Development of a Life Cycle Cost Model for Conventional and Unconventional Aircraft

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Master of Science Thesis

TU Delft Delft University of Technology

Challenge the future

Development of a Life Cycle Cost Model for Conventional and Unconventional Aircraft

by

S.O.L. Zijp

June 26, 2014

in partial fulfillment of the requirements for the degree of

Master of Science
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First of all, I would like to thank my direct supervisor dr. ir. Roelof Vos. His courses on aircraft design are the best I have had in my entire study and inspired me to graduate under his supervision. Although costs are not directly his specialty he was able to put me in contact with people at the faculty who did. Moreover, the discussion we had and the critical questions asked contributed to the result of this research. My second supervisor, dr. ir. Wim Verhagen from the Master Program Air Transport and Operations was a great source of help with respect to cost engineering. His theoretical knowledge contributed to my background knowledge on cost engineering and showed great feedback on the methods selected for the cost model.

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My years as a student has come to an end and looking back I realize I have to thank a lot of people who made this an enjoyable ride. Especially during my thesis research their support and distraction kept me motivated. Especially the students from *Kamertje 1* which whom I worked together in the same room with caused plenty of laughter.

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Abstract

Due to the recent economic crisis, ever rising fuel prices and government regulation to lower emissions, aircraft will need to be more cost and fuel efficient. Unconventional aircraft like canard aircraft, three-surface aircraft and prandtl plane have the potential to be more efficient compared to conventional aircraft. In order to prove that a design is cost efficient the Life Cycle Cost (LCC) needs to be analyzed and should be done as early in the design phase as possible. The latter is due to the fact that 70% of the total Life Cycle Costing (LCC) is already fixed after the conceptual design phase. At the conceptual design phase it is difficult to give an absolute cost estimate, hence the focus of this research is to develop a model that estimates the relative cost and therefore allows for design trade-off.

This research investigates cost estimation methods applicable at the conceptual design phase and to all configurations. Two methods are selected and implemented in the Initiator design tool of the department of Flight Performance and Propulsion to assess the cost of an aircraft design. The first method is a top-down estimation method based on regression analysis of historical aircraft. The second is denoted bottom-up and uses existing parametric relations. The cost estimation module in Initiator is developed from the perspective of the manufacturer. The LCC cost components computed by both methods are: Non-Recurring Cost (NRC), Recurring Cost (RC), Unit Cost, list price, Direct Operating Cost and Indirect Operating Cost. Furthermore, for the manufacturer the Nett Present Value and quantity of aircraft for break-even are determined.

In order to analyze different configurations a so called Non Communality Factor (NCF) is introduced. It expresses the level of innovation of a design with respect to conventional configurations. Per aircraft part a NCF is provided which results in a factor for the overall aircraft and directly influences the NRC. The NCF factor also allows to asses a family of aircraft with respect to the NRC.

Both methods are verified using commercial cost estimation software. It is shown that both methods are able to give a relative cost estimate. The bottom-up method was qualified as best method since it showed more realistic behavior for RC and provides cost information per aircraft component. The cost of both methods are underestimated mainly due to low weight estimates of the aircraft designed by the design tool. The bottom-up method has more potential to give more accurate results in the future.

Based on this preferred method proof exist that the canard aircraft offers the lowest LCC, although differences with conventional aircraft are low. The three-surface aircraft is slightly more expensive and prandtl plane showed the highest LCC. The low LCC obtained for the canard aircraft implies that the aircraft is a potential win for both manufacturer and operator.

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GLOSSARY

A€	Actual Euro
AC	Acquisition Cost
ABC	Activity Based Costing
AMP	Aircraft Market Price
ANC	Airline Net Cash flow
APU	Auxiliary Power Unit
ASM	Available Seat Mile
BAe	British Aerospace
BOM	Bill Of Materials
BWB	Blended Wing Body
CAD	Computer Aided Design
CBR	Case Based Reasoning
CEF	Cost Escalation Factor
CER	Cost Estimating Relationship
CFD	Cash Flow Diagram
CTA	Cost/Time Analysis
DACE	Dutch Association of Cost Engineers
DEE	Design and Engineering Engine
DFA	Design for Assembly
DFM	Design for Manufacturing
DOC	Direct Operating Cost
DOIS	Date of Initial service
DSS	Decision Support System
DTC	Design to Cost
EAC	Estimation at Completion
EBU	Engine Build Unit
EOM	Empty Operating Mass
ESA	European Space Agency
ESPPF	Engine Spare Part Price Factor
FBC	Feature Based Costing

FPP	Flight Performance & Propulsion
FUC	First Unit Cost
HT	Horizontal Tail
ICA	Institute of Cost Analysis
ICEAA	International Cost Estimating and Analysis Association
ICEC	International Cost Engineering Council
IOC	Indirect Operating Cost
ISPA	International Society of Parametric Analysis
KBE	Knowledge Based Engineering
LCC	Life Cycle Costing
LP	List Price
MLM	Maximum Landing Mass
MFM	Mission Fuel Mass
MMG	Multi Model Generator
MPFM	Maximum Payload Fuel Mass
MTOM	Maximum Take-Off Mass
MZFM	Maximum Zero Fuel Mass
NASA	National Aeronautics and Space Administration
NCF	Non Communality Factor
NES	National Estimating Society
NGO	Non Governmental Organization
NPV	Nett Present Value
NPW	Nett Present Worth
NRC	Non-Recurring Cost
O&M	Operating & Maintenance
PA	Parametric Analysis
PP	Prandlt Plane
RC	Recurring Cost
R€	Real Euro
RAND	Research and Development
RDT&E	Research, Development, Testing & Evaluation
RFP	Request for Proposal
RMSE	Root Mean Squared Error
ROI	Return on Investment

ROM	Rough Order Magnitude
RPK	Revenue Passenger Kilometer
RPM	Revenue Passenger Mile
SCEA	Society of Cost Estimating and Analysis
SE	Standard Error
SFC	Specific Fuel Consumption
SIG	Special Interest Group
SPF	Super Plastic Forming
TAW	Tube and Wing
TFUC	Theoretical First Unit Cost
TOC	Total Operating Cost
TSA	Three Surface Aircraft
UC	Unit Cost
UPC	Unit Production Cost
VLA	Very Large Aircraft
VT	Vertical Tail
WBS	Work Breakdown Structure
XML	Extensible Markup Language

Latin Symbols

$\bar{f}$	Average inflation rate	$[-]$
A_{rev}	Annual revenue	$[US\$]$
b	Learning curve exponent	$[-]$
C_{D0}	Zero lift drag coefficient	$[-]$
C_{mat}	Material cost	$[US\$]$
D	Depreciation value	$[US\$]$
D	Discount	$[US\$]$
d	Diameter	$[m]$
E	Earnings	$[US\$]$
F	1. Fuzzy set, 2. Factor	$[-]$
f	Membership function	$[-]$
I	Annual interest	$[US\$]$
I	Investment cost	$[US\$]$
i	Annual interest rate	$[US\$]$
Inv_{init}	Initial investment	$[US\$]$
l	Length	$[m]$
L/D	Lift over drag ratio	$[-]$

MHR	Man hours	$[-]$
N	Number of items in subscript	$[-]$
n	1. Number of data points 2. Number of years for interest calculation	$[-]$
P	Price	$[US\$]$
pr	Production rate	$[-]$
PV	Price per volume	$[US\$/l]$
Q	Batch size	$[-]$
R	1. Range [nm] 2.Salary rate [US$/hour]	$[-]$
r	Labor rate	$[US\$/hr]$
R_m	Machine rate	$[-]$
R_o	Operator's rate	$[-]$
S	Surface	$[m^2]$
S_{value}	Salvage value	$[US\$]$
$T_{initial}$	Time required for the first production unit	$[s]$
T_{no}	Non-productive time	$[s]$
T_N	Time required for the Nth production unit	$[s]$
T_{ot}	Operation time time	$[s]$
T_{su}	Setup time	$[s]$
w	Width	$[m]$
w_{ij}	Connection weight between two neurons	$[-]$
x	Value of an element in the domain of f	$[-]$
X_i	input variable for neural networks	$[-]$

Greek Symbols

θ_{ij}	1. Bias term for a given neuron. 2 Median in normal distribution.	$[-]$
α^2	Variance in normal distribution	$[-]$
μ	Value of f at x	$[-]$
ν	Degree of freedom for student t-distribution	$[-]$

Subscripts

ac	Aircraft
aed	Airframe Engineering and Design
af	Airframe
amb	Applied maintenance burden
app	Approach
assy	Assembly
av	Avionics
bel	Beltramo's method
bl	Block
cad	Computer added design
ca	Cabin attendant
cb	Carbon brakes

cb	Connector
co	Co-pilot
cp	Cockpit
cr	Cruise
ctr	Controls
c	Chord
c	Cowl
depr	Depreciation
des	Design
diff	Degree of complexity
dom	Domestic
dst	Development Support and Testing
econ	Economy class
eng	Engineering
etr	Engine exhaust thrust reverser
e	Engine
fca	Freight commission and advertising
fe	Flight engineer
fin	Finance
first	First class
fo	Fuel and Oil
fr	Freight
fs	Fuel system
fta	Flight Test Airplanes
fto	Flight Test Operations
ftr	Fan thrust reverser
f	Fuselage
ga	General and administrative
ht	Horizontal tail
h	Handling
infl	Inflation
int	International
kts	Knots
lab	Labor
lf	Landing fees
lg	Landing gear
lh	Load handling
lp	Low pressure
max	Maximum
mt	Maintenance
nc	Nacelle
pax	Passengers
pneu	Pneumatics
prop	Propeller
pro	Profit
pu	Power unit

py	Pylon
rc	Regression coefficients
rev	Revenue
sp	Spares
st	Static test
sys	System
s	Static
td	Top-down
temp	Temporary
to	Take-off
tsf	Test and Simulation Facilities
vt	Vertical tail
w	Wing

1
INTRODUCTION

The technical life cycle of a product can be represented by an *S-curve*. In the beginning of the product life cycle, technology changes slowly due to a lack of understanding and applications. As these increase the potential of that technology increases rapidly and the technology can be exploited in all possible ways. Finally, only minor improvements can be made to the technology and new applications are scarce. At that point, the technology is often disposed of and replaced by a new technology. The medium for storing music for example changed from LPs to tapes, from tapes to CDs and nowadays people stream music from the internet. At this point in time, current aircraft design is said to be at the end of its S-curve and engineers strive to develop new aircraft designs that adhere to market demand [24].

With the recent economic crisis and government regulation to lower emissions, aircraft will need to be more cost and fuel efficient [49]. A more economically viable aircraft is one that has reduced cost and is profitable for both manufacturer and operator. Hence, the LCC of an aircraft should be monitored. For new aircraft designs the LCC has to be estimated as early as possible. This is due to the fact that 70% of the LCC is already fixed during early design phases [22].

1.1. GLOBAL MARKET FORECAST

The aircraft industry is growing. In 2012 there were over 16,000 passenger aircraft and 1,600 freight aircraft in service. The market demand was close to 5.5 trillion RPK. In 2032 this demand will more than double to 13.9 trillion RPK. In order for airlines to meet this demand they can relay on aircraft currently in fleet, however new aircraft need to be ordered as well. By 2030 a total of 33,700 passenger and 2,900 freight aircraft will be delivered by the manufacturers. For passenger aircraft the total aircraft in service will double. Over 20,000 single-aisle aircraft will need to be produced. For twin-aisle aircraft this is 7,300 and 1,700 for Very Large Aircraft (VLA) like the Airbus A380. The total market value of this forecast is US$ 4.4 trillion and aircraft manufacturers compete to get the largest market share [49].

The world can be segmented in regions either having an emerging or a mature economy. North America, Western Europe and Japan are classified as mature others as emerging. The growth in yearly demand for RPK is 6% for the emerging regions compared to the 4% for mature economies. Nowadays, emerging economies represent 39% of the world wide passengers and aircraft in service. In 2030, this will increase to 54%. Hence, airlines and manufacturers focus on these emerging economies as well [49].

It is interesting to see that the demand for air travel is resilient to external shocks. Since the attack on the World Trade Center in New York in 2001, annual travel has increased by 67%, see Figure 1.1. In this period the market did suffer from small set backs due to the outbreak of SARS in 2003 and the financial crisis in 2008. The aircraft demand has also overcome multiple oil crises.

In general, the main drivers for air travel growth and thus for aircraft demand are [49]:

- Aviation will be more at the center of people's journeys.
- Growth in the world's population. People will become more wealthy and life in bigger cities.
- Growth of emerging markets. There will be more first time flyers. The middle class will grow from 2.2 billion in 2012 to 5.2 billion in 2032.

- Governments will continue to allow more liberalization, particularly in Asia, Africa and Latin America.
- Replacement of old, less eco-efficient aircraft.
- Growth in number of so called Aviation mega-cities, driving the demand for VLA.

It is obvious that there is a market demand for a range of aircraft. Unconventional design could play a role in the future especially since there is a growing demand for more fuel efficient aircraft due to the continuous rise in fuel prices. However, more research is required to prove that the proposed configurations are realistic from a economic point of view.

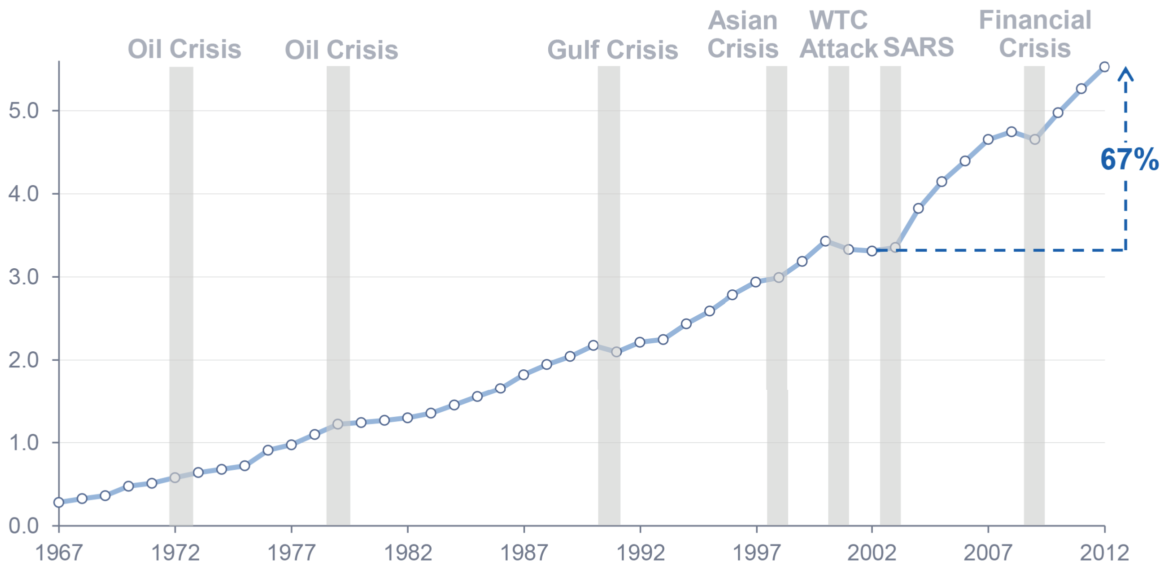


Figure 1.1: World annual traffic (in trillionRPK) [49].

1.2. INITIATOR

In line with the demand for more efficient aircraft the faculty of Aerospace Engineering at Delft University of Technology develops a new aircraft design tool called Initiator. The origin of the Initiator design tool lies within the Design and Engineering Engine (DEE), also developed at Delft University of Technology [46]. Initiator requires high level inputs: range, passengers, maximum take-off weight, cruise Mach number, landing and take-off distance and cruise altitude [29]. It consists of several modules that evaluate a design's aerodynamics, estimate weights and determine the aircraft's performance.

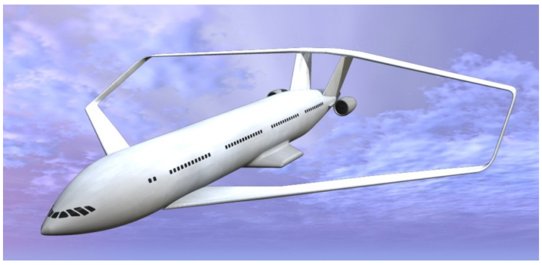
At this point, no module is available in Initiator that is able to give an economic analysis on the costs of the aircraft designed. The development of such a module is the main goal of the research presented. The module fully depends on results obtained from prior modules since it will be integrated at the end of a design loop.

1.3. UNCONVENTIONAL CONFIGURATIONS

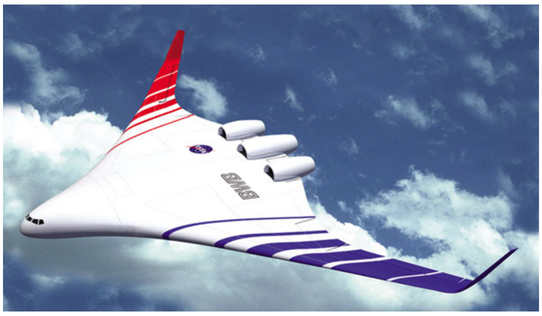
The Initiator design tool is able to design conventional and unconventional aircraft. The unconventional configurations considered are: canard aircraft, three-surface aircraft, prandtl plane and Blended Wing Body (BWB) aircraft. Examples of these configurations are shown in Figure 1.2. Their unique properties are discussed in short.

(a) Canard aircraft, Beechcraft Starship 2000 [1].

(b) Small three surface aircraft, Piaggo P.180 Avanti [3].



(c) Concept of a prandtl plane [32].



(d) Concept BWB aircraft, NASA [2].

Figure 1.2: Example of unconventional configurations

1.3.1. CANARD AIRCRAFT

The main difference between the canard aircraft and conventional aircraft is the positioning of the horizontal stabilizers. Conventional aircraft have them installed rear of the wing at the aircraft's tail. Both wing and horizontal stabilizer are positioned aft of the aircraft's center of gravity. In order to control longitudinal stability a negative lift is required to compensate the moment induced by the wing's lift force. For a canard aircraft the horizontal stabilizer is positioned in front of the wing and is denoted canard. Hence, the center of gravity is located between the wing and canard and thus a positive lift is required from the horizontal stabilizer to stabilize the aircraft. As a result, both lifting surfaces generate positive lift which is in contrast to conventional aircraft where the main wing needs to produce additional lift to compensate for the negative lift of the horizontal stabilizer. Hence, for the canard aircraft the induced drag decreases [29]. For large commercial aircraft the induced drag is 45-50% of the total aircraft drag [32]. With decreased drag less thrust is required from the engine and therefore this configuration has potential to consume less fuel .

1.3.2. THREE SURFACE AIRCRAFT

The three-surface aircraft is a combination of the conventional and canard aircraft. Two horizontal stabilizers are present, one in front of the main wing and the other aft of it. It allows for more design freedom since both are used to stabilize the aircraft [29]. This configuration has the same advantages as the canard aircraft with respect to induced drag. However, this depends on how the horizontal stabilizers are deflected. Often, this configuration has a T-tail and the canard installed on the bottom side of the fuselage to prevent interference between the three lifting surfaces.

1.3.3. PRANDLT PLANE

The theory behind the prandtl plane configuration dates back to 1924 [58]. According to Ludwig Prandtl a box-like configuration results in a lifting system with the lowest induced drag possible. This system is denoted *Best wing system.* The characteristic principle of the prandtl plane is the equal lift distribution of front and rear wing and the butterfly shaped lift distribution on the vertical wing tips [32]. The latter are denoted connectors in this thesis report. For the condition of minimum induced drag, the induced velocities by the free vortices are constant along the span of both front and rear wings and zero for the connectors. This condition is called Munk's condition for minimum induced drag. The gap between both wings is key in achieving high efficiency.

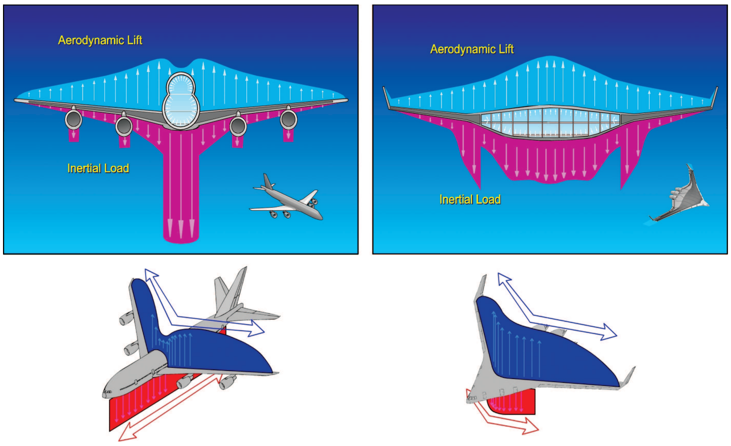


Figure 1.3: Comparison of aerodynamic, inertial and cabin pressure loads [50].

The induced drag decreases if the gap-to-span ratio increases [32]. In honor of the early identification of the Best wing system this configuration is denoted Prandtl Plane.

1.3.4. BLENDED WING BODY

The BWB aircraft is like a flying wing. The fuselage and wings blended into each other, hence the name. The fuselage has the shape of an airfoil and therefore generates lift like the wings. Also, since the fuselage is wider, compared to conventional aircraft, the fuselage is shorter for the same amount of passengers. Both features result in a change in loading and moments that apply on the aircraft. For conventional aircraft the fuselage is loaded in perpendicular direction of the wings, hence more structural stiffness is required and therefore the weight increases. For BWB aircraft the fuselage is loaded in the same direction as the wings and the loading is more equally distributed. The entire principle is shown in Figure 1.3. With this type of loading the aircraft can become lighter and thus more fuel efficient. One of the challenges of the BWB concept is defining a pressurized cabin. The more oval fuselage is not as resistant to internal pressure as conventional cylindrical fuselages. Without this implementation the concept is not applicable to commercial passenger aircraft yet [50].

1.4. OBJECTIVE

The goal of this research is the development of a module that is able to estimate the life cycle cost of an aircraft. The objective of this research is formulated as follow:

"The development of a life cycle cost estimating model that provides a relative cost estimate to perform a design trade-off between different aircraft configurations at the end of the conceptual design phase."

Three sub goals are formulated which combined form the overall goal:

1. Investigate which cost estimating method can be used that is applicable to conventional and unconventional aircraft.
2. Implement and verify the selected methods .
3. Analyze the performance of the cost estimating method by a selection of case-studies. These case-studies are:
    - Sensitivity analysis with respect to prominent parameters of the model.
    - Trade-off between aircraft configurations.
    - Application of the model to a family of aircraft.

It should be noted that the objective is formulated from the perspective of the manufacturer. Manufacturing costs should prove that an aircraft is economically viable for the manufacturer and operating cost should indicate that the design adheres to market demand.

Also the research focuses on relative costs and not absolute costs since the model is used to perform a design trade-off. Moreover, absolute costs are difficult to estimate at the conceptual design phase due to a lack of detailed product information [57].

1.5. RESEARCH QUESTION

In order to reach the objective a research question is formulated as follow:

"What cost estimation method can be used to develop a relative LCC model applicable for trade-off between conventional and unconventional aircraft at the end of the conceptual design phase?

Several sub-questions are formulated which help to answer the main research question:

1. What is Life Cycle Costing?
2. What type of cost estimating methods exist?
3. Which of these methods are applicable to conventional and unconventional aircraft?
4. Can the model be verified and thereby guarantee the quality of the relative cost estimates of the model?

1.6. MODEL REQUIREMENTS

The cost estimation model needs to adhere to several requirements:

1. The model needs to be compatible with conventional aircraft,canard, three-surface aircraft, prandtl plane an blended wing body aircraft.
2. The model needs to be sensitive with respect to design parameters.
3. The model needs to give a clear insight into the most important cost components: Non-Recurring Cost, Recurring Cost, Unit Cost, List Price, Direct Operating Cost and Indirect Operating Cost.
4. The model should be based on clear methods understandable to the user. They should be well documented and assumptions should be clearly stated.
5. The model should be independent of input data.
6. The model should be sensitive for economic changes such as inflation, labor rates and interest rates.

1.7. RESEARCH SCOPE

The scope can be summarized in a graph as shown in Figure 1.4. It shows three axis, one for all the design phases, one for the LCC phases and one for the aircraft configurations.

The disposal phase of the life cycle is not included in the scope. The cost of disposal is dependent on the strategy of the operator and can therefore not directly be related to the design of the aircraft. Moreover, as stated before the research objective is formulated from the perspective of the manufacturer.

1.8. REPORT STRUCTURE

The report kicks off with a literature review on cost engineering in Chapter 2. It focuses on the importance of LCC, estimating techniques and costs associated with aircraft manufacturing and operation. Chapter 3 presents the methodology used to develop the cost estimation model. Two different methods are selected which are implemented in the Initiator design tool. This implementation is explained in Chapter 4 along with guidelines on how to operate the cost estimation module. Chapter 5 verifies the model based on commercial software and collected data. Both methods are subjected to different design cases in Chapter 6. A baseline aircraft is introduced to demonstrate the module's capabilities and to present a sensitivity analysis. Also different configurations are analyzed and compared. A family of aircraft is analyzed as a final case study. The results of all case studies are presented and discussed in this Chapter. Conclusions on the case studies and the research overall are provided in Chapter 7 along with recommendations for future work.

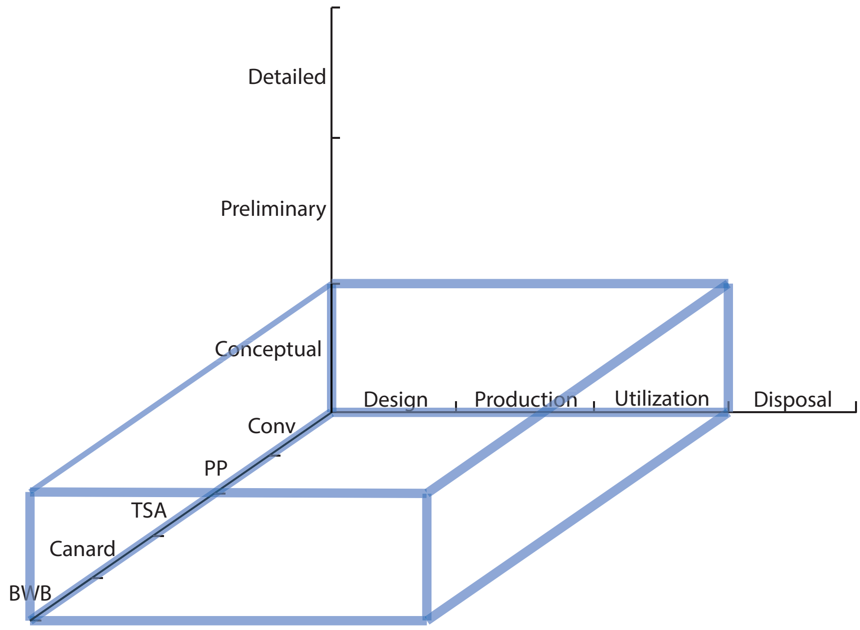


Figure 1.4: The primary scope for the cost estimating tool.

2

Background Information

As part of the graduation thesis a literature study was performed to build a foundation of knowledge. This knowledge helps the author to develop an estimation tool that is reliable, flexible, complete and usable. Although the field of aircraft cost estimation is difficult and comprises many topics such as statistics, production processes and other fields, this literature study is limited to three disciplines. In section 2.1 the concept of LCC is explained along with its importance with respect to cost estimation. All aspects of the product's life will influence the costs associated (complete). In section 2.2 cost estimation techniques are discussed. It will be clear that there is no guidebook that tells you what method to use or how to start building a cost estimation model. Classical and more recent methods will be explained along with their advantages and disadvantages. It helps in selecting the best method that is compatible with all configurations (flexible). Also some industrial use of estimation models and models discussed in literature will be presented in section 2.3. In section 2.4 the accuracy and validation of models is discussed (reliable). Finally, section 2.5 will present some basic knowledge of engineering economics that will need to be implemented in the cost estimation tool. It will allow the tool to be used as decision making tool for company management (usable).

2.1. The use of Life Cycle Costing in aerospace industry

In a market with high demands on performance and affordability of aircraft one cannot simply look at the purchase price of aircraft to validate investments. In order for an aircraft to be affordable for the operator, most of the times an airline, the producer has to take all cost that could occur during the life of an aircraft into account within the early design phases of the aircraft. This approach is called *Life Cycle Cost analysis* and is used for the benefit of manufacturer and operator. The producer has a better insight in the actual costs of producing an aircraft, e.g. the amount of spares needed during the life of a product, and hence could implement this knowledge to optimize production and stimulate profit. More information on the life of the aircraft allows the user to chose an aircraft that suits its strategy best and how it can be operated best. This section will explain the concept of LCC and its importance.

2.1.1. The definition of LCC

What makes LCC so unique is the fact that the complete life cycle of a product is kept in consideration and treated in each phase of the product's life. Every aspect of its life will be given the required technical and economic consideration [41]. For the production and design phase objectives could be to obtain the lowest average unit production cost, and do this at the lowest operation & support cost per operating hour [54]. Design using LCC is also often called concurrent engineering [7]. The definition of LCC can be stated as:

"The process of building abstractions or models of the three primary components of the system life cycle for the purpose of gaining insight into the interactions between these components, and their mutual interactions and inter-dependencies with the manufacturer and the airlines."'

The three components are: non-recurring cost, recurring cost and operations and support cost [54]. A product is born from the moment an initial design is available and ends when the product is disposed of. The way in which the life cycle of a product is segmented differs in literature. Alting is said to use six phases to describe a product's life, being: need recognition, design development, production, distribution, use, and disposal [7]. Keys makes it even more elaborate by stating that LCC includes three life cycles: the product's, the process', and the logistic support's [41]. The author has chosen to use the differentiation most often used in literature according to [7]. The phases and subsequent cost breakdown is shown in figure 2.1.

THE DESIGN PHASE

The design process proceeds from a set of stated requirements for the product and its steps are: conceptual design (the establishment of performance parameters, operational requirements, and support policies), preliminary-systems design, and detailed design. Actions performed by engineers are: evaluating other design approaches, preparing of functional design layouts, building prototype models and software, for more see [31]. The effect of the stated activities on the environment is also a concern in this phase [7].

THE PRODUCTION PHASE

The production phase begins when the system design is considered fixed and includes the total flow of materials. It involves inventories, material, acquisition and control provisions, tooling and test equipment, transportation and handling methods, facilities, personnel, and data. Emphasis at this point is to ensure that those characteristics which have been designed into the system during the earlier phases of the program are indeed maintained throughout the production process [31]. The costs associated with production can be suppressed using the Design for Assembly (DFA) method developed by Boothroyd and Dewhurst or the assembly evaluation method by Hitaichi [7]. Based on a number of criteria and on computing a numerical score assemblies can be evaluated with the intend to predict the ease of assembly and to find ways to improve the design to reduce costs.

THE UTILIZATION PHASE

Functioning of the product constitutes of the consumer use, incorporation of product or system modifications and improvements, logistic support to keep the product operationally available, and planning of the disposal phase. These functions can be performed by the user itself or can be outsourced as is often done for maintenance [31]. The operation and support costs are the highest of the LCC, but are most difficult to predict. This is due to the fact that the operating cost strongly depend on the operator's business strategy and that maintenance cost depends on failure rates and therefore statistics. The associated costs for operation and support may exceed the initial Acquisition Cost (AC) by ten times [68].

THE DISPOSAL PHASE

Disposing a product is often a costly matter but through reclamation and recycling one can lower these costs [31]. Another goal of the disposal or retirement phase as it is often called is the reduction of environmental waste. This is regulated in the European Union by the 'originator principle' which states: "he who inflicts harm on the environment has to pay for cleaning the damage on the environment". At the end of a products life the product can be recycled, re-manufactured, reused or disposed [7]. Since a product can never be completely recycled one wants to maximize the recycled resources while minimizing the effort to accomplish this [44].

2.1.2. THE IMPORTANCE OF LCC

The concept for LCC was first introduced by the US Department of Defence, who found out that operation and support cost for typical weapon systems could be as much as 75% of the total cost [7]. Having this knowledge gives the opportunity to account for it during the design phase. It appears that the design phase itself contributes less than 10% of the product cost while fixing approximately 70% of the costs [22]. Hence industry started to treat cost as a design variable along with traditional performance variables [54].

Areas such as production cost estimating, organizational learning, pricing and marketing, subcontracting production and predicting competitor's costs are important in the development of proper LCC models. An example of bad implementation of organizational learning is the production of the Lockheed L-1011 *Tri-Star*. It was a commercial transport aircraft developed in the 1970s. Due to cuts in the production and a lack of following typical learning curves, standard procedure in LCC, the costs rose to exceed selling price and stayed that way. The result was a program loss of $1 billion [54].

Maintenance, occurring during the utilization phase, is an important cost driver for airlines because of the man hours and cost of spare parts. But also due to the fact that an aircraft that is grounded cannot earn money

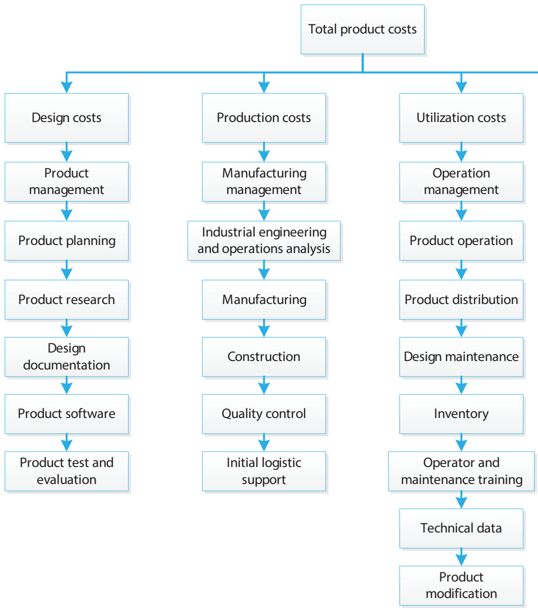


Figure 2.1: Cost breakdown per LCC phase [7].

for the airline. Maintenance can be split into active and passive repair times. The active repair times that can be influenced by the design of the product are for instance: localization of the problem, problem diagnosis, disassembling, interchanging, reassembly, alignment and verification [7]. The diagnosing phase can be 30-50% of the total repair time. Having early insight into maintenance cost is a benefit since it increases the completeness of the LCC estimate.

LCC also contributes to safety. The prediction of aircraft life and thus the reliability assessment of aircraft structures has an important effect on the safety of aircraft structures. The life of an aircraft can be determined using full scale testing of its structure for fatigue, crack initiation and crack propagation [69]. Using an economic life model the economic life and inspection period of an aircraft can be determined and accounted for during design. These models can also be used for life extension programs of aircraft.

As stated earlier LCC helps manufacturers identify all costs associated with production. It could occur that costs are unknown in magnitude or are not known at all. This could have disastrous consequences for the program as for the Lockheed example. During initial or conceptual design Research, Development, Testing & Evaluation (RDT&E) cost are well known but more vague for the next LCC phases. Hence program management can suffer from the so called iceberg effect. This concept is visualized in figure 2.2.

Hence it can be concluded that LCC is important in developing affordable products. Moropoulos describes how a product's life cycle is used for validation and verification of products during several design stages and evaluates existing models [53]. For all stated reasons LCC analysis should be used in developing the cost estimation tool for conventional and unconventional aircraft.

2.2. AN OVERVIEW OF COST ESTIMATING TECHNIQUES

Cost estimating is an important process during the initial design phase of aircraft production. Based on the estimate a company is able to determine its selling price and know if the product is worth while the investment. Unfortunately it is a difficult task and is information and knowledge intensive. Within the techniques that will be discussed some classifications can be made. The most prominent classification used in literature is between *top-down* and *bottom-up* techniques. Top-down uses high level part or assembly information and historical relations to give an estimate. It is often quick but lacks a high level of accuracy. The Bottom-up approach requires detailed knowledge of the product and uses relations giving exact amount of production hours, materials used, etc. It is time intensive but accurate. Niazi et al. developed a hierarchical classification based on extensive literature research [57]. This classification approach is found best since it covers most techniques and has the most sub-levels which makes differentiation between techniques more clear. More attention will be given to the popular estimating techniques of which some are traditional whereas others are

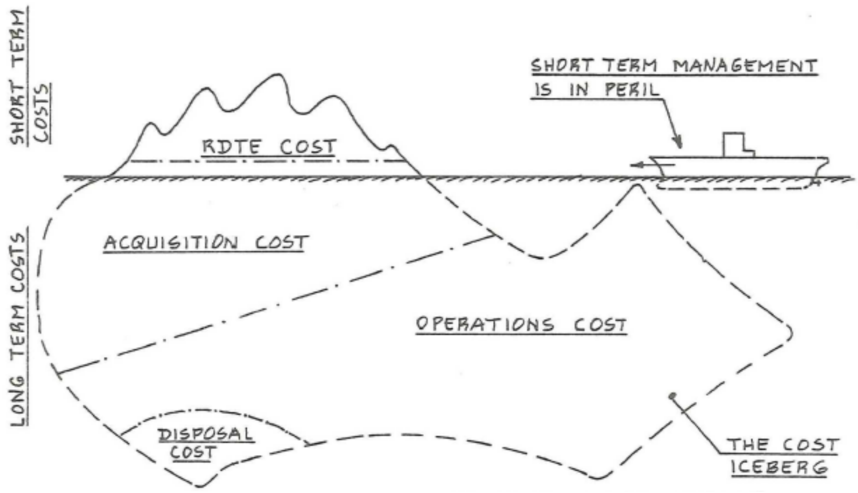


Figure 2.2: The management iceberg-effect [60].

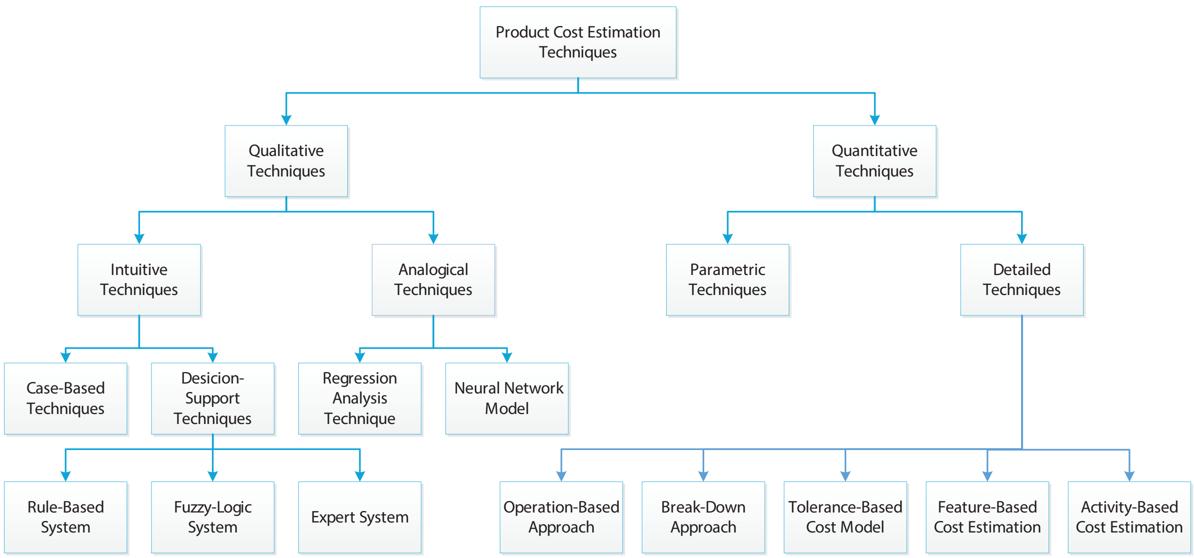


Figure 2.3: Classification of cost estimation techniques by [57]

denoted as advanced. At the end of this section a reflection of all the techniques will be provided.

The classification of techniques presented by Niazi et al. is given in figure 2.3 [57]. The first level classification of techniques is between qualitative and quantitative. Qualitative techniques are based on comparison analysis of the new product with existing products. These are further segmented in to Intuitive and Analogical techniques, which a respectively discussed in section 2.2.1 and 2.2.2. Quantitative techniques are depend on a more detailed analysis of the product design, its features, and manufacturing processes. Cost are calculated using analytical functions or as a sum of sum components and the resources and processes used. Quantitative techniques are further segmented in to Parametric and Analytical techniques and are discussed in section 2.2.3 and 2.2.4. Qualitative techniques are used during conceptual design phase whereas quantitative technique are used during detailed design.

2.2.1. QUALITATIVE: INTUITIVE TECHNIQUES

Past production experience plays a central role for intuitive techniques. The knowledge of a domain expert is used as a primary input to generate part or assembly estimates. This could be in the form of design-rules, decision-trees, judgment, etc. This input is stored in databases and should be up to date. At this level intuitive techniques are differentiated between case-based and decision support techniques.

CASE-BASED METHOD

This technique is often called Case Based Reasoning (CBR). It uses past products that closely match the new design and retrieves this information from databases. Changes are made and missing attributes are added to the existing data. It starts with stating all specifications of the new product in order to find a related design. The output of the estimation in turn is stored in the database for later use. It is a quick method since one does not have to start from scratch and is useful for conceptual design, but is limited by available data. The techniques does allow room for innovative designs [57].

DECISION SUPPORT SYSTEM

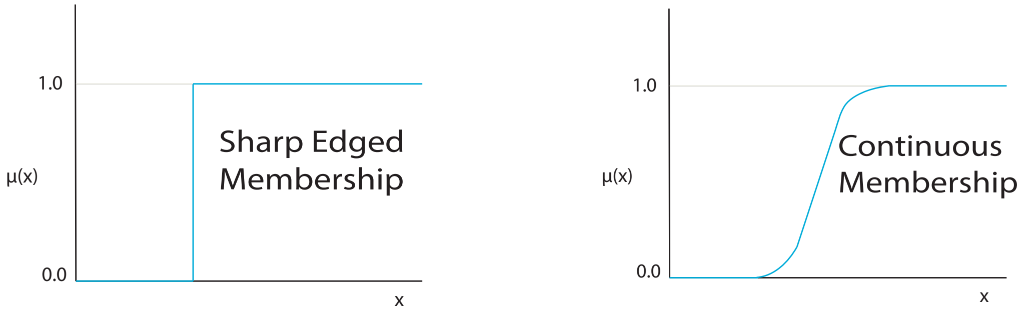
This techniques is not only a tool that provides the user a cost estimation, but also helps in evaluating design alternatives. The estimator is assisted in making better judgments and decisions at different levels of cost estimations. It requires expert knowledge that is to be stored within the model. This could be knowledge of machining processes, manufacturing constraints, or important product characteristics and their relation with other features. Examples exist for the use of Decision Support System (DSS) in knowledge-based cost models at conceptual design [63], integration model for planning into cost estimation [51], and manufacturing process optimization [35]. Three types of DSS estimation techniques can be identified: rule based, fuzzy-logic, and expert-systems.

Rule-based The rule-based technique uses process time and cost calculation of feasible processes that are available to the estimator. Parts based on design and manufacturing constraints are dealt with using a respective rule class build on expert knowledge. The constraints are input values. Rule-based algorithms need to be written to establish design constraints. Using databases such as machining handbooks or formula data, systems cost estimates can be generated if the cost of material, set-up time, tool costs, etc. are known. From the mentioned databases one specifies what processes are used and hence the product cost can be determined. Important is that the technique uses a sanity check where it asks the user if the estimation is acceptable. If not the user is able to adjust design constraints and run the model again. This technique is useful for cost optimization based on processes used, but can be very time consuming proportional to the amount of processes required [57].

Fuzzy-logic The introduction of the fuzzy-logic techinque was a result of the need to deal quantitatively with imprecision and uncertainty. Lotfi Zadeh conceived it in 1965. The technique is based on the fact that many parameters are uncertain in nature. Traditional techniques described in section 2.2.5 are based on so called crisp methods. Fuzzy-logic is to connect binary computing and the continuous world [37]. It is a way to represent vague and imprecise knowledge. One could also see the fuzzy approach as a technique that uses qualitative expressions that link linguistic variables, $\mathrm{L_{ij}}$ and $\mathrm{M_i}$, as its system's algorithm. It takes the form: if $\mathrm{V_1}$ is $\mathrm{L_{i1}}$ and $\mathrm{V_2}$ is $\mathrm{L_{i2}}$ and ... $\mathrm{V_p}$ is $\mathrm{L_{ip}}$ then U is $\mathrm{M_i}$, hence simple 'if-then' statements are used to convert a certain input to the required output [22].
The technique uses a fuzzy set of conditions that a fuzzy variable can belong to, denoted F. F is defined as a set of ordered pairs $(x,\mu(x))$, and uses a membership function f to define the relationship between x and $\mu(x)$. x is a value of an element in the domain of function f and $\mu(x)$ (the value of f at x) [22]. If $\mu(x) = 0$ then we have an x with no membership within F while one would have full membership if $\mu(x) = 1$. Jumping from no to full membership normally does not happen in an abrupt manner as was explained for traditional techniques as is shown in figure 2.4a. Fuzzy-logic accounts for a smooth transition as visualized in figure 2.4b.

What makes the fuzzy technique so useful is the fact that the fuzzy transition can be of any form. Most of the time simple relations are used, such as: piece-wise linear function, Gaussian distributions, Sigmoid curves and quadratic or cubic polynomial curves, or can be described by straight lines [43]. An example is seen in figure 2.5, which is a trapezoidal membership function. Fuzzy-logic has three main procedures, which are:

1. Recognize assigned physical conditions that will need to be analyzed or controlled.
2. Process these physical conditions using the fuzzy 'if-then' rules.
3. Convert all the output from all the rules to one single defuzzified output by averaging and weighting them. The single output will initiate or call the need for decisions and/or actions of the system.



(a) Crisp set (b) Fuzzy set

Figure 2.4: Membership function of a crisp set [22]

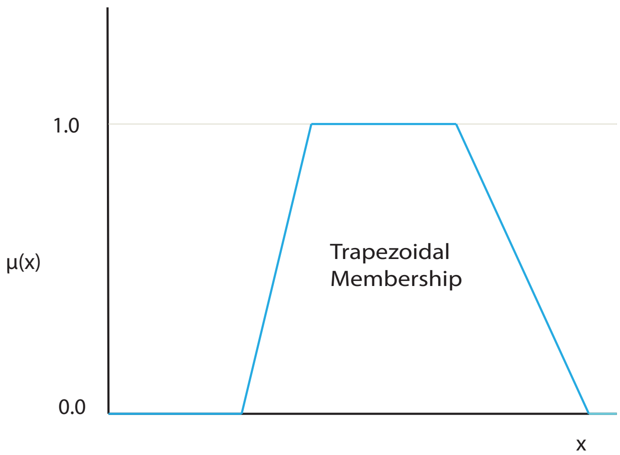


Figure 2.5: Trapezoidal membership function distribution [22].

Fuzzy-logic is best used for very complex models with little or judgmental understanding, secondly when processes occur where human reasoning, human perception, or human decision are inextricably linked [22]. When properly used, the estimator can benefit from three main advantages. All are related to cost and the first gain is from the simplicity and transparency of the mathematical concepts used. The second is from the ability to match any set of input-output data. Thirdly, the possibility to integrate this technique with the traditional techniques which of course also contain knowledge rules.

