircraft speed and range for cost estimation, the estimation model is categorized as a feature-based model. CERs are parametrized mainly based on weight information, so that the calculation method used is parametric cost estimation method. Additionally, regression parametrization techniques are often employed to support the development of CERs. In summary, combined top-down and bottom-up process based parametric cost estimation is implemented on the high-level cost estimation by the support of regression parametrization techniques.

4.1.2. DETAIL-LEVEL MODEL

Detail-level model is implemented when the data relevant to the product design and its life cycle operations are predictable and accessible. In addition, inference mechanisms relevant to the process properties derivation should also be available when applying this model. On the basis of the inference mechanisms and the life cycle processes generalized in Chapter 3, the process steps for a specific aircraft component can then be predicted. The process properties are supplied to CPs, which encapsulates the component geometry, process and cost related properties, thus the process specific product views can be constructed for the life cycle. The detail-level cost estimation allocates the corresponding CBS to the right CPs, and assigns the CERs to each process step of the CPs. Hence, the cost items in the CBS for each CP can be obtained by aggregating the CERs of process steps. Thereafter, the LCC is estimated by collecting the cost items of each CP for the product. Comparing with the high-level model, an extra layer of process step prediction and relevant processing activities are inserted in the model between the product geometry and the cost estimation, which can also be observed from Figure 4.1 that labour time estimation/collections are conducted on each process step level. The driving parameters for the time analysis are not limited on weight/mass but parameters more closely linked with the process steps based on physics and/or statistics. Once the labour times of the detailed process steps are obtained, cost time analyses are implemented to accumulate the LCC. The general formulations of the process step cost time evaluations are highlighted in Eqs. 4.6-4.10. Thereafter, Eq. 4.5 is utilized to gather respective cost elements.

$$(H_{CP})_{i,k,j} = f_{i,k,j}(x_{CP}) \quad \text{(when } j \text{ refers to labour cost)} \tag{4.6}$$

$$(C_{CP})_{i,k,j} = (H_{CP})_{i,k,j} R_{i,k,j} \quad \text{(when } j \text{ refers to labour cost)} \tag{4.7}$$

$$(C_{CP})_{i,k,j} = r_{i,k,j} W_{CP} \text{ or } (C_{CP})_{i,k,j} = r_{i,k,j} \Delta W_{CP} \quad \text{(when } j \text{ refers to material/fuel cost)} \tag{4.8}$$

$$(C_{CP})_i = \sum_k (C_{CP})_{i,k} = \sum_k \sum_j (C_{CP})_{i,k,j} \tag{4.9}$$

$$C_i = \sum_{CP} (C_{CP})_i \tag{4.10}$$

where f represents the equation evaluating the labour time (H) for each process step in the aircraft life cycle. Generally, the expression is obtained from statistical data analyses based on design and process attributes, so-called cost driving parameters (x), using regression models, theoreitical models, or physical approximations. For example, the composite manufacturing processes are approximated by first order law models and further adapted to hyperbolic function models [118]. Although i implies the major cost types defined in the

LCC in most cases, in some specific conditions when the CBS under the major cost type is hierarchically defined, it can also represent intermediate cost types shown as nodes in the hierarchical CBS structure. For example, the O&M cost contains the operation cost and the maintenance cost, which is further divided into scheduled maintenance cost and unscheduled maintenance cost. The symbol i generally represents any of these cost types, see Section 4.2.3. The added footnote k represents process steps derived based on the process meta models. j is the same as it is defined in the high-level costing. W and ΔW are the product weight and the weight (or the fuel weight in a flight trip operating process) increase/decrease during the operation of each process step. Depending on the data extracted for formulating the parametrical relationships, various weight types or weight differences are employed. The key of the detail-level cost estimation is to obtain the $C_{CP,k,j}$, which is also the focus of the following sections.

For detail-level cost estimation, the analysis is conducted from part level to aircraft level in PBS, and from material cost and labour cost to the higher level cost in CBS. As such, a bottom-up process is performed. The cost drivers are the product properties, process parameters and financial factors. The life cycle process is predicted using KBE techniques specifically the rule-based inference mechanisms for the LCC estimation, designated to process -based estimation model. The estimation model is also combined with the genetic-causal model since the cost driving parameter is employed as the causes of the incurred cost. The CERs are developed based on physical relations and/or regression parameterizations from industry as well as academic literature, therefore, the mathematical relations comply with the parametric cost calculation category. In addition, KBE techniques are adopted to support the cost design integration as well as the cost analysis. In summary, the detail-level model adopts a bottom-up process based parametric cost estimation, which is implemented by the support of KBE techniques.

4.1.3. GENERAL SETUP AND CONVERSION FACTORS

In the following sections, the cost estimation methods of the major cost types are integrated systematically in the LCC model. Both the high-level and detail-level cost estimations are developed for the cost of each life cycle process. The cost elements highlighted within the CBS of each cost type are the ones focused on by this research. Note that only the highlighted cost elements at the bottom level of a CBS are presented. The highlighted cost elements in the medium level of a CBS is the aggregation of its lower level cost elements by default. The cost for each life cycle process is further wrapped up to LCC by applying miscellaneous cost estimations. Additionally, typical cost indicators are illustrated to serve the analysis as optimization objectives. In order to provide a consistent abstraction, the following items of each cost estimation are discussed: assumptions on the model set-up, input data for the cost model, the goal of the estimation, the method category, CERs, inference rules, the accuracy of the analysis, the applicability and limitation of the methods. Those items summarize the pre-condition of the cost analysis, and determine the cost drivers in categories (product properties, process parameters and financial factors) either required from the user or derived based on existing parameters, the output of the estimation is identified. Based on the classification of the cost estimation method introduced in Chapter 2, the method is grouped by analysing the cost estimation process, estimation model, calculation method and assis-

tant techniques. CERs which formulate the cost estimation are explained in detail. Rules reflecting the inference mechanisms are displayed in examples. Next, a qualitative indication of the estimation accuracy of the analysis method and a discussion about the proper situation when the cost can be evaluated by this method is elaborated. In addition, due to the data accessibility and availability, the engine cost and system (such as the avionic system and the hydraulic system) costs are excluded in this research. Moreover, due to the same reason, some of the cost items such as the energy consumption, the facility cost, the tooling & equipment cost, as well as the testing cost cannot be shown in detail for every major cost type. In order to demonstrate the methodological development in a consistent fashion, the material cost and labour cost are emphasized for all major cost types. Needless to mention that the framework of constructing the cost estimation model and the method of conducting the high-level and detail-level models are generally applicable for all the other cost elements.

Generally, all the analyses adopt constant year dollars and employs the metric unit system throughout the analysis, therefore, necessary conversion factors such as the currency exchange rate (r_{CE}) and the inflation factor (I) are incorporated in the CER expressions. Moreover, Since the high-level model normally utilizes the parameter of the whole aircraft such as the aircraft OEW, the aircraft speed and the number of aircraft produced, the estimation result from the high-level model is on the basis of unit aircraft, i.e., cost per aircraft. While the detail-level estimation adopts parameters corresponding to CPs, which can either refer to an aircraft or a component/part according to the product model and the cost type to be evaluated. Therefore, the cost estimated for the detail-level is on the basis of a CP, i.e., cost per CP. Therefore, when the high-level model and detail-level model are performed jointly, it needs to be assured that the evaluations are conducted on the same basis. The same rule applies when the comparisons between both levels are conducted or when the detail-level model evaluation contains several cost types for respective CPs. To this end, assumptions about the cost-weight ratio (C/W)are made for conventional commercial aircraft. Note that the weight and cost symbols for aircraft are those which are not specified by subscripts. If the weight percentage and the cost percentage of the CP with respect to an aircraft (W_{CP}/W and C_{CP}/C) are available, it is assumed that the cost-weight ratio of a known aircraft or a CP applies to an analogous aircraft or an analogous CP at the corresponding level of detail, i.e., $C/W = (C/W)_{analogy}$ or $C_{CP}/W_{CP} = (C_{CP}/W_{CP})_{analogy}$ [15][281]. It is noteworthy that the cost ratio between a CP and an aircraft is not necessarily the same as the ratio between the CP weight and the aircraft weight in this case, i.e., $C_{CP}/C = W_{CP}/W$, when $(C_{CP}/W_{CP})_{analogy} = (C/W)_{analogy}$; $C_{CP}/C \neq W_{CP}/W$, other conditions. While if the weight percentage and the cost percentage for the CP are not known, it is assumed that the cost-weight ratio of an aircraft is the same as that of the CPs, i.e., $C/W = C_{CP}/W_{CP}$. In this case, the ratio between the CP cost and the aircraft cost equals to the ratio between the CP weight and the aircraft weight, i.e., $W_{CP}/W = C_{CP}/C$. This assumption enables the conversion between the 'cost per aircraft' and the 'cost per CP'. And it should be noted the latter conversion is less precise than the former case since the former assumption is more realistic, while they both required a consistent use of the weight types for the aircraft and the CPs. This is considered a reasonable assumption when dealing with the costs relevant to the airframe while not involving significant complex systems and very expensive materials [104]. Note that a CP can be an aircraft or a component depends on a cost type being evaluated. When

the CP refers to an aircraft, i.e., $W_{CP}/W = C_{CP}/C = 1$, this assumption is still valid. The exact definition of weight and cost terms used for the LCC analysis can be referred to Appendix D.

4.2. COST ESTIMATION FOR MAJOR COST TYPES

4.2.1. RDT&E COST ESTIMATION

Based on the product representation and process generalization elaborated in Section 3.2.1 and the CBS of the RDT&E cost shown in Figure 4.4, the CERs of the interested RDT&E cost elements for both high-level model and detail-level model are highlighted.

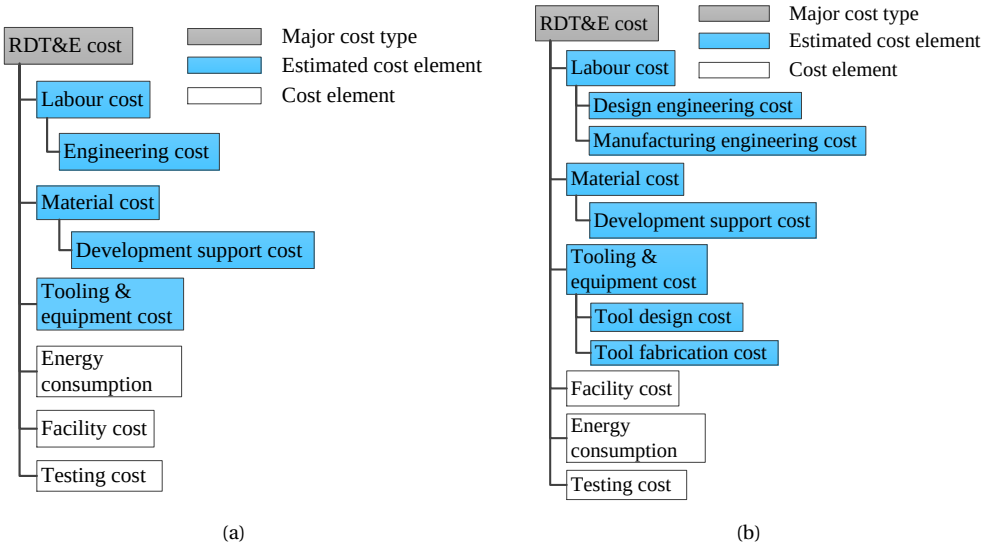


Figure 4.4: RDT&E cost CBS: (a) High-level model; (b) Detail-level model

4.2.1.1. HIGH-LEVEL MODEL

When the known details of the RDT&E process are not sufficient for the detailed cost estimation, the high-level model is adopted. The high-level model employs Raymer's cost estimation [61], which is modified on the basis of DAPCAIV model and proved to be able to provide reasonable results for not only military aircraft but also transport aircraft [117]. It utilizes the aircraft OEW, the aircraft speed and the number of aircraft produced as cost driving parameters. It evaluates the cost of a product unit for the use of designers, manufacturers and cost engineers. This model is grouped as the top-down feature-based parametric method using cost-time analysis techniques. Although DAPCAIV model can provide reasonable results for some classes of aircraft, the estimation error is above 0.18 and the applicability can be limited due to the database of CER developments are limited to 34 military aircraft flown during 1948 and 1978 [61][117]. Therefore, in order to obtain a better CER set, Raymer's model have included the factors related to aircraft material types, and it has considered the influence of

labour rates for distinct engineering actions. By incorporating the inflation factors, the cost is adapted from constant 1986 (FY_0) dollars to constant year dollars. In Raymer's model, the RDT&E cost and the production cost elements are evaluated together in an analysis [61]. In order to provide a clear demonstration in accordance with the LCC CBS defined in Chapter 2, although Raymer's model is adopted as the high-level models for both the RDT&E and Production cost estimations in this research, the CERs are grouped separately based on the cost elements involved in each cost type. Only the cost items relevant to airframe are considered while the engine cost and the system cost are excluded.

The RDT&E cost includes those consumed by the design and research engineering, prototype fabrication, flight and ground testing, and evaluation for operating suitability [61]. According to Raymer's definition, the engineering cost includes the cost of design, analysis and system engineering effort, which are labour intensive activities. Therefore, the engineering cost per aircraft is considered as an equivalent to RDT&E labour cost. While the development cost contains the material consumptions of the mock-up and structural test items for RDT&E process, thus it is recognized as an approximation of the RDT&E material cost. Moreover, the design and fabrication cost of the tools and equipment, so-called the tooling & equipment cost, is also included. By incorporating the inflation factor between the constant 1986 dollars used in Raymer's model to the constant year dollars in this research, the CERs for RDT&E cost are listed in Eqs. 4.11-4.15 [61].

$$H_{RDT\&E,labour} = H_{RDT\&E,engineering}/Q = 4.86 \times (2.2OEW)^{0.777}(0.54V)^{0.894}Q^{0.163}/Q \tag{4.11}$$

$$C_{RDT\&E,labour} = H_{RDT\&E,labour}R_{RDT\&E,labour}(1+I)^{FY-FY_0} \tag{4.12}$$

$$C_{RDT\&E,material} = C_{RDT\&E,support}/Q = 45.42 \times (2.2OEW)^{0.630}(0.54V)^{1.3}(1+I)^{FY-FY_0}/Q \tag{4.13}$$

$$H_{RDT\&E,tooling\&equipment} = 5.99 \times (2.2OEW)^{0.777}(0.54V)^{0.696}Q^{0.263}/Q \tag{4.14}$$

$$C_{RDT\&E,tooling\&equipment} = H_{RDT\&E,tooling\&equipment}R_{RDT\&E,tooling\&equipment} \cdot (1+I)^{FY-FY_0} \tag{4.15}$$

where, H refers to the RDT&E labour hours. R refers to the labour rate. The reference labour rates adopted in this model are listed in Table 4.1 or it can be obtained from labour statistics related to aerospace engineers [282]. The corresponding cost type and cost element are

shown as the subscripts. OEW is in kg. V is the maximum velocity (km/h), Q is the production quantity. The inflation factor (I) converting the cost from the reference fiscal year FY_0 to the year of the estimation fiscal year FY is incorporated. In the RDT&E high-level model, it is employed to convert the 1986 dollar to the year of evaluation. The reference material is aluminium, aircraft made from other materials is recommended to adopt the 'fudge factors', shown in Table 4.2. It is noteworthy the modified DAPCA IV model is on the basis of a development programme for a production run. In order to guarantee the evaluation is consistent on 'per aircraft basis' for the high-level model, the evaluated hours are averaged by the quantity of the aircraft produced (Q) in the production run. The cost aggregation can be calculated via Eq. 4.4, where i refers to the major LCC type-RDT&E, j refers to the cost items-labour, material, or tooling & equipment.

Table 4.1: Reference labour rates

	Labour rates (1986$) [61]	Aerospace engineering mean hourly wage (2014$) [282]
$R_{RDT\&E,engineering}$	$ 59.10	$ 51.78
$R_{tooling\&equipment}$	$ 60.70	

Table 4.2: Material related fudge factors [61]

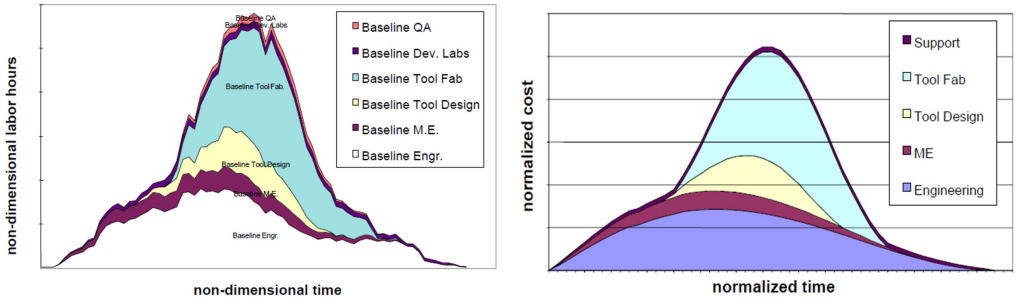
	Fudge factor
Aluminium	1.0
Graphite-epoxy	1.5-2.0
Fiberglass	1.1-1.2
Steel	1.5-2.0
Titanium	1.7-2.2

4.2.1.2. DETAIL-LEVEL MODEL

The RDT&E cost detail-level model is built on the high-level cost estimation for the design program on 'per aircraft' basis. It can be conducted when the total RDT&E cost and the RDT&E process timeline are known. The main cost driving parameters are the RDT&E process time durations, weight distribution percentages and cost distribution percentages, which are illustrated in Appendix D. The purpose is to evaluate the costs of each detailed RDT&E steps for a CP. It can be used by designers, manufacturers and cost engineers to inspect the RDT&E cost elements and to improve the efficiency of the RDT&E process. It is categorized as top-down process-based parametric method supported by data fitting techniques. This cost evaluation model is further detailed to each cost element in a design phase, while it is still an approximation due to the limited data sources on RDT&E cost.

An RDT&E process takes several years for a new commercial aircraft [61], where the conceptual, preliminary and detail design normally would take weeks to months, months to years, and several years to be conducted respectively [22]. After the production definition

is released, the initial production will be started, followed by the ground test and the maiden flight in several years. Later, another one or two years are needed starting from its type certification till the introduction into service. According to the normalized cost data, a beta distribution power function is extracted by Markish to approximate the profile of various cost changes over the RDT&E timeframe [130][283]. The RDT&E cost includes the cost elements such as the design engineering, manufacturing engineering, tool design, tool fabrication and support (incl. quality assurance and development of labs) cost along with the aircraft development process. It can be seen from Figure 4.5(a) that the non-dimensional labour hours are distributed over the development process in a non-dimensional time scale. Figure 4.5(b) shows the normalized cost distribution over the development time based on the beta distribution model.



(a) (b)

Figure 4.5: Non-dimensional development cost (Figure sources: [130][283]): (a) Boeing data for large commercial jet; (b) Markish's cost model

The beta distribution model is formulated in Eq. 4.16 in a normalized timeframe ([0,1], horizontal axis) [61]. For a specific cost element, the cost is incurred between the starting time t_0 till the time duration (Δt) is ended, say $t_1 = t_0 + \Delta t$. When the time point $t_{RDT\&E}$ is beyond the starting time t_0 and the end time t_1, no cost is incurred. The starting time and the duration for a cost element under the RDT&E cost category differ from the each other. The cost value of each cost element is equivalent to labour hours (H). $H(t_{RDT\&E})$ then refers to the amount of labour hours consumed at the time point $t_{RDT\&E}$. Beta distribution provides a relation between the labour hour consumed and the time point of the cost element incurred.

$$H(t_{RDT\&E}) = K t_{normalized}^{\alpha-1}(1-t_{normalized})^{\beta-1},\ t_{RDT\&E} \in [t_0, t_1] \tag{4.16}$$

where, $t_{normalized} = \dfrac{t_{RDT\&E} - t_0}{t_1 - t_0}$, represents the normalized time period. K is a normalized constant for each cost element. The summation of K values equal to 1. It is similar to the Beta distribution expression, while since it is a normalized constant within [0,1], it does not rigorously equal to the reciprocal of the Beta function defined in the Beta distribution. $t_{RDT\&E,k,j}$ refers to the duration of the corresponding cost element. α and β are positive shape factors of the cost profile. Markish has provided the RDT&E cost element incurred time, duration,

and values of a Boeing jet data [61]. Further, by approximating the K values via curve fittings and normalizations, the parameter list of the RDT&E cost elements is shown in Table 4.3.

Table 4.3: Parameter list of the RDT&E cost elements (normalized)

	Design engineering	Manufacturing engineering	Tool degisn	Tool fabrication	Support
Constant (K)	0.1491	0.0585	0.2576	0.5318	0.0030
Cost incurred time t_0	0	0	0.22	0.27	0
Duration (Δt)	1.00	0.85	0.45	0.50	1.00
Cost ceased time (t_1)	1.00	0.85	0.67	0.77	1.00
α	2.2	2.5	3.5	3.0	1.5
β	3.0	3.0	3.0	3.0	1.5

The labour hour accumulation of each cost element is then the integral of the labour hours over the RDT&E process, which can be represented by the cumulative function Eq. 4.17.

$$H = \int_0^1 H(t_{RDT\&E}) = \int_0^1 (\frac{t_{RDT\&E} - t_0}{t_1 - t_0})^{\alpha-1}(1 - \frac{t_{RDT\&E} - t_0}{t_1 - t_0})^{\beta-1} dt \tag{4.17}$$

By considering the RDT&E sub-process k of an aircraft component or part, this method is further developed. Given the starting time and the duration of certain sub-process, the timeframe of the cost elements incurred and ended within this sub-process can be identified by comparing the process timeframe with the cost timeframe. Accordingly, the active cost profile of the related cost element in the sub-process can then be expressed by Eq. 4.18.

$$\begin{gathered} H_{RDT\&E,k,j}(t_{RDT\&E,k,j}) = K(\frac{t_{RDT\&E,k,j} - t_0}{t_1 - t_0})^{\alpha-1}(1 - \frac{t_{RDT\&E,k,j} - t_0}{t_1 - t_0})^{\beta-1}, \\ t_{RDT\&E,k,j} \in [(t_0)_{RDT\&E,k,j}, (t_1)_{RDT\&E,k,j}] \end{gathered} \tag{4.18}$$

where, $t_{RDT\&E,k,j}$ represents any time point in the timeframe, which integrated the time frame of the process step k and the time frame of the cost element j. $(t_0)_{RDT\&E,k,j}$ is the cost incurred time for the cost element of sub-process k. $(t_1)_{RDT\&E,k,j} = (t_0)_{RDT\&E,k,j} + (\Delta t)_{RDT\&E,k,j}$ refers to the cost ceased time for the cost element j of sub-process k. The time duration is $(\Delta t)_{RDT\&E,k,j}$. Therefore, the Markish's model is upgraded by dividing the RDT&E process into detailed process steps in correspondent time frames, demonstrated in Figure 4.6. The period from launching the project through the conceptual design concept definition to the preliminary design concept definition is considered as conceptual & preliminary design definition phase. After releasing the preliminary design till the detail design concept freeze is recognized as detail design definition phase. The stage of producing the first aircraft is denoted as initial production phase. While the period between the initial production and the maiden flight belongs to the ground test phase. Last but not the least, the type certification phase from the first fly till service is also counted in RDT&E process. In Figure 4.7, the accumulated normalized costs at specific time points can be identified along

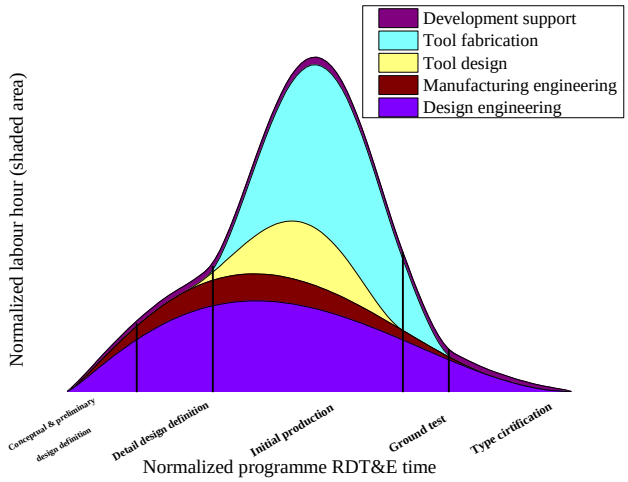


Figure 4.6: Upgraded Markish's model for non-dimensional RDT&E cost

with the timeline progress for the design project. The cost accumulation for each cost element is illustrated by the shaded area.

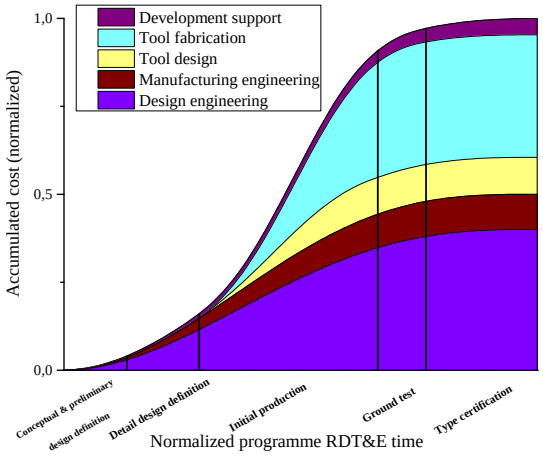


Figure 4.7: Upgraded Markish's model for non-dimensional RDT&E cost accumulation

Next, the labour hour accumulation of each cost element of a sub-process is then the integral of the labour hours from the starting time point along the time duration till the end

time point, which can be represented by the cumulative function Eq. 4.19.

$$\begin{aligned} H_{RDT\&E,k,j} &= \int_{(t_0)_{RDT\&E,k,j}}^{(t_1)_{RDT\&E,k,j}} H_{RDT\&E,k,j}(t_{RDT\&E,k,j}) \\ &= K \int_{(t_0)_{RDT\&E,k,j}}^{(t_1)_{RDT\&E,k,j}} (\frac{t_{RDT\&E,k,j} - t_0}{t_1 - t_0})^{\alpha-1} (1 - \frac{t_{RDT\&E,k,j} - t_0}{t_1 - t_0})^{\beta-1} dt \end{aligned} \tag{4.19}$$

By converting the accumulated labour hours in a normalized fashion, see Eq. 4.20. The normalized labour hour then implies the fraction of each cost element of a sub-process in the total RDT&E cost, so-called the cost element weighting factor ($(H_{normalized})_{RDT\&E,k,j}$).

$$(H_{normalized})_{RDT\&E,k,j} = H_{RDT\&E,k,j} / \sum_k \sum_j H_{RDT\&E,k,j} = H_{RDT\&E,k,j} / H_{RDT\&E} \tag{4.20}$$

Assume the labour rates for all the RDT&E sub-processes are equivalent to the average labour rate for the overall RDT&E process, therefore, Eq. 4.21 can be obtained.

$$C_{RDT\&E,k,j} = H_{RDT\&E,k,j} R_{RDT\&E,k,j} = C_{RDT\&E} (H_{normalized})_{RDT\&E,k,j} \tag{4.21}$$

Moreover, according to the assumption made for the cost conversion (Section 4.1.3), the costs of CP or component are expressed in Eq. 4.22 by applying the weight percentages (W_{CP}/W). It is noted that the total RDT&E cost estimated from the high-level model is an input for the detail-level model estimation. The influence of the inflation factor has been included in the RDT&E cost input. The process step k refers to the conceptual design, preliminary design, detail design, initial production, prototype test and type certification; the cost item j refers to the design engineering cost, manufacturing engineering cost, development support cost, tool design cost or tool fabrication cost.

$$(C_{CP})_{RDT\&E,k,j} = C_{RDT\&E,k,j} \frac{W_{CP}}{W} \tag{4.22}$$

4.2.2. PRODUCTION COST ESTIMATION

On the basis of the product representation and process generalization elaborated in production view generation (Section 3.2.2), the cost elements of the production cost for both high-level and detail-level model are emphasized in Figure 4.8(a) and 4.8(b) respectively. It is noted the facility cost refers to the cost of the manufacturing plant amortized to each production run, which is categorized into the recurring cost. While it can also be paid as a lump sum in advance, which should be grouped into the non-recurring cost. In the following sections, the CERs of the focused production cost elements for both high-level model and detail-level model are elaborated.

4.2.2.1. HIGH-LEVEL MODEL

When the production process plan cannot be derived or is not available for the aircraft or the components, the high-level model is employed. Similar to the high- level RDT&E cost analysis, it adopts aircraft OEW, as the main cost driving parameters. Other properties such

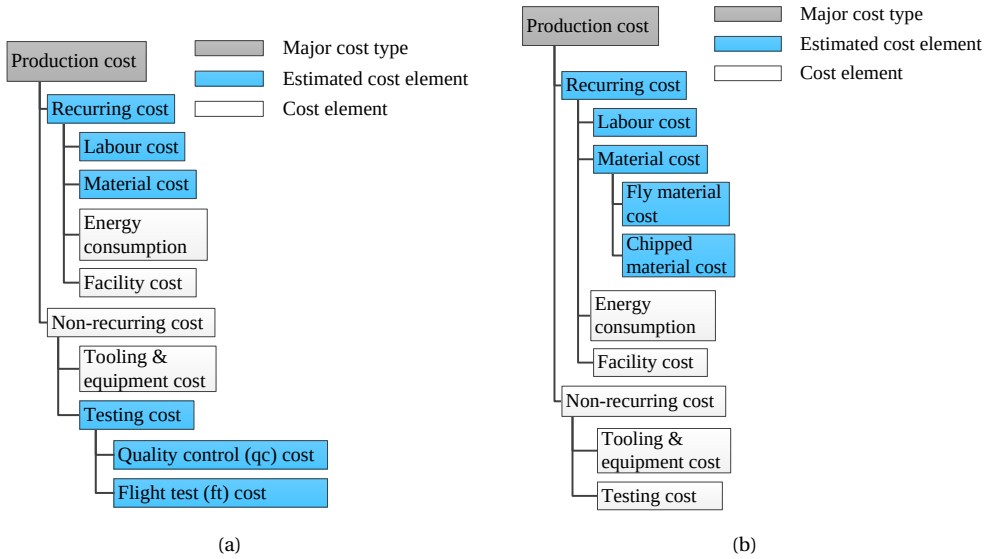


Figure 4.8: Production cost CBS: (a) High-level model; (b) Detail-level model

as the aircraft maximum velocity and production quantity are also utilized in the analysis. The output is a unit production cost for an aircraft. The CERs are extracted from regression analyses in the form of exponential equations. By further incorporating the cost items related to the product manufacturing/assembly and the inflation factor, Raymer's model for production cost analysis is updated to represent the high- level model. It is a top-down feature-based parametric method using cost-time analysis techniques. The production cost contains the labour cost, material cost and quality control cost. The labour cost refers to the labour incurred by manufacturing processes (e.g. machining, forming) and assembly processes (e.g. fastening, part installation). The materials include the raw materials (e.g. aluminium alloy, prepreg graphite layer) and hardware (e.g. fasteners, clamps) and purchased systems/equipment (electrical, hydraulic systems). The quality control cost ($C_{production,qc}$) during the production process is included in the production test cost. Besides, the flight testing cost ($C_{production,ft}$), which involves the cost of the airworthiness certification along with the total production run, is also part of the production cost. The CERs of the high- level model are shown as follows (Eqs. 4.23-4.26) [61].

$$H_{production,labour} = 7.37 \times (2.2OEW)^{0.82}(0.54V)^{0.484}Q^{0.641}/Q \tag{4.23}$$

$$C_{production,labour} = H_{production,labour}R_{production,labour}(1+I)^{FY-FY_0} \tag{4.24}$$

$$C_{production,material} = 11 \times (2.2OEW)^{0.921}(0.54V)^{0.621}Q^{0.799}(1+I)^{FY-FY_0}/Q \tag{4.25}$$

$$
\begin{aligned}
C_{production,testing} &= C_{production,qc} + C_{production,ft} \\
&= r_{production,qc} H_{production,labour} R_{production,qc} (1+I)^{FY-FY_0} \\
&+ 1243.03 \times (2.2OEW)^{0.325} (0.54)^{0.822} FTA^{1.21} (1+I)^{FY-FY_0} / Q
\end{aligned}
\tag{4.26}
$$

When the aircraft is a cargo plane, the $r_{production,qc}$ is 0.076; for the other aircraft, the $r_{production,qc}$ is 0.133. The *FTA* refers to the number of fly test aircraft, and is typically from 2 to 6 [61]. The labour rates are listed in Table 4.4 as references. The same fudge factors listed in Table 4.2 are recommended to be incorporated based on the use of different materials. In order to be consistent for the high-level model on 'per aircraft basis', the costs are normalized by the number of aircraft produced in the production run. The cost summation can be obtained by Eq. 4.4, where i refers to the Production cost type, j represents labour, material, or testing cost item.

Table 4.4: Reference labour rates

	Labour rates (1986$) [61]	Aerospace engineering mean hourly wage (2014$)
$R_{production,labour}$	$50.10	$51.78
$R_{production,qc}$	$55.40	

4.2.2.2. DETAIL-LEVEL MODEL

For detail-level model, it is assumed that logic rules are available for manufacturing and assembly process prediction. The cost driving parameters are product properties including geometric sizes such as the product length and the area, material types such as the density and the unit price, and weight properties such as the fly-weight, the chipped-weight; process properties involving the manufacturing and assembly processes such as hand-layup, resistance welding, part numbers based on the number of the production runs and the production lot size. It aims at evaluating the cost of a product unit for the use of manufacturers, designers and engineers. It is categorized as bottom-up process-based parametric method supported by KBE techniques. This model is detailed and accurate in revealing the relationships between cost driving parameters and the process costs. It is also combined with the genetic-causal model since the cost driving parameter is employed as the causes of the incurred cost. And it is limited to airframe recurring cost estimation while the engine cost and airframe nonrecurring cost are excluded.

The production cost mainly contains the labour cost and the material cost items, which are aggregated from the cost consumed by each manufacturing/assembly process. Moreover, the production process for a part/component is divided into a series of manufacturing/assembly process steps (k). Those process steps are split up based on the engineering conventions (expert opinions). The data of the process steps are stored in the process KB, which also contains knowledge of conventional process step breakdown resourced from engineers. However, the process step breakdown can be subjective due to a lack of objective

and unified standardizations. Therefore, it is limited to production runs in a specific factory. The time for every process step ($t_{production,k,labour}$) is estimated via the estimation relationships driven by the cost drivers. Those CERs are collected from industry as well as academic literature, which complies with the parametric cost estimation method. Specifically, it includes CERs from ACCEM project [284] on the basis of power law model (Eq. 4.27), COSTADE project [285][286][287] on the basis of first-order model, hyperbolic function model (Eqs. 4.28 and 4.29) [105], and Haffner's updates [106] based on the hyperbolic function model [106]. The power law model is generally applicable for metal materials as well as composite materials, and the latter two models focus on production processes applied to composite materials. The process step labour hour evaluated is an average value assigned to each product unit over a production run [284]. They all adopt cost driving parameters x, which is a general representation of geometric sizes (e.g. length, area), material types (e.g. density, unit price), weight (e.g. fly-weight, chipped-weight), part numbers, etc.

$$(t_{CP})_{production,labour} = A_{production,k,labour}((x_{CP})_{production,k,labour})^{b_{production,k,labour}} \tag{4.27}$$

$$\frac{(x_{CP})_{production,k,labour}}{(v_0)_{production,k,labour}(\tau_0)_{production,k,labour}} = \frac{(t_{CP})_{production,k,labour}}{(\tau_0)_{production,k,labour}} - (1 - e^{-(t_{CP})_{production,k,labour}/(\tau_0)_{production,k,labour}}) \tag{4.28}$$

$$(t_{CP})_{production,k,labour} = \sqrt{(\frac{(x_{CP})_{production,k,labour}}{(v_0)_{production,k,labour}})^2 + \frac{2(\tau_0)_{production,k,labour}}{(v_0)_{production,k,labour}}(x_{CP})_{production,k,labour}} \tag{4.29}$$

Attentions have been drawn to the physical implications and the application examples of the three CER forms adopted for the process step labour hours. The **power law model** is extracted from the curve fit according to data collected from historical manufacturing practices [284]. It involves two factors: $A_{production,k,labour}$ and $b_{production,k,labour}$. The former is the cost coefficient and the latter is the exponential coefficient, determining the shape of the cost curve varying along with the change of cost driving parameter. Generally, the power law model is formulated in the way that the labour hour increases along with an increase in the cost driving parameter. The power law model is extensively utilized in industry and generally applicable for different production processes. It is accurate when the historical data of each process is available [105], while it is not flexible for adaptation when the process condition changes. The **first-order model** is related to the physics of the production process. It is derived by Neo based on the size scaling effect on the extensive production processes, which are the manufacturing/assembly processes involving dynamic motions in space [288]. Generally speaking, the larger the product, the longer the process step labour hour is needed. The parameters are interpreted physically. The physical factors influence the time consumed by

each process. $(\tau_0)_{production,k,labour}$ is the manufacturing/assembly process step time constant and $(v_0)_{production,k,labour}$ is the manufacturing/assembly process step steady state speed. When $(t_{CP})_{production,k,labour} = (\tau_0)_{production,k,labour}$,then $v_{production,k,labour} = 0.63(v_0)_{production,k,labour}$, which indicates that the process step time constant is the time taken to reach 63% of the steady speed [105].The first-order law model is generally applicable to extensive production processes such as cutting process, hand layup process, and 3D-printing process. This model is with improved predictability compared with the power-law model and can be quickly adjusted if the process step steady speed and the process step time constant are changed. However, due to the first-order function format, it is inconvenient to be solved directly for the process step labour hour. The **hyperbolic function model** is originated from Boeing Commercial Aircraft Group [288] and is also an approximation of the first order model where the same variables are retained. It contains a linear item and a transient item. The process step labour approaches $x^{1/2}$ when x is small while it gets close to x when x is large. An example comparing the power law model, the first order model and the hyperbolic function model is shown in Figure 4.9 in metric units [284]. It illustrates a composite hand layup process (k is referred to $hand-layup$), which contains the following sequential operations: unroll tape on the tool, template or preceding ply, smooth down, cut and peel backing paper [284]. The operator manually places layers of the materials on a tool smoothly. Each ply is positioned in accordance with the predefined fibre orientation and location. The operator cuts the ply and removes the release film to form the basic part shape [105]. The tape length for this example is 762 mm. The power law model utilizes the cost of the length of the stripe (l) as the cost driver, while the cost coefficient is 0.0027 and the exponential coefficient is 0.6018. The first-order model and the hyperbolic function employee the 0.0191 hr as the process step time constant and 278130 mm/hr as the process step steady state speed. The first order model is derived according to the physical properties of the process, therefore, it is seen the closest estimation of the real cost. The power law model estimation is good for long length while is slightly lower in cost for short and very long length. The hyperbolic function model is good for the short-length product while is lower for the long-length product.

Some other CERs can be found from Castagne *et al.* [132] and Kassapoglou *et al.*[135][136][137][138]. Depending on the labour hour formulation of a specific process, the cost expression can be subject to minor modifications such that more than one cost drivers can be included in the CER [120][284]. Many production processes often require a setup time constant ($(H_{setup})_{production,k,labour}$) before the process execution. It has to be the setup process conducted recurrently for each production run other than the setup process before the production started. For example, the setup time for hand layup process for 762mm tape is 0.05 hr. The labour cost, depending on the average labour hour ($(H_{CP})_{production,k,labour}$) and the average labour rate ($R_{production,k,labour}$), equals the sum of the setup process labour cost and the actual process labour cost, see Eq. 4.30. Eventually, the labour cost is obtained while applying the corresponding inflation factors. The material cost including the fly material cost and the chipped material cost are formulated in Eq. 4.31. When the material cost of a part is evaluated, the total materials contain the materials remained in the aircraft for flying and the materials scrapped during the manufacturing process. When the material cost of an assembly connection is evaluated, the total material is then the additional material

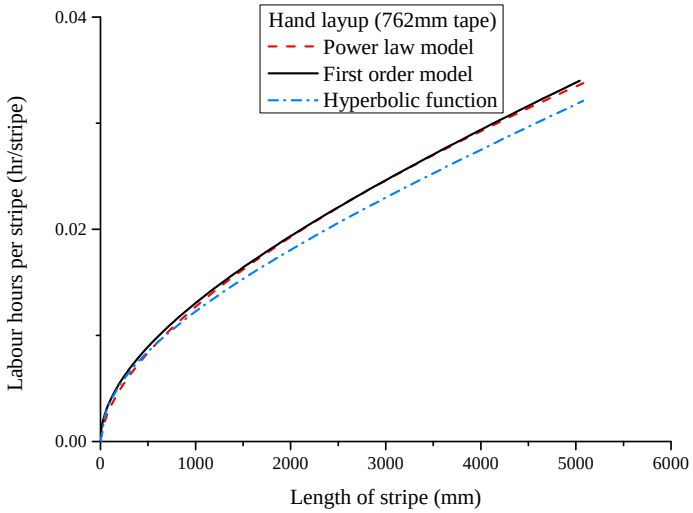


Figure 4.9: Power law model, first order model and hyperbolic function model - Hand layup example (adapted according to [288])

such as fasteners and bonding materials consumed for the assembly process. The cost evaluated is on the basis of the product model, which can be an aircraft, a component and/or a part, therefore, conversion on the cost basis is needed when it is necessary. Afterwards, the production cost for a CP can then be collected through Eq. 4.9, where i stands for the Production (or M&A) cost type; the process steps k are manufacturing and assembly steps such as milling, press-forming, or bonding; the cost items j indicate labour, fly material or chipped material cost.

$$\begin{aligned}(C_{CP})_{production,k,labour} &= (H_{CP})_{production,k,labour} R_{production,k,labour} (1+I)^{FY-FY_0} \\ &= [(H_{setup})_{production,k,labour} (r_{setup})_{production,k,labour} \\ &\quad (t_{CP})_{production,k,labour} (r)_{production,k,labour} (1+I)^{FY-FY_0}\end{aligned} \tag{4.30}$$

$$\begin{aligned}&(C_{CP})_{production,k,labour} \\ &\quad = W_{CP}[1+(r_{chipped})_{production,k,labour}](P)_{production,k,labour}(1+I)^{FY-FY_0}\end{aligned} \tag{4.31}$$

Moreover, the learning curve effect should also be considered. Every time the aircraft production quantity is doubled, the labour cost per aircraft is reduced, which also applies to the labour cost per aircraft component. Using the labour hour consumption to represent the labour cost for each production process step, the labour hour is $(1-r_{learning})_{production,k,labour}$ times the initial cost, see Eq. 4.32. This indicates a learning curve factor and correspondingly a learning curve exponent, $(r_{learning})_{production,k,labour}$ and z. To integrate the aircraft quantity into the calculation, the process labour hour when every time one more product is added can be obtained by applying the learning curve exponent on the production quantity

ratio [120]. The generalized equivalent mathematical expression is written as Eq. 4.33.

$$H_{production,k,labour}/(H_0)_{production,k,labour} = (r_{learning})_{production,k,labour}, \quad \text{when } Q_{production,k,labour}/(Q_0)_{production,k,labour} = 2 \tag{4.32}$$

$$H_{production,k,labour} = (H_0)_{production,k,labour}(Q_{production,k,labour}/(Q_0)_{production,k,labour})^{(z_{production,k,labour}-1)} \tag{4.33}$$

where, $(H_{CP})_{production,labour}$ is the process hour per aircraft/component, $(H_0)_{production,k,labour}$ is the initial process hour per aircraft/component, $(Q_{CP})_{production,k,labour}$ is the production quantity, $(Q_0)_{production,k,labour}$ is the initial production quantity. Given the learning curve factor, the learning curve exponent can be derived. According to Eq. 4.32 and Eq. 4.35, we have Eq. 4.34, which can be transformed to Eq. 4.35. Therefore, the learning curve exponent is expressed as Eq. 4.36.

$$(r_{learning})_{production,k,labour} = 2^{(z_{production,k,labour}-1)} \tag{4.34}$$

$$2^{z_{production,k,labour}} = 2(r_{learning})_{production,k,labour} \tag{4.35}$$

$$z_{production,k,labour} = 1 + \frac{log(r_{learning})_{production,k,labour}}{log2} \tag{4.36}$$

Figure 4.10 lists a series of learning curve examples. It is assumed that there are 300 shipsets in a production run. The labour hour is presented in a normalized fashion. Aircraft production typically follows a 75-80% learning curve [80]. For example, when every time the aircraft production quantity is doubled, the labour cost per aircraft goes down 20%, implying an 80% learning curve. The corresponding learning curve exponent is 0.68.

In order to incorporate the learning curve effect into the model, the labour hour can then be formulated for each of the three CER types. It should be noted when the production condition is changed, such as the introduction of the new tool or equipment, the relationship of labour hour evaluation needs to be updated to incorporate the learning curve. For power law model, this adaptation can be done by regression analysis on the basis of a new set of data; while for the first order model and the hyperbolic function model, to replace the process step time constant and the steady speed with a new set of values is necessary.

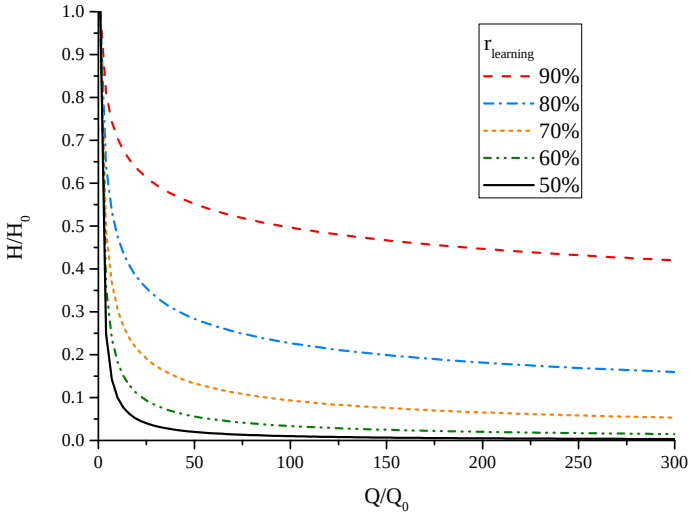


Figure 4.10: Examples of production learning curve

4.2.3. O&M COST ESTIMATION

According to the product representation and process generalization elaborated in Section 3.2.3 and the cost elements of the O&M cost focused on the high-level and detail-level model are shown in Figure 4.11(a) and 4.11(b) respectively, the CERs of the focused production cost element estimations on both levels are elaborated.

4.2.3.1. HIGH-LEVEL MODEL

The high-level model of the O&M cost adopts the $DOC + I$ model, which aggregates the operating and the maintenance cost elements together in an analysis [289]. It is based on a collective effort of the commercial aircraft manufacturers and institutions up to that date. The $DOC + I$ model is updated from the original ATA DOC model [290] by adjusting the CBS structure and adding the indirect cost items to the cost estimation while focusing on the airplanes with turbofan engine technology. Besides the use of weight properties as the cost drivers, other parameters influenced by the use of turbofan propulsion systems, such as the block hour, block fuel and typical average flight trip length, are considered. In the thesis analysis, it only focuses on the airframe cost, therefore, the cost items related to the engine are not included. Referring to the cost estimation method classification, this model belongs to the top-down feature-based parametric method using regression analyses. The CERs are illustrated below for the trip operating cost and the maintenance cost separately. Due to the limit of its historical database, correction factors might be needed for current and/or new aircraft studies. In order to keep a consistent unit system, the conversion factors from the imperial unit to the metric unit is incorporated. Since $DOC + I$ adopts the mid-1993 money, which needs to be converted to constant year FY dollar by applying the constant inflation rate I from the reference year FY_0 to the year FY in the analysis. In addition, the high-level

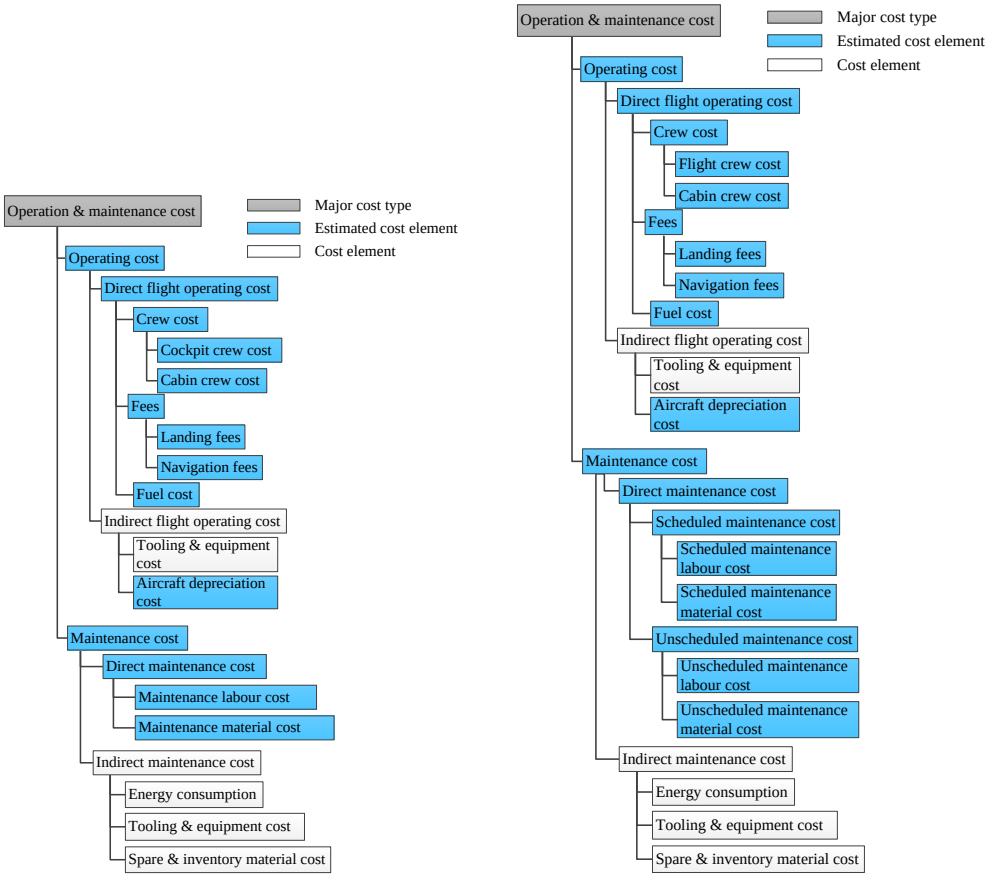


Figure 4.11: O&M cost CBS: (a) High-level model; (b) Detail-level model

model O&M cost estimation is set on 'per trip per aircraft' basis. A flight trip comprises a Flight Cycle (FC) and a number of Flight Hours(FH). A FC refers to one take off and its subsequent landing [291]. The FH refers to the length of time in the flight service [291]. The FH differs from the Block Hour (BH), which is defined as the time from airplane pushback from the gate at origin to arrival at the gate of the destination and is also called aircraft hours [292]. In this research, the FH and BH are inputs extracted according to the airline statistics for a specific aircraft on a yearly basis.