Unfortunately, the technique of fuzzy-logic is not well established and are limited by the knowledge input from experts. Hence, this technique is constrained by rules implied and the scope of its application [13].

Expert system This technique uses expert knowledge by storing it in a database. The data can be manipulated to allow more consistent, accurate and quicker results. The goal of altering the database is to replace the expert by an automated logical reasoning system. This often goes hand in hand with rule-based programming. Knowledge encapsulated by the system is often of theoretical ground instead of more practical. Hence the technique is limited by the degree to which the programmer can store expert knowledge and further research in this area is required [57].

2.2.2. Qualitative: Analogical techniques

The second type of qualitative technique is the analogical technique and uses cost estimations of past projects. It drives on actual cost data whereas the intuitive technique was based on human knowledge, hence it is already a bit more of a quantitative approach. The analogical techniques discussed are the regression-analysis and back-propagation neural-network.

Regression Analysis

This technique uses relationships between the product cost of past designs and the value of certain variables selected. It requires a large set of data in order to give a reliable relationship [57]. Take for instance the wing of an aircraft. Based on wing data of existing aircraft one could plot the relation between wingspan, lift over drag ratio or any other parameter versus the cost. Using a regression analysis a formula can be derived that can be used to estimate the cost of newly designed wings. The accuracy of this estimate depends on the degree of correlation between the relationship and historical data, otherwise said the overall deviation of the single data points with respect to the curve. Regression analysis makes use of linear, quadratic, exponential or logarithmic functions

(Back-Propagation) Neural network

This technique, like fuzzy-logic, is based upon simulating the human thought process. It learns to predict an outcome that has an effect on cost when presented with a range of product-related attributes. In order to get to this effect the system derives from analogy a hierarchical set of neurons. These neurons function as gates that simulates multiple procedural permutations and combinations. Based on these simulations the system trains itself in being able to come up with a logical conclusion. The inputs of the system are historical projects or studies in order to present cost estimations of a new project [22].

The user of a program based on neural networks has to deliver the domain of the problem, cost drivers and the cost data that is important. Neural networks have ability to produce better cost estimations than regression techniques [15]. The technique also allows the possibility to detect relationships within the input database, which is a plus. On the other hand studies have shown that the accuracy, variability and the ability to create and examine is not always of the required level. The technique requires a large historic data bank where it learns from and the content of the data should have the same properties as the data that serves as the input. Hence, the quality of the cost estimation is directly related to the database and its quality, quantity and relevance.

The most popular technique is the Back-propagation neural network. It uses a non-linear sigmoid transfer function to calculate the output of neurons [42]. A network of neutrons means that the output of one is the input for another. A typical sigmoid function is given in equation (2.1). X_i is the input variable, w_{ij} is the connection weight between two neurons, and θ_{ij} is the bias term for the given neuron.

$$f(x_j) = \frac{1}{1 + \exp(-(\sum_{1}^{n} X_i \cdot w_{ij} - \theta_{ij}))} \tag{2.1}$$

Neural networks lack the ability to be used by new or innovative products that are too different from historical designs since there is no history it can learn from [28]. It also functions a bit like a black box with its sets of rules and training of which influencing it is difficult. Hence this technique lacks transparency so will not likely be used by analyst requiring an overview of reasoning and/or assumptions.

2.2.3. Quantitative: Parametric technique

The parametric technique is a 'Top-down' approach [7]. It uses parameters such as weight, performance and complexity to determine cost. These parameters are often called cost-drivers. Based on historically produced aircraft a set of data exist that can be used to translate these parameters into an estimate. The relations used are called CERs and are obtained using mathematical algorithms that are often based on linear, multiple linear, or curve-linear regressions. One could say that the regression analysis technique is implemented into the parametric technique.

Within the parametric relations you have dependent variables, and independent variables, which are the cost-drivers, tend to change the costs. The parametric approach is often used to quantify the unit cost of a model. The technique makes use of a WBS, which lists all cost components and activities related to the product. This includes all actions required to manufacture the product, like management, planning and logistics [57].

The origin of parametric cost estimating is said to be linked to the work of Wright around 1936 as he introduced the concept of the learning curve. The learning curve gives the relation between the unit cost of an aircraft as a function of the number of aircraft produced. It was often used during World War II when the production of military aircraft increased exponentially. It was then that knowledge of how cost can be decreased with increasing production scale became more important. One example is the production of the Douglas C-47 or Dakota aircraft. This aircraft should have had a unit cost a quarter of its initial cost after building 10,000 aircraft. But for some reasons this was already obtained after 3,000 units build. After World War II people started to investigate this phenomena and came up with a formula relating the decrease in cost to an exponential term that determines the slope of the learning curve. This exponential term is a function of the efficiency of a company's internal processes, new technology and the complexity of the design [22].

Using the parametric technique one has to segment the aircraft to the smallest part as CERs are present to increase accuracy. Special attention should be paid to prevent the use of CERs outside the database range since no proof exist that estimations are accurate. The Research and Development (RAND) corporation was the first to develop CERs. Their data is still used although aircraft producers have developed their own relationships. The RAND CERs are publicly available.

Advantages of the parametric technique lie within the fact that it is fast and that little product and work output needs to be known except for physical characteristics. This makes the parametric technique useful for early stages of product development [61]. It requires little estimating skills, which makes it rather easy to implement [62]. It also allows scope for quantifying risk. A first disadvantage is the difficulty to identify the primary cost drivers for part of the aircraft. Next is that developing your own CERs requires a significant volume of data. Also RAND CERs are rather old and CERs itself could contain errors in trends of time that went unnoticed. CERs can also have a lack of direct cause-and-effect relationship, meaning why a particular parameter correlates with dependent variables [22]. Beltramo emphasized that modelers should carefully document their assumptions in order to help users to operate the model in the proper way [11]. A final drawback is that parametric estimating is not a proper technique to be used for new technologies [7]. Judgment and knowledge is required to decide if particular CERs are feasible for new technologies and if outputs are even relevant [22].

The parametric technique's capabilities where recognized by other civil industries. The best example was the impact in the construction industry. Three categories of parametric relationships are central for CERs developed by RAND [22]:

- Performance and physical parameters are measures of *technical capability* and may be further divided into parameters that are scale dependent and independent.
- Technical risk and design maturity parameters measure or quantify the *relative difficulty* of developing and producing a particular system.
- Programmatic parameters address issues related to the way in which programs are *operated*.

2.2.4. QUANTITATIVE: ANALYTICAL TECHNIQUES

This technique has a bottom-up approach. It uses labor time and rates combined with material quantities and their prices to make an estimate of the direct cost of a product or activity. One simply has to determine the time needed to perform an activity and obtain the hourly rates for manning the machine. This has to be multiplied by each other and repeated for all activities required in the production process. The time and rates could be in-house or industry standard or could be obtained from expert judgment [7]. They are best applied when identical products with a long and stable production are considered [31]. A few characteristics of this technique are as follows [22]:

- The use of a WBS, like the parametric technique.
- Basic tasks such as engineering design, tooling, manufacturing engineering, and quality control have a cost estimate.
- Cost of the materials is obtained from the supplier, collected from industrial standards or estimated.
- The approach requires detailed and accurate data.

The detailed technique is known as the most time consuming and also the most expensive approach. In return one obtains a cost estimation with a high level of accuracy. It also requires very detailed knowledge of the product and processes. The technique is also flexible, since the information used can be reused for other processes as well. The main difficulties lie within [67]:

- determining or collecting the basic standard times;

- determining the hourly rates and keeping them up to date;
- management of a large amount of information;
- a large number of simple but tedious calculations, and
- the skill and experience required to use the basic information properly.

Five analytical techniques have been identified: Operation-Based approach, Breakdown-Approach, Tolerance-Based approach, Feature-Based Costing approach, and the Activity-Based Costing approach. Each will be explained in short since it is unlikely that an analytical technique will be used as will be explained in section 2.2.5.

OPERATION-BASED

The technique uses the time of performing manufacturing operations, non-productive time, and setup time to estimate the costs. Formulation of this relation is given in equation 2.2. R_o is the operator's rate, R_m the machine rate, T_{su} the setup time, Q the batch size, T_{ot} the operation time, and T_{no} the non-productive time. The method can not be used to evaluate different designs for design trade-off since it can only be applied in the final design stage. A benefit that different production processes can be evaluated and the cheapest process with highest quality can be selected. The technique is time consuming and requires detailed product information and process planning [57].

$$\mathrm{Manufacturingcost} = \left(R_o + R_m\right)\left[\frac{T_{su}}{Q} \cdot T_{ot} + T_{no}\right] + C_{mat} + \mathrm{factoryexpenses} \tag{2.2}$$

BREAK-DOWN APPROACH

This technique also determines the total cost by summing all the costs that occur during the production life cycle of the product. This also includes overhead and material costs. Resources such as purchasing, processing and maintenance are to be known in detail for this techniques.

TOLERANCE-BASED

This technique uses a function that relates the design tolerances of a product to the product cost. The tolerances are set to get a required production output and guidelines for the manufacturing of parts. Assigning the correct tolerances is not easy for two reasons. The first is that the production tolerances influence the functionality of the design. Secondly, different design tolerances are often interrelated. The tolerances are a measure of complexity and can thus indicate the time required for production and give a cost estimation [27].

FEATURE-BASED MODELING

According to Wierda relational drivers are often design features for two reasons[67]. First, cost functions can be derived for classes of similar objects that serve as key drivers of global cost estimation and are linked to the engineering domain. Second, the causes of costs should be known so they can influence committed cost directly using the design features. Wierda also defined three cost components that are linked to design features and are valid for any class of similar objects to which the costs are related:

- Feature or assembly level: cost related directly to individual design features.
- Component or batch level: cost caused by a collection of design features.
- Order or facility level: cost assigned to design features.

Between these three levels also interrelationships exist, especially for complex products and processes. For simple implementation these can be ignored. Material selection is an example of a design feature and their cost can be directly related to the material blank, with some additional design features being incorporated when they have an impact on materials costs. These changes can be seen as that material costs can be directly assigned to a feature if it entails a positive volume. It is a negative volume for negative material costs, or waste revenue [67]. Difficulty arises when features overlap or not perfectly fit within the definition of one of its features. The latter is especially difficult for operations carried out for groups of inter-related features making allocation difficult. Another problem in using feature-based costing is that the focus of reducing costs for

Table 2.1: Examples of feature classification in feature-based costing [22]

Feature type	Examples
Geometric	Length, width, depth, perimeter, volume, area
Attribute	Tolerance, finish, density, mass, material, composition
Physical	Hole, pocket, skin, core, PC board, cable, spar, wing
Process	Drill, lay, weld, machine, form, chemi-mill, Super Plastic Forming (SPF)
Assembly	Interconnect, insert, align, engage, attach
Activity	Design engineering, structural analysis, quality assurance

each feature separately does not necessary lead to a overall reduction in costs [22]. In general feature-based costing is driven by the method to describe products by the number of features that both designer and manufacturer relate to. Examples are presented in figure 2.1. The more feature a product has the higher is the degree of designing, manufacturing, and planning and the higher is the committed cost downstream in the life cycle [17].

The feature-based method of estimating cost is not often used yet. Its feasibility requires more research, but companies do seem to like the concept of it since they already use features to decompose or define a design concept.

ACTIVITY BASED COSTING (ABC) METHOD

The method estimates the cost of a product on the activities required to manufacture it. All activities can be classified into four categories: unit, batch, product and factory level activities [7]. It also takes overhead cost into account and distributes in proportion to the activities performed. A reasonably level of accuracy can be obtained which makes it a good alternative for traditional cost estimation methods [57]. The cost is given by multiplying the amount of a certain activity and the consumption intensity. The latter is the unit price of a cost driver, which in this context is the measure for demand of an activity. The technique is rather easy but requires lead-time in early design [7].

2.2.5. A REFLECTION ON COST ESTIMATING TECHNIQUES

After introducing different type of cost estimating techniques and analyzing them it can be concluded that there is no "overall consolidated theoretical approach for the domain" [22]. Though this section will present a reflection on the methods to help selecting a technique. First, more types of classifying methods is presented, secondly a more scientific approach is discussed. Thirdly, a decision making tool from literature is presented. This section will conclude with some general remarks on cost estimating techniques.

MORE CLASSIFICATIONS OF ESTIMATION TECHNIQUES

In section 2.2 the classification of techniques was introduced and as stated multiple perspectives and approaches to classify the techniques. Another classification is functional classes. The first is based on compilation costing, which aggregates various identified costs. The second class is based on relational costing and uses comparative relations of product defining parameters [22]. To compilation costing belongs: ABC, Analytical estimation, and Feature Based Costing (FBC). To relational costing belongs: parametric estimation, neural networks, analogous costing, and fuzzy-logic [22].

Within the presented techniques also a distinction can be made between traditional and more advanced techniques [22]. The techniques denoted as traditional are Analogical, Parametric, and Analytical. The techniques denoted as advances are Fuzzy-logic, Neural Network, and Feature Based. These often require more research and are not a proven concept. The more advanced types of cost estimating techniques deal with uncertainty in estimating, whereas traditional methods purely focus on getting the quantitative estimation [20]. The main emphasize in the stated comments is the lack of sufficient scientific theory in the process of developing and applying cost methods. This scientific theory of the basis of science depends on the degree of understanding and the principle of cause and effect. This scientific bases should be more explored and used. For this reason Curran suggest a Genetic-causal approach [22].

THE GENETIC-CAUSAL APPROACH

This technique is about the causal definition of the relation between cost and design drivers. It uses product and process families. This model is characterized by having a more scientific basis than other techniques.

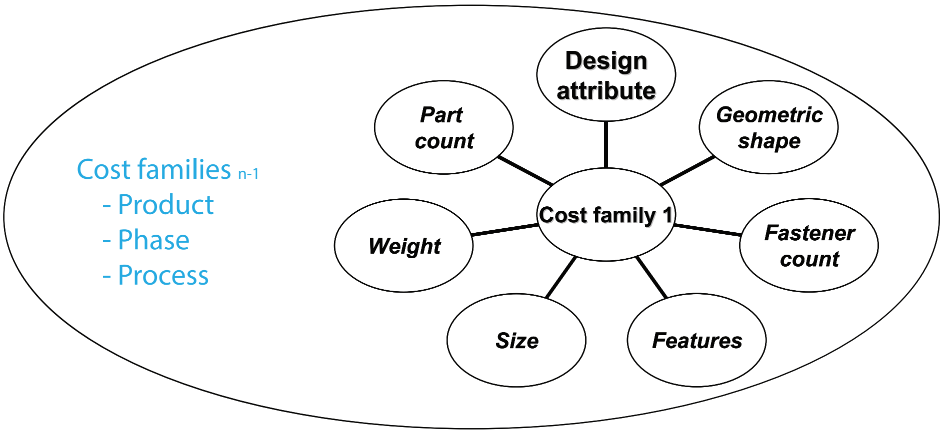


Figure 2.6: Structure of the Genetic-causal cost estimating method [22].

The principle of categorization (genetic) and the rigor of requiring causality (causal) stands central. Genetic assumes that a process has a start-point and is unidirectional from that point on, so it can be maped. Also economics has proven to have genetic nature within its processes [18]. Hence the cost of a product uses can be determined by certain building blocks that give the resultant cost structure and are therefore the method's cost drivers. The costs are most often always classified to material, part fabrication, and assembly. The reason for including causality is the need for completeness and the ability to explain each step in cost estimating. First of all, since it drives the user to get to an outcome and secondary because it helps in stating useful rules and formulating guiding principles. For example, within aerospace industry there appears to be a direct relation between the weight of an airplane and its unit costs [22]. So when one designs a new aircraft one simply has to make it light to make it market competitive. But one should ask the question: why does this relation hold? Study shows that the main reason is that industry strives to reduce weight in order to reduce the area of lifting surfaces and thus the fuel consumption of an airplane, making it operationally less expensive and more competitive. Techniques using causality forces the users to think about these things and therefore helps them to make better decisions. Hence, all costs are an effect of causal drivers. The Genetic-causal concept is visualized in figure 2.6. At the left hand side we see the genetic's families and at the right hand side the causal drivers such as geometric shape and part count.

One benefit of this technique is that it deals with a wide range of cost elements. It also implements both design definitions as well as performance. It does not present a clear or unique function on how to define cost, but it does help an estimator to understand life cycles and develop manufacturing models. This unfortunately requires the analyst or estimator to have a good understanding in the cost drivers used. Another advantage is that understanding causality improves the accuracy of the estimation [20].

AN APPROACH FOR DECISION MAKING IN METHOD SELECTION

Besides providing a classification of estimation methods Niazi et al. also proposed a decision model for selection the proper method for a cost estimation model, see figure 2.7 [57]. Figure 2.8 provides an overview of types of cost estimation are used at each life cycle phase of a product. Note that Engineering and Extrapolation are detailed approaches of cost estimation. It can be seen that for conceptual design, thus for Initiator, the analogy method should be the first choice closely followed by the parametric method.

Table 2.2 gives an overview summarizing all the pros and cons of techniques presented.

A GENERAL REFLECTION ON ESTIMATION METHODS

When looking at the history and current trends several general observations can be made [22]:

- Instead of developing a causal understanding in modeling, people tend to focus entirely on directly estimating costs. ⟶ Function over foundation.
- The main focus is on particular elements of cost estimating rather than on the overall picture of cost architecture. ⟶ Detailed over parametric.
- Modeling is directed towards a particular stage in LCC with little or no focus on the holistic cost structure. ⟶ Inhibiting over inheriting.

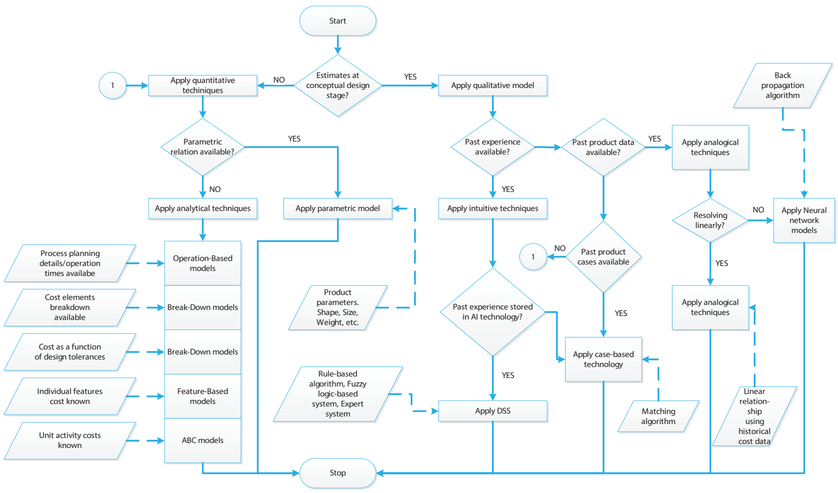


Figure 2.7: Decision model for selection of cost estimation method [57]

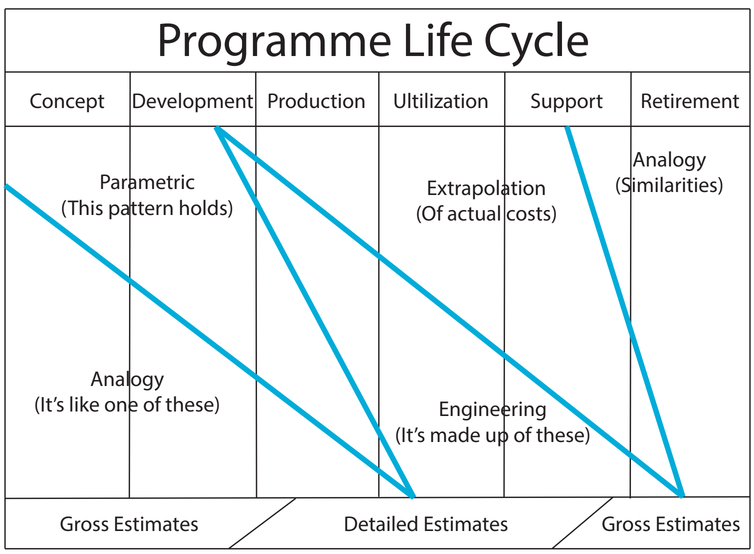


Figure 2.8: Cost estimation methods per life cycle phase [12]

Table 2.2: Overview of pros and cons of cost estimating techniques [57].

Cost Estimating Techniques				Pros	Cons
Qualitative	Intuitive		Case-Based	Fast technique. Useful for conceptual and innovative design.	Available data is limited.
		Decision Support	Rule-Based System	Includes sanity check by user. Expert knowledge is stored in design rules. Can provide optimized results.	Can be time consuming proportional to the amount of processes.
			Fuzzy-Logic System	Deals with imprecision and uncertainty.	Technique is not well established.
			Expert-System	Incorporates expert knowledge. Faster, more consistent and accurate results.	Limited by the amount expert knowledge can be stored. Complex programming required
	Analogous		Regression Analysis	Simple technique.	Limited by data.
			Neural Network	The system trains it self. Rather precise estimates. Deals with uncertainty and non-linear problems.	Highly data dependent. Not applicable to innovative designs. Lacks transparency.
Quantitative			Parametric	Fast technique, requires little product information. Useful for early stage estimating. Easy technique that requires little estimating skills.	Limited by ability to identify cost drivers. Requires large data set.
	Analytical		Operation-Based	Allows evaluation of production processes.	Not useful for early design trade-off. Requires detailed design information and process planning. Time consuming.
			Break-Down	Easy technique.	Requires knowledge on purchasing, processing and maintenance.
			Tolerance-Based	Tolerances identify complexities.	Requires detailed design information. Assigning correct tolerances is difficult.
			Feature-Based	Features with high costs can be identified.	Allocating parts or properties to features can be difficult for small and complex products.
			Activity-Based	Easy and effective technique using unit activity costs.	Requires lead times in early design stages.

- Cost methods are primarily based on a mechanistic approach instead of causal truth. ⟶ Casual over causal.
- Modeling is a product specific activity rather than generic. ⟶ Generative over genetic.
- Costing is most of all experience based instead of scientific. ⟶ Experience over experiment.

The main emphasize in the stated comments is the lack of sufficient scientific theory in the process of developing and applying cost methods. This scientific theory of the basis of science depends on the degree of understanding and the principle of cause and effect relations. This scientific bases should be more explored and used.

For the design process cost estimation tools are required that: take into account complete life-cycle of products, can be used at very early design stages, and can inform the designer at a timely manner [7].

Within the different design stages, the early design phases are to meet the performance requirements. In the later design stages it is possible to make a first estimate on manufacturing costs [57].

2.3. EXISTING COST ESTIMATING TOOLS

This section introduced some of the cost estimation tools used in industry. Some of them are well known and respected methods and are presented in the first part of this section. The second part presents some methods found in literature which the author found worth mentioning since they may be of use later. An overview of these cost estimation methods was presented by [14] of which some are presented here. Of this list only the top-down methods with public available data is chosen.

2.3.1. EXISTING COST ESTIMATING TOOLS USED IN INDUSTRY

Many aerospace companies have their own cost estimation software and use their own in-house data for it. However, a lot of commercial software is available as well. PRICE systems is major player world wide and is for instance used by Lockheed Martin, British Aerospace (BAe) [23], European Space Agency (ESA) [7], and National Aeronautics and Space Administration (NASA) [25]. A second large software developer for cost estimating is Galorath, which is used by Airbus [33]. Most of the available software are based on existing models, two other popular public available methods are the Roskam and Raymer method.

ROSKAM COST MODEL

Dr. Jan Roskam wrote several books on airplane design of which the last part was on cost estimation. It presents very detailed relations for all types of costs associated with aircraft LCC. This method is quite outdated but is still used in industry for conceptual design.

The Roskam method uses the RAND corporation established CERs and allows for RDT&E, production and operational costs estimation. For the production method it gives an estimated acquisition cost, which is the sum of manufacturing cost and a profit. The airplane program production cost consist of the following components: cost of engine and avionics, cost of interior, manufacturing labor cost, manufacturing material cost, tooling cost, and quality control cost. Th general input would be the take-off weight, aeronautical manufacturers planning report weight, maximum speed, number of aircraft build in RDT&E phase, monthly production rate, amount of flight test hours, and operating cost per block hour. It should also be noted that Roskam uses cost factors that influence the cost for a given component depending on the type of aircraft [60].

RAYMER METHOD

Daniel P. Raymer is a notorious aircraft designer an also covers the topic of cost estimation. Cost estimation as he mentioned is largely statistical during the conceptual design, hence it is a top-down method [14]. Because of this statistical nature the outcome of the established relations often need to be corrected. This is done using so called *fudge factors* and should involve differences between the assumptions of your design and the realities of existing aircraft. Raymer proposes the use of the so called RAND DAPCA IV model. It estimates the hours required by engineering, tooling, manufacturing, and quality control groups and are multiplied by the hourly rates. This done for the RDT&E and production phase combined. Also development support cost, flight-test cost, manufacturing costs, and engine production cost are estimated. The input for these relations are: empty weight, maximum velocity, production number in five years, number of flight-test aircraft, total number of engines needed, engine, maximum thrust, engine maximum Mach number, and turbine inlet temperature. The DAPCA model is not that suitable for advanced designs, but if used the hourly rates should be increased by about 20-40%. Raymer also touches upon the operational costs of aircraft, but less intensive than other sources [59].

2.3.2. EXAMPLES OF COST ESTIMATING TOOLS PRESENTED IN LITERATURE

A lot of cost estimation methods have been published for all types of cost estimating techniques. This part of the section gives an example of both a top-down and bottom-up approach to give the reader an idea of what is available.

AIRCRAFT UNIT COST ESTIMATION METHODOLOGY

It analyzes the correlation between aircraft design parameters and costs and thus is top-down.The aircraft is broken down into different parts: horizontal stabilizer, vertical stabilizer, fuselage, engines, undercarriage, and wing. Also five cost element categories are chosen: geometry, material, manufacturing, parts, and complexity. Three different aircraft generations were identified for which the most representative design parameters were selected, hence estimates should be more accurate per generation. Regression analysis are performed and regression coefficient R^2 larger than 80% are selected, though this was not stringent. An aircraft cost estimating relationship software AUCER is used which can combine multiple regression models to one single relation containing up to four design variables. The model shows high accuracy for conventional aircraft, except for the Airbus A380 which is too different from other conventional types [64].

GENERIC COST MODEL FOR ENGINE NACELLES

This is a model for conceptual and mature design. The engine nacelle is broken down to, nose cowl, fan cowl, thrust reverser, tail cone assembly, and Engine Build Unit (EBU). The cost of each of these components are segmented into, material cost, fabrication cost, assembly cost, support cost, amortization cost, and miscellaneous cost. It compares weights of two types of nacelles per part and per segmented cost. It looked at parametric relations for weight, air-wash area, fan diameter and thrust and showed that weight has the best correlation of $R^2 = 0.955$. All parameters were normalized in order to see which had the largest impact on cost. This resulted to be the fan-diameter. Beside this they also looked at the complexity of nacelle design. Hence, the cost was a function of fan diameter, geometric complexity, manufacturing complexity, and specification complexity [21].

PARAMETRIC AND ANALOGOUS MODEL FOR UNIT COST OF ACQUISITION ESTIMATING

Watson developed a cost model based on both the parametric and analogous technique for unit cost of acquisition estimating for outside production machined parts [65]. The model is called Pro-COST and divides the unit cost into make, material, and treatments costs. A case study is performed on the production of aircraft bulkheads. Data in the form of process, supply, and detailed design information is obtained from 24 Bombardier related companies. A Rough Order Magnitude (ROM) approach is used to analyze this data and showed that parts similar in nature require similar treatment processes and thus process costs. As a result 82 CERs were derived from data [65].

AN INTELLIGENT KBE SYSTEM FOR PRODUCT COST MODELING

Shehab and Abdalla present a method that selects material and process parameters based on design and production parameters. It can estimate the total production costs ranging from material cost to assembly cost. Fuzzy-logic is used to deal with uncertainty. A case study is presented on an injection moulding component. The method is applicable to early design phases to reduce the cost of redesign [63].

MULTI-DISCIPLINARY DESIGN FOR AIRCRAFT WING

Gantois and Morris wrote a paper on the multi-disciplinary design of a large-scale civil aircraft wing, taking account of manufacturing cost. Hence is a study on concurrent engineering. The objective was to have a Multi Model Generator (MMG) tool to support the development of the Airbus A380. It used an aerodynamic, structural, and aeroelastic analysis model for design. The design parameters chosen were: 1/4-chord sweep, wing area, aspect ration, thickness, outboard twist, and rear spar location. The objective variables were: weight, drag, and DOC [34].

RAPID COST MODELING AT THE CONCEPTUAL STAGE OF AIRCRAFT DESIGN

Kundu developed a model based on Design for Manufacturing (DFM) for commercial transport aircraft. It also incorporates risk and project planning. The objective is to ensure acquisition of aircraft and its components with a balanced trade-off between aircraft performance and cost. Again a case-study was performed

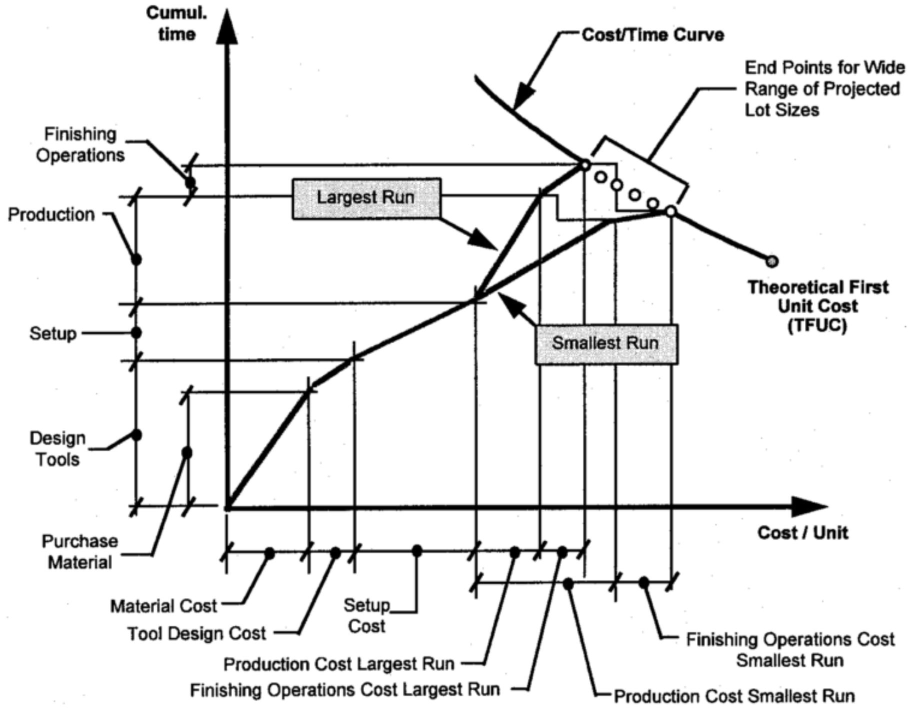


Figure 2.9: Cost/time analysis plot for theoretical aircraft production [55]

on a generic turbofan nacelle by selecting eleven cost drivers. The entire model is based on the analogous cost modeling technique [45] .

COST/TIME ANALYSIS FOR THEORETICAL AIRCRAFT PRODUCTION

Marx proposes a bottom-up method based on an analysis with cost and time as an output. This method is visualized using a Cost/Time Analysis (CTA) plot, see figure 2.9. Based on the production process and other related choices and actions a path is created ending at a certain point on the graph. The learning curve is clearly shown. On the bottom-right the Theoretical First Unit Cost (TFUC) is shown, and the cost per aircraft decrease over time. It can be used as a tool to: show the effect of process changes, identify the cost drivers, and serves as a constraint curve for product and process design [55].

2.3.3. ASSOCIATIONS FOR COST ENGINEERING

Around the world many cost engineers share knowledge on cost estimating through associations of cost engineers. This section will present in short some of those associations.

The International International Cost Engineering Council (ICEC) is a worldwide confederation for the promotion of cost engineering, quantity surveying, and project management societies. It is a Non Governmental Organization (NGO) which was founded in 1976 and is located in more than 40 countries and active in 120 countries. It has a network of over 120,000 cost engineers.

Another international organization is the International Cost Estimating and Analysis Association (ICEAA). It was formed only recently by a merger of the International Society of Parametric Analysis (ISPA) and theSociety of Cost Estimating and Analysis (SCEA) in 2012, but worked together for many years. ISPA was founded in 1979 specifically to promote the technique of parametric cost estimating. SCEA in turn was founded by a merger of the National Estimating Society (NES) and the Institute of Cost Analysis (ICA) in 1990. ICEAA also offers training and certification for cost engineers.

Many countries have their own association of cost engineering. The DACE focuses on cost and value engineering and is a ICEAA member. Value engineers tend to improve value, while maintaining or improving the quality of products and services. Value is defined as the ratio between performance and costs. DACE has an active Special Interest Group (SIG) on Parametric Analysis (PA). Every year SIG PA organizes several network and training events. The author attended the network event of September 19th 2013 about Design to

Cost (DTC). DTC is a principle in which cost is replaced by mass and is widely used in aerospace and defense industry. It was clear that DTC is acknowledged by industry, however companies find it difficult to implement since it requires every project participant to care about cost and to function a bit like a cost engineer. However, it can make project more affordable and less risky. Moreover, the focus on identifying the proper cost drivers was emphasized. DACE publishes a industry wide price list for the manufacturing of engineering systems but focuses mainly on civil engineering and process engineering.

2.4. THE VALIDATION OF COST ESTIMATING MODELS

In order to validate cost estimating models there needs to be a set of requirements. An example of requirements for a cost model were formulated by Layer et al. [48]:

- *Accuracy.* This is difficult to determine and is case dependent. It should be high enough to make the model usable in a broad sense.
- *Transparent description of the cost structure.* The model should allow the user to identify cost drivers easily.
- *Design-concurrent use.* The model should always be available for design concurrence.
- *Dynamic adaptivity.* The model should be flexible in the sense that changes in manufacturing processes and operational changes can easily be implemented.
- *Calculation of complex parts.* The method should also be usable when complex products or parts are to be evaluated.

2.4.1. ACCURACY IN COST ESTIMATING

Making use of good cost estimating models allows a company to give a reasonably good offer to the client. When the estimation is too low the company might be risking financial losses. If initial plans for staffing , scheduling, and machining for instance appears to be insufficient, reorganization is required. This is a costly matter [23]. If they somehow have overestimated the project costs it might not even get any customers and will not be able to make a profit at all. Hence, good estimating is importance for internal use (e.g. cost management, budgeting) and external use (e.g. market position with respect to competitors). The importance of accuracy is emphasized and the concept just explained is shown in the Freiman curve figure 2.10. Fortunately, there is a broad region that allows for some error within cost estimation [7]. When cost overestimating occurs a company may face Parkinson's law behavior. This means that people feel the money surplus must be spent anyway and hence an opportunity for making a higher profit has been lost.

During the different phases of a product's life cycle different estimating accuracy can be expected. At the conceptual design stages and planning stages data is limited and cost analysts depend heavily on various parametric cost estimating techniques. The accuracy during these phases is approximately -30 to +50% [7]. Later in the life cycle when more detailed data comes at hand analyst will be able to differentiate between the new product and existing products and hence can correct for these differences within the CERs [31]. Here the analogous method is used most often. Cost estimates will be within the range of -15 to +30% and are for budgetary purposes. During the detailed design phase the analyst has a full package of information at his disposal. This would contain detailed drawings for dimensions and finishes, all processes required and process parameters. Even product support and its reliability will be known. Hence, cost estimates can be within the -5 to 15% range [7].

2.4.2. CERTAINTY AND RISK IN COST ESTIMATING

If a cost estimate is not accurate enough, but the project is still being launched, it becomes a risky project to pursue. Projects can be classified as certain, risky or uncertain.

A decision made under certainty is one in which each action always results in the same known outcome [7]. This never holds for estimating costs. A risky decision is one in which each action may result in more than one outcome, depending upon the state of nature having a known or presumably known probability. The sum of all probabilities is always one, hence all possible outcomes are known. A decision under uncertainty is one for which all outcomes are known. The outcome depends on the state of nature which holds a certain factor of unknown probability.

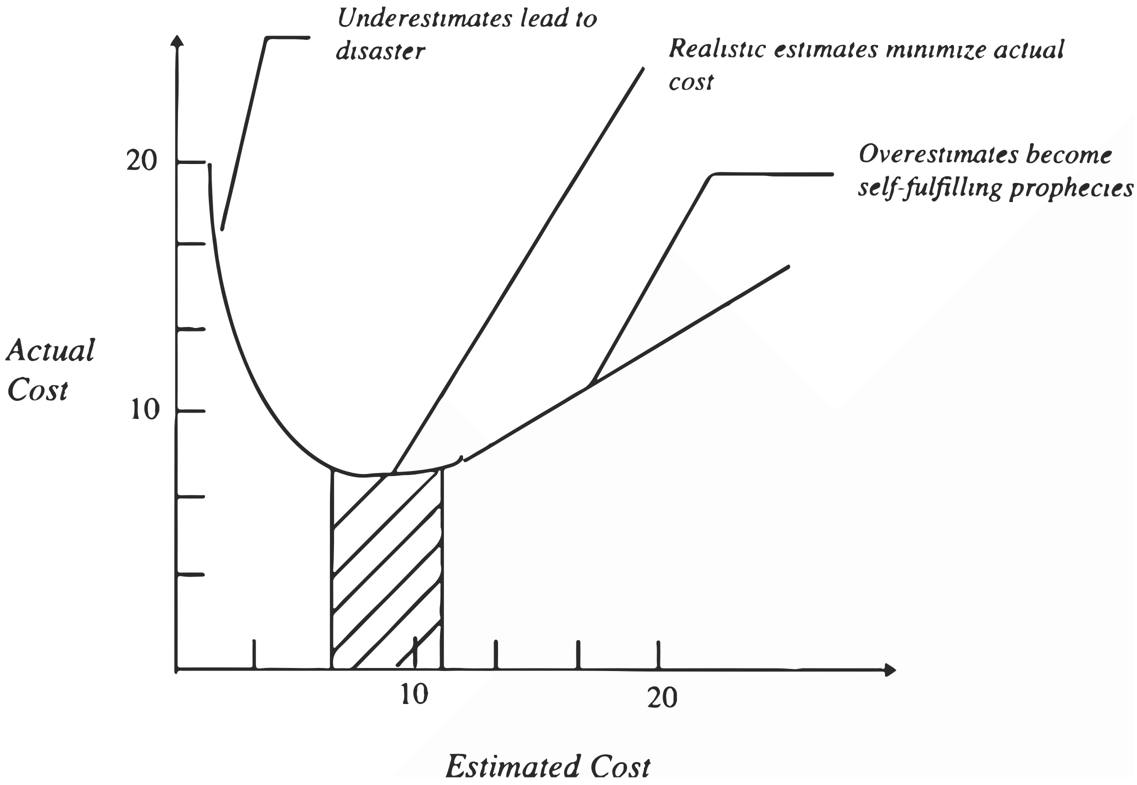


Figure 2.10: The Freiman curve [23]

Uncertainty can be dealt with by understanding four types of problems related to it: generation of individual cost element distribution, generation of additive distributions, generation of compound distributions and treatment of dependency between cost elements [7]. Uncertainty in the in-service or utilization phase is more difficult to deal with than uncertainty in the development and production phase [30]. This is because support contracts and especially supplier contracts give a high level of uncertainty since they could span multiple decades. Also during production the uncertainty in quality and timely delivery of goods by suppliers is a factor of uncertainty.

2.4.3. UNCERTAINTY ANALYSIS

Curran et al. states that the objective of uncertainty analysis is to determine the variations in data and errors in cost estimating [19]. A *Monte Carlo analysis* is used for which random variables need to be determine. The analysis is a simulation that is run many times in order determine the probability of an event as if one was performing a series of test and recording the results. A card game in a casino for instance could be simulated, hence the name Monte Carlo analysis. It is said that predictions based on the Monte Carlo method for cost and schedule overruns than the human intuition or other soft methods [38]. As said the Monte Carlo analysis needs a set of random variables determined using a *t-distribution*, which is even useful for small data sets and regression analysis.

The t-distribution is known for that a random variable Y only has a t-distribution if its probability density function is given by equation 2.3 and 2.4. Here, B and Γ are given Beta and Gamma functions, ν is the degree of freedom and as ν approaches infinity the t-distribution will become a normal distribution with median θ and variance α^2. This degree of freedom is the number of data points n minus the coefficients of the regression line. For y=A· x+B (ν=n-2) and for y=A·x (ν=n-1). The t-distribution also has a bell shape but has a higher variance and thus more spread out, hence its tail is heavier. What the t-distribution simply represents is the variance of the data used for regression analysis. A simpler version also exist, called the *Student's t-distribution.*

All cost components can be represented by normal distributions using the t-distribution method. The total cost can therefor also be represented by a normal distribution by aggregating those of the cost components. Such a distribution can shown with certainty that costs will stay between the minimum and maximum allowable costs set by the manufacturer [19].

$$f_t(y|\theta,\alpha,\nu) = c_t{-1}\left[1+\frac{1}{\nu}\left(\frac{y-\theta}{\alpha}\right)^2\right]^{-(\nu+1)/2}, -\infty < y < \infty, -\infty < \theta < \infty, \alpha > 0, \nu > 0 \tag{2.3}$$

$$c_t = c_t(\nu) = B\left(\frac{1}{2},\frac{1}{2}\nu\right)(\nu\alpha^2)^{1/2} = \frac{\Gamma(\frac{1}{2}\nu)\sqrt{\pi}}{\Gamma(\frac{\nu+1}{2})}(\nu\alpha^2)^{1/2} \tag{2.4}$$

2.5. ENGINEERING ECONOMICS IN AEROSPACE INDUSTRY

This section is to introduce some basic knowledge of economics related to manufacturing and operating aircraft. Engineering economic analysis helps to answer many difficult questions such as [56]: which projects are worth the investments? how to achieve long-term financial goals? how to compare different ways to finance purchases? The first part presents some economic definitions after which more aircraft manufacturer and airline specific topics will be treated.

2.5.1. INTRODUCTION TO ENGINEERING ECONOMIC ANALYSIS

Within businesses it is import to maintain profitability by running affordable projects. In order to develop and choose these projects they use engineering economic analysis. Several economical definitions and concepts are discussed in this section. Some may already be known to the reader, but is discussed just in case.

Engineering costs Cost structure describes how product cost is broken down and allocated to a certain entity such as a functional department, feature or product part. Classification of cost is performed by looking at the behavior of cost with respect to things such as the amount of manufacturing steps or total manufacturing time [20]. Costs are a prominent variable within business engineering and multiple types of cost exist. Fixed costs are costs that are constant or unchanging regardless of the level of output or activity. Variable costs on the contrary depend on the level of output or activity. The sum of both is the total cost. The average cost is of course the total cost divided by the number of units built, whereas marginal cost is the variable cost for one more unit to be built [56]. A company wants its revenues to be higher than its total costs, hence the breakeven point should be determined. This gives the amount of units needed to be sold to get in the profit region of a breakeven chart.

Sunk costs defines costs which already have been paid for as a results of past decisions. This type of costs is to be ignored in engineering economics since it focuses on present and future opportunities and thus costs only [56]. Opportunity cost is the cost made for using a resource in a certain activity instead of another. So one chooses to loose the opportunity or benefit of using that resource elsewhere.

Recurring costs are costs that are known in advance, anticipated for and occur at regular intervals. They can also be defined as cash flows that occur every year or every five years. Examples are annual maintenance to facilities or license fees. Nonrecurring costs on the other hand are unique expenses occurring at irregular intervals. They are difficult to predict and thus plan for, nor is it easy to anticipate the budgeting. Examples are costs for installing new machinery or close-down costs for terminating operations.

In order to manage costs and receipts cash flows are important. Cash flows are cash transactions, or stream of money, of a certain currency from one person or organization to another. Cash flow is the basis for engineering economic analysis and all cash flow is summarized in a Cash Flow Diagram (CFD) which shows size, sign, and timing of individual cash flows. In engineering projects expenses and receipts fall within one of the following categories [56]:

- First cost = expense to build or to buy and install.
- Operating & Maintenance (O&M) cost = annual expense, such as utilities, labor and minor repairs.
- Salvage value = receipt at project termination for sale or transfer of the equipment.
- Revenues = annual receipts due to sale of products or services.
- Overhaul = major capital expenditure that occurs during the asset's life.

Interest and equivalence If one can chose to have €100 today or in a year he would rather have it today since it will loose its value over time. Even though he does not need it now he can lend it to someone else and ask an interest rate. This is the same as keeping money on your savings account and receiving interest from your bank so the bank can use it to make money elsewhere with a higher return. Hence there is a time value of money in the form of willingness of people, businesses, and banks to pay an interest for using it [56]. There are multiple forms of interest such as simple interest or compound interest (interest on top of interest). If the value of money now equals that in the future because of interest rates, the sums of money is equivalent. Equivalence of money is an important aspect of comparing investments and is affected by three factors: the amount of sums, the times of occurrence of sums, and the interest rate [54].

Nett Present Worth (NPW) is a technique were the cash flows in the life of a project are discounted to time zero. It uses an interest rate that represents the minimum acceptable return on capital. A project having the highest NPW is preferred [54]. Another important indicator is the rate of return. It is the interest rate at which the benefits are equivalent to the costs or the NPW equals zero [56].

Depreciation Depreciation is a decrease in value of an asset to the owner or to the market. The value of machinery can depreciate due to deteriorating or by obsolescence. Accountants define depreciation as "allocating an asset's cost over its useful or depreciable life". Depreciation is a non-cash cost which requires no exchange in currency. Depreciation must be considered in after-tax economic analysis. Business assets are only optional for depreciation if they meet the following requirements [56]:

1. The asset should be used to create company income.
2. The asset must have a useful life that can be predicted and is longer than one year.
3. The asset must decay, wear out, hence must loose value to the owner or market.

According to Doganis the purpose of depreciation is twofold. First of all it aims to spread the costs of an aircraft over its entire life. Second, it allows to put money out of revenues in a reserve fund which in turn can be used to pay of any loans with which the the aircraft was bought [26].

Inflation Inflation is the effect of money loosing purchase power. Hence, future euros are less valuable than present euros. If one speaks of the cost of an aircraft today one speaks of Actual Euro (A€) which includes inflation. Often euros, or other currencies, are expressed in terms of a constant purchase power base year (e.g. 2013-euros). They carry no effects of inflation and are called Real Euro (R€) or constant euros. The relation between both type of euros is defined in equation (2.5). Here n is the number of years and $\bar{f}$ the average inflation rate.

$$Re = \frac{1}{(1+\bar{f})^n} \cdot Ae \tag{2.5}$$

The opposite of inflation can happen as well and is called deflation. These phenomena are important in comparing projects and thus decision making. The change in purchase power is expressed as inflation rate. It has an influence on interest rates as well. Real interest rates are rates accounted for inflation.

The learning curve In 1936 Wright introduced the concept of the learning curve. The learning curve gives the relation between the unit cost of an aircraft as a function of the number of aircraft produced. By repeating activities performance becomes faster and more accurate. The learning curve captures this increase in performance. As the output of an activity doubles, the time or cost required will reduce by a certain percentage. This percentage is called the learning-curve percentage or learning-curve rate [56]. This phenomena is represented by equation 2.6. Here $\mathrm{T_N}$ is time required for the $\mathrm{N^{th}}$ production unit, $\mathrm{T_{initial}}$ time required for the first production unit, N the number of completed units, and b the learning curve exponent. This exponential term is a function of the efficiency of a company's internal processes, new technology and the complexity of the design [22].

$$\mathrm{T_N} = \mathrm{T_{initial}} \cdot \mathrm{N^b} \tag{2.6}$$

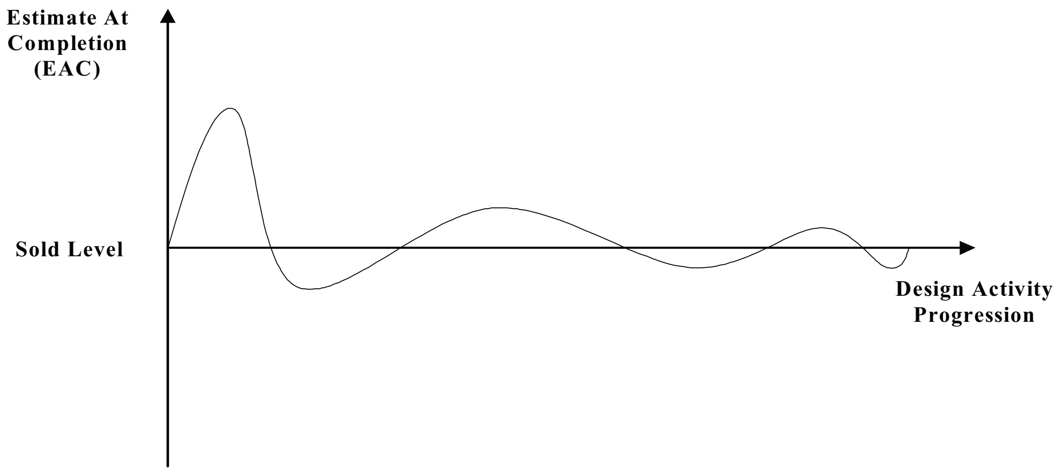


Figure 2.11: Monitoring EAC cost with respect to sold level cost as function of design activity progression [20]

Cost accounting in estimating costs Cost accounting is the basis of what a company sees as the cost of building a product and hence for cost estimating. Some methods will see aspect of building that will not be seen as direct cost whereas other methods will. A popular method is ABC. Some of its features and benefits will be described in short.

Traditional management accounting methods are used in times when product diversity was low, production processes where mainly driven by direct labor, and information processing was expensive. Nowadays industries are using more advanced technologies and are facing a more global competitive environment [40]. Overhead cost is a good example of how things could go wrong using the traditional methods. Overhead is mainly allocated based on direct labor cost. As companies started to automate, the amount of direct labor decreases while so called 'hidden' cost could rise dramatically to 50% while direct labor could become as low as 5%. The term hidden cost states all cost associated to documentation, depreciation, engineering changes, rework, inspection, and repair.

Contract bidding A selling price is the target price for the contract. The target cost is the selling price minus the target profit. The target price is often defined in the Request for Proposal (RFP) [20]. First a company will make a top-down cost estimate so to set a first target cost estimate. The company will also define its target profit, which is only bounded by maintaining market competitiveness. Next a bottom-up estimate will be made based on the Bill Of Materials (BOM) to see if the company can meet his target cost. If it seems that they fail to meet the cost target a company can do four things:

- They can discuss with the top-down estimators to raise the target cost, based on their own findings.
- They can revise the bottom-up estimate to lower it.
- They can perform both previous actions.
- They can decline the offer of work.

However, if the company meets the target cost it becomes the sold level cost which the company is mandatory to meet after the contract has been signed. All additional costs made have to be absorbed by the company self and is why the cost estimation is so important. During production the company keeps track of current project cost by monitoring so called Estimation at Completion (EAC). This is a function design activity progression and is with respect to the sold level cost, see figure 2.11. Having an EAC lower than sold level cost is good, but if it is higher companies can use DFM, Lean Manufacturing or Sigma Six to temper the cost exceeding.

2.5.2. ENGINEERING ECONOMICS RELATED TO AIRCRAFT MANUFACTURERS

The production and design of an aircraft is complex and involves a high amount of sub-components and activities. The costs can be classified as [21]:

- *Material costs.* This can be divided into raw material and finished material costs.

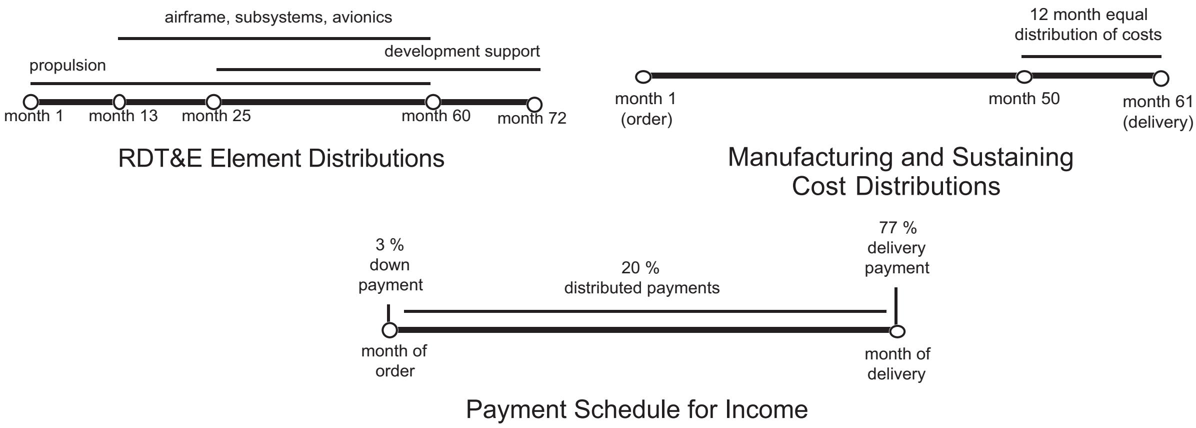


Figure 2.12: Example of payment schedule for five year production time [54]

- *Fabrication costs.* This is fundamental in manufacturing cost structures and consist of cost drivers such as geometry, technical specifications, manufacturing philosophies, and labor-rates.

- *Assembly costs.* Uses the same cost drivers as fabrication costs.

- *Support costs.* These are costs associated with quality inspection after production. It is the costs of rework and redesign. These costs are relatively small and quite hard to determine. Normal values are 5% of the total manufacturing costs, which is the sum of material, fabrication, and assembly costs.

- *Amortization costs.* This includes the costs of tooling and, methods, and design which are non-recurring.

- *Miscellaneous costs.* This includes costs that are additional and unavoidable. Examples are costs of insurance and packaging, but also unforeseen costs for manufacturing of the product. Like support costs this is a small fraction of all the costs. Curran et al. sets this costs component to 5% of the total costs [21].

These cost components can be determined for each part of the aircraft. An aircraft is often divided into the parts: wing, fuselage, engines, landing gear, empennage, and systems.

Unit Production Cost (UPC) The UPC represent the airframe manufacturing costs for classes of aircraft. Also the theoretical First Unit Cost (FUC) can be determined by summing costs for airframe, avionics and instrumentation, propulsion, and final assembly. Engine costs are most often estimated on thrust, the cruise Mach number, and quantity produced [54].

Selling price The selling price of an aircraft is obtained by combining recurring and nonrecurring costs and dividing it by the total number of aircraft to be produced to give the average cost per aircraft. Next a profit is added which yields the selling price [54].

Aircraft manufacturer's cash flow The cash flow of an aircraft manufacturer is based on the RDT&E cost, manufacturing and sustaining cost, and annual income. The five elements of RDT&E are: airframe development, subsystem development, avionics development, propulsion development, and development support. Manufacturing costs are the same as for UPC. The sustaining cost equals the total production cost minus the cost of operational vehicles and the profit fee of the manufacturer. Sustaining cost is defined by the cost of airframe and engine spares, facilities, sustaining engineering, sustaining tooling, ground support equipment, technical data, miscellaneous equipment, training equipment, initial training, and initial equipment. The income of an aircraft manufacturer start with the down payment of its buyer, normally 3% of the purchase price. Next approximately 77% follows on delivery and the rest is equally distributed over the months between order and delivery [54]. An overview of how cost and income are distributed for a production time of five years is shown in figure 2.12.

2.5.3. ENGINEERING ECONOMICS RELATED TO AIRCRAFT OPERATORS

The operator of aircraft can be airlines, private companies, lease companies, and individuals. The focus of the thesis will lie on airlines only. The way costs of airlines are broken down differ per airline as it depends on the purpose of the break down, hence the information it must show. Four key requirements must be met by this cost information: it must function as a management and accounting tool, it must show cost of flight and route for operating decisions, it should serve as an input for pricing strategies, and finally it must be able to evaluate investments, for instance for new aircraft. The next section will give the breakdown of costs according to the traditional approach.

THE TRADITIONAL APPROACH TO AIRLINE COSTS

Most airlines separate their accounts into operating and non-operating. Non-operating are all costs and revenues that do not directly relate to the air services of the airline. The should not be incorporated into analysis of how well an airline is performing since it is not part of their core business. Operating costs and revenues are the best performance indicators. In general non-operating factors are [26]:

- The profits or losses associated with retirement of property and equipment.
- The interest received from banks or other deposits, but also the interest paid on loans.
- The profits and or losses from affiliated companies. Some airlines are shareholders in other airlines or even non-aerospace companies.
- The gains or losses related to other economic dependencies, such as currency fluctuations or sales of shares, bonds, and other securities.
- Subsidies from government or taxes on profits or other corporate taxes.

The operating costs are classified into DOC and IOC. DOC are specified as all costs that are aircraft type dependent, hence all expenses related to keep the aircraft flying. IOC are more or less fixed and relates on the passengers. The breakdown of DOC is as follows [26]:

Direct Operating Cost

1. Flight operations
   - *Flight crew salaries and expenses.* Hourly flight crew costs multiplied with block time for the route.
   - *Fuel and oil.* Is based on fuel throughput charges of the airport, fuel handling charges by supplier, and relevant fuel taxes by governments.
   - *Airport and en-route charges.* Airport charges vary per airport and consists of a landing fee depending on Maximum Take-Off Mass (MTOM) and a passenger charge based on departing passengers boarded at the airport. En-route charges are route navigation services and other aids used while flying, landing, and take-off.
   - *Aircraft insurance.* This is a small cost component and is a percentage of the aircraft purchase price. This percentage ranges between 1.5-3% and depends on total number of aircraft and geographical areas. Airlines can even insure itself against warfare.
   - *Rental/lease of flight equipment/crews.* (Rental could also fall under depreciation). Comes in two types. First is operating lease, which is generally for five years and ownership rests with the lessor. The second is financial lease, in which after ten years the ownership is transferred to the airline.
2. Maintenance and overhaul
   - *Engineering staff costs.*
   - *Spare parts consumed.* Also includes costs of workshops, maintenance hangars, and offices.
   - *Maintenance administration (could be IOC).*
3. Depreciation and amortization
   - *Flight equipment.*

- *Ground equipment and property (could be IOC).*
- *Extra depreciation (in excess of historic cost depreciation).*
- *Amortization of development costs and crew training.*

Maintenance costs are difficult to classify since it is a broad discipline. There are many levels of maintenance all with different cost rates. One example of maintenance categories used in the US is: airframe maintenance, engine maintenance, and maintenance burden. Some airlines structure their maintenance costs per aircraft type. This allows the conversion of maintenance costs per block hour flown.

For depreciation airlines often use straight-line depreciation with 0-15% residual value. The depreciation period depends on aircraft type (size, age, technology) and the airlines financial status. During a crisis they tend to lengthen the period to reduce annual costs. After the depreciation policy is determined annual costs can be calculated. Increasing the utilization of the aircraft lowers the hourly depreciation costs and is why airlines push daily and annual utilization. The cost breakdown for IOC is as follows [26]:

Indirect Operating Cost

1. Station and ground expenses
   - *Ground staff.* All staff for handling and servicing of aircraft, passenger and freight.
   - *Buildings, equipment, transport.*
   - *Handling fees paid to others.*
2. Passenger services
   - *Cabin crew salaries and expenses (could be DOC).* This includes expenses such as cost associated with overnight stops and training costs.
   - *Other passenger service costs.* Cost of in-flight catering, cost of accommodation for transit flights, cost of other facilities on the ground, and cost due to delays in flights.
   - *Passenger insurance.*
3. Ticketing, sales, and promotion
   - *General and administration.*
4. Other operating costs

The station and ground expenses logically are the highest at an airline's home base. Since the crisis in 2001-2004 outsourcing of handling at small bases became trending and served the goal of reducing costs. Low-cost carriers adopted this strategy as one of the principles of their business model.

It should be noted that staff expenses for cabin crew are stated as IOC since they are allowed to work on different type of aircraft, whereas pilots and co-pilots are limited to one aircraft type. Hence, these costs are not aircraft type dependent. Passenger insurance premiums are determined based on the total number of passengers transported by an airline based on the previous year. The premiums also depend on the airline's safety record, the regions it operates in, and the specific type of insurance it covers.

Ticket, sales, and promotion costs are related to the staff engaged, offices and accommodations, call centers, reservation systems and internet website.

General and administrative costs are small compared to other cost categories. This is because overhead costs, when directly related to a specific activity should be included in operational cost of that activity. It is not a proper inter-airline comparison factor.

The final category is that of other operating costs. If some costs cannot be allocated to a certain account it can be stated here. If this account is to high it is a clear indication of bad cost control or inadequate accounting procedures.

Airlines look at euros per Revenue Passenger Mile (RPM) ($\$/RPM$) and is a function of the euros per Available Seat Mile (ASM) ($\$ASM$) and the load factor, see equation 2.7. The airline's Return on Investment (ROI) is determined for 110%, 120%, 130% and 140% of the acquisition costs. It uses the NPW of the cumulative net cash flow. The Airline Net Cash flow (ANC) is given in equation 2.8, where A_{rev} is the annual revenue, S_{value}

the salvage value, $\mathrm{Inv_{init}}$ the initial investment, D the depreciation, I the annual interest, and Tax the annual income tax [54]. The annual revenue is based upon on the capacity of aircraft, the load factors, average yields from different class configurations, stage length, intensity of use, and block time of flights. This is represented by equation 2.9.

$$\$/\mathrm{RPM} = \frac{\$/\mathrm{ASM}}{\mathrm{load_{factor}}} \tag{2.7}$$

$$\mathrm{ANC} = \mathrm{A_{rev}} + \mathrm{S_{value}} - \mathrm{Inv_{init}} - \mathrm{TOC} + \mathrm{D} + \mathrm{I} - \mathrm{Tax} \tag{2.8}$$

$$\mathrm{A_{rev}} = (\mathrm{AVGY_i} \cdot \mathrm{NP_i} \cdot \mathrm{LF_i}) \cdot \mathrm{SL} \cdot \frac{\mathrm{U}}{\mathrm{BT}} \tag{2.9}$$

TRENDS IN AIRLINE COSTS

In the past two decades the percentage DOC of Total Operating Cost (TOC) has increased from 49% in 1994 to 61.9% in 2007. This increase was due to two reasons. First, the extreme rise in fuel prices. Between 1994 and 2007 it rose from 11.4 to 25.4%. Second, cost of ticketing and sales IOC decreased due to an increase in online sales. In general the DOC of an airline should lie between 55 and 70% of TOC. The costs associated with maintenance and depreciation were not affected by inflation and stayed constant in the past two decades. This is due to the increase use of wide-body aircraft which are technically more competent and required less maintenance. Also their annual productivity was higher than older aircraft which compensated the higher purchase price and hence depreciation in real terms was constant.

It is interesting to look at the relation between cost and aircraft size [66]. Different studies between 1970 and 1974 have shown that for larger aircraft the cost per seat per mile is less than for smaller aircraft. In 1985 it was shown by examining six aircraft types that the cost per seat per mile decreases with increasing stage length [9].

3

The Methodology of the Model

As was seen in Section 2.2 many estimating techniques exist. Each technique has its advantages, disadvantages and limitations. Due to the fact that most cost estimating techniques are based on either detailed product information or historical data not one technique is directly appropriate to develop a cost estimating model for unconventional aircraft. This is since the model is used in the conceptual design phase, hence no detail product information is available. Also, none of the unconventional aircraft have ever been build and operated before, hence no historical data is available. Due to these reasons two decisions are. First, there is no preference for either a top-down or bottom-up approach, see Section 2.2. Therefore, a model is developed that estimates the cost using both approaches. Secondly, a cost model for conventional aircraft is developed first. This model is elaborated to make it compatible with unconventional aircraft. The entire process is shown in Figure 3.1. It should be noted that the model is split in production and operating cost.

This chapter presents an overview of the methodology in Section 3.1. Two different methods are used for the cost estimation model and are explained in Sections 3.2 and 3.3. In these section the focus lies entirely on conventional aircraft. Section 3.5 presents implications of unconventional configurations and how the model is made compatible with these configurations. Finally, Section 3.6 explains an extra feature of the model by combing both methods.

3.1. Overview of the model

As stated in the introduction of this Chapter two methods are used. The methods are classified as *top-down* and *bottom-up*. This is in line with the traditional classification in literature as was presented in Section 2.2. An overview of the model for both methods is shown in Figure 3.2. Both methods are shortly explained in this Section.

The steps involved in obtaining a cost estimate using the top-down method are highlighted in blue in the top part of Figure 3.2. For the top-down approach the parametric estimating technique is used 2.2.3. It is therefore based on historical data. Data is collected into a database which contains aircraft parameters on dimensions, weights and performance. A regression analysis is performed on these parameters and several CERs are obtained for each part of the aircraft. These CERs are applied to the design parameters of the design aircraft, resulting in a price per part of the design aircraft. Adding all parts together gives a total list price of the aircraft. This list price is denoted *initial list price*. Using reverse engineering the Unit Cost (UC) of the aircraft is determined. The NRC is calculated using a method by Roskam [60]. As can be seen by the dotted line, the method for NRC uses part prices as well. Next the RC is determined. When the initial list price, UC,

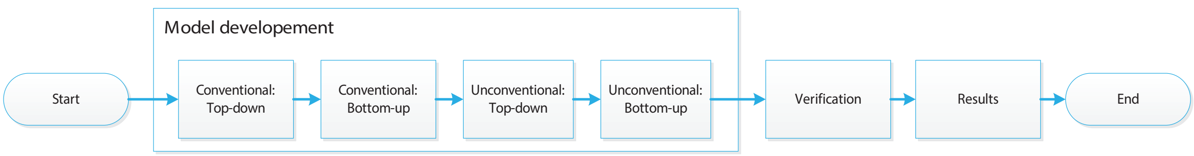


Figure 3.1: Research outline for developing the cost model.

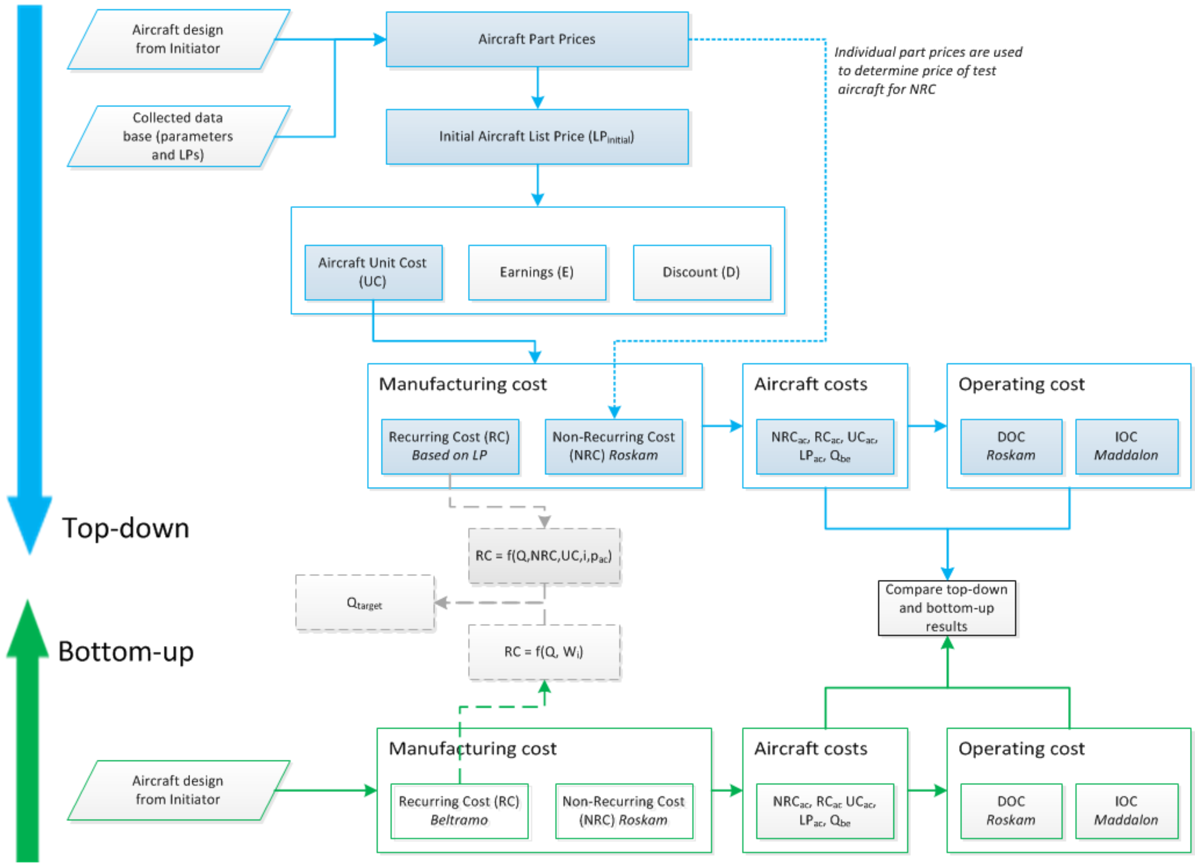


Figure 3.2: Overview of the cost estimation model.

NRC and RC are known the quantity of aircraft for break-even Q_{be} is determined. The DOC and IOC are determined using respectively methods from Roskam [60] and Maddalon [52]. The outputs of these operational cost methods depend on the initial list price of the aircraft and part prices.

The bottom-up process is highlighted in green in Figure 3.2. For the bottom-up approach no historical data is needed. The RC is determined using a method described by Beltramo [11]. This method does require the weights of individual aircraft components. Almost all of these weights are available in Initiator. The NRC is determined in the same way as the top-down approach, thus by using Roskam. When both NRC and RC are known the UC and list price are determined. Also for the bottom-up approach Q_{be} is calculated. Again, the DOC and IOC are determined using respectively methods from Roskam [60] and Maddalon [52]

Both methods give different cost estimates which are compared and discussed in Chapter 6. The preference for one of the methods is presented in the conclusions, see Chapter 7.

3.2. TOP-DOWN METHOD

This section will explain the top-down method in more detail. The unique feature of this method is that most of the life cycle costs depend on the initial list price obtained from historical data. First, this process of obtaining the intitial list price is presented in Section 3.2.1. Secondly, Section 3.2.2 explains how the manufacturing costs are determined. Finally, the methods used to determine the operating cost are presented in Section 3.2.3.

3.2.1. INITIAL LIST PRICE

The initial list price is determined using the parametric technique, a top-down technique as explained in section 2.2. The process of developing a parametric estimation model requires sufficient knowledge about the product and project. Without this knowledge potential parameters cannot be identified, causality cannot be guarantied and the process will be time consuming. The steps that need to be taken to determine the initial list price are presented and explained next.

Step 1: Collecting data. The first step is to gather enough data from existing aircraft. Per aircraft, dimensions, weights and performance parameters are required. Also their list prices need to be obtained. Data is available on the web and in literature, however collecting them is time intensive. Also, there exist differences in parameter values between different sources. The parameters are often given as a range. In both cases the average value is taken unless one is deemed more trustworthy. A database of 44 different turbo-fan powered aircraft is used in this study. These aircraft included short, medium and long haul aircraft. A total of 58 parameters are listed in this database. The corresponding list prices are obtained from *Jane's, all the world's aircraft* [39], Lloyd's Aviation Department [8] and prices listed by aircraft manufacturers online [5, 16]. All list prices are given in US dollars since this is standard in aircraft industry.

Step 2: Normalizing the data. The data form step 1 is normalized to obtain a direct relation between the parameter and the list price. The general process to normalize any data set is shown in Figure 3.3. This process is explained in the Handbook of parametric estimation [6]. The list prices in the database are converted to 2013 US$using inflation rates. Finally, the database is categorized according to age. This is done since technology has changed since the dawn of commercial aviation. The initial service date of the 44 aircraft are used to categorize them in age classes. In total three different age classes are generated.

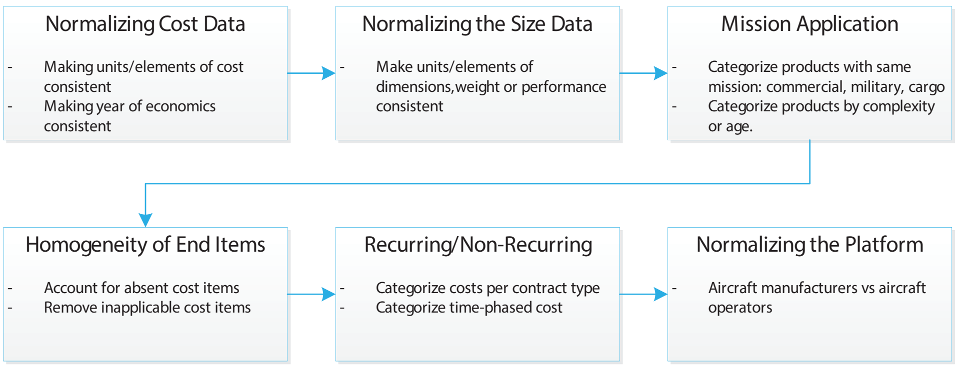


Figure 3.3: Process of data normalization [6].

Step 3: Excluding outliers. The quality of the database is very important. Data points could contain errors due to typos or unreliable sources. These data points are identified and excluded from the regression. Normally, one inspects the database and obtained regression plots and looks if any data is out of order. If so an investigation is started to determine the quality of the data point. Only if one is absolutely sure the data point in question is an outlier it needs to be removed. Removal of an outlier is done manually.

Step 4: Segmenting into parts. At this point the database is ready to be subjected to a regression analysis. However, in order to get more insight in the price of individual aircraft parts the database is first segmented into the different aircraft parts. Six parts are qualified: *fuselage, wing, horizontal tail, vertical tail, engines and landing gear*. The parameters that cannot be linked to one of these parts are collected in a separate database called *others*. Instead of having one database now there are seven with the parameters divided as shown in table 3.1. Each of these databases have the same aircraft and list price. In order to get a price per aircraft part the list price is divided among the databases of all the parts. This is done by stating the percentage of this list price per aircraft part. These percentages may differ for single and double aisle aircraft, two or four engine aircraft or other design differences. The assumed percentages could be obtained from literature or from manufacturer experience. The database containing the *other* parameters will retain the original list price since these parameters are related to the entire aircraft.

Step 5: Perform regression analysis. The seven databases are subjected to a regression analysis. This is done using the Statistical Toolbox in MATLAB. The Statistics Toolbox provides statistical and machine learning algorithms and tools for organizing, analyzing, and modeling data [4].

The Fit Nonlinear Regression Model *fitnlm* is used for the regression analysis since it can handle both lin-

Table 3.1: Segmentation of parameters for regression analysis

Fuselage	Wing	HT	VT	Engine	Landing Gear	Others	
l_f	L/D_{cr}	S_{ht}	S_{vt}	N_e	$N_{lg,wheels}$	PLM	V_{app}
h_f	$C_{L,max,to}$	b_{ht}	b_{vt}	$T_{s,1}$	$N_{struts,main}$	h_{cr}	SFC_{cr}
w_f	$C_{L,max,landing}$	AR_{HT}	AR_{VT}	M_e		M_{cr}	SFC_{loiter}
	V_{tank}	λ_{ht}	λ_{vt}	l_e		R	DOIS
	S_w	$\Lambda_{1/4c,ht}$	$\Lambda_{1/4c,vt}$	d_e		$C_{D0,clean}$	PAX_{2class}
	b_w	$C_{v,HT}$	$C_{v,VT}$			MTOM	$M_{pax,2class}$
	AR_w		T_{tail}			EOM	
	λ_w					MLM	
	$c_{w,root}$					MZFM	
	$\Lambda_{1/4c,w}$					MPFM	
	$X_{LE,root}$					L_{to}	
	y_{kink}					$L_{landing}$	
	c_{kink}					V_2	

ear and non-linear functions. It requires an independent variable (database parameter), dependent variable (list price), the model function (regression function) and initial values of the model coefficients as input. The regression functions used are:

1. Linear: $y = a \cdot x + b$
2. Quadratic: $y = a \cdot x^2 + b \cdot x + c$
3. Exponential with additive: $y = a + b \cdot x^c$
4. Exponential: $y = a \cdot x^b$

Where *a*, *b* and *c* are coefficients that need to be determined. *fitnlm* estimates model coefficients using an iterative procedure starting from the initial values. These initial values are determined by evaluating the data for each parameter. For each function type this is done as follow:

- Linear: $a_0 = \frac{y_{max}-y_{min}}{x_{max}-x_{min}}$, $b_0 = y_{max} - a_0 \cdot x_{max}$
- Quadratic: $a_0 = 1$, $b_0 = \frac{y_{max}-y_{min}}{x_{max}-x_{min}}$, $c_0 = y_{max} - b_0 \cdot x_{max}$
- Exponential with additive: $a_0 = y_{max} - b_0 \cdot x_{max}$, $b_0 = \frac{y_{max}-y_{min}}{x_{max}-x_{min}}$, $c_0 = 1$
- Exponential: $a_0 = \frac{y_{max}-y_{min}}{x_{max}-x_{min}}$, $b_0 = 1$

The non-linear model represents a least-squares fit as a response to the data, returned as an object. Fitnlm uses a constant error model, also called additive error [4]. The object returns output for the coefficients of the regression and for the overall regression function. Both are discussed next.

Fitnlm returns the coefficients of the regression function. For each coefficient the following properties are determined:

- **Estimate.** This is the value of the coefficient as estimated by fitnlm.
- **Standard Error (SE) of the estimate**. It gives the accuracy of the predicted estimate. It is a function of Pearson's product-moment correlation coefficient R^2 and the sum of squared errors in y-directions SSY. R^2 is obtained using Equation 3.1.

$$R^2 = \frac{\sum_{i=1}^{n}\left((X_i-\mu_x)\cdot(Y_i-\mu_y)\right)}{\sqrt{\sum_{i=1}^{n}(X_i-\mu_x)^2}\cdot\sqrt{\sum_{i=1}^{n}(Y_i-\mu_y)^2}} \tag{3.1}$$

Equation 3.2 shows how SSY is determined.

$$SSY = \sum_{i=1}^{N}\left(Y-\mu_y\right) \tag{3.2}$$

Here, N is the number of data points, Y is the the value of the list price of each data point and μ_y is the mean of these list prices as listed in the database. The SE can now be determined based on Equation 3.3. Equation 3.2 shows how SSY is determined.

$$SE = \sum_{i=1}^{N} \left(\frac{(1 - R^2) \cdot SSY}{N - N_{rc}} \right) \tag{3.3}$$

N_{rc} is the number of regression coefficients in the regression function. Hence, the SE is determined using the error's degrees of freedom, which is represented by the denominator [36].

- **t-statistic.** This is a test that to see if the coefficient is zero. First, a null hypothesis H_0 is formulated. If the hypothesis is true the coefficient does not contribute to the relation between the dependent and independent parameters. This is the case if the t-stat value is small. It is obtained by dividing the coefficient's estimate, c_i, by the SE.

$$tStat = \frac{c_i}{SE} \tag{3.4}$$

  If the coefficient is large and the SE small one can say that the coefficient is probably different from 0. Hence, H_0 is rejected and the alternative hypothesis H_a is accepted. H_a states that the coefficient contributes to the regression function [36].

- **p-value of the t-statistic.** Above, a value for the t-stat was obtained. However, nothing is said on how large the value should be in order to reject H_0. The so called p-value is used to make this judgment. It is obtained by comparing the t-stat value with the *Student's t-distribution*. The Student's t-distribution describes how the mean of a sample with a certain number of observations, in this case the parameters, is expected to behave. The t-distribution is symmetric and bell-shaped, like the normal distribution. However, the tails are more heavy. The p-value is the probability of seeing a result as extreme as the one obtained by the regression analysis. If, for instance, 95% of the t-distribution is closer to the mean than the t-stat value found, the p-value is 5% or 0.05. This is also called a significance level of 5%. Hence, there is only a 5% chance the resulting value of the coefficient is wrong or came up randomly. Since the tails of a t-distribution are more heavy the chance of heaving a random value is larger. Therefore, it is useful for understanding the statistical behavior of random quantities. Normally, a p-value of 0.05 or less is sufficient to reject H_0. Note that the size of the p-value says nothing about the effect the coefficient has on the regression function [36].

Besides returning these parameters for the individual coefficients the model also determines the values for the overall regression function. This is done in using the same methods. However, the calculation of the p-value differs. For the overall regression model also the RMSE is determined. Both parameters are explained next.

- **Overall p-value.**Fitnlm does not return the p-value of the regression function. Hence, an other function in Matlab is used, called *coefTest*. This function computes the p-value for an *F-test*. An F-test is based on a F-distribution. This differs from a t-distribution since the F-distribution is skewed. Therefore the mean is located further away from the tail. H_0 this time states that all coefficients, except for the intercept term, are 0. Again, a p-value equal or less than 0.05 is required to reject H_0. The p-value of the regression function also quantifies if there actually exist a relation between predictor variable, the aircraft parameter, and the response variable, the list price [36].

- **RMSE.** The root mean squared error quantifies the errors between the data points in the database and the estimated values for those data points. It represents the standard deviation of all error terms and thus the accuracy of the model. It should be noted that the RMSE represents the entire model and is scale dependent. The latter means it can be used as a tool to compare different models of the same parameter. However, it can not be used to compare models of different parameters [36].

Since multiple regression functions are applied to a single parameter the best fit is used to make the estimate for the design aircraft. Selection is based on the value of R^2 and the p-value, which are saved for later use. Both values should meet a certain threshold. The regression with the highest R^2 and lowest p-value is chosen and applied to the parameter of the design aircraft.

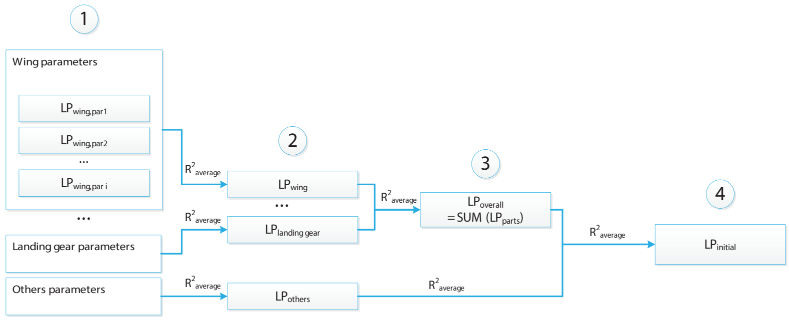


Figure 3.4: Process of obtaining the initial list price from the selected parameters.

Step 6: Determine the initial list price. The final step is to apply the qualified regression functions to the design aircraft. It should be noted that only regression functions of parameters are used for which a design value is known as well. The process of obtainig the initial based on the parts and class Others is shown in Figure 3.4 and is explained using the four steps in this Figure:

1. Per aircraft part a price is determined for each individual parameter. Each of the parts has an value for R^2 and RMSE. This is done for all six part classes and the class Others.

2. Per aircraft part one price is computed. The R^2 is used to give a certain weight to an individual price of a parameter, see Equation 3.5.

$$LP = \frac{\sum_{i=1}^{n} (R_i^2 \cdot LP_i)}{\sum_{i=1}^{n} R_i^2} = \frac{R^2_{PLM} \cdot LP_{PLM} + \ldots + R^2_{S_{wing}} \cdot LP_{S_{wing}}}{\sum_{i=1}^{n} R_i^2} \tag{3.5}$$

   Hence, a parameter with a high R^2 contributes more to the price per part. Again, this is done for all six part classes and the class Others.

3. Per part the average R^2 of the parameters forms the new R^2 of the total part. The total aircraft price according to the parts is computed by adding up all parts. The R^2 is again computed as the average of the individual parts. This step only holds for the part prices.

4. At this point there are two prices that represent the entire aircraft. First, the price according to the parts as obtained in step 3. Secondly, the price of the class Others obtained in step 2. Equation 3.5 is used for a second time to obtain the so called initial list price $LP_{initial}$. The final R^2 is again the average.

3.2.2. MANUFACTURING COST

The manufacturing cost can be divided into the cost for design and production phase and are respectively NRC and RC. The model will determine the NRC using the method of Roskam [60]. Roskam calls the design phase the Research, Development, Testing & Evaluation (RDT&E) phase. This method is suitable for both commercial and military aircraft and dates back to 1990. It is suitable for both conceptual and preliminary design phases.

NON-RECURRING COST

The NRC is divided into seven cost components [60]:

1. Airframe Engineering and Design Cost, C_{aed}

2. Development Support and Testing Cost, C_{dst}

3. Flight Test Airplanes Cost, C_{fta}

4. Flight Test Operation Cost, C_{fto}

5. Test and Simulation Facilities Cost, C_{tsf}

6. Cost of Profit, C_{pro}
7. Cost to finance the RDTE phase, C_{fin}

All seven cost components are introduced next. It should be noted that the values are converted to the desired year US$. This is done using historical inflation rates and is represented by a so called Cost Escalation Factor (CEF).

Airframe Engineering and Design Cost The cost for airframe engineering and design is a function of the total engineering man hours required MHR_{aed} and the Engineering rate per hour R_{eng}, see Equation 3.6.

$$C_{aed} = MHR_{aed} \cdot R_{eng} \tag{3.6}$$

In turn MHR_{aed} is a function of a so called aeronautical manufacturers planning report weight W_{ampr}, the maximum speed in knots $V_{max,kts}$, the number of aircraft build in RDT&E phase, a program complexity factor F_{diff} and a factor that represents the degree of Computer Aided Design (CAD) used F_{cad}. W_{ampr} is a fraction of the Empty Operating Mass (EOM) and is assumed to be 49% of it as suggested by Roskam [60].

$$MHR_{aed} = 0.0396 \cdot W_{ampr}^{0.791} \cdot V_{max,kts}^{1.526} \cdot N_{rdte}^{0.183} \cdot F_{diff} \cdot F_{cad} \tag{3.7}$$

Development Support and Testing Cost The cost for development, support and testing is a function of the same parameters introduced above.

$$C_{dst} = 0.008325 \cdot W_{ampr}^{0.873} \cdot V_{max,kts}^{1.890} \cdot N_{rdte}^{0.346} \cdot CEF \cdot F_{diff} \tag{3.8}$$

Flight Test Airplanes Cost During the RDT&E phase test aircraft are required. The cost to manufacture them is given in Equation 3.9.

$$C_{fta} = C_{ea} + C_{man} + C_{mat} + C_{tool} + C_{qc} \tag{3.9}$$

- Cost of engines and avionics

$$C_{ea} = C_e \cdot N_e + C_{prop} \cdot N_{prop} + C_{ac} \cdot \left(N_{rdte} - N_{st}\right) \tag{3.10}$$

  It depends on the number of engines and propellers and their cost C_e and C_{prop} and the cost of avionics. The total is multiplied with the number of aircraft used for flight testing. This equals the number of aircraft required in RDT&E phase minus the aircraft required for static tests.

- Manufacturing cost

$$C_{man} = MHR_{man} \cdot R_{man} \tag{3.11}$$

  The number of man hours required for manufacturing MHR_is multiplied with the manufacturing rate R_{man}. The first is given by Equation 3.12.

$$MHR_{man} = 28.984 \cdot W_{ampr}^{0.740} \cdot V_{max,kts}^{0.543} \cdot N_{rdte}^{0.524} \cdot F_{diff} \tag{3.12}$$

- Material cost

$$C_{mat} = 37.632 \cdot F_{mat} \cdot W_{ampr}^{0.689} \cdot V_{max,kts}^{0.624} \cdot N_{rdte}^{0.792} \cdot CEF \tag{3.13}$$

  A factor for the type of material used is required F_{mat}.

- Tooling cost

$$C_{tool} = MHR_{tool} \cdot R_{tool} \tag{3.14}$$

  The amount of tooling hours required are given in Equation 3.15. pr_r is the production rate in units per month for the RDT&E phase.

$$MHR_{tool} = 4.0127 \cdot W_{ampr}^{0.764} \cdot V_{max,kts}^{0.899} \cdot N_{rdte}^{0.178} \cdot pr_r^{0.066} \cdot CEF \tag{3.15}$$

- Quality control

$$C_{qc} = 0.13 \cdot C_{man} \tag{3.16}$$

Flight Test Operation Cost

$$C_{fto} = 0.001244 \cdot W_{ampr}^{1.160} \cdot V_{max,kts}^{1.371} \cdot \left(N_{rdte} - N_{st}\right)^{1.281} \cdot CEF \cdot F_{obs} \tag{3.17}$$

F_{obs} represents the factor for stealth requirements. For commercial aircraft this factor should be set to 1.

Test and Simulation Facilities Cost The cost for test and simulation facilities is a factor of all prior cost components $C_{rdte,sub}$, see Equation 3.18.

$$C_{tsf} = F_{tsf} \cdot C_{rdte,sub} \tag{3.18}$$

F_{tsf} is the factor which represents the degree of test and simulation facilities required. $C_{rdte,sub}$ is given by Equation 3.19

$$C_{rdte,sub} = C_{ead} + C_{dst} + C_{fta} + C_{fto} \tag{3.19}$$

Cost of Profit The cost of profit is also a function of the previously introduced cost components.

$$C_{pro} = F_{pro} \cdot C_{rdte,sub} \tag{3.20}$$

Cost to finance the RDTE phase The final cost component represents cost to finance the RDT&E phase. Again, it is a factor of prior costs and is calucated using F_{fin}.

$$C_{fin} = F_{fin} \cdot C_{rdte,sub} \tag{3.21}$$

RECURRING COST

The RC is determined using the initial list price as determined in Section 3.2.1. This initial list price is split in the UC of the aircraft, the discount D and earnings E as shown in equation 3.22. The earnings is a predefined margin for the manufacturing to earn money on selling the aircraft. The discount allows a margin for negotiation with the customer. This discount is given to loyal customers and customers who order a large number of aircraft [47].

$$LP_{initial} = UC + D + E \tag{3.22}$$

The UC consist of the RC of the aircraft, the NRC per quantity of aircraft build Q and the investment costs I per quantity of aircraft build, see Equation 3.23.

$$UC = RC + \frac{NRC}{Q} + \frac{I}{Q} \tag{3.23}$$

The investment is the total NRC and corresponding interest paid over the production period. This is shown in Equation 3.24. Here a constant annual interest rate i is assumed, Q is the quantity to build and the production rate pr is per year. It should be noted that Q divided by pr gives the production life time in years.

$$I = NRC[(1+i)^{Q/p} - 1] \tag{3.24}$$

Equations 3.23 and 3.24 can be rewritten to give the RC for the top-down method of a single aircraft. The results is seen in Equation 3.25

$$RC_{td} = UC - \frac{NRC}{Q}(1+i)^{Q/pr} \tag{3.25}$$

3.2.3. OPERATING COST

As was stated in Section 2.5.3 the operating cost consist of DOC and IOC. Both are presented in this section. An overview of the operating cost breakdown is shown in figure 3.5

DIRECT OPERATING COST

Roskam provides a method for operating cost expressed in US$ per nautical mile [60]. The method for DOC uses the following cost components:

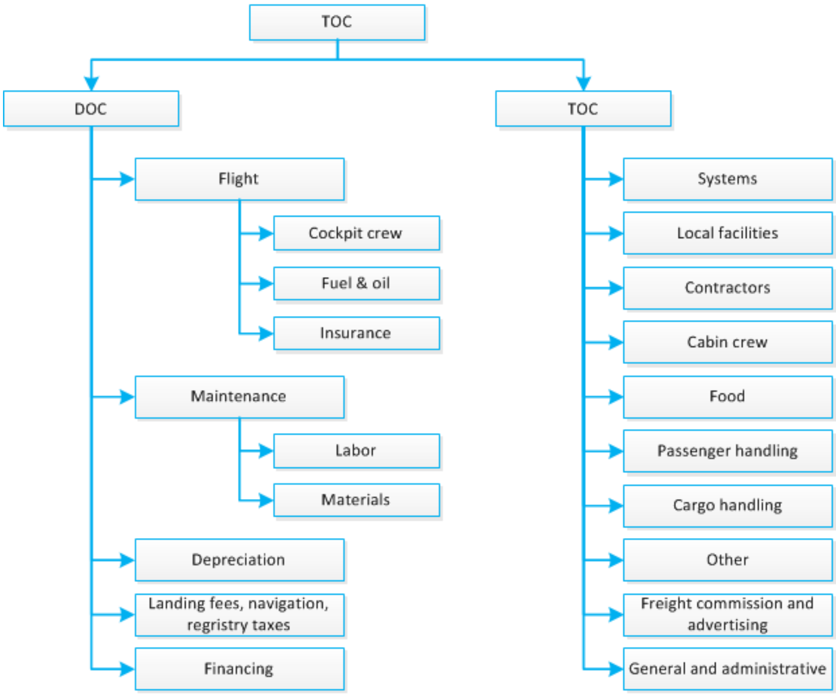


Figure 3.5: Breakdown of the operating cost [52, 60].