- **Flight operating cost**

The operating cost containing the crew, fee, fuel and depreciation cost elements are shown from Eq. 4.37 to Eq. 4.41.

$$\begin{aligned} C_{operating,crew} &= [440 + 0.532 \times (2.2MTOW/1000) \\ &\quad + (n_{seat}/35) \times 60] H_{operating,crew}(1+I)^{FY-FY_0} \text{[Domestic]} \\ C_{operating,crew} &= [482 + 0.590 \times (2.2MTOW/1000) \\ &\quad + (n_{seat}/30) \times 78] H_{operating,crew}(1+I)^{FY-FY_0} \text{[International]} \end{aligned} \tag{4.37}$$

$$\begin{aligned} C_{operating,fee} &= 1.5 \times (2.2MLW/1000)(1+I)^{FY-FY_0} \text{[Domestic]} \\ C_{operating,fee} &= [4.25 \times (2.2MTOW/1000) \\ &\quad + 0.136 \times (0.54 \times 926) \times \sqrt{2.2MTOW/1000}](1+I)^{FY-FY_0} \text{[International]} \end{aligned} \tag{4.38}$$

$$W_{fuel} = MTOW(W_{fuel}/MTOW) \tag{4.39}$$

$$C_{operating,fuel} = r_{operating,fuel} W_{fuel} \tag{4.40}$$

$$C_{operating,depreciation} = [(P_{AC} - P_{residual})/t_{depreciation}]/U \tag{4.41}$$

where, the operating time for crew cost ($H_{operating,crew}$) is equivalent to the Block Hour (BH) of a flight trip, which can be calculated from the range (R) and speed (V) properties. The operating crew cost ($C_{operating,crew}$) is estimated based on the Maximum Take Off Weight ($MTOW$) and the seat capacity (n_{seat}). The operating fee ($C_{operating,fee}$), containing landing and navigation charges, is based on the Maximum Landing Weight (MLW) and the $MTOW$. And only international flights count the navigation fee, which is based on the first $926km$ of a trip. The fuel cost is the production of the jet fuel price ($r_{operating,fuel}$) and fuel weight (W_{fuel}), which is related to the fuel weight fraction ($W_{fuel}/MTOW$). The depreciation cost is evaluated on 'per aircraft per trip basis' according to the difference between the aircraft price (P_{AC}) and its residual price ($P_{residual}$) within a depreciation period ($t_{depreciation}$) and is further averaged by the number of trips in a year, so called the aircraft yearly utilization (U). The residual price is approximated to 10% of the aircraft prices in general [33].

- **Maintenance cost**

The maintenance cost contains the maintenance expenses of labour and material. The estimation method is originated from the analysis of the Boeing Commercial Airplane Group (BCAG) and evolved to "$DOC+I$" method. The airframe maintenance labour hour and material cost ($H_{maintenance,labour}$ and $C_{maintenance,material}$) per flight trip is influenced by the maintenance hours occurred for each FC and the maintenance hours induced based on the

FHs. Therefore, the costs consist of both the 'per FH' term and the 'per FC' term (Eqs 4.42 to 4.48

$$H_{maintenance,labour}/FH = 1.260 + (1.774 \times 2.2AFW/10^5) - 0.1071 \times (2.2AFW/10^5)^2 \quad (4.42)$$

$$H_{maintenance,labour}/FC = 1.614 + (0.7227 \times 2.2AFW/10^5) + 0.1024 \times (2.2AFW/10^5)^2 \quad (4.43)$$

$$H_{maintenance,labour} = (H_{maintenance,labour}/FH)(FH/trip) + H_{maintenance,labour}/FC \quad (4.44)$$

$$C_{maintenance,labour} = H_{maintenance,labour} R_{maintenance,labour} (1+I)^{FY-FY_0} \quad (4.45)$$

$$C_{maintenance,material}/FH = [12.39 + (29.80 \times 2.2AFW/10^5) + 0.1861 \times (2.2AFW/10^5)^2](1+I)^{FY-FY_0} \quad (4.46)$$

$$C_{maintenance,material}/FC = [15.20 + (97.33 \times 2.2AFW/10^5) - 2.862 \times (2.2AFW/10^5)^2](1+I)^{FY-FY_0} \quad (4.47)$$

$$C_{maintenance,material} = (C_{maintenance,material}/FH)(FH/trip) + C_{maintenance,material}/FC \quad (4.48)$$

where, the maintenance labour cost ($C_{maintenance,labour}$) is the production of the maintenance labour hour per flight trip and the maintenance labour rate ($R_{maintenance,labour}$). The Airframe Weight (AFW), which is the manufacturer's empty weight less the weight of the engines, represents the main cost driver. In summary, the O&M cost items measured in the high-level model are labour cost, fee, depreciation and material cost, see Eqs. 4.49 to 4.52.

$$C_{O\&M,labour} = C_{operating,crew} + C_{maintenance,labour} \quad (4.49)$$

$$C_{O\&M,fee} = C_{operating,fee} \quad (4.50)$$

$$C_{O\&M,material} = C_{operating,fuel} + C_{maintenance,material} \tag{4.51}$$

$$C_{O\&M,depreciation} = C_{operating,depreciation} \tag{4.52}$$

Thereafter, the operating part of the O&M cost aggregation according to Eq. 4.4 can be formulated, where i refers to the O&M, j refers to cost items of labour, fee, material or depreciation. The O&M insurance, interest and the maintenance burden presented in the "$DOC+I$" method are separately grouped into the operator relevant miscellaneous cost category corresponding to the LCC CBS, see Section 4.2.5.

4.2.3.2. DETAIL-LEVEL MODEL

The detail-level model for O&M cost is built on the properties of the operating and maintenance process steps. It is assumed the process step properties for operating and maintenance cost analysis are known or predictable based on the rules stored in the process-KB. Time and fuel calculations for the segments of the mission profile are adopted for the detail-level trip operating cost model. More than 60 parameters are needed for this estimation. For maintenance cost estimation, the labour hours consumed for the maintenance tasks are collected to estimate the scheduled maintenance labour cost. Furthermore, by incorporating the ratio between the scheduled maintenance labour cost and the unscheduled maintenance labour cost, as well as the ratio between the scheduled material cost and the unscheduled material cost, the total maintenance costs are obtained. This method aims at constructing an O&M cost model that links the aircraft design parameters, the operating parameters including the operating procedure and the maintenance schedule, and eventually to connect those causal factors to CERs. Similar to the detailed cost estimation method for the other cost types, the detail-level O&M cost model is dedicated to bottom-up process-based parametric method category, and is supported by KBE techniques. To be consistent with the high-level model, the detail-level O&M cost estimation is also set on 'per trip per aircraft/component' basis. Since the aircraft geometry for flight operation is the whole aircraft, while the geometric segmentation for maintenance processes is divided into maintenance zones, therefore, the estimation for operating cost and for maintenance cost are separated into two sets of equations. In order to further perform cost aggregation and optimization studies, the transformation between 'per aircraft' and 'per component' are conducted when necessary. Inference rules for specific operating and maintenance process prediction are extracted and formulated in "if…then…" statements. The method is generally applicable for standard operating and maintenance process. In detail, the flight trip operating cost is divided into the costs of the operating segments. The maintenance cost is subdivided into the costs allocated to each maintenance task.

- **Flight operating cost**

A typical aircraft mission profile representing a flight trip operating is illustrated in Figure 4.12. Time and fuel consumption are deployed on each operating process segment. The Reserve

fuel required includes the contingency trip fuel, alternative fuel and the final reserve fuel. Three operating cost items, viz., the crew cost, the airport charge fee and the fuel cost are estimated for the flight mission profile. The CP of flight operating cost is the overall aircraft, therefore, the subscript 'CP' is not necessarily labelled in the calculation but for the consistent use of symbols.

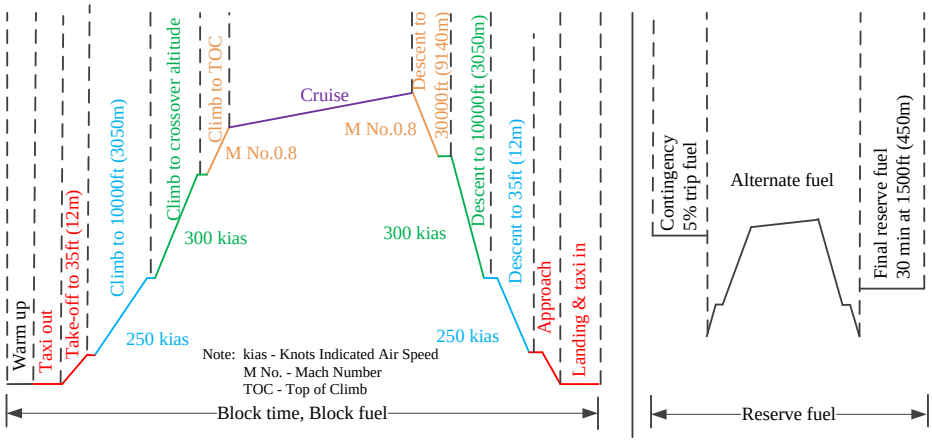


Figure 4.12: Aircraft mission profile [130] [283]

where the warm-up crew cost ($C_{operating,warm-up,crew}$) is estimated based on an average warm-up time ($H_{operating,warm-up}$) [293], the hourly rates ($R_{operating,warm-up,flight-crew}$, $R_{operating,warm-up,cabin-crew}$) and the numbers of flight and cabin crew ($n_{flight-crew}$, $n_{cabin-crew}$), see Eq. 4.53. The fuel cost is obtained from the fuel rate ($R_{operating,warm-up,fuel}$) and the consumed fuel mass ($W_{operating,warm-up,fuel}$) according to the empirical weight fraction, see Eqs. 4.54 to 4.55.

$$
\begin{aligned}
&(C_{CP})_{operating,warm-up,crew} \\
&= (H_{operating,warm-up} R_{operating,warm-up,flight-crew} n_{flight-crew} \\
&\quad + H_{operating,warm-up} R_{operating,warm-up,cabin-crew} n_{cabin-crew})(1+I)^{FY-FY_0}
\end{aligned} \tag{4.53}
$$

$$
W_{operating,warm-up,fuel} = \Delta W_{warm-up} = (1 - \frac{W_{warm-up}}{MTOW}) MTOW \tag{4.54}
$$

$$
\begin{aligned}
&(C_{CP})_{operating,warm-up,fuel} \\
&\quad = (R_{operating,warm-up,fuel} W_{operating,warm-up,fuel})(1+I)^{FY-FY_0}
\end{aligned} \tag{4.55}
$$

Taxi-out and take-off: Since the time of a smooth taxi-out and take-off is very little, the crew cost due to this operation segment can be neglected. The fuel weight fraction is employed for the fuel cost evaluation by using $\frac{W_{TO}}{MTOW}$ in Eq. 4.54 and corresponding fuel weight ($W_{operating,TO,fuel}$) in Eq. 4.55. In addition, the take-off charge is assessed as part of this segment cost. Based on the airport charge report [294], Eq. 4.56 shows that the cost including the weight based take off charge ($R_{TO}W_{TO}$), and the service charge ($_{R_{service}n_{seat}r_{occupancy}}$), security fee ($R_{security}n_{seat}r_{occupancy}$), and Passengers with Reduced Mobility (PRM) levy ($R_{RPM_levy}n_{seat}r_{occupancy}$), which all based on the number of available seat ($n_{seat}r_{occupancy}$).

$$(C_{CP})_{operating,TO,fee} = (R_{TO}W_{TO} + R_{service}n_{seat}r_{occupancy} + R_{security}n_{seat}r_{occupancy} + R_{PRM_levy}n_{seat}r_{occupancy})(1+I)^{FY-FY_0} \tag{4.56}$$

Climb: According to the typical climb law, three climb segments are considered (Figure 4.12): from $0m$ to $3050m$ at constant $128.6m/s$. Indicated Air Speed (IAS); from $3050m$ to crossover altitude above $9140m$ at constant $154.3m/s$ (IAS); from $9140m$ to the Top of Climb (TOC) $11000m$ at constant $0.8Mach$ [295]. The climb IAS should be converted to Ground Speed (GS) [293]. Therefore, the time to climb ($H_{operating,climb}$) is the aggregation of the time ($(\Delta H_{climb})_l$) for each climbing segments l, which is the integral of altitude (h) over the Rate of Climb (R/C), also represents the vertical velocity [80], see Eqs. 4.57 and 4.58.

$$H_{operating,climb} = \sum_l (\Delta H_{climb})_l \tag{4.57}$$

$$(\Delta H_{climb})_l = \int_{h_{initial}}^{h_{final}} \frac{dh}{R/C} \tag{4.58}$$

Assume the changes linearly with the change of the altitude, then we have Eq. 4.59:

$$(\Delta H_{climb})_l = \frac{h_{l+1} - h_l}{R/C_{l+1} - R/C_l} ln(\frac{R/C_{l+1}}{R/C_l}) \tag{4.59}$$

where the R/C can be evaluated according to force equilibrium during climb [292], Eq. 4.58 applies. It is calculated by applying formulas of thrust (T) and density (ρ) at altitude h, converting IAS to GS as V_∞ ([292] and [295]), and substituting the average weight during climb ($\bar{W}$), wing reference area (S), zero-lift drag coefficient (C_{D_0}) and drag due to lift coefficient (K). Thereafter, the operating climb crew cost can be obtained by employing Eq. 4.60 while using $H_{operating,climb}$ for the time term.

$$R/C = V_\infty [\frac{T}{\bar{W}} - \frac{1}{2}\rho V_\infty^2 (\frac{\bar{W}}{S})^{-1} C_{D_0} - K\frac{2}{\rho V_\infty^2}(\frac{\bar{W}}{S})] \tag{4.60}$$

The operating climb fuel cost is estimated by accumulating fuel consumption for each climb segment based on the average Specific Fuel Consumptions ($(SFC)_{ave,l}$), the thrust

(T_l) and the segment time (($\Delta H_{climb})_l$), see Eq. 4.61. By combining it with the Eq. 4.55 while adopting the weight element $W_{operating,climb,fuel}$ in the calculation, the fuel cost is obtained.

$$W_{operating,climb,fuel} \approx \sum_l (\Delta W_{climb})_l = \sum_l (SFC)_{ave,l} T_l (\Delta H_{climb})_l \tag{4.61}$$

Cruise: Assume the aircraft cruises at altitude 11000m at $Mach$ 0.8. The crew cost is calculated based on the time to cruise by Eq. 4.8 from the high-level cost model while employing the cruise range (R_{cruise}) and the cruise speed ($V_{\infty,cruise}$), and substituting in Eq. 4.53. The Breguet range equation (Eq. 4.62 is adopted to estimate the *SFC*, where the lift drag ratio (L/D) and the aircraft weight properties are needed, see Eqs. 4.63 and 4.64. The fuel cost is again obtained by utilizing Eq. 4.55.

$$R_{cruise} = \frac{L/D}{SFC} \frac{V_\infty}{g} ln \frac{W_{cruise,initial}}{W_{cruise,final}} \tag{4.62}$$

$$W_{cruise,final} = W_{cruise,initial} exp \frac{-R_{cruise} SFC_g}{V_\infty (L/D)} \tag{4.63}$$

$$W_{operating,cruise,fuel} = \Delta W_{cruise} = W_{cruise,initial} - W_{cruise,final} \tag{4.64}$$

Descent: A descent process is a reversed process of climb. Three descent segments are considered: from the Top of Descent (TOD) 11890m to 9140m at constant 0.80 $Mach$; from 9140m to 3050m at constant 154.3m/s IAS; from 3050m to 10.7m at constant 128.6m/s[295]. During the descent process, the engine thrust is normally set to flight idle, i.e., the thrust is close to zero, and the speed is controlled by the aircraft altitude [292]. Similar to *R/C*, the rate of descent (*R/D*) is applied for crew cost evaluation (Eqs. 4.65 and 4.66), while the empirical weight fraction ($\frac{W_{descent}}{MTOW}$) is adopted by fuel cost calculation using Eqs. 4.54 and 4.55 while replacing the corresponding weight parameter ($W_{operating,descent,fuel}$) for descent segment.

$$(\Delta H_{descent})_l = \frac{1}{\alpha} \int_l^{l+1} \frac{1}{R/D} d(R/D) = \frac{h_{l+1} - h_l}{R/D_{l+1} - R/D_l} In(\frac{R/D_{l+1}}{R/D_l}) \tag{4.65}$$

$$R/D = -\frac{1}{C_L/C_D} V_\infty = -V_\infty [C_{D_0} (\frac{1}{2} \rho V_\infty^2)(\frac{\bar{W}}{S})^{-1} + K(\frac{1}{2} \rho V_\infty^2)^{-1} (\frac{\bar{W}}{S})] \tag{4.66}$$

Approach, landing and taxi-in: Similar to taxi-out and take-off segment, the time of a smooth approach, landing and taxi-in is negligible. The fuel cost is based on the weight fraction ($\frac{W_{landing}}{MTOW}$), Eqs. 4.54 and 4.55 apply while adopting the counterpart parameters. The airport landing fee is considered for this segment including the weight based landing fee

($R_{operating,landing,fee}$, $MTOW$), the government noise levy ($R_{gov_noise/insulation_levy}$) and weight based planning compensation levy ($R_{gov_planning_levy}$ $MTOW$) [294](Eq. 4.67).

$$(C_{CP})_{operating,landing,fee} = (R_{operating,landing,fee} MTOW + R_{gov_noise/insulation_levy} + R_{gov_planning_levy} MTOW)(1+I)^{FY-FY_0} \quad (4.67)$$

Reserve It is assumed the reserve fuel is carried but not used, therefore, the crew cost due to the time for the reserve is zero. According to Raymer, 5% reserve fuel and 1% trapped fuel are considered [80].

In summary, the operating part of costs for a CP can be constructed according to Eq. 4.9, where i stands for the major cost type - O&M cost. The process step k refers warm-up, taxi-out & take-off, climb, cruise, descent, approach & landing & taxi-in or reserve. The cost item j can be one of the crew, fuel or fee cost elements. The total operating trip cost is obtained from the following Eq. 4.68:

$$(C_{CP})_{operating} = (C_{CP})_{operating,warm-up} + (C_{CP})_{operating,to} + (C_{CP})_{operating,climb} + (C_{CP})_{operating,cruise} + (C_{CP})_{operating,descent} + (C_{CP})_{operating,landing} + (C_{CP})_{operating,reserve} \quad (4.68)$$

- **Maintenance cost**

In order to derive the maintenance tasks for each aircraft component covered by various maintenance zones, the maintenance programme development has been investigated. The maintenance programme is evolved from the Maintenance Steering Group (MSG)-1 in 1968 to the MSG-2 in 1970, till the MSG-3 for current use. The MSG-2 follows a bottom-up approach which firstly identifies the part fault till the component/aircraft fault, while the MSG-3 follows a top-down approach where the failure of the aircraft/component is considered before targeting the failure of a part or a unit. In this way, MSG-3 logic eliminates some of the unnecessary maintenance operations and is accepted by the airworthiness authorities, the commercial airplane manufacturers and most of the major business manufacturers [296][297]. Currently, MSG-3 is employed as a standard to determine the essential scheduled maintenance for new airplanes. MSG-3 is based on a rigorous knowledge based decision tree analysis concerning the failures of the parts to the failures of the aircraft system [298]. The summarized MSG-3 maintenance programme is shown in Figure 4.13. Its objective is to produce scheduled maintenance tasks performed by the Maintenance Working Groups (MWG). The causality of the maintenance programme is based on the part/component's function, its failure modes, the failure effects, and the failure causes [299]. MSG-3 considers three maintenance programme groups: systems & power plant maintenance programme, structures maintenance programme and zonal maintenance programme. The system & powerplant group provides maintenance programme for aircraft systems and engines. The structural group focuses on the maintenance programme of airframes. The zonal inspection group deals with the maintenance programme for items in each pre-divided zone area. Depending on the safety, operational and economic aspects of failures, maintenance

tasks with specific actions, intervals and durations are assigned. The tasks are listed in a sequence from a lower level to a higher level according to its difficulty and cost.

Program	MSG-3 maintenance program							
Maintenance program groups	Structural program	System &power plant program						Zonal program
		hydraulics & flight controls	environmental	powerplant & APU	avionics	fuel system	landing gear	interior
Tasks	• Lubrication / Servicing (LU / SV or LUB / SVC) • Operational / Visual Check (OP / VC or OPC / VCK) • Functional Check /Inspection (FC / IN* or * / FNC), including General Visual Inspection (GV or GVI), Detailed Inspection (DI or DET), Special Detailed Inspection (SI or SDI), Scheduled Structural Health Monitoring (S-SHM) • Restoration (RS or RST) • Discard (DS or DIS)							

Figure 4.13: MSG-3 maintenance programme (Summarized according to [296][297][300][301][302]

The initial outcome of the MSG-3 programme was combining the least required scheduled maintenance tasks from the Maintenance Review Board Report (MRBR), the Certification Maintenance Requirement (CMR) and the Airworthiness Limitations (AL), is stored in the Maintenance Planning Document (MPD) [297]. In order to identify the maintenance costs of the maintenance tasks for a specific component or system, especially those made from the composite materials. A methodology of detailed maintenance cost analysis is constructed. It is utilized to represent the detail-level model of the maintenance cost estimation. By adding the capability of maintenance scheduling and cost analysis based on KBE techniques, it enables rule/knowledge extraction, analysis process automation and acceleration. In the detail-level mode, the scheduled maintenance labour cost is firstly evaluated. It is initially predicted on a yearly basis and is later averaged to each flight trip by the number of flight trips in a year. Furthermore, the unscheduled maintenance labour cost, the scheduled and unscheduled maintenance material costs are assessed on the basis of the scheduled maintenance labour cost.

In order to conduct the actual scheduled maintenance labour cost estimation, the maintenance schedule should be predicted in advance. It involves to derivation of the number of each maintenance task is performed per year and the allocation of each maintenance task in the maintenance packages. According to the task thresholds (the deadline for the first maintenance) and intervals, the number of times n_k the maintenance task k performed in a reference fiscal year (FY_0) can be predicted. Extracted rules for planning are incorporated. For the maintenance task with a threshold value and a check interval, Eq. 4.69 is applied.

$$n_k = \begin{cases} floor\left[\dfrac{FH_{post}}{interval_k}\right] - floor\left[\dfrac{FH_{pre}}{interval_k}\right] (FH_{pre} < FH_{post} < threshold_k) \\ 1 + floor\left[\dfrac{FH_{post} - threshold_k}{interval_k}\right] (FH_{pre} < threshold_k \leqslant FH_{post}) \\ floor\left[\dfrac{FH_{post} - threshold_k}{interval_k}\right] - floor\left[\dfrac{FH_{pre} - threshold_k}{interval_k}\right] \\ \qquad (threshold_k \leqslant FH_{pre} \leqslant FH_{post}) \end{cases} \tag{4.69}$$

where, $floor$ rounds down to the nearest integer. k represents the maintenance task, n_k is the number of times the maintenance task k is performed in a FY. FH refers to the hours the aircraft has flowing in a FY, where $FH = FH_{post} - FH_{pre}$. FH_{post} is the cumulative hours since the aircraft entered into service till the end of the FY_0 (equal to the average fleet age in this research). FH_{pre} is the cumulative hours since the aircraft entered into service till the start of a FY_0. The $threshold_k$ stands for the time duration that the maintenance task k is firstly taken place since it entered into service. The $intervals$ is the maintenance interval for the maintenance task k. In this research, the $interval_k$ is obtained from a set of statistical data from the MPD. An analytical method which involves the structural failure mode and reliability analyses can also be employed to acquire the maintenance intervals [303]. However, due to the complexity of this analytical method, it needs to be further refined and validated and therefore is not elaborated in the thesis. During the calculation, the unit of the time variables should be consistent in hours (hr) or years (YE).

For the maintenance task with a threshold value and two check intervals, the interval expiring first shall apply. It is interpreted in Eq.4.70. Both intervals are considered. The number of times of performing the maintenance task is the summation of the number of times derived based on each maintenance intervals while eliminating the duplicated operations.

$$n_k = n_{k,1} + n_{k,2} - n_{k,duplicate} \tag{4.70}$$

where, $n_{k,1}$ is the number of times the maintenance task k is performed in a YE based on $interval_{k,1}$. $n_{k,2}$ is the number of times the maintenance task k is performed in a YE based on $interval_{k,1}$ (referencing Eq. 4.70 for the calculation of $n_{k,1}$, $n_{k,2}$. $n_{duplicate}$ refers to the number of duplicated operations when applying both intervals. When $l_{k,1} interval_{k,1} = l_{k,2} interval_{k,2}$, then $n_{k,duplicate} = n_{k,duplicate} + 1$, where $l_{k,1} \in \left(floor\left[\frac{FHpre}{interval_{k,1}}\right], floor\left[\frac{FHpost}{interval_{k,1}}\right]\right)$, $l_{k,2} \in \left(floor\left[\frac{FHpre}{interval_{k,2}}\right], floor\left[\frac{FHpost}{interval_{k,2}}\right]\right)$.

Besides determining the number of maintenance tasks on a yearly basis, maintenance tasks performed at different time points should be allocated into certain maintenance packages to be performed collectively. The most commonly used work packages are A-check, C-check and D-check. There is also B-check package adopted by some airlines scheduled in-between the A-check and C-check, and is performed every 3 to 5 days at gate [304]. Table 4.5 shows a summary of the A, C and D check descriptions, the intervals and the durations, which formulates the rules of task allocation.

Other categorizations for MSG-3 maintenance tasks are also applicable. According to the place where the maintenance tasks are performed, line maintenance and base maintenance are classified [118]: **IF** the task is "departure-oriented", the task interval is on transit, daily, weekly to monthly basis, and the task is performed from 1 to 24 man hours, **THEN** it is line maintenance. Examples of line maintenance tasks are LU/SV, OP/VC.It covers transit check and some tasks from A check. **IF** the task is "fix-oriented", **THEN** it is base maintenance. Examples of base maintenance tasks are FC/IN, RS, and DS. It covers some tasks from A check, C check, and D check. Alternatively, according to the task function, it is grouped into preventive maintenance and corrective maintenance: **IF** the task is applied to a non-repairable item, **THEN** it is allocated to preventive maintenance package. Examples of preventive maintenance tasks are LU/SV, OP/VC, and FC/IN*. It covers transit check, A check, C check, and

Table 4.5: Maintenance letter checks (adapted according to [4][6])

Check	Description	Duration	Interval	Location	Operation
A	General inspection of the interior/exterior of the airplane with selected area opened, example tasks: LU/SV, OP/VC	≈ 24 man-hours	biweekly to monthly /500-800 FHs/200-400 flight cycles	At gate/ Hanger	In service
C	The whole aircraft is inspected: structural inspection of airframe	Up to 6000 man-hours/ ≈ 3 days to 1	15-20 month	Hanger	Out of service
D	Major structural items are inspected: paint, exterior components, interior and equipment are removed. Example tasks: FC/IN, RS, DS	Up to 50,000 man-hours/ ≈ 1month to 2 months	6-12 year	Hanger	Out of service

some tasks from D check. **IF** the task is applied to a repairable item, **THEN** it is allocated to corrective maintenance package. Examples of corrective maintenance tasks are RS and DS. It covers some tasks form D check.

In addition, ageing aircraft costs more maintenance resources [304], which gives rise to the maturity factor. The maturity factor is originally extracted from the Boeing's maturity curve when the airframe ageing effect is considered in the analysis [304]. It is used to adjust the estimated maintenance cost for aircraft at different ages. Generally, the aircraft age (Y_{AC}) is divided into three groups: Newness (<6 years or starts at the 1st D-check), mature (6 to 12 years or between the 1st D-check and the 2nd D-check) and ageing (>6 years or starts at the 2nd D-check). The maturity factor is normalized to '1' during the mature period, and the costs are less for the maintenance in the newness period whereas more for the maintenance during the ageing period. According to Boeing's observations, two sets of maturity factors are necessary to be applied to two structurally different aircraft categories: Pre-1980 and post-1980, see Figure 4.14. By taking more inclusive cost data into account and incorporating the dummy variables such as the aircraft-type dummy variable (μ_{AC_type}), the fiscal-year dummy variable (γ_{FY}) and the airline-related or technology-relevant dummy variable (ε), the Rand Corporation proposes a series of relations between the natural logarithmic maintenance cost per FH (In($C_{maintance}/FH$)) and the aircraft age, see Eq. 4.71. The age coefficients($\beta_{maturity}$), which directly impact on the aircraft age, are of the most interest. The factor $\alpha_{maturity}$ is the maturity curve intercept value. Note that some of the mathematic symbols used by the RAND Corporation are adapted to be consistent with the ones utilized in the thesis. The maintenance costs per FH for a specific aircraft of an airline in a fiscal year ($C_{maintenance}/FH$) can then be obtained through this relation along with the increase of the aircraft age. Those cost values are further normalized by the maintenance cost per FH at the aircraft age of 6 years old, the relation between the normalized maintenance cost per

FH and the aircraft age is illustrated in Figure 4.15. According to Eq. 4.72, it is noted that the implication of the normalized maintenance cost per FH is the same as the maturity factor ($r_{maturity}$). Figure 4.15 is actually the RAND version of the Boeing's Figure 4.14 [304].

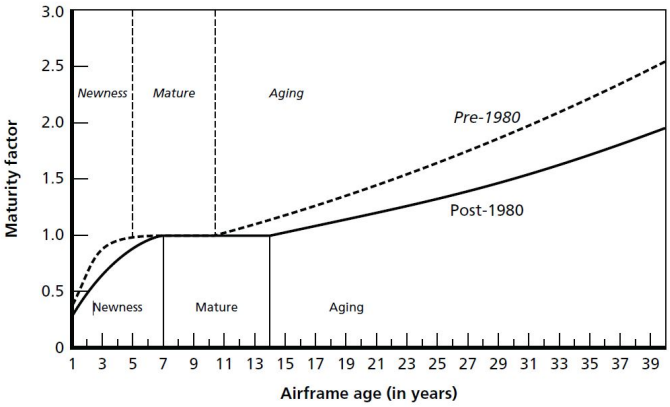


Figure 4.14: Airframe maturity factor vs. airframe age (modified from Boeing data [304])

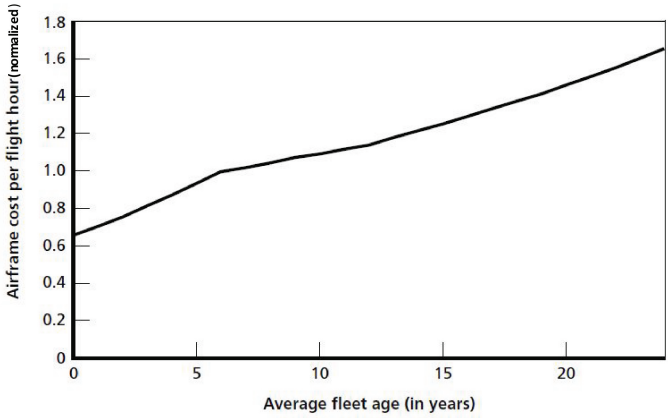


Figure 4.15: Airframe maintenance cost per FH (normalized) vs. average fleet age (estimated with form 41 data [304])

$$ln(C_{maintenance}/FH) = \alpha_{maturity} + \beta_{materity} Y_{AC} + \mu_{AC_type} + \gamma_{FY} + \varepsilon \tag{4.71}$$

$$\gamma_{maturity} = \frac{(C_{maintenance}/FH)_{Y_{AC}}}{(C_{maintenance}/FH)_{Y_{AC}=6}} \tag{4.72}$$

In essence, the maturity factor directly affects the maintenance downtime and the material consumptions for aircraft at different ages. Hence, the airframe maturity factor is applied to the scheduled maintenance costs in the mature period. Since the scheduled maintenance labour hours extracted from the MPD is a general guidance provided by the Maintenance Review Board (MRB), thus, the values are deemed to correspond to the mature period [305]. Therefore, the maturity factor considering the ageing influences should be included in the Eq. 4.74. The data of obtaining the maturity factor from Rand's maturity curve regression analyses are employed in this research, see Appendix E.

Thereafter, the scheduled maintenance labour cost can be developed according to the process parameters derived from the above-mentioned analyses and the labour hours ($H_{scheduled_mainteance,k,labour}$) as well as the number of labour forces documented in the MPD. It can be evaluated by two types of cost performance indicators. The scheduled maintenance labour cost estimated for a CP, normally referring to a component of an aircraft from a fleet in a year FY, can be expressed on the 'per trip' basis by dividing the aircraft utilization parameter (U), see Eqs. 4.73 to 4.75.

$$(C_{CP})_{scheduled_maintenance,labour} = \sum_{k} (C_{CP})_{scheduled_maintenance,k,labour} \tag{4.73}$$

$$\begin{aligned}(C_{CP})_{scheduled_maintenance,labour} = {} & (H_{CP})_{scheduled_maintenance,k,labour}\, n_k\, n_{k,labour} \\ & \cdot R_{scheduled_maintenance,k,labour}\, r_{maturity} (1+I)^{FY-FY_0}/U\end{aligned} \tag{4.74}$$

$$\begin{aligned}FH/trip = {} & H_{operating,warm-up} H_{operating,climb} + H_{operating,cruise} \\ & + H_{operating,descent}\end{aligned} \tag{4.75}$$

where, $R_{scheduled_maintenance,k,labour}$ is the scheduled maintenance labour rate for task k, i.e., the maintenance cost per hour ($\$/hr$). $(H_{CP})_{scheduled_maintenance,k,labour}$ refers to the labour time required to inspect, repair or replace an item by performing the maintenance task $k(hr)$. $n_{k,labour}$ is the number of labour forces for maintenance task k. Examples of the $(H_{CP})_{scheduled_maintenance,k,labour}$ and $n_{k,labour}$ can be found from the 'M/H' and 'MEN' columns in the Airbus MPD for A330 aircraft [305]. The $FH/trip$ is collected from the aforementioned calculation of the trip operating times including the warm-up, climb, cruise and descent times while omitting the negligible operating time periods such as the taxi-out and take-off, approach, landing and taxi-in times. The scheduled maintenance part of the cost formulation can be obtained based on Eq. 4.9, in which i stands for the major cost type - O&M cost. The process step k represents the maintenance tasks such as lubrication, visual check or restoration. The cost item j refers either labour or material cost item.

Alternatively, the mean labour cost for a maintenance task on 'per trip' basis can also be obtained, see Eqs. 4.76 to 4.78 (adapted from [128]). It provides an averaged evaluation while

the influence of aircraft ageing is eliminated.

$$C_{scheduled_maintenance,mean_labour} = \frac{FH \times R_{scheduled_maintenance,k,labour} MTTR}{MBTF}(1+I)^{FY-FY_0}/U \quad (4.76)$$

$$MTTR = \left(\sum_k \lambda_k n_k H_{scheduled_maintenance,k} n_{k,labour}\right) / \sum_k \lambda_k n_k \quad (4.77)$$

$$MTBF = \sum_k \lambda_k n_k interval_k / \sum_k \lambda_k n_k = \sum_k n_k / \sum_k \lambda_k n_k \quad (4.78)$$

where, the $MTTR$ is the mean time to repair, meaning the average repair time including the influence of the failure rate for a component. $\lambda_k = \frac{1}{interval_k}$ refers to the failure rate of a maintenance item, which can be repaired by maintenance task k. It is relevant to the reliability of a maintenance item. $MTBF$ is the mean time between failures, the average time interval including the influence of the failure rate for a component. $MTTR$, λ_k and $MTBF$ are applicable to corrective maintenance package, when the task is allocated to the preventive maintenance package, the position of the three parameters in Eqs. 4.76 to 4.78 will be replaced by the mean preventive maintenance time ($MPMT$), frequency of the task (f_k) and the mean time to failures ($MTTF$) correspondingly.

In principle, other cost items, such as the scheduled maintenance material cost, the unscheduled maintenance labour and material costs, can also be estimated according to the actual labour and material consumptions of their corresponding maintenance tasks. However, due to the lack of data sources, the detailed material usage of each maintenance task and the rules of deriving the unscheduled maintenance tasks are not available. The estimations of those cost types are then simplified. The scheduled maintenance material cost is obtained by multiplying the scheduled maintenance material rate ($R_{scheduled_maintenance,material}$) in $\$/FH$, the flight hour required for a flight trip operation ($FH/trip$) and the maintenance maturity rate ($r_{maturity}$). The $R_{scheduled_maintenance,material}$ can be extracted from the statistical data stored in the ATA data form 41 according to the aircraft type [306] (Eq.4.79).

$$(C_{CP})_{scheduled_maintenance,material} = R_{schedule_maintenance,material}(FH/trip) r_{maturity}(1+I)^{FY-FY_0} \quad (4.79)$$

It is observed that the scheduled maintenance and the unscheduled maintenance follow different maturity rate [307], therefore, the ageing effect involved cost ratio ($r_{unscheduled/schedule}$) ought to be applied to the scheduled maintenance labour cost and material cost respectively. Figure 4.16 generalizes a range of ratios of unscheduled and scheduled maintenance costs. By conducting a linear regression analysis on the mean values between the upper and lower boundaries the grey area, this cost ratio can be approximated as a parameter changes along

with the increase of the aircraft age (Eq. 4.80) [303]. Subsequently, the unscheduled maintenance labour and material costs are estimated, see Eqs. 4.81 and 4.82. Consequently, the total maintenance cost for a CP can be attained via Eq. 4.83.

$$r_{unschedule/schedule} = 0.0487 Y_{AC} + 0.8397 \tag{4.80}$$

$$(C_{CP})_{unscheduled_maintenance,labour} = (C_{CP})_{scheduled_maintenance,labour} r_{unschedule/schedule} \tag{4.81}$$

$$(C_{CP})_{unscheduled_maintenance,material} = (C_{CP})_{scheduled_maintenance,material} r_{unschedule/schedule} \tag{4.82}$$

$$\begin{aligned}(C_{CP})_{maintenance} = {} & (C_{CP})_{scheduled_maintenance,labour} + (C_{CP})_{scheduled_maintenance,material} \\ & + (C_{CP})_{unscheduled_maintenance,labour} + (C_{CP})_{unscheduled_maintenance,material}\end{aligned} \tag{4.83}$$

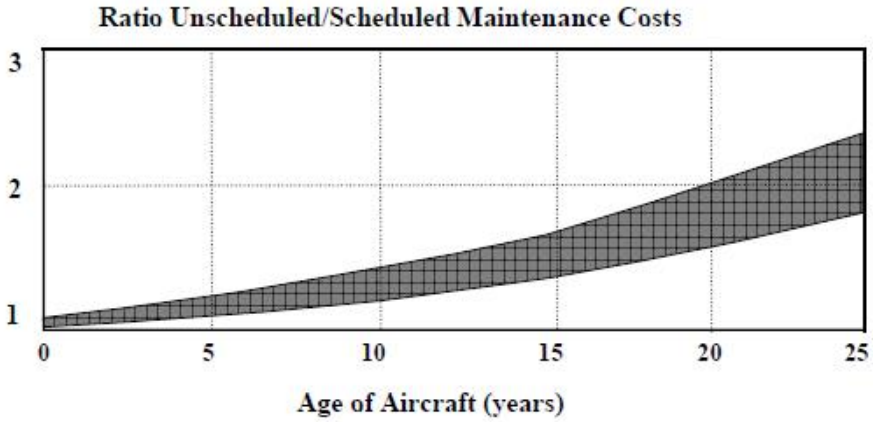


Figure 4.16: Unscheduled/scheduled maintenance cost [308]

4.2.4. D&R COST ESTIMATION

In line with the product representation and process generalization illustrated in Section 3.2.4 and the CBS of the D&R cost shown in Figure 4.17, the estimation of the focused D&R cost elements for both high-level and detail-level models are illustrated. It should be noted that the D&R costs are interpreted differently for airlines and for disposal companies.

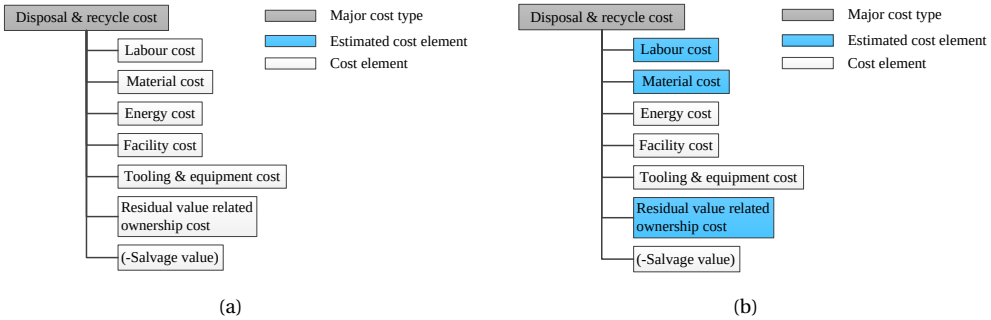


Figure 4.17: D&R cost CBS: (a) High-level model; (b) Detail-level model

4

4.2.4.1. HIGH-LEVEL MODEL

The high-level model estimation for D&R cost directly adopts an experiential factor. A detailed division of cost elements listed under this major cost type is not evaluated. Retired aircraft still worth a certain value in the resale market, therefore, they bring a negative disposal cost for airlines. Excluding the condition that the aircraft is sold by the flag airline to a low cost carrier as a second-hand aircraft, the disposal cost equals to the aircraft residual value, which is a ratio ($r_{residual}$) multiplies the aircraft purchase price, and it is around 10% in general, see Eq. 4.84 [309]. The aircraft residual value refers to the estimated aircraft price once it is retired. This evaluation assumes the aircraft residual value ($P_{residual}$) can be fully recovered by the D&R process. For the disposal company, the D&R cost is the difference between the residual value and the salvage value ($C_{salvage}$) when the residual value is fully harvested. The salvage value is defined as the actual or estimated resale price of an aircraft, engine or component based on the value of marketable parts that could be salvaged for reuse on other aircraft or engine or for other reusable purposes according to the International Society of Transport Aircraft Trading (ISTAT) [310]. It includes the valorisation of the product after the D&R process. Similar terms such as the part harvested value or the component market value are also utilised [277][311]. This high-level model is categorised as a financial model using a simple experiential factor based on the accounting method.

$$C_{D\&R} = -P_{residual} = -r_{residual} P_{AC} (1+I)^{FY-FY_0} \tag{4.84}$$

4.2.4.2. DETAIL-LEVEL MODEL

The detail-level D&R cost estimation considers the labour usage and the material consumption for the process steps such as the aircraft storing, disassembly, dismantling, material sorting and separating [312] conducted by the disposal company. For airlines, the total D&R cost is then the cost the labour and material costs of repairing or modifying the components,a residual-value-related-ownership cost of the yearly investment for the disposal company to keep the aircraft for the moment based on its residual value, and the salvage gains extracted from the resale of the recycled components and materials see Eqs. 4.85 and 4.87. It follows a bottom-up process-based cost aggregation. In order to be consistent with the high-level

model, the estimations are constructed for the airlines, while the salvage value ($(C_{CP})_{salvage}$) term in Eq. 4.87 needs to be removed when evaluating the cost of the disposal companies. In the analysis, the residual-value-related-ownership cost is approximated as 5% the aircraft residual value multiplies the number of years required for conducting the D&R process[277]. Although there are costs from energy consumptions, facility usages and tooling & equipment investments, it is not estimated due to limited data access. Moreover, since the aircraft D&R processes varies in many ways, it could be a challenge to obtain a detailed data list for the analysis. The D&R cost for each CP can be constructed via Eq. 4.87, where i refers to D&R cost type, the process step refers to the disposal steps such as storing, dismantling or sorting; j refers to material or labour cost items.

$$(C_{CP})_{D\&R,k,labour} = (H_{CP})_{D\&R,k,labour} R_{D\&R,k,labour} (1+I)^{FY-FY_0} \tag{4.85}$$

$$(C_{CP})_{D\&R,k,material} = W\left[1+(r_{chipped})_{D\&R,k,material}\right] P_{D\&R,k,material} (1+I)^{FY-FY_0} \tag{4.86}$$

$$\begin{aligned}(C_{CP})_{D\&R} &= (C_{CP})_{D\&R,labour} + (C_{CP})_{D\&R,material} + (C_{CP})_{D\&R,residual-related} - (C_{CP})_{salvage} \\ &= \sum_k (C_{CP})_{D\&R,k,labour} + \sum_k (C_{CP})_{D\&R,k,material} + (C_{CP})_{D\&R,residual-related} - (C_{CP})_{salvage}\end{aligned} \tag{4.87}$$

4.2.5. MISCELLANEOUS COST ESTIMATION

The miscellaneous costs are generally estimated by applying the relevant impact factor to the cost aggregated for each major cost type in the LCC. It is no need to distinct the analysis on high- and detail-levels. The calculations of the depreciation, interest, tax and so on can be easily found from the economics field and are not elaborated in this thesis.

4.3. IMPLEMENTATION

The implementation of the LCC estimation method focuses on the development of KBs and CMs which facilitate the pre-processing, the cost estimation and the post-processing embedded in the cost analysis integrated design framework. Those developments are intensively enabled by KBE techniques such as the knowledge extraction and formulation, knowledge mapping and process automation using inference mechanisms. The CMs backed up by the KBs are then fulfil the functions including the data collection, the modularized cost calculation, the output results collection and the integration between modules. In the following sections, KBs and CMs are exemplified via the production cost analysis. Due to the means of implementing the other cost types are similar to the production cost analysis, thus, the KBs and CMs for those are not discussed in detail. Moreover, according to the LCC estimation method, most of the KBs and the CMs needed for the high-level cost estimation can be embodied in those for the detail-level model. Additionally, some of the KBs and the CMs specifically for the detail-level model always exist in the application, and is just not utilized by the high-level model. Therefore, the KBs and CMs of the detail-level model are illustrated. In this way, they supply a comprehensive insight into the application implementation.

4.3.1. KNOWLEDGE BASES (KB)

The overall KB is a generalization of the product-KB, process-KB and the cost-KB. The static structure diagram of the KBs is shown in Figure 4.18. The parameters related to product geometric properties are stored in the product object and further inherited in the CPs, this can be referenced back to Section 3.3.2. The parameters relevant to manufacturing/assembly processes are stored in the process-KB. When the process steps derived for the CPs match one of the processes in this KB, the process properties needed to instantiate relevant CERs are then linked to the CPs. The parameters categorized as 'cost properties' are stored in the cost-KB. It also contains the CBS hierarchies linking all the cost elements under each of the major LCC cost types, see Figure 3.14. Similarly, the parameters and the CERs for cost estimation will be assigned to the CPs once the mechanisms of corresponding capability modules are performed. In addition, the material properties are grouped in material-KB used by the other KBs. When the material type of a product is found from the KB, the material properties such as the density and the material unit price can be identified and extracted for the use of cost estimation. Since the actual process-KB and material-KB contains a large amount of manufacturing/assembly processes and material types employed by the aircraft production phase. Figure 4.19 and Figure 4.20 illustrates two examples instead of the complete KBs, which schematically indicate the KB formulations. The material KB is composed by the general material such as metal and composite for the use of part production, and the additional material such as paint and sealant for the final assembly and/or sub assembly processes. The general material classification according to Ashby and Jones is referenced [313]. The process KB contains possible process steps of the aircraft life cycle. Particularly in the production process, it contains the manufacturing processes and the assembly processes respectively.

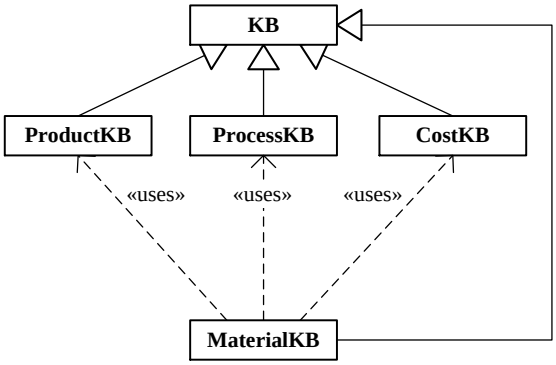


Figure 4.18: Static structure diagram of KBs

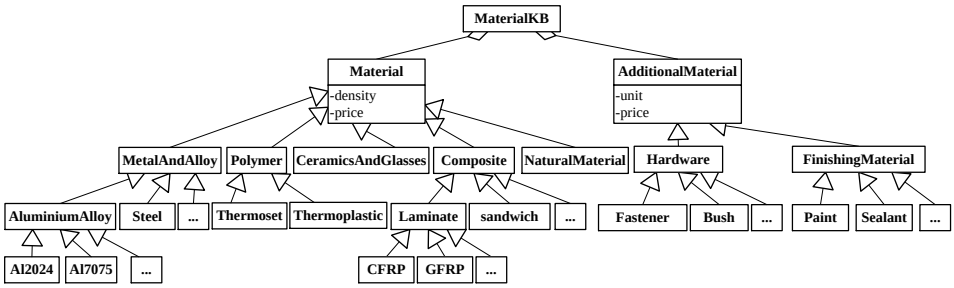


Figure 4.19: Static structure diagram of material KB

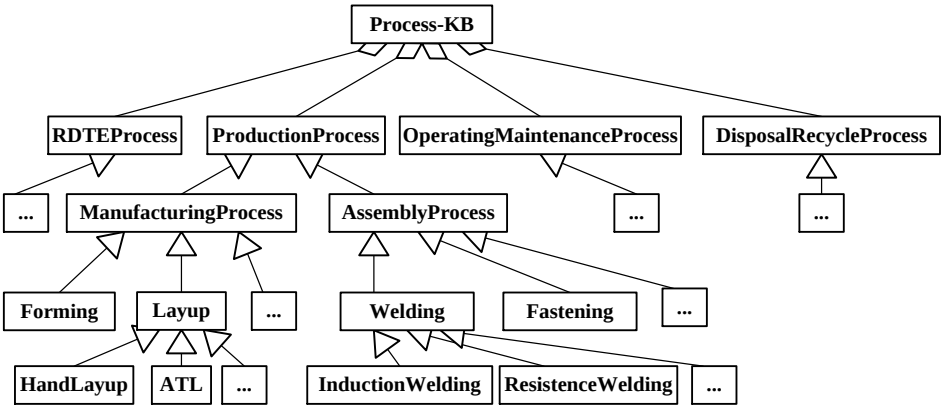


Figure 4.20: Static structure diagram of process KB

4.3.2. CAPABILITY MODULES (CM)

In order to facilitate the aforementioned LCC estimation method, there are three main functionalities enabled by the CMs involved in the cost analysis module: To encode the LCC estimation framework, to provide interface connections between the cost analysis module and the other modules in the cost integrated DEE or within the cost analysis module and between distinct functions, and to formulate the proposed CERs.