Cost of flight The cost of flight consist of three cost components. First, the cost for cockpit crew C_{crew}. The method distinguishes as cockpit crew members: captain, co-pilot and flight engineer. If the total block time of a flight is less than 10 hours one of each type is required. If the block time exceeds 10 hours, two of each type are required. The cost for each cockpit crew member is shown respectively in Equations 3.26, 3.27 and 3.28. The total cost of cockpit crew is determined by taking the sum of all, see Equation 3.29.

$$C_{crew,capt} = N_{capt} \cdot \frac{1 + K_{capt}}{V_{bl}} \cdot \frac{Sal_{capt}}{AFH_{crew}} + \frac{TEF}{V_{bl}} \tag{3.26}$$

$$C_{crew,co} = N_{co} \cdot \frac{1 + K_{co}}{V_{bl}} \cdot \frac{Sal_{co}}{AFH_{crew}} + \frac{TEF}{V_{bl}} \tag{3.27}$$

$$C_{crew,fe} = N_{fe} \cdot \frac{1 + K_{capt}}{V_{bl}} \cdot \frac{Sal_{fe}}{AFH_{crew}} + \frac{TEF}{V_{bl}} \tag{3.28}$$

$$C_{crew,cp} = C_{crew,capt} + C_{crew,co} + C_{crew,fe} \tag{3.29}$$

The second cost component is the cost for fuel and oil C_{fo}. It is determined by the weight of fuel W_{fuel} and oil W_{oil} used during the flight, the price of fuel PV_{fuel} and oil PV_{fuel}, and the density of fuel ρ_{fuel} and oil ρ_{fuel} see Equation 3.30.

$$C_{fo} = \frac{W_{fuel}}{R_{bl}} \cdot \frac{PV_{fuel}}{\rho_{fuel}} + \frac{W_{oil}}{R_{bl}} \cdot \frac{PV_{oil}}{\rho_{oil}} \tag{3.30}$$

Thirdly, the cost of insurance C_{ins}, see Equation 3.31. The annual insurance cost of the aircraft are based on the annual insurance rate i_{ins}, annual utilization U_{ann} and Aircraft Market Price (AMP). The latter is assumed to be equal to the list price.

$$C_{ins} = \frac{i_{ins} \cdot AMP}{U_{ann} \cdot V_{bl}} \tag{3.31}$$

The total cost of flight is given by Equation 3.32.

$$C_{flt} = C_{crew,cp} + C_{fo} + C_{ins} \tag{3.32}$$

Cost of maintenance The maintenance cost is based on the labor hours in block hours and materials required for the airframe and the engines. The labor hours required for the airframe is a function of the airframe weight, see equation 3.33.

$$MH_{af,bl} = 3 + \frac{0.067 \cdot W_{af}}{1000} \tag{3.33}$$

The labor cost for airframe maintenance is a function of the labor hours and the labor rate for maintenance r_{mt}.

$$C_{lab,af} = 1.03 \cdot \frac{MH_{af,bl} \cdot r_{mt}}{V_{bl}} \tag{3.34}$$

The labor hours for engine maintenance is a function of the total take-off thrust T_{to}, number of engines N_e and the hours between engine overhaul H_{em}, see Equation 3.35.

$$MH_{e,bl} = 0.718 + 0.0317 \cdot \frac{T_{to}}{N_e \cdot 1000} \cdot \left(\frac{1100}{H_{em}} + 0.1\right) \tag{3.35}$$

The cost of these labor hours for engine maintenance is determined by the labor rate,

$$C_{lab,e} = 1.34 \cdot \frac{N_e \cdot MH_e \cdot r_{mt}}{V_{bl}} \tag{3.36}$$

The cost of materials for airframe maintenance per block hour is based on the airframe price P_{af} and an aircraft type factor, see Equation 3.37. The latter is a factor based on the MTOM. If the MTOM exceeds 10,000 lbs, ATF = 1, if it is between 5,000 and 10,00 lbs, ATF = 0.50, and if it less than 5,000 lbs, ATF = 0.25.

$$C_{mat,af,bl} = 30 \cdot ATF + 0.79 \cdot 10^{-5} \cdot P_{af} \tag{3.37}$$

The cost of materials for airframe maintenance per nautical mile is shown in Equation 3.38.

$$C_{mat,af} = 1.03 \cdot \frac{C_{mat,af,bl}}{V_{bl}} \tag{3.38}$$

The cost of materials required for engine maintenance depends on the a factor for the attained period between engine overhaul K_{hem}, see Equation 3.39.

$$K_{hem} = 0.021 \cdot \frac{H_{em}}{100} + 0.769 \tag{3.39}$$

This factor is used to determine the material cost for the engine per block hour $C_{mat,e,bl}$ along with the engine price and Engine Spare Part Price Factor (ESPPF). See Equation 3.40

$$C_{mat,e,bl} = 5.43 \cdot 10^{-5} \cdot \frac{P_e \cdot ESPPF}{K_{hem}} \tag{3.40}$$

The total material cost for engine maintenance per nautical mile is given by Equation 3.41.

$$C_{mat,e} = 1.34 \cdot \frac{N_e \cdot C_{mat,e,bl}}{V_{bl}} \tag{3.41}$$

The final maintenance cost component for maintenance is cost related to applied maintenance burden C_{amb}. It is a function of a factor for applied maintenance burden for labor hours of airframe F_{af} and engine F_e and above mentioned cost components and parameters, see Equation 3.42.

$$C_{amb} = 1.03 \cdot \frac{F_{lab,amb} \cdot (MH_{af,bl} \cdot r_{mt} + N_e \cdot MH_{e,bl} \cdot r_{mt}) + \left(F_{mat,amb} \cdot (C_{mat,af} + N_e \cdot C_{mat,e}\right)}{V_{bl}} \tag{3.42}$$

The total maintenance cost is the sum of above mentioned costs as is seen by Equation 3.43.

$$C_{mt} = C_{lab,af} + C_{lab,e} + C_{mat,af} + C_{mat,e} + C_{amb} \tag{3.43}$$

Cost of depreciation The depreciation of aircraft parts is segmented as follow: airframe, engine, propellers, avionics, airframe spares and engine spares. All are a function of their original price and the depreciation period.

The depreciation cost of the airframe is given in Equation 3.44. As can be seen it is the price of the airframe P_{af} minus the price of the propellers P_{prop} and avionics P_{av} that is depreciated. This price is multiplied with a depreciation factor for the airframe $F_{depr,af}$ and is divided by the depreciation period of the airframe DP_{af}. Next these cost are converted to US$ per nautical mile by dividing it by the annual utilization in block hours and the speed in block hours V_{bl}.

$$C_{depr,af} = F_{depr,af} \cdot \frac{P_{af} - P_{prop} - P_{av}}{DP_{af} \cdot U_{ann} \cdot V_{bl}} \tag{3.44}$$

The engine depreciation cost is shown in EquationEquation 3.45. The depreciation cost is determined for the use of the engines. All engines are depreciated, hence it is multiplied by N_e. It requires a depreciation factor $F_{depr,e}$ and period (DP_e) for the engines.

$$C_{depr,e} = F_{depr,e} \cdot \frac{P_e \cdot N_e}{DP_e \cdot U_{ann} \cdot V_{bl}} \tag{3.45}$$

Propeller depreciation is similar to the engines. Only now a depreciation factor $F_{depr,prop}$ and period DP_{prop} for the engines is used, see Equation 3.46.

$$C_{depr,prop} = F_{depr,prop} \cdot \frac{P_{prop} \cdot N_{prop}}{DP_{prop} \cdot U_{ann} \cdot V_{bl}} \tag{3.46}$$

The depreciation cost for avionics is given in Equation 3.47. It requires the price of the avionics P_{av} and depreciation period DP_{av}.

$$C_{depr,av} = F_{depr,av} \cdot \frac{P_{av}}{DP_{av} \cdot U_{ann} \cdot V_{bl}} \tag{3.47}$$

Besides the aircraft parts in use spare parts need to be depreciated as well. Roskam destinquishes airframe and engine spare parts. The airframe spares include the avionics and propellers. The costs for airframe spare depreciation is given in Equation 3.48 and requires a factor for the amount of spares needed $F_{af,sp}$ and a factor for the depreciation cost with respect to airframe price $F_{depr,af,sp}$.

$$C_{depr,af,sp} = F_{depr,af,sp} \cdot F_{af,sp} \cdot \frac{P_{af}}{DP_{af} \cdot U_{ann} \cdot V_{bl}} \tag{3.48}$$

The same holds for the engines as is seen in Equation 3.49. An additional factor for is needed for the price of a spare engine, ESPPF.

$$C_{depr,e,sp} = F_{depr,e,sp} \cdot F_{e,sp} \cdot \frac{N_e \cdot P_e \cdot ESPPF}{DP_{af} \cdot U_{ann} \cdot V_{bl}} \tag{3.49}$$

The total cost of depreciation is given by Equation 3.50.

$$C_{depr} = C_{depr,af} + C_{depr,e} + C_{depr,prop} + C_{depr,av} + C_{depr,af,sp} + C_{depr,e,sp} \tag{3.50}$$

Cost of landing fees, navigation and registry taxes The cost for landing fees is determined as a factor of the MTOM as is seen in Equation 3.51.

$$C_{lf} = \frac{0.002 \cdot MTOM}{V_{bl} \cdot t_{bl}} \tag{3.51}$$

The navigation fee equals the landing fee. The registry taxes are determined as factor of the all DOC components presented thus far, denoted DOC_{sub}, and is shown in Equation 3.52.

$$DOC_{sub} = C_{flt} + C_{mt} + C_{depr} + C_{lf} + C_{nf} \tag{3.52}$$

The factor for registry taxes cost (F_{rt}) is shows in Equation 3.53. The cost for registry taxes (C_{rt}) is given by Equation 3.54.

$$F_{rt} = 0.001 + MTOM \cdot 10^{-8} \tag{3.53}$$

$$C_{rt} = F_{rt} \cdot DOC_{sub} \tag{3.54}$$

Cost of financing The cost of financing is also determined as a factor F_{fin} of the DOC thus far, see Equation 3.55. Roskam advises to use a finance factor of 0.10 [60].

$$C_{fin} = F_{rt} \cdot DOC_{sub} \tag{3.55}$$

The total DOC is the sum of all cost components as is seen in Equation 3.56

$$DOC = C_{flt} + C_{mt} + C_{depr} + C_{lf} + C_{nf} + C_{rt} + C_{fin} \tag{3.56}$$

INDIRECT OPERATING COST

Roskam estimates the IOC as a fraction of the DOC [60]. Since a breakdown of the IOC is preferred an other method is selected. A method developed by Maddalon that dates back to 1980 is used[52]. The relations provided by Maddalon include a factor that allows to distinguished domestic and international flights and is denoted K_i. An overview of K_i for every cost component is shown in Table 3.2. Most IOC relations are a function of block time t_{bl}, block range R_{bl} and revenue inflation rate $\bar{f}_{rev}$. Therefore they are not explicitly mentioned when introducing an equation. The method consists of cost components as shown in Figure 3.5.

Table 3.2: Cost factors for IOC components for domestic and international flight [52]

Cost factor	**Domestic**	**International**
K_1	0.52	0.56
K_2	1.86	1.64
K_3	23.83	67.72
K_4	29.33	37.00
K_5	0.96	0.63
K_6	6.56	15.84
K_7	98.2	150.69
K_8	0.0065	0.0088
K_9	0.0082	0.0099
K_{10}	0.048	0.053

Cost of systems The cost of systems is based on airframe and engine labor cost $C_{lab,af}$ and engine $C_{lab,e}$ as is shown in Equation 3.57

$$C_{systems} = K_1 \cdot (C_{lab,af} + C_{lab,e}) \cdot (1 + \bar{f}_{rev}) \tag{3.57}$$

Cost of local facilities The cost of local facilities is a function of the MTOM as can be seen in Equation 3.58.

$$C_{local} = K_2 \cdot \frac{MTOM}{1000} \cdot \frac{1 + \bar{f}_{rev}}{R_{bl}} \tag{3.58}$$

Cost of contractors The cost of contractor C_{contr} solely depends on the factor K_3, see Equation 3.59.

$$C_{contr} = K_3 \cdot \frac{1 + \bar{f}_{rev}}{R_{bl}} \tag{3.59}$$

Cost of cabin crew First the number of cabin attendants is determined N_{ca}. The total number of seats N_{seat} is divided by the number of passengers an individual cabin attendant can serve $N_{ca,pax}$ plus one extra cabin attendant, see Equation 3.60. The total cabin crew cost $C_{crew,cab}$ is shown in Equation 3.61.

$$N_{ca} = \frac{N_{seat}}{N_{ca,pax}} + 1 \tag{3.60}$$

$$C_{crew,cab} = K_4 \cdot \frac{N_{ca} \cdot t_{bl} \cdot (1 + \bar{f}_{rev})}{R_{bl}} \tag{3.61}$$

Cost of food The cost of food C_{food} depends on whether it is an international or domestic flight like any of the other cost components based on the factor K_i. For the cost of food an additional distinction is made that results in two different equations. Equations 3.62 and 3.63 give the cost of food for respectively domestic and international flight. Both are a function of passenger load factor LF_{pax}, number of first class $N_{pax,first}$ and economy class passengers $N_{pax,econ}$.

$$C_{food,dom} = K_5 \cdot \frac{LF_{pax}(2.25 \cdot N_{pax,first} + N_{pax,econ}) \cdot t_{bl} \cdot (1+\bar{f}_{rev})}{R_{bl}} \tag{3.62}$$

$$C_{food,int} = K_5 \cdot \frac{LF_{pax}(3.5 \cdot N_{pax,first} + N_{pax,econ}) \cdot t_{bl} \cdot (1+\bar{f}_{rev})}{R_{bl}} \tag{3.63}$$

Cost of passenger handling The cost for passenger handling $C_{h,pax}$ depends on the number of passengers on board. This is determined by multiplying the load factor LF_{pax} by the number of seats available on the aircraft N_{seats}, see Equation 3.64. Note that with respect to the cost of food no distinctions is made between passengers from different classes.

$$C_{h,pax} = K_6 \cdot \frac{LF_{pax} \cdot N_{seat} \cdot (1+\bar{f}_{rev})}{R_{bl}} \tag{3.64}$$

Cost of cargo handling The cost for cargo handling $C_{h,cargo}$, is determined by Equation 3.65. It is as function of the cargo weight W_{cargo}.

$$C_{h,cargo} = K_7 \cdot \frac{W_{cargo} \cdot R_{bl} \cdot (1+\bar{f}_{rev})}{R_{bl}} \tag{3.65}$$

Cost of other cost components Additional cost are made with respect to the passengers. Unfortunately Maddalon does not elaborate what activities are included. It is a function of the passenger load factor and number of seats.

$$C_{other} = K_8 \cdot \frac{LF_{pax} \cdot N_{seat} \cdot (1+\bar{f}_{rev})}{R_{bl}} \tag{3.66}$$

Cost of freight commission and advertising The cost for freight commission and advertising C_{fca}, is determined by Equation 3.67. As can be seen it is a function of the freight's weight W_{fr}.

$$C_{fca} = K_9 \cdot \frac{W_{fr} \cdot R_{bl} \cdot (1+\bar{f}_{rev})}{R_{bl}} \tag{3.67}$$

Cost of general and administrative cost The general and administrative cost for IOC is a function of all previous stated cost components (IOC_{sub}), DOC and cost of depreciation (C_{depr}). The first is shown in Equation 3.68. The general and administrative cost (C_{ga}) is shown in Equation 3.69

$$IOC_{sub} = C_{system} + C_{local} + C_{contr} + C_{ca} + C_{food} + C_{h,pax} + C_{h,cargo} + C_{other} + C_{fca} \tag{3.68}$$

$$C_{ga} = K_{10} \cdot (IOC_{sub} + (DOC - C_{depr}) \cdot \frac{(1+\bar{f}_{rev})}{R_{bl}} \tag{3.69}$$

The total IOC is shown in Equation 3.70.

$$IOC = IOC_{sub} + C_{ga} \tag{3.70}$$

The DOC and IOC combined gives the TOC as is shown in Equation 3.71.

$$TOC = DOC + IOC \tag{3.71}$$

3.3. BOTTOM-UP METHOD

Before the the bottom-up method is explained the name of this approach needs to be clarified. As was seen in section 2.2 a bottom-up technique normally requires detailed product information and knowledge about processes, materials and man hours. The bottom-up method used for the cost model is actually based on parametric analysis like the top-down method. However, it requires more detailed information than the top-down method and for that reason it is denoted as bottom-up.

This section will first present the manufacturing cost in Section 3.3.1 and the operating cost in Section 3.3.2. Both life cycle cost components show overlap with the top-down method.

3.3.1. MANUFACTURING COST

The top-down method first determined an initial list price followed by the NRC. Both were then used to determine the RC. The bottom-up method first calculates the NRC and RC. Next the list price is determined. Hence, the bottom-up method uses an inverse approach with respect to the top-down method.

NON-RECURRING COST

The NRC is determined in exactly the same way as the top-down method, see Section 3.2.2. Since the NRC depends on the list price and price of avionics and engines, which at this point are not yet known for the bottom-up method, the prices as obtained by the regression analysis are used. Hence, the NRC for both top-down and bottom-up methods is the same.

RECURRING COST

The method used to determine the RC is different than that of the top-down method. As stated in Section 3.1 a method by Beltramo is used [10]. It should be mentioned that Beltramo only calculates the RC for the airframe and not the engine. The costs for engines should be obtained from engine manufacturers. For the bottom-up method the engine part prices from regression analysis are used. However, Beltramo does offer cost functions for the nacelle and cowl of the engine. These are included in the engine price from top-down method. From several example studies presented by Beltramo it appears that nacelle and cowl represent 20% of the engine cost. Hence, 80% of the engine part prices are used as engine price for bottom-up method.

Beltramo requires the weight of a number of aircraft components. These weights, in turn, are used to to determine the cost of these components, which are:

- Wing
- Tail
- Fuselage
- Landing gear components: structural components, landing gear control components, wheels and brakes, tires.
- Nacelle components: cowl, pylon, tail mounted nacelles. Latter is optional.
- Propulsion components: thrust reverser, fuel systems and engine systems.
- Flight controls
- Hydraulics
- Electrical systems
- Pneumatics
- Air conditioning
- Auxiliary Power Unit (APU)
- Anti-ice systems
- Furnishing
- Instruments
- Avionics
- Load handling. Is the cost made for handling of listed components during production.
- Assembly

Weight of aircraft components Beltramo provides relations to determine the weights of the listed components. However, Initiator computes most of these component weights. Here only the weights are presented, for sub components of the landing gear and engine,which Initiator is not able to deliver.

Landing gear component weight First a temporary total landing gear weight is determined $W_{lg,temp}$. $W_{lg,temp}$ depends on the MTOM of the aircraft. If MTOM > 11,000 lbs it aircraft is considered to be a medium to larger commercial aircraft. This is denoted as a type 1 aircraft. The temporary total landing gear weight is determined by Equation 3.72. However, if MTOM is ≤ 11,000 lbs it is a small commercial aircraft and denoted as type 2. For a type 2 aircraft the total weight of the temporary landing gear is given by Equation 3.73.

$$W_{lg,temp,1} = 0.044 \cdot MTOM - 672 \tag{3.72}$$

$$W_{lg,temp,2} = 0.0395 \cdot MTOM \tag{3.73}$$

The weights of the individual landing gear components are a function of the temporary total landing gear weight and MTOM. All sub components of the landing gear are listed next followed by the equation for weigth.

- Structural

$$W_{str} = W_{lg,temp} \cdot (0.450 + 23.1 \cdot 10^{-8} \cdot MTOM) \tag{3.74}$$

- Controls

$$W_{ctr} = W_{lg,temp} \cdot (0.130 - 6.56 \cdot 10^{-8} \cdot MTOM) \tag{3.75}$$

- Wheels and brakes

$$W_{whbr} = W_{lg,temp} \cdot (0.286 - 8.12 \cdot 10^{-8} \cdot MTOM) \tag{3.76}$$

- Tires

$$W_{tires} = W_{lg,temp} \cdot (0.125 - 8.38 \cdot 10^{-5} \cdot MTOM) \tag{3.77}$$

- Low pressure tires

$$W_{tires,lp} = 0.038 \cdot W_{lg,temp} \tag{3.78}$$

- Inflation systems

$$W_{infl} = 0.184 \cdot W_{lg,temp} \tag{3.79}$$

- Carbon brakes

$$W_{cb} = W_{lg,temp} \cdot (0.0786 - 0.071 \cdot 10^{-6} \cdot MTOM) \tag{3.80}$$

Based on the sum of above listed weights the total landing gear weight according to Beltramo ($W_{lg,bel}$) can be determined. See Equation 3.81.

$$W_{lg,bel} = W_{str} + W_{ctr} + W_{whbr} + W_{tires} + W_{tires,lp} + W_{infl} + W_{cb} \tag{3.81}$$

Beltramo calculates the cost of four landing gear components: structural, controls, wheels and brakes and tires. These weights are needed for the design aircraft and are obtained by using the ratio of the total landing gear weight available in Initiator $W_{lg,design}$ over the total landing gear weight according to Beltramo $W_{lg,bel}$. This method is explained by Equation 3.82.

$$W_{lg,i} = W_{lg,i} \cdot \frac{W_{lg,design}}{W_{lg,bel}} \tag{3.82}$$

Here *i* represents a landing gear components.

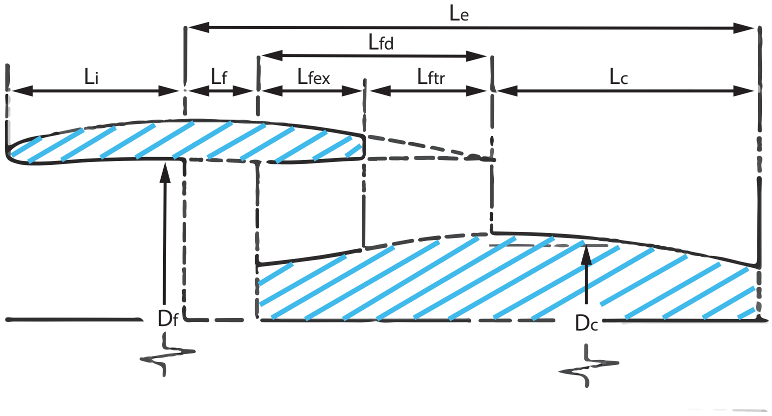


Figure 3.6: Schematic overview engine [10].

Table 3.3: Overview of engine and pylon dimensions as a function of design engine diameter ($D_{e,des}$) and length ($L_{e,des}$) [10].

Symbol	Explanation	Function
D_c	Diameter of the cowl	$D_c = 0.4 \cdot D_{e,des}$
D_f	Diameter of the fan	$D_f = 0.8 \cdot D_{e,des}$
L_c	Length of the cowl	$L_c = 0.3 \cdot L_{e,des}$
L_e	Length of the engine	$L_e = 0.8 \cdot L_{e,des}$
L_f	Length of the fan	$L_f = 0.1 \cdot L_{e,des}$
L_{fd}	Length of the fan duct	$L_{fd} = 0.4 \cdot L_{e,des}$
L_{fex}	Length of the fan exhaust duct	$L_{fex} = 0.2 \cdot L_{e,des}$
L_{ftr}	Length of the fan thrust reverser	$L_{ftr} = 0.2 \cdot L_{e,des}$
L_i	Length of the	$L_i = 0.2 \cdot L_{e,des}$
L_{py}	Length of the pylon	$L_{py} = L_{e,des}$
H_{py}	Height of the pylon	$H_{py} = 0.25 \cdot D_{e,des}$

Engine component weight For the engine weights a similar approach is used as for the landing gear. The engine has two sub level components: nacelle and propulsion unit. Both depend on detailed dimensions of the engine. These are not available in Initiator. Therefore they are assumed based on a schematic scaled drawing of an engine, see Figure 3.6. The required dimensions are expressed in terms of engine length and diameter which are available for the design aircraft. The dimensions are listed in Table 3.3.
At first, Beltramo expected a positive relation between engine thrust and the weight of the cowl. However, after inspection of a data set of engines there appeared to be no direct correlation. Fortunately, the cowl weight was found to be related to a weighted area index [10]. It is determined as a function of the engine dimensions as shown in Equation 3.83.

$$I_c = (1.316 + 0.0125 \cdot D_f) \cdot L_i \cdot D_f + (1.316 + 0.191 \cdot D_f) \cdot L_{fex} \cdot D_f + L_c \cdot D_c \tag{3.83}$$

Also a weight index of the pylon is required. It is obtained by applying Equation 3.84. It is a function of the design engine weight W_e.

$$I_{py} = \frac{W_e \cdot l_{py}}{H_{py} \cdot S_{py}} \tag{3.84}$$

I_{py} is also a function of the dimensions of the pylon. It is assumed they are a function of the engine length and diameter. The length of the pylon is equal to the length of the engine, the height is $1/4^{th}$ of the engine diameter as is seen in Table 3.3. The surface of the pylon is twice the length and height multiplied with each other. The weights of the nacelle components are listed next:

- Cowl

$$W_c = 0.0415 \cdot N_e \cdot I_c \tag{3.85}$$

- Pylon

$$W_{py} = S_{py} \cdot N_e \cdot (8 + 0.0144 \cdot I_{py}) \tag{3.86}$$

The total nacelle weight is the sum of the cowl and pylon, see Equation 3.87.

$$W_{nc} = W_c + W_{py} \tag{3.87}$$

The second sub level component is the propulsion unit. The components and functions for their weight are listed next.

- Thrust reverser. Two thrust types of reverser are identified:
  - Fan thrust reverser
    $$W_{ftr} = N_e \cdot \left(0.218 \cdot D_f \cdot L_{ftr} + 0.012 \cdot T_{ftr}\right) \tag{3.88}$$
    The thrust the fan thrust reverser is able to deliver T_{ftr} is assumed to be 20% of the engine total static thrust.
  - Engine exhaust thrust reverser
    $$W_{etr} = N_e \cdot \left(x_1 \cdot D_t \cdot L_{pex} + x_2 \cdot T_{ptr}\right) \tag{3.89}$$
    The variables x_1 and x_2 differ per engine exhaust thrust reverser type. Five types are listed next.
    - Cascade or target type reverser with translating sleeve $\longrightarrow x_1 = 0.179, x_2 = 0.0389$
    - Simple target type reverser with separate flow exhaust nozzle $\longrightarrow x_1 = 0.131, x_2 = 0.0239$
    - Simple target type reverser with mixed flow exhaust nozzle $\longrightarrow x_1 = 0.105, x_2 = 0.0122$
    - Separate flow engine exhaust system without thrust reverser $\longrightarrow x_1 = 0.113, x_2 = 0.0144$
    - Short duct engine exhaust system without thrust reverser $\longrightarrow x_1 = 0.096, x_2 = 0.0094$

    The total weight of thrust reverser components is the sum of the fan and engine exhaust reversers, see Equation 3.90.
    $$W_{tr} = W_{ftr} + Wetr \tag{3.90}$$
  - Fuel systems. The fuel system is a function of the number of fuel tanks N_{ft} and the wing span, see Equation 3.91.
    $$W_{fs} = 2.71 \cdot \left(0.5 \cdot b \cdot N_{ft}\right)^{0.956} \tag{3.91}$$
  - Engine systems. The weight of the engine system depend on whether the engine has auto-throttle. If so Equation 3.92 is used, otherwise Equation 3.93.
    $$W_{e,sys,1} = 117 \cdot N_e \tag{3.92}$$
    $$W_{e,sys,2} = 133 \cdot N_e \tag{3.93}$$

The total weight of the propulsion unit is the sum of the three sub components, see Equation 3.94.

$$W_{pu} = W_{tr} + W_{fs} + W_{e,sys} \tag{3.94}$$

Note that the weights thus far are the weights according to Beltramo. As was done for the landing gear these weights are converted based on the ratio of the engine weight obtained from Initiator and the total weight according to Beltramo. Equation 3.82 is used where i now represents the three engine sub components: thrust reverser, fuel system and engine system.

Cost of aircraft components The cost of aircraft components is a function of the weight of the component and the quantity of aircraft build. All components and the cost formula are listed next:

- Wing
  $$C_w = 1730 \cdot W_w^{0.766} \cdot Q^{-0.218} \tag{3.95}$$
- Tail
  $$C_{tail} = 1820 \cdot W_w^{0.766} \cdot Q^{-0.218} \tag{3.96}$$
  It should be noted that the tail comprises both horizontal and vertical stabilizer in Beltramo's method.

– Fuselage

$$C_f = 2060 \cdot W_f^{0.766} \cdot Q^{-0.218} \tag{3.97}$$

– Landing gear

$$C_{lg} = C_{str} + C_{ctr} + C_{whbr} + C_{tires} \tag{3.98}$$

The cost of the landing gear sub components are:

◇ Structural. If the weight of the structural components is less than 10,000 lbs the cost are given by Equation 3.99, otherwise it is obtained by applying Equation 3.100.

$$C_{str} = 1180 \cdot W_{str}^{0.766} \cdot Q^{-0.218} \tag{3.99}$$

$$C_{str} = 136 \cdot W_{str}^{0.766} \cdot Q^{-0.218} \tag{3.100}$$

◇ Controls

$$C_{ctr} = 157 \cdot W_{ctr} \cdot Q^{-0.0896} \tag{3.101}$$

◇ Wheels and brakes

$$C_{whbr} = 23.8 \cdot W_{whbr} \cdot Q^{-0.0896} \tag{3.102}$$

◇ Tires

$$C_{tires} = 2 \cdot W_{tires} \tag{3.103}$$

– Nacelle

$$C_{nc} = 3470 \cdot W_{nc}^{0.766} \cdot Q^{-0.218} \tag{3.104}$$

– Propulsion components: thrust reverser, fuel systems and engine systems.

$$C_{pu} = C_{tr} + C_{fs} + C_{e,sys} \tag{3.105}$$

◇ Thrust reversers

$$C_{tr} = 380 \cdot W_{tr}^{0.766} \cdot Q^{-0.218} \tag{3.106}$$

◇ Fuel system

$$C_{fs} = 61.9 \cdot W_{fs} \cdot Q^{-0.0896} \tag{3.107}$$

◇ Engine system

$$C_{e,sys} = 159 \cdot W_{e,sys} \cdot Q^{-0.0896} \tag{3.108}$$

– Flight controls

$$C_{flc} = 205 \cdot W_{flc} \cdot Q^{-0.0896} \tag{3.109}$$

– Hydraulics

$$C_{hyd} = 54.4 \cdot W_{hyd} \cdot Q^{-0.0896} \tag{3.110}$$

– Electrical systems. If the weight of electrical systems is less than 5,000 lbs Equation 3.111 is used, otherwise Equation 3.112 applies.

$$C_{elec} = 209 \cdot W_{elec} \cdot Q^{-0.0896} \tag{3.111}$$

$$C_{elec} = 178 \cdot W_{elec} \cdot Q^{-0.0896} \tag{3.112}$$

– Pneumatics. If the weight of the pneumatics is less than 400 lbs Equation 3.113 is used, otherwise Equation 3.114 applies.

$$C_{pneu} = 151 \cdot W_{pneu} \cdot Q^{-0.0896} \tag{3.113}$$

$$C_{pneu} = 201 \cdot W_{pneu} \cdot Q^{-0.0896} \tag{3.114}$$

– Air conditioning

$$C_{airco} = 234 \cdot W_{airco} \cdot Q^{-0.0896} \tag{3.115}$$

– APU

$$C_{apu} = 243 \cdot W_{apu} \cdot Q^{-0.0896} \tag{3.116}$$

- Anti-ice systems

$$C_{ice} = 230 \cdot W_{ice} \cdot Q^{-0.0896} \tag{3.117}$$

- Furnishing. If the weight of the furnishing is less than 25,000 lbs lbs Equation 3.118 is used, otherwise Equation 3.119 applies.

$$C_{furn} = 102 \cdot W_{furn} \cdot Q^{-0.0896} \tag{3.118}$$

$$C_{furn} = 115 \cdot W_{furn} \cdot Q^{-0.0896} \tag{3.119}$$

- Instruments. Instruments exist for the fuel system and the power unit system, see respectively Equations 3.121 and 3.122. Combined this gives the total instrument cost.

$$C_{instr} = C_{instr,fuel} + C_{instr,pu} \tag{3.120}$$

  - Fuel

$$C_{instr,fuel} = 1930 \cdot W_{instr,fuel} \cdot Q^{-0.184} \tag{3.121}$$

  - Power unit

$$C_{instr,pu} = 154 \cdot W_{instr,pu} \cdot Q^{-0.184} \tag{3.122}$$

- Avionics

$$C_{av} = C_{av,eq} + C_{av,other} \tag{3.123}$$

  - Equipement

$$C_{av,eq} = 1930 \cdot W_{av} \cdot Q^{-0.184} \tag{3.124}$$

  - Others

$$C_{av,other} = 154 \cdot W_{av} \cdot Q^{-0.184} \tag{3.125}$$

- Load handling. The cost for load handling C_{lh} is a factor of the fuselage cost. The factor is the ratio of the load handling weight over the fuselage weight as is seen in Equation 3.126

$$C_{lh} = \frac{W_{lh}}{W_f} \cdot C_f \tag{3.126}$$

- Assembly. The assembly cost is 25% of all N listed cost components, see Equation 3.127. Here *i* represents an aircraft component

$$C_{assy} = 0.25 \cdot \sum_{i=1}^{N} \left(C_i\right) \tag{3.127}$$

LIST PRICE

In order to compute the list price for the bottom-up method, first the UC is determined. This is done by applying Equation 3.128.

$$UC = RC + \frac{NRC}{Q} \tag{3.128}$$

The list price in turn is determined using Equation 3.129. Where r_D and r_E are respectively the discount and earnings rate.

$$LP = UC \cdot \left(1 + r_D + r_E\right) \tag{3.129}$$

3.3.2. OPERATING COST

The operating costs for the bottom-up method is obtained in the same way as for the top-down method. The only difference is that the list price, which is required for depreciation and maintenance cost differs between both methods.

3.4. NETT PRESENT VALUE

An important indication of the success of an aircraft program is the Nett Present Value (NPV). It measures the benefit for the company's stakeholders when the program is launched [56]. It is assumed that the investment equals the NRC. The NPV is computed using Equation 3.130.

$$NPV = -NRC + \sum_{j=1}^{Q} \frac{LP - D - RC}{(1+i)^j / pr} \tag{3.130}$$

A constant year interest rate and production rate is used. The NPV is discounted over time. At $Q = 1$ the NPV equals the negative of the NRC. The quantity of aircraft needed to produce to get $NPV = 0$ is called the break-even quantity, Q_{be}. After Q_{be} the company has a positive cash flow. Hence, an operating profit is expected [56].

3.5. UNCONVENTIONAL AIRCRAFT

In the previous Sections the method for conventional aircraft was presented. No specific attention was paid to the unconventional aircraft. This section explains how the model is made compatible with unconventional aircraft. Adjustments are presented for the initial list price, NRC and RC. The methodology for operational cost requires no changes.

3.5.1. INITIAL LIST PRICE

First, one should remember that the initial list price is only used for the top-down method. The regression analysis as explained in section 3.2.1 gives list prices per part of the aircraft based on parameters in the database. Unfortunately it does not provide list prices for unconventional parts. In order to overcome this problem some of the CERs for conventional parts are used for unconventional parts as well. A canard for instance is similar to a conventional horizontal tail. Hence, it is assumed that the same CERs apply. This directly means that the same parameters are used. However, there are also differences. A canard, for instance could have no control surfaces whereas a conventional horizontal might have an elevator. This has an impact on the cost. To overcome this obstacle a fudge factor can be applied to a single CER.

One could say an unconventional part is a function of one or more conventional parts. An overview of all unconventional parts and analogous conventional parts are listed next. A connector is the vertical structure that connects both wing tips of the front and rear wing of a prandtl plane.

- Canard = f(horizontal tail)
- Connector = f(vertical tail)
- Boxwing = f(2 · wing + 2 · vertical connector)
- Blended wing = f(wing)
- Oval fuselage = f(fuselage)

3.5.2. NON-RECURRING COST

Since the top-down and bottom-up methods use the same method to determine NRC, all changes stated in this section hold for both of the methods. For the NRC, unconventional parts are also a function of conventional parts like for the initial list price.

The impact unconventional parts have on the cost is determined by introducing a Non Communality Factor (NCF). This factor is given for the following aircraft parts: wing, fuselage, systems, empennage, canard and engine. The landing gear is neglected since it only contributes 1% of the total NRC [47]. This is done for every configuration as well. The factor states the level of innovation of a part. A part falls within one of four segments which are shown in Table 3.4. Building an existing design of a conventional part requires no RDTE cost, hence the value is zero. One could say it is 100% in common with existing parts and thus has 0% not in common.

Table 3.4: Segmentation of aircraft part design for the Non Communality Factor (NCF)

Type of part design	NCF
Existing conventional part	NCF=0
New family member of conventional part	0<NCF<1
New conventional part	NCF=1
Unconventional part	NCF>1

For the wing of a BWB the individual NCF could be set to 1.4 whereas for a canard aircraft it could be set to 1.1. This is since the wing is almost similar to a conventional wing. Rating the NCF requires a detailed product information and experience with manufacturing processes.

The total NCF of the aircraft is calculated by first multiplying the percentage a single part contributes to the NRC by the NCF of that part. These percentages are obtained for single aisle aircraft by Lammering [47]. Secondly, the NCF of all parts are combined. This procedure, for a conventional aircraft, is shown in Equation 3.131. The percentages shown are obtained by Lammering. For a canard or three-surface aircraft a term for the canard part is added.

$$\mathrm{NCF_{ac}} = 20\% \cdot \mathrm{NCF_{wing}} + 37\% \cdot \mathrm{NCF_{fuselage}} + 26\% \cdot \mathrm{NCF_{systems}} + 9\% \cdot \mathrm{NCF_{empennage}} + 8\% \cdot \mathrm{NCF_{engine}} \tag{3.131}$$

Introduction of the NCF also allows existing aircraft programs to be analyzed and thus entire aircraft families. The latter will be discussed in Section 6.

Some of the NRC components obtained by Roskam are multiplied by the total aircraft NCF. This is done for all cost components mentioned in Section 3.2.2 except for the production cost of the flight test aircraft [47]. Here an exception is made for the tooling cost, which are subjected to the NCF. Hence, the NRC is strongly influenced by the NCF.

3.5.3. RECURRING COST

The top-down and bottom-up approach use different methods to compute the RC. The adjustments required for unconventional aircraft are explained in this section.

RC for the top-down method The top-down method to determine the RC was explained in Section 3.2.2. It is based on the UC and NRC as was shown in Equation 3.25. Hence, adjustments for the RC depend on the adjustments of these cost components which were explained in previous sections.

RC for the bottom-up method As explained in Section 3.3.1 weights of all aircraft parts are required in order to give a cost estimate of each part. The weights of the unconventional parts are computed in Initiator. In order to determine the cost a cost relation of an existing part is used. Like is done for the initial list price.

For each unconventional part installed on one of the unconventional aircraft, the following cost relations are used:

- Canard
  Since Beltramo offers a relation for the entire empennage, denoted tail, no direct relation for an horizontal tail can be used. Therefore the relation of the wing is used. Hence, the cost for a canard part is shown in Equation 3.132.

$$C_{canard} = 1730 \cdot W_{canard}^{0.766} \cdot Q^{-0.218} \tag{3.132}$$

- Connector
  Since the shape of the connector is not precisely defined and Initiator is not able to compute the connector's weight, it is difficult to compare it with a conventional part. However, it is assumed to be a structural component like a horizontal and vertical stabilizer. Hence, the relation for the empennage is used as is shown in Equator 3.133.

$$C_{cn} = 1820 \cdot W_{cn}^{0.766} \cdot Q^{-0.218} \tag{3.133}$$

- Boxwing
  The boxwing consist of a front and rear wing and the two connectors. The cost for front and rear wing are equal to a conventional wing. Hence, the cost can be computed using Equation 3.134.

$$C_{w,front/rear} = 1730 \cdot W_{w,front/rear}^{0.766} \cdot Q^{-0.218} \tag{3.134}$$

  The total RC for the wing of a Prandlt Plane (PP) is computed using Equation 3.135.

$$C_{boxwing} = C_{w,front} + C_{w,rear} + 2 \cdot C_{cn} \tag{3.135}$$

- Blended wing
  For the wing of a BWB the relation for conventional wings is used, see Equation 3.136.

$$C_{w,bwb} = 1730 \cdot W_{w,bwb}^{0.766} \cdot Q^{-0.218} \tag{3.136}$$

- Oval fuselage
  For an oval fuselage the relation for a conventional fuselage is used, see Equation 3.137.

$$C_{f,oval} = 2060 \cdot W_{f,oval}^{0.766} \cdot Q^{-0.218} \tag{3.137}$$

For unconventional configurations the cost made for assembly is still 25% of all other cost components like in Equation 3.127. The unconventional parts are added to this equation. This concludes the adjustments to the methodology to ensure compatibility with unconventional aircraft.

3.6. TARGET QUANTITY FOR MARKET ANALYSIS

As stated in the introduction of this chapter two different methods are used to estimate cost, of which the results are compared. However, both methods can also be integrated. This section explains how this is done and what the benefit is of combining both methods.

Figure 3.2 shows in gray where both methods meet. According to Lammering the two methods used for RC can be equated [47]. If, up front, no quantity of aircraft to produce is defined, Q is a variable in the model. The equation for RC of the top-down method is repeated in Equation 3.138.

$$RC_{td} = UC - \frac{NRC}{Q}(1+i)^{Q/pr} \tag{3.138}$$

The method of Beltramo, used to determine the RC of the bottom-up method, is a function of the weight of the aircraft parts and Q. Equation 3.139 shows this in formula form.

$$RC_{bu} = \sum_{i=1}^{n} RC_i = \sum_{i=1}^{n} f(Q, W_i) \tag{3.139}$$

Since UC and NRC can be computed without knowing Q and i and pr are known, the RC of the top-down model only depends on Q. For the bottom-up RC the weights are known as well, hence it also soley depends on Q. For this reason Equations 3.138 and 3.139 can be equated and solved for Q. The value of Q found is called the *target quantity*, Q_{target}.

Q_{target} represents the amount of aircraft that need to be sold during the life cycle of the program purely based on historical data. Note that the list prices in the database are based on a number of aircraft produced for each aircraft, since the manufacturer includes this when publishing the list price. Since the initial list price of the design aircraft is based on these aircraft this initial list price is also based on the number of aircraft to produce although it is not known yet. RC_{td} is therefore also based on this unknown quantity.

At this point is should be noted that the RC_{bu} is the most realistic and accurate estimate of the RC since it is based on individual components and the learning curve. By equating RC_{td} and RC_{bu} a RC is found and therefore also the corresponding quantity, which is Q_{target}.

Q_{target} is compared with the market demand. If the market demand exceeds Q_{target} one can assume the program is expected to be a success. Hence, Q_{target} helps to indicate the potential of an aircraft design according to Lammering [47].

4

Implementation of the Model

The cost estimation model is integrated into the Initiator framework of Delft University of Technology and is one of the performance modules. The module is called *CostEstimation*. It is called upon after the aircraft design is converged.

This Chapter explains how the model as described in Chapter 3 is implemented in this module. First, an overview of the module is presented in Section 4.1. Secondly, a user manual provided which explains how the module is operated in Section 4.2.

4.1. Overview of the module

The module is developed in a Matlab environment. An overview of the module is shown in Figure 4.1. This overview represents the main file in the cost estimating module, denoted *run.m*. Both top-down and bottom-up methods are subjected to parts of the module. The module's sub components are explained next.

4.1.1. Load data and store in objective

First, the required input files and user settings are loaded:

1. All information of other Initiator modules stored in the object called *obj*.
2. Excel files containing:
   - Aircraft database: dimensions, weights, performance parameters and historical list price.
   - Names of these parameters in format compatible for plotting vector images and LaTeX output.
   - Outliers in the aircraft database.
   - Inflation rates of US$.
3. *.xml* file named *CostData.xml* containing input with regard to:
   - UserSettings: run options for the module.
   - RegressionSettings: settings for the regression analysis.
   - ACdesign: additional design information.
   - Manufacturer: settings of a fictive manufacturing company.
   - NonCommunality: level of innovation per aircraft part and per configuration.
   - Operator: settings for a fictive airline.
   - PartsPercLP: percentage an aircraft parts contributes to the list price.
   - PercNCF: percentage an aircraft part contributes to the NRC, per configuration.
4. Optional user input via command window.
5. Optional *.mat* file named *RegressionModel.mat*. This file contains the regression models as computed by a prior run.

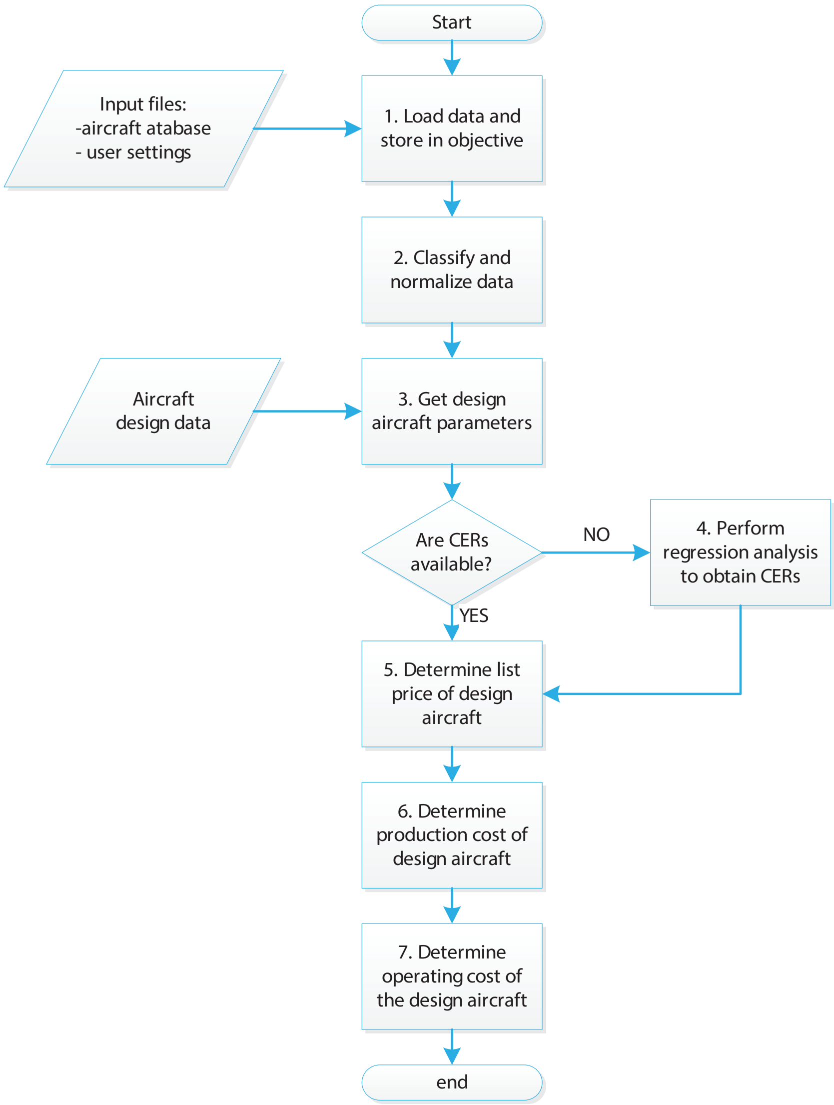


Figure 4.1: Activity diagram of the cost estimating module.

All settings as listed in *CostData.xml* are explained in detail in Section 4.2. The optional user input is an extra feature that asks the user if he or she needs help operating the tool. If so, the user gets help defining the UserSettings. The manual inputs of the user overwrite the values in the *CostData.xml* file. The data in this file is saved to the path *obj.DataSets*.

The first time the module is run a regression analysis is performed. All subsequent runs use the results of this regression analysis by loading the file *RegressionModel.mat*. This done to shorten the run time of the module.

4.1.2. Classify and normalize data

Section 3.2.1 explained why and how the data is normalized and classified. Figure 4.2 shows how this process is implemented in the file *classifyData.m*. All aircraft are looped and are classified using the age bounds. The same is done for the outliers in *obj.DataSets.Outliers*. Next, the list prices are changed for all classes except for the class *others*

4.1.3. Design aircraft parameters

The design parameters of the design aircraft are collected. This is done in the file *designData.m* and an overview is shown in Figure 4.3. By calling the *Class25WeightEstimation* module all weights are loaded.