Each of them contains a number of specific capability functions. The first capability is facilitated by the overall control of the cost estimation workflow and the construction of the CBS for the LCC. Figure 4.21 depicts the activity flow conducted by both high-level and detail-level LCC estimations. All major cost types of the LCC can be estimated. It is noted there exists estimation cases combined both levels of detail for different cost types, therefore, a conversion mechanism is incorporated accordingly. It conducts the transition through the C_{CP}/C_{AC} and W_{CP}/W_{AC} introduced earlier in Section 4.1. The transition is acceptable for the major cost types once they are either estimates for the same aircraft or for the same components/parts. However, it is not possible to conduct transitions within each major LCC cost types. For each major cost type, an in-depth activity workflow is needed respectively.

As an example, Figure 3.15 elaborates a detailed production cost estimation process. Figure 3.2 can also be referenced for illustration of a generalized cost analysis workflow. The interfaces between the modules include the I/O interfaces between the modules facilitated by different software and the data processing between the original input/output and the derived input/output. It contains CMs of assigning cost driving parameters, generating cost report and so on, which are mostly encapsulated packages of rule-based mechanisms. Table 4.6 shows the rule-based logics of some CM examples in production cost analysis. According to the cost type required by the estimation routine, cost type specific BOM data form is then invoked by the application. Based on the manufacturing process derived from the manufacturing view, the cost driving parameter can be called and assigned to the corresponding CERs. In accordance with the purpose of utilizing the cost report, the format of the cost report either for review or for optimization studies are adopted. The CER formulations mainly contain the encoding of the mathematical equations and the storage of the necessary parameters. All of them are aimed at extracting the repetitive analytical operations and automating the cost estimation process, so that the analysis is speeded up to improve the computational efficiency.

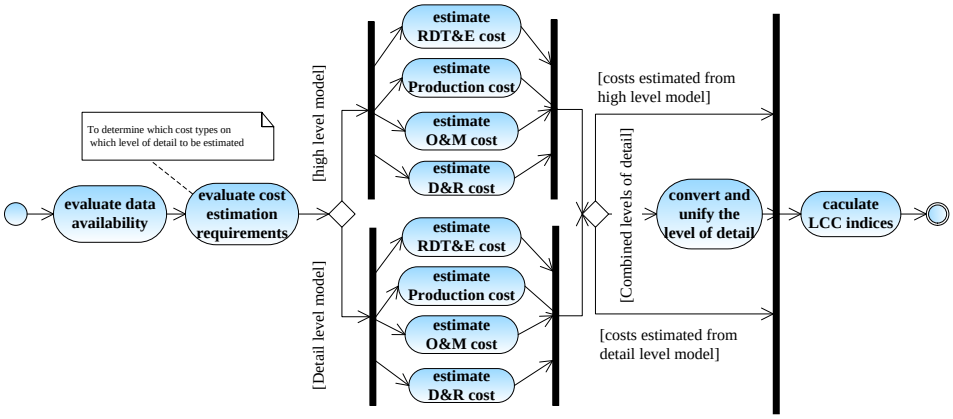


Figure 4.21: Activity diagram of LCC estimation on both high and detail-levels

Table 4.6: Examples of the rule based logics for CMs

CMs	Rule based logic
Importing extended BOM	Cost type required ⇒ extended BOM data form
Assigning cost driving parameters	Main manufacturing/assembly process ⇒ cost driving parameters
Generating cost report	Purpose of the cost report ⇒ cost report format

4.4. SYNTHESIS AND CONCLUSIONS

The LCC estimation method and its implementation construct the main block of the cost analysis module. By extracting the design and process parameters from the product model and the disciplinary views developed for each of the LCC cost types, the cost analysis is integrated with the design concept and its lift cycle operating process. Moreover, within the LCC analysis module, the syntheses between each of the major cost type are also performed to make sure all the cost elements are estimated in a consistent manner. Additionally, synthesis is also needed between the LCC analysis and the optimization studies. Given the interest of the stakeholders, distinct LCC indicators can be developed to represent the optimization objective. The cost module is linked with the optimization application through the CMs. By pursuing the optimum cost performance under certain constraints, a set of new design and process parameters can be obtained to improve new designs and to achieve a better aircraft life cycle process. And the LCC estimation has provided a solid foundation for this integration.

In summary, a comprehensive LCC estimation model is developed in two level of details, constructing so-called scalable two-level LCC estimation framework. It divides the aircraft life cycle process into RDT&E, production, O&M and D&R processes, while detailed process steps within each life cycle phase are considered in the detail-level model other than in the high-level model. Accordingly, four major cost types are focused. Each cost type contains various cost elements. Normally, weight properties are adopted as main cost driving parameters for the high-level model cost estimation. The detail-level model evaluates the LCC for CPs. For each LCC cost type, different CPs are defined. One CP can either be an aircraft component for manufacturing or the overall aircraft for flight operating, and it is determined based on the design and process properties required by the cost type to be estimated. In order to keep the consistency for all cost types, conversions between the aircraft cost and the component cost are taken into consideration. The detail-level model investigates the costs induced from the sub-divided process steps in each life cycle phase. The product design parameters and the process properties are employed as cost driving parameters. In this way, it solves the problem that the data resource for LCC estimation is not always available. The high-level model can provide fast estimation, while the detail-level model can provide a comprehensive analysis. Since the cost conversion is considered between the aircraft and aircraft components either within the high-level model and detail-level model or between them, the mixture of cost estimates evaluated through both models for different cost types is possible. The main advantages of the developed method are as follows: It provides an approach for a complete LCC estimation; the cost properties are linked with product and process properties, so that design and costing are bridged together; two levels of the cost estimation provide the cost engineers with a flexible access to the aircraft cost while reduce the negative influence of data availability for the estimation.

The implementation of the method is stressed via the extraction of the Product-Process-Cost procedures, the modelling of the life cycle process, the invention of CPs, and the standardization of the cost analysis methods. Those are then implemented by applying KBE techniques, so that it is able to integrate the aircraft LCC analysis into the design and optimization process. Moreover, by implementing corresponding CPs and CMs specifically for cost analysis, KBE techniques including geometric modelling and knowledge-based infer-

ence mechanisms can also improve the LCC analysis itself in an efficient and modularized manner. Those KBE techniques are originated from AI, OOP and CAD respectively. During the implementation, the techniques employed are mainly knowledge extraction, geometric handling, and knowledge inference. A programming language such as Common Lisp embedded in Genworks GDL and parameterized geometric modelling such as the use of the NURBS (Non-Uniform Rational B-Spline) based geometry kernel empowered by Genworks GDL.

However, there are still challenges within the development. For both high and detail-level models, not every cost element summarized in the LCC breakdown is estimated mainly due to a lack of data resources. Especially there is a lack of analyses of the indirect cost category. The high-level models are extracted and adapted from the model in the 90s, in which some recent aircraft types such as B787 and A350 are not analysed. A comprehensive data set is needed for new analyses. For the detail-level model, since the RDT&E phase is normally not emphasized, a more comprehensive process breakdown including the labour and material consumption are needed to be investigated further for the detailed RDT&E cost analysis. For the detailed production cost estimation, up-to-date and verified CERs are necessary. The detailed flight operating cost model need to be more tightly connected with the specific airline flight plans. In the detailed maintenance cost estimation, the maintenance intervals which can potentially build the connections between the aircraft design parameters and the maintenance planning schedules should be further investigated. The rules and data for evaluating the scheduled maintenance material cost, the unscheduled maintenance labour and material costs should be extracted further improve the detail model for maintenance cost estimations. The detailed D&R model also needs to be enhanced by more analyses on the D&R process steps.

By considering the overall method of the cost estimation, it mainly applies to commercial aircraft with conventional configurations which use supercritical divergent trailing edge aerofoil and pylon mounted engines. For novel aircraft configurations, the logic of the method still applies, while some of the aircraft type specific factors need to be adapted. Additionally, the conversions of aircraft/component cost and money types are considered to guarantee the estimation consistency, the conversion between the currency types is also necessary. Although the LCC estimation method has been improved, the accuracy is still a matter of concern. The absolute cost value may be questionable due to errors induced by lack of information or differences in labour rates, monetary rates, procedures between estimation and practice. However, the model developed is treated consistently for alternative products, therefore, relative comparisons are valid. In addition, the method verification and result validation are conducted to some extent.

5

METHODOLOGY OF COST INTEGRATED DESIGN OPTIMIZATION

The LCC analysis provides a way of evaluating the product economic properties through the causal factors including aircraft design and life cycle process variables. The ultimate goal is then to optimize the design and the life cycle operating process with the intention of reducing costs without losing any other performances in a life cycle. In this chapter, optimization problems are constructed for this purpose. To formulated the optimization objective functions, cost indices are developed based on the LCC estimation method. Structural and process constraints are extracted and applied on the cost indices. Disciplinary analyses incorporated in those studies are related to weight, structure and life cycle processes, which are utilized to either facilitate the objective formulation or to build up necessary constraints. In the end, new design and process parameters are obtained in term of a better economic performance. In the methodology section, the cost integrated MDO architecture including the framework, the problem formulation and the optimization method are proposed first. Secondly, the cost indices utilized for different stake holders are established. Thirdly, the analyses on the optimization constraints are exemplified. Next, a section associated with the method implementation is addressed. Followed by a summary of methodology synthesis and a conclusion of this chapter.

Most of the challenges identified in MDO are related to the MDO architecture involving the problem definition, the disciplinary integration and interaction, and the algorithm efficiency. There are also improvements needed for MDO evaluation, application, and management. However, given that only a few research has been dedicated to cost integrated MDO, the development of a generalized and modularized architecture including relevant disciplinary analyses are addressed, see Section 5.1. The cost integrated MDO architecture is built up based on the KBE assisted DEE framework and on the foundation of the developed LCC estimation method. Moreover, other disciplinary analyses such as weight, structural, life cycle process analyses are incorporated. The weight analysis is adopted to facilitate the cost evaluation, the structural analysis is established to define the constraints. Some of the process-related analyses such as manufacturing/assembly process derivation and operating process time analysis enable the cost estimations, while the others, e.g., to extract the manufacturing/assembly process constraints, are used to identify the process related limitations. In Section 5.2, the objective function and the optimization algorithm are discussed. The disciplinary constraints are demonstrated by taking stiffened-panel structural analysis as an example in Section 5.3. It is followed by a discussion of the workflow implementation and the corresponding development of CMs in the DEE.

5.1. COST INTEGRATED MDO ARCHITECTURE

In order to provide an overview of the cost integrated MDO formulated in this research, the MDO extended design structure matrix, which is a method of MDO architecture representation introduced by Martin and Lambe [161], is presented in a general form. The detailed work flow is illustrated by an N2 chart focusing on the optimization module. The exact data transmission and analysis are case dependent, and are elaborated in Chapter 6.

A monolithic Multidisciplinary Feasible (MDF) architecture is built straightforwardly for cost integrated design optimization studies and is consistent with the DEE framework. The design and disciplinary analyses are nested in an integrated optimization. An MDO extended design structure matrix is shown in Figure 5.1. It includes a control module (rounded rectangle), a master geometry module and a couple of analysis modules (rectangles): optimization, parameterized geometry, disciplinary analyses and optimization functions. $X^{(0)}$ refers to the initial guess. Optimization work flow controls iterations and updates the new parameters (X^*). The geometric, material and process property are supplied to the correspondent modules respectively. The data flow is represented by the thick grey lines, while the thin black solid lines stand for the process flow. In current problem set-up, most of the data flows are overlapped with the process flow, while they can be different when the output data of certain module is not further supplied to other modules in the control loop. Both the data flow and process flow above the diagonal modules are processed from left to right and from top to bottom, while the direction is reversed below the diagonal modules. Numbers are shown to express the order of processing the modules controlled by the optimization. In this optimization work flow, the model starts from the optimization (with number 0). Then the LCC indicator (with number 7) is executed after the parameterized geometry module (with number 1) and disciplinary analyses (including weight, life cycle process, structural and cost analyses with numbers 2 to 6) are performed. Structural and cost analyses are performed based

on the input from the weight and process analyses. Since there is not data dependency between those two analyses, they can be compiled simultaneously. The data for objective and constraint functions (with number 7) are constructed after the disciplinary analyses are executed. The optimization algorithm stored in the optimization control module is executed after the optimization functions are supplied in step 8. A new group of parameters with an updated product geometry is generated for each iteration process (shown as 8→1). The optimization stops when the optimal design is found or the optimization process converged.

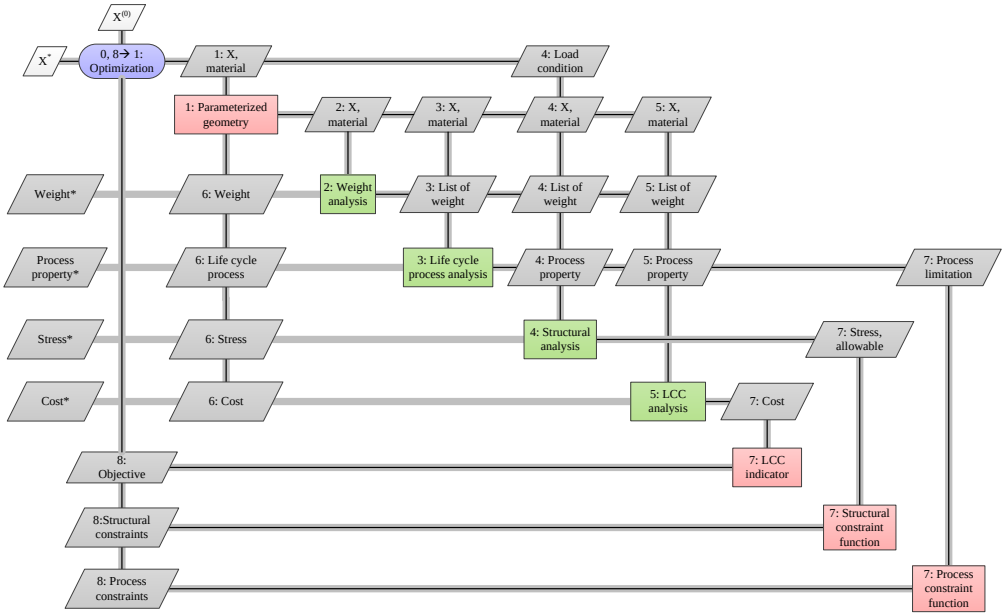


Figure 5.1: Extended design structure matrix for cost integrated design performance and optimization

To further illustrate the interactions and data transmissions specifically for the optimization module, an N2 chart is provided zooming into the optimization function formulations and the optimization solver, see Figure 5.2. The input is collected from the disciplinary analyses from the process, structural and LCC modules. Based on the interest of the stakeholders, the cost indicator to be optimised is formulated. The structural constraints are formulated based on the stress calculated and the corresponding allowable. The process constraints are constructed from the limit due to a specific tool, the operating facility and/or the aviation regulations. The objective and constraint functions are supplied to the optimization solver for optimization studies. The optimum design and/or process parameters are produced after iterations.

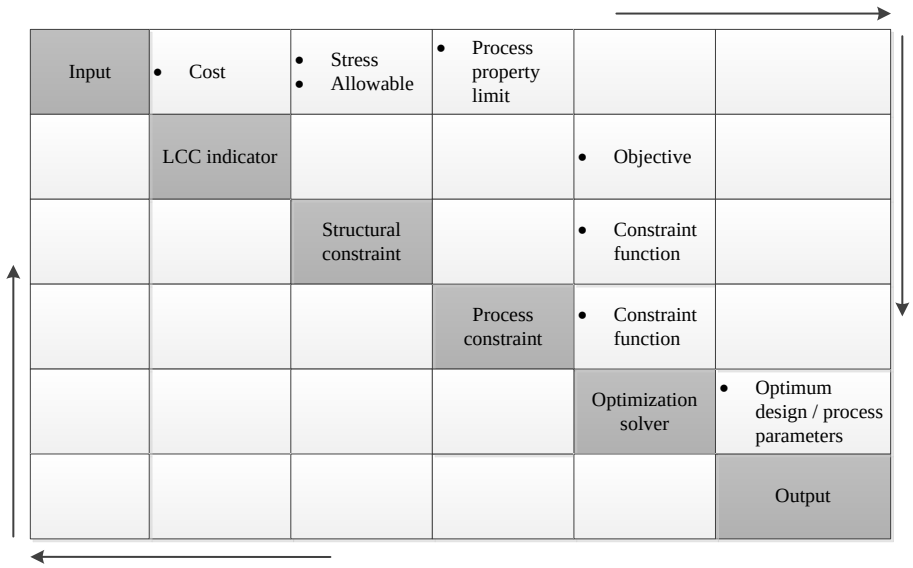


Figure 5.2: N2 chart of the optimization module

5.2. OPTIMIZATION PROBLEM

5.2.1. PROBLEM DEFINITION

In an aircraft life cycle, there are various stake holders who have different focuses on LCC for their respective benefits. It would be challenging to provide a unified measure to represent the interests of all stakeholders. A practical solution is to build distinct LCC indices to meet their specific needs in optimization studies.

For instances, the LCC indicator for the manufacturer would be the combination of R&D cost and M&A cost; while for the airline operator, the LCC index would either be DOC, SV or the LCC indicator including the influence of the acquisition cost and the disposal expenses. For disposal company, the LCC index is then the difference between the cost of the purchase, disposal and recycle processing and the gains of salvage, see Eq. 5.1.

$$\begin{aligned} \text{minimize} \quad & Cost(X) \\ \text{with respect to} \quad & X \\ \text{subject to} \quad & \sigma_{allow}(X) - \sigma(X) \geq 0 \ \text{(structural constraints)} \\ & X \subset [lb,\ ub] \ \text{(life cycle process related constraints)} \end{aligned} \tag{5.1}$$

where X refers to the component geometry design and/or life cycle process related parameters, which will differ for any specific aircraft or component type. σ_{allow} is the maximum stress in the panel, which should be less than the structural allowable. Those parameters also need to satisfy the limitation from each phase of the life cycle process. For example, the size

of a component manufactured by cutting process should be smaller than the biggest size the cutting tool allows.

5.2.2. OPTIMIZATION ALGORITHM

The optimization algorithm is selected in the optimization solver. According to the problem definition, this constraint nonlinear optimization problem can be solved by either non-gradient based optimization or gradient based optimization. For the purpose of evaluating the performance of the optimization processes, four optimization techniques are applied: Genetic Algorithm (GA), gradient optimization, GA with pattern search and GA with gradient optimization. As a typical non-gradient optimization technique, GA has a high probability of finding the global optimum. It is the representation of the natural selection process [223]. Design parameters are treated as genes. Starting with a population of design vectors, which will experience the search process including reproduction, crossover and mutation, the best fit is selected. While the gradient optimization searches along the direction of steepest descent in a local region; the optimum is found when the value approaches its minimum along the direction [223]. Its advantage is to retain sensitivities of the design parameters and converge fast. By considering both the optimization accuracy and the computation expenses, hybrid optimization techniques are focused. The hybrid optimization technique combines different optimization algorithms for the same problem to balance the advantages and disadvantages of the individual algorithms. In order to ensure the global optimum, GA is often combined with pattern search. Pattern search finds the optimum by increasing or decreasing the design variables in a certain step size to improve the fit value experimentally at each step. It is converged through the decreases of the step size. In addition, GA combined with gradient optimization is adopted. GA is used to zoom in the design space into the region where the global optimum exists, which potentially excludes the local optimum at the first step. After extracting the solution obtained from GA, the gradient based optimization is used to search the actual optimum design. Since the cost module is seen as a black box for the optimization control loop, a gradient should be provided to the optimization solver. Finite differentiation is used to calculate the gradient, which also provides the sensitivity indications of the design variables.

5.2.3. COST INDICATORS AS OPTIMIZATION OBJECTIVES

In general, the purpose of cost integrated optimization is to achieve an economic optimum for a specific stakeholder. Therefore, it is not favoured by either manufacturer or the airline to minimise the overall LCC. For different stakeholders, the cost indicators to be optimised vary based on their benefits. One could argue that the optimization on aircraft LCC would provide an optimum balancing each stakeholder's advantage, so that the most economical aircraft design over its life time could be obtained. However, this would not be interesting for any relevant stakeholder, therefore, LCC indicators ought to be developed for specific stakeholders in conformity with the industrial requirements. In the following sections, the LCC indicators related to the designers, the manufacturers, the airlines and the disposal companies are addressed.

- **LCC indicators for designers**

Generally speaking, the RDT&E cost is under the control of designers. While besides optimising the RDT&E expenses, designers must also stand on the perspectives of manufacturers, airlines and disposal companies in order to better position the proposed design better in the market. Therefore, designers are also focused on the minimization of the production cost, the O&M cost and the D&R cost are also focused. In particular, the relation between the design parameters and each cost type in LCC should be investigated.

- **LCC indicators for manufacturers**

The focus of the manufacturers is to produce the product with low production cost, Obtaining the minimum production cost constrained by the functional requirements is hence the task of the optimization studies. Furthermore, the design group is often a department in ODMs. Therefore, the lower the RDT&E and the production cost the more the profitability the ODMs may achieve. Given this consideration, the RDT&E and production costs are often analysed together, where the RDT&E cost, the production tooling/equipment cost and the testing cost are treated as non-recurring cost items. Those items should be appropriately distributed on aircraft unit price. According to the RDT&E cost estimations on 'per aircraft basis' in Section 4.1.3, it can be seen that the RDT&E cost apportioned to each aircraft decreases along with the increase in the number of aircraft produced. In addition, certain assumptions should be made to determine through how many sales the non-recurring cost will be recovered and to identify the break-even point [87].

- **LCC indicators for airlines**

Airlines pursue low acquisition cost (also called procurement cost/aircraft purchase cost) and low operating cost so that to obtain a high profit. The acquisition cost includes the RDT&E cost, production cost and a fair profit for the manufacturers. Although airlines would also like to catch some value from the disposal process with a high resale price, while this resale price is mainly influenced by the aircraft age, the depreciation rate and the global market situation [276], therefore, there is little control on the resale price from the airline.

There are a few LCC indicators developed for airlines. A typical one is the Direct Operating Cost (DOC). One way of the DOC formulation is to aggregate the cost items under the direct flight operating and the direct maintenance cost categories from the O&M CBS in Section 4.2.3. The other prevalent method is to adopt the 'DOC+I' model directly [289]. As for simplification, a simplified DOC model is often employed only for optimization purpose. The simplified DOC formulation is presented in the following. By analysing the cost driving parameters for each cost item from "DOC + I" model, the elements of the crew, fees, fuel and maintenance cost are operating-oriented and are consequently evaluated based on the weight properties (MTOW and AFW). The depreciation, insurance and interest are financial-oriented and are then generated from the aircraft acquisition cost, which is related to the aircraft production cost ($C_{production}$). For simplification, the DOC is constructed by two terms: The product of the weight penalty (p) and the airframe weight and the multiplication of the production cost with a weight factor (n), thereby the DOC can be reformulated as Eq. 5.2 [132][148]. The airframe weight, including the mass of main structures and additional materials such as fasteners, is a mass property of the corresponding product (an aircraft or a CP). The production cost can be calculated by employing the aforementioned high-level or

detail-level cost estimation models. The weight penalty is evaluated according to Eq. 5.3. It is based on aircraft operating parameters: fuel consumption (fc), aircraft life duration (t_c), the annual aircraft utilization in the number of flights (U), aircraft flight distance per flight (R), fuel price (P_{fuel}) and Aircraft Gross Weight (AGW). The overall cost is transformed to the component from here. Weight factor has the typical value of 2 to 3.5 [132].

$$DOC = pAFW + nC_{production} \tag{5.2}$$

$$p = \frac{fct_cUR}{AGW} P_{fuel} \tag{5.3}$$

Along with the DOC analysis, Surplus Value (SV) is introduced as another LCC indicator for airlines. SV is developed for enabling a relatively simple ranking of different engineering options on a financial basis without performing detailed future forecasts [146], see in Eq. 5.4.

$$SV_{cost} = D_p N_{market} \left[-D_C U(C_{flight}) - C_{man} \right] - C_{Dev} \tag{5.4}$$

where D_p is the producer discount multiplier, D_c is the customer discount multiplier, N_{market} is the annual market size, U is the annual product utilization, C_{flight} is the operating cost per flight, C_{man} is the manufacturing cost, C_{Dev} is the development cost. According to the C_{flight} and the C_{man} defined by Hollingsworth and Patel [96][146], the high-level and detail-level models for $C_{O\&M}$, $C_{production}$, and $C_{RDT\&E}$ calculation can be adopted to in Eq. 5.4 to represent the terms C_{flight}, C_{man}, and C_{Dev} respectively, shown as Eq. 5.5. As the optimization work in this research mainly focuses on identifying the design parameters for the better financial properties, and there is little connection between the RDT&E cost model and the design parameters, therefore, it is possible to leave out the relatively fixed $C_{RDT\&E}$ for a design program. By conducting this simplification, the SV formulation can be transformed to Eq. 5.6. The value is ought to be maximized for trade-off studies.

$$SV_{cost} = D_p N_{market} \left[-D_C U(C_{O\&M}) - C_{production} \right] - C_{RDT\&E} \tag{5.5}$$

$$SV_{cost} = D_p N_{market} \left[-D_C U(DOC) - C_{production} \right] \tag{5.6}$$

Comparing Eq. 5.2 and Eq. 5.6, DOC and SV are interrelated values: one stresses the cost spend on the airplane operating, while the other indicates the benefit obtained from the operating process. Both reflect the value integrated with the design and the production.

- **LCC indicators for disposal companies**

The disposal and recycle companies are keen to spend low purchase cost, low processing cost so that they can obtain high salvage value of the disposals. The total cost of the disposal and recycle should be minimized while the salvage value should be maximized.

5.2.4. WEIGHT AND PROCESS RELATED ANALYSES

As illustrated in Figure 5.1, weight analysis and process analysis are necessary for LCC estimation, further facilitate the formulation of the cost indicators. Some of the parameter needed for weight and process analyses have been elaborated in Chapter 3 and Chapter 4, the weight and process parameters necessary for cost indicator is highlighted in this section.

5.3. DISCIPLINARY CONSTRAINTS

The studies conducted in this research mainly employee the constraints from the structural aspect. A small portion of the constraints is from the process related limits. Although the constraints from aerodynamic perspective and safety analysis are not considered, it still established the optimization procedure. The optimization architecture has the flexibility of involving other disciplinary constraints when the disciplinary analyses are conducted.

5.3.1. STRUCTURAL CONSTRAINTS

In this section, an analysis of the structural constraint for a stiffened-panel is exemplified to illustrate the procedure of the structural constraints formulations. This analysis is chosen because it contains the typical steps for a complete procedure of the structural constraints formulation, and it will also be used for the case study conducted in Chapter 6. Figure 5.3 schematically shows a panel with inverted T stiffeners. The parameters L, W,t, b_s, b_f, h_s, t_w, t_f are the skin length, skin width, skin thickness, stiffener pitch, flange width, stiffener height, web thickness, and flange thickness respectively. The panel is assumed as a segment extracted from the upper wing box. Therefore, the length and the width are fixed. A panel is divided into several panel bays naturally, which is a section including the stiffener and the attached skin with the width of the stiffener pitch. The cross section area (A) of each panel bay is calculated in Eq. 5.7. and are skin and stiffener cross section areas.

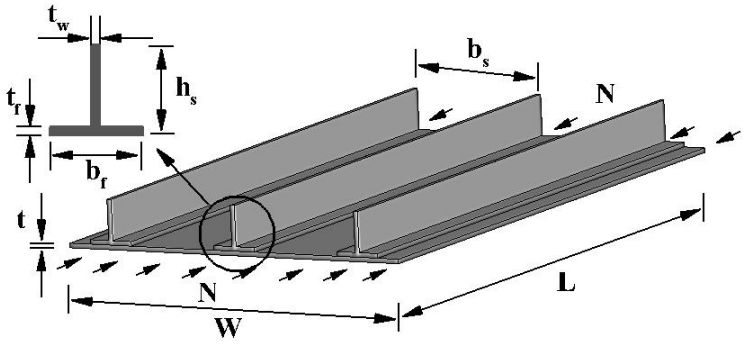


Figure 5.3: Stiffened panel with inverted T stringers

$$A = A_{sk} + A_{st} = b_s t + \left[b_f t_f + t_w (h_s - t_f) \right] \tag{5.7}$$

In general, four steps are conducted to determine the structural constraints. Those in-

clude the load condition identification, stress analyses, allowable stress determination and the constraints formulation:

1. Load condition

Since the panel is considered as a simply supported segment from aircraft upper wing box, the compression load intensity N is applied on the neutral axis of the panel, shown in Figure 5.3.

2. Stress calculation

For each panel bay, normal stress σ_N of the panel is calculated as Eq. 5.8. Since the skin, stiffener and the panel have the same strain (ε), see Eq. 5.9, which can then be equivalent to Eq. 5.10. By eliminating the Young's modulus (E) from both sides of the equation, we obtain Eq. 5.11, where, P_{sk} and P_{st} represent the skin and stiffener compression loads respectively. Therefore, the stress in skin and stiffener (σ_{sk} and σ_{st}) are calculated in Eq. 5.12.

3. Definition of allowable stresses

Based on the load condition, the allowable stresses corresponding to different failure modes are evaluated. The failure modes frequently appear in stiffened-panel structures are skin local buckling, stiffener crippling, stiffener attached flange inter-rivet buckling, stiffener web local buckling, stiffened panel column buckling and material failure, shown as Figure 5.4. The skin, stiffeners and the overall structure are assigned with corresponding failure modes. Accordingly, different allowable stresses are calculated.

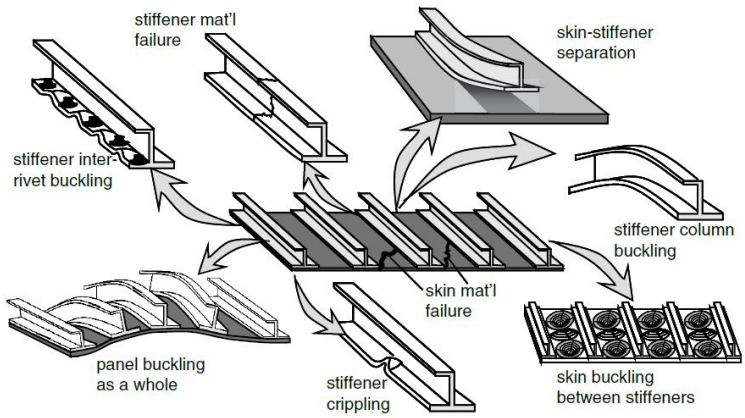


Figure 5.4: Failure modes of a stiffened panel [314]

$$\sigma_N = \frac{Nb_s}{A_{sk} + A_{st}} \tag{5.8}$$

$$\varepsilon_{sk} = \varepsilon_{st} = \varepsilon \tag{5.9}$$

$$\frac{P_{sk}}{EA_{sk}} = \frac{P_{st}}{EA_{st}} = \frac{P_{sk}+P_{st}}{E(A_{sk}+A_{st})} \tag{5.10}$$

$$\frac{P_{sk}}{A_{sk}} = \frac{P_{st}}{A_{st}} = \frac{P_{sk}+P_{st}}{A_{sk}+A_{st}} \tag{5.11}$$

$$\sigma_{sk} = \sigma_{st} = \sigma_N \tag{5.12}$$

- **Skin local buckling stress**

The skin of the panel is constrained by local buckling. Once the skin reaches the local buckling allowable, it will not take additional loads. The adjacent stiffener will still withstand additional loads until it reaches its crippling stress. The skin local buckling stress is derived from the Euler buckling equation (Eq. 5.13) [315].

$$\sigma_F = \frac{c\pi^2 EI}{AL^2} \tag{5.13}$$

where, c is the constant related to buckling coefficient (k) and the plastic reduction factor (η_p). k=4 is applied on the skin. The stiffness (EI) of the skin is expressed as $\frac{EI}{1-\mu^2}$, the moment of inertia (I) is calculated as $\frac{b_s t^3}{12}$, the cross section area (A) is $b_s t$. By replacing the correspondent element in Eq. 5.13, the skin local buckling allowable (σ_L) is calculated as Eq. 5.14.

$$\sigma_L = \frac{k\eta_p \pi^2 E}{12(1-\mu^2)}(\frac{t}{b_s})^2 \tag{5.14}$$

where, μ is the Young's modulus. The plastic reduction factor is equal to Eq. 5.15.

$$\eta_p = \sqrt{\frac{E_t}{E}} \tag{5.15}$$

where E_t is Tangent modulus, which is derived from Ramberg-Osgood equation [316]. It is calculated as in Eq. 5.16:

$$E_t = \sqrt{\frac{1}{1+(\frac{0.002E_m}{\sigma_{0.7}})(\frac{\sigma}{\sigma_{0.7}})^{m-1}}} \tag{5.16}$$

where σ and $\sigma_{0.7}$ are the actual stress in the skin and the stress value when $E_t = 0.7E$.

- **Stiffener crippling stress**

The stiffener of the panel including the stiffener web and stiffener flange(s) are limited by the crippling stress (σ_{cc}) [315][317]. It differs based on the manufacturing process applied on the stiffener. For formed stiffener section, the following empirical relations are used (Eqs. 5.17and 5.18):

$$\text{Z section/U section, } \sigma_{cc} = 4.05\left(\frac{1}{A_{st}/t_s^2}\right)^{0.82}\sqrt[3]{E^{0.82}\sigma_y^{2.18}} \tag{5.17}$$

$$\text{Other sections, } \sigma_{cc} = 0.58\left(\frac{1}{A_{st}/g\,t_s^2}\right)^{0.8}\sqrt[3]{E^{0.8}\sigma_y^{1.2}} \tag{5.18}$$

where the g value is defined according to the stiffener shape, using g=4 for the T-stiffener panel.

For extruded stiffener section, the following empirical relations are applied for each segment of the stiffener to calculate segment crippling allowable σ_{ccn}, shown as Eqs. 5.19 and 5.20. The stiffener crippling stress is then evaluated as the average of all the segments σ_{ccn}(Eq. 5.21):

$$\text{For a segment with free edge, } \sigma_{ccn} = 0.6121\sigma_{yn}\left[\frac{b_n}{t_n}\sqrt{\frac{\sigma_{yn}}{E}}\right]^{-0.7735} \tag{5.19}$$

$$\text{For a segment with no free edge, } \sigma_{ccn} = 1.1819\sigma_{yn}\left[\frac{b_n}{t_n}\sqrt{\frac{\sigma_{yn}}{E}}\right]^{-0.7882} \tag{5.20}$$

$$\sigma_{cc} = \frac{\sum b_n t_n \sigma_{ccn}}{\sum b_n t_n} \tag{5.21}$$

where the edges are determined as free edges when they are not supported by or attached to other segments. σ_{yn}, b_n and t_n are yield compression stress, width and thickness of the segment n.

- **Stiffener attached flange inter-rivet buckling stress**

To avoid the inter-rivet buckling on the stiffener attached flange, the allowable can be calculated according to the given fastener pitch (r_p) and flange thickness (t_f) in Eq. 5.22 [315]:

$$\sigma_r = 0.9c_r E\left(\frac{t_f}{r_p}\right)^2 \tag{5.22}$$

where c_r is the constant based on fastener head type. For example, c_r=4 is chosen for universal fastener head.

- **Stiffener web local buckling stress**

The stiffener web is also restrained by the local buckling allowable, while replacing the skin thickness from Eq. 5.14 with stiffener web thickness t_w and web height $h = h_s - h_f$, it gives Eq. 5.23. k is the buckling coefficient. For this stiffener web, k=0.4. η_p is the plastic reduction factor.

$$\sigma_{L,web} = \frac{k\eta_p \pi^2 E}{12(1-\mu^2)} (\frac{t_w}{h})^2 \tag{5.23}$$

- **Stiffened panel column buckling stress**

Since the whole stiffened panel is influenced by the interaction of the Euler buckling and local buckling, the Johnson-Euler buckling equation [315] for panel column buckling (σ_{CB}) is applied, as given in Eq. 5.24.

$$\sigma_{CB} = \sigma_{cc} - \frac{\sigma_{cc}^2 \left[\frac{L'}{\rho}\right]^2}{4\pi^2 E} \tag{5.24}$$

where equivalent length $L' = \frac{L}{\sqrt{c}}$, radius of gyration $\rho = \frac{I}{A}$. c is the constant related to buckling mode and stiffener fixity for flexural buckling. c=1.5 is used for simply supported panel.

- **Stiffened panel material yield stress**

The panel stress should also be less than the yield stress, which is determined by the material type.

4. Structural constraints formulation

In this analysis, the failure modes are assumed independently incurred by different loading types on different parts or components. When some critical failure modes occur simultaneously on the design, it would imply an efficient design without over-designed components in certain cases. However, due to it does not always obtain an optimum design [314], those situations are not considered in this research. The constraints considered are imposed on global buckling of the stiffened panel as well as local failure of the skin and stiffeners, which are formulated as follows (Eq. 5.25):

$$\begin{cases} \sigma_{sk_{max}} \leqslant \sigma_L \\ \sigma_{st_{max}} \leqslant \sigma_{cc} \\ \sigma_{staf_{max}} \leqslant \sigma_r \\ \sigma_{stw_{max}} \leqslant \sigma_{L,web} \\ \sigma_N \leqslant min(\sigma_{CB}, \sigma_y) \end{cases} \tag{5.25}$$

where $\sigma_{sk_{max}}$, $\sigma_{st_{max}}$, $\sigma_{staf_{max}}$, $\sigma_{stw_{max}}$ and σ_N represents the maximum stress of skin, stiffener, stiffener attached flange, stiffener web and the panel stress, respectively. From the

stress analysis (Eq. 5.12), we have $\sigma_{sk_{max}} = \sigma_{st_{max}} = \sigma_{staf_{max}} = \sigma_{stw_{max}} = \sigma_N$, then the constraint becomes Eq. 5.26.

$$\sigma_N \leqslant min(\sigma_L, \sigma_{cc}, \sigma_r, \sigma_{L,web}, \sigma_{CB}, \sigma_y) \tag{5.26}$$

5.3.2. LIFE CYCLE PROCESS RELATED CONSTRAINTS

Life cycle process related constraints are those limited by the capabilities of the tools/ equipment and the operating strategies of the stakeholders in each phase of the aircraft life cycle. For example, the stiffened panel sizes are often restricted by manufacturing capabilities, otherwise, it will be difficult to produce a complex panel. The sizes of the components should lie within the threshold limits of tools or equipment. Moreover, in order to obtain a practical design for the stiffened panel, the width of the flange should be less than the stiffener pitch, which should be less than the skin width. The manufacturing constraints influenced upper and lower bounds.

5.4. IMPLEMENTATION

The cost integrated MDO application is built on the basis of the DEE design and optimization framework. The MMG contains the parameterized master geometry and the disciplinary views for various LCC process. Design parameters are imported to facilitate the geometric visualization of the design concept. Disciplinary analyses are conducted within each of the disciplinary modules implemented either by in-house developed or Commercial Off The Shelf (COTS) application. The optimization problem formulation is stored in the optimization module, which also contains the optimization solver. Similarly, the optimization solver is also flexible for both in-house developed and COTS applications. While in this application, MATLAB optimization toolbox is utilized. The data derivation and the data transfer are conducted by CMs. For example, some CMs deal with the material properties and the process properties, some others deal with the data transfer between the disciplinary analysis module and the optimization module, between the optimization and the master geometry or the data interaction among the multiple disciplinary analyses.

In this analysis, the optimization control loop and structural analysis are built through MATLAB [318]. The parameterized geometry, cost analysis are carried out via GDL [319], which is capable of geometric development and Object Oriented Programming (OOP) development. The application also performs communications for data transfer and updates the new data set during the iterations.

5.4.1. OPTIMIZATION WORKFLOW AND CMS

The optimization workflow can be seen from the activity diagram shown in Figure 5.5. This module will first initialize the product model using, then obtain the objective function relevant to LCC indicator evaluation and constraints from structural analysis and process analysis. Afterwards, the optimization algorithm is run iteratively until the results satisfy the convergent requirements. The results obtained normally are then recognized as the optimum solution. Note that if the results are not obtained corresponding to the convergent situation,

they are not valid. The parameters corresponding to the optimum solution are then used to update the product model.

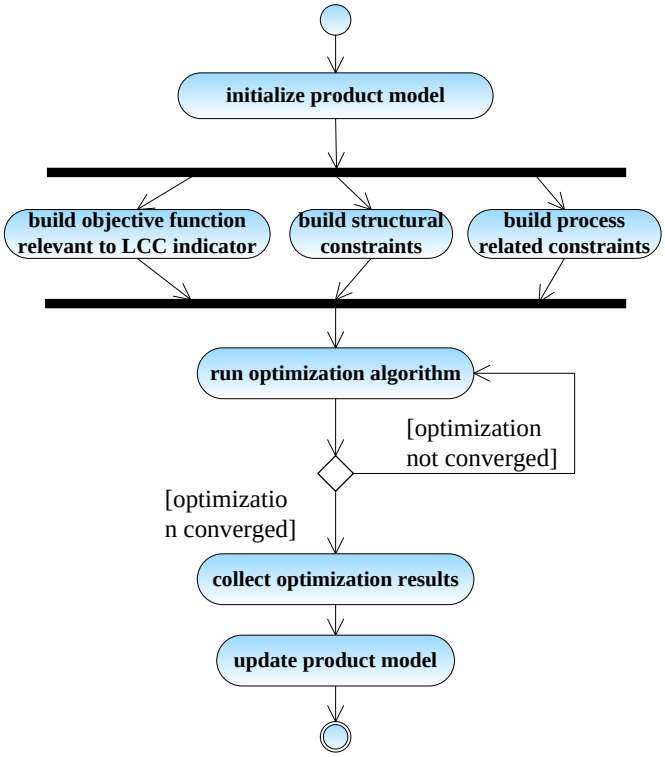


Figure 5.5: Activity diagram for optimization

The implementation of the aforementioned optimization process can be seen from the modularized structures shown in Figure 5.6. The software used for implementing each modules are denoted in the brackets in the module blocks. It emphasizes the interaction between modules and the data flow by zooming into the optimization process while not specifically grouping the analysis modules into 'MMG' or 'analysis tools' of DEE. Yet it still complies with the overall DEE framework.

The optimization module is implemented in MATLAB, which also controls the data input for initializing the geometry, formulating the objective function and constructing the constraint functions. The optimization solver contains algorithms for solving the problem formulated according to the objective and the constraints. Moreover, the results from the optimization are processed by the optimization module. In addition, the optimization module also handles the interaction between the geometry and the optimization results via data transmissions through the CMs for data processing and interaction, which are built in GDL and MATLAB. The data supplied to the objective function is from the LCC indicator evaluation, which is enabled by the LCC analysis implemented in both GDL and MATLAB. The con-

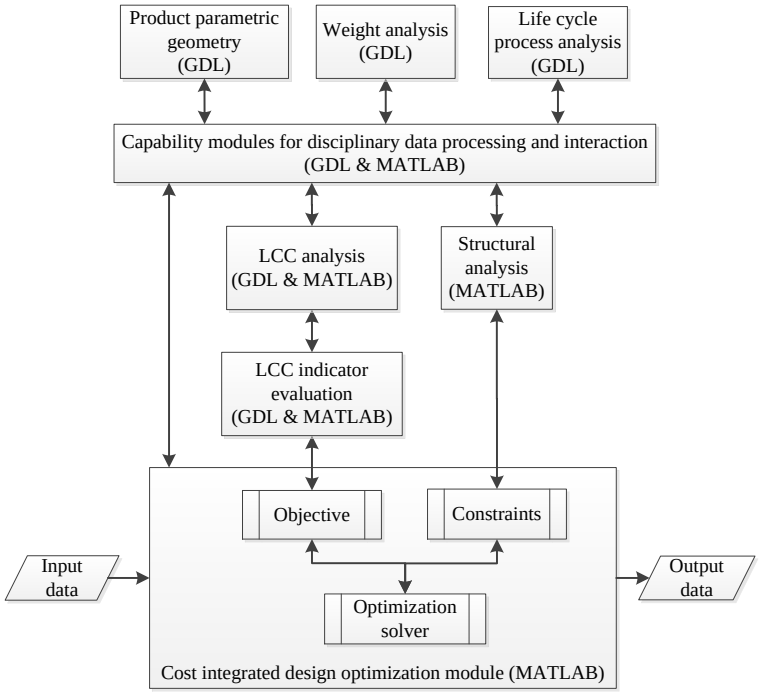


Figure 5.6: Optimization module and its interactions with the other modules

straints are mainly provided by the structural analysis in MATLAB. Some other constraints are from the life cycle process analysis via the data processing and interaction CMs. Additionally, those CMs also responsible for the data interaction between disciplinary modules, and between the parameterized geometry and the disciplinary modules. For example, data from the parameterized geometry is fed into weight analysis, life cycle process analysis and cost analysis respectively; data from weight analysis and life cycle process analysis are used for the LCC analysis.

5.4.2. SENSITIVITY ANALYSIS (SA)

Since sensitivity can compensate the lack of understanding of the variables' influence. The design factors are highly inter-connected, while in what degree the design factors influence the output is often neglected. The Sensitivity Analysis (SA) is applied to enable this capability. Moreover, designers need a sensitivity indication with respect to the design factors, which enables them to intentionally focus on main factors and to reasonably simplify design models. Instead of focusing on all factors, the design parameters that primarily drive cost are identified. With a proper focus on these factors, the design process becomes more efficient.

In order to provide the sensitive ranking of the interested design parameters and to assist the designer in reasoning the behaviour of the modelled system. The sensitivity analysis is

performed for the cost indicators. Taking DOC as an example, for $X = (x_1, x_2, ..., x_n)$, $DOC = f(X)$, sensitivities ($\varnothing$) are calculated in Eq. 5.27 [320].

$$\varnothing = \frac{\partial DOC}{\partial x_i}\left(\frac{x_i}{DOC}\right) \tag{5.27}$$

A general procedure of SA is shown as follows: First, to define the target function and essential inputs; second, to implement perturbations on the inputs; third, to evaluate the model to obtain the output change; and fourth, to assess the sensitivity of each input based on the target function.

5.5. SYNTHESIS AND CONCLUSIONS

The cost integrated aircraft design optimization naturally fits into the cost integrated DEE framework (Figure 3.2). It also leads to the utilization of KBE techniques to support the knowledge (rule) extraction and process automation. Specifically, the process threshold and the optimization problem definition and algorithms are treated as knowledges stored in the optimization solver. While the optimization strategy and workflow can be reflected by the optimization control flow for automation and data processing. Furthermore, the integration of cost analysis is necessary for design optimization studies. In essence, the objective of a commercial aircraft/component design is always the economic efficiency while fulfilling the safety and other performance requirements defined by the stakeholders. Minimize cost or maximize benefit typically in conformity with the goals. In addition, the proposal of considering different cost indicators according to the relevant stakeholders is a more strategic approach for industry to conduct optimizations than the conventional proposal of only evaluating one cost indicators for all stakeholders. In this way, the parameters influence a specific cost indicator would get the opportunity to be explored extensively by interested stakeholders. And it is possible to find different influential parameters for related stakeholders to meet their specific needs.

In conclusion, this chapter established a generalized cost integrated MDO framework, where the utilization of LCC indices for different stakeholders are highlighted. By incorporating the high-level and detail-level LCC estimation, this work construct a cost and value leading MDO method for either the aircraft or the aircraft component depending on the cost type and the analysis detail. Cost analysis and structural analysis are performed to formulate the optimization problem. The inclusive character of the disciplinary analysis gives rise to a thorough consideration of a design concept. Moreover, optimization techniques are investigated and compared.

There are still more developments to be explored in the future regarding the cost integrated MDO studies. For example, to conduct multi-objective optimizations for the sake of achieving the interest of different stakeholders, to develop an LCC index balancing each stakeholder's interest, to consider the influence of the data uncertainty to the objective function, and to involve the other discipline especially the aerodynamic analysis. Besides, the efficiency of the cost involved optimization based on various problem formulations and optimization algorithms also need to be explored in more depth. In addition, it is necessary to

further develop a comprehensive sensitivity analysis model not only for the design parameters but also for the constant parameters in the analytical evaluation process. In summary, improvements in cost incorporated MDO, ranging from optimization architecture, evaluation, application to management, still need to be investigated further.