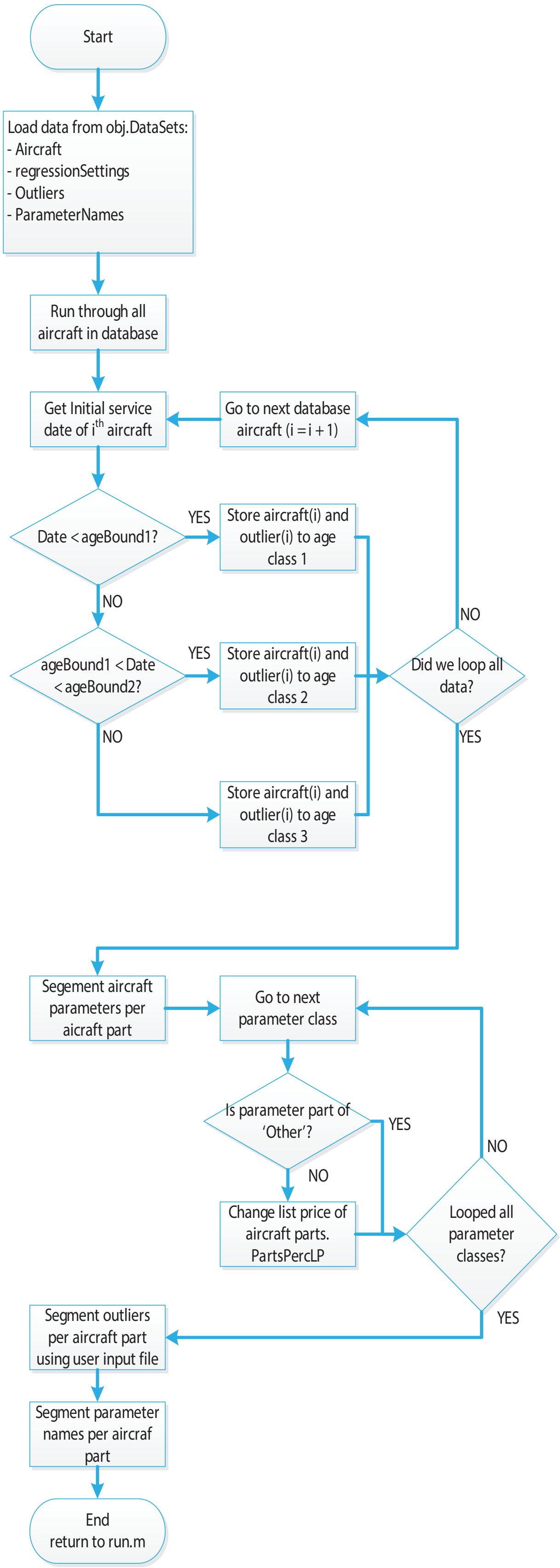


Figure 4.2: Activity diagram of the sub-module to classify and normalize data.

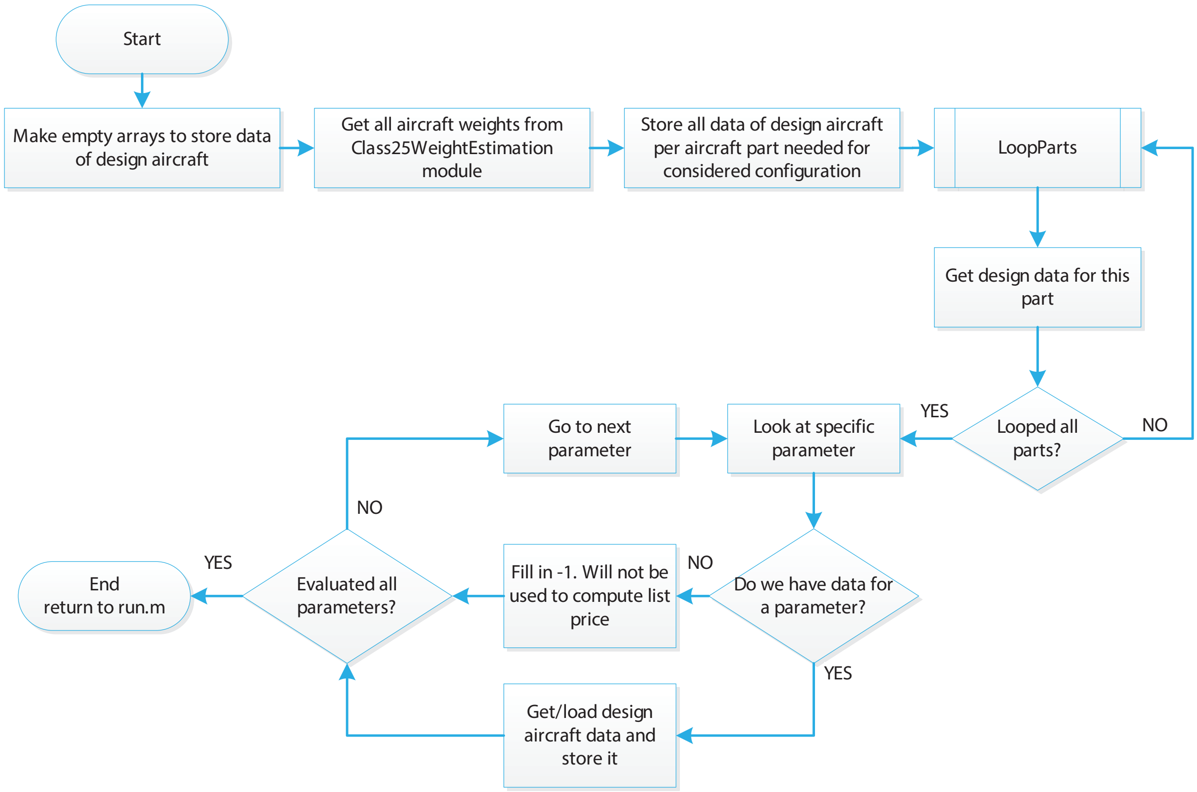


Figure 4.3: Activity diagram of the sub-module to obtain the design data.

All parts listed for the aircraft are looped and the correct data is pulled from the design aircraft for each part. How the parts are looped is shown in Figure 4.4. If no data is available in Initiator the parameter is given the value -1 and is excluded from the regression analysis.

4.1.4. OBTAIN CERS

The regression analysis is performed in the file *RegressionModel.m*. An activity diagram is shown in Figure 4.5. It has three levels of regressions that are performed. First, the parameter class, which are the parameters as segmented by *classifyData.m*. Second, all parameters within these classes. Third, the four regression functions introduced in Section 3.2.1. In total there are 58 parameters, hence a regression is performed 232 times. The process of selecting the best regression per parameter and excluding parameters for which no proper regression is found was explained in Section 3.2.

4.1.5. DETERMINE INITIAL LIST PRICE

Figure 4.6 visualizes how the initial list price for the top-down method is computed. First the price per part is determined by looping all parts as was shown in Figure 4.4. Per part all qualified parameters give a part price as presented in Figure 4.7.The overall list price $LP_{overall}$ is obtained by summing up all parts.

4.1.6. DETERMINE PRODUCTION COST

A detailed explanation of how the production cost are computed was presented in Sections 3.2.2 and 3.3.1. The general steps taken are shown in Figure 4.8. First, the NRC is calculated use the method of Roskam in the file *roskamNRC.m*. The RC of the bottom-up method is calculated using a method of Beltramo [10]. The component weights required are calculated in file *beltramoWeights.m* using the method presented in Section 3.3.1. The cost of these components are computed in the file *beltramoRC*. For both methods the the list prices are computed as well as the quantity for break-even. Finally, the results are saved to *obj*.

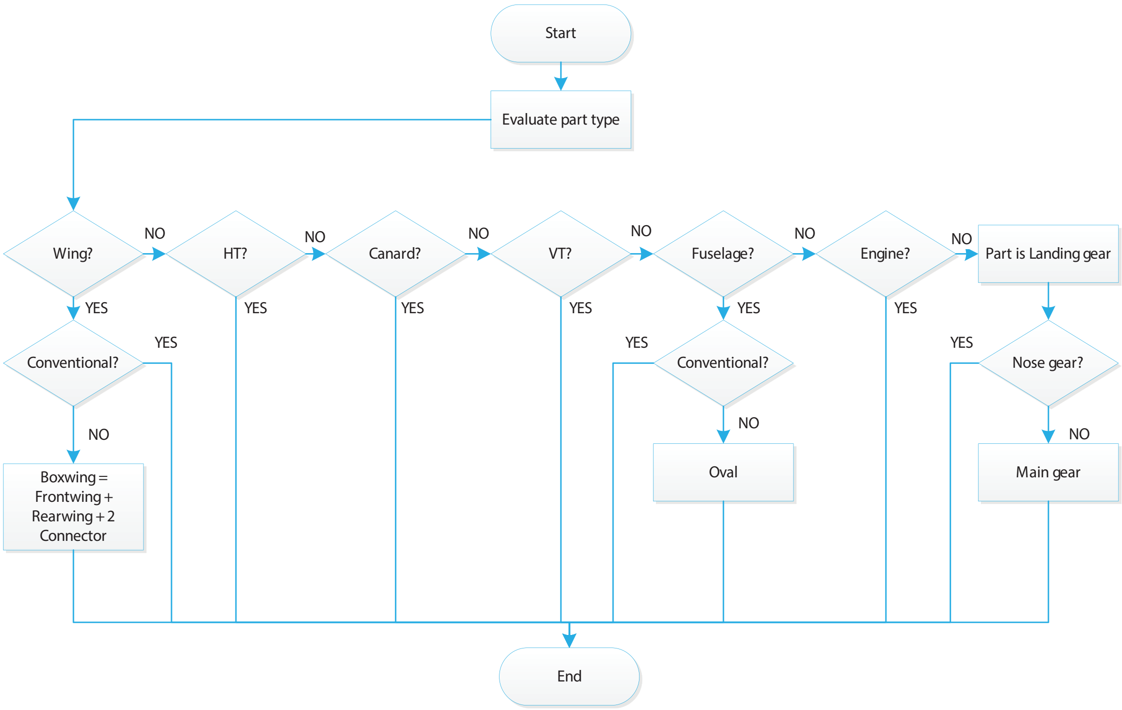


Figure 4.4: Activity diagram of looping all aircraft parts.

4.2. USER MANUAL

This Section explains how the module should be operated by the user. First, it demonstrates how the module is run. Secondly, it shows how the module settings are loaded and what these settings mean. Thirdly, it is explained how outputs are retrieved from the module. Finally, possible warnings are explained.

4.2.1. RUNNING THE MODULE

The CostEstimation module is run by starting a new Initiator session. Open Matlab R2013b, go to the path where Initiator is installed and type in the command window:

```
Initiator;
C = InitiatorController('B737-800.xml');
C.runModule('CostEstimation');
```

Note that the Boeing 737-800 serves as an example.

4.2.2. MODULE SETTINGS

Section 4.1.1 listed the input files used by the module. The settings are written in the Extensible Markup Language (XML) format. This file is called *CostData.xml*. An example of the content of this file is given in Appendix A. Below detailed explanations are offered for each input parameter of the module.

- UserSettings ⟶ see Table 4.1.
- RegressionSettings ⟶ see Table 4.2.
- ACdesign ⟶ see Table 4.3.
- Manufacturer ⟶ see Table 4.4.

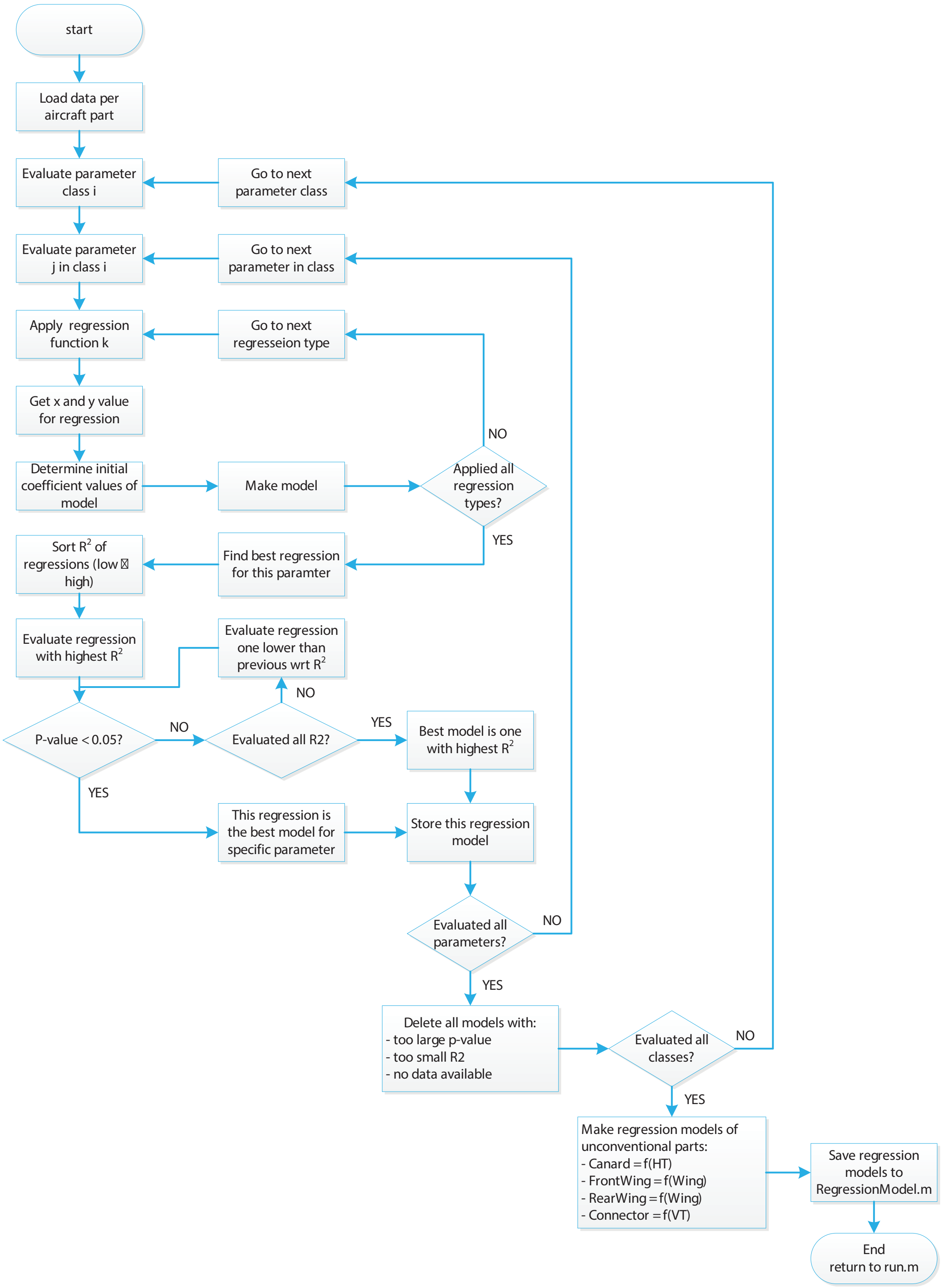


Figure 4.5: Activity diagram of the sub-module regression analysis.

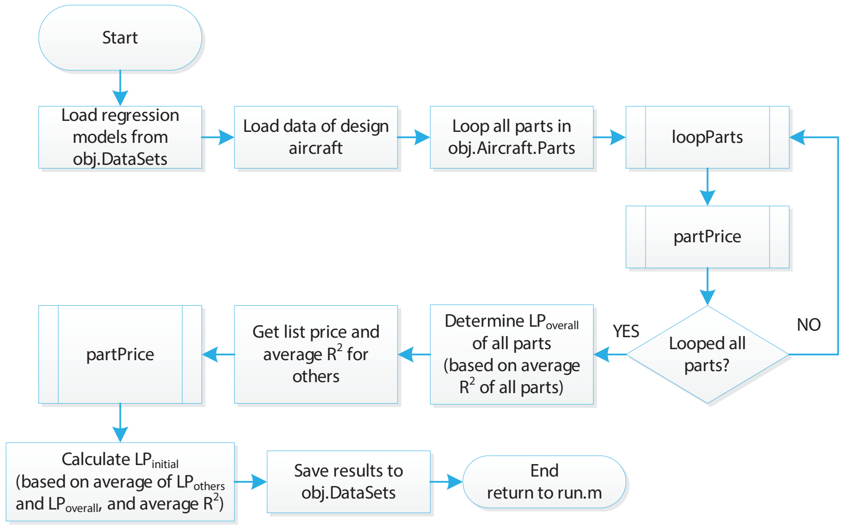


Figure 4.6: Activity diagram of sub-module to compute the initial list price.

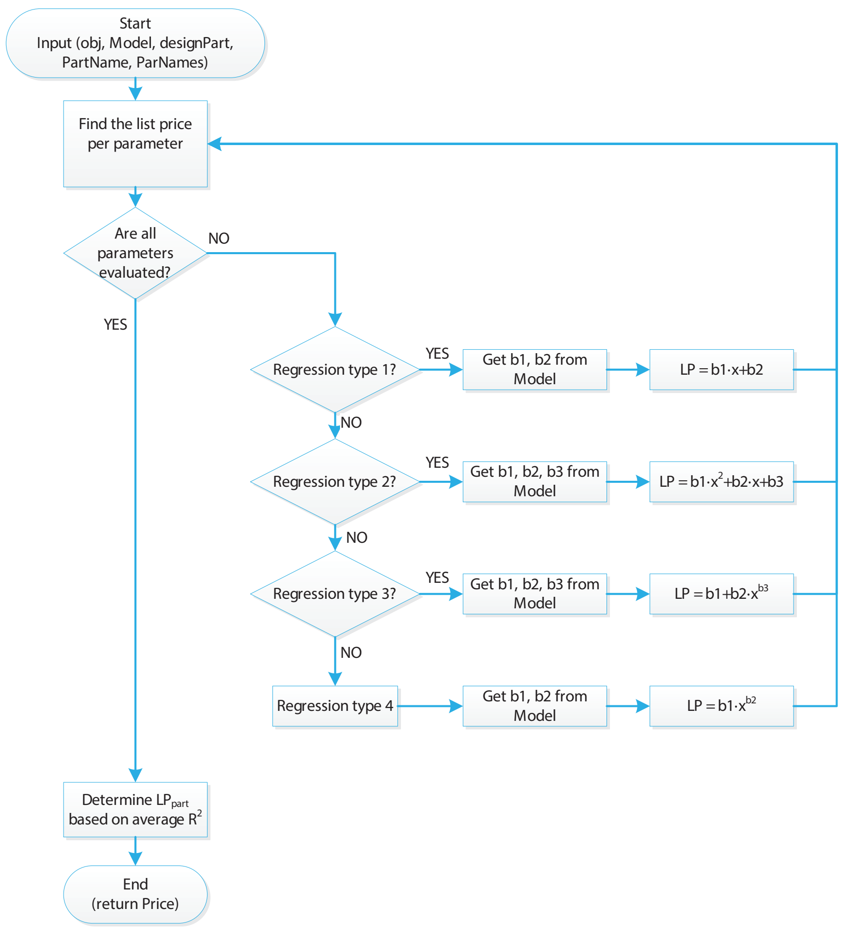


Figure 4.7: Activity diagram of sub-module to compute the part price.

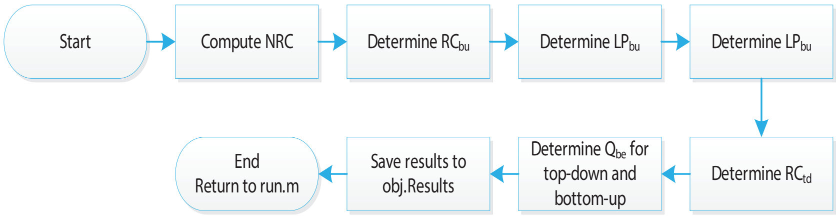


Figure 4.8: Activity diagram of sub-module to determine production cost.

- NonCommunality ⟶ The Non Communality Factor (NCF) per aircraft part and per configuration. The aircraft NRC is influenced by the level of innovation of the aircraft. This is accounted for by introduction of a NCF. Four types are identified as presented in Section 3.5.2. The NCF has to be filled in for all parts and all configurations.
- PercNCF ⟶ The percentage an individual aircraft part contributes to the total NCF. The total NCF of an aircraft consist of the individual NCF of the parts. The contribution an individual part has to the total NCF is expressed in percentages. These percentages are based on the contribution an individual part has on the NRC of the aircraft [47]. Percentages have to be filled in for all parts of all configurations.
- Operator ⟶ see Table 4.5.
- PartsPercLP ⟶ The percentage an aircraft part contributes to the initial list price. These percentages are used to breakdown the list price per part. In this way the impact of each individual part can be seen. The percentages are based on the impact a part has on the recurring cost of an aircraft. This is assumed to be valid since the recurring cost are normally 80-90% of the unit cost of an aircraft and thus also for the list price [47].

Table 4.1: Explanation of input data for *UserSettings*

Parameter	**Description**	**Unit**
Plots	Do you want to plot the results? (1=yes, 0=no)	[-]
PlotColor	Main color of the plots in RGB format (TU Delft blue = [0.1176 0.327 1]).	[-]
Sensitivity	Do you want to perform a sensitivity analysis? (1=yes, 0=no)	[-]
QuantityProduce	Amount of quantity to produce.	[-]
SensitivityBoundPerc	Upper and lower deviation for sensitivity analysis. (e.g. 25% = 0.25).	[-]
SensitivityStepPerc	Step size per sensitivity analysis.	[-]
DiscountRate	Additional margin on Unit Cost to give discounts to customer. An aircraft is never sold for his list price.	[-]
EarningsRate	Earnings margin for the aircraft manufacturer.	[-]
InterestRate	Rate of interest. Used to discount future cash flows.	[-]
ProductionRate	Amount of aircraft produced per year.	[-]
FiscalYear	Year of currency (US$) the estimate should be given in.	[-]

4.2.3. MODULE OUTPUTS

Results of the module are retrieved by typing the following line in the command window of Matlab after running the module.

```
C.getModuleResults('CostEstimation')
```

Outputs can also be found in the XML file of the aircraft that is analyzed. Plots of the module are saved to the following path: *.plots/CostEstimationOutputs*. Here all regression plots and plots for production and operating phase are stored.

Table 4.2: Explanation of input data for *RegressionSettings*

Parameter	Description	Unit
AgeBound1	The aircraft data base is divided in three age classes. This gives the lower bound and thus the oldest age class.	[-]
AgeBound2	This gives the upper bound and thus the youngest age class. All aircraft between AgeBound1 and AgeBound2 belong to the middle age class.	[-]
AircraftAgeClass	This gives the age class the user is interested in: 1 = oldest age class aircraft < AgeBound1 2 = middle age class AgeBound1 < aircraft ≤ AgeBound2 3 = youngest age class aircraft > AgeBound2	[-]
AcceptableR2	Lowest value of Pearson's product moment correlation coefficient that is acceptable to the user. R2 gives the quality of a regression. Value of 0.8 is advised.	[-]
AcceptablePvalue	Highest value of p-Value acceptable to the user. p-Value gives the validity of the causal relation between dependent and independent variable.	[-]
ParWing	Columns, thus parameters, in aircraft data base that belong to the class Wing.	[-]
ParHT	Columns, and thus parameters, in aircraft data base that belong to the class Horizontal tail.	[-]
ParVT	Columns, and thus parameters, in aircraft data base that belong to the class Vertical tail.	[-]
ParFuselage	Columns, and thus parameters, in aircraft data base that belong to the class Fuselage.	[-]
ParEngine	Columns, and thus parameters, in aircraft data base that belong to the class Engine.	[-]
ParGear	Columns, and thus parameters, in aircraft data base that belong to the class Landing gear.	[-]
ParWing	Columns, and thus parameters, in aircraft data base that belong to the class *others* and are not directly related to individual parts of the aircraft.	[-]
EngineParTST	Column number of the Total Static Thrust parameter. This column will be deleted from the data base since only the individual engine performance is required.	[-]

4.2.4. EXPLANATION OF WARNINGS OR ERROR MESSAGES

The module can give warnings or messages if things go wrong when running the module and are listed below:

- Wrong version of Matlab. Matlab R2013b is required to run the module since the Statistical Toolpack of this version is required to perform the regression analysis and obtain CERs. This warning message will only be displayed if manual input is activated.
- Q_{be} not found. For some combinations of list price, production rate and interest rate it is possible that the number of aircraft for break-even cannot be determined. In this case the module gives a warning. If so, Q_{be} is set to 1 so the module does not terminate. However, the results of the module are incorrect. This warning can occur twice, for top-down and bottom-up methods.
- Q_{target} not found. Both RC_{td} and RC_{bu} are a function of Q and are equated to solve for Q. This is done by using the Matlab function *fzero* with Q ranging from 1 to 2000. Again, whether the message will appear dpends on the combination of list price, production rate and interest rate.

Table 4.3: Explanation of input data for *Acdesign*

Parameter	Description	Unit
TypeThrustRev	The type of thrust reversers installed on the engine: 1 = Cascade or Target reverser with translating sleeve. 2 = Simple Target type reverser with separate flow exhaust nozzle. 3 = Simplet Target type reverser with mixed flow exhaust nozzle. 4 = Separate flow engine exhaust system without thrust reverser. 5 = Short duct engine exhaust system without thrust reverser.	[-]
AutoThrottle	Does the engine have an auto throttle? (1=yes, 0=no)	[-]
NoPropellers	Number of propellers	[-]

Table 4.4: Explanation of input data for *Manufacturing*

Parameter	Description	Unit
EngineeringRate	Engineering cost rate.	[US$]
SalYearEngineering	Year of engineering cost rate.	[-]
ManufacturingRate	Manufacturing cost rate.	[US$]
SalYearManufacturing	Year of manufacturing cost rate.	[-]
ToolingRate	Tooling cost rate.	[US$]
SalYearTooling	Year of tooling cost rate.	[-]
Nrdte	Number of aircraft build in the RDT&E phase. According to Roskam for commercial aircraft about 2-8.	[-]
ProgramComplexity	Judgment factor for complexity of the aircraft program: 1 = conventional aircraft, 1970 era. 1.5 = aircraft with moderately aggressive use of advanced technology. 2 = aircraft with very aggressive use of advanced technology.	[-]
CADFactor	Judgment factor for effect of Computer Aided Design on RDT&E cost: 1.2 = for manufacturers which are in CAD learning mode. 1 = for manufacturers which are using 'manual' drafting techniques. 0.8 = for manufacturers which are experienced with CAD.	[-]
TypeMaterial	Correction factor for type of material used for construction of airframe: 1 = conventional alloys. 1.5 = stainless steel airframes. 2-2.5 = primary structure is conventional composite materials Li/Al or ARAL. 3 = for carbon composite airframes.	[-]
StealthFactor	Correction factor for degree of stealth required: 1 = commercial aircraft. 3 = military aircraft.	[-]
FacilityFactor	Judgment factor depending on the degree of facilities needed: 0 = no extra facilities are required (build using existing facilities). 0.2 = if extensive test and simulation facilities are needed.	[-]
ProfitFactorRDTE	Profit factor for the RDT&E phase.	[-]
ProfitFactorMan	Profit factor for the manufacturing phase.	[-]
FinanceFactorRDTE	Factor for cost of financing the RDT&E phase.	[-]
CEFbeltramo	Correction factor for Cost Escalation Factor for Beltramo method.	[-]
Nstatictest	Number of static test aircraft required.	[-]
ProdRateRDTE	Production rate during the RDT&E phase in units per month. Normally $^{1}/_{3}{}^{rd}$ per month, according to Roskam.	[-]
PricePropeller	The price per propeller.	[US$]

Table 4.5: Explanation of input data for *Operator*

Parameter	Description	Unit
YearsInService	Number of years the aircraft will be in service for the operator.	[-]
InternationalFlight	Is it an international flight? (1=yes, 0=no).	[-]
AltitudeHoldingFT	Altitude at which the aircraft will be in holding.	[ft]
DailyUtilizationBLHRS	Daily utilization of the aircraft in block hours.	[block hours]
AcAcquired	Number of aircraft acquired and thus in fleet.	[-]
FactorSalaryVacationEtc	Factor added to salary for vacation pay, training, insurance etc.	[-]
SalaryCaptain	Salary of the captain.	[US$/year]
SalaryCopilot	Salary of the co-pilot.	[US$/year]
SalaryFlightEngineer	Salary of the flight engineer.	[US$/year]
AnnualCrewHours	Annual hours of work per cabin crew.	[hours]
TravelExpenseFactor	Travel expense factor for cabin crew.	[-]
FuelPrice	Price of fuel.	[US$/USgallon]
FuelDensity	Density of fuel.	[lbs/USgallon]
OilPrice	Price of oil.	[US$/USgallon]
OilDensity	Density of oil.	[lbs/USgallon]
AnnualInsuranceRate	Annual insurance rate of the aircraft hull.	[US$/US$/ac/year]
MaintHrsPerFlHr	Number of maintenance hours required per flight hour.	[hours]
MaintLabRate	Maintenance labor rate.	[US$/hour]
EngOverhaulHours	Hours between engine overhaul.	[hours]
FoverheadMaintLab	Maintenance overhead factor associated with labor.	[-]
FoverheadMaintMat	Maintenance overhead factor associated with materials needed.	[-]
FapSpares	Airplane spare parts factor, Roskam suggest 0.10.	[-]
FengSpares	Engine spare parts factor, Roskam suggest 0.10.	[-]
DCFperiod	Period Discounted Cash Flow is evaluated for.	[years]
ESPPF	Engine Spare Part Price Factor, Roskam suggest 1.5.	[-]
DeprPeriodAc	Depreciation period of the aircraft overall.	[years]
DeprPeriodAf	Depreciation period of the airframe.	[years]
DeprPeriodEng	Depreciation period of the engine.	[years]
DeprPeriodProp	Depreciation period of the propeller.	[years]
DeprPeriodAv	Depreciation period of the avionics.	[years]
DeprPeriodApSpares	Depreciation period of the airplane spares.	[years]
DeprPeriodEngSpares	Depreciation period of the engine spares.	[years]
ResidualValuePercAf	Residual value of the airframe.	[%]
ResidualValuePercEng	Residual value of the engine.	[%]
ResidualValuePercProp	Residual value of the propeller.	[%]
ResidualValuePercAv	Residual value of the avionics.	[%]
ResidualValuePercApSpares	Residual value of the airframe spares.	[%]
ResidualValuePercEngSpares	Residual value of the engine spares.	[%]
NavigationFee	Navigation fee per flight.	[US$/flight]
FinanceFactor	Factor for financing the operations, Roskam suggests 0.07.	[-]
PaxPerCabAtt	Number of passenger per cabin attendant.	[-]
RevInflationRate	Revenue inflation rate.	[-]
PaxLoadFactor	Passenger load factor.	[-]
FactorFirstClassPax	Factor of total seats for first class passengers.	[-]
FactorEconomyClassPax	Factor of total seats for economy class passengers.	[-]
YieldFirstClass	Yield factor for first class passengers.	[cents/pax/nm]
YieldEconomyClass	Yield factor for economy class passengers.	[cents/pax/nm]
YieldCargo	Yield factor for cargo.	[US$ cents/-pax/nm]
FreightWeight	Weight of the freight.	[kg]
InterestRate	Interest rate.	[-]
TaxRate	Tax rate.	[-]
InterestRateROI	Interest rate for Return On Investment calculations.	[-]

5

VERIFICATION OF THE MODEL

The cost estimating model developed is verified. Both methods used are only assessed for the manufacturing cost. First, Section 5.1 shows a verification using commercial software. Secondly, the list prices are verified based on online sources in Section 5.2 [39].

5.1. VERIFICATION USING COMMERCIAL SOFTWARE

The software used to verify the model is developed by Galorath [33]. SEER H is one of the many software packages Galorath develops and focuses on hardware, electronics and systems. It is a decision support tool that reliably and accurately estimates the total cost of ownership for new product development projects. Airbus, for example, uses this software for estimating and managing costs of new and existing projects. This section will first introduce the functioning of SEER H. However, more detailed explanation is presented in Appendix E. In the section that follows NRC, RC_{td} and RC_{bu} obtained by the model are validated.

5.1.1. FUNCTIONING OF SEER H

SEER H provides a cost estimating project for a new commercial aircraft. This project is used to develop a new project that adheres to the data available from the design aircraft. The WBS in SEER H is therefore altered. In this WBS structural and system components are listed. For the structural parts the cost estimate is based on the parameter's weight and volume. The latter is not available from Initiator so only the component's weight are used. The weight is given as a tree point estimate. The likely value is the weight obtained from Initiator and it is assumed that the least likely value to be 5% lower and the most likely to be 10% higher for all the weights in the WBS. Also a three point estimate is required for several variables such as the complexity of the design and production experience. These are all qualitatively ranging from very low (VLo) to extremely high (EHi). For conventional aircraft the original settings of the example project were used and are shown in Appendix A.

A total of five conventional aircraft are used to verify the model. They are listed in Table 5.1 along with their design requirements. All aircraft are verified for four cases:

1. NCF = 1, Q = 1000, pr = 120.
2. NCF = 0.2, Q = 1000, pr = 120.
3. NCF = 1, Q = 500, pr = 72.
4. NCF = 0.2, Q = 500, pr = 72.

For the developed cost model all three parameters are changed per case. However, for the project in SEER H only Q and pr are changed. Since it is unknown what level of communality SEER H uses in the existing project a range of NCFs in the cost model are compared with the results from SEER H. Overall, the best correlation between the model and SEER H was found for NCF = 0,2. Thus it is likely that the project in SEER H uses a 80% commonality which is not strange since it is only able to asses conventional configurations.

Hence, the values for NCF listed for the four cases are not chosen randomly. The value for 0,2 is already explained. A NCF of 1 is analyzed since it shows the most extreme comparison between the model and SEER H.

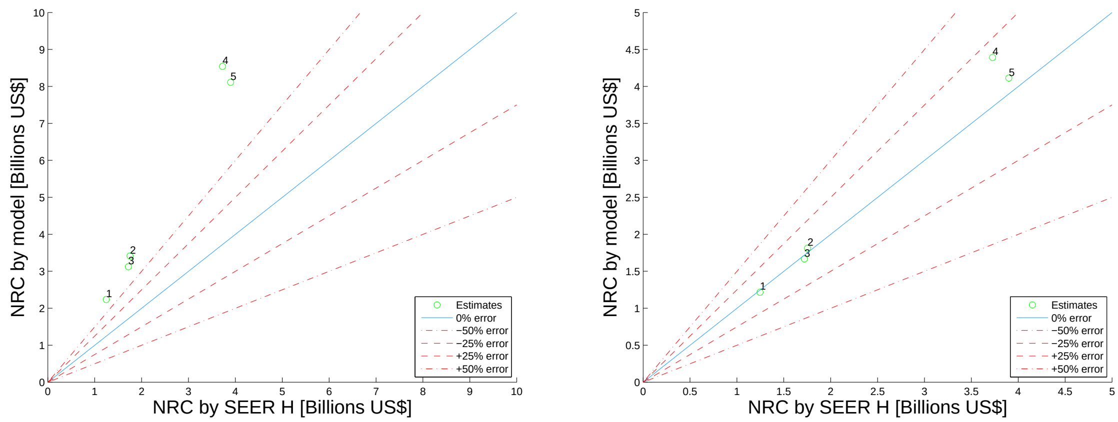
Table 5.1: Overview of aircraft used for verification

Nr.	Aircraft	Passengers	Range	Payload mass	M_{cr}	Altitude	L_{to}	$L_{landing}$	No. of flights
-	-	-	km	kg	-	m	m	m	-
1	Fokker 100	107	2,556	11,300	0.72	10,668	1,856	1,321	100,000
2	Boeing 737-800	162	1,363	21,319	0.79	11,887	2,101	1,440	100,000
3	MD 80	155	1,453	18,236	0.76	10,668	2,195	1,481	100,000
4	Airbus A340-300	295	9,167	50,800	0.82	11,887	3,000	1,964	100,000
5	Boeing 777-300	394	3,142	64,000	0.84	10,668	2,574	1,860	100,000

5.1.2. VERIFICATION OF NRC

As was explained in Chapter 3 both top-down and bottom-up methods compute the NRC in the same way. Hence, the verification holds for both methods.

Figure 5.1 shows the result for cases 3 and 4 where Q is set to 500 and pr to 72. The results for case 1 and 2 are not shown since Q and pr have no influence on NRC. As can be seen the in Figure 5.1a the model overestimates the NRC with more tan 50% if NCF equals 1. However, good results are obtained when NCF is set to 0.2 as is seen in Figure 5.1b. Especially for the smaller aircraft the estimates of the model are in line with estimates from SEER H. For the larger aircraft the NRC on average is overestimated by 10%.



(a) Case 3: NCF = 1, Q = 500, pr = 72

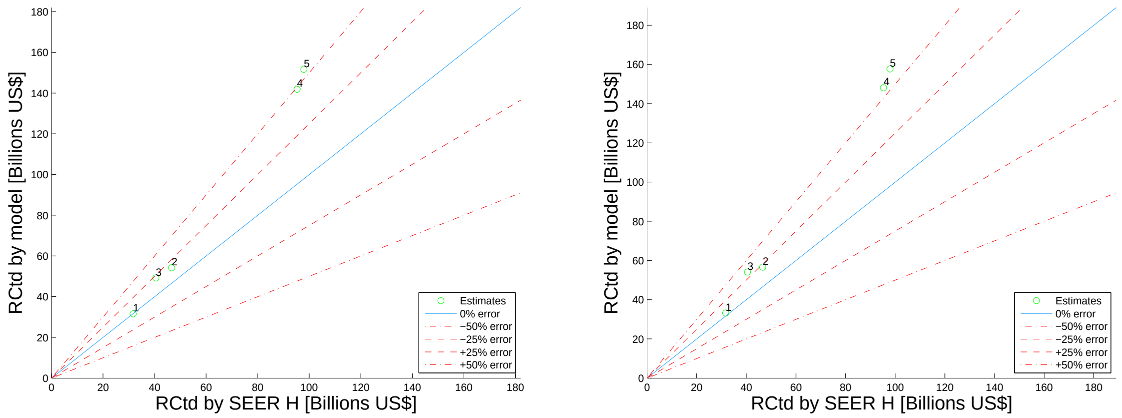
(b) Case 4: NCF = 0.2, Q = 500, pr = 72

Figure 5.1: Comparison between model and SEER H for NRC

5.1.3. VERIFICATION OF RC FOR TOP-DOWN

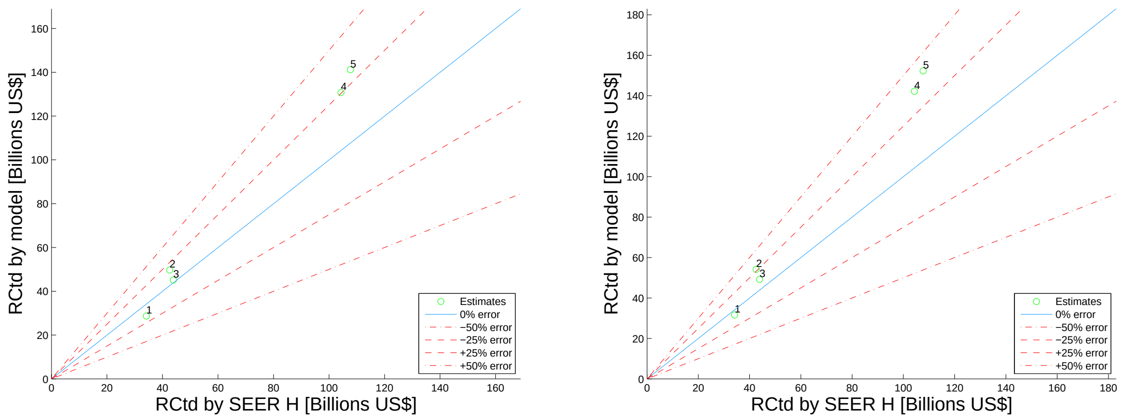
The verification results for cases 1 and 2 are shown in Figure 5.2 and cases 3 and 4 in Figure 5.3. As seen from Figures 5.2a and 5.2b RC_{td} is overestimated. For small aircraft this is within 25% and for the larger aircraft 50%. The NCF has a small impact on the estimates.

For cases 3 and 4 the impact of NCF is larger. Also, for Q = 500 the model overestimates the RC_{td} less than for Q = 1,000.



(a) Case 1: NCF = 1, Q = 1,000, pr = 120 (b) Case 2: NCF = 0.2, Q = 1,000, pr = 120

Figure 5.2: Comparison between model and SEER H for RC_{td}, cases 1 and 2.

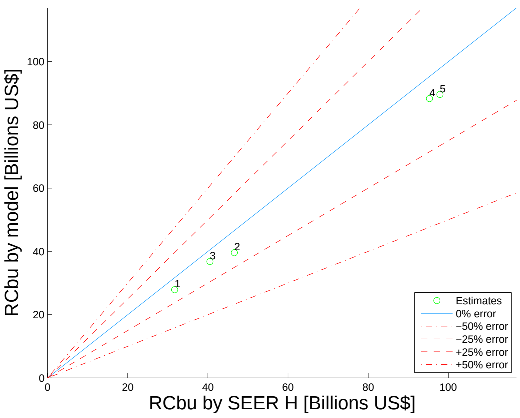


(a) Case 3: NCF = 1, Q = 500, pr = 72 (b) Case 4: NCF = 0.2, Q = 500, pr = 72

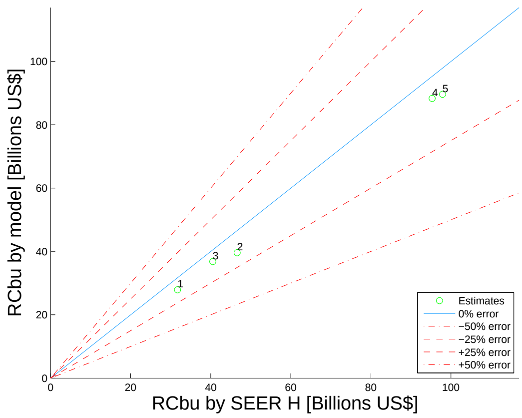
Figure 5.3: Comparison between model and SEER H for RC_{td}, cases 3 and 4.

5.1.4. Verification of RC for bottom-up

Figures 5.4 and 5.5 show that the bottom-up estimation of RC is in line with the estimates for SEER H. The model underestimates RC_{bu} for cases 1 and 2 with 10% on average. This is less for cases 3 and 4 where the maximum error is 5% on average. Again, producing less aircraft will give a better correlation between the model and SEER H.

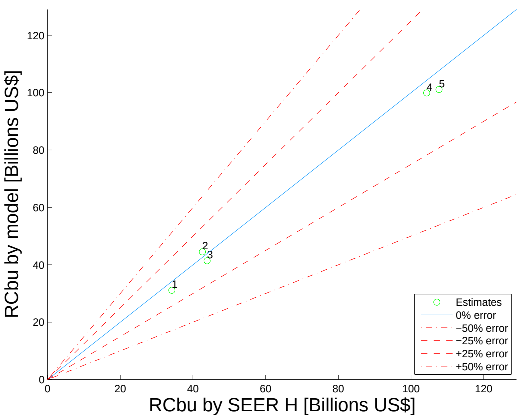


(a) Case 1: NCF = 1, Q = 1,000, pr = 120

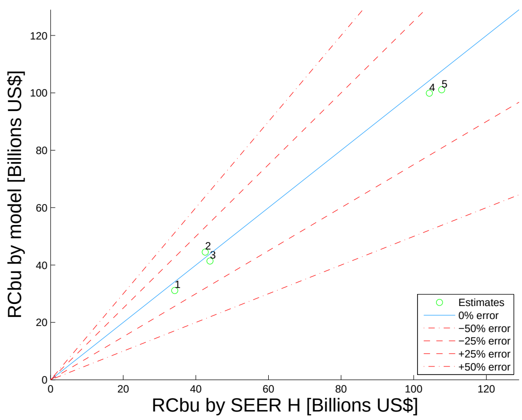


(b) Case 2: NCF = 0.2, Q = 1,000, pr = 120

Figure 5.4: Comparison between model and SEER H for RC_{bu}, cases 1 and 2.



(a) Case 3: NCF = 1, Q = 500, pr = 72



(b) Case 4: NCF = 0.2, Q = 500, pr = 72

Figure 5.5: Comparison between model and SEER H for RC_{bu}, cases 3 and 4.

All verification results for RC and NRC are examined with respect to the ability to give a correct relative cost estimation. The aircraft are listed from low to high cost for Figures 5.1 to 5.5. The results are summarized in Table 5.2, with the numbers as listed in 5.1. Columns with heading M and S respectively show the results obtained by the cost model and SEER H. Differences between them are shown in bold. This occurred for six instances.

The NRC based on SEER H shows an higher estimate of the Airbus A340-300 with respect to the Boeing 777-300. The developed cost model however shows the inverse.

For the RC it is seen that cases 3 and 4, thus for Q equal to 500, show irregularities between the Boeing 737-800 and the MD 80. This occurs for both top-down and bottom-up methods. Fortunately, the differences are small as can be seen in Figures 5.3 and 5.5.

5.2. VERIFICATION BASED ON COLLECTED DATA

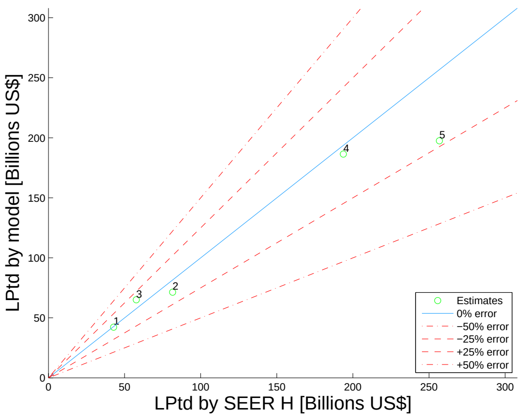
The database used for the regression analysis contains data on list prices of the aircraft. These prices are obtained from sources presented in Section 3.2 and are used to verify the list prices. This is done for the top-down and bottom-up method in respectively Sections 5.2.1 and 5.2.2.

Table 5.2: Relative estimates of NRC and RCs for all four verification cases.

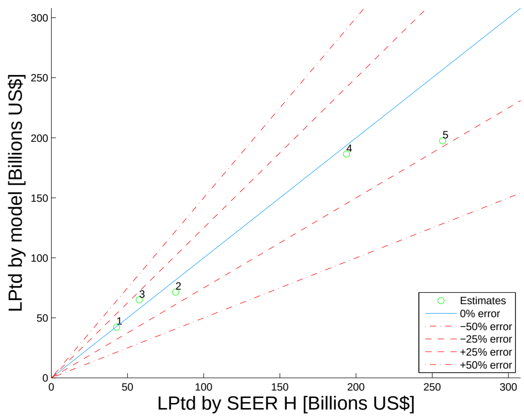
Parameter	NRC				RC_{td}								RC_{bu}							
Cases	1		2		1		2		3		4		1		2		3		4	
Source	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
1^{st}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2^{nd}	3	3	3	3	3	3	3	3	**3**	**2**	**3**	**2**	3	3	3	3	**3**	**2**	**3**	**2**
3^{rd}	2	2	2	2	2	2	2	2	**2**	**3**	**2**	**3**	2	2	2	2	**2**	**3**	**2**	**3**
4^{th}	**5**	**4**	**5**	**4**	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
5^{th}	**4**	**5**	**4**	**5**	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

5.2.1. VERIFICATION OF LP FOR TOP-DOWN METHOD

Since the top-down method to determine the list price is no function of NCF, Q and pr the same list price is obtained for all four cases. Figure 5.6 shows the results for cases 1 and 2 which support this statement. The estimates of LP_{td} of the model are in line with the database. Only the Boeing 777-300 is underestimated by 25%.