6

CASE STUDY – STIFFENED PANEL

This Chapter applies the methodology of cost estimation and cost optimization on a typical aircraft structure – stiffened panel. The overall workflow is implemented on the basis of the KBE supported DEE framework. The application screenshot, the actual rules stored in the KB, the inference mechanisms and the automation functions encapsulated in CMs are explained in detail using thermoplastic stiffened panel case. Moreover, the LCC evaluation for stiffened-panel products is elaborated specifically for the RDT&E and production costs. By following the implementation steps, the applications for other cost types are developed based on the same method. Optimization studies are performed in the optimization module to obtain the optimum design for objectives such as the production cost, the direct operating cost and the surplus value. Results of the analysis are elaborated in detail.

6.1. STUDY CASE IMPLEMENTATION

Stiffened panels are often used for major airframe components such as fuselages, wings, decks and floors. Conventionally, aluminium alloy materials are adopted to construct stiffened panels. For example, Al7075 is often used for aircraft upper wing skin (under compression) due to its high strength property, while Al2024 is often used as aircraft lower wing skin (under tension and prone to fatigue) based on its high strength, toughness and good fatigue-resistant properties [321]. Composite materials, as strong competitors versus lightweight aluminium alloy materials, are brought into the industry due to their low weight properties. It is possible to replace an aluminium stiffened panel with an equivalent composite one [314]. The fibre reinforced plastics such as the fibre reinforced thermosets and the fibre reinforced thermoplastics have been adopted extensively. Depending on the composition of different fibre reinforcement and matrix types, their material properties vary. Thermoset resins are formed from the chemical reaction and are non-reversible processes, while thermoplastic resins can repeatedly be softened with heating and hardened with cooling within certain temperature scales. The fibre reinforced thermosets are widely employed for Boeing 787, A380 and A350XWB. The fibre reinforced thermoplastics are also promising due to the high strength, stiffness, toughness, chemical resistance, impact resistance properties and can be used over a wide range of temperatures. Moreover, due to the potential of achieving short production cycle time and high production rate, e.g. less cooling time needed for the forming process, the production costs are low. However, since they may require higher temperature and pressure than those for thermoset materials, the manufacturing and maintenance techniques for thermoplastic materials might need adaptations. Thermoplastic materials have been selected for A380 wing trailing edge. It is also applied to the stiffening structure (clips) of the body of the A350XWB [322]. This case study has been conducted on stiffened panels extracted from an aircraft upper wing skin made of aluminium alloy-Al7075, thermoset composite material-T300/epoxy and thermoplastic composite material-T300/PPS respectively. It is assumed that the stiffened panel is attached to the A330-200 aircraft type. According to the proposed material type specifically employed for the stiffened panel, the structural weight of the aircraft varies. It is assumed that the three material types are only tested on the wings without large changes on the aircraft configuration. Therefore, the variations of the aircraft weight are mainly introduced by the changes of the wing weight. Moreover, the production quantity is assumed to be 400 units.

6.1.1. STIFFENED PANEL PRODUCT MODEL

The product model generation module is illustrated in Figure 6.1. The configuration of the stiffened panel for estimation is described by the geometric properties introduced in Chapter 5, including the skin length(l), skin width(w), skin thickness(t), stringer pitch(b_s), flange width(b_f), stringer height(h_s), web thickness(t_w), and the flange thickness(r_f). The initial PBS, input parameters and the master geometry displaying on the application screen shot are indicated. The master geometry sketched on the right side is generated based on the user inputs. The initial PBS corresponding to the master geometry is also defined by the designers. It contains structural parts such as the skin, stringer flange and web in a predefined hierarchy. This is the fundamental step which provides input for the production view generation module.

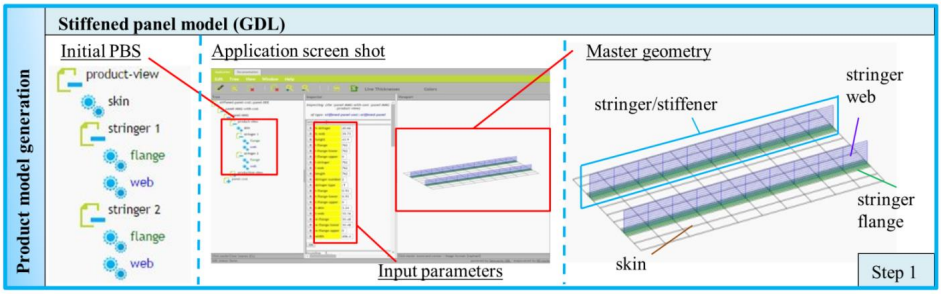


Figure 6.1: Product model generation module

6.1.2. STIFFENED PANEL LIFE-CYCLE-PROCESS-SPECIFIC VIEW

For stiffened-panel case, the original product geometry is taken as the geometric view for RDT&E cost analysis. For production cost estimation, a specific view is derived. As shown in Figure 6.2, three main steps are taken to generate the production view: generate product representation, derive process representation and formulate production view.

In order to segment manufacturable stringer (Figure 6.2 Step 2), the geometry handling rules apply. As the stringers are made of a thermoplastic composite material, a T-stringer is separated to two L segments. The left side stringer segment is labelled as 'stringer-l', while the right side stinger segment is labelled as 'stringer-r'. This is illustrated in the 'PBS for production view'. To extract the connection-interfaces, once the interface between the skin and stringer is detected, meaning the distances between the two surfaces are close to zero or those two surfaces are intersected, a virtual surface will be generated to represent the geometry of the connection. Next, the manufacturing process is derived for the stringer, and the assembly process is derived for the skin-stringer-connection-interface (Figure 6.2 Step 3). Because the stringer is made of T300/PPS, the available manufacturing strategy of the manufacturer is hand-layup. As both the skin and stringer are made of T300/PPS, the induction-welding assembly process is chosen. In addition, besides the connection interface between the skin and the stringer, the two L stringer segments also induce a connection interface from stringer to stringer. As they are made of thermoplastic composite materials, this interface will also be assembled by induction welding. It is noted this manufacturing strategy is mainly used for demonstration purpose, the feasibility and efficiency of the manufacturing process in mass production still needs to be verified and validated. Figure 6.2 Step 4 shows the production view demonstrated on the user interface including a specific PBS, a display of attributes and a manufacturable geometry. It is noted the PBS is different with the initial one since the manufacturable parts and connection-interfaces are generated in this step. Correspondingly, an extended BOM is generated in XML or TXT files. Examples of the BOM items are listed.

The process automation is achieved by inference mechanisms based on rules, shown in IF-THEN pseudo-code form. Relevant rules used for production view generation are shown from Table 6.1 to Table 6.4. The 'IF condition THEN operation' form, which refers to the logic of performing corresponding operations under the applicable condition, are shown to

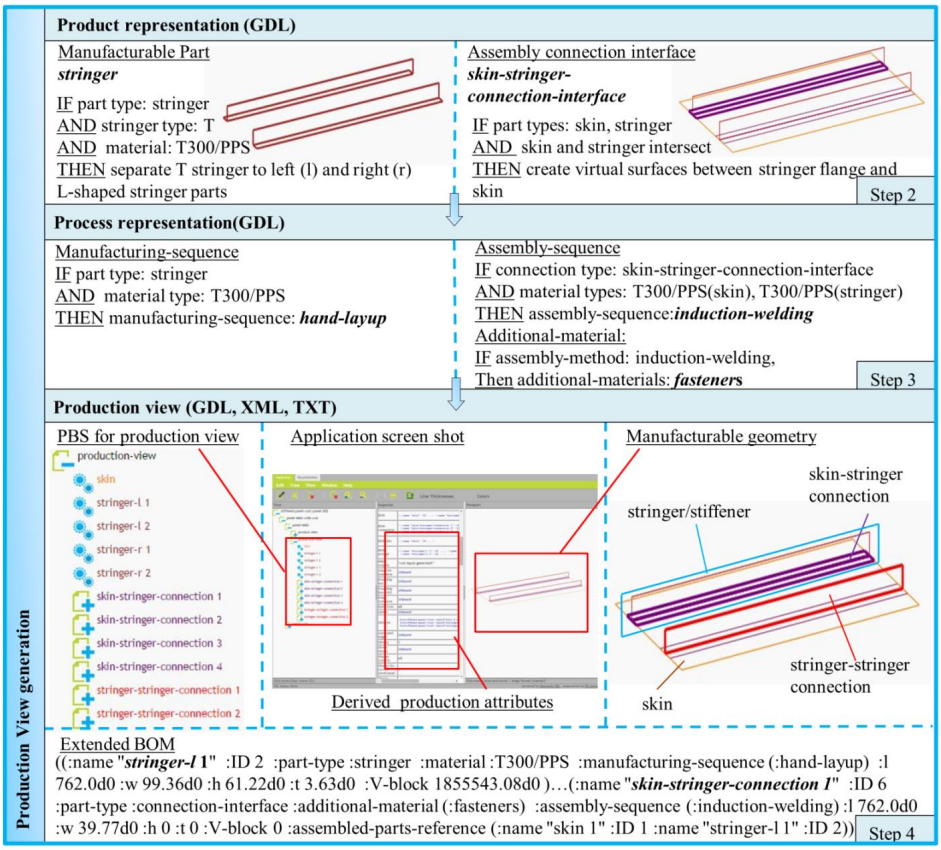


Figure 6.2: Production view generation module

illustrate the rules. For example, in 6.1, if the part type is T stringer, the part material is aluminium, then the stringer flange and the stringer web of the original product model should be merged together as the geometric representation to be manufactured; if the part type is T stringer, the part material is composite, then both the stringer flange and the stringer web of the original product model should be separated from the middle surface and merged to two L-shaped segments to represent the geometric view for manufacturing. This is extracted from the manufacturing practice: a metal stiffener is manufactured as one integrated part, while a composite stiffener is often composed of the left-hand side and the right-hand side parts to construct the T shape. Note that only a selection of typical and general rules applied to the study case are presented. In detail, Table 6.1 shows rules for production geometry segmentation. Some representatives in production process prediction can be found in Table 6.2. Table 6.3 lists the examples of assigning the additional material. And Table 6.4 presents typical rules of assigning assembled parts reference.

Table 6.1: Rules for production geometry segmentation

IF	Condition	Then	Operation
Part type, material	T stringer, metal	Stringer flange and stringer web	Merge
	T stringer, composite		Separate stringer from the virtual middle surface, then merge separated web and separated flange to L-shape segments for both left hand and right hand sides.

Table 6.2: Rules for production process prediction

IF	Condition	Then	Operation
Part-type, material	Skin, alumininum	Production sequence	Sheet-metal-machining
	Skin, thermoplastic composite		Hand layup
	Skin, thermoset composite		Automatic Tape Layup (ATL)
	Stringer, aluminium		Milling
	Stringer, thermoplastic composite		Hand layup, press forming
	Stringer, thermoset composite		ATL, forming
	Skin-stringer connection, aluminium materials		Fastening
	Skin-stringer connection, thermoplastic composites		Induction welding
	Skin-stringer connection, thermoset composites		Adhesive bonding, fastening
	Skin-stringer connection, thermoset composite and thermoplastic composite		Adhesive bonding, fastening
	Stringer-stringer connection, thermoplastic composites		Induction welding
	Stringer-stringer connection, thermoset composites		Adhesive bonding, fastening

6.1.3. KBE SUPPORTED STIFFENED PANEL COST ANALYSIS

The cost analysis module packages Step 5 to Step 7 of the implementation, see Figure 6.3. By applying the method illustrated in Chapter 3 on stiffened panel cases, the screenshot and the inference mechanisms for the progressive steps are shown in Figure 6.3. Examples of rules for pre- and post- processing are illustrated correspondingly. The actual CPs and CERs

Table 6.3: Rules for assigning additional material

IF	Condition	Then	Operation
Assembly process	Fastening	Additional-material	Fasteners (the number is determined by the length of the connection)
	Induction welding		Two fasteners
	Adhesive bonding		Adhesive

Table 6.4: Rules for assigning assembled part reference

IF	Condition	Then	Operation
Assembly connection interface	Is from skin♯1 and stringer ♯2	Assembly parts reference	Skin ♯1, stringer ♯2

utilised for cost estimation are also presented in detail.

6.1.3.1. PRE-PROCESSING

In order to estimate stiffened panel production cost, the integration of PBS and CBS is accomplished in Step 5 (see Figure 6.3). For the overall stiffened panel cost, all the objects in the integrated PBS and CBS use production data from the extended BOM. The hierarchical structure conforms with the PBS of the production view, where the product topology is referenced. It also includes the production cost topology. To zoom into the example of the object cost-stringer, it is of the production cost type. Accordingly, it inherits all the properties of the production cost, which is further divided into more detailed cost classes. As a result, the integrated stiffened panel PBS and CBS is structured as a tree for cost accumulation. By comparing the hierarchical structures 'PBS for production view' in Figure 6.2 and 'the PBS and CBS integration' in Figure 6.3, the changes are shown. The CPs are also instantiated in this step. At this stage, only the attributes relevant to the product and its production are available for each CP, while the cost values will be assigned after Step 6 is being implemented.

6.1.3.2. COST ESTIMATION

Cost estimation module contains the analysis procedure of both high-level and detail-level costing methods. Based on the data availability and user requirement, one of the routine or both cost estimation routines can be invoked

The high-level model extracts original product data and weight properties to conduct a cost analysis. It is formulated as a group of functions in the cost analysis module, which requests inputs from the pre-processing steps and to provide estimation results to the post-processing function.

The detail-level model requires process-specific product properties, which contains two main functional developments: Cost Primitives and Cost Estimation Relationships. One is used for data extraction, derivation and storage, the other is to perform calculations. The CPs of stiffened panel are cost-skin, cost-stringer, cost-skin-stringer-connection-interface and cost-stringer-stringer-connection-interface. The former two are instances of cost-part

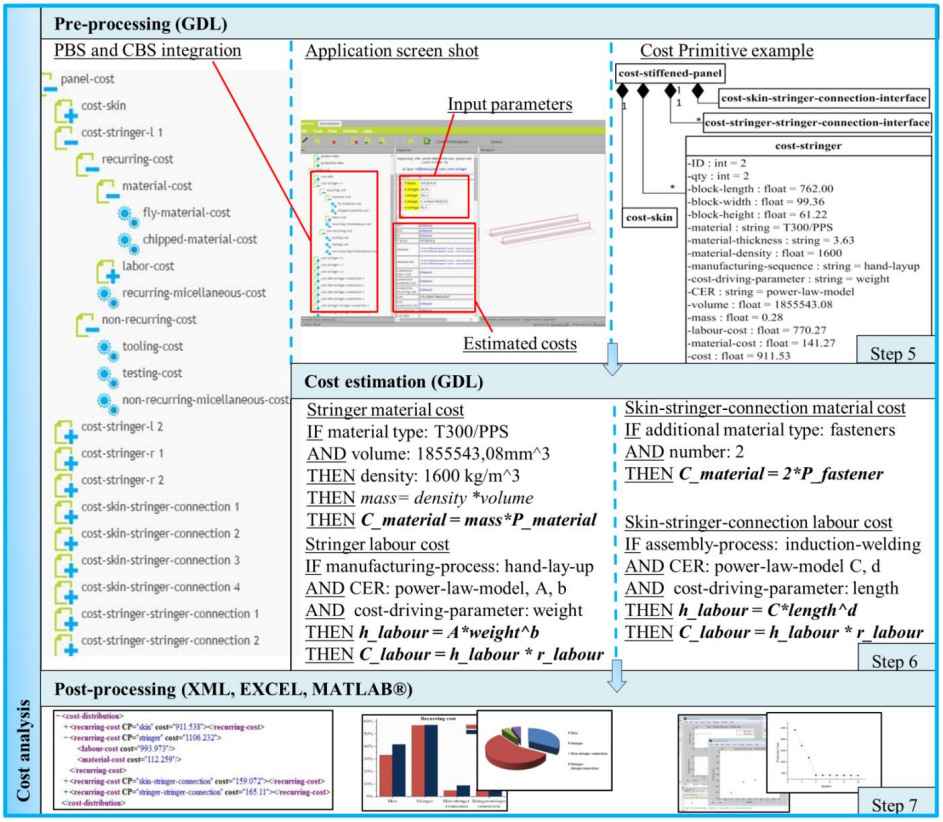


Figure 6.3: Cost analysis module

HLCP, while the latter two are instances of cost-assembly HLCP. The CERs for every CP differ because of their complex geometric, material and manufacturing properties. The distinction is reflected in material cost CERs and manufacturing labour hour CERs. The cost of material changes with the geometries and material types of the CPs. The manufacturing labour hours vary with the manufacturing sequence categorized to each CP. A UML class diagram is shown in Figure 6.3 to illustrate the CPs for the stiffened panel, where the attributes of cost-stringer instances are shown in detail. It contains the properties such as the product, process and the computed cost values. The detailed cost estimation for each CP of a stiffened panel can be found from Chapter 4. Each labour hour has been estimated using one of the three forms from Eqs.4.27 to 4.29 while adopting corresponding parameters. Those CERs link the cost driving parameters with the manufacturing time required for the manufacturing/assembly processes. For the stiffened panel case, around twenty CERs are formulated on the basis of those general equations and stored in the KB. Rules specific to the derivation of cost driving parameters in pre-processing are shown in Table 6.5.

According to Figure 6.3 Step 6, material and labour cost estimation examples for stringer

Table 6.5: Rules for derivation of cost driving parameter

IF	Condition	Then	Operation
Main manufacturing process	Milling	Cost driving parameter	Chipped-weight
	Sheet metal machining		Area
	Induction welding		Width(of the assembly connection interface)
	ATL		Weight
	Hand-layup		Weight
	Fastening		Number of fasterners
	Press-forming		Area

and skin-stringer-connection-interface are explained by inference chains and indicative computations. The stringer material cost is obtained if the material type, volume, density, mass and material price are supplied. The material cost of the skin-stringer-connection-interface counts the cost of the additional material such as fasteners when the number of fasteners and fastener prices are predicted. The labour costs for the stringer and the skin-stringer-connection-interface are implemented in two steps: to compute the labour hours and to transfer the labour hours to costs. When the production processes, the CER type, CER parameters, cost driving parameters are extracted from the KB, the labour hours can be obtained. In addition to the labour rate for each process, the labour hours are converted to costs.

6.1.3.3. POST-PROCESSING

The activities of post processing contain cost results retrieving and cost report generating. Cost results are formatted and exported analysis and optimization studies. The output report files and analysis results using XML, Excel and MATLAB® are shown in Figure 6.3 Step 7. The rules chosen for the post-processing are largely dependent on the use of the cost values and the tools adopted for further analyses. In the current application, the output results contain the cost distributions over the manufacturable elements and the cost distributions over cost types. In order to generate cost distribution diagrams, the result lists are exported from GDL to Microsoft Excel. In addition, a capability function is coded in GDL to generate column diagrams in Microsoft Excel. If the cost results are further adopted for optimization analysis, they are then exported to MATLAB®, where the optimization module is developed, as shown in Table 6.6.

Table 6.6: Rules for generating cost report

IF	Condition	Then	Operation
Cost estimation	Produces output reports	KBE system	Connect to Microsoft Excel
	Provides input for optimization		Connect to MATLAB

6.2. COST RESULTS

In this section, the results of the high-level and detail-level costing for stiffened panels are illustrated. Major cost types of the LCC are evaluated respectively. In order to avoid presenting repetitive information in both stiffened panel and rudder case studies. The RDT&E cost and the Production cost are emphasized for stiffened panel study case, while the O&M and D&R cost estimates are addressed in the rudder study case in Chapter 7.

Since the stiffened panels are modelled as aircraft components employing parametrized geometric representation and knowledge based process representation, the detail- level LCC estimation is more suitable for the analysis, and it can also provide cost distributions on detailed process steps. Therefore, the results obtained from the detail-level model are emphasized. While the high-level estimation is conducted to illustrate the proposed analysis procedure and at the same time to validate the results obtained from the detail-level estimation. In general, results obtained from high-level and detail-level model validate each other on the same value scale. The cost estimation method is also validated by estimating costs of various panel configurations, which are described by a group of geometric properties. The estimations are applied on six stiffened panels with T stringers (♯1 to ♯6), which involve two geometric configurations and three types of materials (Table 6.7). These two configurations are with the same length and width, while the other geometric properties are different. ♯1, ♯2 and ♯3 panels contain four stiffeners, and they are composed of thin skin, narrow stiffener flange, short stiffener height and thick stiffener web; ♯2, ♯4 and ♯6 panels contain two stiffeners, and they comprise thick skin, wide stiffener flange, tall stiffener height and thin stiffener web. Both configurations can stand a compression load intensity of 1751 N/mm based on structural analysis. The materials include aluminium material (Al7075), carbon fibre reinforced thermoplastic material (T300/PPS) and carbon fibre reinforced thermoset material (T300/epoxy).

6.2.1. RESULTS OF RDT&E COST ANALYSIS

6.2.1.1. HIGH-LEVEL MODEL RESULTS

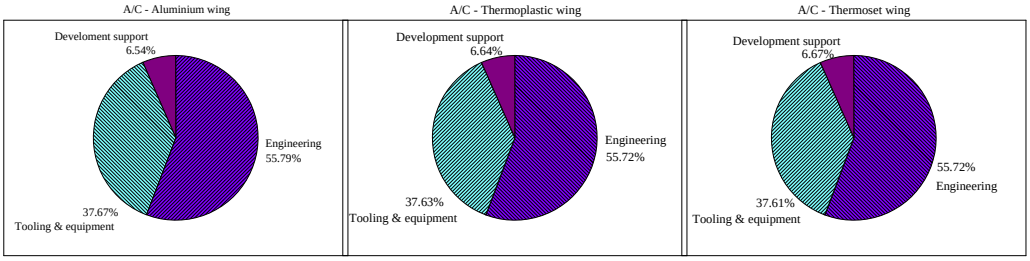
The high-level model RDT&E cost estimation are firstly applied on the overall aircraft containing wings made of three different material types. Later, the stiffened-panel costs are obtained via weight conversion from aircraft to component. Since the high-level model is adapted from the DAPCAIV model, it inherits relevant factors employed originally. One of the material related fudge factors is also adopted, however, it is found that the influence of the fudge factors on the final results can sensitively lead to changes on material choice by only scaling up/down the total costs. Therefore, both results including and excluding this factor are investigated. The former has been presented in this section, the latter can be found in Appendix G. The fudge factors are decided based on reference values in Table 4.2. Factors 1, 1.45 and 1.75 have been applied on aircraft contains aluminium wing, thermoplastic wing and thermoset wing respectively.

The results for the overall aircraft is shown in Figure 6.4 and Figure 6.5. The cost distributions for all three material types agree with each other. More than half of the RDT&E cost is distributed on engineering cost element. The tooling & equipment cost counts more than one-third of the total expenses. And the development support cost only takes the smallest

share. In total, the costs are around $30 million. The aircraft with thermoset wing consumes the most among all three materials, while the aircraft with aluminium wing costs the least. It is noted the development cost of the aircraft, which has eliminated the influence of the production, is different with the development cost of a programme.

Table 6.7: Stiffened panel configurations

Panel	materials	ρ (kg/m^3)	b_s (mm)	t (mm)	b_f (mm)	t_f (mm)	h_s (mm)	t_w (mm)	L (mm)	W (mm)
♯1	Al7075	2795	101.6	3.2	30.5	0.9	30.5	10.2	762.0	406.4
♯2	Al7075	2795	203.3	6.1	49.9	1.0	40.7	5.4	762.0	406.4
♯3	T300/PPS	1600	101.6	3.2	30.5	0.9	30.5	10.2	762.0	406.4
♯4	T300/PPS	1600	203.3	6.1	49.9	1.0	40.7	5.4	762.0	406.4
♯5	T300/epoxy	1500	101.6	3.2	30.5	0.9	30.5	10.2	762.0	406.4
♯6	T300/epoxy	1500	203.3	6.1	49.9	1.0	40.7	5.4	762.0	406.4



(a) (b) (c)

Figure 6.4: Aircraft RDT&E cost distribution by cost elements (high-level model)

Next, by applying the cost conversion factor, which is the weight ratio between the sampled aircraft and the stiffened-panels defined in Table 6.7, the RDT&E cost of a stiffened panel can be obtained. It should be noted that the RDT&E cost is one of the trade-off criteria for design decision making and it can provide the component LCC analysis with a necessary cost element in an acceptable value scale, although it is not always the focus of a stakeholder and some estimation errors can be brought to the value by the cost conversion factor. The results of the high-level model are shown in Figure 6.6 for three types of stiffened panel materials from the wings of the sampled aircraft. They are separated to two groups by geometric configurations: ♯1, ♯3, ♯5 panels and ♯2, ♯4, ♯6 panels. Each group contains panels made of respective materials: Al7075, T300/PPS and T300/epoxy. Moreover, the product PBS for RDT&E process follows the PBS of the original product configuration, therefore, the stiffened panel is considered the composition of skin and stiffeners. The RDT&E costs distributed over the skin and stiffeners are illustrated in Figure 6.6(a) and 6.6(b). The main drivers of the difference among those cost distributions are the differences of weight ratios introduced by geometric sizes and material types. Due to low weight properties of the composite panels, it is shown

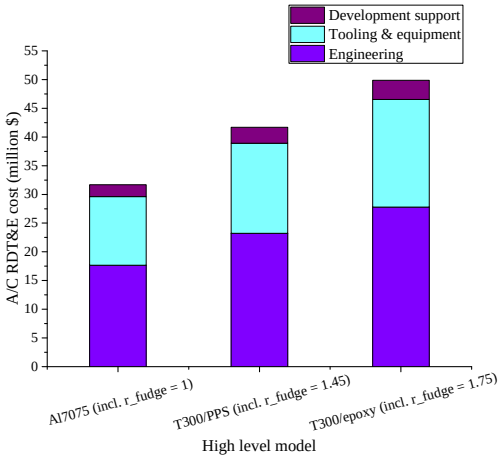


Figure 6.5: Aircraft RDT&E cost (high-level model)

that the RDT&E costs of the aluminium panel (♯1, ♯2) outweigh those of composite panels (♯3 to ♯6). Since the weight properties of ♯1,♯3 and ♯5 panel group is slightly lower than those of the ♯2, ♯4 and ♯6 group, it can be seen that the RDT&E costs of the ♯1,♯3, and ♯5 panels are slightly lower than those of the ♯2, ♯4 and ♯6 panels. The cost distribution over the stiffener and skin also align with the weight properties. Due to the weight percentile of stiffeners in the ♯1,♯3, and ♯5 panel group is bigger than that of the other panel group, the stiffeners of ♯1,♯3, and ♯5 panel group consumes more RDT&E cost resources.

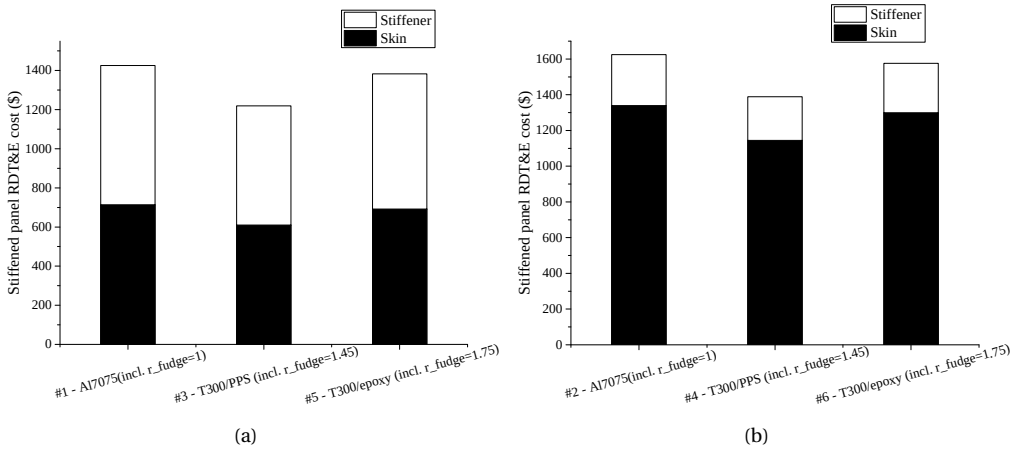


Figure 6.6: Stiffened panel RDT&E cost distribution by parts (high-/detail- level model):(a)♯1, ♯3, ♯5; (b)♯2, ♯4, ♯6.

Similar to the aircraft RDT&E cost, the total costs of the stiffened panel based on the cost distribution is shown in Figure 6.7. The shares of cost elements are kept the same as those of

the total aircraft RDT&E costs, while the amount of the expenses are scaled down hugely for stiffened panels. The differences in values between ♯1, ♯3, ♯5 panels and ♯2, ♯4, ♯6 panels can also be inspected. The same trend is also reflected in the skin and stiffener costs, Table 6.8 and Table 6.9 provide the actual cost values of skin and stiffeners amortized to each cost element and process step.

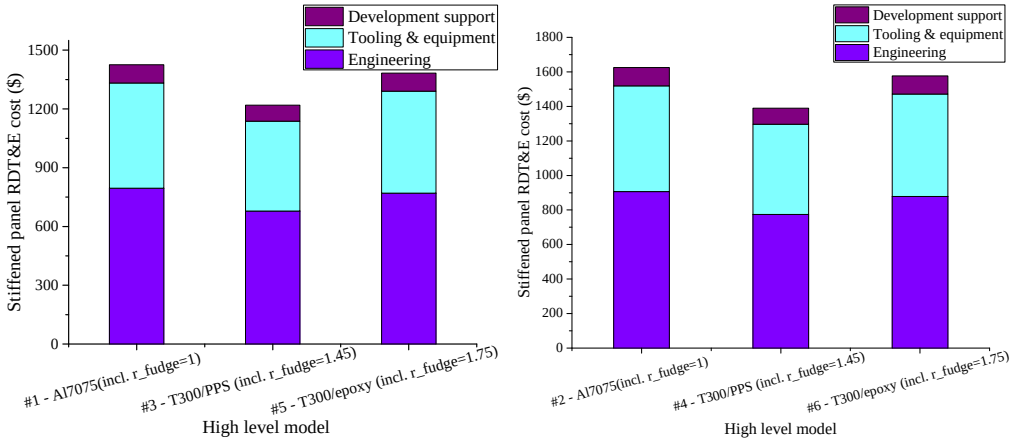


Figure 6.7: Stiffened panel RDT&E cost distribution by cost elements (high-level model):(a)♯1, ♯3, ♯5; (b)♯2, ♯4, ♯6.

Table 6.8: Skin RDT&E cost distribution over cost elements (high-level model)

Skin	RDT&E cost elements($)		
	Engineering	Tooling & equipment	Development support
♯1	398.1	46.7	268.8
♯2	747.1	504.4	87.5
♯3	339.9	40.6	229.5
♯4	637.9	430.7	76.2
♯5	385.6	46.1	260.3
♯6	723.6	488.5	86.5

6.2.1.2. DETAIL-LEVEL MODEL RESULTS

Cost elements including development support, design engineering, manufacturing engineering, tool design and tool fabrication are analysed in the detail- level model. Besides the cost estimation on RDT&E cost elements, one more layer of analysis is added into the detail-level model, i.e., the cost of RDT&E process steps from conceptual and preliminary design definition, detail design definition, initial production, ground test to type certification. Figure 6.8 shows the commercial aircraft development timelines extracted from the aerospace

Table 6.9: Stiffener RDT&E cost distribution over cost elements (high-level model)

Stiffener	RDT&E cost elements($)		
	Engineering	Tooling & equipment	Development support
♯1	397.4	268.3	46.6
♯2	159.5	107.7	18.7
♯3	339.3	229.1	40.5
♯4	136.2	92.0	16.3
♯5	384.9	259.9	46.0
♯6	154.5	104.3	18.5

industry practice. The horizontal axis stands for the year when the aircraft type is in development. This can be utilized as a reference for specific study case where the total development time is known or for new design projects. According to those timelines, the RDT&E subprocess starting time and duration are approximated and normalized for current study case within 13% of error margin based on the sampled aircraft, see Table 6.10. It should be noted that given the approximation is influenced by different aircraft types and ODMs, specific beta distribution parameters and the cost incurred/ceased time frames are required for real development cases. The results obtained from the detail-level model is demonstrated and discussed in the following sections. Firstly, the results generally applicable for both high-level model and detail-level model are presented, including the overall cost distribution of the total cost in terms of the cost element and the process steps. Secondly, the estimates for aircraft are illustrated, the actual cost shares divided by cost elements and process steps. Thirdly, the estimation on stiffened panel from the aircraft upper wing is introduced.

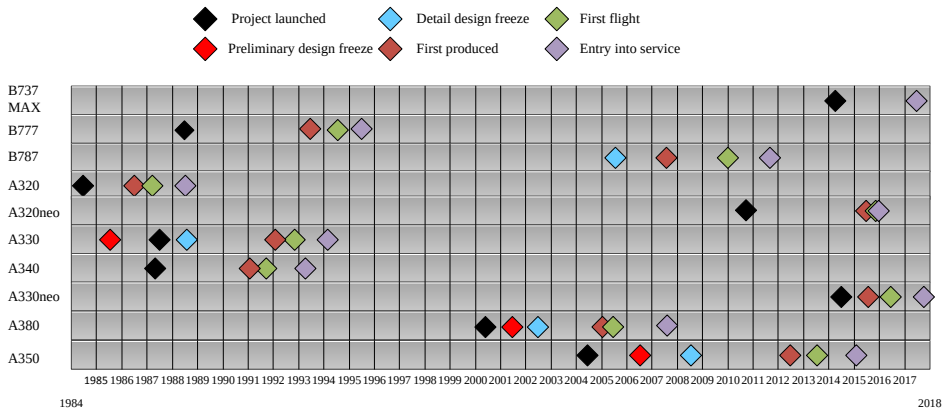


Figure 6.8: Commercial aircraft RDT&E timelines

Since the beta distribution based on the aircraft development project are assumed the same for aircraft with different wing material types for the detail-level model, therefore, the cost distribution in terms of cost elements and process steps are the same for all the aircraft

Table 6.10: RDT&E sub-process average starting time and duration (normalized)

Normalized process time (Year)	Conceptual & Preliminary design definition	Detail design definition	Initial production	Ground test	Type certification
Process starting time $(t_0)_{RDT\&E,k,j}$	0	0.14	0.29	0.67	0.76
Process duration $t_{RDT\&E,k,j}$	0.14	0.15	0.38	0.09	0.24
Process ended time $t_{RDT\&E,k,j}$	0.14	0.29	0.67	0.76	1

and the stiffened panels regardless of their material types or if the fudge factors are applied. According to Figure 6.9, the cost of design engineering and the tool fabrication takes big shares of the RDT&E cost, 40.6% and 34.4% respectively. While low expenses are consumed via the development support category. Tool design cost and manufacturing engineering cost are ranked in the middle. Figure 6.10 shows the costs spent for each process step in the RDT&E process. Design definitions including the conceptual, preliminary and detail design process steps take relatively small sections of the total RDT&E cost. The initial production process step consumes 74.6% of the whole RDT&E cost, which indicates that the high expenses on RDT&E process is actually induced by the initial aircraft production. A possible explanation is that part of the design engineering and tool fabrication costs contribute to the initial production process. Moreover, there are also expenses allocated to the ground test and type certification processes.

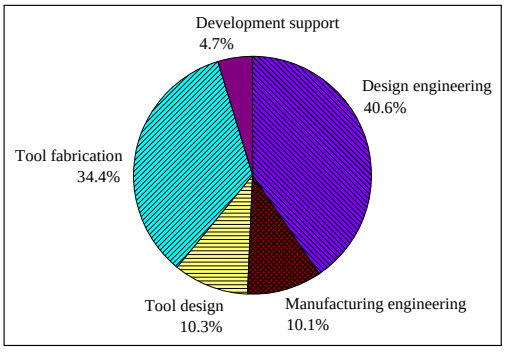


Figure 6.9: RDT&E cost distribution by cost elements (detail-level model)

The material types impact the RDT&E cost through their effects on weight properties. However, since the detail-level model requires inputs from the high-level model, the factors influence the high-level model also have impacts on the detail-level model. The high-level model proposes a fudge factor related to the material type, while the influence of this factor

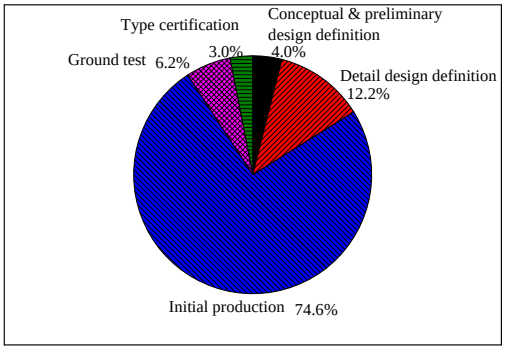


Figure 6.10: RDT&E cost distribution by process step (detail-level model)

on the RDT&E costs can easily outweigh the influence of the weight change. This can directly impact on the decision-making process, therefore, a careful choice of the fudge factors is required. Due to this reason, the analysis with and without the application of fudge factors are both conducted. In the thesis, only cost estimates obtained without applying the fudge factor is shown. And the results of analysis involving fudge factor is illustrated in Appendix G. The total RDT&E for the aircraft containing aluminium, thermoplastic and thermoset material for the wings are shown in Figure 6.11. The total costs are inputs from the high-level model. They are further divided by cost elements (Figure 6.11(a)) and process steps (Figure 6.11(b)) with respect to their respective cost percentages.

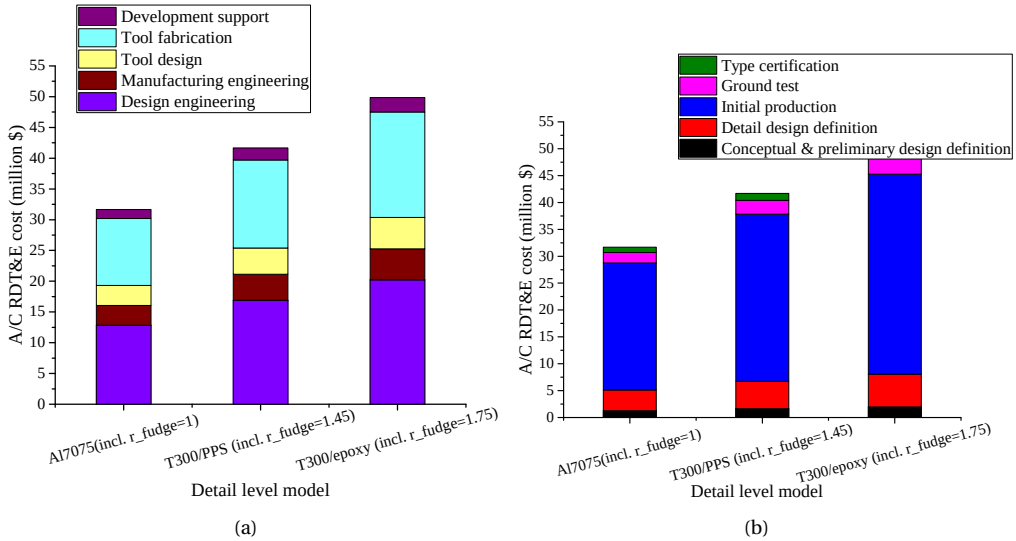


Figure 6.11: Aircraft RDT&E cost (detail-level model)

In more detail, the cost distribution considering the aircraft RDT&E cost elements is gen-

erated, see Figure 6.12. It contains the amount of RDT&E expenses (vertical axis) allocated to each cost element (horizontal axis). One cost element is further distributed over the relevant process steps (coloured blocks). Moreover, the costs of the three material types constructing the aircraft wing structure are provided respectively and distinguished with filled patterns. Besides following the same trend of the RDT&E costs over different materials, the attention has been drawn on the cost distribution over the process steps. There are big contributions from the design engineering cost and tool fabrication cost to the initial production process. The design engineering cost is also dedicated to the conceptual & preliminary design definition, ground test and type certification processes. The manufacturing engineering cost is mainly spent on the initial production and detail design definition processes, and it covers a small amount on conceptual & preliminary design definition and ground test processes. Nearly all cost of the tool design is spent within the initial production process. A large portion of the tool fabrication cost is devoted to the initial production process whilst a relatively small portion is contributed to the ground test process. Last but not least, the development support cost covers all process steps while contributes small shares for each process step and for the total amount.

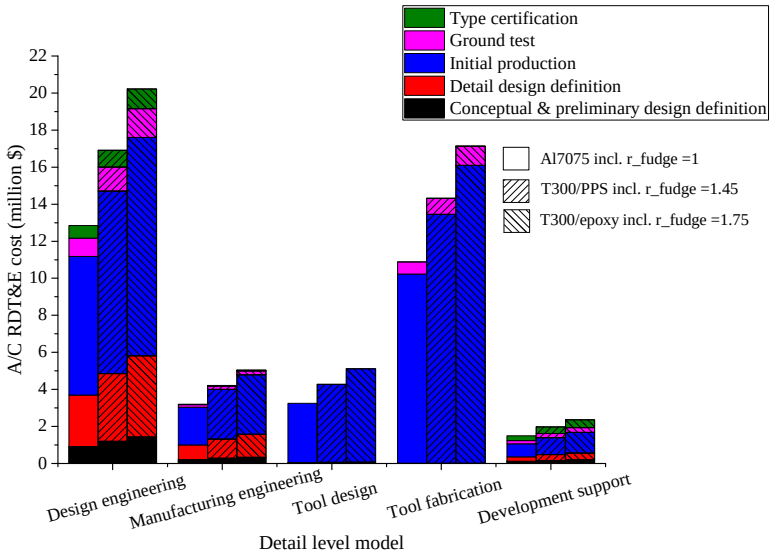


Figure 6.12: Aircraft RDT&E cost distribution by cost element (detail-level model)

Similarly, the cost composition concerning the aircraft RDT&E process steps is also produced, see Figure 6.13. It includes the costs (vertical axis) of each process step composed of involved cost elements (horizontal axis). Respective RDT&E costs for the aircraft containing three different material types are calculated at the same time, shown as three filled patterns. It emphases the coloured block of cost elements grouped in each process steps. The conceptual & preliminary definition process consists of manufacturing engineering cost, design engineering cost and development cost in a relatively low value. The design detail defini-

tion process involves all cost elements, while the design engineering takes the main part. The most cost consumption process is the initial production, which covers all cost elements while the design engineering cost and the tool fabrication cost take the major parts. The costs of design engineering and development support are also involved in the initial production process, whilst this process also spent minor expenses on manufacturing engineering and tool fabrication.

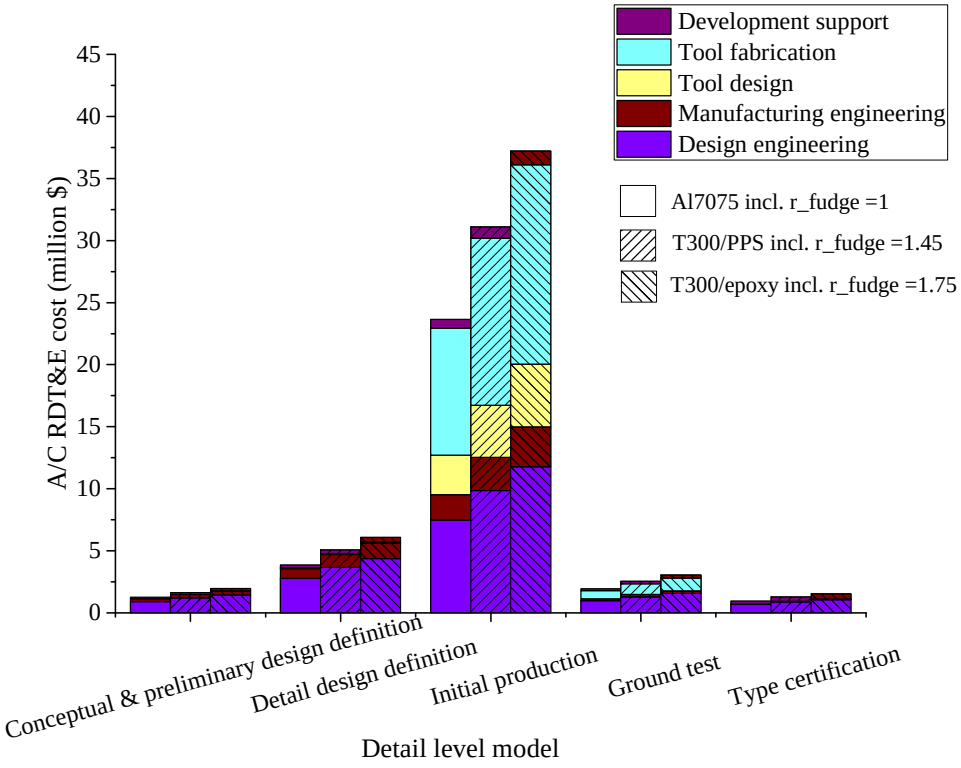


Figure 6.13: Aircraft RDT&E cost distribution by process steps (detail-level model)

The RDT&E costs of the stiffened panels are calculated via the application of cost conversion factors, which are the same as the factors adopted by the high-level model, so that the detail-level model follows Figure 6.6 cost distribution. The total costs and the cost distributions over the cost elements and the process steps can be obtained for the stiffened panel, see Figure 6.14. The shares of cost elements and the blocks of process steps are shown a different trend as those depicted in the total aircraft RDT&E costs. This can be caused by the specific weight distribution of the stiffened panels. The differences in costs among the panels can also be identified from the actual values. The skin and stiffener costs, following the same trend as the panel costs, is recorded in Table 6.11 to Table 6.14 for each cost element and process step. It is noteworthy, the cost of the process can only be obtained by the detail-level model other than the high-level model.

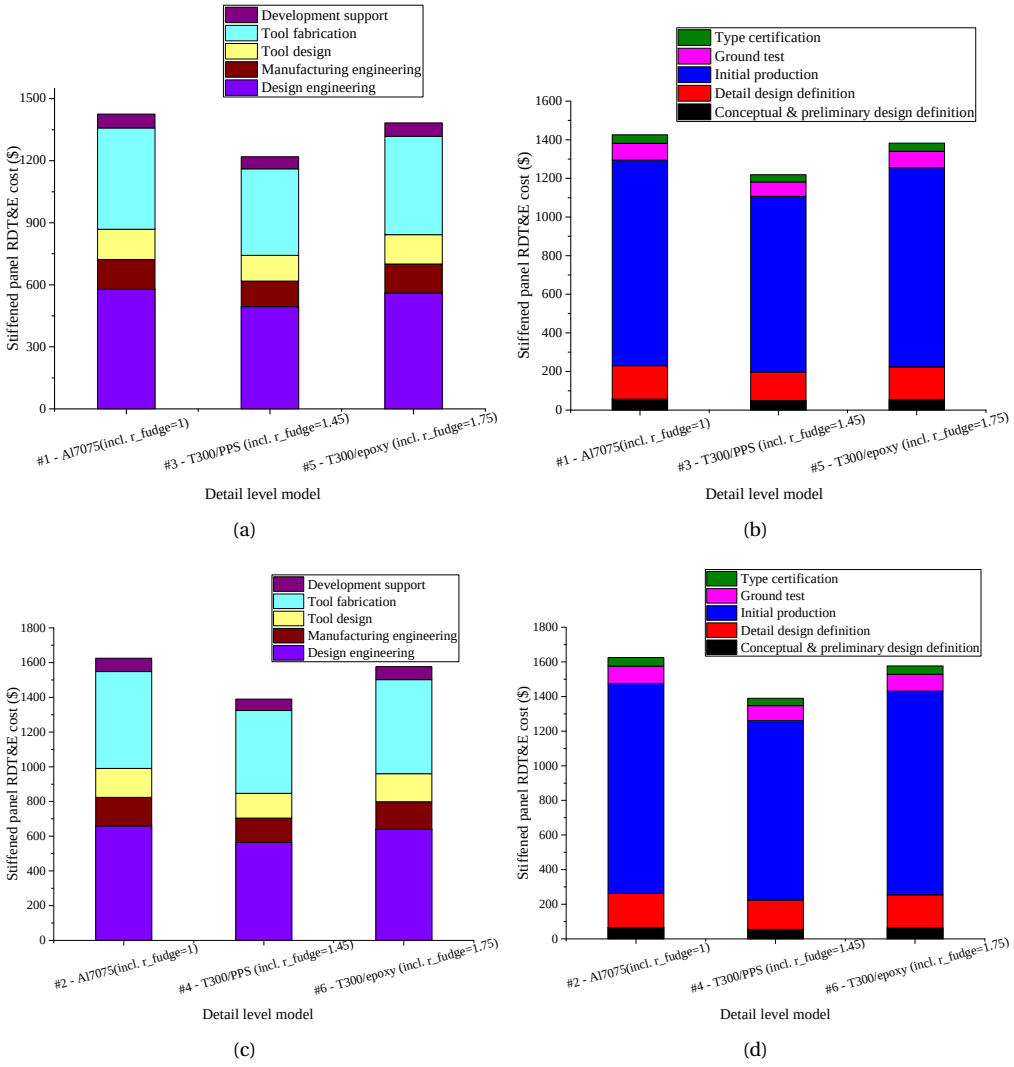


Figure 6.14: Stiffened panel RDT&E cost (detail-level model):(a) divided by cost elements (♯1, ♯3, ♯5);(b) divided by process steps (♯1, ♯3, ♯5); (c) divided by cost elements (♯2, ♯4, ♯6);(d) divided by process steps (♯2, ♯4, ♯6).

Table 6.11: Skin RDT&E cost distribution over cost elements (detail-level model)

Skin	RDT&E cost elements($)				
	Design engineering	Manufacturing	Tool design	Tool fabrication	Development support
♯1	289.4	72.1	73.2	245.1	33.8
♯2	543.1	135.4	137.3	460.0	63.4
♯3	247.4	61.7	62.5	209.5	28.9
♯4	464.3	115.7	117.3	393.2	54.2
♯5	280.7	70.0	70.9	237.7	32.8
♯6	526.7	131.3	133.1	446.1	61.5

Table 6.12: Skin RDT&E cost distribution over process steps (detail-level model)

Skin	RDT&E cost elements($)				
	Conceptual& preliminary design definition	Detail design definition	Initial production	Ground test	Type certification
♯1	28.2	87.1	532.5	43.9	21.9
♯2	52.9	163.5	999.2	82.4	41.1
♯3	24.1	74.5	455.2	37.5	18.7
♯4	45.2	139.8	854.2	70.4	35.1
♯5	27.3	84.5	516.4	42.6	21.2
♯6	51.3	158.6	969.1	79.9	39.9

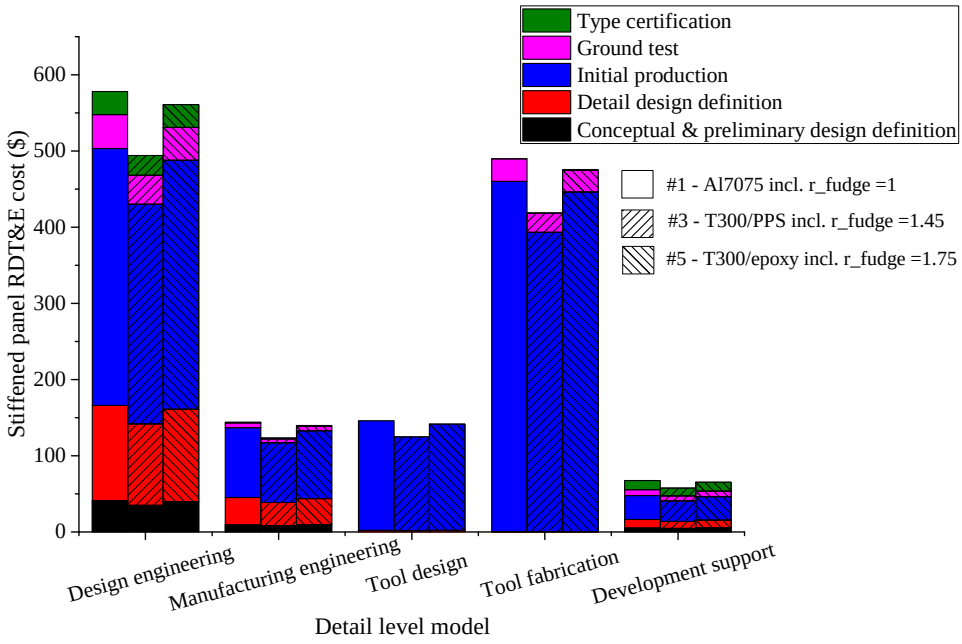
Table 6.13: Stiffener RDT&E cost distribution over cost elements (detail-level model)

	RDT&E cost elements($)				
Skin	Design engineering	Manufacturing	Tool design	Tool fabrication	Development support
♯1	288.9	72.0	73.0	244.7	33.7
♯2	116.0	28.9	29.3	98.2	13.5
♯3	246.9	61.6	62.4	209.2	28.8
♯4	99.1	24.7	25.1	84.0	11.6
♯5	280.1	69.8	70.8	237.3	32.7
♯6	112.5	28.0	28.4	95.3	13.1

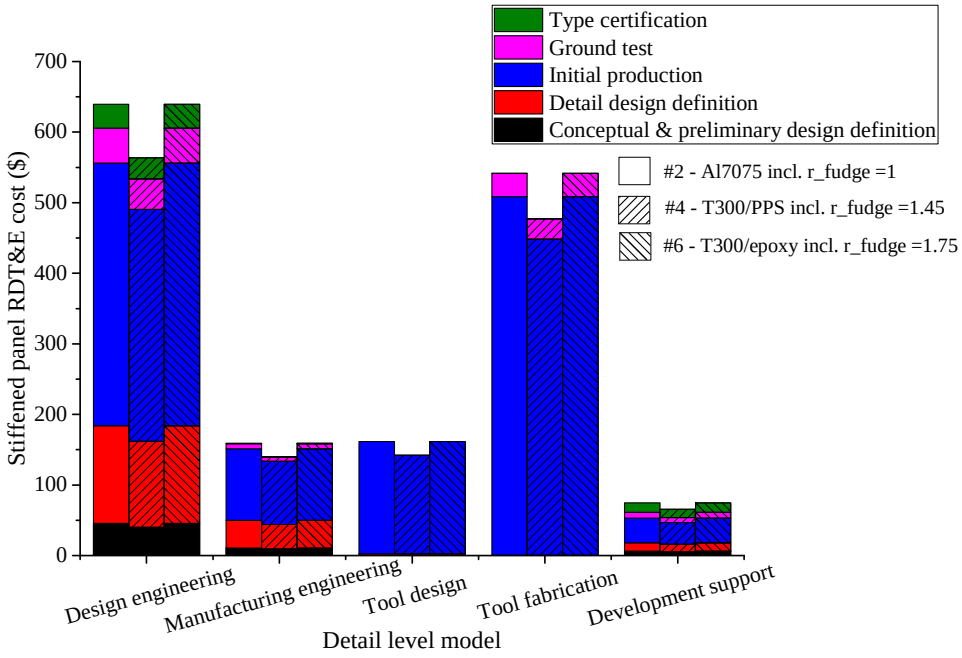
Table 6.14: Stiffener RDT&E cost distribution over process steps (detail-level model)

	RDT&E cost elements($)				
Skin	Conceptual& preliminary design definition	Detail design definition	Initial production	Ground test	Type certification
♯1	28.1	87.0	531.3	43.8	21.8
♯2	11.3	34.9	213.4	17.6	8.8
♯3	24.0	74.4	454.4	37.5	18.7
♯4	9.7	29.9	182.4	15.0	7.5
♯5	27.3	84.3	515.4	42.5	21.2
♯6	11.0	33.9	206.9	17.1	8.5

Furthermore, Figure 6.15 is presented to demonstrate each cost element (horizontal axis) of stiffened panel RDT&E distributed over the relevant process steps (coloured blocks). And Figure 6.16 is illustrated to represent the cost of each process step (horizontal axis) composed by various cost elements(coloured blocks). Again, the trend of the stiffened panel RDT&E costs does not follow the general trend of the aircraft RDT&E costs. Comparing the two geometric configurations, ♯1, ♯3, ♯5 panels generally have a lower cost than ♯2, ♯4, ♯6 panels mainly due to their weight influence. The analysis can be further detailed on skins and stiffeners of all panels, same distributions with respective cost values can be obtained.

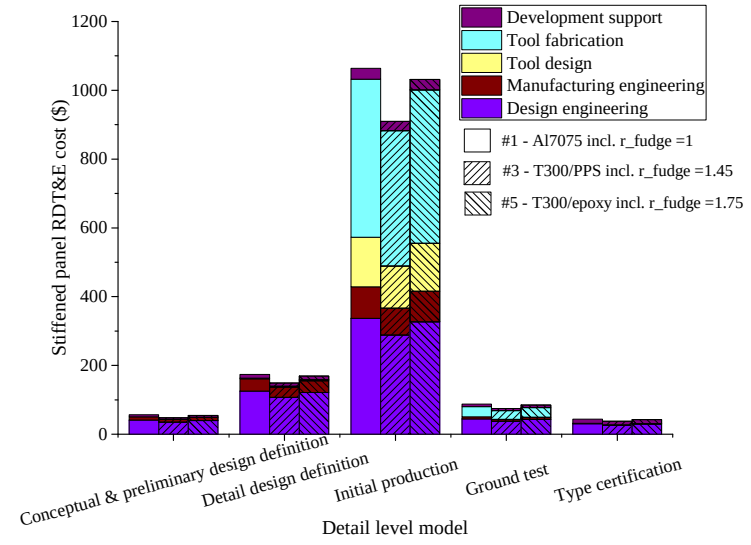


(a)

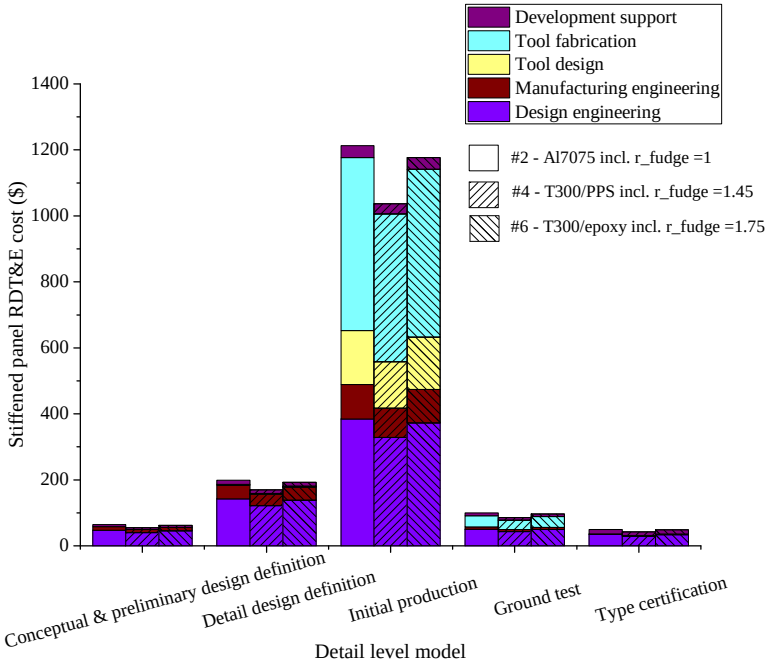


(b)

Figure 6.15: Stiffened panel RDT&E cost distribution by cost elements (detail-level model):(a)♯1, ♯3, ♯5; (b)(a)♯2, ♯4, ♯6.



(a)



(b)

Figure 6.16: Stiffened panel RDT&E cost distribution by process steps (detail-level model):(a)♯1, ♯3, ♯5; (b)(a)♯2, ♯4, ♯6.

6.2.1.3. MODEL VERIFICATION AND VALIDATION

The verification of the actual cost should be checked with the aircraft development programme. By amortizing the overall program cost by the number of the aircraft ordered, the aircraft RDT&E cost can be verified. Generally, an aircraft development cost stays on the scale of 'billion $', based on an order of a few hundred aircraft, the aircraft development cost would finally reach the scale of 'million $' based on the amortization schedule in the company. However, due to little official data is available for the programme costs, an exact error cannot be provided. It is suggested to reference the historical programme development expenses in a company and to establish the evaluation with calibration based on the actual development conditions.

In terms of model validation, the high-level model cost distribution Figure 6.4 and the detail-level model cost distribution Figure 6.9 is compared by grouping the percentages of relevant cost elements, i.e., design engineering & manufacturing engineering, tool fabrication & tool design, from the detail-level model. Minor differences in absolute percentage values have been found: 5.1% in engineering cost, 6.9% in tooling & equipment cost, 1.8% in development cost.

6.2.2. RESULTS OF PRODUCTION COST ANALYSIS

6.2.2.1. HIGH-LEVEL MODEL RESULTS

According to the top-down approach of the high-level production cost evaluation, the stiffened-panel costs are amortized based on the aircraft production cost via the cost-weight ratios. The aircraft production cost distributions are shown in Figure 6.17, which illustrates similar percentiles of labour, material and testing costs for all three aircraft models with different wing materials. The total production costs are shown in Figure 6.18.

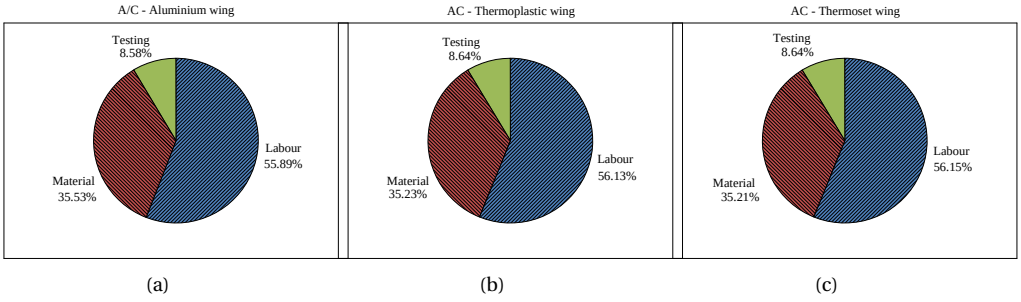


Figure 6.17: Aircraft production cost distribution by cost elements (high-level model)

Since the high-level model does not distinguish costs for parts or assembly interfaces, therefore, the total production cost can only be distributed over skin and stiffeners via the cost-weight ratios, see Figure 6.19. Because of more stiffeners are installed on the ♯1, ♯3, ♯5 panel configuration, the cost of stiffeners is higher than those of ♯2,♯4,♯6 panels.

In addition, the cost distributions over cost elements can be calculated, shown in Figure 6.20. Interestingly, the trend of the cost for panels does not follow the trend shown in

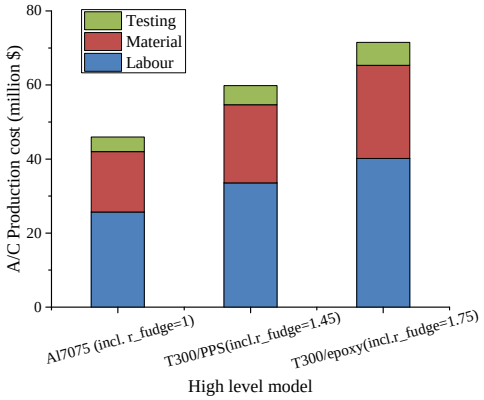


Figure 6.18: Aircraft Production cost (high-level model)

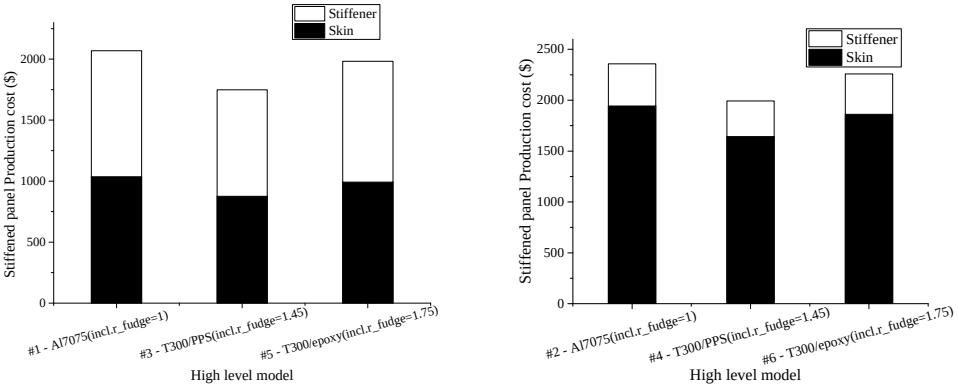


Figure 6.19: Stiffened panel Production cost distribution by parts: (a)♯1, ♯3, ♯5; (b)♯2,♯4,♯6.

the total costs. This can be explained by the influence of the panel geometry and its weight properties induced by different material types. it should be noted that the fudge factors can also cause different cost distributions. In more detail, the costs of skin and stiffener are also listed in Table 6.15 and Table 6.16.

6.2.2.2. DETAIL-LEVEL MODEL RESULTS

The production cost detail-level model directly adopts the product and process properties of the stiffened panels as inputs. Based on the CPs defined for stiffened panels and the manufacturing and assembly steps derived for the production process, not only the costs of skin and stiffeners can be provided, but also the expenses on assembly connections can be evaluated. All the results are normalized by a reference cost, which represents a cost of 100% as shown in the bracket under each figure. For instance, The '♯3 panel recurring cost -100%'

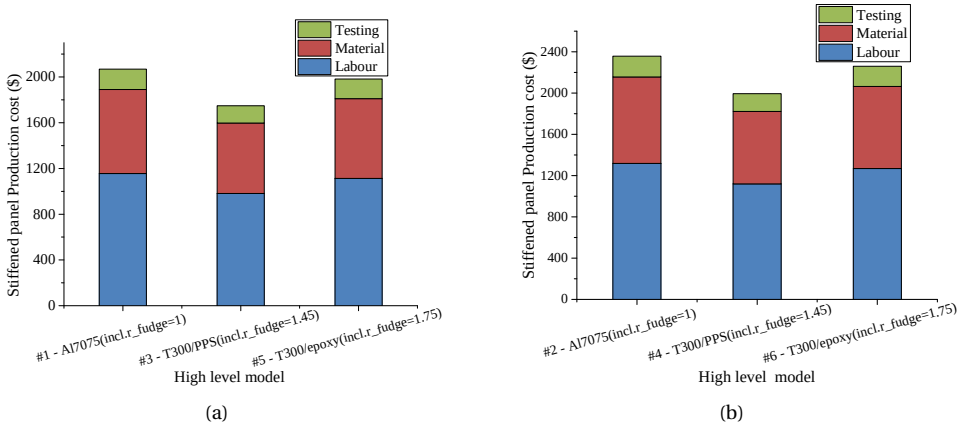


Figure 6.20: Stiffened panel production cost distribution (high-level model): (a)♯1, ♯3, ♯5; (b)♯2,♯4,♯6.

Table 6.15: Skin Production cost distribution over cost elements (high-level model)

Skin	Production cost element($)		
	Labour	Material	Testing
♯1	578.5	367.8	88.8
♯2	1085.6	690.3	166.6
♯3	491.3	308.4	75.6
♯4	921.9	578.7	141.9
♯5	557.0	349.3	85.7
♯6	1045.2	655.4	160.9

Table 6.16: Stiffener Production cost distribution by cost elements (high-level model)

Stiffener	Production cost element($)		
	Labour	Material	Testing
♯1	577.5	367.2	88.6
♯2	231.8	147.4	35.6
♯3	490.4	307.8	75.5
♯4	196.9	123.6	30.3
♯5	556.0	348.6	85.6
♯6	223.2	140.0	34.3

in Figure 6.21 implies the cost elements are proportionalised by the recurring cost of the ♯3 panel. This is because some of the CERs employed by the detail-level model are extracted from a confidential resource.

The total costs together with the cost distributions in terms of cost elements and process steps are illustrated in Figure 6.21. The production cost is zoomed into recurring cost since

only labour cost and material cost have been included in the analysis, while the influence of the production quantity and the learning curve are involved in the CERs. It is found that the material costs share a small part of the total cost, while the labour costs are the main consumptions of the stiffened panel production. Comparing to the high-level model, the share of labour cost is higher in the detail-level model. This can be induced by the consideration of specific manufacturing and assembly effort in the detail-level model, while the weight property is more sensitive in the high-level model. By dividing the total cost into process steps, manufacturing processes for stiffened panel are the main drivers, while the costs of the assembly processes vary based on the connection types.

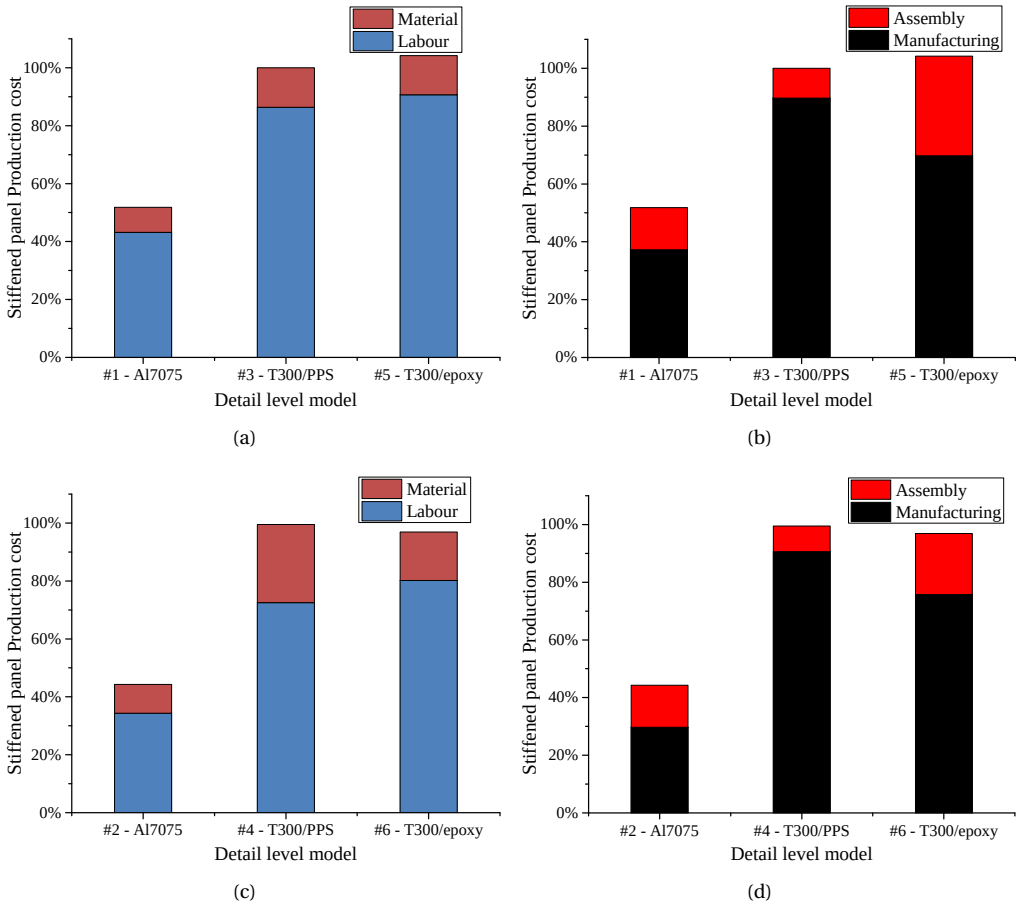


Figure 6.21: Stiffened panel production cost distribution (detail-level model) (♯3 panel recurring cost -100%).: (a)divided by cost elements (♯1, ♯3, ♯5); (b)divided by process steps (♯1, ♯3, ♯5);(c)divided by cost elements (♯2,♯4,♯6);(d)divided by process steps (♯2,♯4,♯6)

Moreover, the advantage of detail-level model is to generate cost compositions for prod-

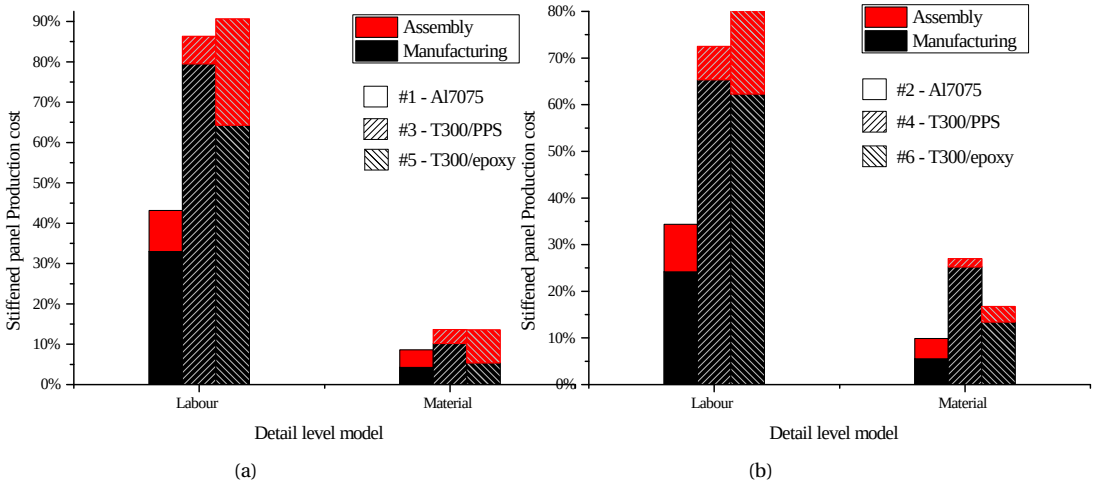


Figure 6.22: Stiffened panel Production cost distribution by cost elements (detail-level model) (♯3 panel recurring cost -100%).

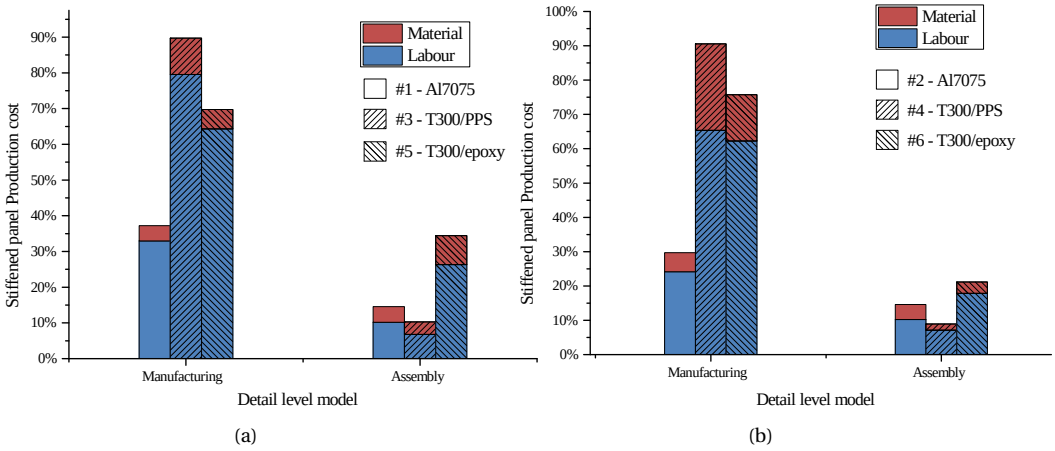


Figure 6.23: Stiffened panel Production cost distribution by process steps (detail-level model) (♯3 panel recurring cost -100%).

ucts, see Figure 6.22 and Figure 6.23. Due to more manufacturing process steps than assembly steps are taken within stiffened panel fabrication process flow, therefore, a big part of labour costs contribute to the manufacturing process steps. While the contribution of the material costs to either the manufacturing or the assembly varies based on the actual process steps, which is indirectly influenced by material types. According to Figure 6.23, the cost composition agree with the total cost distribution, where the labour costs stay on high per-

centages. And it clearly shows that low assembly costs are spent on T300/PPS panels, which is mainly caused by its efficient production process steps.

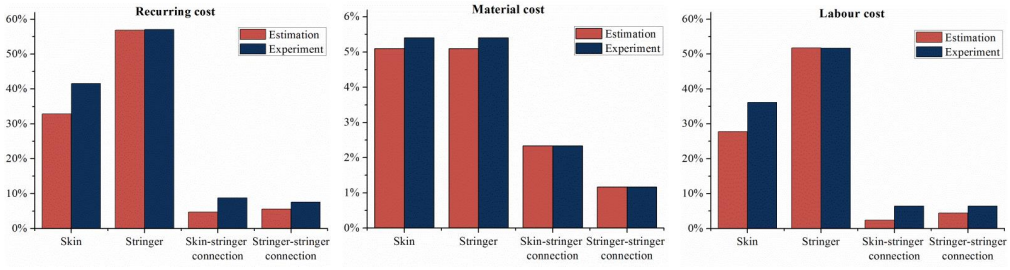
6.2.2.3. MODEL VERIFICATION AND VALIDATION

The detailed production cost estimation for the thermoplastic panel is verified by experiments conducted on GF/PEI (a type of thermoplastic material) panel fabrications, see Table 6.17. A thorough analysis is performed on estimates of parts and assembly connections for model validations.

Figure 6.24 shows that the overall distribution of the estimation results conforms to the experiment results. It is also shown that the skin, stringer take more costs than the assembly connection interfaces for thermoplastic material stiffened panel. The estimation results show a good agreement with the experimental data. The percentage of the material cost for both estimation and experiment differs less than 1%. Labour cost, as the main contribution of the recurring cost, deviated less than 10%. It provides a reference of the estimation accuracy.

Table 6.17: Stiffened panel parameters for verification

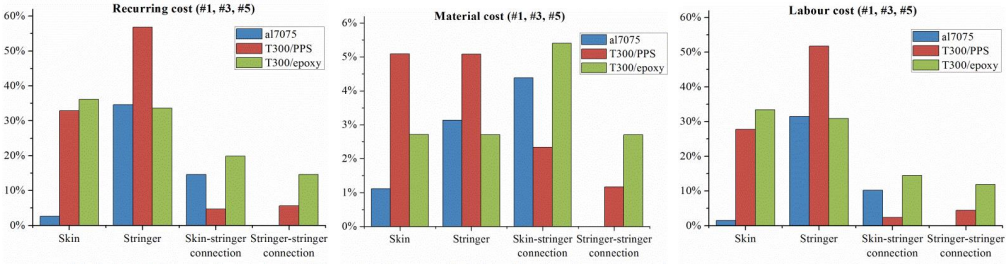
Panels	Material	ρ (kg/m^3)	b_s (mm)	T (mm)	b_f (mm)	t_f (mm)	h_s (mm)	t_w (mm)	L (mm)	W (mm)
Estimation	T300/PPS	1600	101.6	3.2	30.5	0.9	30.5	10.2	762.0	406.4
Experiment	GF/PEI	1700	101.6	3.2	30.5	0.9	30.5	5.4	762.0	406.4



(a) (b) (c)

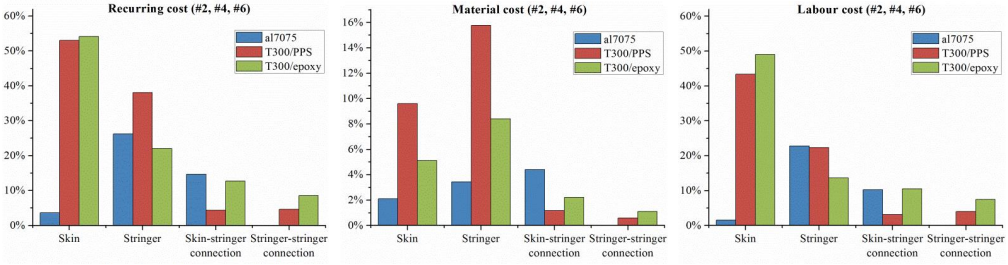
Figure 6.24: Cost verification (Estimation, Experiment) (Estimation recurring cost-100%).

The cost comparisons of aluminium, thermoplastic composite and thermoset composite panels are shown in Figure 6.25 and Figure 6.26. From Figure 6.25(a), the recurring cost of panel ♯1 amounts to 51.8% of panel ♯3 cost, and panel ♯5 takes 104.2% compared with panel ♯3. Similar ratios are found in Figure 6.26(a) among ♯2, ♯4, ♯6 panels. Therefore, for the same configuration, an aluminium stiffened panel generally has lower recurring cost than thermoplastic and thermoset composite stiffened panels. Thermoset composite stiffened panel cost is slightly higher than that of the thermoplastic composite stiffened panel. Interestingly, the recurring cost of the connections for thermoplastic composite is the lowest among the



(a) (b) (c)

Figure 6.25: Cost comparison by materials for stiffened panels ♯1, ♯3, ♯5 (♯3 panel recurring cost -100%)



(a) (b) (c)

Figure 6.26: Cost comparison by materials for stiffened panels ♯2, ♯4, ♯6 (♯3 panel recurring cost -100%)

three material types, indicating that a low cost can be achieved by newly developed thermoplastic composite assembly processes such as induction welding. The low costs on assembly processes make the thermoplastic composite component competitive since it compensates the disadvantages of high material costs. It is noted that the stringer-stringer connections apply on the composite panels but not the aluminium panels, which is determined by their predicted manufacturing processes. Considering the material cost shown in Figure 6.25(b) and Figure 6.26(b), skin costs of the Al7075 panel are less than those of the T300/PPS and T300/epoxy panels. The percentages of the stringer material costs differ depending on the number of the stringers for each configuration. T300/PPS panels have the highest expenses on skin materials, while its connection material costs are lower than the others. Again, this is due to that thermoplastic material itself being expensive while the additional materials such as fasteners used for the connections cost less than additional materials for the aluminium and thermoset stiffened panels. Labour costs of the skins made of lay-up processes are always high. It can be seen from Figure 6.25(c) and Figure 6.26(c) that the cost of thermoplastic and thermoset skin are significantly higher than labour cost for the aluminium skin. The stringers are costly in labour generally for all the three materials from 15% to 50% referenced by the T300/PPS recurring cost of the same configuration. The labour costs are less for the T300/PPS skin-stringer connection and stringer-stringer connection than the T300/epoxy

connections. In addition, the labour consumptions for Al7075 panel connections are moderate.

6.3. OPTIMIZATION RESULTS

Study cases were carried out for stiffened panels employing four types of objectives: DOC, AFW, Production Cost and –SV, while three of which are LCC indicators. Besides, four kinds of optimization techniques were applied: Genetic Algorithm (GA), gradient based constraint minimum optimization (GD), hybrid GA and pattern search(GAPS), and hybrid GA and gradient based constraint minimum optimization(GAGD). Those four techniques are denoted as GA, GD, GAPS, GAGD. Comprehensive comparisons are performed from multiple aspects: the optimal design parameters, the optimum objective values, the computation times and the convergent generations/iterations. The optimal solutions are compared for each single objective in Tables 6.4 to 6.7. In each table, the results obtained from different optimization techniques are listed respectively. The optimization convergent processes are shown in Figures 6.27 to 6.30.The results listed are illustrated in the metric unit. The DOC, Production cost, and -SV are shown in constant 2014 dollars.

6.3.1. OPTIMIZATION SETUP

As a segment extracted from the upper wing box, the length and the width of the stiffened panel are fixed as $L = 762mm$, $W = 406mm$. Both skin and stiffeners are aluminium Al7075-T651, the properties are shown as in Table 6.18. Skin material property (m) is chosen from 7075 aluminium alloy sheet/plate table, stiffener material property is selected from 7075 alloy extrusion table [323].

Table 6.18: Material properties [323]

Material	$\rho(g/cm^3)$	m	μ	$E(pa)$	$\sigma_y(pa)$	$\sigma_{0.7}(pa)$
Skin	2.80	13	0.33	$7.24e^{10}$	$4.76e^{8}$	$5.10e^{8}$
Stiffener	2.80	26	0.33	$7.24e^{10}$	$5.31e^{8}$	$5.45e^{8}$

Besides determining the basic geometric and material properties, parameters for structural constraint analyses are also identified. In this analysis, the compression load intensity $N = 1751.27(N/mm)$. The fastener pitch is given as $r_p = 28.96mm$. The panel utilizes the inverted T stiffeners. The structural constraints illustrated in Chapter 5 apply. In addition, the manufacturing constraints are defined in Table 6.19.

Table 6.19: Design variable bounds

Design variables (mm)	b_s	t	b_f	t_f	h_s	t_w
Lower bound	101.6	1.0	30.5	0.5	30.5	0.5
Upper bound	254.0	12.7	101.6	10.2	101.6	10.2

6.3.2. RESULTS OF OPTIMIZATION STUDIES

The optimization implementation follows the method developed in Chapter 5, which contains the formulation of objective functions and constraint analysis. Four objective formulations are considered separately for current analysis: DOC, Production cost, AFW and -SV. By comparing the four objectives, the optimizations for DOC, Production Cost and -SV achieved the similar optimum in general, while the optimizations for AFW resulted in high DOC, high Production Cost and low SV. Therefore, AFW as an objective is not preferable if the project budget is limited. Moreover, the optimization for SV converges faster than the optimization for DOC by comparing the computation times. From Table 6.20 to Table 6.23, the optimization for -SV obtained a better fit than the other objectives by using GA. The optimizations for both -SV and DOC using GD converge to the same optimum, which is also a better solution comparing with the optimization for Production Cost and for AFW using GD. The optimization for Production Cost got the lowest production Cost, DOC and -SV via GAPS algorithm among all four objectives. The optimization for DOC acquired the lowest AFW, DOC and -SV through GAGD technique compared to solutions for the other objectives. In summary, when the optimization for SV reaches higher SV value, it is accompanied with low Production Cost and low DOC. The convergent process requires less computation time. While the results for maximum SV are not always as good as the optimization for DOC, this influenced by the market and operation related constraints. In addition, by comparing the stiffened panel geometries, it was found that the stiffened panels with bigger stringer pitches, taller stringer height and thicker skin are preferred for low-cost performance. This indicates that when the structural and life cycle process constraints are satisfied, fewer stringers but stronger stringers and skin configurations are preferred for lower cost.

The optimization convergent processes are shown in Figures 6.27 to 6.30. Figures 6.27(a) to 6.30(a) illustrates optimizations conducted via GA. Figures 6.27(b) to 6.30(b) are performed by GD optimizations. According to Figures 6.27(d) to 6.30(d), the pattern search algorithm is performed until the global optimum is found by taking the result from GA as an initial guess. Similarly, by taking the solution of GA and the gradient provided by the finite differentiation, the GAGD approach is iterated until the minimal is obtained, see Figures 6.27(c) to 6.30(c). In terms of the four optimization techniques from Table 6.20 to Table 6.23, it is seen that GA has the potential to obtain the global optimum but not always. GD converges to the minimum at the fastest speed, while the solution is found locally. For all four objectives, optimum solutions are always obtained via the GAPS algorithm. GAPS obtained a better global solution while with an inefficient computation time. Although GAGD is expected to converge to the global optimum with less computation time than GAPS, it is found that GAGD is terminated at a local optimum. This is caused by the unsuitable initial value supplied by GA and the inexact gradient calculated by finite differentiation for the second step GD optimization.

Table 6.20: Optimal panel configurations for min(DOC)

Parameters	GA	GD	GAPS	GAGD
b_s (mm)	106.9	106.6	203.6	101.6
t (mm)	8.2	3.4	6.1	3.4
b_f (mm)	31.1	30.5	30.5	30.5
t_f (mm)	6.2	1.0	0.9	1.0
h_s (mm)	36.4	30.5	43.8	30.5
t_w (mm)	6.1	7.4	4.8	7.4
AFW (kg)	10.8	5.2	6.4	5.2
Production cost ($)	2246.7	1907.3	1258.5	1907.3
DOC ($)	14378.7	9413.5	8296.0	9413.5
$-$SV ($\times 10^8$$)	3.92	2.59	2.26	2.59
Time (sec)	744.9	53.0	1222.0	912.7

Table 6.21: Optimal panel configurations for min (Production Cost)

Parameters	GA	GD	GAPS	GAGD
b_s (mm)	103.8	101.6	206.6	101.6
t (mm)	8.0	3.2	6.0	3.2
b_f (mm)	30.8	30.5	30.5	30.5
t_f (mm)	5.5	0.9	1.0	0.9
h_s (mm)	31.0	30.5	34.6	30.5
t_w (mm)	10.1	10.2	10.2	10.2
AFW (kg)	11.1	5.7	6.9	5.7
Production cost ($)	2020.5	1877.0	1087.1	1877.0
DOC ($)	13912.1	9681.7	8109.9	9681.1
$-$SV ($\times 10^8$$)	3.78	2.66	2.19	2.66
Time (sec)	698.0	83.5	1179.7	925.9

Table 6.22: Optimal panel configurations for min (AFW)

Parameters	GA	GD	GAPS	GAGD
b_s (mm)	102.7	101.6	203.3	121.9
t (mm)	7.8	3.4	6.1	3.8
b_f (mm)	30.8	40.5	49.9	93.2
t_f (mm)	8.4	1.0	1.0	1.0
h_s (mm)	38.1	45.8	40.7	52.8
t_w (mm)	5.1	4.8	5.4	5.2
AFW (kg)	10.7	5.3	6.6	7.0
Production cost ($)	2330.6	2558.8	1615.0	4655.0
DOC ($)	14573.5	11441.1	9494.0	18892.9
$-$SV ($\times 10^8$$)	3.98	3.17	2.59	5.27
Time (sec)	661.6	190.0	1046.1	998.6

Table 6.23: Optimal panel configurations for min (-SV)

Parameters	GA	GD	GAPS	GAGD
b_s (mm)	234.1	101.6	237.3	135.5
t (mm)	6.8	3.4	6.9	4.5
b_f (mm)	32.6	30.5	30.5	32.7
t_f (mm)	1.9	1.0	0.9	1.0
h_s (mm)	39.9	30.5	40.7	33.0
t_w (mm)	5.8	7.6	5.6	7.4
AFW (kg)	7.2	5.2	7.1	6.4
Production cost ($)	1224.8	1907.3	1215.1	3312.2
DOC ($)	8774.8	9413.5	8654.1	10587.5
$-$SV ($\times 10^8$$)	2.38	2.59	2.35	2.39
Time (sec)	328.8	37.9	479.3	758.2

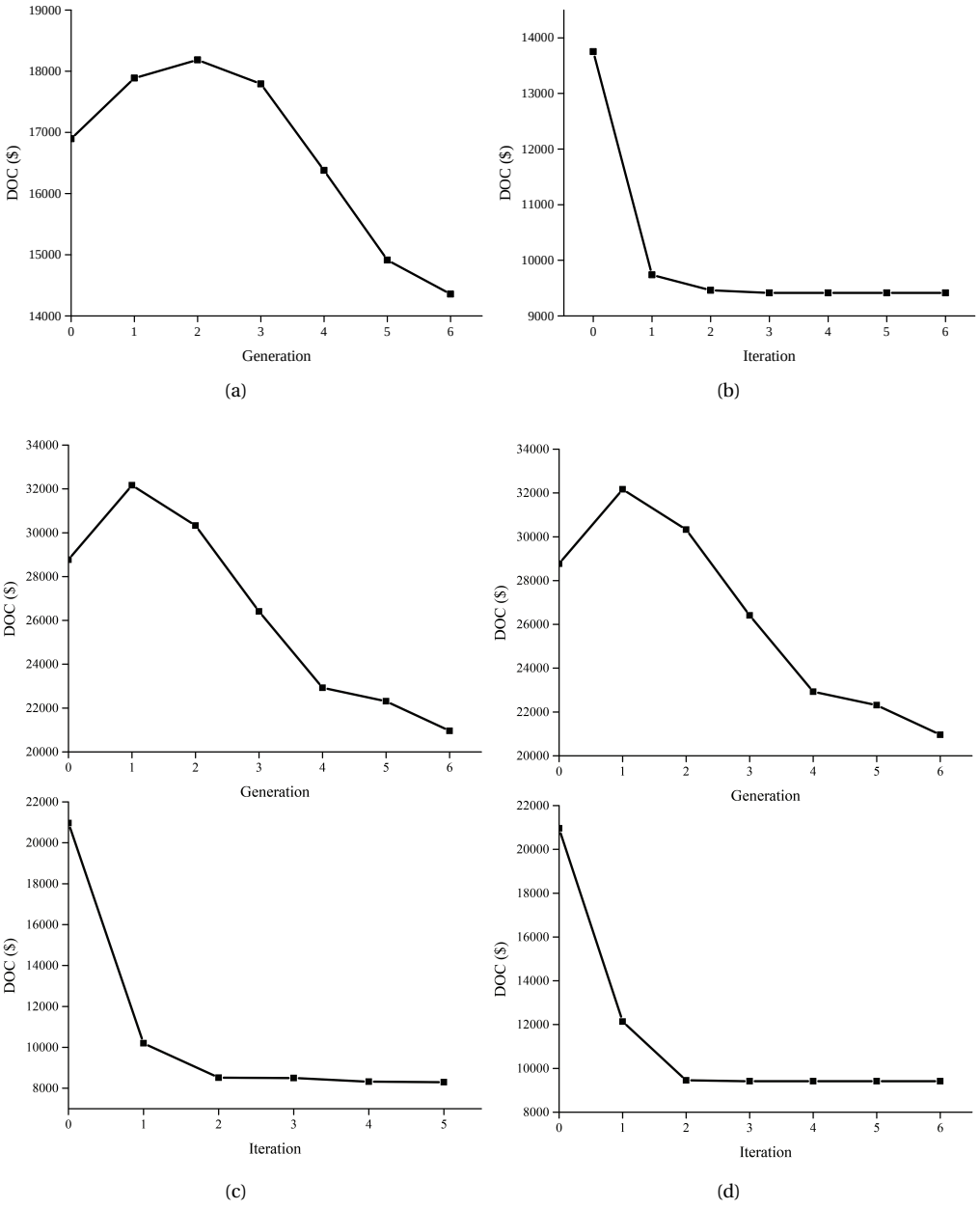


Figure 6.27: Optimization convergence processes for min(DOC):(a) GA; (b) GD; (c) GAPS; (d) GAGD.

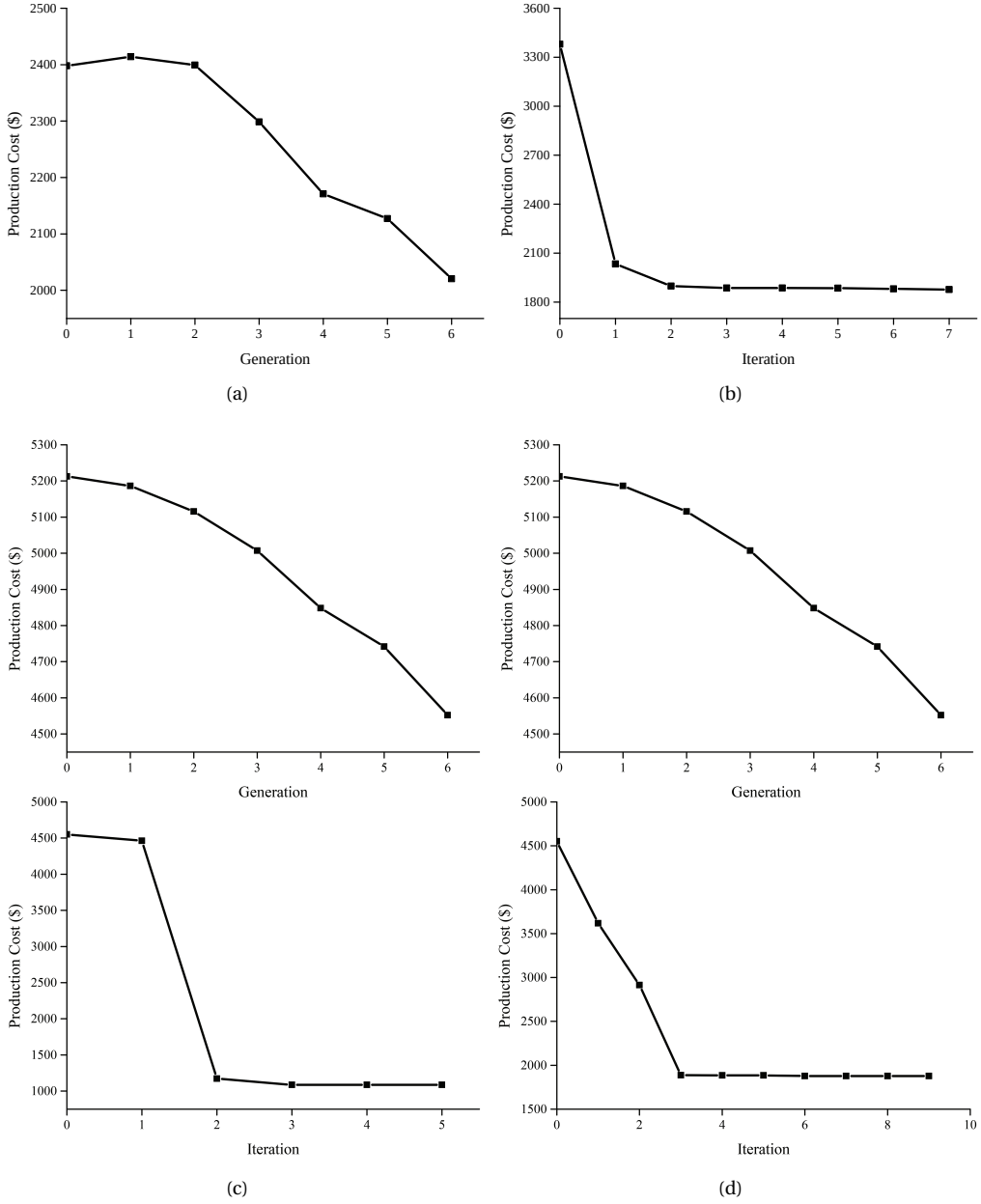


Figure 6.28: Optimization convergence processes for min (Production Cost):(a) GA; (b) GD; (c) GAPS; (d) GAGD.

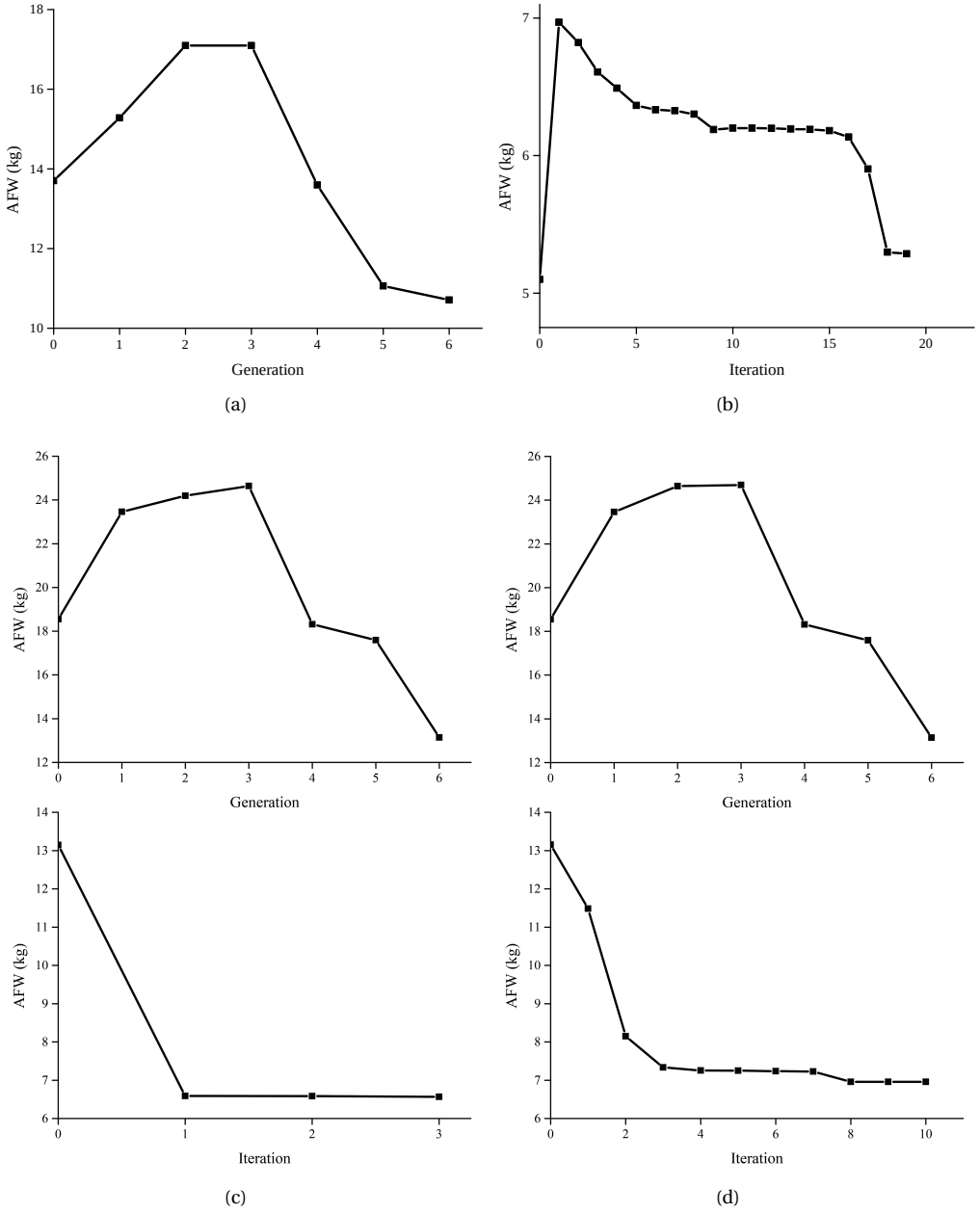


Figure 6.29: Optimization convergence processes for min (AFW):(a) GA; (b) GD; (c) GAPS; (d) GAGD.