(a) Case 1: NCF = 1, Q = 1000, pr = 120

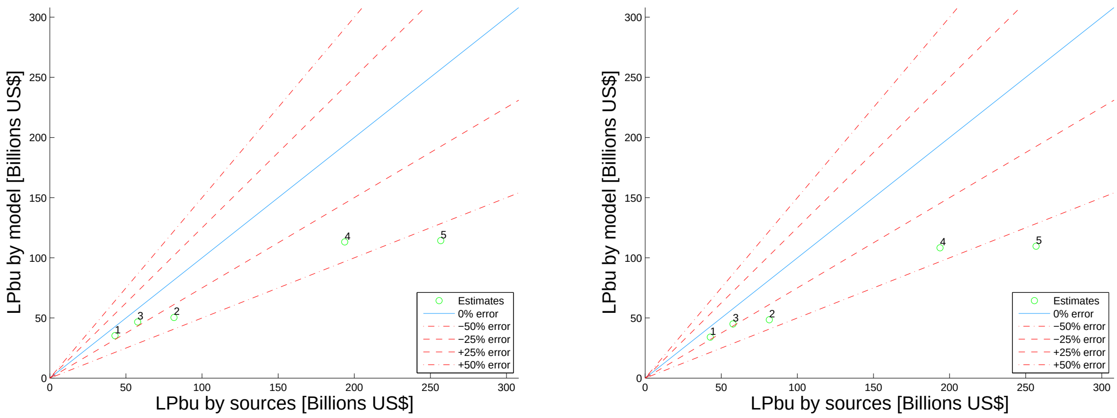


(b) Case 2: NCF = 0.2, Q = 1000, pr = 120

Figure 5.6: Comparison between model and SEER H for LP_{td}

5.2.2. VERIFICATION OF LP FOR BOTTOM-UP METHOD

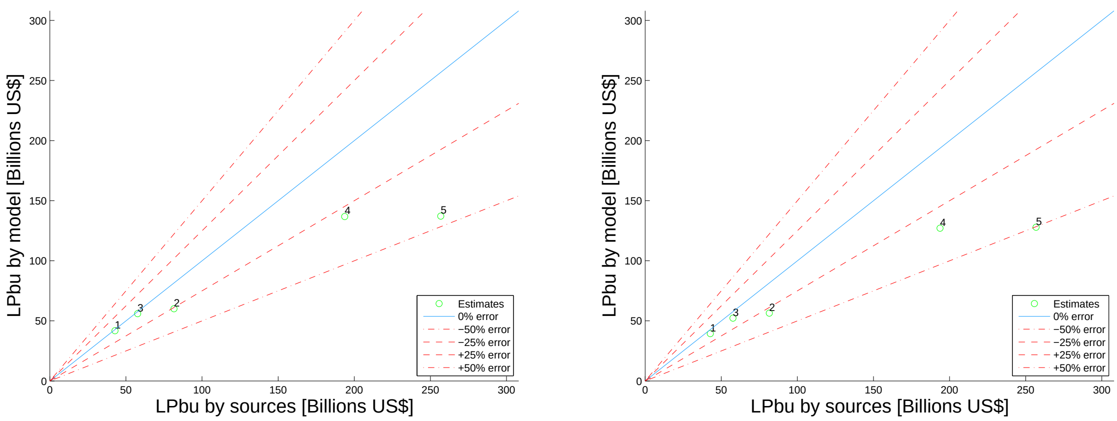
Figures 5.7 and 5.8 show the results of RC for the bottom-up method. The model clearly underestimates the LP_{bu} for all four cases. This hold for any value of NCF. The latter is since the NRC contributes only little to the UC and thus to the LP. The contribution of NRC is larger if Q is smaller and therefore the model shows a small improvement for cases 3 and 4.



(a) Case 1: NCF = 1, Q = 1,000, pr = 120

(b) Case 2: NCF = 0.2, Q = 1,000, pr = 120

Figure 5.7: Comparison between model and database for LP_{bu}, cases 1 and 2.



(a) Case 3: NCF = 1, Q = 500, pr = 72

(b) Case 4: NCF = 0.2, Q = 500, pr = 72

Figure 5.8: Comparison between model and database for LP_{bu}, cases 3 and 4.

Table 5.3 shows the ability of the model to give a good relative list price estimate. This results are shown for all four cases and both methods. According to the model the LP_{bu} estimates that the list price of the Boeing 777-300 is lower than the Airbus A340-300, which is not in line with the database. Hence, it is plausible that the estimate of LP_{bu} is good enough for small aircraft.

Table 5.3: Relative estimates of LPs for all four verification cases.

Parameter	LP_{td}								LP_{bu}							
Case	1		2		3		4		1		2		3		4	
Source	M	S	M	S	M	S	M	S	M	S	M	S	M	S	M	S
1^{st}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2^{nd}	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
3^{rd}	2	2	2	2	2	2	2	2	2	3	2	3	2	2	2	2
4^{th}	4	4	4	4	4	4	4	4	**5**	**4**	**5**	**4**	**5**	**4**	**5**	**4**
5^{th}	5	5	5	5	5	5	5	5	**4**	**5**	**4**	**5**	**4**	**5**	**4**	**5**

In general, the verification showed promising results. The verification using SEER H shows that the model estimates the cost in the correct order of magnitude. The NRC showed that good results are obtained if NCF is set to 0.2. The estimate of RC using the top-down method did not show promising results since it overestimated the cost by 25-50%. However, the bottom-up approach did showed promising results for all cases with errors lower than 10%. Therefore, the bottom-up is preferred.

Verification of the list price showed that the model is able to give a good relative estimate for smaller aircraft. For larger aircraft the list price as obtained by the bottom-up approach showed irregularities.

Overall, it plausible that the model is able to give a good relative cost estimate. This is an important conclusion since it is the main objective of this research.

6
CASE STUDIES

At this point the methodology of the model is explained, verified and implementation completed. This Chapter presents the capability of the cost estimating model by the use of case studies. In Section 6.1 the model is demonstrated using a baseline aircraft. Secondly, a sensitivity analysis of this baseline aircraft with respect to program, operating and design parameters is presented in Section 6.2. A comparison between conventional and unconventional aircraft is shown in Section 6.3. Finally, Section 6.4 demonstrates how the model is used to analyze aircraft families based on a case-study of the Airbus A340 family.

6.1. BASELINE AIRCRAFT

This section presents the results of the developed cost model by use of a baseline aircraft. Market demand of the next decades states that single-aisle aircraft, like the Airbus A320, are needed most [49]. In 2030 over 20,000 of these single-aisle aircraft are needed compared to 9,000 twin-aisle aircraft and VLA like the Airbus A380-800. Since an Airbus A320 is not available in Initiator a Boeing 737-800 is used as baseline aircraft. This Section provides the results of both top-down and bottom-up methods. All monetary values are given in 2014 US$.

6.1.1. DESIGN REQUIREMENTS AND MODULE SETTINGS

The baseline aircraft for which the results are demonstrated has design requirements as listed in Table 6.1. For the baseline aircraft it is assumed that 1,000 aircraft are build with a production rate of 120 aircraft per year. Hence, the production life time is 9 years. A NCF of 1 is used for all aircraft parts since this gives the worst case scenario for the costs. A discount, earnings and interest rate of respectively 7%, 10% and 5% is used [47].

Table 6.1: Design requirements for the baseline aircraft

Parameter	**Values**	**Units**
Passengers	162	-
Range	1,363	km
Payload mass	21,319	kg
Cruise Mach number	0.79	-
Altitude	11,887	m
Take-off distance	2,101	m
Landing distance	1,440	m
Number of flights	100,000	-

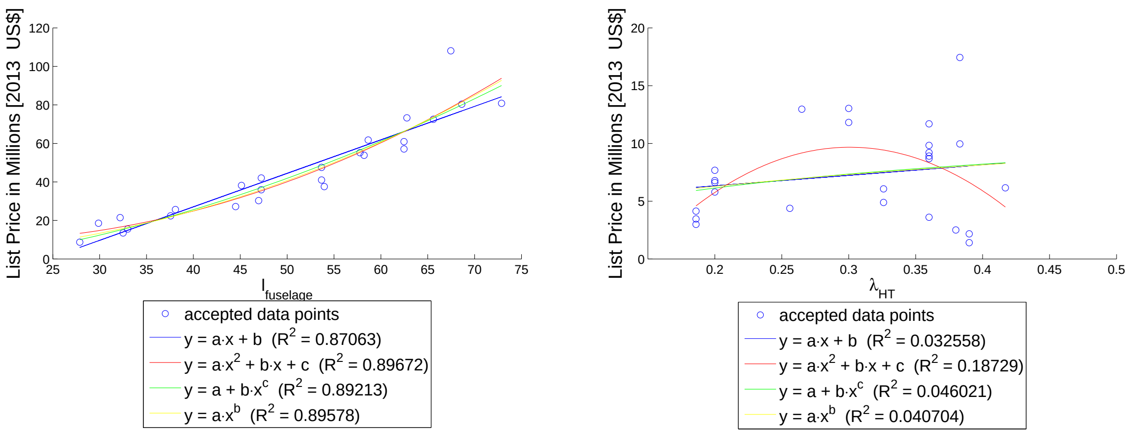
As stated in Chapter 3 the top-down method splits the historical list prices up in parts based on RC percentages. The same is done for the contribution of individual part NCFs to the total NCF of the aircraft. However, these are based on NRC percentages. Both percentages are obtained from literature and apply for single aisle aircraft only [47]. It should be noted that literature showed additional cost components in the cost breakdown. For the RC assembly and systems are an extra cost components and accounts for respectively 20% and 38% of the total RC and are divided per ratio over the other components. As said in Chapter 3 the NRC of the landing gear is omitted since it is only 1%. The percentages used are shown in Appendix C.

6.1.2. INITIAL LIST PRICE

The initial list price is computed by the method explained in Section 3.2.1. It only applies for the top-down method and the results presented are compared with the list price of the bottom-up method in Section 6.1.5.

All 58 parameters in the database are subjected to a regression analysis. The obtained regression functions are plot for all parameters. Figure 6.1a shows an example of a good regression for the fuselage length. However, bad regressions also occur as can be seen in Figure 6.1b for the taper ration of the horizontal tail. The R^2 per regression function is shown in the legend. Obviously, the parameter fuselage length is accepted and the taper ratio of the horizontal tail rejected.

An overview of all accepted parameters per parameter class, the regression function, R^2, RMSE, p-value and coefficients is shown in Table 6.2. A total of 20 parameters are accepted by the model. The number of the type of regression function corresponds with the numbering in Section 3.2.



(a) Good regression (Fuselage length)

(b) Bad regression (Taper of horizontal tail)

Figure 6.1: Example regression plots including regression functions.

For each part class the price is computed for all accepted parameters. The price and RMSE are plotted per class to visualize the estimates and compare parameters. Figure 6.2a and 6.2b respectively show the prices for the classes Wing and Horizontal tail. The estimates for the wing lie within the same range and the RMSEs are acceptable. However, Figure 6.2b shows that for the Horizontal tail the estimates differ a lot and the RMSEs are relatively high. For the span of the horizontal tail a negative price is obtained, which is of course impossible. This would imply that a customer receives money when ordering an horizontal tail.

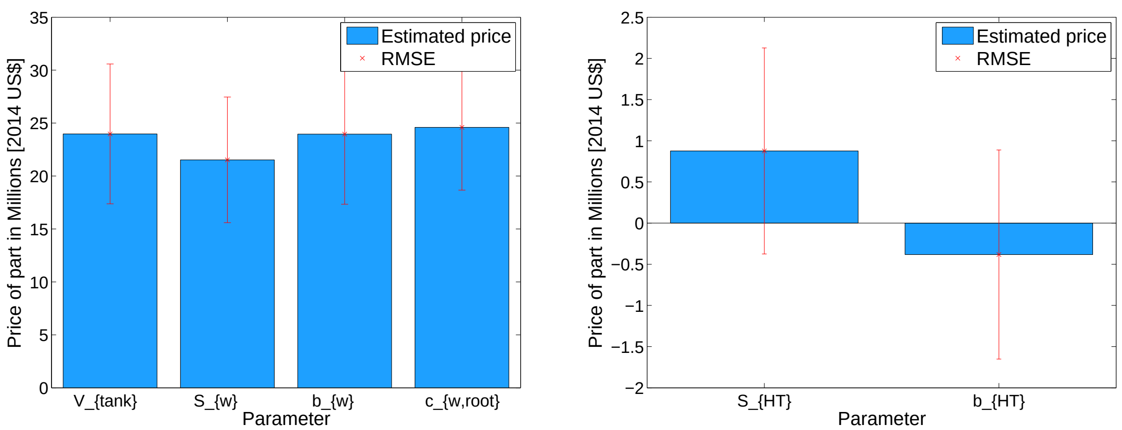
An incorrect estimate could be caused by unrealistic values of the design aircraft. If so, this value could lie outside the range of the data points in the database used for the regression analysis. Use of CERs outside this range could result in odd estimates. As said before, the RMSE for the horizontal tail is relatively high. It should be noted however, that this RMSE gives the mean error of the entire model for the parameter considered. As an example, if the list prices in the database ranges from 100 to 200 mln US$ it could have a RMSE of 20mln US$. However, if the estimate is 110 mln US$ the value of the RMSE

Table 6.2: Accepted parameters of the baseline aircraft

Class	Par	Function	R^2	RMSE	p-value	a	b	c
Wing	V_{tank}	3	0.95	6.60	$2.22\cdot10^{-41}$	0.736	0.044	0.621
Wing	S_w	2	0.96	5.93	$2.93\cdot10^{-22}$	$-8.347\cdot10^{-5}$	0.220	-3.381
Wing	b_w	2	0.95	6.62	$3.27\cdot10^{-21}$	0.009	1.065	-21.952
Wing	$c_{w,root}$	3	0.96	5.93	$2.21\cdot10^{-38}$	0.291	0.827	1.683
HT	S_{HT}	2	0.91	1.25	$8.05\cdot10^{-19}$	$-2.856\cdot10^{-4}$	0.147	-0.988
HT	b_{HT}	2	0.91	1.27	$1.11\cdot10^{-18}$	-0.004	0.950	-7.848
VT	S_{VT}	2	0.87	1.52	$5.84\cdot10^{-17}$	$-9.300\cdot10^{-4}$	0.270	-1.945
VT	b_{VT}	3	0.82	1.80	$2.41\cdot10^{-30}$	-0.715	0.284	1.594
Fuselage	l_f	2	0.90	8.39	$4.53\cdot10^{-18}$	0.025	-0.762	14.853
Fuselage	h_f	2	0.90	8.22	$2.88\cdot10^{-18}$	-0.866	27.237	-69.220
Fuselage	w_f	3	0.92	7.22	$3.00\cdot10^{-36}$	7.424	0.235	3.093
Engine	N_e	2	0.95	1.35	$6.15\cdot10^{-23}$	$6.248\cdot10^{-5}$	0.032	2.769
Engine	$T_{stat,1}$	3	0.93	1.62	$1.55\cdot10^{-43}$	4.454	$2.543\cdot10^{-5}$	1.513
Landing gear	$N_{lg,wheels}$	2	0.92	0.98	$5.00\cdot10^{-19}$	-0.017	1.087	-1.734
Other	PLM	3	0.96	17.45	$2.49\cdot10^{-46}$	25.161	$3.428\cdot10^{-4}$	14.853
Other	MTOM	3	0.96	16.05	$4.01\cdot10^{-45}$	-32.028	0.077	1.212
Other	OEM	3	0.98	12.07	$2.29\cdot10^{-48}$	-36.115	0.073	0.643
Other	MLM	3	0.98	11.84	$2.47\cdot10^{-49}$	-21.748	0.018	0.775
Other	MZFM	3	0.98	10.63	$1.74\cdot10^{-50}$	-18.771	0.013	0.802
Other	PAX_{2class}	2	0.98	12.37	$1.51\cdot10^{-25}$	-3.796	0.811	-34.324

is relatively larger compared to an estimate of 250 mln US$. Still, it is useful to plot it in the same graph since it directly states the accuracy of the model used to obtain the estimate.

An overview for all classes are shown in Appendix B. The classes Wing, Fuselage, Engine, Main gear, and Others show promising results, whereas the Horizontal and Vertical tail do not. Fortunately, these parts only represent 10% of the list price. Hence, the impact of the estimates of these parameters on the total list price is small. The value of the RMSE per parameter is listed in Table 6.2.



(a) Wing (b) Horizontal tail

Figure 6.2: Examples of prices per part parameter including RMSE.

For each parameter class a final part price is determined along with the average R^2. Equation 3.5 showed how this is done. An overview is given in Table 6.3. Table 6.3 also shows the overall aircraft price based on all structural parts and the price for the total aircraft as obtained from the parameter class Other. The latter two also have an average R^2 which is used to compute the initial list price. The baseline aircraft has an initial list price of 71.8 mln US$.

Table 6.3: Breakdown of initial list price per parameter class in 2014 US$ for baseline aircraft.

Class	**List Price [US$ mln]**	**R^2**
Fuselage	32.1	0.91
Wing	23.56	0.95
HT	0.2	0.91
VT	1.0	0.84
Engines	14.0	0.88
Landing gear	5.1	0.92
Overall parts	75.9	0.92
Other	68.0	0.97
Initial LP	71.8	0.95

As can be seen in Table 6.3 the fuselage, wing and engines are the most expensive parts. The list price of the entire aircraft as obtained from the parameter class Other is 10% lower than the sum of the individual parts. However, the estimate of the parameter class Other has an higher R^2.

6.1.3. NON-RECURRING COST

Results for NRC are the same for both methods. The baseline aircraft has a NRC of 3,416 mln US$ which seems reasonable compared to literature [47]. The cost breakdown for NRC is shown in Figure 6.3. Airframe engineering and design cost, man-hour cost and tooling cost are the three mayor cost components.

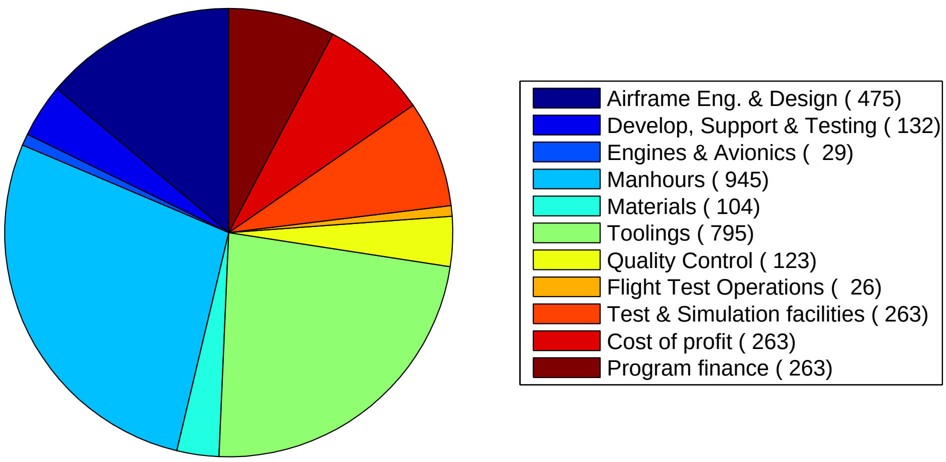


Figure 6.3: Cost breakdown of NRC for baseline aircraft (values in 2014 US$ mln).

6.1.4. RECURRING COST

In contrast to NRC, the RC differs per method. The top-down and bottom-up methods used to compute RC were presented in respectively Sections 3.2.2 and 3.3.1.

RC_{td} is determined using Equation 3.25. For the production parameters provided in Section 6.1.1 the RC_{td} is 54.5 mln US$.

For the bottom-up approach the weights of the aircraft components are determined. The weight and cost results for the baseline aircraft are listed in Table 6.4. The corresponding RC per part is shown in Figure 6.4 along with their share of RC_{bu}. An RC_{bu} of 46.2 mln US$ is found for the baseline aircraft, which is 15% lower than RC_{td}.

Table 6.4: Component weights (kg) and costs (2014 US$ mln) of baseline aircraft for bottom-up method.

Component	**Weight [kg]**	**Cost [US$ mln]**
Wing	5,524	4.7
Empennage	683	1.0
Fuselage	6,823	6.5
Landing gear	3,061	1.9
Engine	4,738	7.0
Nacelle	657	1.8
Power unit systems	1,712	0.8
Flight controls	251	0.5
Hydraulics	1,860	0.9
Electronics	419	0.8
Pneumatics	290	0.5
Airco	1,298	2.8
APU	1,837	4.1
Anti-ice	117	0.2
Furnishing	922	0.9
Instruments	138	1.1
Avionics	766	1.2
Load handling	18	0.03
Assembly	-	9.2
Total	**31,114**	**46.2**

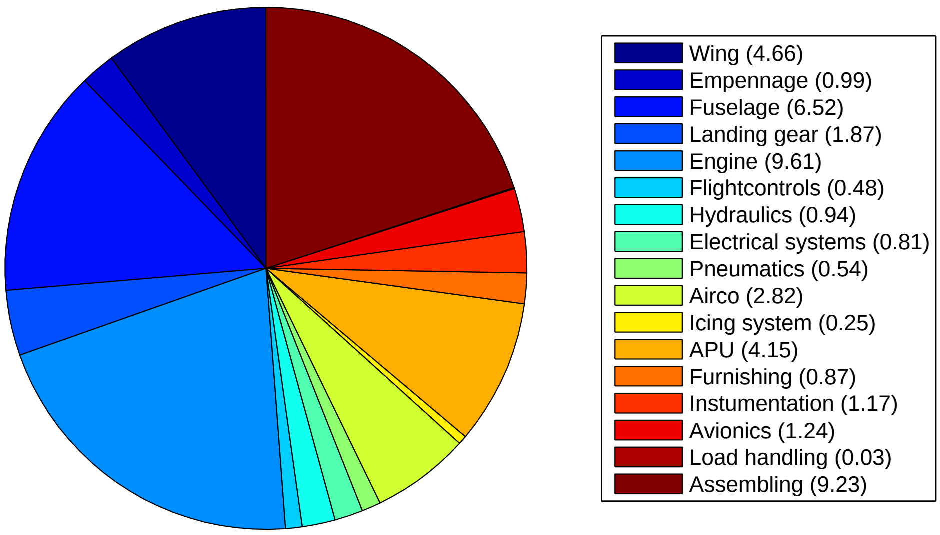


Figure 6.4: Cost breakdown of RC_{bu} for baseline aircraft (values in 2014 US$ mln).

6.1.5. LIST PRICES

The UC of the aircraft were determined using Equation 3.23. The investment cost was given by Equation 3.24. Next, the list price is computed based on UC, the rate of discount r_D and earnings r_E as given in Equation 6.1

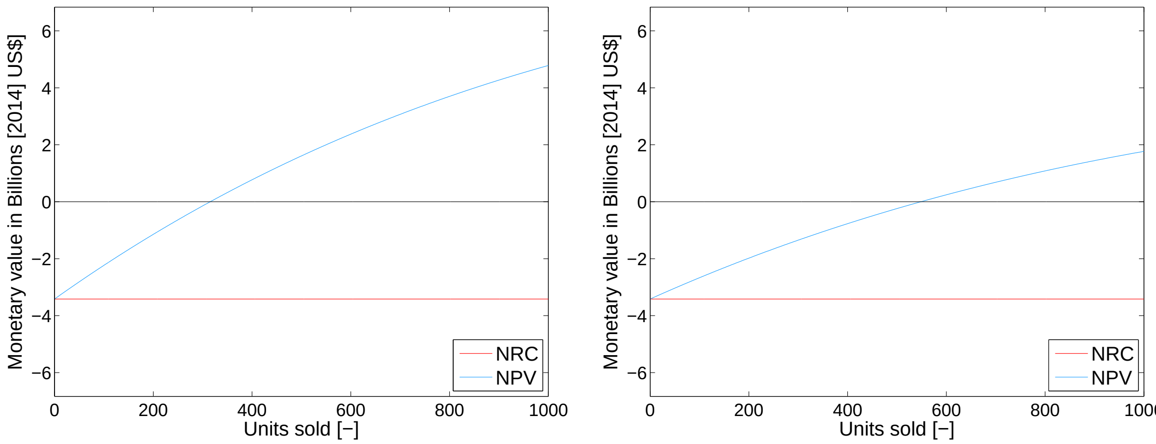
$$LP = UC \cdot (1 + r_D + r_E) \tag{6.1}$$

The top-down method has a list price of 71.8 mln US$ as was obtained in Section 6.1.2. Inverse use of Equation 6.1 gives a UC of 59.6 mln US$. The bottom-up method first computes the UC, which results in 49.6 mln US$. Applying Equation 6.1 gives a list price of 58.0 mln US$.

Obviously, both methods are too low, especially the bottom-up method, since a Boeing 737-800 should be in the range of 107 mln US$. This appears to be a results of a low EOM for the design aircraft. The design aircraft has an EOM of 31,114 kg, which is low compared to to 41,145 kg a real 162 passenger Boeing 737-800 has [39]. Apparently, Initiator computes incorrect components weights. The low EOM has a stronger impact on the bottom-up method since it fully depends on the component weights. Also, the top-down method directly relies on weights like EOM and MTOM. However, it also depends on other aircraft parameters like fuselage diameter, wing span etc. However, these dimensional parameters may cause the low component weights. Hence, there is an indirect relation with respect to the weight for the top-down method.

6.1.6. BREAK-EVEN QUANTITY & NPV

The NPV gives the potential of the aircraft program in terms of cash flow. The method to determine NPV was presented in Section 3.4. Figures 6.5a and 6.5b show the NPV as a function of Q for respectively top-down and bottom-up method. The point in the graphs where the NPV line intersects with the x-axis gives the quantity for break even Q_{be}. The baseline aircraft has a NPV of 4,784 and 1,768 mln US$ for respectively top-down and bottom-up method if 1,000 aircraft are produced. Q_{be} is respectively 316 and 549. Hence, the program of the baseline aircraft is almost three times as lucrative for the top-down method compared to the bottom-up method. This is a very large difference and is directly related to the difference in list prices since NRC, production rate and interest rate are equal.



(a) Top-down (b) Bottom-up

Figure 6.5: Nett Present Value (NPV) of baseline aircraft for top-down and bottom-up methods.

6.1.7. OPERATING COST

Section 3.2.3 explained the method used to compute the operating cost. It was mentioned that both top-down and bottom-up approach use the same methods.

The results for TOC, DOC and IOC are listed in Table 6.5. The TOC of the bottom-up method was 8% less than the top-down method. For the DOC and IOC respectively differences of 10% and 1% are found. The differences for DOC have their origin in the cost for maintenance and depreciation. This is a direct consequence of the different part prices obtained by both methods for airframe, engine and avionics. The top-down method respectively computes the following prices: 42.0, 7.0 and 8.1 mln US$. These values are computed using bases on percentages of RC from literature [47]. For the bottom-up method this was: 37.5, 7.0 and 1.2 mln US$. The values for top-down method are higher for the airframe and avionics, hence the DOC is higher.

Fuel cost is an important cost component and is equal for both methods. The fuel costs is 9.89 US$ per nautical mile, which is low compared to the 12.56 US$ for a Boeing 737-700 obtained from online sources.

These differences have their effect on the cost breakdown of both methods for DOC. Figure 6.6 shows the cost breakdown for the top-down method. The top-down method has a maintenance and depreciation percentage of 29% and 19% respectively compared to the 30% and 16% for bottom-up. The IOC breakdown is similar for both methods, hence only the top-down results are shown in figure 6.7.

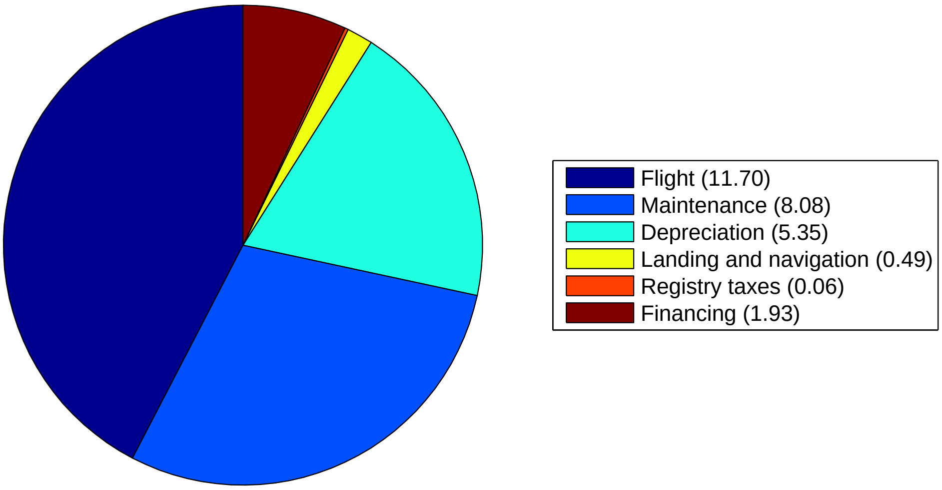


Figure 6.6: Cost breakdown of DOC of top-down method for baseline aircraft (values in 2014 US$/nm).

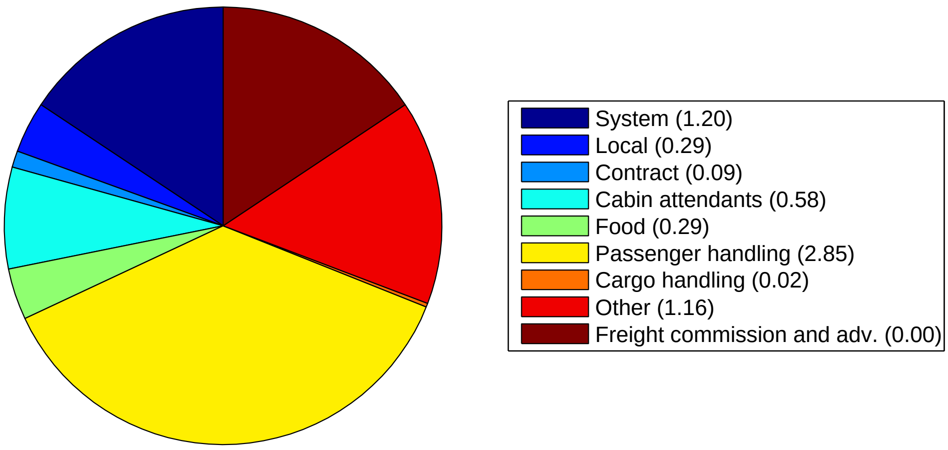


Figure 6.7: Cost breakdown of IOC of top-down method for baseline aircraft (values in 2014 US$/nm).

6.1.8. TARGET QUANTITY

As was presented in Section 3.6 both top-down and bottom-up methods can be combined according to literature [47]. The RCs for both methods are expressed as a function of Q. The formulas for RC are equated and solved for Q, returning Q_{target}. This is visualized in Figure 6.8. The projection of the intersection point on the x-axis shows Q_{target}. For the baseline aircraft Q_{target} is 301. Market demand should exceed this number in order to initiate this program. Note that RC_{bu} clearly shows the learning curve effect as explained in Section 2.5.1.

All possible outputs the cost estimation module is able to generate were presented in the above sections. Costs that differ per method were separately presented and results were compared. Table 6.5 gives a final overview of the results for the baseline aircraft. A column with the differences between both methods in percentages shows that overall the results for the bottom-up method are lower.

6.2. SENSITIVITY ANALYSIS

The output of the cost module depends on multiple input parameters. Therefore a sensitivity analysis is performed with respect to these parameters. Only parameters which are most likely to influence the

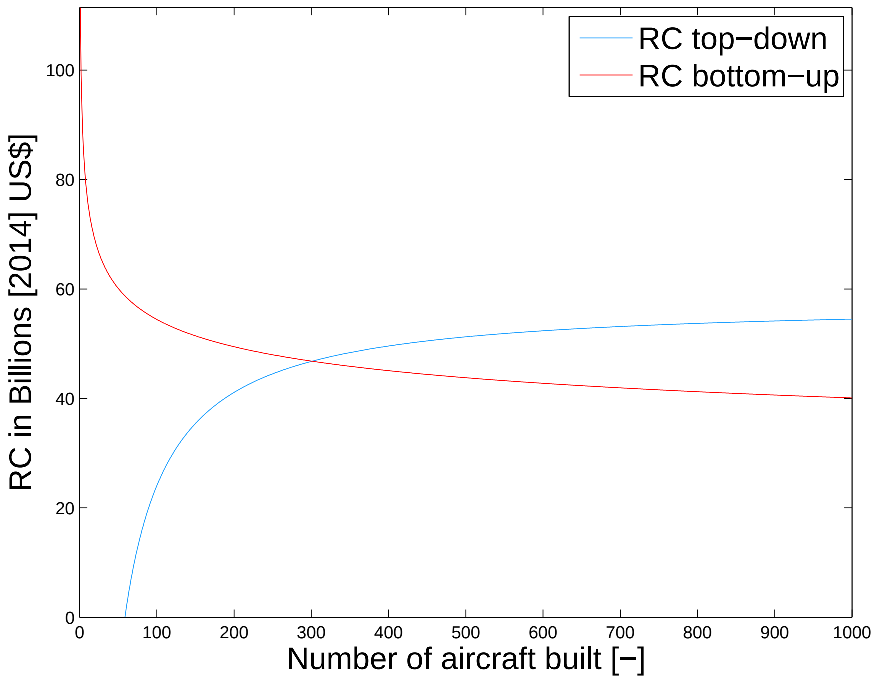


Figure 6.8: RC_{td} and RC_{bu} as a function of Q to determine Q_{target}.

Table 6.5: Overview of results for baseline aircraft.

Parameter	Units	Top-down	Bottom-up	Δ%
List Price (LP)	Million 2014 US$	71.8	58.0	-19
Unit Cost (UC)	Million 2014 US$	59.6	49.6	-17
Non-Recurring Cost (NRC)	Million 2014 US$	3,416	3,416	0
Recurring Cost (RC)	Million 2014 US$	54.5	46.2	-15
Quantity for break-even (Q_{be})	-	316	549	74
Nett Present Value (NPV)	Million 2014 US$	4,784	1,768	-63
Total Operating Cost (TOC)	2014 US$/nm	35.31	32.54	-8
Direct Operating Cost (DOC)	2014 US$/nm	27.61	24.92	-10
Indirect Operating Cost (IOC)	2014 US$/nm	7.69	7.62	-1

results of the module are analyzed. These parameters are classified as program, operator and design parameters and are subsequently discussed in the next sections. The parameters are changed ranging form −25% to +25% with steps of 5%. Most parameters show linear or close to linear behavior. Hence, elasticity results for the most extreme sensitivities, ±25%, are presented. Examples of the sensitivity graphs are shown in Appendix D.

6.2.1. PROGRAM PARAMETERS

The sensitivity analysis is performed with respect to the parameters: labor rate, interest rate, earnings rate, discount rate, production rate, NCF and Q. The elasticities of LP, RC, NRC, NPV, Q_{be}, DOC and IOC are shown for the top-down and bottom-up methods in respectively Table 6.6 and 6.7. The operating cost are shown as well since it is influenced by prices of aircraft parts as was discussed in Section 6.1.7. The sensitivities of both methods are explained next.

TOP-DOWN

For the top-down method the LP and IOC are not influenced by the program parameters. For the LP this is due to the fact that it is obtained using regression. The database used is not influenced by the program parameters. The influence on DOC is also small, which explains why IOC shows no sensitivity. The latter is since part of the IOC is a function of DOC. RC appears to be sensitive to all program parameters. For labor rate and NCF changes are caused by NRC. However, these changes show an inverse effect with respect to the change in NRC. The sensitivity with respect to earnings and discount are due to the fact that UC is a function of these parameters as was shown in Equation 3.23 and therefore RC is. Again, an inverse effect is found. RC is directly related to interest and production rate as shown in Equation 3.25.

The latter remark explains the sensitivity for NRC. However, NRC also shows to be strongly sensitive to the labor rate. The NPV is a function of many of the program parameters and costs which already showed sensitivity towards these parameters. Hence, it is logical that the NPV shows sensitivity as well. It should be noted that is shows the strongest sensitivity with respect to earnings rate. Since the NPV changes so does Q_{be}.

The number of aircraft produced influences the RC slightly. The largest effect is seen with respect to NPV, which makes perfect sense. Due to the small increase in RC, Q_{be} increases since the NPV curve is less steep. The DOC and IOC are not affected.

Table 6.6: Sensitivity analysis of program parameters for top-down method in percentages.

Parameter	**Δ%**	**LP_{td}**	**RC_{td}**	**NRC_{td}**	**NPV_{td}**	**$Q_{be,td}$**	**DOC_{td}**	**IOC_{td}**
Labor rate	-25%	0	2	-22	-4	-16	0.2	0
	25%	0	-2	22	-6	14	-0.2	0
Interest rate	-25%	0	0.9	0	10	1	0.2	0
	25%	0	-1	0	-9	-1.3	-0.2	0
Earnings rate	-25%	0	3.4	0	-25	20	0.7	0
	25%	0	-3.4	0	25	-14	-1.7	0
Discount rate	-25%	0	2.3	0	-2.0	0	0.5	0
	25%	0	-2.3	0	-1.2	0	-0.5	0
Production rate	-25%	0	-1.4	0	-13	-1.8	-0.3	0
	25%	0	0.8	0	8	0.6	0.1	0
NCF	-25%	0	1.4	-15	-4	-11	0.1	0
	25%	0	-1.5	16	0	10	-0.1	0
Q	-25%	0	-1.9	0	-17	-8.6	0	0
	25%	0	1.1	0	13	5.7	0	0

BOTTOM-UP

In contrast to the top-down method the RC is not influenced by the program parameters, except for Q. This makes sense since it only depends on the weights of the aircraft's part and Q. Both are not affected by the program parameters. NRC shows the same sensitivity towards labor rate and NCF as the top-down method, since both use the same method. UC, which is not shown, is a function of NRC. Hence, the labor rate and NCF influence UC and therefore also LP. LP is directly influenced by the earnings and discount rate as was shown in Equation 3.22.

The NPV again shows the strongest sensitivity with respect to the earnings rate. However, the interest and production rate are important parameters as well. The NPV depends on many program parameters and other costs, hence it shows sensitivity to all program parameters. Since Q_{be} is directly related to NPV it is sensitive to all parameters as well. For DOC and IOC the same holds as for the top-down method. Hence, both fully depend on the sensitivity on the LP.

For the bottom-up method an increase in Q decreases the average RC. In turn the list price decreases. Since the decrease in list price is larger than for the RC the slope of the NPV curve is less steep and Q_{be} increases. The total NPV increases only slightly if 25% more aircraft are build. The lower list price decreases the DOC which in turn causes a small decrease in IOC

It should be noted that both methods differ most for LP and RC. The NPV of the bottom-up method is more sensitive to the program parameters compared to the top-down method

Table 6.7: Sensitivity analysis of program parameters for bottom up method in percentages.

Parameter	Δ%	LP_{bu}	RC_{bu}	NRC_{bu}	NPV_{bu}	$Q_{be,bu}$	DOC_{bu}	IOC_{bu}
Labor rate	-25%	-1.8	0	-22	15	-15	-0.4	0
	25%	1.8	0	22	-15	13	0.4	0
Interest rate	-25%	0	0	0	36	-7	0	0
	25%	0	0	0	-31	9	0	0
Earnings rate	-25%	-2.1	0	0	-52	24	-0.1	0
	25%	2.1	0	0	52	-16	0.1	0
Discount rate	-25%	-1.5	0	0	8	-3	-0.1	0
	25%	1.5	0	0	-9	3.6	0.1	0
Production rate	-25%	0	0	0	-47	14.5	0	0
	25%	0	0	0	32	-6	0	0
NCF	-25%	-1.2	0	-15	10	-10	-0.3	0
	25%	1.3	0	16	-11	9	0.3	0
Q	-25%	5.9	3.9	0	-6.1	-19	1.6	0.1
	25%	-4.0	-2.9	0	1.3	17	-1.1	-0.1

6.2.2. OPERATOR PARAMETERS

Since none of the operator parameters will influence production results only the operating costs are discussed. Table 6.8 shows the results of a sensitivity study with respect to operating parameters. These parameters are: fuel price, passenger load factor, crew salary, depreciation period, annual utilization. Operating parameters related to flying the aircraft show direct relation with DOC. Parameters related to the passengers influence IOC. It should be mentioned again that the IOC is a function of DOC. When the DOC changes this has the same, although smaller, impact on IOC.

The fuel price directly influences the DOC. This effect is stronger for the bottom-down method since the percentage of cost of flight with respect to the total DOC is higher. For top-down it is 42% and for bottom-up 47%. The fuel price in turn clearly impacts the cost of flight.

The load factor only influences the IOC since it is directly related to passenger handling and services. The effect is the same for both methods.

Sensitivity of DOC with respect to crew salary differs between both methods for the same reasons as it did for the fuel price. IOC is the same for both methods since the cost per nautical mile are almost the same and the break-down of IOC is the same for both methods.

The depreciation period directly influences DOC. The prices of airframe, engine and avionics that are depreciated are higher for the top-down method as was stated in Section 6.1.7. Therefore, the top-down method is more sensitive since depreciation cost account for a higher percentage of DOC. The DOC shows an inverse relation with the depreciation period. This is due to the fact that the total part prices are divided by the depreciation period as shown in Equations 3.44 to 3.47.

The annual utilization shows an inverse relation for the same reasons as the depreciation period. The effect is again stronger for the top-down method since higher part prices need to be depreciated.

Table 6.8: Sensitivity analysis of operating parameters for both method in percentages.

Parameter	Δ %	DOC_{td}	IOC_{td}	DOC_{bu}	IOC_{bu}
Fuel price	-25%	-8.7	-1.7	-10	-1.7
	25%	8.7	1.7	10	1.7
PAX load factor	-25%	0	-14	0	-14
	25%	0	14	0	14
Crew salary	-25%	-1.5	-2.2	-1.7	-2.2
	25%	1.5	2.2	1.7	2.2
Depreciation period	-25%	6.9	0.1	5.2	0.1
	25%	-4	-0.1	-3.1	0
Annual utilization	-25%	8.5	0.4	6.5	0.3
	25%	-5.1	-0.2	-3.9	-0.2

6.2.3. DESIGN PARAMETERS

The Initiator design tool makes use of high level design requirements as shown in Table 6.1. A sensitivity analysis is performed with respect to amount of passengers, range and payload mass. These three parameters are the most prominent of all and most likely to influence the final design and therefore the LCC. The sensitivity analysis is performed with respect to both methods. First, the sensitivity of manufacturing cost are presented in Section 6.2.3 followed by the operating cost in Section 6.2.3.

MANUFACTURING

The response to the sensitivity analysis with respect to manufacturing costs, list price, quantities for break-even and NPV are presented next. First, the results for the top-down method are discussed. Secondly, the bottom-up method's results are presented.

Top-down As is shown by Table 6.9 the list price, RC, NRC, NPV and Q_{be} show sensitivity with respect to the number of passengers. Q_{be} shows an inverse response. In general, it is difficult to state what causes the sensitivities. This is due to the fact that a lot of design changes can occur by changing one variable. This is the snow ball effect. An increase in passengers results in a larger fuselage, therefore the fuselage weight increases. Hence, the wings need to produce more lift, thus the size of the wing increases and their weight increases. Due to a total increase in weight more powerful engines are required. This is only a simple example of how design parameters are related to each other. Table 6.10 presents the sensitivity results of EOM, MTOM and Mission Fuel Mass (MFM). The EOM, MTOM and MFM show a small increase of maximum 1.1% if 25% more passengers are required. This small increase causes a small increase in LP for top-down method along with the increase of the passenger parameter self. Lammering also performed a sensitivity analysis with respect to design parameters. In this study a slightly larger aircraft was analyzed [47]. The results for a change in passengers required showed similar trends. However, the results for list price, RC and NRC range from -1% to 1% for a -25% to 25% change in passengers which is smaller than results from the cost estimation model. The inverse holds for Q_{be}.

For the range negligible sensitivity results are found. For the weights only a strong sensitivity of the MFM is seen in Table 6.10. However, this has no influence on the EOM and MTOM and thus the manufacturing cost. These negligible results are low compared to the results obtained by Lammering [47]. The sensitivities for list price, RC and NRC for -25% and 25% are respectively -8% to 10%. Hence, the results obtained by the cost estimation model are too low compared to Lammering.

The sensitivity results with respect to the payload mass showed similar behavior as for the amount of passengers, only with a stronger effect. Table 6.10 shows that the EOM and MTOM are very sensitive to a change in payload mass, which causes the sensitivity results of the list price, RC and NRC and therefore also induces an increase in NPV. As a result of the increase in NPV the value for Q_{be} decreases. The results for payload mass are almost identical to those obtained by Lammering [47].

Table 6.9: Sensitivity analysis of design parameters for top-down method in percentages.

Parameter	Δ%	LP_{td}	RC_{td}	NRC_{td}	NPV_{td}	$Q_{be,td}$
Passengers	-25%	-3.7	-3.9	-1.1	-3.7	1.9
	25%	3.5	3.8	0.8	3.6	-1.9
Range	-25%	-0.2	-0.2	-0.5	-0.2	-0.3
	25%	0.2	0.2	0.3	0.2	0
Payload mass	-25%	-5.6	-5.7	-4.6	-5.6	0.6
	25%	5.5	5.6	4.0	5.5	-1.0

Bottom-up For a change in passengers the RC shows negligible sensitivity results, see Table 6.11. The same holds for the LP, which is mainly influenced by the RC. The NRC increases with almost 1% if the amount of passenger is increased by 25%. Although, it is a small change it decreases the NPV. In turn, Q_{be} increases.

The sensitivity results for the range show similar results as for the passengers. However, the Q_{be} shows no sensitivity at all. This is strange since it depends on NPV which in turn is a function of all the other

Table 6.10: Sensitivity analysis of design parameters for top-down method in percentages.

Parameter	Δ%	EOM	MTOM	MFM
Passengers	-25%	-1.3	-0.8	-0.4
	25%	1.1	0.6	0.3
Range	-25%	-0.6	-0.2	-16.2
	25%	0.5	-1.7	16.4
Payload mass	-25%	-6.0	-13.5	-12
	25%	5.2	13.1	13

cost parameters. It should be noted that the sensitivity results shown is the total NPV at Q = 1,000. Hence, it says nothing about the shape of the curve.

A change in payload mass shows to be more sensitive to the cost parameters. Both RC and NRC increase with increasing payload mass. The increase in RC is due to the increase in EOM as shown in Table 6.10. As a result the list price shows a similar trend. Interesting to see is that the increase in list price and thus earnings compensates the 4% increase in NRC. Hence, resulting in an higher NPV.

Table 6.11: Sensitivity analysis of design parameters for bottom up method in percentages.

Parameter	Δ%	LP_{bu}	RC_{bu}	NRC_{bu}	NPV_{bu}	$Q_{be,bu}$
Passengers	-25%	-0.2	-0.2	-1.1	0.4	-0.5
	25%	0.1	0	0.8	-0.6	0.5
Range	-25%	-0.4	-0.4	-0.5	-0.4	0
	25%	0.3	0.3	0.3	0.3	0
Payload mass	-25%	-4.2	-4.2	-4.6	-3.9	-0.3
	25%	3.6	3.5	4.0	3.2	0.3

OPERATING

The results for the operating cost of both methods are shown in Table 6.12. Clearly the IOCs are directly related to the amount of passengers, whereas the DOC does not. For an increase in passengers the cost for passenger handling and services will increase. Also, the size of the aircraft will increase. However, this has only a small impact on the part prices which are depreciated as part of the DOC.

The IOC is also sensitive for changes in range. However, an inverse sensitivity is found. This makes perfect sense since the IOC is expressed in US$ per nautical mile. Hence, increasing the range will lower the costs per mile. The same holds for the DOC only the effect is less extreme.

A change in required payload mass has the largest impact on DOC. This parameter strongly impact the weight of the aircraft design and therefore the cost of design and production. Hence, the DOC increase due to the increase in part prices. The IOC increases since the cost for passenger and baggage handling increases.

Table 6.12: Sensitivity analysis of program parameters for both method in percentages.

Parameter	Δ %	DOC_{td}	IOC_{td}	DOC_{bu}	IOC_{bu}
Passengers	-25%	-1.4	-15.4	-0.4	-15.5
	25%	1.3	15.7	0.3	15.8
Range	-25%	7.1	16.3	7.6	16.4
	25%	-4.2	-9.8	-4.5	-9.8
Payload mass	-25%	-7.0	-2.4	-7.0	-2.3
	25%	7.3	2.3	7.2	2.3

6.3. COMPARISON OF DIFFERENT CONFIGURATION

The objective of the research is to see if a relative cost estimation model can be developed that is compatible with all types of configurations and can be used for a design trade-off. This section will compare conventional and unconventional configurations for the same top-level design requirements. It should be mentioned that the same input settings for the module are used as for the baseline aircraft, see Section 6.1.1. Moreover, the BWB aircraft is not analyzed since Initiator is not able to give a converged design yet.

First, the design requirements and NCF settings are presented in Section 6.3.1. Next, the top-down results are shown in Section 6.3.2 followed by the bottom-up results in Section 6.3.3. The discussion will focus on comparing the unconventional with the conventional configuration and the unconventional aircraft mutually.

6.3.1. DESIGN REQUIREMENTS AND NCF SETTINGS

The design requirements are listed in Table 6.13. The values for NCF are shown in Appendix A at lines 58 to 99. For all configurations the maximum value for each part is given. These values are assumptions based on engineering judgment.

For the conventional aircraft all NCFs are set to 1. For the canard aircraft the wing is assumed to be slightly more uncommon. Although it has the same shape as a conventional aircraft the loading might be different, hence extra design efforts need to be made. For the empennage the NCF is set to 0.8 since it only comprises the vertical tail. The canard is set to 1.05 like the wing since it is a new part. However, high resemblance with a normal horizontal tail is likely. All other NCFs are set to 1.

For the three-surface aircraft the same NCFs are used as for the canard aircraft. However, the NCF of the empennage is set to 1.05. This is due to the fact that it is similar to a conventional empennage. However, extra engineering effort is required since the stability for pitch will be different compared to conventional aircraft.

The prandtl plane is the most innovative design and will therefore require more additional design effort. The wings are rated with a NCF of 1.3 since now two wings need to be designed. Compared to conventional wings they are more slender. Also, a more in depth aerodynamic analysis is likely to be required. The configuration has two vertical tails, which is also unconventional. Hence, a value of 1.1 is assigned to the empennage.

The overall NCFs of the configurations are shown in Tables 6.14 and 6.15. The NCF for the canard aircraft and three-surface aircraft is equal to the conventional aircraft since the impact of the canards and changes in empennage represent only 9% of the overall NCF. Only the prandtl plane shows an increase in overall NCF of 1.1.

Table 6.13: Design requirements for configurations used for trade-off.

Parameter	Values	Units
Passengers	150	-
Range	2,870	km
Payload mass	20,536	kg
Cruise Mach number	0.78	-
Altitude	11,278	m
Take-off distance	2,101	m
Landing distance	1,440	m
Number of flights	100,000	-

6.3.2. TOP-DOWN

The conventional configuration has the lowest LCC, although the canard aircraft is not much more expensive. It is interesting to see that the NRC of the canard aircraft is lower compared to the conventional aircraft. This is compensated by a higher RC which strongly impacts the LP. Due to the higher list price and lower NRC the NPV of the canard aircraft is slightly higher compared to the conventional aircraft. This also causes Q_{be} to be lower for the canard aircraft. Both conventional and canard aircraft have exactly the same DOC and their IOC is almost identical as well.

The three-surface aircraft and prandtl plane are both more expensive in all respects and are equally priced. The NRC is lower for the three-surface aircraft which makes sense since it is a less innovative design. This results in a lower RC for prandtl plane and a higher Q_{be}. The NPV in turn is also lower for

Table 6.14: Overview of top-down results for different aircraft configurations.

Parameter	Units	Conventional	Canard	TSA	PP
NCF	-	1.0	1.0	1.0	1.1
List Price (LP)	Million 2014 US$	68.4	69.0	71.3	71.3
Unit Cost (UC)	Million 2014 US$	56.8	57.3	59.2	59.2
Non-Recurring Cost (NRC)	Million 2014 US$	3,335	3,206	3,612	3.845
Recurring Cost (RC)	Million 2014 US$	51.8	52.5	53.8	53.4
Quantity for break-even (Q_{be})	-	321	311	329	343
Nett Present Value (NPV)	Million 2014 US$	4,557	4,594	4,750	4,746
Total Operating Cost (TOC)	2014 US$/nm	29.37	29.35	32.11	32.15
Direct Operating Cost (DOC)	2014 US$/nm	23.98	23.98	26.51	26.52
Indirect Operating Cost (IOC)	2014 US$/nm	5.39	5.36	5.60	5.63

Table 6.15: Overview of bottom-up results for different aircraft configurations.

Parameter	Units	Conventional	Canard	TSA	PP
NCF	-	1.0	1.0	1.0	1.1
List Price (LP)	Million 2014 US$	56.8	55.4	60.5	63.2
Unit Cost (UC)	Million 2014 US$	48.5	47.4	51.7	54.0
Non-Recurring Cost (NRC)	Million 2014 US$	3,335	3,216	3,605	3.845
Recurring Cost (RC)	Million 2014 US$	45.2	44.1	48.1	50.2
Quantity for break-even (Q_{be})	-	548	543	554	562
Nett Present Value (NPV)	Million 2014 US$	1,733	1,704	1,830	1,884
Total Operating Cost (TOC)	2014 US$/nm	27.01	26.78	29.83	30.16
Direct Operating Cost (DOC)	2014 US$/nm	21.67	21.49	24.28	24.58
Indirect Operating Cost (IOC)	2014 US$/nm	5.33	5.30	5.54	55.78

the prandtl plane. Hence, between these two configurations the three-surface aircraft is preferred. This statement is supported by the fact that the three-surface aircraft has lower operating cost.

6.3.3. BOTTOM-UP

In Table 6.15 the results for the bottom-up method are shown. Interesting to see is that the canard aircraft has the lowest LCC. The NRCs are equal to the top-down method, hence lower for the canard aircraft. The RC is also lower which indicates that the parts have a lower weight. This is correct since the EOM is lower for the canard aircraft, see Table 6.16. Consequently, the UC is lower for the canard, which explains the lower list price. The operating cost is reasonable lower as well and is mainly caused by a lower DOC. Since the MTOM is lower the landing fees and cost for local facilities are cheaper. The fuel cost is also lower since less fuel is required for the same mission, see Table 6.16.

Both three-surface aircraft and prandtl plane are more expensive configurations. Between the two, the three-surface aircraft has the lowest LCC in any respect. It should be noted that although the three-surface aircraft has a lower EOM and MTOM, the prandtl plane requires less fuel for the same mission, see Table 6.16.

The mayor difference between the top-down and bottom-up method is that the canard aircraft is cheaper than the conventional aircraft for the bottom-up aircraft. The prandtl plane is clearly more expensive with respect to the three-surface aircraft, which makes more sense compared to the equally priced values for the top-down method. The latter is due to the fact that overall the design of the prandtl plane is more innovative and is therefore more likely to be expensive compared to the three-surface aircraft.

Table 6.16: Weights per aircraft configuration.

Parameter	Units	Conventional	Canard	TSA	PP
Empty Operating Mass (EOM)	kg	31,114	29,711	34,145	35,303
Maximum Take-Off Mass (MTOM)	kg	60,132	58,870	65,364	66,119
Mission Fuel Mass (MFM)	kg	8,495	8,623	10,683	10,593

6.4. FAMILY OF AIRCRAFT

Aircraft manufacturers offer variants of an aircraft type. Aircraft of the same type belong to the same family. This is done to adhere to differences in customer demand while keeping overall development costs low. A high communality is found between different types. As an example, demand for more passenger capacity can results in a longer fuselage. Hence, additional sections are integrated forwards and aft of the wing. The rest of the fuselage sections are similar to other family members.

The cost estimation module is run for the Airbus A340 family. This aircraft is chosen since two version are available in Initiator, the A340-300 and A340-600. The first version was the A340-300, which entered service in 1993 directly followed by the A340-200 later that year. The A340-600 and A340-500 entered service in respectively 2002 and 2004. The number of aircraft produced by Airbus for the -200, -300, -500 and -600 are respectively 28, 218, 34 and 97. These numbers are used for Q while running the module.

For all members the production costs and list price are determined. The NRC strongly depends on the NCF as was shown in Section 6.2 and thus depends on the communality between members. Therefore, Table 6.17 shows the NCFs assigned to each part of each member. The -300 was introduced first and has a NCF of 1 for all parts. The -200 was designed for 261 passengers compared to the 295 passengers for the -300. The result was a shorter fuselage of 59.4 m with respect to the original 63.6 m. The -200 version has the same wings, an updated version of flight avionics and the same empennage. Hence, the wing, system and empennage part are assigned with respectively the values 0, 0.1 and 0. The engine is of the same type although a newer version. The -300 has the CFM56-5C4 engines installed and the -200 the CFM56-5C4. Hence, NCF for the -200 is set to 0.2 [39].

The -600 was partly redesigned. A maximum of 379 passengers required a fuselage length of 75.3 m and therefore the NCF for the fuselage was set to 0.2. The NCF of the wing was set to 0.2 since the wing span and surface were increased. Since flight systems such as avionics were updated the system part has a NCF of 0.2 as well. Almost similar horizontal and vertical tails are used, therefore the empennage is rated 0.1. A new type of engine, the Rolls Royce Trent 556, was installed so the engine NCF is set to 0.8 [39].

The -500 was a derivative of the -600 with a passenger capacity of 313 seats. This resulted in a shorter version with a fuselage length of 67.9 m. Hence, the fuselage was partly redesigned and thus rated with the value 0.2. The same wings and flight systems were used as for the -600. Hence, these parts were given a NCF of 0. Horizontal tails and vertical tails were increased in size and the empennage is rated with a NCF of 0.2. Finally, the engine installed is also a Rolls Royce, however for the -500 the Trent 553 was installed. Therefore the engine in not completely different and rated 0.2 [39].

The overall NCF is given in Table 6.17.

Table 6.17: NCF values for Airbus A340 family.

Type	**Fuselage**	**Wing**	**System**	**Empennage**	**Engine**	Total
A340-300	1	1	1	1	1	1.00
A340-200	0.2	0	0.1	0	0.2	0.12
A340-600	0.2	0.2	0.2	0.1	0.8	0.24
A340-500	0.2	0	0	0.2	0.2	0.11

For each family member an Initiator file was created and run. Unfortunately, Initiator was not able to converge the design of the -500 and -600 since the module for landing gear could not find a proper location to position the landing gears. To get results, the design requirements are lowered till the point where the designs were able to converge. Table 6.18 lists these design requirements for the family members. Equal module settings are used as for the baseline aircraft. However, the Q is changed as already mentioned and the production rate is set to 72 aircraft per year

Table 6.18: NCF values for Airbus A340 family.

Type	Units	A340-300	A340-200	A340-600	A340-500
NCF	-	1.0	0.13	0.35	0.11
Passengers	-	295	261	379	313
Range	km	9,167	9,000	9,167	9,500
Payload mass	kg	50,800	50,800	55,000	52,000
Cruise Mach number	-	0.82	0.82	0.82	0.82
Altitude	m	11,887	11,887	11,887	11,887
Take-off distance	m	3,000	3,000	3,000	3,000
Landing distance	m	1,964	1,964	1,964	1,964
Number of flights	-	100,000	100.000	100,000	100.000

6.4.1. TOP-DOWN METHOD

The results for the top-down method are shown in Table 6.19. The list price as obtained from regression analysis is too low compared to true prices published by Airbus [5]. Respectively for the -300. -200, -600 and -500 true list prices are 238.0, 193.97, 275.4 and 261.8 mln US$. However, it is interesting to see how the NRC behaves since it is most influenced by the NCF and is the main reason the family concept is analyzed. As shown in Table 6.19 the NRC of this aircraft family is very high. The original version has a NRC of 8,543 mln US$. For the -200 the NRC is almost half of the original value. It is clear that the NRC decreases for new family members.

For the top-down method, the consequence of a high NRC and producing a low number of aircraft produced is that NRC has a large share in the UC and thus LP. This results in a low RC. The values for RC shown in Table 6.19 are unrealistic, especially for the -200 and -500 members. For the top down method the break-even quantity was reached for all family members.

Table 6.19: Overview of results for Airbus A340 family top-down.

Parameter	Units	A340-300	A340-200	A340-600	A340-500
List Price (LP)	Million 2014 US$	188.1	180.7	215.0	206.8
Unit Cost (UC)	Million 2014 US$	156.1	150.0	178.4	171.6
Non-Recurring Cost (NRC)	Million 2014 US$	8,543	3,833	5,190	4,388
Recurring Cost (RC)	Million 2014 US$	110.7	8.6	121.3	35.3
Quantity for break-even (Q_{be})	-	147	25	70	30

6.4.2. BOTTOM-UP METHOD

For the bottom-up method the NRCs are once again equal to the top-down method. Hence, the same discussion of the results applies here. The RC differs since it depends on the quantity of aircraft produced. It is also a function of the weights estimated by Initiator. The -300 designed by Initiator has an EOM of 100,730 kg and is low compared to a real A340-300 of 129,850 kg. This results in a lower RC. The same holds for the other family members of which the most important weight components are presented in Table 6.21. As can be seen the relative weight estimates of the EOM of all members is different than for the RC. This indicates that the amount of aircraft produced has a stronger impact on the RC than the differences in weight.

Since the RC differs between members, so does the UC and LP. Also for the bottom-up method the demand for break-even was met compared to historic deliveries.

Table 6.20: Overview of results for Airbus A340 family bottom-up.

Parameter	Units	A340-300	A340-200	A340-600	A340-500
List Price (LP)	Million 2014 US$	181.5	351.9	239.0	363.1
Unit Cost (UC)	Million 2014 US$	155.2	300.8	204.9	310.3
Non-Recurring Cost (NRC)	Million 2014 US$	8,543	3,883	5,190	4,388
Recurring Cost (RC)	Million 2014 US$	116.0	162.1	150.8	181.3
Quantity for break-even (Q_{be})	-	183	24	77	29

Table 6.21: Weights per Airbus A340 family member.

Parameter	**Units**	**A340-300**	**A340-200**	**A340-600**	**A340-500**
Empty Operating Mass (EOM)	kg	100,730	97,314	116,080	107,650
Maximum Take-Off Mass (MTOM)	kg	228,510	223,010	259,210	244,700
Mission Fuel Mass (MFM)	kg	76,975	74,895	88,129	850,550

For the analysis of family members is should be clear that for each member a separate production program was created. Hence, there are four separate learning curves for the RCs of these aircraft. In real life, this is probably not the case. Only the original member, the -300, would have a high first unit cost and other members would benefit from it. It makes more sense to represent the four members with a single learning curve. However, the impact a new member has should be accounted for. Hence, a small increase should still be present in the transition to a new member. Figure 6.9 shows the idea behind this concept. The green line shows a normal learning curve and the red line the learning curves for four fictive family members, denoted I - IV. The blue line represents the idea as proposed. However, the blue line should always be above the green line since a perfect learning curve can not be achieved. It should be noted that the NRC should be kept separate as was done in the analysis presented.

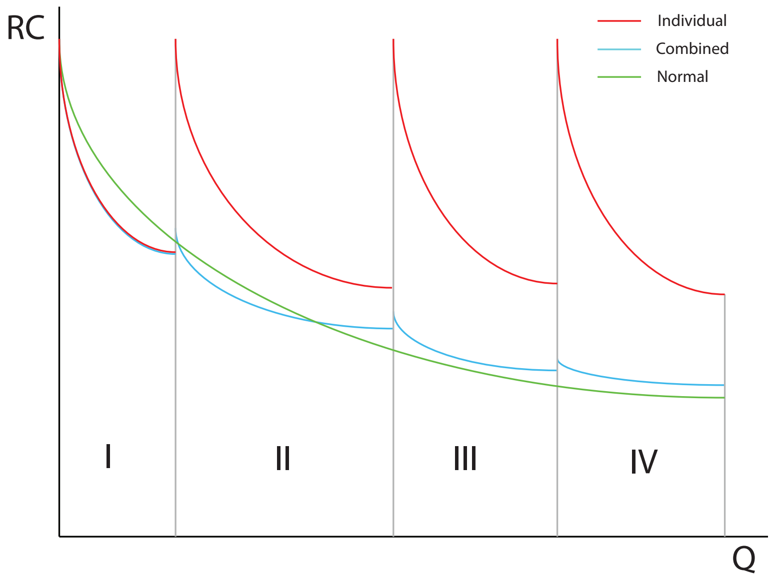


Figure 6.9: Example of RC for aircraft family with four members

7

Conclusions & Recommendations

This Chapter presents the conclusions of the research in Section 7.1. The recommendations for future work are stated in Section 7.2.

7.1. Conclusions

The sub-goals of this research as stated in Chapter 1 are: (1) to investigate which cost estimating method can be used and are applicable to conventional and unconventional aircraft at the end of the conceptual design phase, (2) to implement and verify the method or methods used and (3) to analyze the performance of the cost model using case-studies. Conclusions with respect to these sub-goals are presented in the next sections.

7.1.1. Cost estimation methods applicable to conventional and unconventional aircraft at the end of the conceptual design phase

From literature it can be concluded that many estimating techniques exist, however no direct technique is directly applicable to estimate the cost of unconventional aircraft. However, two methods are selected which are most likely to be applicable and are denoted top-down and bottom-up.

The top-down method first estimates an initial list price using regression analysis performed on a database of historical aircraft. The database is split up in aircraft parameters belonging to individual parts and parameters that represent the overall aircraft. The regression models for the wing, fuselage, engine and overall parameters showed good estimates with an average RMSE of 25%, which is good acceptable for the conceptual design phase. The models and therefore estimates of the horizontal tail, vertical tail and landing gears resulted in low estimates with a relatively high RMSE. Applying the top-down method for the B737-800 resulted in a initial list price of 71.8 mln US$, which is low. The cost model estimated a RC of 54.5 mln US$. The NRC was estimated using a method by Roskam and resulted in 3,416 mln US$ which is in line with real values.

The bottom-up method differs since it first computes the RC using the method of Beltramo. This method is a direct function of component weight and the quantity of aircraft build. The estimated RC is 46.2 mln US$ and is too low. It is caused by the low component weights and thus low EOM of the aircraft designed by Initiator. This in turn results in a low list price. The result for NRC is equal to the top-down method.

The operating cost are determined using methods of Roskam for DOC and Maddalon for IOC. It can be concluded that the estimates give realistic values and results of the top-down and bottom-up method only differ since the part prices per method differ.

The methods are made compatible with unconventional aircraft by applying a so called Non Communality Factor. This factor indicates if the design is completely new or has communality with other programs. The higher the value for NCF the more novel the design is and for values larger than 1 it is a unconventional design.

7.1.2. Implementation and verification of the methods

The model has successfully been implemented in the Initiator design tool. Unfortunately, the BWB aircraft is not tested since Initiator is not able to give a converged design.

Both approaches compute the NRC using the same method. Verification using Galorath's SEER H software showed that the model overestimates the NRC by more than 50%. However, SEER H does not use white sheet design settings in the default project used for verification but for a communality of 80% or a NCF of 0.2. Hence, for a NCF of 0.2 the NRC showed high correlation with SEER H. The relative cost estimation of the NRC appeared to be correct for five aircraft ranging from 100 to 390 passenger aircraft.

Based on verification it can be concluded that the top-down method overestimates the RC, for large aircraft by 25-50%. It also showed that the NCF has almost no impact on the RC. For the top-down method the RC is lower when producing a lower amount of aircraft. The bottom-up method showed good correlation with SEER H. The model underestimated the RC on average by 10%, even for large aircraft. Hence, it can be concluded that the bottom-up method is best for RC. Also the relative cost estimation is adequate for RCs of both methods.

The list price of the top-down method was best compared to historical list prices. This is not surprising since this method performs a regression analysis based on this data. It can be concluded that the regression analysis performed is successful with respect to SEER H.

7.1.3. Performance of the cost model using case-studies

The cost model is applied to three case-studies. Conclusions of both methods with respect to these studies are presented next.

Sensitivity analysis

A sensitivity analysis is performed with respect to program, operating and design parameters. It can be concluded that the NRC of both methods shows high sensitivity with respect to the labor rate and NCF. The top-down method shows a strong sensitivity for the RC with respect to earnings rate and discount rate. Both have an inverse effect on the RC. The NPV is sensitive to all program parameters, especially the interest rate, earnings rate, production rate and quantity of aircraft produced. The number of aircraft for break-even depends on the NRC and thus the labor rate and NCF. Also the earning rate strongly influences the break-even quantity as does the quantity produced.

The RC of the bottom-up method is only sensitive to the quantity of aircraft produced. This program parameter also influences the list price and both cost parameters show an inverse relation. The NPV is extremely sensitive for the earnings rate. A 25% increase results in a 50% increase in NPV.

Both methods show close to similar behavior for operating parameters. The fuel price strongly impacts the DOC which is no surprise. The passenger load factor only influences the IOC and the effect is large. The crew salary has a modest impact on both DOC and IOC and the depreciation only shows to be sensitive to the DOC. Moreover, an inverse relation applies. The annual utilization shows the same trend as the depreciation period.

For the design parameters with respect to the manufacturing cost it can be concluded that the top-down method is more sensitive to the number of passengers than the bottom-up method. The amount of passengers strongly impact the IOC of both methods. It is interesting to see that the range has a negligible effect on the manufacturing cost of both methods. The operating cost show a different story. Both DOC and IOC have an inverse relation with respect to the range. The payload mass has the highest influence on the manufacturing cost of both methods. It can be concluded this is due to the high sensitivity of the aircraft's EOM with respect to the payload mass. The operating cost are also sensitive to the payload mass only now the effect is smaller compared to the amount of passengers and range.

Comparison of different configurations

The LCCs for conventional aircraft, canard aircraft, three-surface aircraft and prandtl plane are compared. For the top-down method it can be concluded that the conventional configuration has the lowest LCC directly followed by the canard aircraft. Interesting to see is that the canard aircraft has a lower NRC but is compensated by a higher RC. The three-surface aircraft and prandtl plane are equally priced.

For the bottom-up method the canard aircraft has the lowest LCC which is caused by a lower RC compared to the top-down method. The list price is reasonable lower and the difference in operating cost is also larger than the top-down method. For the bottom-up method the three-surface aircraft shows lower LCC and is more realistic since the design has more in common with the conventional and canard aircraft than the prandtl plane which shows the highest LCC of all configurations.

FAMILY OF AIRCRAFT

From the case-study on the Airbus A340 family it can be concluded that the NCF has an high impact on the NRC. New family members with high communality show a NRC of approximately 50% of the original NRC. Hence, it con be concluded that the NCF is a useful factor. Both methods show incorrect estimates for RC and list prices. For the top-down method this is directly related to the low quantity of aircraft. From this observation it can be concluded that the top-down method shows unrealistic behavior for RC if a low number of aircraft is produced and is therefore not applicable for these type of programs.

The bottom-up method is also sensitive to the quantity of aircraft produced, however it shows more realistic behavior for the RC. However, each family member has a high first unit cost since each member has a completely new learning curve.

Overall, it can be concluded that the model adheres to all requirements and the objective is met. The research question was formulated: "What cost estimation method can be used to develop a LCC model applicable for trade-off between conventional and unconventional aircraft at the end of the conceptual design phase?" It is answered by stating that the bottom-up method is the preferred method. First off all, it shows more realistic behavior of RC since it follows the learning curve principle. Secondly, the bottom-up method is able to provide a clear cost breakdown of the RC and values can be investigated using the weights per aircraft component. Thirdly, it is clear that Initiator computes component weights which are too low compared to real aircraft. However, if this is corrected for it is likely that the bottom-up method is able to give more accurate estimates in terms of absolute values.

Now that the preferred method is selected a final conclusion can be given with respect to the different configurations. The canard aircraft has the lowest LCC and is therefore preferred, followed by consecutively the conventional aircraft, three-surface aircraft and prandtl plane. A small gain in list price and operating cost is found for the canard aircraft which implies that the canard aircraft is a potential win for both manufacturer and operator.

7.2. RECOMMENDATIONS

With respect to the methods used recommendations for future work can be given. The top-down method depends on how the database list prices are split in different parts. The percentages used are based on RC percentages obtained from one source and apply only for single aisle aircraft. In order to properly analyze larger aircraft these percentages should be obtained. The same holds for the percentages for NRC used to compute the NCF. Also the process of computing part prices from individual parameters should be evaluated. In this research an average R^2 is used to weight the individual prices. The total part computed gets the average R^2 as new R^2, which is not a proven concept.

A second recommendation for the top-down method is to try multi-variable regression. This is the same technique used by Roskam and Beltramo in which multiple variables are used to compute one cost component. However, one must be absolutely sure these parameters are independent of each other. Multi-variable regression analysis offers techniques to quantify this dependency. The use of multi-variable regression can increase the amount of parameters qualified for the development of CERs. Two parameters can be found unqualified for single variable regression but combined can form a relation which is valid. Potential parameters for multi-variable regression can be found by looking at parameters used in cost relations from Roskam and Beltramo.

The database limits the quality of the estimate of the top-down method. Hence, more aircraft should be added to the database. More parameters are welcome as well since this increases the sensitivity of the estimate with respect to the design aircraft. If more aircraft are added to the database the aircraft could be classified according to size. A separate databases for single-aisle, twin-aisle and VLA should result in more accurate estimates for both small and large aircraft.

In this research the bottom-up method by Beltramo does not offer CERs for the engine. In order to overcome this problem the list price of the top-down method was used. Hence, a connection is present between both methods which is not preferred and thus another approach for obtaining engine prices is to be found. A suggestion is to collect individual engine prices from engine manufacturers and perform a separate regression analysis with respect to engine parameters only. The same goes for the NRC which requires part prices as well in order to determine the cost of flight test aircraft.

For future work a recommendation can be made with respect to the use of SEER H, the commercial software used for verification. A better understanding of the SEER H will increase the credibility of the verification results. Also, for consecutive design phases the software can still be used for verification. Moreover, Galorath is willing to give training at Delft University of Technology on how to use this software and already offered academic licenses. Combined with training from DACE this is a nice opportunity for the university to launch a new platform for cost engineering.

For the methodology used the design of the aircraft combined with the manufacturing and operating settings form the input of the cost model. Manufacturing cost, list prices and operating cost are determined. The results should be compared to market demand. However, it would be interesting to do the inverse. State the design requirements and add cost constraints. Cost constraints could be the request for a design that has a list price less than 100 mln US$ and operating cost lower than 30 US$ per nautical mile. Eventually the impact on the aircraft designed by Initiator should be evaluated.

Another opportunity with respect to the Initiator design tool is also identified. At this point the initial design point in Initiator is selected by taking the highest wing loading and lowest thrust to weight ratio allowable to the design space since it will result in the lightest aircraft. However, it is no guarantee that this point returns the lowest LCC. Hence, a method should be though of that implements LCC while selecting the initial design point.

For the case study the Airbus A340 family it was found that NRC decreases for an increase in communality between family members. This is in line with reality and stressed the purpose of having families in the first place. Unfortunately, the model showed unrealistic RCs for both top-down and bottom-up methods. For the top-down this is a direct consequence of using this method in combination with a low quantity of aircraft build. For the bottom-up method this is due to the fact that each new family member start with a high first unit cost as if it is a completely new aircraft. Hence, an alternative method should be developed to analyze the entire LCC for aircraft families. For the bottom-up method a suggestion was already given in Section 6.4. It is also advised to run the cost estimating module for a family of smaller aircraft like the Boeing 737, since a higher amount of aircraft have been delivered and therefore the model should shown more realistic results.

The final recommendations are with respect to the BWB aircraft. This configuration has not been evaluated yet and should be done in the future. However, since this configuration has a much higher level of innovation it is not likely that both methods used will result in realistic estimates. Hence, further research is required with respect to this configuration.

A

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B

Part prices

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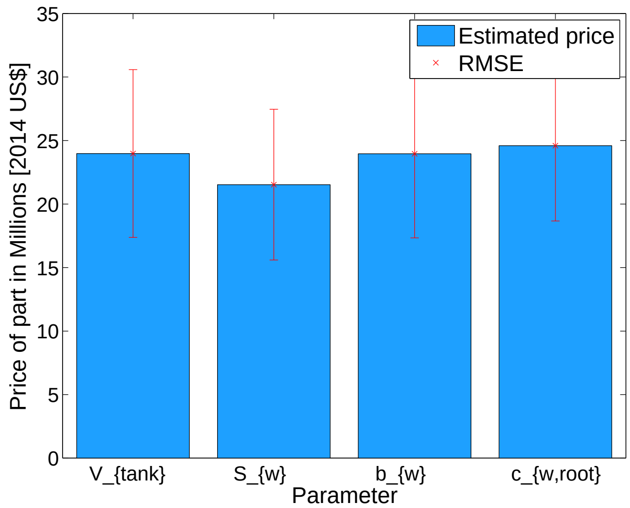


Figure B.1: Bar chart of part parameter class Wing.

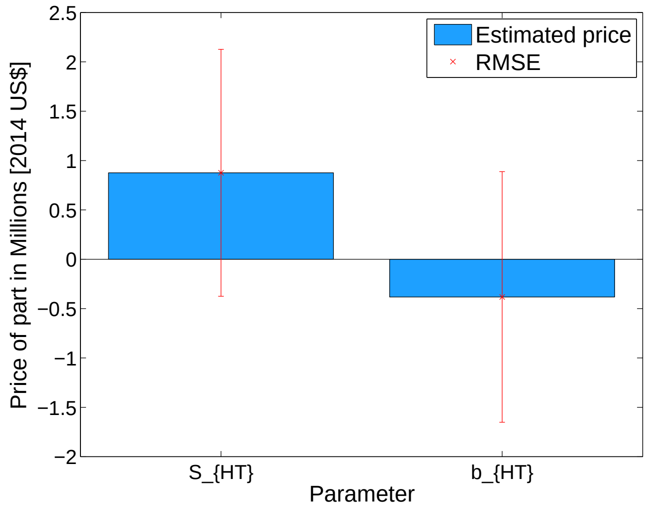


Figure B.2: Bar chart of part parameter class Horizontal Tail.

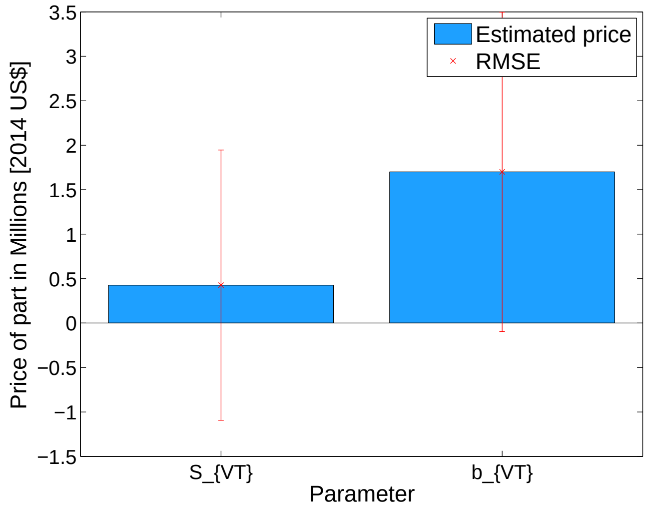


Figure B.3: Bar chart of part parameter class Vertical Tail.

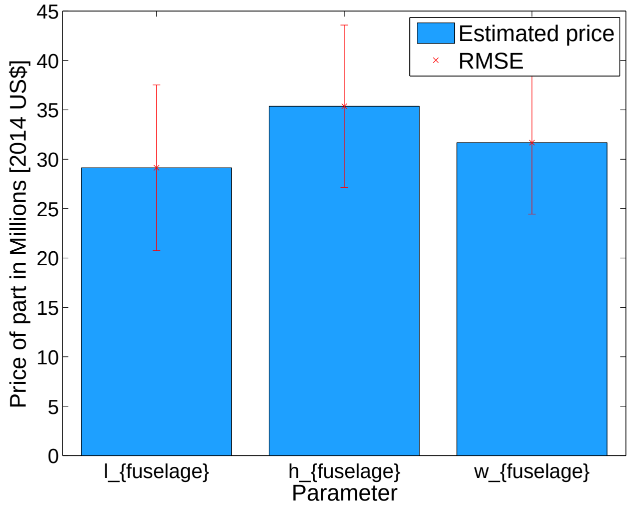


Figure B.4: Bar chart of part parameter class Fuselage.

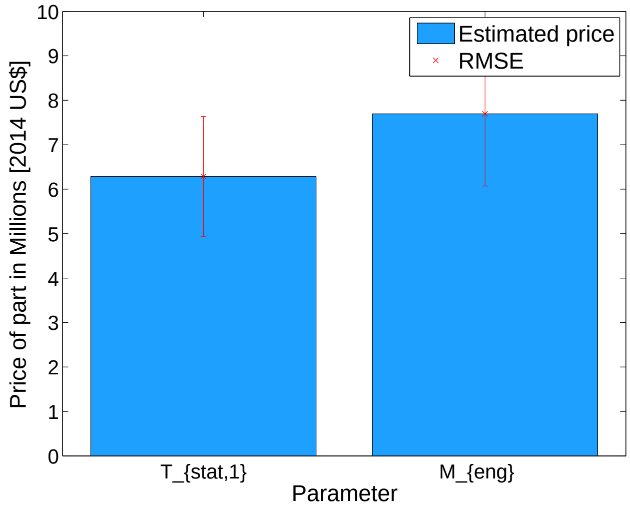


Figure B.5: Bar chart of part parameter class Engine.

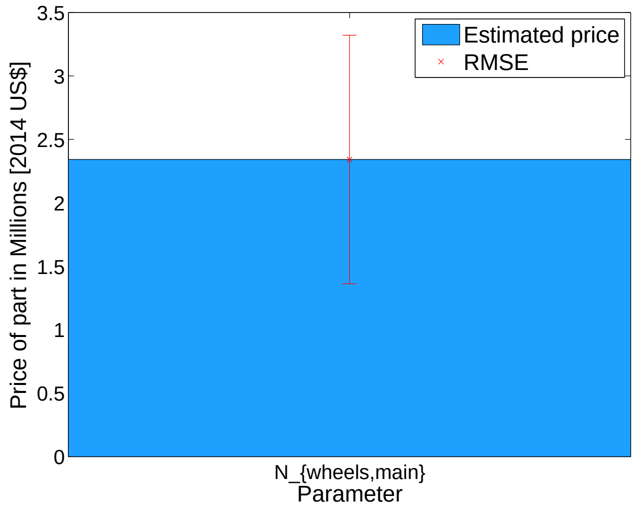


Figure B.6: Bar chart of part parameter class Main gear.

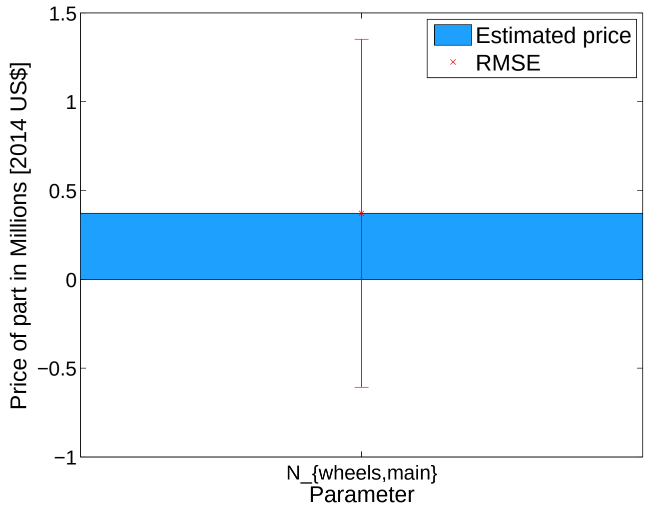


Figure B.7: Bar chart of part parameter class Nose gear.

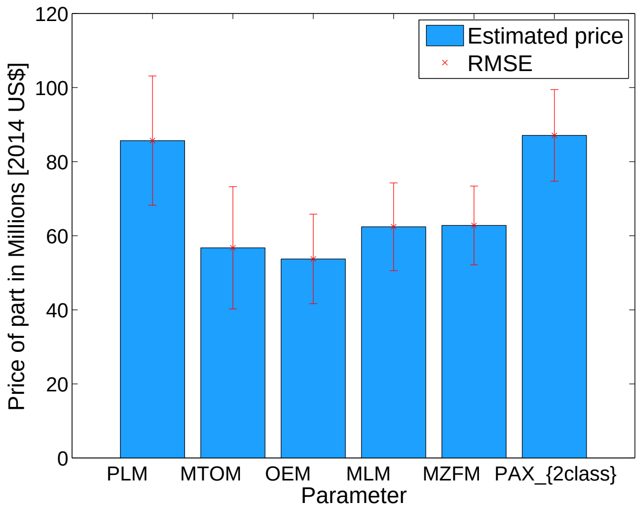


Figure B.8: Bar chart of part parameter class Other.

C

PERCENTAGES: LP & NCF

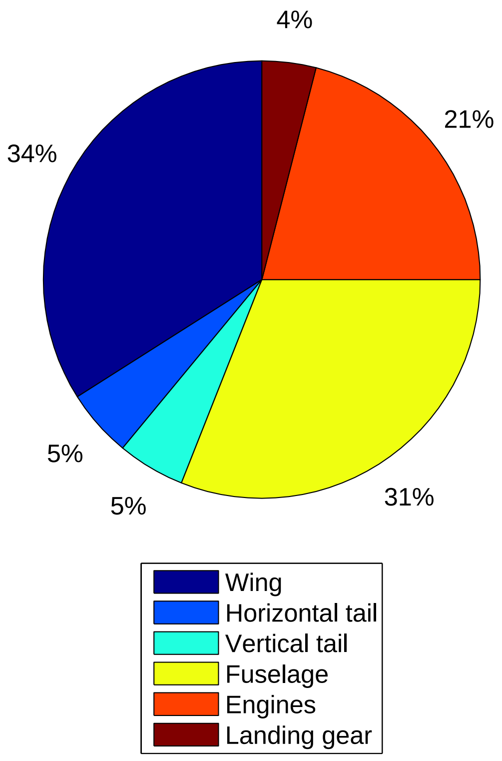


Figure C.1: LP part breakdown for historical aircraft [47].

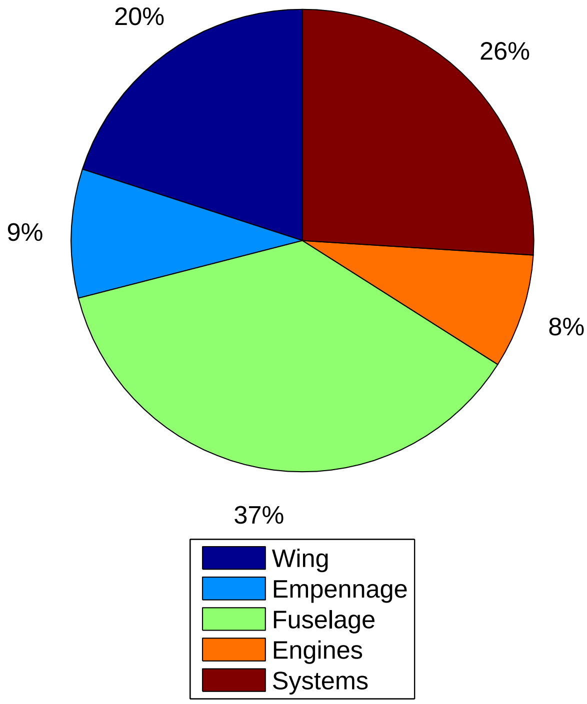


Figure C.2: NCF part breakdown of an entire aircraft [47].

D

Sensitivity graphs

As stated in Section 6.2 a sensitivity study is performed with respect to program, operating and design parameters. In this Appendix example graphs are presented that show the close to linear behavior of most of the cost parameters. Only the results of the bottom-up method are shown

Program parameters

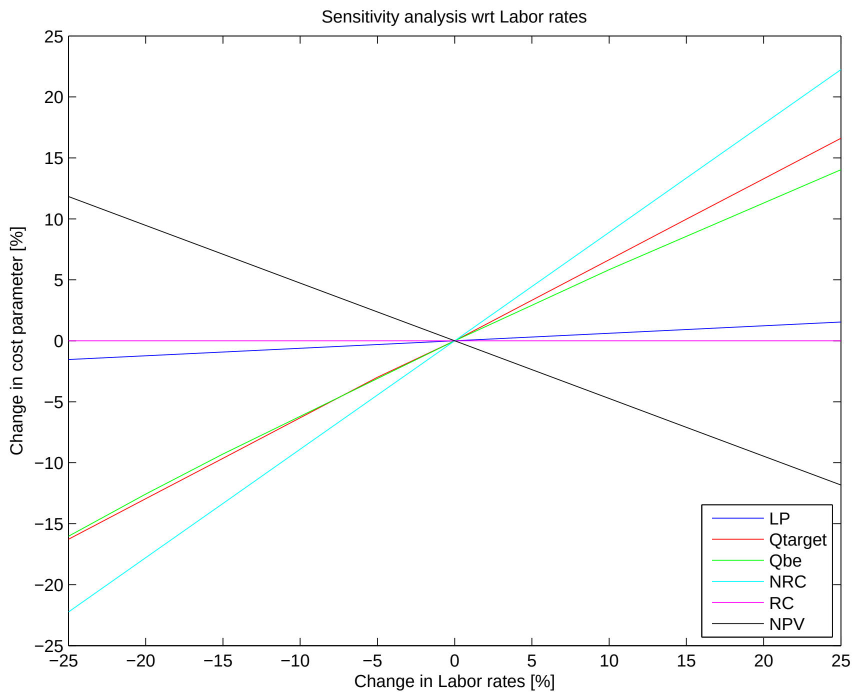


Figure D.1: Sensitivity analysis with respect to labor cost for the manufacturing cost.

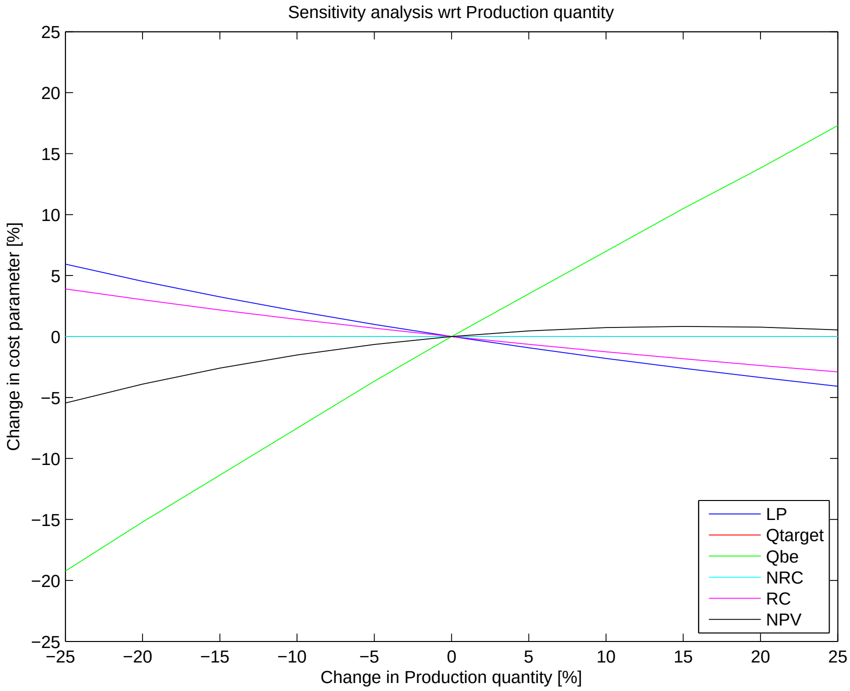


Figure D.2: Sensitivity analysis with respect to production qunatity for the manufacturing cost.

OPERATOR PARAMETERS

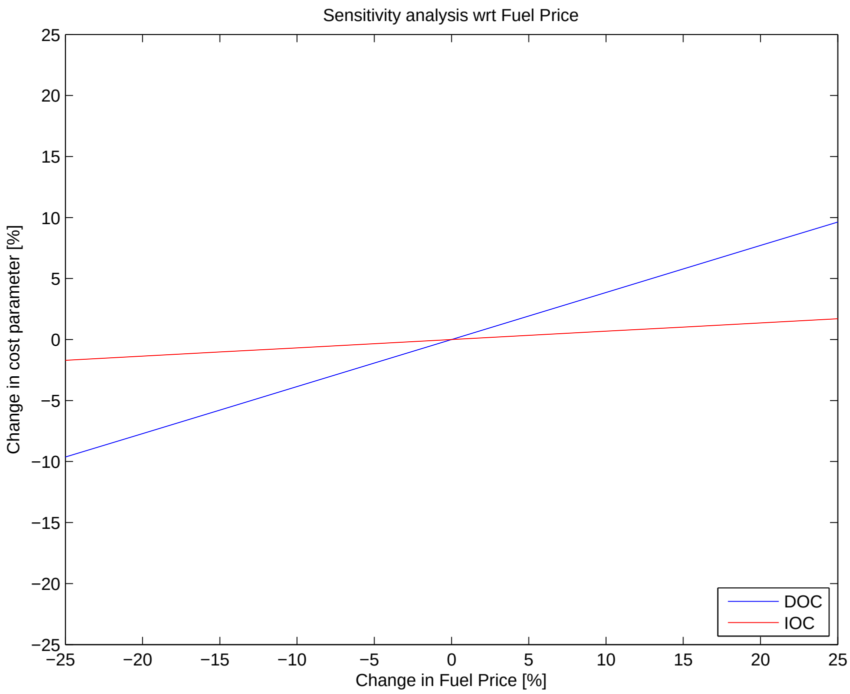


Figure D.3: Sensitivity analysis with respect to fuel price for the operating cost.