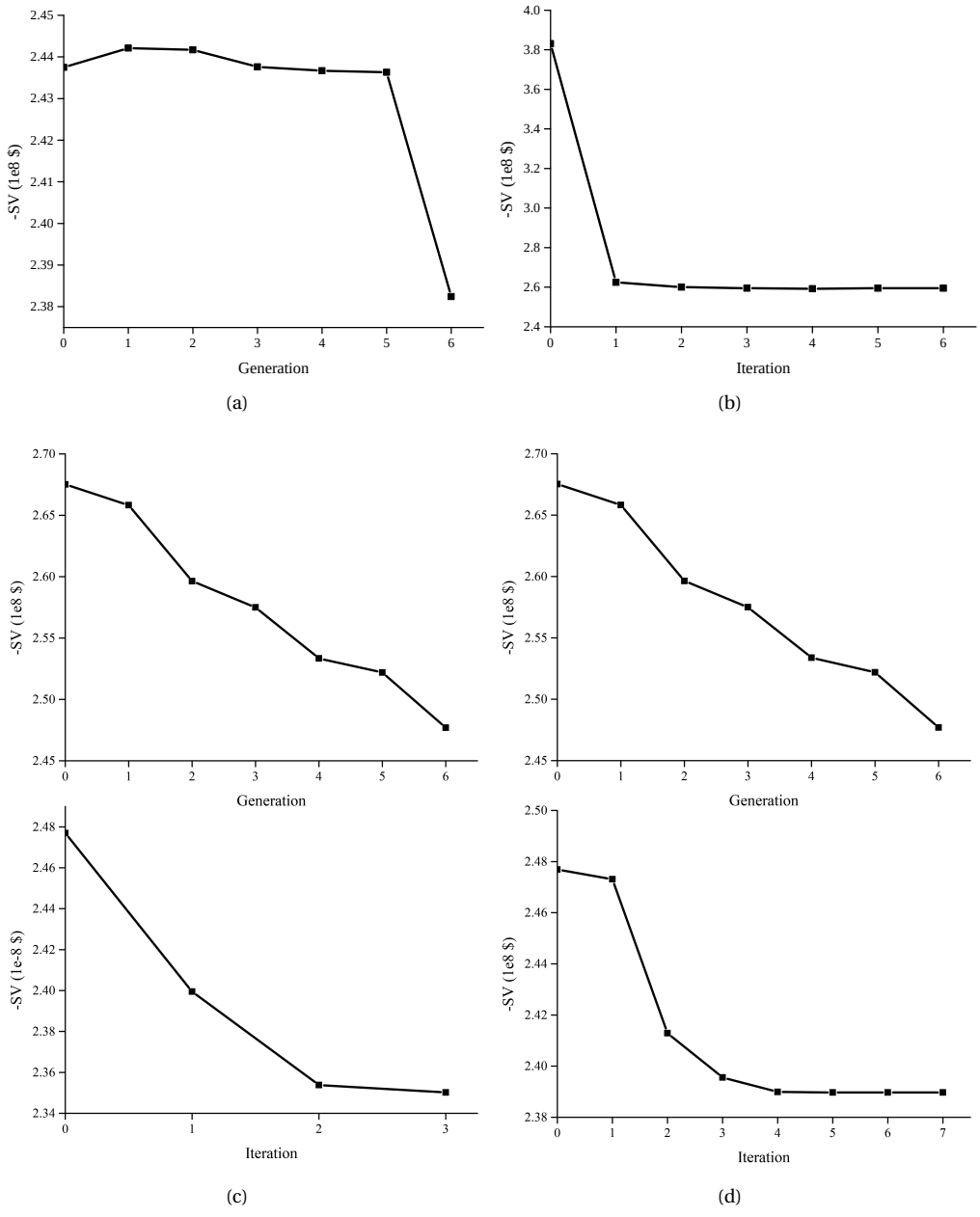


Figure 6.30: Optimization convergence processes for min (-SV):(a) GA; (b) GD; (c) GAPS; (d) GAGD.

Taking the optimized panel obtained from GAPS for minimum AFW as a reference, the optimized panel properties obtained from the optimization of minimum DOC, Production cost and –SV are shown advantages in reducing cost with little compensation in weight increases. Table 6.24 shows the difference in panel properties resulted from the comparison, the minor sign refers to the reduction in corresponding properties. It can be seen that by minimizing DOC, production cost and –SV, around 12.6%, 32.7% and 9.3% reductions in respective cost indicators can be obtained. Those cost reductions outweigh the increases in AFW. A similar conclusion can be found from the comparison in optimizations using different algorithms.

Table 6.24: Comparing the properties of the Optimal panels (reference panel: min(AFW), GAPS)

	Min(DOC)	Min(Production cost)	Min(-SV)
AFW	-3.0%	+4%	+7.6%
Production cost	-22.1%	-32.7%	-24.8%
DOC	-12.6%	-14.6%	-8.8%
-SV	-12.7%	-15.4%	-9.3%

6.4. SYNTHESIS AND CONCLUSIONS

In conclusion, an integrated cost estimation and design optimization framework were demonstrated on a stiffened panel case. It involved the support of KBE techniques, high/detail-level cost estimation models on RDT&E cost and Production cost, and design optimizations considering LCC indicators. Conclusions and challenges on respective aspects are drawn.

6.4.1. KBE PERSPECTIVE

With the support of KBE techniques, it opened up a route from the product configuration to life cycle process steps till its cost properties. It was built on modularized functions where knowledge based inference mechanisms were largely employed. This provided the application a strong capability on knowledge handling and automating, so that it improved the efficiency of performing the analytic tasks. Specifically for aircraft cost estimation, the KBE techniques supported the construction of a modularized analysis process. Those techniques also provided huge support on design, costing and optimization integration. It was evidenced by the cost estimations and cost integrated design optimizations for stiffened panels with different geometries and materials, which were conducted within half an hour for each analysis run. However, it requires efforts on extracting knowledge and modelling the rule-based CMs. While this was true for the first time development, the application development time could be reduced on the basis a well-constructed knowledge base including a storage of general CMs.

6.4.2. COSTING PERSPECTIVE

Considering the cost analysis, the proposed high/detail-level cost estimation models not only solved the problem of limited data accessibility but also showed its capability of gen-

erating extensive cost information. The cost estimates obtained from the detail-level model provided an insight of the cost distribution over life cycle process steps. It improved the traceability of the cost generation. In more detail, properties related to the high-level and detail-level models for RDT&E cost and production cost are summarized in the following sections. It is needless to mention that the operating & maintenance cost and the disposal & recycle cost can also be identified for the stiffened panel case by following the proposed LCC model. To avoid repetitiveness, the application and results of those two major cost types are elaborated in the next case study for A330-200 rudder, see Chapter 7.

The high-level RDT&E cost model supplies estimates grouped into cost elements for aircraft and stiffened panels, and the detail-level model generates results not only considering cost elements but also process steps. Both the high/detail-level RDT&E cost estimations and the high-level production cost estimation are influenced by the material-related properties: weight and fudge factor. The influence of weight properties is associated with geometric configurations and material densities. While the impact of the fudge factors can be related to specific labour hours and labour rates for different materials, material buy-to-fly ratio, raw material price, and so on. However, the actual relation between those factors and the fudge factor is not clear at this stage, further research should be performed on this aspect through data collection and analysis. Furthermore, since the detail-level estimates are still obtained on the basis of the high-level model results, the estimation error resided in the high-level model is also brought to the detail-level model. The accuracy can be improved by adopting actual programme cost into the detail-level model when the data is available.

The high-level production cost estimation model produces cost consumptions classified by cost elements including labour cost, material cost and testing cost for sampled aircraft and stiffened panels, however, it can only allocate costs to parts other than assembly interfaces of stiffened panels since the high-level model is weight sensitive while it cannot be detailed to process steps. The detail-level production cost estimation model address production expenses not only by cost elements, parts and assembly interfaces, and process steps. Since the need of a large amount the data for process steps involved, it requires extensive pre-processing including the geometry handling and inference knowledge rule collection in implementation, where vast data are requested. It is potentially feasible to carry out the testing cost analysis based on the detail-level model. However, due to limited data accessibility on process steps of quality control and flight testing concerning stiffened panel components, the testing cost is currently not available.

Within the cost analysis, the influence of the material types on LCC prediction has been considered for three kinds: aluminium, thermoplastic material and a thermoset material. However, only the material influence on weight and production processes are considered, more investigations on material induced structural changes should be considered further.

6.4.3. OPTIMIZATION PERSPECTIVE

Last but not least, this work developed a cost and value leading MDO application on aircraft stiffened panels. Production cost, DOC and -SV were included in the design optimization consideration. Detailed cost analysis and structural analysis were performed to formulate the optimization problem. The optimum design shows that the cost reductions can be achieved by the proposed method computationally using minimum cost as the objective,

Table 6.20 to 6.23. According to Table 6.24, the percentage of cost reductions outweigh the increases in AFW when using the proposed method. It proves that the proposed approach obtained a better design.

The study case showed optimization studies on the stiffened panels made of aluminium alloy. Similar optimization studies could also be applied by considering structural constraints on composite materials, which should be further included in this research. Moreover, optimization techniques were investigated and compared. We concluded that the detailed disciplinary performance analysis could provide a thorough consideration on the design concept. In general, the design solution for minimum DOC achieved a better performance, which not only reduced the AFW but also the cost indicators. The minimum production cost and maximum SV consideration also resulted in lower cost performance but with compensations of increasing weight performance. Moreover, in terms of the optimization algorithm, the combination of GA and pattern search always converged to the global optimum with long computation time. The gradient optimization technique and the combination of GA and gradient optimization technique have the advantage on convergent speed and sensitivity availability, while the global optimum could not be guaranteed due to the influences of initial guess and the finite differentiation supplied gradient value. Last, it was found that fewer stringers while stronger stringers and skin configurations could achieve lower cost.

Since the finite differentiation reduced the accuracy of the gradient, the accuracy of the optimization results was affected. Other techniques such as automatic differentiation can be considered. Moreover, the sensitivity of the constant parameters in DOC and SV analysis also influence the optimal solution. The influence of parameters should be quantified. In addition, the current optimization application includes weight, cost, value, and structural analyses, it also can be further developed to include other disciplines.

7

CASE STUDY – RUDDER

This chapter focuses on the implementation of the proposed cost estimation method on a rudder case. The product model, process-specific product views are discussed. Relevant KBE techniques, especially the inference rules which enable the integration of the product, process and cost analysis, are elaborated. The LCC analysis procedure and the results obtained for the major cost types, O&M cost and D&R cost, are emphasized. It should be noted that since the product geometric modelling is not the focus of this research, the geometry handling strategies are not dug into detail. Moreover, the RDT&E cost and the Production cost analyses are not exemplified since the analyses can be performed for the rudder using the same routine introduced in Chapter 6.

7.1. STUDY CASE IMPLEMENTATION

A rudder is a type of movable structures located at the trailing edge of an aircraft tail, which controls the directional stability of an aircraft. Analyses for rudder component can be easily generalized to other types of movables, even wing structures. Moreover, the component made of composite materials is also interested due to the increase of the usage. A330 is a wide-body, twin-engine aircraft type known by its low operating cost for long-haul operations. Around 11% composite material has been used, resulting in more than 10 tonnes of light weight composite airframe structure [4]. Therefore, the A330-200 rudder, which is a typical composite component from the A330 shorter fuselage variant, is chosen for this case study.

7.1.1. RUDDER PRODUCT MODEL

A330-200 rudder is made of composite sandwich structure, the material composition and the structural configuration are shown in Table 7.1 and Figure 7.1. The inner skin, the spars, and the ribs are made of Carbon Fibre Reinforced Polymer (CFRP)for both the Left Hand (LH) side and the Right Hand (RH) side. The outer skin is made of Glass Fibre Reinforced Polymer (GFRP). The sandwich core is Nomex Honeycomb. Hinges and actuators are made from metal materials. Figure 7.2 sketches the top view of the rudder structure. The parts and assembly connections including additional parts such as fasteners, fillers and hinge attachment are illustrated.

Table 7.1: A330-200 rudder material composition

Part		Material	Remark
Side shell	Inner skin	CFRP	LH & RH
	Core	Nomex Honeycomb	LH & RH
	Outer skin	GFRP	LH & RH
Spar		CFRP	Front
Rib		CFRP	Lower & upper
Hinge, actuator		Non-composite	Hinge/actuator arm, fitting

7.1.2. RUDDER LIFE-CYCLE-PROCESS-SPECIFIC VIEWS

The product geometric representation and data needed to analyse the O&M and D&R costs are defined for both high-level and detail-level models. In this case study, high-level cost estimations directly link general properties of the aircraft and the life cycle phases, such as weight, number of seats, and operating and maintenance hours of a trip, with cost consumption. The detail-level cost estimations require extra properties related to specific geometric segmentation and the operation process step of O&M and D&R phases. Examples include the aircraft flight segments, maintenance tasks, dismantling and disassemble tasks, and so on. Those properties are either user inputs from the product model and operating or derived parameters according to knowledge based inference mechanisms. It is aimed at modelling the logic behind the process evolvement based on engineering rules. For instance, the execu-

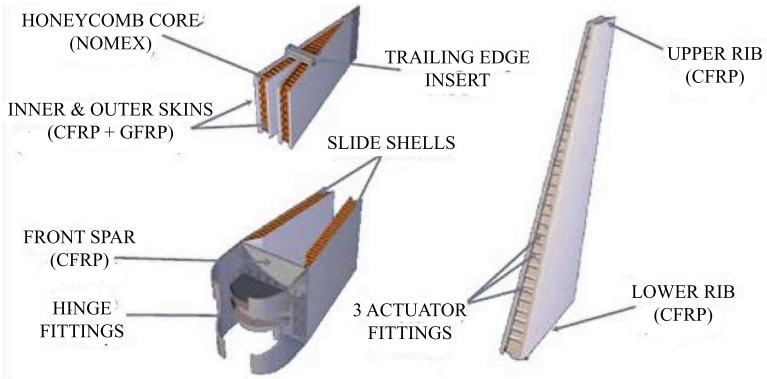


Figure 7.1: Rudder structure configuration [324].

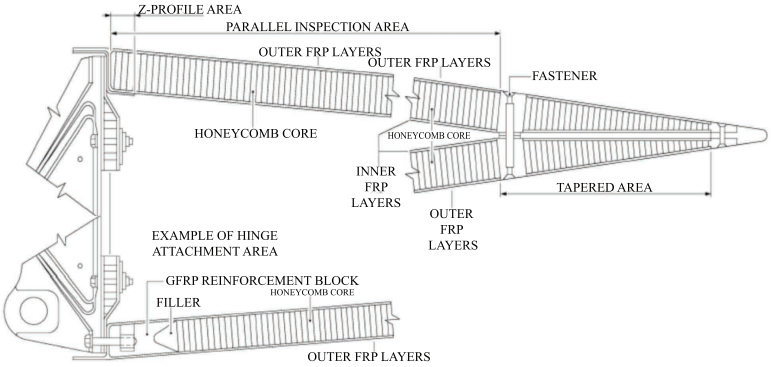


Figure 7.2: Rudder top view [324].

tion of a maintenance task is associated with the component failure modes, geometric sizes, material types, and operating regulations. Therefore, the effort of capturing, formalizing and packaging relevant knowledge is essential. By extracting and formulating general inference rules, the process attributes can be derived automatically, which can reduce the time used for data collection in each analysis run.

Within operating cost analysis, a city pair with the fly distance of 9556 km is used for both high-level and detail-level models. The drag coefficient is calculated without considering the compressibility. The distances that the aircraft has flown during the climb and descent phases are negligible comparing to the distance of the cruise phase, so that they are not deducted from the cruise distance.

For maintenance cost, an extra layer of zonal division should be added into the product geometric segmentation, which forms a maintenance-specific view including the geometry and process representations for maintenance cost. The product breakdown containing zonal divisions is required for the scheduling of the maintenance process. An aircraft is divided into numbered zones by the manufacturers according to the standard ATA iSpec 2200

[325]. An example of aircraft zones is shown in Figure 7.3. Generally, an aircraft is composed of several major zones, which can be subdivided into major sub-zones. If necessary, the major sub-zones are further divided into zones. Frames, ribs, stringers, and bulkheads are set to be boundaries of the zones, see Figure 7.4. Therefore, in particular for airframe, a structural component can be covered by one or more zones, which contains functional parts, connections and relevant systems. At least one functional part is located in one zone. The categorizations of 'part' and 'connection' are similar to those for the Production cost analysis. A 'part' is a generalization of the main structure such as skin, spar, rib and the miscellaneous part including the fastener, fitting and attachment. A 'connection' mainly refers to the interface between two or more parts. The relevant system represents the hydraulic system or the electrical system, which keeps the component functioning properly. Large parts and complex systems are distributed in one or more zones. Then the maintenance tasks are scheduled for each item allocated in different zones.

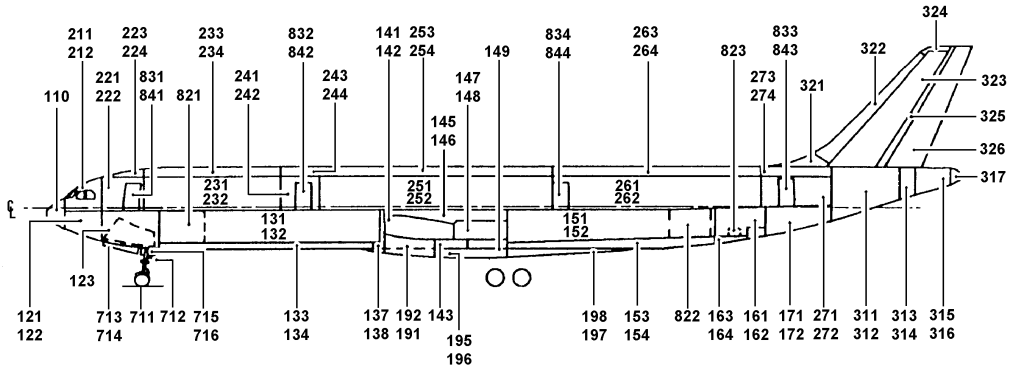


Figure 7.3: Example of aircraft zones.

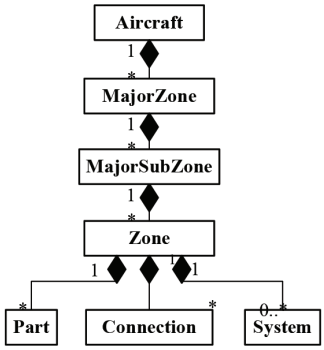


Figure 7.4: UML diagram for aircraft maintenance.

By considering an A330-200 fleet condition [326] and the IATA summary of world A330-200 fleet [327] for maintenance cost analysis the operation parameters are listed in Table 7.2,

where the Daily Utilization is expressed as $(FH/AC)/365$. The maintenance labour rate for line and base maintenance tasks are assumed to be \$38.7/hr and \$60.9/$hr(FY2014)$ respectively [328].

Table 7.2: Airline operation parameters (2012 status)

Fleet aircraft type	Aircraft No.	Avg Age (year)	FH/FC ratio	Daily Utilization	FH/AC (hr)	FC/AC
A330-200	12	5.9	4.3	11.2	4088	951

According to the zonal division of A330-200, the rudder is covered by one physical zone, its relevant systems are distributed in various zones from a cockpit, fuselage belly to tail [329]. The product breakdown is shown in Figure 7.5. Maintenance tasks are assigned to each item based on rules for maintenance program planning. A maintenance task is identified with a unique task number, a task interval and a maintenance time. Task intervals are shown as A, C, 2C, 4C, 8C match 600 FHs, 18 months, 36 months, 6 years and 10 years operating time respectively [305]. Maintenance times followed after the slash symbol are shown in the unit of man hours.

Specifically for rudder D&R process, the aircraft acquisition cost and the weight of rudder are simply the data inputs for the high-level model. Whilst the process steps and their execution times and material consumptions related to rudder parts are required for the detail-level model estimation.

7.1.3. KBE SUPPORTED RUDDER COST ANALYSIS

Similarly, KBE techniques are also employed within the pre-processing, cost estimation and post-processing modules to support the rudder cost analysis. CMs are formulated with similar functionality as the ones introduced in the production cost analysis. Because each major cost type of the LCC has its own characteristics, therefore, the extended BOM, the integration of the PBS and CBS, the formulation of CPs, and the cost output differ from one cost type to another. Inference rules employed to derive the O&M and D&R processes can be found from Chapter 4.

7.2. COST RESULTS

The results of the high-level and detail-level costing for A330-200 rudder are shown in this section. Since the RDT&E and Production cost estimations have been demonstrated in Chapter 6, this chapter mainly focuses on the O&M and D&R costs. The results of the rudder case are presented and discussed.

In this study case, the trip operating cost is analysed for A330-200 aircraft flying the exemplified route between Stockholm and Los Angeles with the flying distance of 9556 km. Because the operating cost is generated from the trip operation of an aircraft, both the high-level and detail-level models are firstly evaluated on the 'per aircraft per trip' basis. It is then allocated to the rudder via cost-weight ratio conversions based on component weight distributions. The operating cost for a component is necessary for the use of optimization proce-

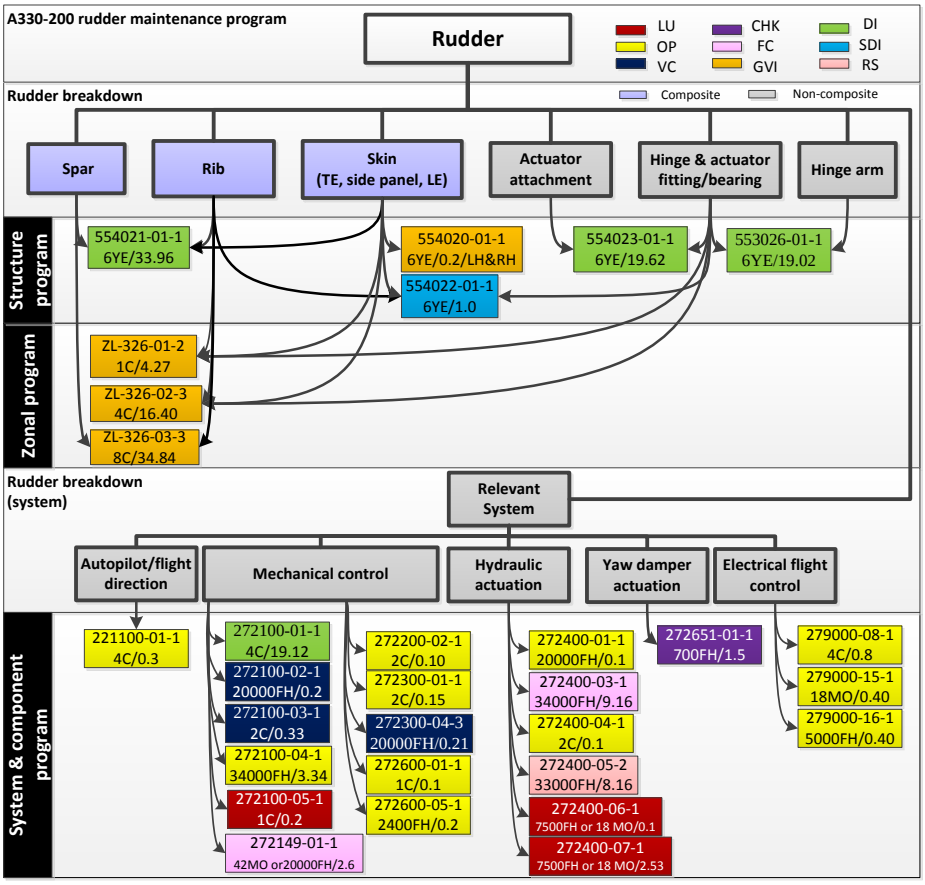


Figure 7.5: Rudder breakdown structure and maintenance tasks.

dures. The high-level maintenance cost follows the same logic as the trip operating cost analysis. The detail-level maintenance cost is estimated based on the allocation of maintenance tasks over aircraft zones, components, and systems. In this way, the scheduled maintenance cost is obtained by aggregating the cost of each maintenance task. And the unscheduled maintenance cost is a prediction based on an unscheduled-scheduled maintenance cost ratio obtained historical statistics.

The D&R cost usually accounts for a small part of the total LCC. Due to data limitations, a simplified model is adopted: The high-level estimation obtains D&R cost according to depreciation regimes of the aircraft acquisition cost; the detail-level estimation considers process steps for the rudder on the basis of a generalized D&R process. An initial attempt of the D&R cost estimation has been made.

7.2.1. RESULTS OF O&M COST ANALYSIS

7.2.1.1. HIGH-LEVEL MODEL RESULTS OF OPERATING COST ANALYSIS

The high-level operating cost analysis is applied on the sampled aircraft. The high-level aircraft operating cost is then allocated to rudder based on its cost-weight ratio. The rudder weight is estimated according to the component weight estimation proposed by Kroo [330]. It approximately weighs 60% more per unit area than the weight per unit area of the vertical fin, which refers to a vertical tail without the rudder. And it is assumed that the rudder surface area is around 25% of the vertical tail surface area.

The operating cost distribution is shown in Figure 7.6. It consumes around 74.3% fuel cost, 22.2% crew cost, and 3.5% of fees. The aircraft trip operating cost estimated via high-level model is around $98 thousand. According to the rudder weight calculation, a weight ratio of 0.0038 between rudder weight and MTOW is obtained. The trip operating cost (excl. maintenance cost and miscellaneous cost) estimated by the high-level model rounds to 4.00 cents/ASK. Based on the rules defined for the cost-weight conversion, around $372.4 trip operating cost, which keeps the same cost distribution with the aircraft trip operating cost, is allocated to the rudder, see Table 7.3.

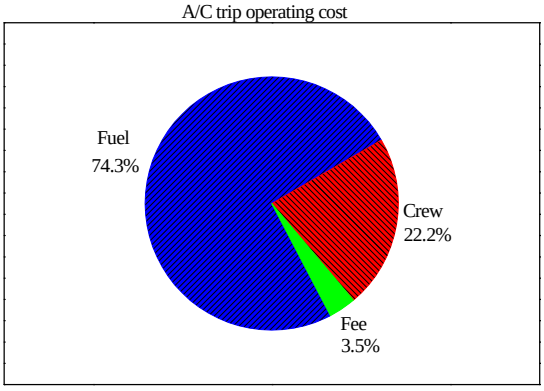


Figure 7.6: High-level model trip operating cost per aircraft

Table 7.3: Rudder trip operating cost distribution over cost elements (High-level model)

Trip operating cost($)	Fuel cost($)	Crew cost($)	Fee($)
372.4	276.8	82.6	12.9

7.2.1.2. HIGH-LEVEL MODEL RESULTS OF MAINTENANCE COST ANALYSIS

The high-level maintenance cost analysis provides the results on labour cost and material cost for the sampled aircraft. No distinction has been made for schedule maintenance cost and unscheduled maintenance cost. The costs are then distributed to the rudder component based on the cost-weight ratio. Figure 7.7 shows the composition of the evaluated cost, the labour cost is slightly higher than the material cost for maintenance. The total airframe maintenance cost is estimated around $ 3934 (excl. engine and overhead maintenance costs). By applying rudder cost ratio, the cost distribution for A330-200 rudder is approximated, see Table 7.4.

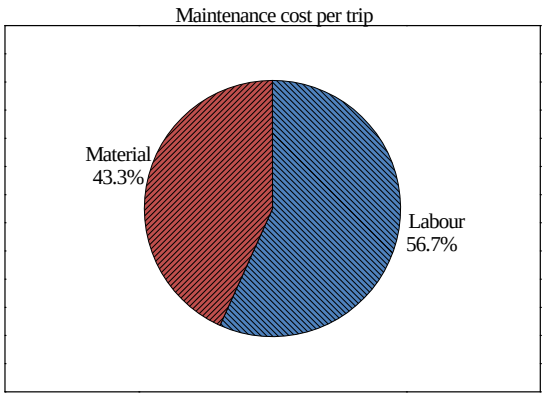


Figure 7.7: High-level model maintenance cost per aircraft per trip

Table 7.4: Rudder maintenance cost distribution over cost elements (per trip) (High-level model)

Maintenance cost($)	Labour cost ($)	Material cost($)
39.6	22.5	17.2

7.2.1.3. DETAIL-LEVEL MODEL RESULTS OF OPERATING COST ANALYSIS

The cost percentages estimated by the detail-level model are illustrated in Figure 7.8. It shows a distribution of around 75.4% fuel cost, 9.9% crew cost, and 14.8% of fees. The total cost evaluated for a flight trip is $69.1 thousand, which is lower than the estimation of the high-level model. The operating cost evaluated by the detail-level model is around 2.9 cents/ASK. Accordingly, the rudder cost is calculated to be $263 per trip operating, which also follows the same cost distribution as the aircraft trip operating costs. Table 7.5 shows the detailed trip

operating cost allocation by cost elements, and by trip operating segments (process steps). Since the high-level model evaluates the lump sum of each cost element, while the detail-level model investigates the costs related to each operating process step. The reason that the detail-level model tends to be lower could be that some indirect cost items are currently not considered. By reviewing both cost distributions. The fuel cost accounts for the major part of a flight trip, which is agreed by both models. The crew cost estimated from the detail-level model are lower than that of the detail model, this is because the operating time considered by the detail-level model tends to reach the lower bound based on the assumption of a time-efficient flight trip, while the airport charge per flight has increased compared with the mid-90s when the parametrical equations of the high-level model were developed.

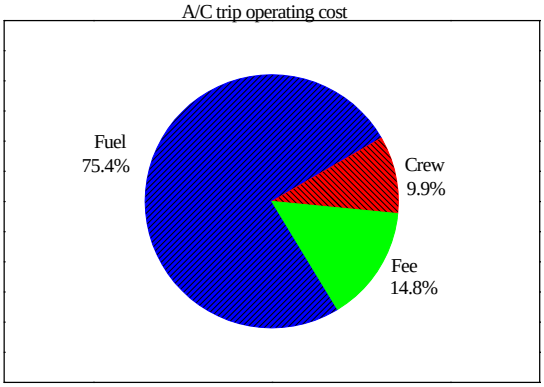


Figure 7.8: Detail-level model operating cost per aircraft per trip

Table 7.5: Aircraft trip operating cost distribution over cost elements and operating segments (Detail-level model)

Rudder Cost($)	Warm up	Taxi out & take off	Climb	Cruise	Descent	Approach & langing & taxi in	Reserve	Sub total
Fuel	3.0	8.9	6.1	158.8	6.0	4.8	10.7	198.2
Crew	0	32.6	0	0	0	6.3	0	38.8
Fee	0.4	0.02	0.4	24.4	0.7	0	26.0	26.0
Sub total	3.4	41.5	6.5	183.1	6.7	11.0	10.7	262.7

Figure 7.9 shows the cost allocation on each segment of a flight operation. The actual percentages are shown on each of the cost types. The airport charges are allocated on the take-off and landing segments separately. A breaking point is applied on the figure to zoom into the shares of crew and fee expenses. This gives a detailed overview of the actual cost distribution over a flight trip, which can be used for trip operating optimization studies. It can be seen that the fuel and crew costs are consumed mostly during cruise, climb and the descent segments. Moreover, fuel consumption is generated during the whole process, which

also explains its major impact on flight operating cost and even the whole LCC.

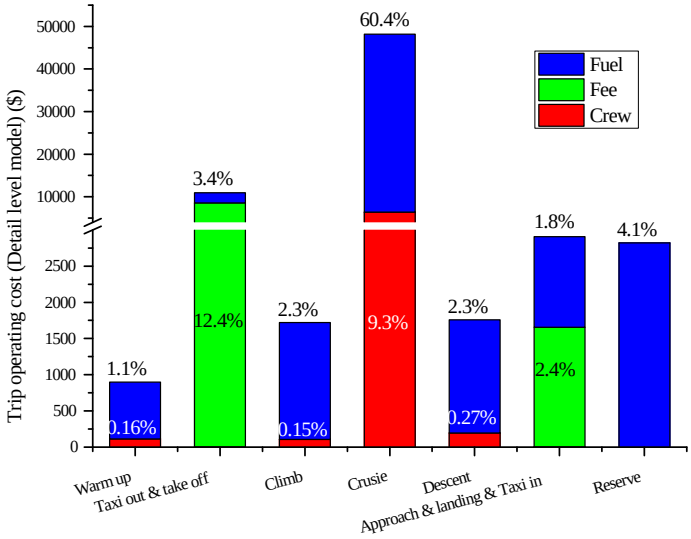


Figure 7.9: Rudder trip operating cost distribution over cost elements and operating segments (Detail-level model)

7.2.1.4. DETAIL-LEVEL MODEL RESULTS OF MAINTENANCE COST ANALYSIS

The detail-level model maintenance cost analysis directly focuses on rudder component. Firstly, analysis on scheduled maintenance labour cost is conducted. Next, the scheduled maintenance material cost is evaluated. By applying maturity factor and the unscheduled and scheduled maintenance cost ratio, the unscheduled costs are then obtained.

Figure 7.10 to Figure 7.15 illustrate the results obtained from the rudder scheduled maintenance labour cost estimation. The cost is presented as the yearly cost per aircraft from A320-200 fleet. The calculation is based on the high-level operating process related parameters as well as the detail-level task intervals and maintenance times resulted from the design itself. The cost indicators shown in Figure 7.10, Figure 7.12 to Figure 7.15 are the actual labour costs of the rudder, which are evaluated according to the scheduled maintenance cost in each FY based on the rudder product breakdown and the maintenance task planning shown in Figure 7.5. The cost indicator of Figure 7.11 is calculated based on the mean labour cost of a general maintenance task, which estimates the cost by considering the impact of failure rates (or reliabilities) corresponding to each task. From FY 2012 to FY2022, it is seen from Figure 7.10 that the cost increases around 26% and 27% in FY2013 and FY2019 compared with the total expense. This predicts the years when the overhauls are taking place. According to Figure 7.11, the average cost for a general maintenance task is fluctuating during the period between $127.5 to $210.3 per task (FY2014 dollar). It is shown that the mean labour task cost is not influenced by the overhaul but the failure rate (or reliability) of the maintenance items. The composite materials and structural parts maintenance cost are emphasized in this paper. Figure 7.12 illustrates that the composite structures take a relatively

small share of the maintenance cost in general, the expenses should be focused during the overhaul period. The composite structures including spar, rib and skin are mostly checked and repaired during overhaul, around 37% in both FY2013 and FY2019 (Figure 7.11). Correspondingly, in the heavy maintenance period, the maintenance tasks such as DI and GVI, allocated in structure programme group and zonal programme, are spent nearly 90% of the yearly cost (Figure 7.14 and Figure 7.15).

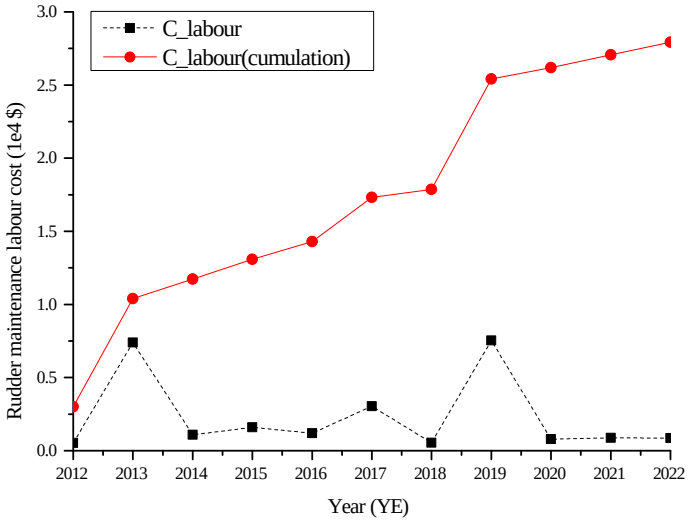


Figure 7.10: Rudder scheduled maintenance labour cost

By involving the maturity factor, the scheduled maintenance cost is scaled up along with the age growth. Accordingly, the cost distribution in terms of material types, part types, maintenance programme groups and task types. Further, the scheduled maintenance labour cost can be expressed on 'per trip' basis by applying the aircraft yearly utilization parameter. Due to the lack of detailed data on the material consumption for each maintenance task, the material cost is obtained according to the cost ratio between labour cost and material cost from high-level model estimation and further incorporated maturity factor. Next, by applying unscheduled/scheduled cost ratio, the unscheduled maintenance labour and material costs are calculated respectively on 'per trip' basis per each year. The estimates are summarized in Figure 7.16. It is found that the rudder yearly total maintenance cost per aircraft ranges from $4.7 per trip to $105.7 per trip depending on the tasks scheduled for each year. The material costs are slightly lower than the labour costs. The high amount of costs is spent during overhauls in 2013 and 2019 respectively. When the aircraft gets older, the expenses get higher for the similar amount of maintenance tasks. This can be seen from the cost comparison between estimates in 2013 and 2019. The average airframe maintenance cost per trip is evaluated as $28.4 per trip.

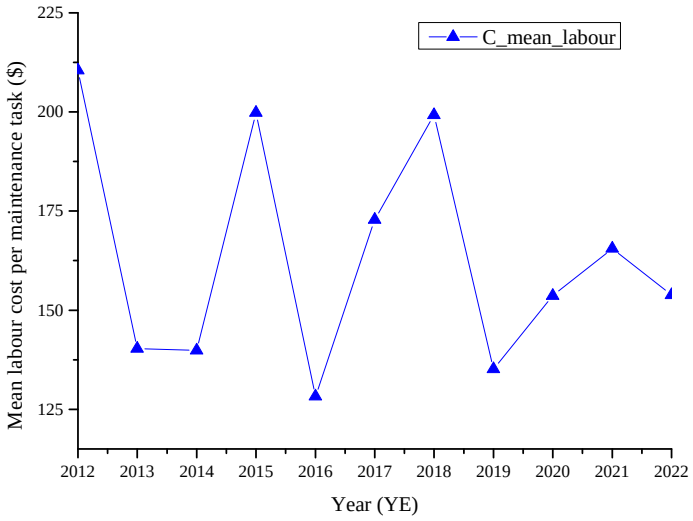


Figure 7.11: Mean labour cost per maintenance task

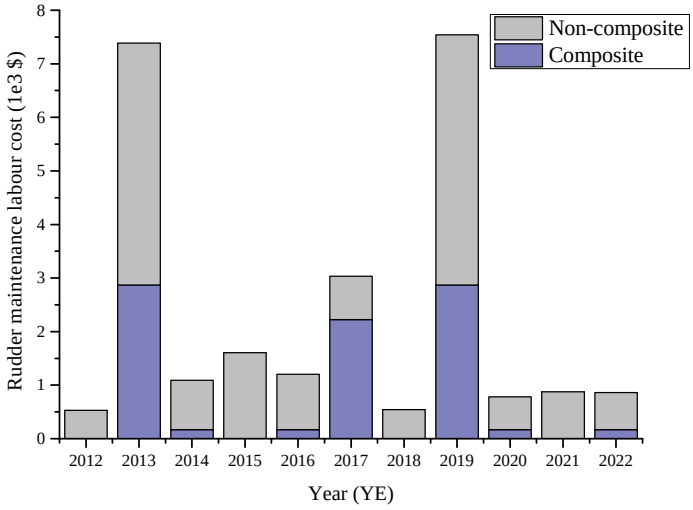


Figure 7.12: Rudder scheduled maintenance labour cost by material types

7.2.1.5. MODEL VERIFICATION AND VALIDATION

As can be seen from the estimation results, the trip operating costs calculated from high-level and detail-level models validate each other with similar magnitude scale, however, the differences between the estimates from both levels still need to be calibrated when performing actual studies. By referencing the statistical data of IATA analyses [306], effort on verification and validation has been made. The CASKs evaluated from both high-level and detail-level

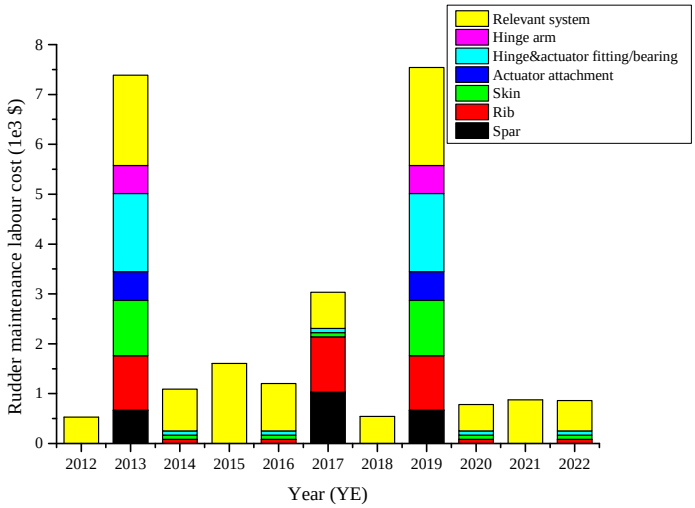


Figure 7.13: Rudder scheduled maintenance labour cost by part types

models are realistic when comparing to the mean CASK of the aircraft flight operation expenses, which are averaged to 5.0 cents/ASK for FY2008 and for 3.6 cents/ASK for FY2009 respectively (in constant 2014 dollars).

The statistics of the expenses for flying aircraft for 10 US Major Airlines are shown in Figure 7.17 and Figure 7.18. The costs of aircraft ownership, other costs of operation (FO),

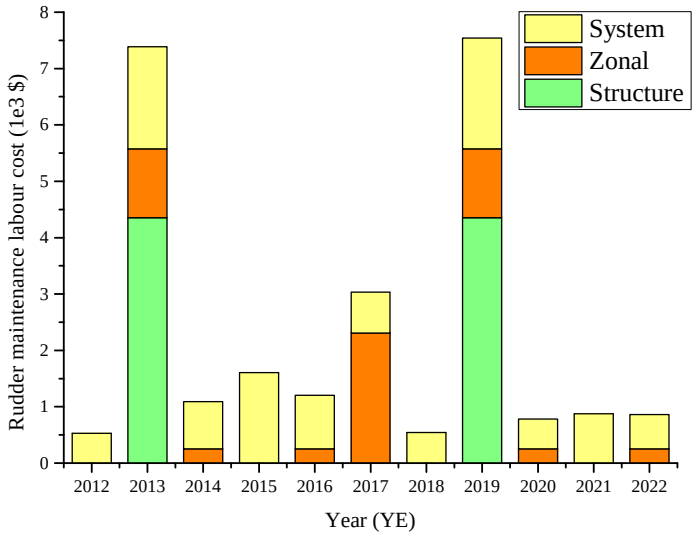


Figure 7.14: Rudder scheduled maintenance labour cost by program groups

and other aircraft Operation (Ops) are excluded, so that comparisons of the estimations can be conducted. The distributions generally agree with the estimation results, especially on the percentage of fuel costs. While the deviation of crew costs may be induced by the use of different labour rates, while the differences of the fees can be caused by the difference of costs

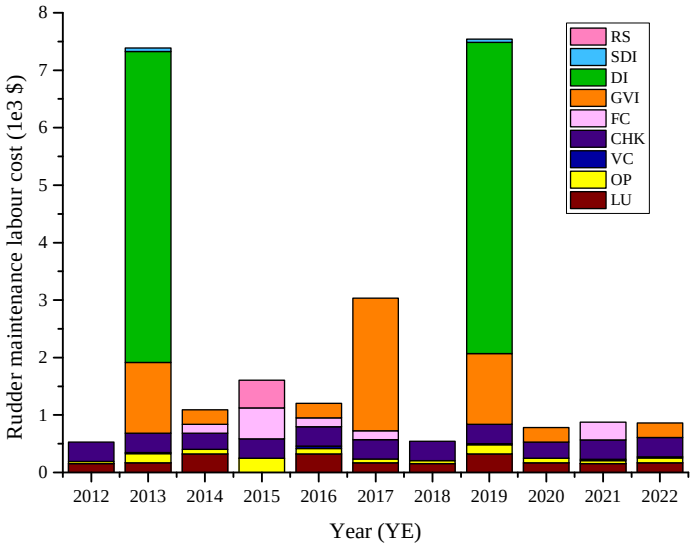


Figure 7.15: Rudder scheduled maintenance labour cost by task types

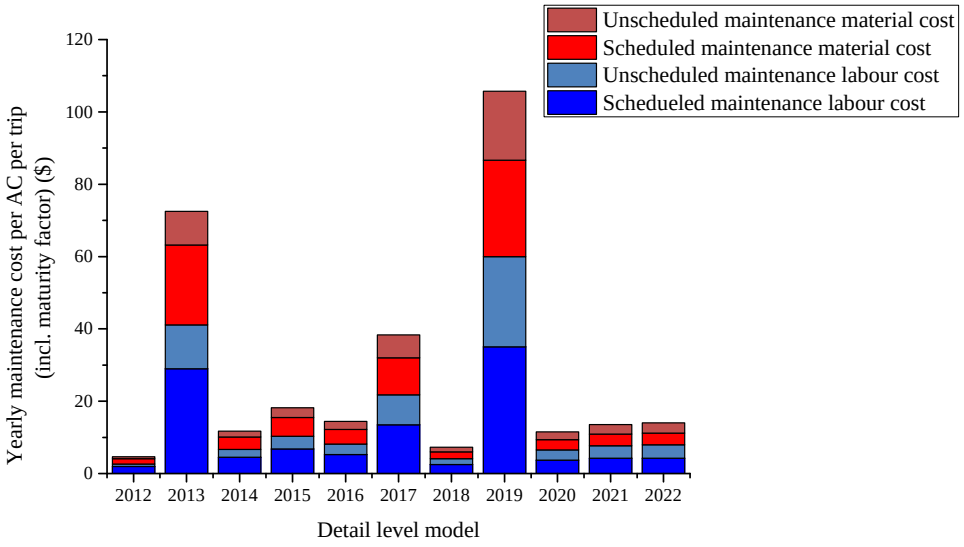


Figure 7.16: Rudder yearly maintenance cost per aircraft per trip

items involved in the fee category. For the high-level estimation, landing fee and navigation fee are considered. For the detail-level model, take-off charge, passenger service fee, security charge, PRM levy, the landing fee, the government noise levy and the government planning levy are all considered. For the statistics of 2008 and 2009 for 10 US major airlines, only the landing fee is considered. In view of those reasons, the cost percentage of the fee for the detail-level model is shown the highest amongst the other cost elements.

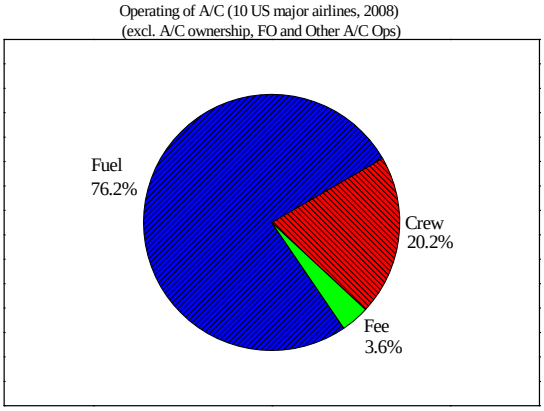


Figure 7.17: Cost for operating of aircraft (10 US major airlines, 2008) [306]

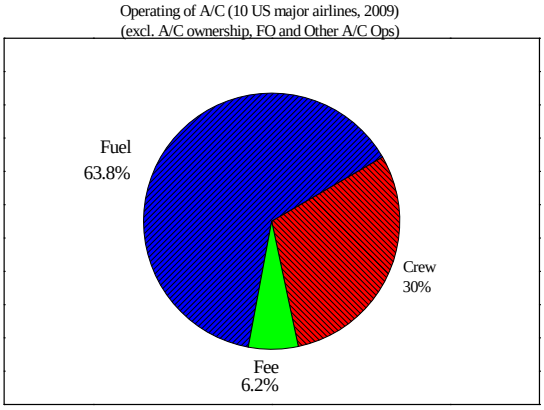


Figure 7.18: Cost for operating of aircraft (10 US major airlines, 2009) [306]

Similarly, comparing the maintenance costs estimated from the high-level model and detail-level model, they are validated each other on the same scale of magnitude. This can be found specifically from the total airframe maintenance costs per trip per aircraft. The high-level model obtains an average estimate for rudder maintenance based on weight properties. The detail-level model contains specific information related to maintenance tasks for each year, therefore, the values change every year.

7.2.2. RESULTS OF D&R COST ANALYSIS

According to the airbus aircraft price list, A330-200 costs $229 million to purchase in 2014. Therefore, the D&R residual price for the sampled aircraft is around $22.9 million, where $87 020 are allocated to rudder component based on weight distribution. While depending on the utility of the aircraft and the airline regime of the D&R process, the value can vary. The same reason applies to the detail-level D&R cost analysis. Based on specific D&R process and the final recycled product required from the customers, there is a big variety of D&R costs even for the same aircraft or components. Due to data limitation, a detail-level D&R costing is currently not available. An experiential statement is presented: The purchase cost for an aircraft (airframe and engine) ranges between $1 million to $10 million US dollars in around 2010, while the cost of disassembly is $100 000 to $250 000, which is little comparing to the purchase cost [276]. According to the statistics [311], the average cost to dismantle an airframe or engine classified by aircraft types can be seen from Table 7.6 and Table 7.7 in FY 2014 dollar.

Table 7.6: Average dismantle cost of an aircraft/engine [311]

	Narrow body ($)	Wide body($)	Regional jet($)
Aircraft	74000	102000	49000
Engine	24000	33000	23000

Table 7.7: Average value of parts harvested from an aircraft/engine [311]

	Narrow body(million $)	Wide body(million $)	Regional jet(million $)
Aircraft	1.5	2.5	2.0
Engine	2.7	3.7	1.5

7.3. SYNTHESIS AND CONCLUSIONS

The proposed cost estimation framework containing high-level and detail-level analyses were applied on the A330-200 rudder. O&M and D&R costing results were presented in detail. In this way, the scalable two-level costing method for LCC analysis was illustrated comprehensively by the O&M and D&R costing demonstrated for the A330-200 rudder case together with the RDT&E and Production costing presented for stiffened panel case. By adopting a similar logic from the stiffened panel costing implementation, the RDT&E and Production costs of the A330-200 rudder could also be obtained. Moreover, by following the generalized optimization problem definition and MDO architecture (Chapters 5 and 6), the rudder configuration could also be optimized in terms of the economic performance. Conclusions related to the implementation of KBE techniques and the cost analyses are drawn in the following sections.

7.3.1. KBE PERSPECTIVE

By employing KBE techniques, the cost estimation was connected to the product properties via the life cycle process extraction. This improved the modularization of the cost analysis. It can be seen that less geometric data while more life cycle process data were needed for O&M cost and D&R cost analyses comparing to those needed by the RDT&E and Production cost estimations. Therefore, the focus would be to model the process knowledge and to automate process relevant data generation based on engineering principles. An intensive study on aircraft operating segments and scheduled maintenance tasks were performed to formulate the process meta model. The logic rules which determine the actual process for a specific aircraft or aircraft component would enable the capability of automatic life cycle process generations. In this research, although some simplified engineering rules were extracted, they were still limited and need to be extended further.

7.3.2. COSTING PERSPECTIVE

By implementing the proposed cost estimation method, it provided rich cost information, which could be used to improve the product design and the life cycle process planning.

According to the operating cost calculation, it was found that more than 60% of the cost was spent on fuel, which was seen the main driver of the trip operating cost. The fuel cost was mainly distributed on cruise segment and reserve mission. It was observed that slightly more fuel cost was spent during taxi out & take off segment than that during approach, landing & taxi in. This could be caused by longer time for preparing flight. However, the fuel consumption of other operating segments was much less than the fuel cost consumed during the cruise. A similar trend applies to the crew cost. Fees are charged for each take off and for each landing.

Considering the maintenance cost estimation, it was able to allocate cost to maintenance tasks. Moreover, it was found that although composite materials have been adopted by rudder component, whilst the scheduled maintenance tasks designated to composite structures did not show an obvious deviation from those of structural components made of metal materials. This is due to a lack of distinction of composite aircraft maintenance programs in the current maintenance practices. From one aspect, composite component maintenance properties should be further investigated. Specifically, the difference between the failure modes, and the maintenance tasks of the composite structure and the metal structure should be identified. From the other aspect, the study on maintenance task scheduling, maintenance task execution time evaluation need to be developed further to improve the maintenance scheduling.

For D&R cost analysis, the simplified analysis was conducted. Data related to the process time cost relationship should also be extracted. An extensive research concerning the aircraft D&R processes is needed to further extract practical rules to automatically determine the actual process execution.

In addition, cost indicators used for optimization studies can be further developed specifically for O&M cost and D&R cost to improve the current cost integrated optimization. Those cost indicators can either include the influence of a single LCC cost type or the combination of two or more major cost types.

8

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the thesis with observations and findings obtained during this research development. Firstly, the research questions, the objectives, and the hypotheses are reviewed. Answers and experiences gained from the application of KBE techniques, the development of LCC analysis method, and the integration of cost analysis and design optimization are summarized. Next, challenges addressed by this research are highlighted. It is followed by a brief discussion of recommendations and outlooks for future research.

8.1. CONCLUSIONS

8.1.1. ADDRESSING THE RESEARCH QUESTIONS

This thesis explored the modularized and automated approach of integrating the LCC analysis and the cost indicators into the aircraft design process. A table is provided to address the work conducted to achieve this capability, see Table 8.1. It shows the research domains where the research questions are generated, the methods proposed and the cases studies performed to validate those methods. The overall capability was realized by constructing a design and optimization framework via the support of KBE techniques for the design process and for cost analysis, the scalable two-level LCC estimation method for the major cost types, and the costing integrated design optimization studies. Those methods were illustrated in detail by the stiffened panel case and the rudder case. Each emphasizes respective aspects of the method, shown by check marks in Table 8.1.

Table 8.1: Summery of research domains, methods, and case studies

Research domain	Design-cost integration		LCC				Design optimization
Method	KBE supported integration		Scalable two-level cost analysis				MDO
	KBE supported design	KBE supported cost analysis	RDT&E cost	Production cost	O&M cost	D&R cost	Optimization studies
Stiffened panel case	✓	✓	✓	✓	-	-	✓
Rudder case	✓	✓	-	-	✓	✓	-

By reviewing the research questions and hypotheses of this thesis (see Chapter 1), it was proved that an automatic and modularized design optimization process can be achieved by incorporating the scalable two-level LCC analysis into design process using KBE techniques. The scalable two-level LCC analysis can provide the cost engineer with an analytical method to evaluate the aircraft or the aircraft component LCC during conceptual and preliminary design phase. The method contains consistent cost estimation approaches for each major cost type of an LCC. Based on the design properties, the cost analysis can be performed on two levels of detail during the early design phase while including the life cycle consideration. The proposed optimization studies obtained a higher percentage of cost reduction than that of the weight increase, and provided a better design balancing cost, weight, structural, and other performance properties.

In more detail, relevant to the aircraft **KBE assisted design**, the design process implemented in ODMs was summarized in Chapter 2. It generally contains the conceptual design,

preliminary design, and detail design phases, which requires repetitive design iterations on different levels of fidelity. It was found the process can be modularized by following the DEE design and optimization framework. The DEE framework consists of initiator, MMG, disciplinary views, analysis tools, and converger & evaluator, which are modules constructing a design iteration. The LCC estimation can be integrated into the aircraft design process by following the product-process-cost procedure. Relevant data and inference mechanisms were extracted and stored in the KB and CMs to facilitate the design and cost analysis integration and automation. Specifically for each cost type in a life cycle, data and knowledge rules related to the product and the life cycle process for the cost evaluation were extracted and formulated. That knowledge was utilized by the CMs embedded in the cost analysis module and grouped into functional blocks such as pre-processing, cost estimation, and post-processing. Therefore, the LCC estimation was integrated into the aircraft design process, see Chapters 3, 6 and 7. KBE techniques such as knowledge capture, process automation were adopted to support the design-cost integration.

Regarding the **LCC analysis**, a scalable two-level LCC estimation framework was proposed. Based on the availability of input parameters, either high-level or detail-level cost estimations conducted for evaluating the cost. The LCC estimation was conducted by following the product-process-cost procedure. It was found that various cost indicators were influenced by the product life cycle performance. Those indicators are not only cost-related but also revenue-/profit- associated, and they are focused by different stakeholders. All cost estimates were generated based on one central product concept based on its product, process, and performance properties such as geometry, material, process, speed, payload, and range. These driving parameters were determined by empirical, parametrical and rule-based inferencing analysis (Chapter 2). The CERs for the overall LCC analysis was constructed in Chapter 4 and implemented in Chapters 6 and 7.This estimation framework was proposed based on generalized aircraft life cycle process, and it consists of four cost modules for RDT&E, Production (or M&A), O&M, and D&R costs evaluation. The cost estimation was enabled by KBE techniques such as inference rules, built-in CERs, and cost type specific CPs. The repetitive tasks of extracting product and process data, generating cost input, developing integrated PBS and CBS, invoking CERs, producing cost results were automated through CMs. When the KB and the CMs were incorporated in the KBE application, the speed for cost analysis was improved from weeks to minutes comparing to the traditional manual analysis process.

Concerning **design optimization**, optimization workflow was embedded in the DEE framework. The optimization studies were conducted in the converger & evaluator of the DEE. The analysis cycles were automated via seamless connection among the MMG, analysis tools, and the converger & evaluator. The optimum design configuration was obtained based on the minimum cost indicators including production cost, DOC, and –SV, which were focused by corresponding stakeholders. Optimum design with regard to lowest production cost is desired by OEMs, while airlines require design configurations for minimum DOC or -SV. Constraints relevant to structural allowable, manufacturing limitations, and performance restrictions were considered optimum design configurations were derived for target cost indicators. According to the stiffened panel study case, it was found that the optimum obtained from minimizing AFW not only results in higher cost properties but also shows the least advantage in weight performance. It indicates that when the project budget is limited, AFW as an objec-

tive is not preferable, while production cost, DOC and SV should be taken into consideration. Since the cost indicators were constructed considering geometric, process, weight, and cost properties, optimum solutions balancing the influence of those properties. According to the case study, it was achieved cost reduction with a small amount of weight compensation. Potential optimization methods were evaluated, the GAPS optimization strategy was found the most robust, see Chapters 5 and 6.

The challenges addressed throughout the thesis are concluded respectively for each aspect of the research. The integration of design, costing, and optimization was mainly enabled by KBE techniques, where the conclusions related to the integration of the three domains can be found from the design perspective. The LCC perspective addresses the development in the cost analysis. The MDO perspective emphasizes the improvement in optimization studies.

8.1.2. KBE PERSPECTIVE

The aircraft **LCC analysis integrated design process** were developed on the basis of DEE framework with respect to a general process of aircraft design and design optimization. The development of disciplinary views and their corresponding analyses for LCC can be easily connected or disconnected with the MMG, which reflects the flexibility of the framework.

Considering **the support of KBE techniques for design-cost integration**, a method to analyse cost following an automated and modularized paradigm was proposed. A cost analysis tool has been developed and integrated into the design process. The method emphasizes the use of KBE techniques for design-cost integrations and for cost analysis. Manual activities such as collecting product geometry attribute, material and processes information; generating an extended BOM; establishing the cost driving parameters, were automated. This eases the work burden for cost engineers. As such, cost engineers were freed up to concentrate on developing, estimating and validating the relations between cost driving parameters and final costs. Simultaneously, designers gain the possibility of bringing cost estimating into the design process, which opens up opportunities for efficient trade-offs using cost as an impact factor among the concepts concerning geometry and material changes. Results about the material and labour costs for parts and assembly connection interfaces can be obtained and analysed. It was also able to illustrate the connections between cost driving parameters and their corresponding CPs.

It contributed to the design-cost integration via various approaches. *Firstly*, it coupled product geometry and cost estimation by generating disciplinary views. The geometric and process properties related to RDT&E, production, O&M, D&R cost analyses were derived according to the original product model and inference rules. Examples of the production view generation, containing geometric segmentations and knowledge inference, were illustrated and fed into the production cost analysis. *Secondly*, it created repeatable and general cost estimations by employing CPs, which are cost elements containing relevant product and process data, as well as CERs. The same CPs for different products and cost types can be reused. For example, a stringer production cost CP can either to adopted by aircraft wings or fuselages, it can also be used for multiple aircraft types. *Thirdly*, the application created traceable cost estimations by building a visible link between the PBS and CBS. During the cost evaluation process, the PBS and CBS were generated and integrated. Therefore, according to a

tree structure, the footprint of the cost evaluated for any product and process can be clearly identified.

By **incorporating KBE techniques into cost analysis**, a tight link was built up between the product model and the cost estimations through the disciplinary views, this improved the accuracy of data extraction for cost analysis, eliminate some errors made via complicated manual approach. The development reduced labour and time for cost estimations by integrating and automating the cost estimations process. Relevant knowledge was invoked by CMs from KB to accomplish process automation. CMs are also responsible for pre- and post- processing activities. It saved labour and the time used to extract product and process in a manual process.

Comparing the design-cost integrated KBE implementation with applications without KBE support, the proposed approach accelerated the integrated design and analysis process. Practices in industry for the cost estimations of a complex component need weeks to finish, while when the KB and the inference mechanism was available, this approach was immediate. *Furthermore*, this approach was generalizable by extending the embedded KB and CMs. If the domain knowledge was extracted extensively, it can be applied on products which comply with the same rules for the production view generation and are consistent with the PBS and CBS meta model. *Moreover*, the KBE assisted cost analysis enables detailed cost estimations in the aircraft conceptual design phase. The problem of limited data within design phase was compensated with the KB. *In addition*, the inclusion of KBE techniques improves the modularity for the cost analysis, providing a better-structured analysis procedure. Last but not the least, this cost analysis method was generally applicable for all cost types for aircraft life cycle consideration. Before developing the respective applications, PBS and CBS for different cost types should be defined separately.

The proposed method was more comprehensive comparing it with other current KBE-assisted cost estimation methods.This is because it emphasised the method and supporting techniques for actual cost estimations other than the geometric modelling for MMG. A detailed process starting from the integration of PBS and CBS to the implementation of CPs and cost calculation has been illustrated.

8.1.3. LCC PERSPECTIVE

To address the challenge of lack of **an LCC framework**, a scalable two-level LCC estimation framework was proposed, which was generalized and modularized for each cost type of an aircraft life cycle. It was flexible for either high-level or detail-level cost estimations based on data availabilities.

The aircraft life cycle process is divided into RDT&E, production, O&M and D&R processes. **Cost estimation methods** for four major cost types correspondent to each process were developed respectively, formulating a complete LCC estimation capability. Each cost consists of multiple cost elements, shown in the CBS. High-level model cost estimations generally took aircraft geometric, weight and performance properties as inputs, while the detail-level model required extra attributes relevant to the detailed process steps of each life cycle process. Those process attributes were often derived based on engineering knowledge rules. *Moreover*, it adopted a new classification of cost estimation methods, which helped to identify the characteristics of the methods proposed for each LCC cost type. Within the high-

level cost estimations, both the RDT&E and Production cost estimation employ top-down feature-based parametric methods using cost-time analysis techniques; the O&M cost estimation follows a top-down feature-based parametric method using regression analysis; and the D&R costing adopts a financial model using simple experiential factors. In the detail-level cost estimations, the RDT&E costing adopts a top-down process-based parametric method supported by data fitting techniques. The detail-level Production cost estimation employs a bottom-up process-based parametric method supported by KBE techniques. The detail-level O&M cost model uses a bottom-up process-based parametric method and process-based cost aggregation supported by KBE techniques. The detail-level D&R cost estimation follows a bottom-up process-based cost aggregation. Furthermore, the cost estimation relationships focused on the configuration attributes, the material properties and the process parameters, which established relations between cost drives and the evaluated costs. In addition, two levels of the cost estimation make the cost information highly accessible during the overall life cycle. Once necessary data and engineering rules have been collected, it enabled detail-level cost estimation within conceptual design phase.

To solve the main issue of disconnection between the life cycle consideration and aircraft design process, the proposed cost analysis was tightly embedded in the design and optimization framework via the life cycle related views and the integration of PBS and CBS. On the basis of **the integrated application**, the LCC analysis and optimization studies were developed in-depth within their respective modules. A fundamental platform was provided to facilitate an automated analysis process where the repetitive procedure and reusable knowledge were critical. Although that knowledge is extensively distributed over the life cycle and not understandable by all stakeholders, this integration enables the analyses of their common concerns within a life cycle - the LCC, which in turn also improves the fidelity of the analysis and benefits the stakeholders via a more comprehensive and objective view of the product.

8.1.4. MDO PERSPECTIVE

In response to the lack of **cost integrated MDO architecture**, an extended design structure matrix was established for cost integrated design optimization. It was incorporated within the DEE framework and was demonstrated on a stiffened panel case. After defining a generalized cost-integrated optimization problem, the utilization of cost indicators for an optimization objective for different stakeholders was highlighted. By incorporating relevant cost types in a life cycle, cost indicators such as production cost, DOC, and SV were constructed for either the aircraft or aircraft component. Cost analysis and structural analysis were performed and the results were fed into the objective and the constraints formulations. It was found the optimum solutions obtained from using cost properties as objectives are better than the ones using weight properties as objectives. Some results showed more cost savings with small compensations on weight increases. *Moreover*, **optimization algorithm**, including GA, GD, GAPS, and GAGD, were investigated and compared. It was noted that although the LCC could be integrated as one synthetic value, while it was not popular to utilize the LCC value as an optimization objective. It is caused by distinct interests from different stakeholders. More effectively, the adoption of cost indicators was proposed. Those indicators represent focuses of specific stakeholders according to their requirements on which cost types a be evaluated.

8.2. CONTRIBUTIONS AND NOVELTY

In summary, the novelty is highlighted within the integration of the LCC analysis and the design and optimization framework using KBE techniques; the LCC estimation framework and the corresponding methodology development; and the LCC indicator involved optimization studies. In particular, the technique enablers, such as the generation of life cycle related product and process views, the development and implementation of the CP concept, the high-level and detail-level cost estimations over each phase of the aircraft life cycle, the derivation of LCC indicators including DOC and SV, and the constructing of the cost involved optimization workflow were proposed. The novel elements of this research consist of the ones covering all those three research fields and the ones dedicated to each specific domain. In general, it proposed a product-process-cost procedure for design-cost integration and for cost analysis method development. The utilization of KBE techniques, such as KB construction and inference rules extraction, facilitates the generalisation, modularization and automation of the design and cost analysis process. Since the proposed method connects design and cost analysis in two levels of detail, it can be computationally applied to an aircraft or a component during the conceptual design and preliminary design phase. It opens for cost engineers from an ODM or from a supplier company to perform the analysis. The results can be provided to ODM or airlines as references for decision making. Furthermore, the approach of utilizing KBE techniques, the scalable two-level LCC analysis, and the cost integrated design optimization framework can also be used for other systems, e.g. auto mobile design, ship design, and building design, since they are generalized methodology which can be adapted based on design-specific properties. In more detail, the contributions are highlighted respectively for the three domains as follows:

- Design process
  - Integrated cost analysis into DEE framework via life cycle process related views, cost estimation modules, pre- and post- processing modules to enable the costing capability in design tools;
  - Extracted data and inference mechanisms to generalise life cycle processes and to develop life cycle process related views to build the connection between the design concept and its cost;
  - Constructed PBS and CBS integration to structure the cost analysis for a product;
  - Developed CP concept to enable the repetitive use of costing tools for different aircraft concepts and cost types;
- LCC analysis
  - Developed scalable two-level LCC estimation framework to overcome the limitation of data availability for cost analysis during design phase;
  - Developed or adapted high-level and detail-level models for each major cost type to formulate a comprehensive and consistent LCC analysis;
  - Developed product-process-cost procedure to facilitate design-driven costing approach and to generalize cost estimation process;

- MDO study
  - Developed extended design structure matrix as a generalized framework for cost integrated design optimization;
  - Integrated cost indicators into optimization studies;
  - Provided better design solutions in terms cost reductions in DOC, production cost and –SV under the structural and life-cycle-process-related constraints.

8.3. LIMITATIONS AND RECOMMENDATIONS

8.3.1. KBE PERSPECTIVE

Regarding **the application efficiency**, the implementation of developing KBE assisted design application involves a large amount of knowledge extractions and formalizations, which is a time-intensive and complicated task, involving technical challenges, human resource and organizational support. *Moreover*, the complexity of knowledge involved in the application also affects the time used for development. Therefore, an investment of time and money in the application development has to be traded off against the anticipated benefits resulting from the application. The efficiency of the KBE application is shown an outstanding advantage when the knowledge is available and is easy to be formulated, so that for a patch of similar analyses, the KBE application is fast and effective. However, for the initial development of the application, the time and effort used are not negligible. These considerations are not trivial and are aspects to be taken into account in future research.

Considering the **application fidelity**, the primary goal of KBE is not to improve the accuracy of the cost estimation but to facilitate the automated and immediate inclusion of cost estimation within a design and optimization framework. The accuracy of the cost analysis is directly dependent on the driving parameters as well as the accuracy of the CERs. In fact, as the cost estimation capability is integrated into the design process, when the fidelity of the geometric models and the life cycle process modules are improved, the accuracy of cost results is also improved. *Furthermore*, for KBE applications with an extensive KB, it is possible to obtain predictions closer to the real design for cost estimation.

The domain knowledge is currently managed in the application without a crisp separation between the actual analyses and **knowledge management**. However, knowledge stored in design applications needs to be maintained and upgraded periodically. It requires new KBE techniques such as knowledge tracking and maintenance to capture the knowledge changes. In order to enable knowledge management specific capabilities, it is recommended to develop a separate knowledge management module (or tool), which focuses on controlling knowledge extraction, storage, update, and maintenance. *Moreover*, it is desired to incorporate the factors related to human interventions during the design process, and the creative activities can be captured in the design process automatically. One of the potential strategies would be to collect logic rules from designers when they implement design modifications within the application, hidden knowledge of the designers is therefore captured for repetitive use. *In addition*, in order to provide a quantitative evaluation of the KBE supported design application in terms of the accuracy and efficiency, methods should be developed to evaluate the execution speed and the accuracy of the estimation results of the application.

8.3.2. LCC PERSPECTIVE

It is recommended to **improve cost estimations for indirect cost elements**. For both high- and detail- level cost estimation models, not every cost element summarized in the LCC breakdown is estimated, particularly the indirect cost estimations are still missing. This is mainly due to a lack of data resources relevant to those cost elements on both levels of detail. It is also because that some cost elements such as overhead cost being company dependent, the calculations are not shown. Future research is recommended to focusing indirect cost elements such as energy consumptions, facility costs, tooling & equipment costs, and testing costs in both levels of LCC estimations by collecting data and establishing estimation methods.

Regarding the fidelity of current cost estimation model, improvement is also needed. The high-level models were extracted and adapted from existing cost estimation models developed in the 90s, in which some recent aircraft types such as B787 and A350 are not included. A close investigation of process steps of each life cycle phase is critical for the detail-level model to improve the estimation fidelity. This includes knowledge extraction, automatic life cycle process step generations and CER developments. Inference mechanisms should be extracted to facilitate the automatic life cycle process planning. The detail-level model often encounters obstacles when CERs for certain process steps in a life cycle are not available. Therefore, a comprehensive data set is needed to produce updated CERs. Those CERs should involve the influence of novel materials, new technologies, and life cycle process attributes. In more detail, Since the current RDT&E phase employees a simplified process subdivision, a more comprehensive process flow including the labour and material consumptions should be further examined for detail-level RDT&E cost analysis. For detailed production cost estimation, the CERs are mainly collected from literature, therefore, up-to-date and verified CERs are necessary for industrial applications. The detail-level flight operating cost model needs to be more tightly connected with specific airline flight plans. In the detailed maintenance cost estimation, an in-depth study of the maintenance intervals can potentially link the product design parameters to the maintenance task scheduling, and can be further related to maintenance cost properties. Moreover, rules and data should be extracted for evaluating the scheduled maintenance material cost, the unscheduled maintenance labour and material costs to improve the level of fidelity. The detail-level D&R model also needs to be enhanced by analyses on D&R process step generations and CER developments.

Last but not least, **risk analysis dealing with the influence of the design uncertainties on product costs should be conducted**. On the basis of the proposed cost estimation method, the cost changes or the opportunity costs for alternative design or life cycle process choices can be developed. This will directly illustrate the impact resulted from differences in cost driving parameters. Additionally, the uncertainty involved in cost estimations can be utilized to evaluate the risk introduced to increase or decrease the cost. However, it should be noted that those improvements can only be well-developed on the foundation of current LCC estimation method.

8.3.3. MDO PERSPECTIVE

In this research, cost indicators for specific stakeholders were considered, while the balance among the major cost types in the LCC should be studied further. It is recommended to **develop simplified cost indicators that can represent the overall LCC performance to be utilized in the single objective optimization**.

In general, the proposed optimization framework (see Figure 5.1) applies to both the aircraft and the component optimization studies, while it should be noted when the overall aircraft is considered, specific optimization decomposition strategies should be further considered within the framework. This research aimed at providing an analytical method in which the optimum design of a component or an aircraft under certain constraints can be found. In order to obtain the global optimum, the combination of a various component in a system is needed and the optimization should be run on the aircraft level. While in order to obtain the optimum aircraft constructed by different components, respective constraints of the components would apply on the local level, in addition to the global constraints and the relation between the global design parameters and the local design parameters, it is believed that the design decision can be made on the basis the global optimum while satisfying both the global and local constraints. It is possible that the component design parameter obtained through the aircraft optimization studies are different with the ones obtained from the local optimization studies, therefore, **multi-level optimization strategies** should be further constructed within the proposed optimization framework. However, although the objective and the constraints of the studies will be adapted, while the proposed design framework still applies, and the method of the cost analysis for aircraft or for the components remain unchanged. From another perspective, in order to fulfil the interest of respective stakeholders in the LCC analysis, optimization architectures such as **multi-objective optimizations** should be conducted. By considering the criteria for different stakeholders, a set of solutions converged to a Pareto front could be found to support design decision making.

One of the focuses was also to **integrate cost analysis in an MDO environment contains more disciplines to further confine the feasible design space**. For example, optimization studies should be conducted by considering aerodynamic performance, cost and weight properties, structural limitations together.

In addition, **extensive sensitivity analysis should be conducted to identify how design and life cycle process parameters constructed in the CERs influence the costs**. Moreover, it is necessary to further develop a comprehensive sensitivity analysis model not only for the design parameters but also for the constant parameters in the optimization. Within the cost analysis, the influence of the material types on LCC prediction has been considered for three kinds: the aluminium, thermoplastic material, and thermoset material. However, only the material influence on weight and production processes are considered, more investigations of material and technology induced structural, life cycle process changes should be considered further.

Last but not least, in order to **improve optimization application performance**, a qualitative evaluation is needed to identify the accuracy and the efficiency of the cost involved optimizations. A general consideration on improving human intervention, design space visualization and organizational management associated with the optimization application performance could also be explored further.

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APPENDICES

A

AVIATION MARKET TREND

In this appendix, the detailed aviation market trend analysis based on the demand and capacity interaction is provided.

A monthly growth of RPK, RTK, ASK and ATK is shown in Figure B.1. A similar upper trend as the yearly RPK and RTK growth is illustrated, while the monthly fluctuations caused by the changes of business confidence, fuel price and regional market are shown in detail. In May 2015, since the increase of business confidence, the decline of fuel price and the expansion of Asia Pacific market, the RPK and ASK are growing robustly. While due to the trend change of world trade in 2015, a demand decline is appeared particularly in the emerging Asia, it also reflects a weak cargo demand and capacity in RTK and ATK in May 2015 [331]. Correspondingly, the percentage changes of those factors are shown in Figure B.1 based on the data from the IATA series of airlines financial health monitor and air passenger market analysis [331][332]. It is shown that the monthly growths of RPK, ASK, RTK and ATK all follow a similar trend to the world GDP growth [333]. Since 2010, the air travel grows continuously and stays above a 20 years' average growth rate of 5% [334]. Historically, the annual growth in the air travel (RPK) nearly doubles that in GDP with a slightly weakened trend in recent years [14]. Air cargo (RTK) is also in an increasing status while it is quite sensitive to the GDP growth [334].

[1] Data source: IATA economics, www.iata.org/economics

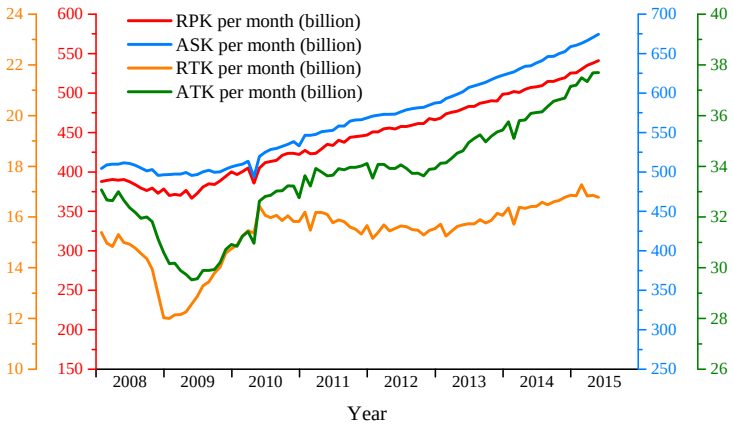


Figure A.1: Monthly growth of RPK, RTK, ASK and ATK (Jan.2008-May.2015, seasonally adjusted monthly value)[1], adapted from [10]

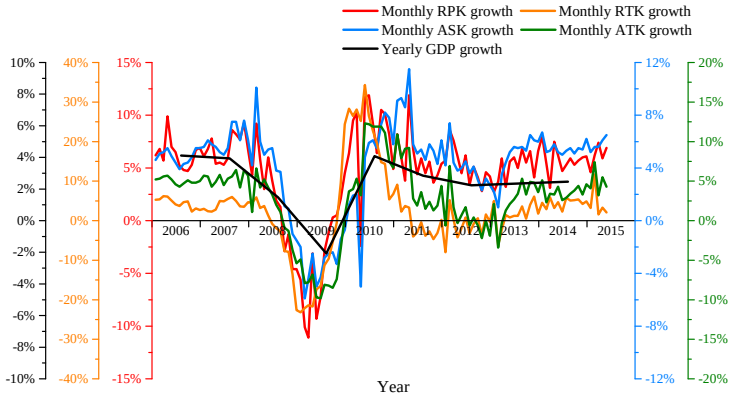


Figure A.2: Monthly percentage changes of RPK, RTK, ASK, ATK and yearly GDP growth (Jan.2006-May.2015, YOY monthly percentage change)[2]

Dividing the demand (RPK, RTK) by the capacity (ASK, ATK), the load factors are obtained. Therefore, the change of load factors in percentages are related to the fuel prices, the demand and the capacity of air travel and transportation. According to Figure A.3, the Passenger Load Factor (PLF) has reached 80% in 2013, which indicates a growth of passenger volumes along with an increase of aircraft seat number. This is led by the improvement of the capacity management [14][331][335]. Over the last decades, the PLF has been increased around 8%, while the overall Freight Load Factor (FLF) is declined due to the increased belly capacity of passenger aircraft. It fluctuates between 40% to 60% in recent years. The yearly FLF required for break-even condition and the yearly FLF achieved are displayed

[2]Data source: IATA economics Industry Performance www.iata.org/economics, world data bank, http://databank.worldbank.org/data/home.aspx

in Figure A.4, which is a direct reflection of the airline profitability [333]. When the yields decrease faster than the cost reduces, the break-even load factor undesirably goes upwards. While when the fuel price falls and the ancillary revenue increases, the break-even load factor favourably falls. The achieved load factor can be improved by the market consolidation and the structured market behaviour. If the achieved load factor is higher than the break-even load factor with a big gab, it implies a high profitability [334].

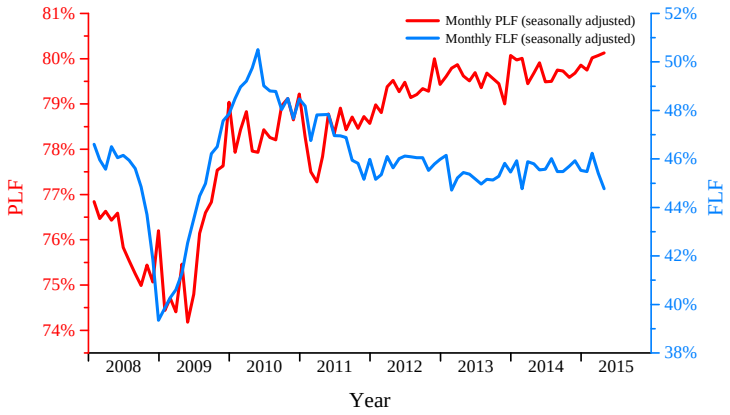


Figure A.3: Load factors for passenger and freight market (Jan. 2008- May. 2015, YOY seasonally adjusted monthly percentage change)[3] [331]

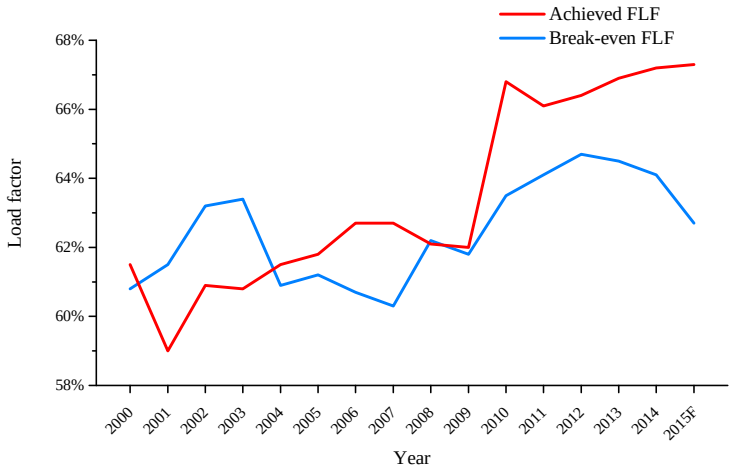


Figure A.4: 4 Break-even FLF and achieve FLF (2000-2015F)[4] [333][334][334]

[3]Data source: IATA economics www.iata.org/economics, Airlines Financial Monitor, Air Transport Market Analysis, Air Passenger Market Analysis, Monthly Traffic Analysis.
[4]Data source: IATA economics www.iata.org/economics.

B

AVIATION ECONOMY

In this appendix, the interaction between the aviation economy and the global economic growth are analysed in detail.

Firstly, the impact of the GDP growth can be inspected from the economic growth in the sectors of air-traveller consumptions and freight transportation businesses. In 1998, the world civil aviation generated a total output of $1360 billion, equivalent to 4.5% output in terms of the GDP, and 27.7 million jobs [50]. It included a direct output of $652 billion from airlines. By eliminating the components of double counting, it was around $370 billion in consolidated direct output, which required at least 6 million jobs [50]. A decades later, it contributed $1.1 trillion to the total economy through its indirect, direct and induced impact and accounted for 2.3% of the world GDP in 2008 [336]. It also provided 31.9 million employment, which involved 5.5 million positions in the air transport sector [336]. In the year 2014, aviation's total global economic impact was $2.4 trillion (FY2012 US$), including the direct, indirect, induced and tourism catalytic impact, which approximated 3.4% of the world GDP [3]. At the meantime, aviation supported 58.1 million jobs worldwide, which included 8.7 million aviation direct positions [3].

Besides the GDP growth, the following factors are also inextricably associated with the aviation economic status: the world trade growth, the industrial production growth and the business confidence. Whenever the world economy, the world trade and the global industrial production cycles remain strong (weak), the airline profits follow a similar upturn (downturn). When the business confidence varies, it will be reflected on the airline industry correspondingly. This can be seen by comparing Figure B.2 and Figure 1. 4 for the influence of the world economic indicators on profit [334][337]. And likewise, the influences on the cost and revenue can be detected from Figure B.3 and Figure 1. 3.

In addition, the monetary conditions and the fuel price fluctuation, which affect the fuel consumption, are also related to the aviation economy. It can be seen from Figure B.2 that the influence of the fuel price is offset by effect of the trade US dollar index due to their inverse relation. The fuel efficiency remains an improvement (decline) during the last decades.

[1] Data source: IATA economics extracted from Netherlands CPB, JP Morgan/Markit

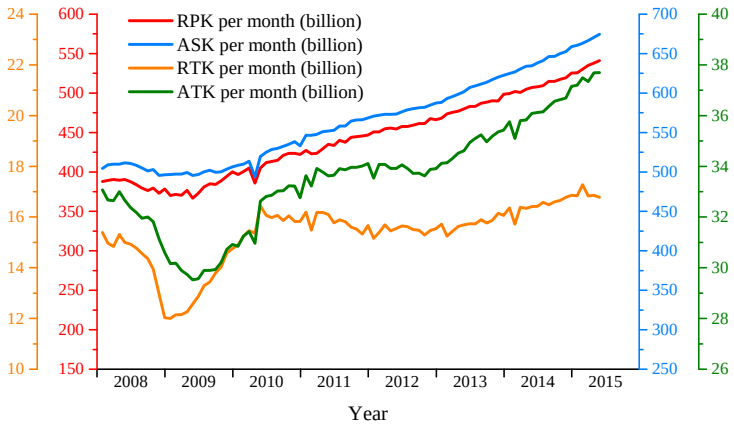


Figure B.1: Economic indices variation (Jan.2008-May.2015, YOY percentage monthly change for world trade growth and industrial production growth, 50 equals no change for business confidence index)[1], adapted from [10]

Although a sharp fall of the fuel price results economic operations of the less fuel efficient aircraft in short term, while it can slow down the rate of fuel efficiency improvement as shown in the year 2009. And because of the intensive competitions in airlines, the reduction of CATK due to low fuel price were consistently passed to the RATK, the fuel efficiency improvement caused by the low fuel price would benefit the customers directly other than the airlines [334]. Therefore, it is not clear that if low fuel price will keep a long term fuel efficiency improvement as well as airline profitability.

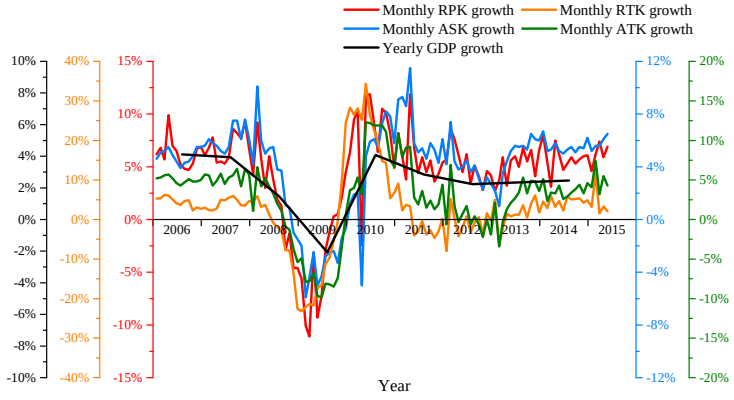


Figure B.2: Annual fuel price, fuel efficiency and dollar rate (2000-2015F)[2], adapted from [12][334]

The interaction between the fuel price and the dollar rate also influences the Weighted

[2] Data source: Platts, IES, ICAO, IATA www.iata.org/economics, FRASER https://research.stlouisfed.org/fred2/categories/105.

Average Cost of Capital (WACC) and the Return On Invested Capital (ROIC). Figure B.3 shows the general trend of annual WACC and ROIC, which indicates a general situation that the airline operation reacts to the aforementioned world economic factors [331]. When the WACC equals to the ROIC, the performance of the industry is considered in a proper condition, which signifies that the investors obtain a return by taking a similar risk when they invest the cost. However, due to the intensive competition and challenges of the aviation industry, the ROIC rarely reaches the WACC. It is expected that in 2015 the aviation industry is obtaining value for its equity investors for the first time [331]. The ROIC is also a reflection of the profitability corresponding to the gap size between the achieved FLF and the break-even FLF (Figure A. 4).

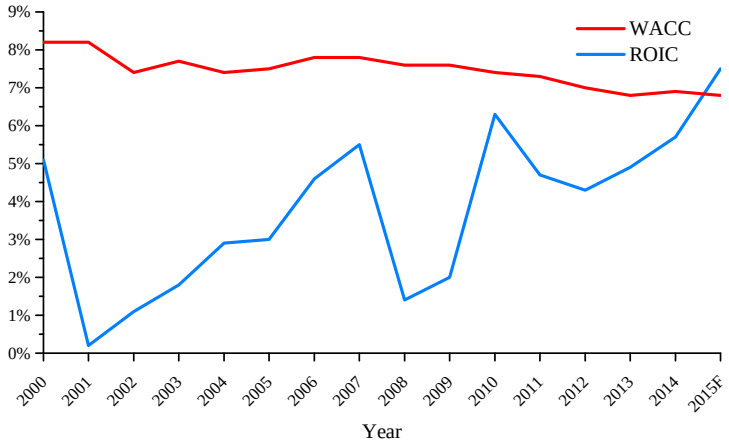


Figure B.3: Annual WACC and ROIC (2000-2015F)[3] [12]

[3]Data source: Mckinsey, IATA economics www.iata.org/economics.

C

CLARIFICATION FOR KBE RELEVANT GLOSSARIES

Capability Module: A functional class to enable the automatic data transmission, disciplinary view generation, analysis and optimization processing. It can be added to HLPs or to other CMs to facilitate the DEE work flow [22][338].

Data: Facts, measurements, or observations. Also, a symbolic representation of facts, measurements, or observations. Data is what we collect and store [72](pp.370).

Data base: A collection of structured **data. Database** is the basic component of an **expert system** [72](pp.370).

Design and Engineering Engine (DEE): an integrated design system, which is built upon loosely coupled and customizable modules, to support multidisciplinary design, analysis and optimization of aircraft [22].

Domain: A relatively narrow problem area [72](pp.372).

Expert System: A computer program that performs at the level of a human expert to solve problems in a specific **domain** [72](pp.28). It contains five basic components: the Knowledge Base, the Database, the Inference Engine, the Explanation Facilities and the User Interface [72](pp. 373).

Expert System shell: A general Expert System tool without domain relevant rules and data, which should be added by the user to develop an Expert System [72](pp.28).

Explanation Facilities: A basic component of an expert system that enables the user to query the expert system about how it reached a particular conclusion and why it needs a

specific fact to do so [72](pp.373).

Facts: A statement that has the property of being either true or false [72](pp.373).

High Level Primitive: Parametric geometry model representing an elementary building block with similarity among different aircraft configurations and can be instantiated in other MMG development [22][338].

Inference Engine: A basic component of an **expert system** that carries out reasoning whereby the expert system reaches a solution. It matches the rules provided in the **rule base** with the **facts** contained in the **database**. Also referred to as **Interpreter** [72](pp.377).

Knowledge: A theoretical or practical understanding of a subject. Knowledge is what helps us to make informed decisions [72](pp.378).

Knowledge Base: A basic component of an expert system that contains **knowledge** about a specific domain [72](pp.379).

Knowledge Based System: A system that uses stored knowledge for solving problems in specific domain. [72](pp.379). It contains five basic components: the **Knowledge Base**, the **Work Space (or Work Area, or Blackboard)**, the **Inference Engine (or Reasoning Engine)**, the Explanation System and the **User Interface** [22](pp.58). It is interchangeable with Expert System in certain context.

Knowledge Based Engineering Application: A computer program that uses a programming language to formalize domain knowledge to solve a specific problem. A **Knowledge Based Engineering Application** shows a strongly intertwined knowledge and inference mechanism [22](pp.73). No crisp separation is involved among the **Knowledge Base**, **the Database** and **the Inference Engine** although it is developed rooted from the Expert System [22] (pp.73).

Knowledge Based Engineering System: An evolution of **Knowledge Base System** towards the specific needs of the **engineering** domain. The added **'engineering'** refers to geometry manipulation and data processing, which means that the engineering work requires the generation and management of complex products configurations, the transmission of data among product geometry, disciplinary analysis tools and optimisation tools in an advanced design loop [22](pp.71). In other words, **Knowledge Based Engineering System** is the merger of **Knowledge Base System** and **engineering**, it is also the integration of **Artificial Intelligence** and **Computer Aided Design Technology** [70]. It is similar to an Expert System shell, and is a general purpose tool without any knowledge about a specific domain to build Knowledge Based Engineering Application [22](pp.73).

Multi-Model Generator (MMG): a KBE application which contains the parametric product model and CMs for disciplinary model generation. The parametrical product model, also called master geometry or product view, is the generative model of the conventional and

novel aircraft/component configurations. The disciplinary models, also called disciplinary views, contain the disciplinary geometric representation and relevant properties for disciplinary analysis [22][338].

User Interface: A means of communication between a user and a machine [72](pp.389).

View: An interpretation of the product model for one disciplinary analysis. It includes the geometric representation and relevant properties, which are derived and extracted from the master geometry and product basic attributes. It can also be called a disciplinary abstraction [22][338].

Work Space: The short memory of Knowledge Based System, including case specific results, intermediate data and user input data [22](pp.58).

D

CONVENTIONS OF TERMS USED AND THEIR RELATIONS

In this research, various terms are used while following a consistent convention. In this appendix, most of the conventional use of terms, their significances, notations and relations are introduced. Some interchangeable terms are also highlighted.

D.1. PRODUCT RELATED TERMS

A PBS covers items such as the product, component and part. A product normally refers to the final assembly in a PBS, and is positioned at the root of the PBS. If the final product is an aircraft, the 'product' refers to the overall aircraft. If the final product is a panel, the 'product' refers to the panel. Components are subassemblies, which are composed of parts and subassemblies. They are presented as nodes in a PBS. Parts are the smallest unit in a PBS, which is represented as leaves in a PBS.

D.2. COST RELATED TERMS

A CBS covers items such as the LCC, major cost type, and cost elements. LCC covers all four major cost types: RDT&E cost, Production cost (M&A cost), O&M cost, and D&R cost. A major cost type contains cost elements such as labour cost, material cost, tooling&equipment cost, testing cost, energy consumption, and facility cost. It can be represented as the root or a node of the CBS. Cost elements are the smallest unit in a CBS, which is represented as leaves in a PBS. A CP can represents any cost items which contains the product, process, and cost properties. A process step refers to any activity step taken during an aircraft life cycle.

D.3. WEIGHT BREAKDOWN CONVENTION

The weight breakdown convention is shown in D.1(adapted from [280][339]). It depicts the weight main groups packaging items from product breakdown structure and the standard

weight terms corresponding to the weight main groups. The abbreviation and the alternative terms (if any) are illustrated in the bracket below each items. The blank boxes indicate the weight margin between the weight items and their respective upper limits authorized by relevant government regulations determined on the basis of design limits such as structural constraints of the aircraft concept, the operating conditions such as the length of the runway and so on.

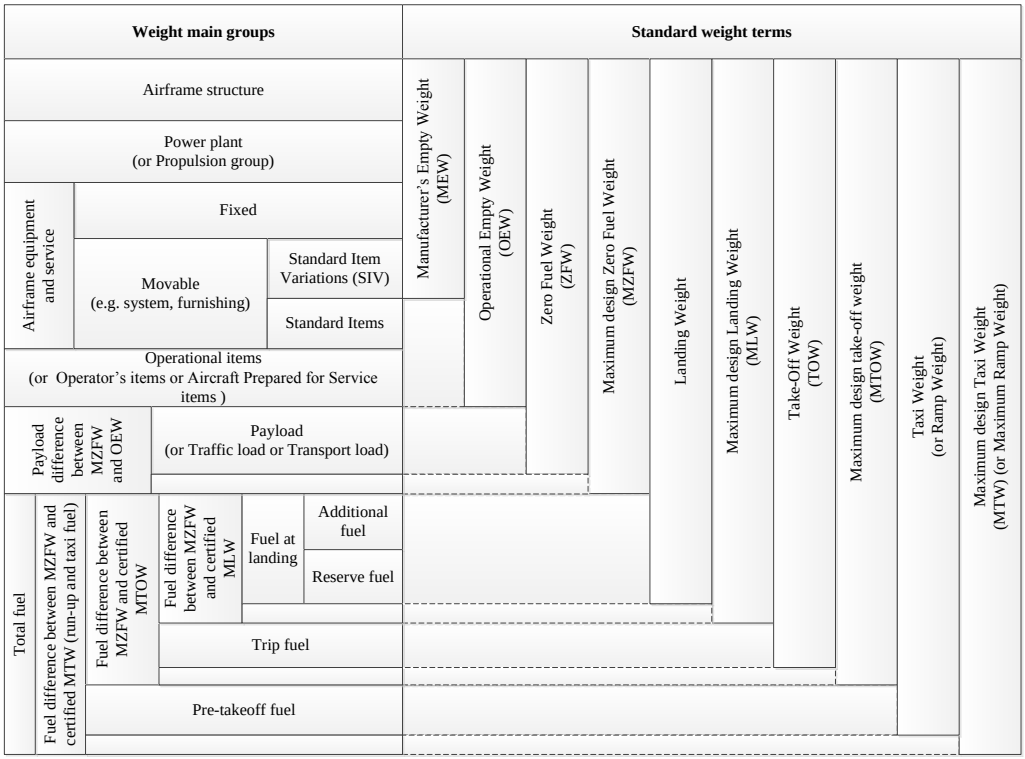


Figure D.1: Weight main groups and standard weight terms

Weight main groups

Airframe structure can be subdivided into wing group, fuselage group, tail group, landing gear group and engine nacelle group [280][339].

Power plant (or propulsion group) refers to the engine(s), items associated with engine installation and operation, the fuel system, and thrust reversing provisions [339].

Airframe equipment and service: Auxiliary Power Unit(s) (APU(s)) (are occasionally considered as operational items), instruments, the hydraulic, electric and electronic systems, furnishings and equipment, air-conditioning, anti-icing systems and other equipment. It is further subdivided into fixed and removable equipment and service [339].

Fixed equipment and service are considered an integral part of a particular aircraft configuration. Those include the weight of fixed ballast (if present) and the fluids which are contained in a closed system (such as hydraulic fluid) [339].

Movable equipment and services are those items of equipment or system fluids that are not considered an integral part of a particular aircraft configuration. E.g. removable separating walls, passenger seats (are occasionally considered as operational items), floor covering, basic emergency equipment and so on [339]. It can be subdivided into standard items and standard items variations [339].

Standard items are those equipment and system fluids defined on the basis of the aircraft type and generally do not vary for the same aircraft type [339].

Standard item variations are those items the operators choose to add to, omit from or change in the removable equipment and service items [339].