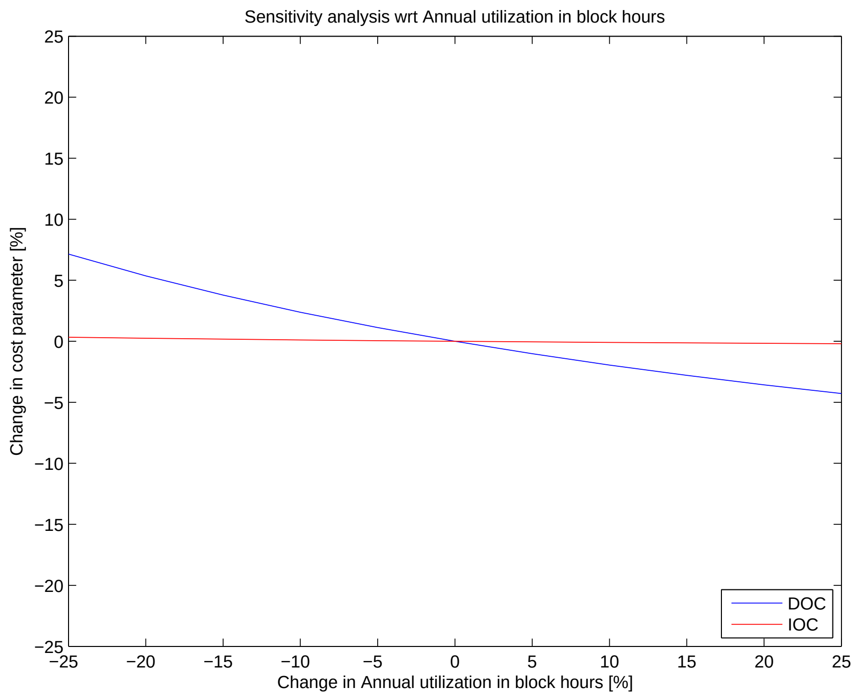


Figure D.4: Sensitivity analysis with respect to annual utilization in block hours for the operating cost.

DESIGN PARAMETERS

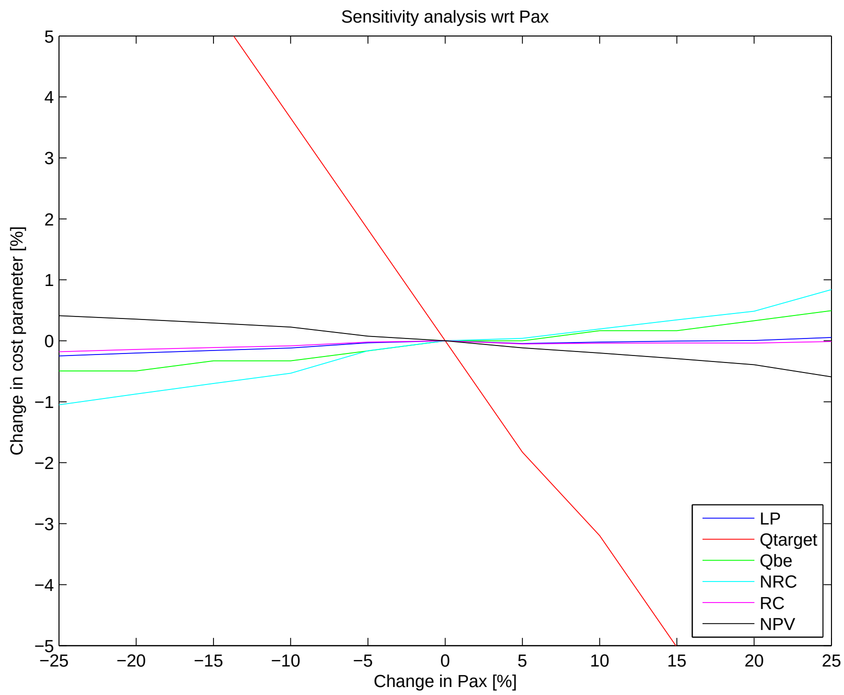


Figure D.5: Sensitivity analysis with respect to amount of passengers for the manufacturing cost.

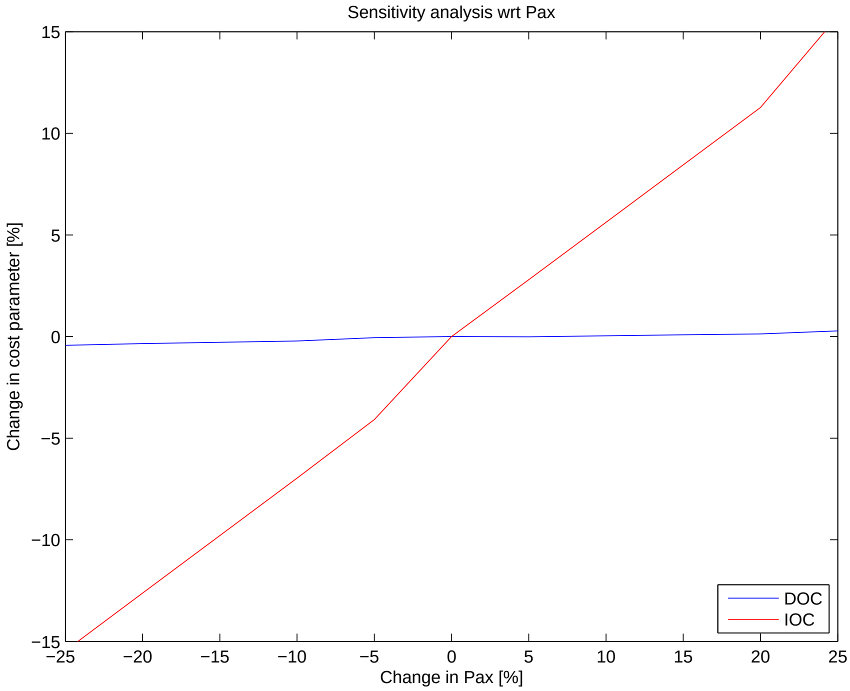


Figure D.6: Sensitivity analysis with respect to amount of passengers for the operating cost.

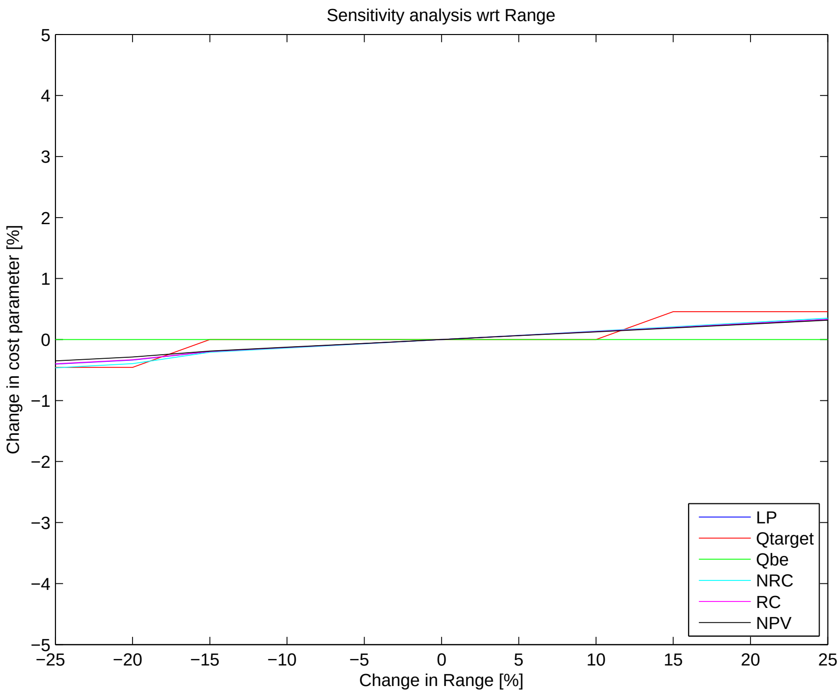


Figure D.7: Sensitivity analysis with respect to range for the manufacturing cost.

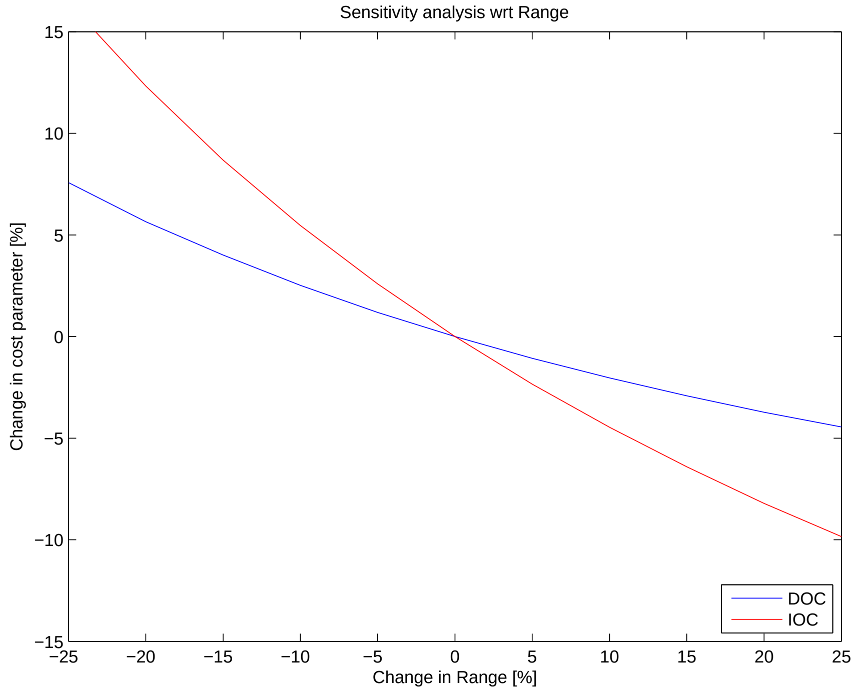


Figure D.8: Sensitivity analysis with respect to range for the operating cost.

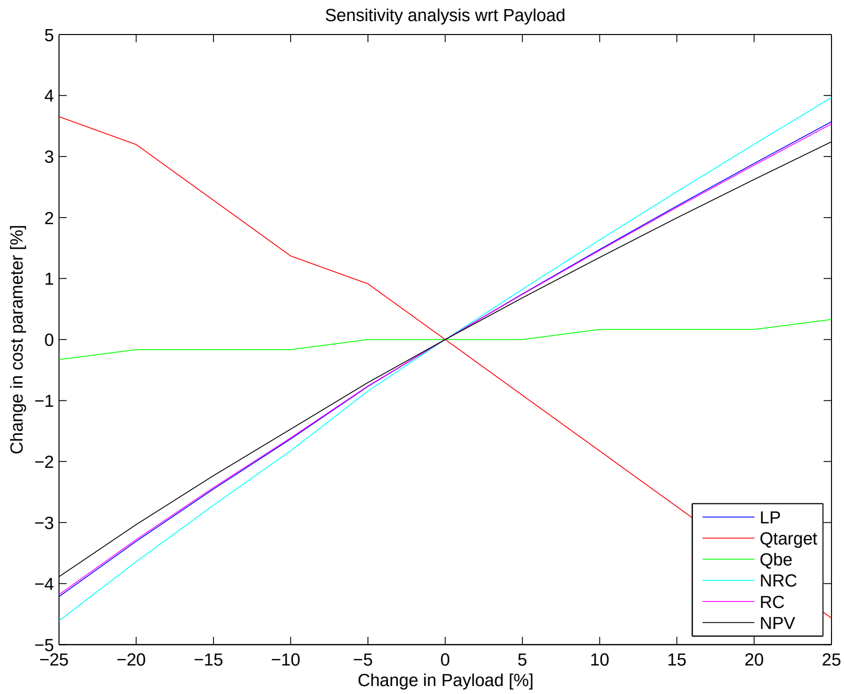


Figure D.9: Sensitivity analysis with respect to payload mass for the manufacturing cost.

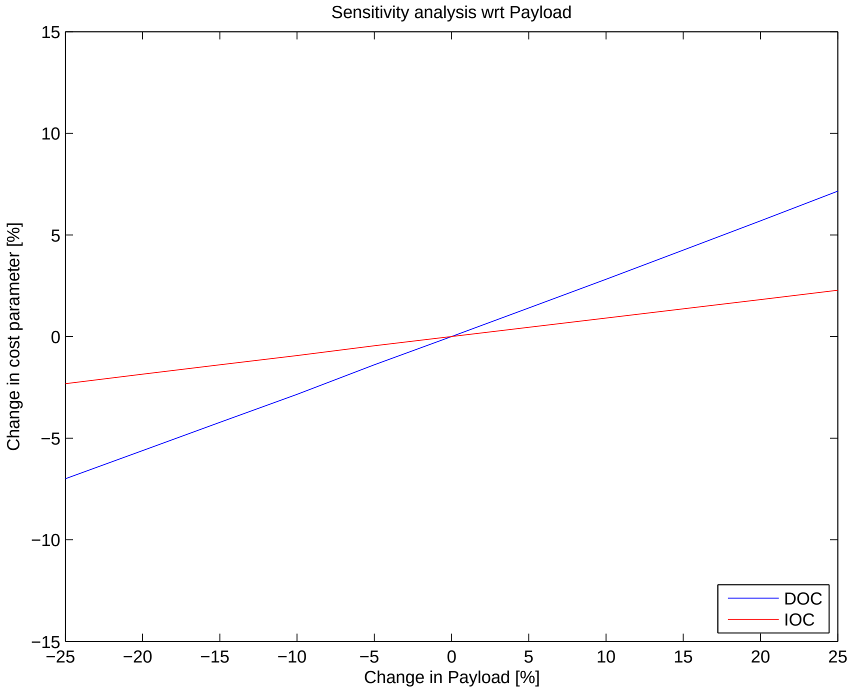


Figure D.10: Sensitivity analysis with respect to payload mass for the operating cost.

E

GALORATH'S SEER H

This Appendix explains the use of SEER H, the cost estimation software developed by Galorath. First, it will shortly give an impression of what the software looks like and how it is operated. Secondly, the settings used to compare configurations are presented in order to reproduce the results.

OPERATING THE SOFTWARE

After opening the software a new project can be created. It is possible to load example projects as is done for verification of the cost estimation model. An overview of the home screen is shown in Figure E.1.

The project can be changed to comply with the aircraft design by changing the components in the WBS. An example of the WBS of the Boeing 737-800 is shown in Figures E.2 and E.3. Parts can be added or deleted. After a part is added the proper input parameters are to be filled in. An example of the inputs for the fuselage is shown in Figure E.4. The weight is the most important parameter and is obtained from Initiator. This value is filled in for the 'likely' value and for 'least likely' and 'most likely' the values respectively -5% and +10% of the 'likely' value is used. This is done since it is more likely to overestimate the weight than estimating a lower value.

As can be seen in the bottom of Figure E.1 the software is able to deliver quick outputs with respect to the total program cost and individual aircraft cost.

Qualitative settings need to be filled in for: material composition, mission description, program complexity, development environment, production environment and engineering inputs. In the top of Figure E.4 different tabs are shown. The Schedule & quantity tab copies the overall production settings explained later. Labor rates and cost factors are provided by SEER H and do not need to be altered. The operation and support tab is optional and the labor category allocation tab can be set to default values.

The overall program settings like planning and production quantity need to be entered. This is done by clicking the B737-800 at the top of Figure reffig:WBS 1. The same tabs appear as for the fuselage, however for the parameters tab different fields need to be filled in as is shown in Figure E.5. The planning and production rate per year need to be filled in along with other parameters as is shown in Figure E.6.

SETTINGS FOR SEER H TO COMPARE CONFIGURATIONS

In order to give estimates for the different configurations different projects are created. The WBS is altered to the parts required per configurations. As an example the prandtl plane has two sets of wings and two vertical tails. For the conventional settings are used as a reference and the innovative designs are rated with respect to the degree of innovation. The values used for the production program are shown in E.7. Red values indicate that it is different compared to the reference aircraft. At the bottom the range of qualitative values that can be given to a parameter are shown. It ranges from Extremely hihg (Eh) to Very low (Vlo).

Also per aircraft part the production settings are filled in with respect to the reference aircraft. An example of the wing part is shown in Figure E.8. The same is done for all parts listed in the WBS. The results obtained are used for verification. The results are presented in Chapter 5.

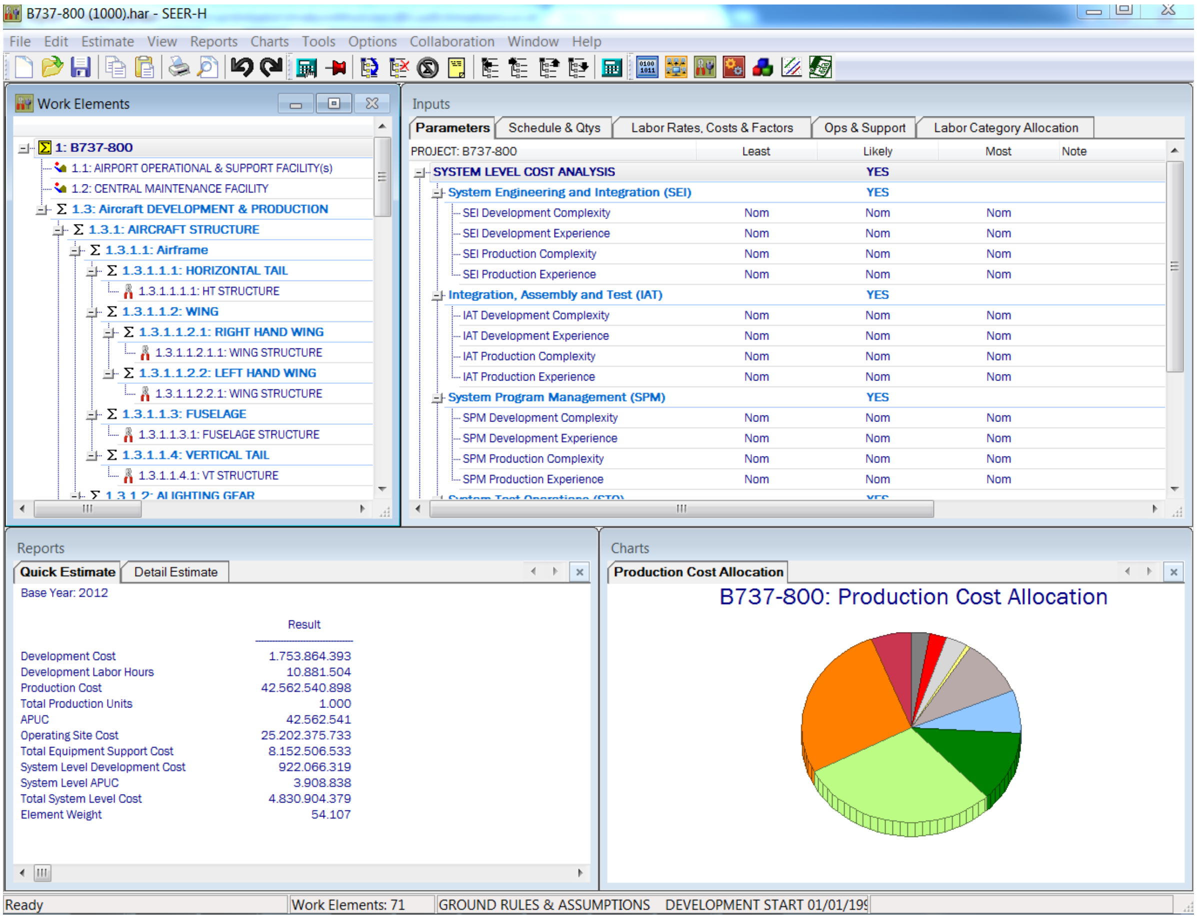


Figure E.1: Overview of the home screen of SEER H software.

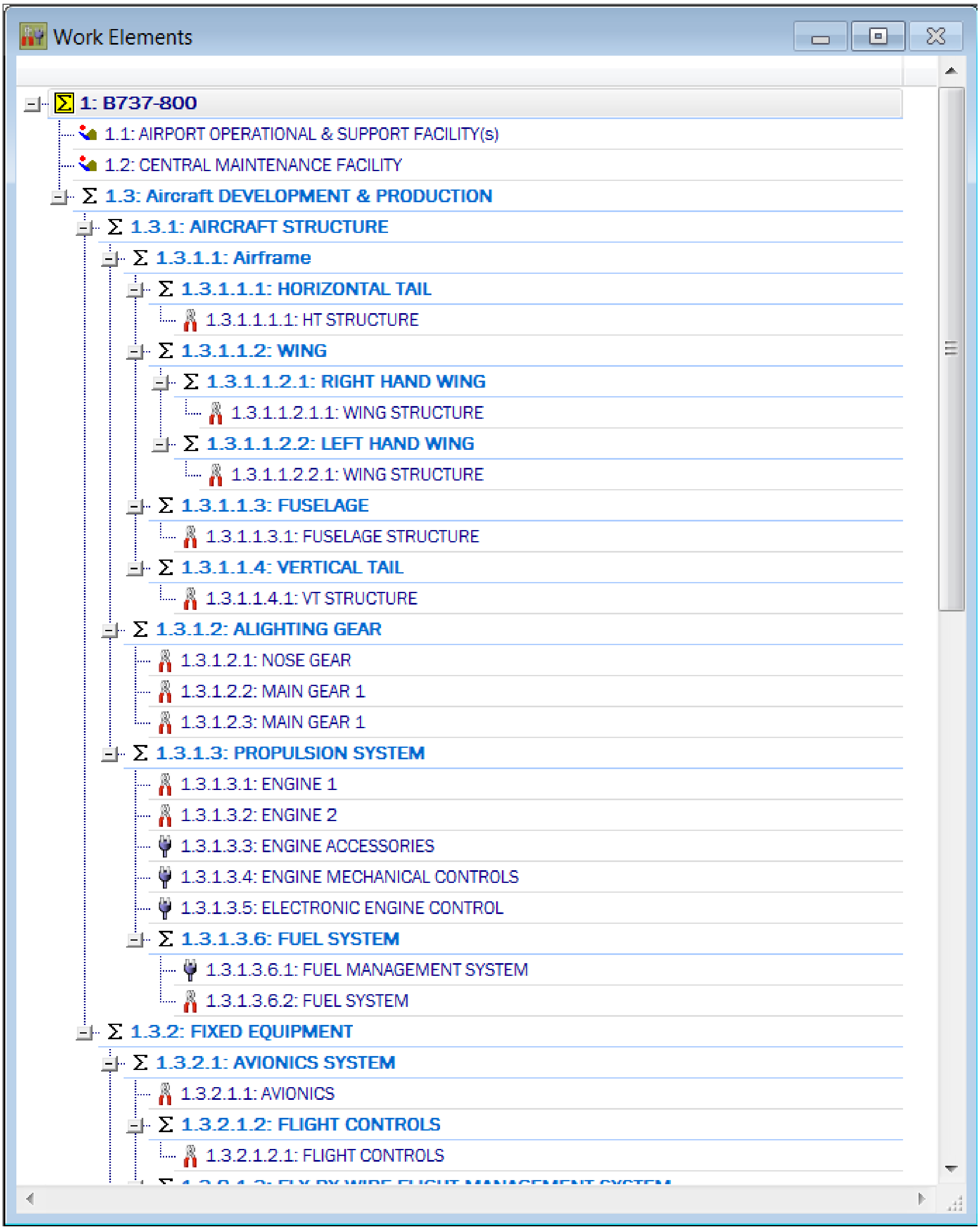


Figure E.2: Overview of the WBS of the Boeing 737-800 (part 1).

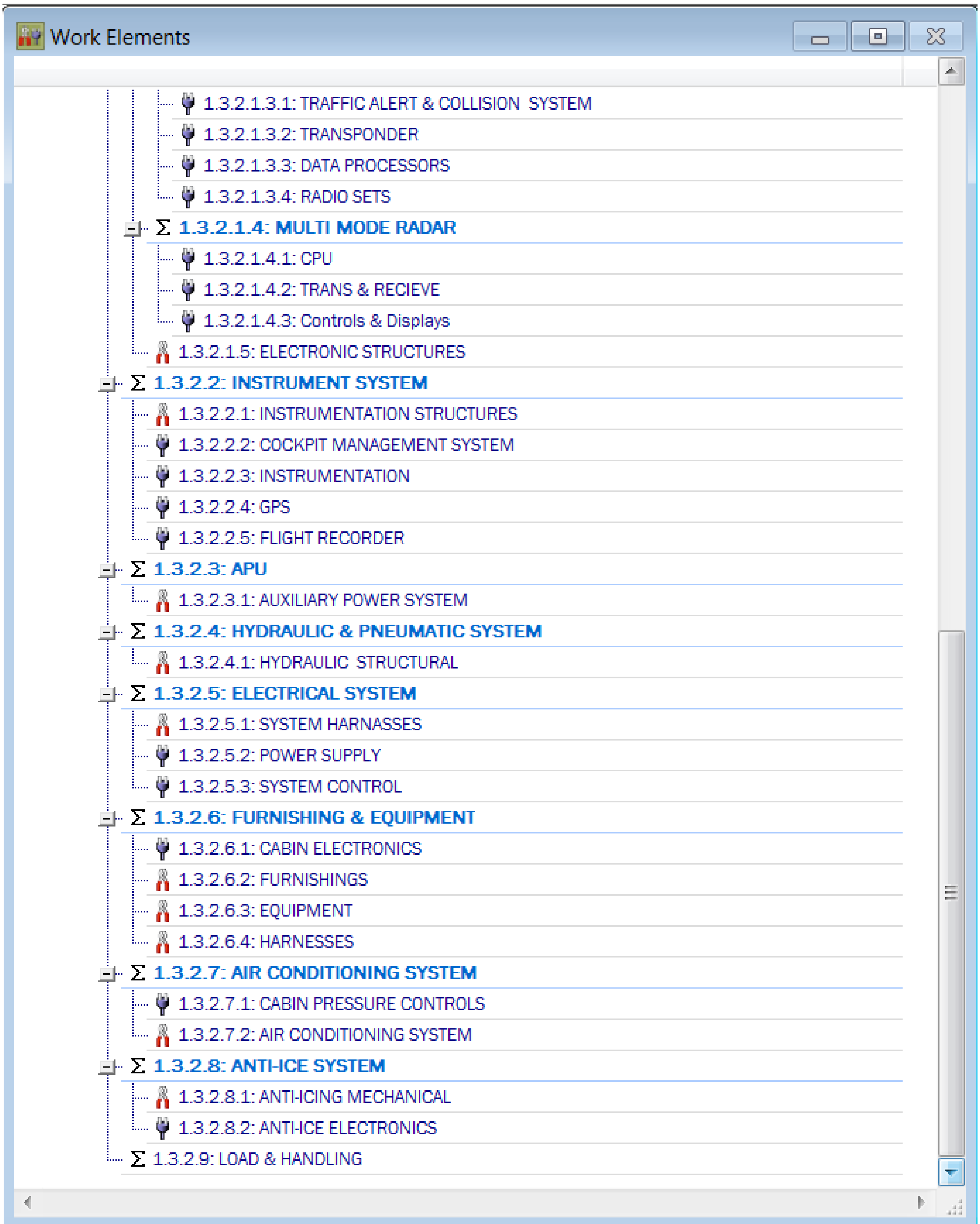
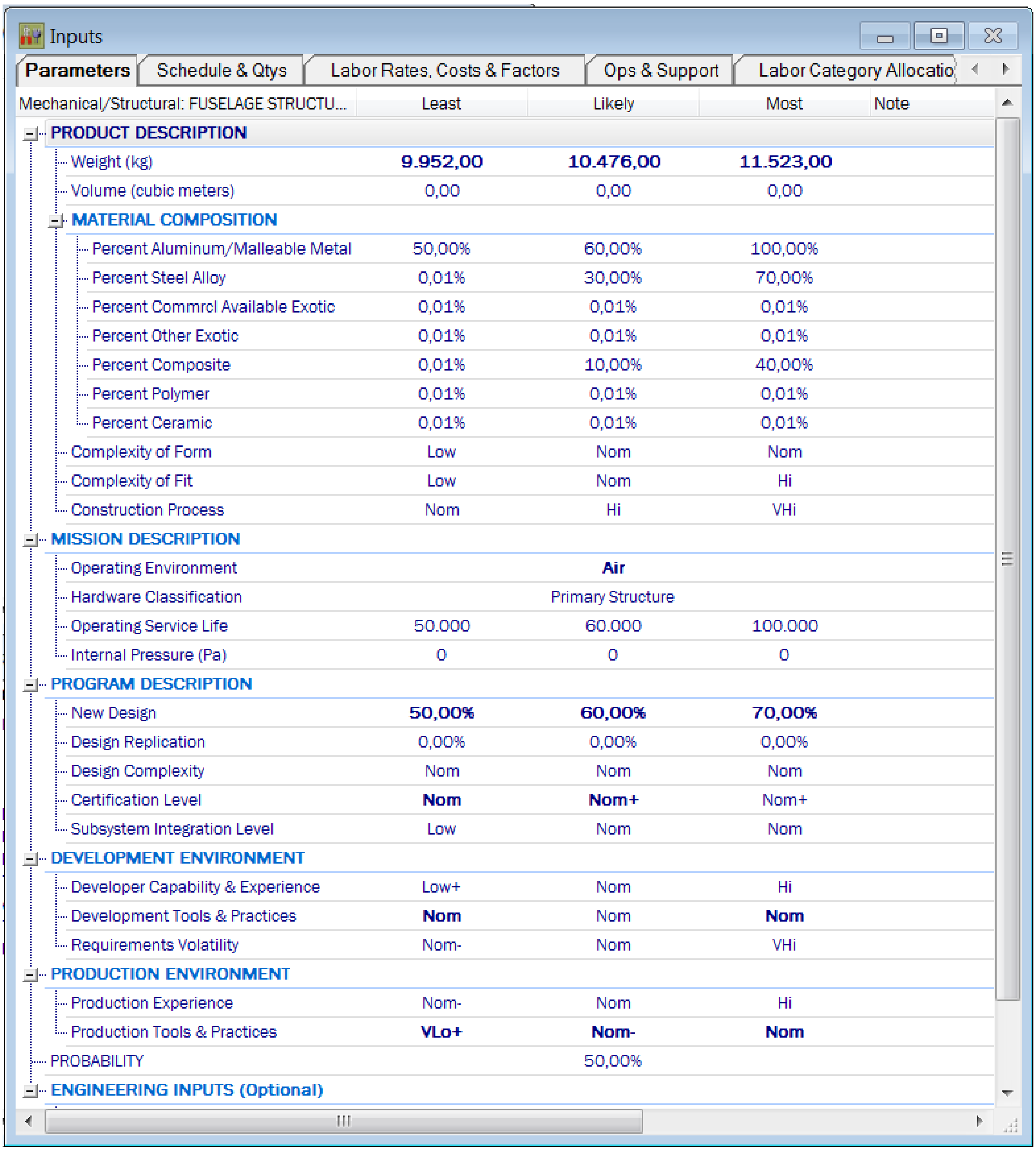


Figure E.3: Overview of the WBS of the Boeing 737-800 (part 2).

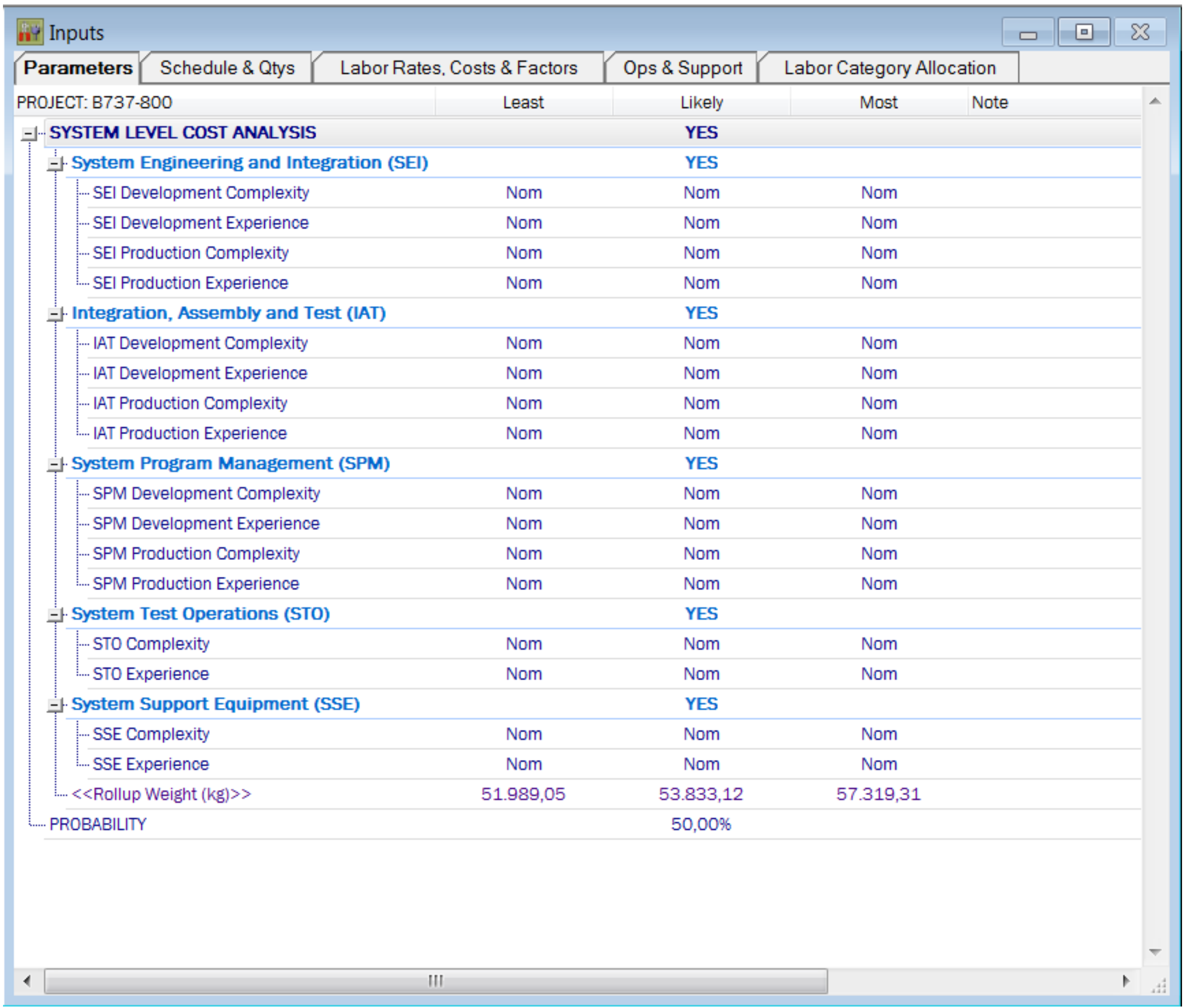


Inputs

Parameters | Schedule & Qtys | Labor Rates, Costs & Factors | Ops & Support | Labor Category Allocatio

Mechanical/Structural: FUSELAGE STRUCTU...	Least	Likely	Most	Note
PRODUCT DESCRIPTION				
Weight (kg)	**9.952,00**	**10.476,00**	**11.523,00**	
Volume (cubic meters)	0,00	0,00	0,00	
MATERIAL COMPOSITION				
Percent Aluminum/Malleable Metal	50,00%	60,00%	100,00%	
Percent Steel Alloy	0,01%	30,00%	70,00%	
Percent Commrcl Available Exotic	0,01%	0,01%	0,01%	
Percent Other Exotic	0,01%	0,01%	0,01%	
Percent Composite	0,01%	10,00%	40,00%	
Percent Polymer	0,01%	0,01%	0,01%	
Percent Ceramic	0,01%	0,01%	0,01%	
Complexity of Form	Low	Nom	Nom	
Complexity of Fit	Low	Nom	Hi	
Construction Process	Nom	Hi	VHi	
MISSION DESCRIPTION				
Operating Environment		**Air**		
Hardware Classification		Primary Structure		
Operating Service Life	50.000	60.000	100.000	
Internal Pressure (Pa)	0	0	0	
PROGRAM DESCRIPTION				
New Design	**50,00%**	**60,00%**	**70,00%**	
Design Replication	0,00%	0,00%	0,00%	
Design Complexity	Nom	Nom	Nom	
Certification Level	**Nom**	**Nom+**	Nom+	
Subsystem Integration Level	Low	Nom	Nom	
DEVELOPMENT ENVIRONMENT				
Developer Capability & Experience	Low+	Nom	Hi	
Development Tools & Practices	**Nom**	Nom	**Nom**	
Requirements Volatility	Nom-	Nom	VHi	
PRODUCTION ENVIRONMENT				
Production Experience	Nom-	Nom	Hi	
Production Tools & Practices	**VLo+**	**Nom-**	**Nom**	
PROBABILITY		50,00%		
ENGINEERING INPUTS (Optional)				

Figure E.4: Overview of the fuselage input of the Boeing 737-800.



PROJECT: B737-800	Least	Likely	Most	Note
SYSTEM LEVEL COST ANALYSIS		YES		
System Engineering and Integration (SEI)		YES		
SEI Development Complexity	Nom	Nom	Nom	
SEI Development Experience	Nom	Nom	Nom	
SEI Production Complexity	Nom	Nom	Nom	
SEI Production Experience	Nom	Nom	Nom	
Integration, Assembly and Test (IAT)		YES		
IAT Development Complexity	Nom	Nom	Nom	
IAT Development Experience	Nom	Nom	Nom	
IAT Production Complexity	Nom	Nom	Nom	
IAT Production Experience	Nom	Nom	Nom	
System Program Management (SPM)		YES		
SPM Development Complexity	Nom	Nom	Nom	
SPM Development Experience	Nom	Nom	Nom	
SPM Production Complexity	Nom	Nom	Nom	
SPM Production Experience	Nom	Nom	Nom	
System Test Operations (STO)		YES		
STO Complexity	Nom	Nom	Nom	
STO Experience	Nom	Nom	Nom	
System Support Equipment (SSE)		YES		
SSE Complexity	Nom	Nom	Nom	
SSE Experience	Nom	Nom	Nom	
<<Rollup Weight (kg)>>	51.989,05	53.833,12	57.319,31	
PROBABILITY		50,00%		

Figure E.5: Overview of the production program parameters of the Boeing 737-800.

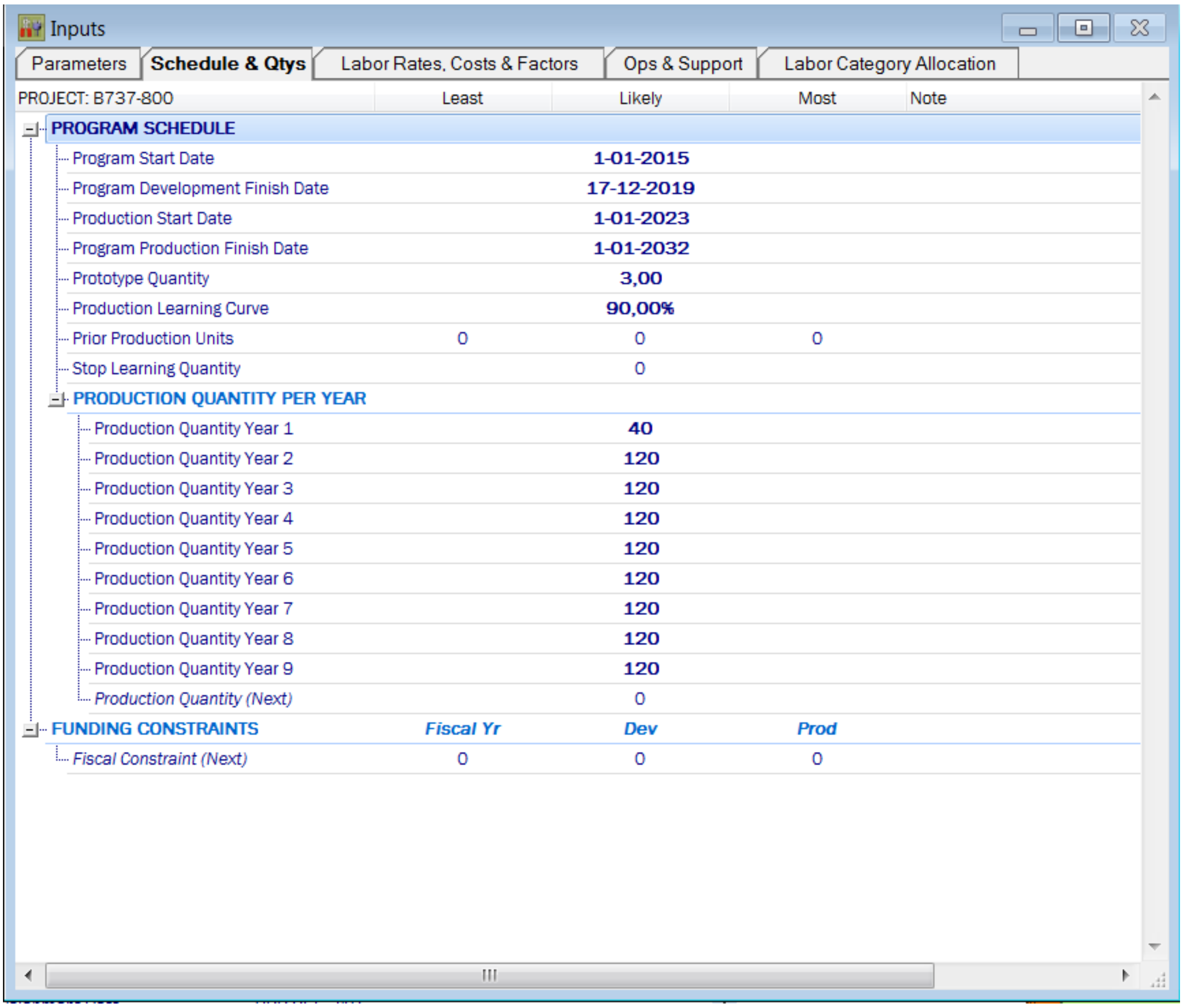


Figure E.6: Overview of the production program planning and production rate of the Boeing 737-800.

Overall settings per aircraft configuration

		Conventional			Canard			TSA			PP			BWB		
SYSTEM ENGINEERING & INTEGRATION	Unit	Le	Li	Mo	Le	Li	Mo	Le	Li	Mo	Le	Li	Mo	Le	Li	Mo
SEI Development Complexity	rel	Nom	Nom	Nom	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Hi-	Hi	Hi+	Hi+	Vhi-	Vhi
SEI Development Experience	rel	Nom	Nom	Nom	Nom	Nom-	Low+	Nom	Nom-	Low+	Low+	Low-	Vlo+	Vlo+	Vlo	Vlo
SEI Production Complexity	rel	Nom	Nom	Nom	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Hi-	Hi	Hi+	Hi+	Vhi-	Vhi
SEI Production Experience	rel	Nom	Nom	Nom	Nom	Nom-	Low+	Nom	Nom-	Low+	Low+	Low-	Vlo+	Vlo+	Vlo	Vlo
INTEGRATION, ASSEMBLY & TEST																
IAT Development Complexity	rel	Nom	Nom	Nom	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Hi+	Hi	Hi+	Hi+	Vhi-	Vhi
IAT Development Experience	rel	Nom	Nom	Nom	Nom	Nom-	Low+	Nom	Nom-	Low+	Low+	Low-	Vlo+	Vlo+	Vlo	Vlo
IAT Production Complexity	rel	Nom	Nom	Nom	Nom	Nom+	Hi-	Nom	Nom+	Low+	Hi-	Hi	Hi+	Hi+	Vhi-	Vhi
IAT Production Experience	rel	Nom	Nom+	Nom+	Nom	Nom-	Low+	Nom	Nom-	Vlo+	Vlo+	Low-	Vlo+	Vlo+	Vlo	Vlo
SYSTEM PROGRAM MANAGEMENT																
SPM Development Complexity	rel	Nom	Nom	Nom	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Nom+	Hi-	Hi
SPM Development Experience	rel	Nom	Nom	Nom	Nom	Nom-	Low+	Nom	Nom-	Low+	Nom	Nom-	Low+	Nom-	Low+	Low
SPM Production Complexity	rel	Nom	Nom	Nom	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Nom+	Hi-	Hi
SPM Production Experience	rel	Nom	Nom	Nom	Nom	Nom-	Low+	Nom	Nom-	Low+	Nom	Nom-	Low+	Nom-	Low+	Low
SYSTEM TEST OPERATION																
STO Complexity	rel	Nom	Nom	Nom	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Nom+	Hi-	Hi	Hi-	Hi	Hi+
STO Experience	rel	Nom	Nom	Nom	Nom	Nom-	Low+	Nom	Nom-	Low+	Nom-	Low+	Low	Low+	Low	Low-
SYSTEM SUPPORT EQUIPMENT																
SSE Complexity	rel	Nom	Nom	Nom	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Nom	Hi-	Hi
SSE Experience	rel	Nom	Nom	Nom	Nom	Nom-	Low+	Nom	Nom-	Low+	Nom	Nom-	Low+	Nom	Low+	Low

Drop down entries

Eh	Eh-	Vhi+	Vhi	Vhi-	Hi+	Hi	Hi-	Nom+	Nom	Nom-	Low+	Low	Low-	Vlo+	Vlo

Figure E.7: Overview of the settings for the production program per configuration.

Aircraft Part																
Wing																
		Conventional			Canard			TSA			PP			BWB		
PRODUCT	Unit	Le	Li	Mo	Le	Li	Mo	Le	Li	Mo	Le	Li	Mo	Le	Li	Mo
Complexity of form	rel	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Nom	Nom+	Hi-	Hi-	Hi	Hi+	Hi	Vhi-	Vhi+
Complexity of fit	rel	Nom-	Nom	Hi-	Nom-	Nom	Hi-	Nom-	Nom	Hi-	Hi	Hi+	Hi+	Hi	Hi+	Hi+
Construction process	rel	Nom	Hi-	Hi	Nom	Hi-	Hi	Nom	Hi-	Hi	Hi-	Hi	Hi+	Hi+	Vhi-	Vhi+
PROGRAM																
New design	%	50%	60%	70%	60%	70%	90%	60%	70%	90%	80%	90%	100%	90%	95%	100%
Design replication	%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Design complexity	rel	Nom	Nom	Nom	Nom+	Nom+	Nom+	Nom+	Nom+	Nom+	Hi-	Hi	Hi+	Hi	Vhi-	Vhi+
Certification level	rel	Nom	Nom+	Nom+	Nom	Nom+	Nom+	Nom	Nom+	Nom+	Nom	Nom+	Nom+	Nom	Nom+	Nom+
Subsystem integration level	rel	Nom	Hi-	Hi	Nom	Hi-	Hi	Nom	Hi-	Hi	Nom	Hi-	Hi	Nom	Hi-	Hi
DEVELOPMENT ENVIRONMENT																
Development experience	rel	Low+	Nom	Hi	Low+	Nom	Hi	Low+	Nom	Hi	Low	Low+	Low+	Vlo+	Low-	Low-
Development tools & practices	rel	Nom	Nom	Nom	Nom	Nom	Nom	Nom	Nom	Nom	Nom	Nom	Nom	Nom	Nom	Nom
Requirements volatiliy	rel	Nom-	Nom	Vhi	Nom-	Nom	Vhi	Nom-	Nom	Vhi	Nom-	Nom	Vhi	Nom-	Nom	Vhi
PRODUCTION ENVIRONMENT																
Production experience	rel	Nom-	Nom	Hi	Nom-	Nom	Hi	Nom-	Nom	Hi	Low	Low+	Low+	Vlo+	Low-	Low-
Production tools & practices	rel	Vlo+	Nom-	Nom	Vlo+	Nom-	Nom	Vlo+	Nom-	Nom	Vlo+	Nom-	Nom	Vlo+	Nom-	Nom

Figure E.8: Overview of the settings for the production of wings per configuration.

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