Operational items are the items of personnel, equipment and supplies that are necessary on a particular operations. Those items may vary for particular airplane configuration according to the operator's allowance for the service intended [339]. Depending on specific occasions, some of the movable equipment and service items can be shifted to the operational items. Operational items for a passenger aircraft include the unusable fuel, oil for engines, Integrated Drive Generator (IDG) and Auxiliary Power Unit (APU), water for galleys and toilets, chemical fluid for waste tank, aircraft documents and tool kits, passenger seats and life vests, galley structure and fixed equipment, catering movable and catering allowance, emergency equipment, crew and baggage, pallets and containers, additional centre tanks, ancillary parts, and specific airline items [280].

Payload is all commercial load which is carried: Passenger and their baggage, cargo and mail.

Total fuel are all usable fuel, engine injection fluids and other consumable propulsion agents. It can be subdivided into pre-take-off fuel, trip fuel, reserve fuel and additional fuel.

Pre-take-off fuel: Fuel consumed during engine run up and taxi prior to take off.

Trip fuel: Fuel consumed during flight between take-off and touch-down in the landing.

Reserve fuel: Operator determined fuel reserved according to relevant operational rules. It may be burnt during taxi after landing.

Standard weight terms

Manufacturer's Empty Weight (MEW): The weight of the airframe structure, powerplant installation and fixed equipment and service items. It is essentially a 'dry' weight excluding unusable fuel and oil, anti-icing fluid, potable waters and chemical in toilets [280].

Operational Empty Weight (OEW): The weight of the airplane without payload and fuel. The MEW plus the weight of operational items [339].

Zero Fuel Weight (ZFW): The OEW plus the payload [339].

Maximum Zero Fuel Weight (MZFW): The maximum weight of an aircraft less the weight of the total fuel load and other consumable propulsive agents in particular sectiosn of the aircraft that are structurally limited by this condition [339]. The OEW plus the maximum payload authorized (xz).

Take Off Weight: The total weight of a dispatch-loaded aircraft at the moment of brake release or start of the takeoff run.

Maximum Take Off Weight (MTOW): The maximum weight authorised at takeoff brake release [339]. The OEW plus the maximum payload and the maximum fuel weight authorized, which are related to the permissible load or maximum useful load. It is related to the structural requirements.

RAMP Weight: The Take Off Weight plus the weight of fuel required for engine run-up and taxiing prior to take off [339].

Maximum Ramp Weight (MRW): The maximum weight authorized/certified for ground manoeuvring prior to brake release in the takeoff [339]. The MTOW plus the maximum fuel authorized for engine run-up and taxiing prior to take off.

Landing Weight: The aircraft weight at the moment of touchdown in the landing [339].

Maximum Landing Weight (MLW): The maximum weight authorized at landing [339]. It is related to the structural requirements.

Maximum (In-)Flight Weight (MFW): the maximum weight at which flight other than takeoff and landing is permitted. The MFW and the MTOW are generally equal, except when provisions for refuelling in flight exist. The "flaps-up" condition is assumed, unless otherwise stated. Alternative term: maximum En Route Weight [339].

Aircraft Gross Weight (AGW): The total aircraft weight at any moment during the flight and ground operation [339] [127]. It equals the Take Off Weight at the moment of brake release, it is en-route eight or in-flight weight [339].

Operating Weight: the OEW plus the total fuel, but without payload. It is limited by the Usable Fuel Capacity:

Airframe Weight (AFW): MEW less the dry weight of the engines [84], which is the airframe structural weight plus the fixed equipment of the aircraft. AFW of the component is assumed as the airframe structural weight and the fixed equipment of the component.

Weight definitions for aircraft component

Foe aircraft component, a couple of weight definitions are clarified [280].

Primary weight: The weight of the primary structure. E.g. the weight of the fuselage shell.

Secondary weight: The weight of the secondary structure. E.g. the weight of the high lift devices.

Optimum weight: The weight which satisfies the structural requirements. E.g. the amount of the material required for the wing, tail or fuselage (sections) to carry the applied load.

Non-optimum (un-modelled) weight: The weight penalties due to joints, attachments, connections, etc.

Additional weight items: the non-optimum (un-modelled) weight and the secondary weight.

E

AIRFRAME MAINTENANCE COST REGRESSION FOR MATURITY FACTOR

The parameters, which are obtained from maintenance cost regression analysis, are employed to derive maturity factors, see Table E.1[304].

Table E.1: Parameters for maturity factors

		$Y_{AC} \leqslant 6$		$6 < Y_{AC} \leqslant 12$		$Y_{AC} < 12$	
		Coefficient	Standard error	Coefficient	Standard error	Coefficient	Standard error
α		-1.87536	0.08228	-1.87995	0.09164	-1.80564	0.12214
β		0.07163	0.01210	0.02257	0.00880	0.03129	0.00581
$\mu_{A/Ctype}$	707	0.22478	0.11730	0.17852	0.08107	-0.14894	0.18736
	720	0.22703	0.14818	0.42314	0.07424	dropped	
	727	omitted*		omitted		omitted	
	737	-0.54595	0.10586	0.27273	0.06356	0.00870	0.08134
	747	0.90606	0.09710	1.13689	0.05933	0.62362	0.07366
	757	-0.31000	0.08533	0.14365	0.05854	0.18106	0.15679
	767	0.11816	0.08948	0.49539	0.06162	0.30366	0.14460
	777	0.24788	0.09793	dropped**		dropped	
	A300	0.65845	0.15046	1.05599	0.11551	0.90570	0.18760
	A310	0.63369	0.18964	dropped		dropped	
	A319	-0.80272	0.12015	dropped		dropped	
	A320	-0.26374	0.09994	0.22572	0.11018	dropped	
	A321	-1.20979	0.24412	dropped		dropped	
	A330	0.62328	0.20846	dropped		dropped	
	BAC111	0.34264	0.15965	dropped		dropped	
	CV880	0.64639	0.25778	0.88500	0.11765	0.19516	0.31263
	CV990	0.71381	0.21434	dropped		dropped	
	CVR580	dropped		dropped		-0.24405	0.19667
	DC10	0.58595	0.09838	0.73812	0.06897	0.65285	0.05718
	DC8	0.16110	0.12940	0.47753	0.08207	0.16234	0.07604
	DC9	-0.05545	0.14354	0.28235	0.11074	-0.19167	0.07285
	F100	0.10131	0.15072	-0.09483	0.18865	dropped	
	L1011	0.72688	0.12683	1.10988	0.10269	0.65236	0.10953
	L188	dropped		0.67910	0.09219	dropped	
	MD11	0.45468	0.10722	0.92926	0.10706	dropped	
	MD80	-0.52539	0.12060	0.15581	0.07020	-0.06376	0.08595
	MD90	-0.27587	0.14066	0.83063	0.15824	dropped	
	SE210	-0.03726	0.25734	0.48311	0.13745	dropped	
	V700	dropped		0.19464	0.15630	-0.30959	0.31218
γ_{FY}	dropped						
ε	Alaska	dropped		0.41033	0.09234	0.13228	0.31671
	America West	0.54692	0.17104	0.45555	0.14549	0.61840	0.13351
	American	omitted		omitted		omitted	
	Continental	0.18028	0.10512	-0.05756	0.11928	0.42503	0.10067
	Delta	-0.10984	0.06274	-0.32579	0.05041	-0.11003	0.07301
	Northwest	-0.23605	0.07011	-0.24937	0.04484	-0.20826	0.06088
	Southwest	dropped		0.23486	0.12082	dropped	
	United	0.15949	0.06235	-0.08734	0.04554	0.00836	0.06082
	US Airways	-0.11766	0.13368	0.04794	0.10197	0.06446	0.10532

* Due to some data is missing in Form 41, the B727 aircraft type is omitted, fiscal year FY1986 is omitted, American airline is omitted.

** If no observations of the variable is available in the subsample, the variable is dropped from the regression.

F

THE OMG'S UNIFIED MODELING Language™ (UML)

The OMG's Unified Modelling Language™ (UML) helps engineers specify, visualize, and document models of software systems, including their structure and design, in a way that meets all of these requirements [340]

UML 2.5 defines two major groups of diagram types: Structure Diagram and Behaviour Diagram. Structure diagrams show the static structure of the objects in a system, while the Behaviour Diagrams shows the dynamic behaviour of the objects in a system [341]. The taxonomy of the UML diagram is shown in Figure F.1.

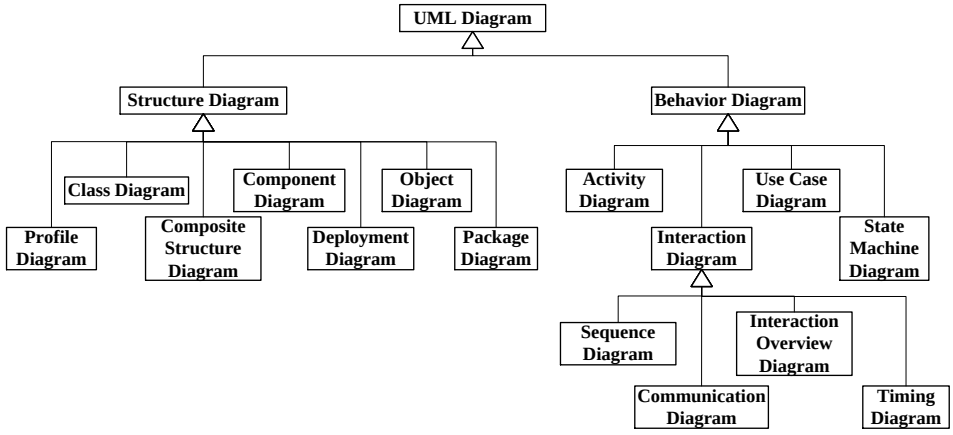


Figure F.1: The taxonomy of UML diagrams [341]

A summary of conventional UML notation of the diagrams used in this thesis is shown as follows (Note: The purpose of UML diagrams in the thesis is only for the illustration of

the integrated application framework, and it is not for demonstration of a rigorous software blueprint. Therefore, only conventional usages of the UML notation are adopted. Moreover, only frequently used notations are demonstrated, while there are more notations available in the OMG UML documentations [341] for comprehensive UML diagrams):

Class Diagram: It describes the static structure of the system or part of the system as related classes and interfaces. Class Diagrams are the building blocks of any object-orientated system. See Figure F.2, where:

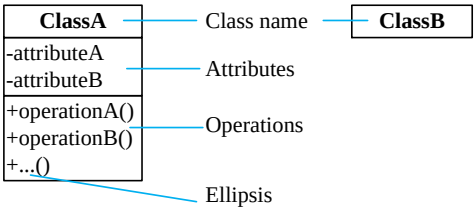


Figure F.2: Class example

- **Class**: It classifies a set of objects and specifies the features that characterize the structure and behaviour of those objects. It is shown using classifier symbol (e.g. ClassA). It can also be shown as a class with all compartments suppressed (with property and operation labels elided) for simplification purpose (e.g. ClassB);
- **Class name**: It is a single word or joint words with the first letter of each word in capital letter. Attributes: It indicates the structural features of a class. An attribute is a single word or joint words with the first letter in lower case while the first letters of the other words in capital letters.
- **Operations**: It signifies the behavioural features of a class. An operation is a single word or joint words with the first letter in lower case while the first letters of the other words in capital letters.
- **Ellipsis**: It is listed as the final element of attributes and/or operations, indicate that additional Features exist but are not shown in that list.

Generalization/Specialization: It is a taxonomic relationship between a more general classifier and a more specific classifier. Each instance of the specific classifier is also an instance of the general classifier. The specific classifier inherits the features of the more general classifier. A generalization is owned by the specific classifier.

Figure F.3 shows ClassB, ClassC and ClassD are generalized by ClassA (Or ClassA is specialized to ClassB, ClassC and ClassD). It can be interpreted as ClassB (or ClassC or ClassD) is a kind of ClassA (Or ClassA contains three kinds of objects - ClassB, ClassC and ClassD.

Generalization set: It provides a way to group generalizations into orthogonal dimensions (It groups the generalizations). All generalization relationships with the same Generalization set name are part of the same Generalization set (Figure F.3(a)). When two or more lines are drawn to the same arrowhead and labelled by a single Generalization set name,

i.e., “shared target” style (Figure F.3(b)). a GeneralizationSet may be designated by drawing a dashed line across those lines with separate arrowheads that are meant to be part of the same set (Figure F.3(c))).

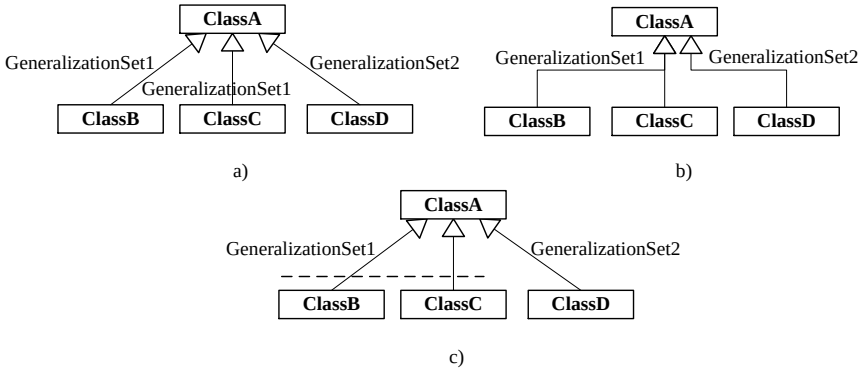


Figure F.3: Generalization example

Multiplicity: It indicates the number of the objects the class can have. For examples, “$*$” represents unlimited, “$1 \ldots *$” represents greater than 1 (including unbounded), “$0 \ldots 1$” represents 0 or 1.

Constraint: It represents a restriction that must be satisfied. It can be expressed by a text string in a formal language, a programming language or natural language. The constraint string is placed in a note symbol or attached to the constrained elements by dashed lines. The example shown in Figure F.4 implies both the length and the width have to be positive values. It can also be set in attributes list, see Figure F.5.

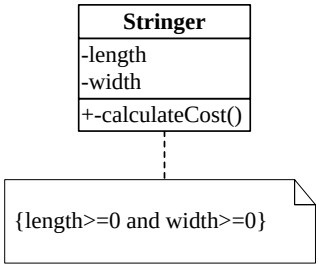


Figure F.4: Constraint in attached notes

Dependency: It indicates a directed relationship between model elements where the modification of a supplier may impact the client model elements. A dependency can be specified in keywords or stereotypes such as usage, abstraction and realization. It is shown as a dashed arrow between two model elements, which can be labelled with a keyword or stereotype name and a dependency name (optional). The client model element (the tail of the arrow) depends on the supplier model element (the arrowhead), see Figure 3. B. 6.

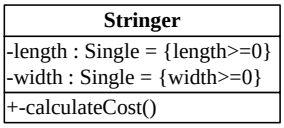


Figure F.5: Constraint in attribute example

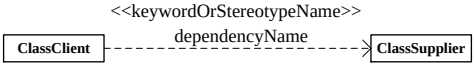


Figure F.6: Dependency

Association: It specifies a semantic relationship that can occur between typed instances. It declares that there can be links between instances whose types conform to or implement the associated types. Figure F.4 shows ClassA and ClassB are associated.

A **binary association** is normally drawn as a solid line connecting two classifiers, or a solid line connecting a single dlassifier to itself (the two ends are distinct).

The **association's name** can be shown as a name string near the association symbol, but not near enough to an **end** (see A or B in Figure F.4) to be confused with the end's name. It starts with upper-case letter.

The property string on an end (see endA and endB in Figure F.4), starts with lower-case letter. The end property of an association that is owned by an end indicates that the association is navigable from the opposite ends; otherwise, the Association is not navigable from the opposite ends. Navigability means that instances participating in links at runtime (instances of an Association) can be accessed efficiently from instances at the other ends of the association.

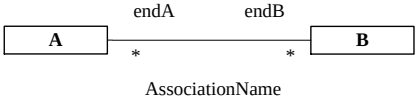


Figure F.7: Association example

A **n-ary** association is drawn as a diamond (larger than a terminator on a line) with a solid line for each association end connecting the diamond to the classifier that is the end's type (Figure F.8). The solid triangle with a tag indicate the order of reading: A dose C.

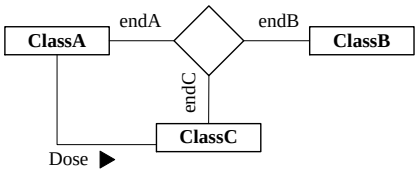


Figure F.8: Ternary Association Example

A **composite aggregation** indicates that a part object is included in at most one composite object at a time. If the composite object is removed, all of the its parts are deleted. It is drawn as an Association with a black diamond notation, which should be smaller than the n-ary association diamond, see Figure F.9.

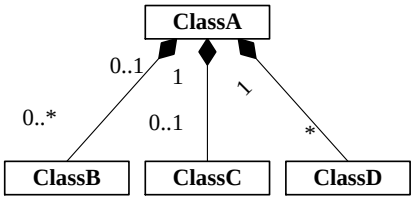


Figure F.9: Composite aggregation example

A **shared aggregation** shows that a part object is included in one or more composition object at a time. If the composite object is removed, its parts still exist. It is drawn as an association with a hollow diamond notation, , which should be smaller than the n-ary association diamond. Other notations such as multiplicity and navigability notation(e.g. dot, open arrowhead and x) can also be applied.

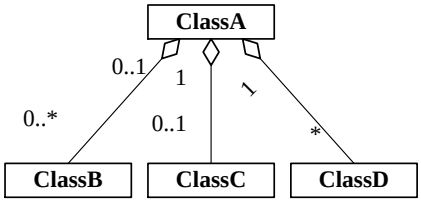


Figure F.10: Shared aggregation example

Activity Diagram: It displays the behaviors of the objects and the sequence of the operations implemented as a control and data flow model, where the **activity** is a kind of Behavior specified as sequencing of subordinate units. The example of Activity Diagram can be seen from Figure 3. B. 11. The notation of each symbol is explained as follows:

- An **activity node** represents an individual step in an Activity. It contains control node, object node and executable node;

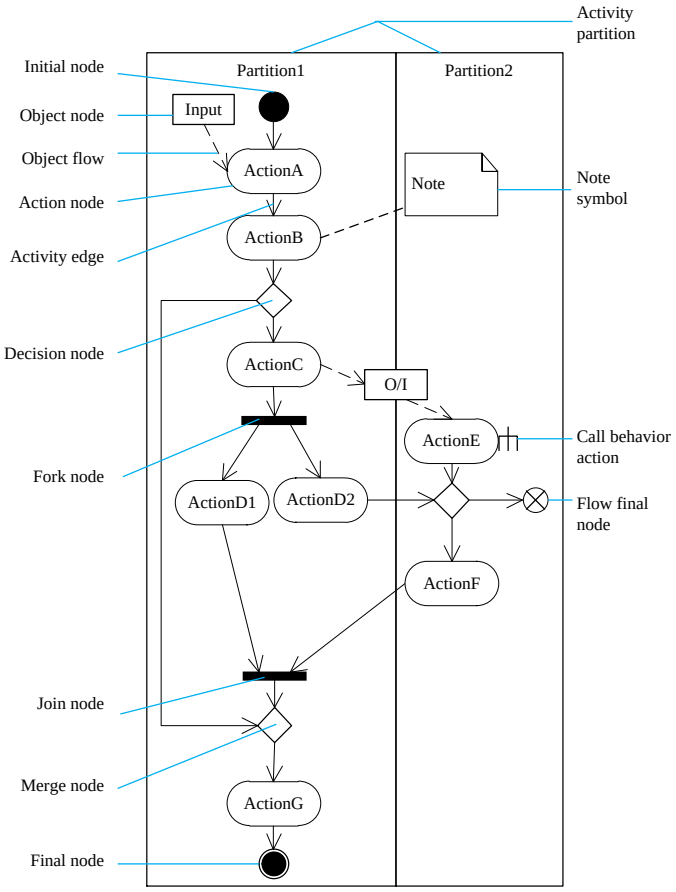


Figure F.11: Example of Activity Diagram

- A **control node** is used for the management the execution of the activity flow. It includes the initial node, final node, flow final node, fork node, join node, merge node and decision node;
- An **initial node** is a starting point for executing an Activity, and is noted as a solid circle;
- A **final node** terminates all flows in an Activity, and is noted as a solid circle within a hollow circle;
- A **flow final node** terminates a flow by aborting the activity flow offered to it other than terminate all flows in an Activity, and is noted as a circle with an "X" cross inside it;
- A **fork node** splits a flow into multiple concurrent flows. A join node synchronizes multiple flows;

- A **merge node** brings together multiple flows without synchronization. It is noted as a diamond-shape symbol and has two or more incoming activity edges and a single output activity edge;
- A **decision node** chooses between outgoing flows. It is also noted as a diamond-shape symbol and has a single incoming activity edge and multiple outgoing activity edges;
- An **action node**, is a kind of the executable node, and is drawn as rounded-cornered rectangle;
- An **object node** is used for the transmission of the object along with the activity flow. It includes the input and output parameters, buffer and data stores. It is drawn as a rectangle;
- An **object flow** carries data through an activity via their values, and is noted by a dashed arrow line connecting an activity node and an object;
- An **activity edge** is a directed connection between two activity nodes, and is noted by an open arrowhead line connecting two activity nodes;
- An **executable node** is a step being executed in the activity and noted as a rectangle with rounded corners;
- An **action node** is a specialised executable node;
- The **call behaviour** action indicates the action node can invoke an activity by its name. The call of an activity is indicated by placing a rake-style symbol within/beside the action symbol. The activity called can be elaborated in a series of actions;
- An **Activity partition** groups activity nodes that have some characteristics in common. It often corresponds to a specific stakeholder of activities in a model. An activity partition is denoted as a swim lane symbol;
- A **note** is a comment shown as a rectangle with the upper right corner bent. It can be connected with other elements such as an activity node, a control node and an activity edge by using a dashed line.

Use Case Diagram: It identifies the main system functions and shows the relationship between the external user(s) of the system and the main system functions. The system represents the subject of the use cases. Figure F.12 shows the example of the use case Diagram, where:

- **Use cas**e: It defines behaviours of the system without referencing to the internal structures of the behaviors and identifies the interactions between the actor and the system, so that to capture what a system is required to do in collaboration with one or more actors. An use case node is drawn as shown as an ellipse;
- **Actor**: It is one of the users or other systems which interacts with the system and is represented by a “stick man” icon;

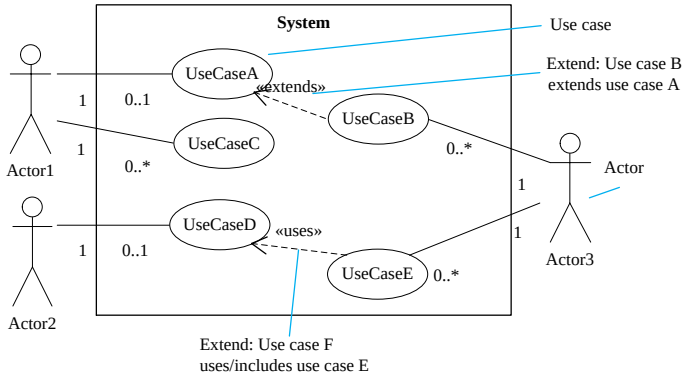


Figure F.12: Examnple of Use Case Diagram

- **Includes/Uses**: It indicates the relationship that the behaviour of the use case (the included use case) is inserted into the behaviour of another use case (the including use case). It is used when there are common parts of the behaviour of two or more use cases. It is shown by a dashed arrow with an open arrowhead pointing from the base use case to the included use case. The arrow is labelled with the keyword (include) or (use);

- **Extends**: It defines a relationship from an use case to be extended (extending use case) to an use case which has been extended (extended use case). It indicates that the behaviour in the extending use case will be inserted into the extended use case, which contains extra activities, to be executed. The extend relation is shown by a dashed arrow with an open arrowhead pointing from the extending use case towards the extended use case. The arrow is labelled with the keyword (extend).

G

COST ESTIMATION EXCLUDING FUDGE FACTORS

This appendix illustrates the results of the stiffened-panel RDT&E and Production cost estimation excluding the use of fudge factors. By comparing those results with the ones where the fudge factors are included, we can see that the influence of the fudge factor can introduce radical changes during decision making process, therefore, it is suggested to consider it carefully in practice.

G.1. RDT&E COST HIGH-LEVEL AND DETAIL-LEVEL MODEL

G.1.1. HIGH-LEVEL MODEL

Table G.1: Skin RDT&E cost distribution over cost element (high level model, excl. fudge factor)

Skin	RDT&E cost element ($)		
	Engineering	Tooling & equipment	Development support
♯1	398.1	268.8	46.7
♯2	747.1	504.4	87.5
♯3	234.4	158.3	28.0
♯4	439.9	297.0	52.5
♯5	220.3	148.8	26.3
♯6	413.5	279.2	49.4

G.1.2. DETAIL-LEVEL MODEL

G.2. PRODUCTION COST HIGH-LEVEL MODEL

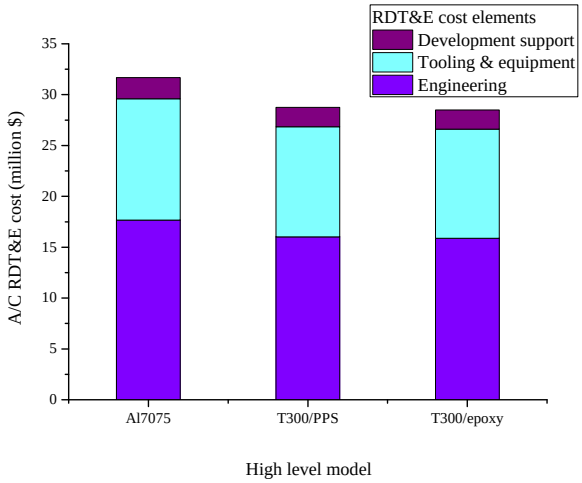


Figure G.1: A/C RDT&E cost (high level model, excl. fudge factor)

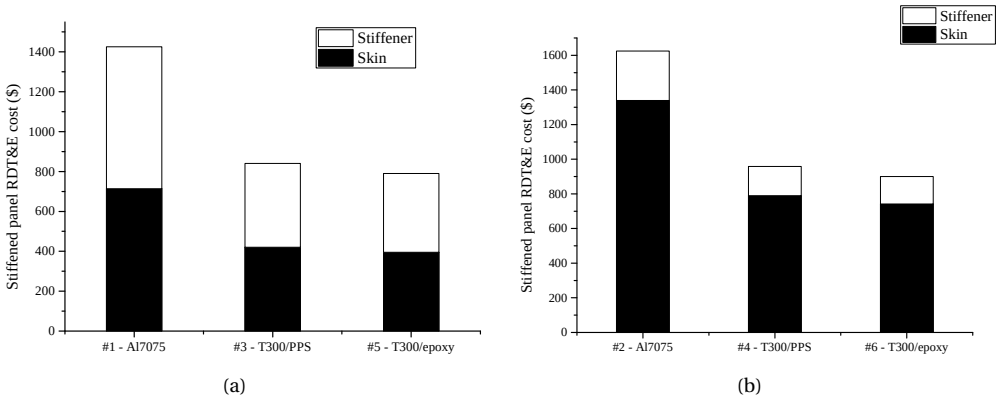


Figure G.2: Stiffened panel RDT&E cost distribution by parts (excl. fudge factor):(a)♯1,♯3,♯5;(b)♯2,♯4,♯6.

Table G.2: Stiffener RDT&E cost distribution over cost element (high level model, excl. fudge factor)

Skin	RDT&E cost element ($)		
	Engineering	Tooling & equipment	Development support
♯1	712.3	397.4	268.3
♯2	285.9	159.5	107.7
♯3	419.9	234.0	158.0
♯4	168.6	93.9	63.5
♯5	394.7	219.9	148.5
♯6	158.5	88.3	59.6

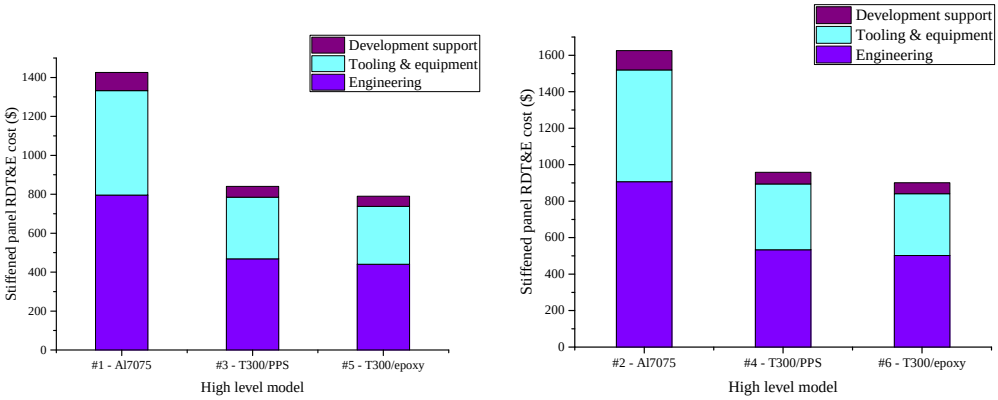


Figure G.3: Stiffened panel RDT&E cost distribution (high level model, excl. fudge factor):(a)♯1,♯3,♯5;(b)♯2,♯4,♯6.

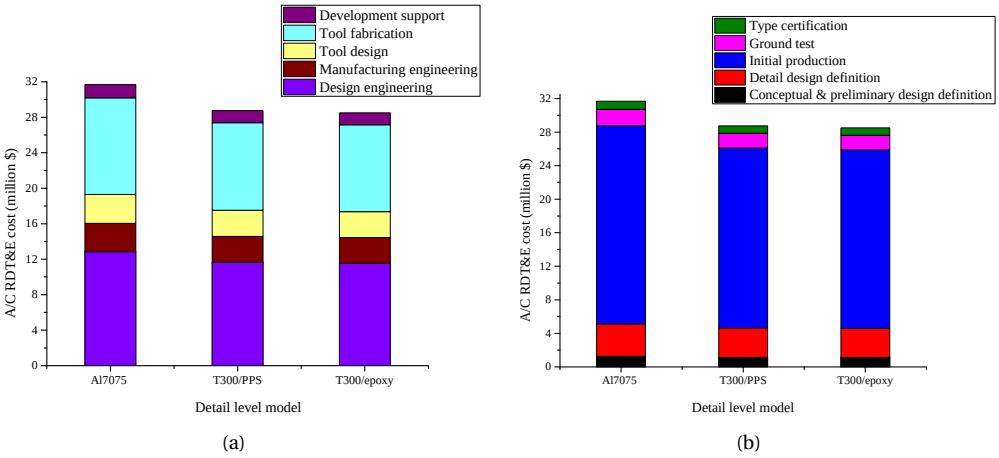


Figure G.4: A/C RDT&E cost (detail level model, excl. fudge factor):(a)Divided by cost elements; (b)Divided by process steps.

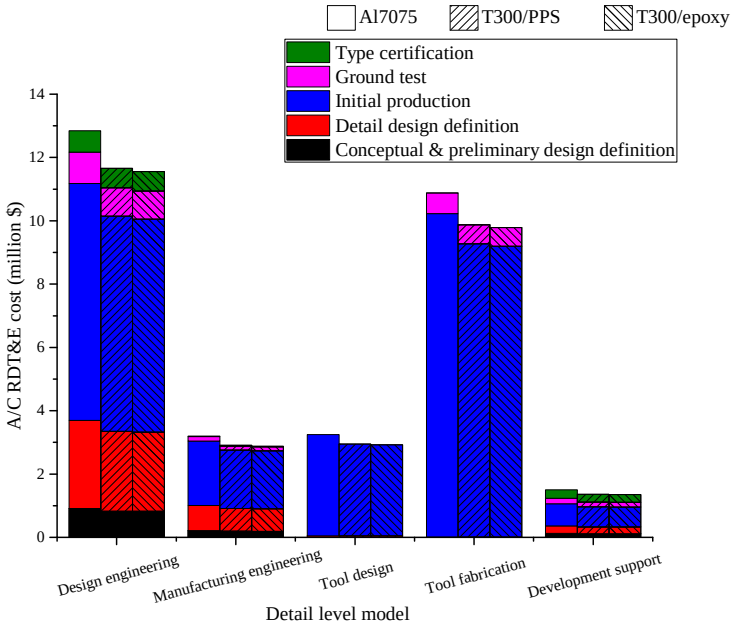


Figure G.5: A/C RDT&E cost distribution by cost elements (detail level model, excl. fudge factor)

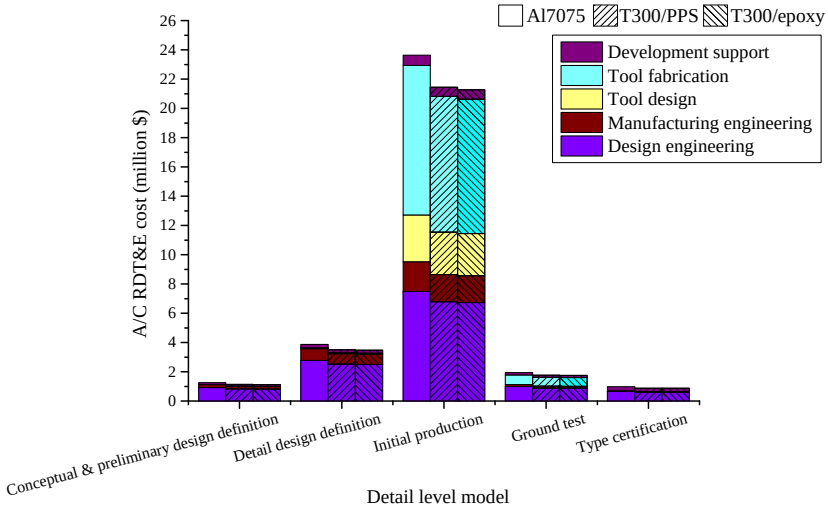


Figure G.6: A/C RDT&E cost distribution by process steps (detail level model, excl. fudge factor)

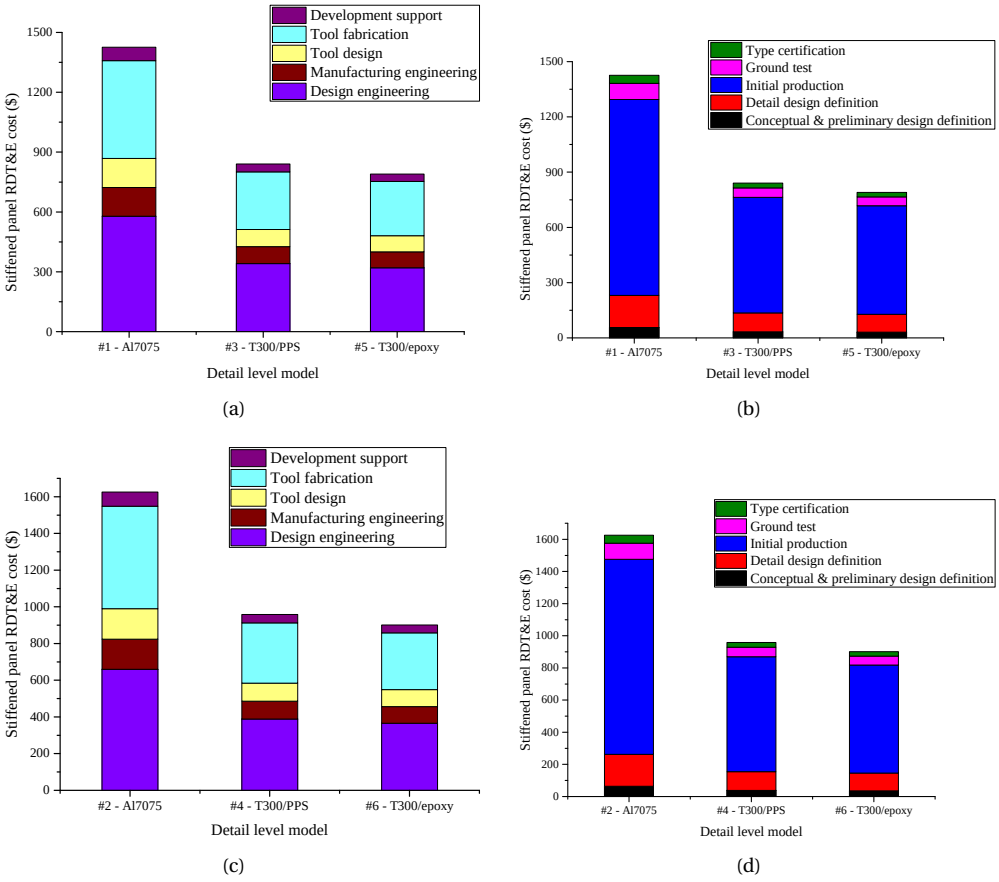


Figure G.7: Stiffened panel RDT&E cost distribution (detail level model, excl. fudge factor): (a)divided by cost elements (♯1, ♯3, ♯5); (b)divided by process steps (♯1, ♯3, ♯5); (c)divided by cost elements (♯2, ♯4, ♯6); (d)divided by process steps (♯2, ♯4, ♯6).

Table G.3: Skin RDT&E cost per cost element (excl. fudge factor)

Skin	RDT&E cost element ($)				
	Design engineering	Manufacturing	Tool design	Tool fabrication	Development support
♯1	289.4	72.1	73.2	245.1	33.8
♯2	543.1	135.4	137.3	460.0	63.4
♯3	170.6	42.5	43.1	144.5	19.9
♯4	320.2	79.8	80.9	271.2	37.4
♯5	160.4	40.0	40.5	135.8	18.7
♯6	301.0	75.0	76.1	254.9	35.1

Table G.4: Skin RDT&E cost per process step (excl. fudge factor)

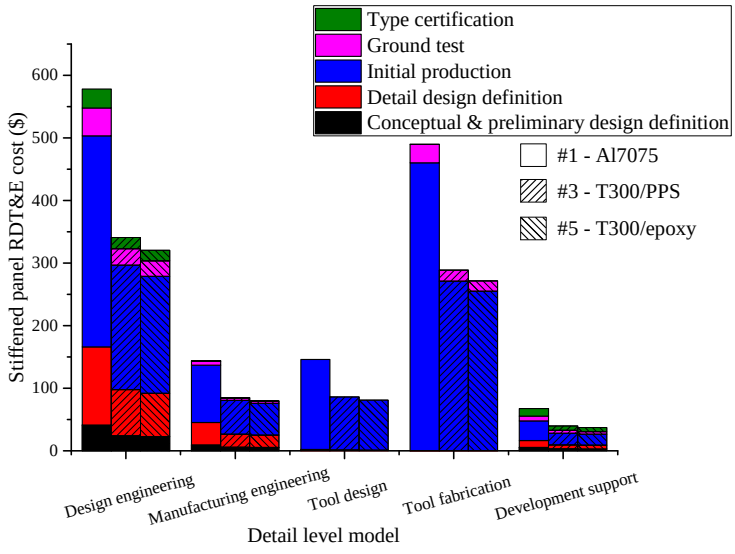
Skin	RDT&E cost element ($)				
	Conceptual & preliminary design definition	Detail design definition	Initial production	Ground test	Type certification
♯1	28.2	87.1	532.5	43.9	21.9
♯2	52.9	163.5	999.2	82.4	41.1
♯3	16.6	51.4	313.9	25.9	12.9
♯4	31.2	96.4	589.1	48.6	24.2
♯5	15.6	48.3	295.1	24.3	12.1
♯6	29.3	90.6	553.7	45.6	22.8

Table G.5: Stiffener RDT&E cost per process step (excl. fudge factor)

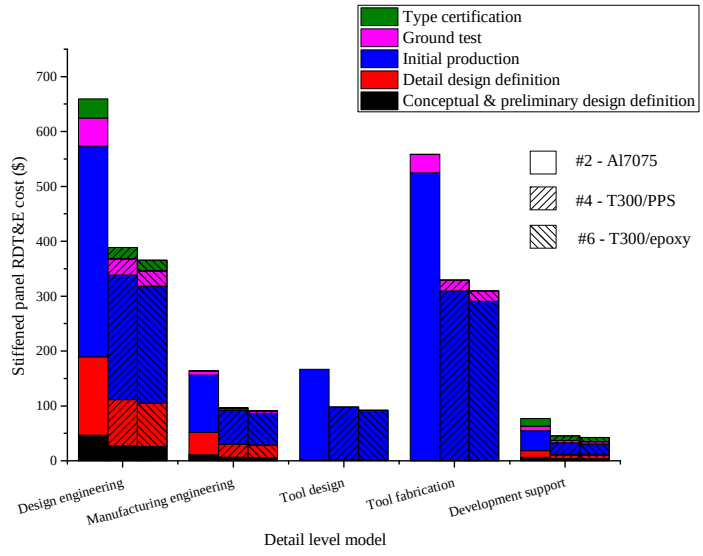
Stiffener	RDT&E cost element ($)				
	Conceptual & preliminary design definition	Detail design definition	Initial production	Ground test	Type certification
♯1	288.9	72.	73.1	244.7	33.7
♯2	116.0	28.9	29.3	98.2	13.5
♯3	170.3	42.5	43.1	144.3	19.9
♯4	68.4	17.0	17.3	57.9	8.0
♯5	160.1	39.9	40.5	135.6	18.7
♯6	64.3	16.0	16.2	54.4	7.5

Table G.6: Stiffener RDT&E cost per process step (excl. fudge factor)

Skin	RDT&E cost element ($)				
	Conceptual & preliminary design definition	Detail design definition	Initial production	Ground test	Type certification
♯1	28.1	87.0	531.5	43.8	21.9
♯2	11.3	34.9	213.4	17.6	8.8
♯3	16.6	51.3	313.4	25.8	12.9
♯4	6.7	20.6	125.8	10.4	5.2
♯5	15.6	48.2	294.5	24.3	12.1
♯6	6.3	19.4	118.3	9.8	4.9

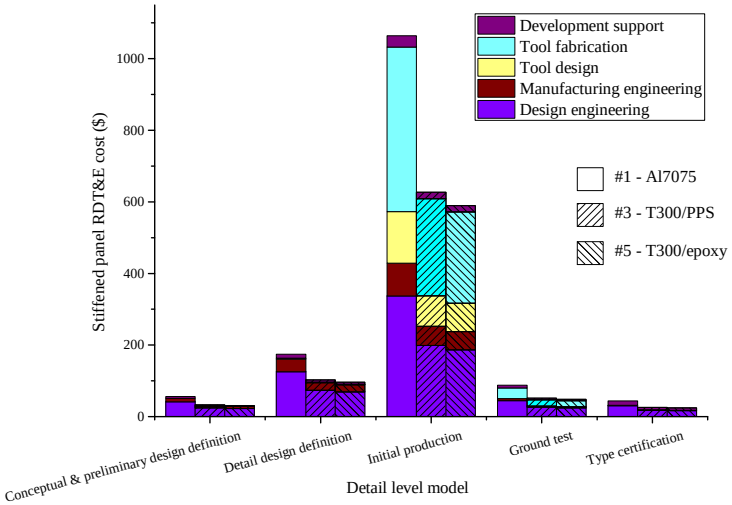


(a)

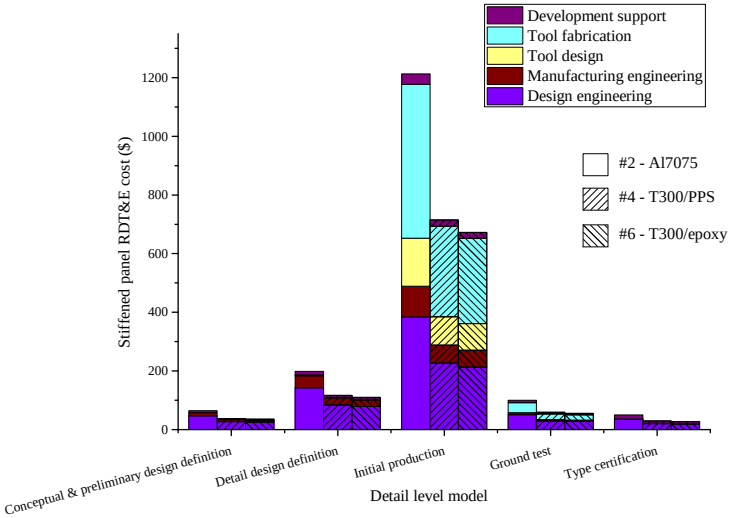


(b)

Figure G.8: Stiffened panel RDT&E cost distribution by cost elements (detail level model, excl. fudge factor): (a)divided by cost elements (♯1, ♯3, ♯5); (b)divided by process steps (♯1, ♯3, ♯5); (c)divided by cost elements (♯2, ♯4, ♯6); (d)divided by process steps (♯2, ♯4, ♯6).



(a)



(b)

Figure G.9: Stiffened panel RDT&E cost distribution by cost elements (detail level model, excl. fudge factor): (a)divided by cost elements (♯1, ♯3, ♯5); (b)divided by process steps (♯1, ♯3, ♯5); (c)divided by cost elements (♯2, ♯4, ♯6); (d)divided by process steps (♯2, ♯4, ♯6)

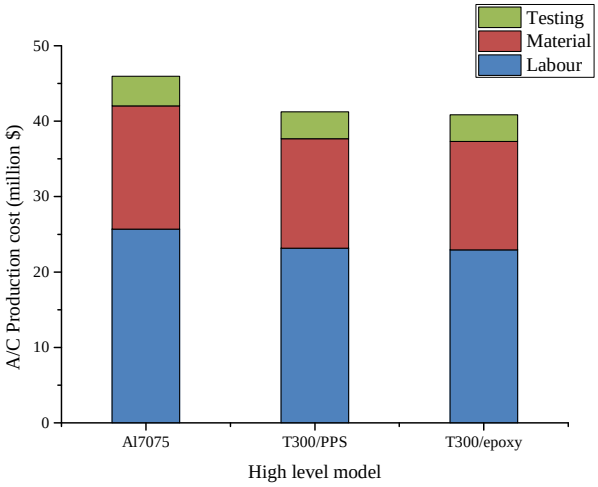


Figure G.10: A/C Production cost (high level model, excl. fudge factor)

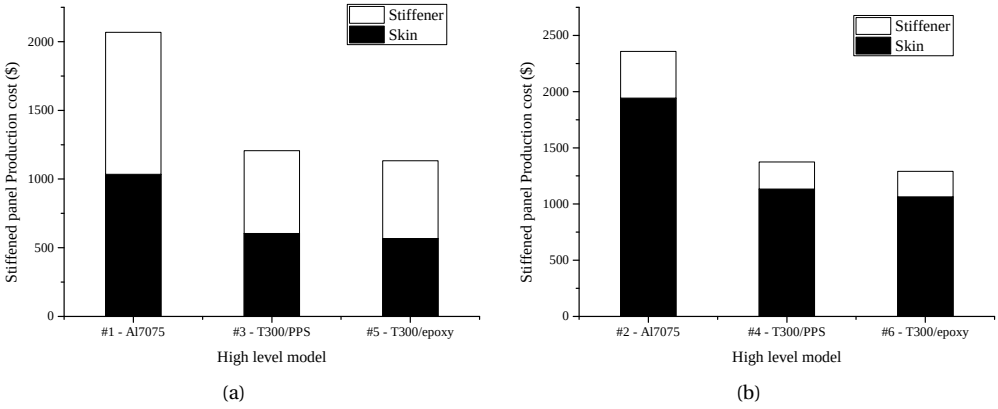


Figure G.11: Stiffened panel Production cost distribution by parts (excl. fudge factor)

Table G.7: Skin Production cost distribution over cost elements (high level model, excl. fudge factor)

Skin	Production cost element ($)		
	Labour	Material	Testing
♯1	578.5	367.8	88.8
♯2	1085.6	690.3	166.6
♯3	338.8	212.7	52.1
♯4	635.8	399.1	97.8
♯5	318.3	199.6	49.0
♯6	597.3	374.5	91.9

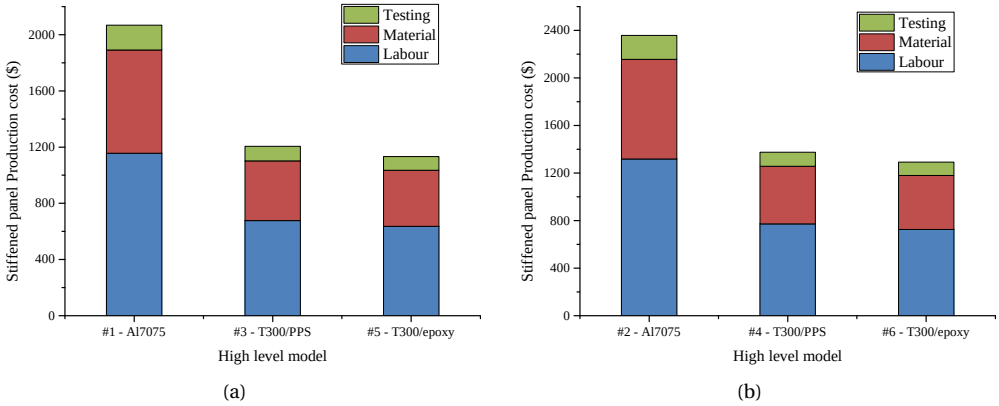


Figure G.12: Stiffened panel production cost distribution (high-level model, excl. fudge factor):(a)♯1, ♯3, ♯5; (b)♯2, ♯4, ♯6

Table G.8: Stiffener Production cost distribution over cost elements (high level model, excl. fudge factor)

Skin	Production cost element ($)		
	Labour	Material	Testing
♯1	577.5	367.2	88.6
♯2	231.8	147.4	35.6
♯3	338.8	212.3	52.0
♯4	135.8	85.2	20.9
♯5	317.7	199.2	48.9
♯6	127.5	80.0	19.6

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LIST OF PUBLICATIONS

1. **X. Zhao**, W.J.C. Verhagen, and R. Curran, *Estimation of Aircraft Component Production Cost Using Knowledge Based Engineering Techniques*, Advanced Engineering Informatics,vol.29, no.3, pp.616-632, 2015 doi:10.1016/j.aei.2015.05.004.

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