Delft University of Technology

Faculty of Aerospace Engineering

Department of Air Transport Operations

MSc Thesis

Aircraft maintenance cost modelling considering the influence of design parameters



***Name**: Massoud Urdu (1536281)*

***Supervisor**: Xiaojia Zhao*

***Graduating**: Professor: R. Curran*

Aircraft maintenance cost modelling considering the influence of design parameters

By

Massoud Urdu

In partial fulfilment of the requirements for the degree of

Master of Science

In Aerospace Engineering

at the Delft University of Technology,

to be defended publicly on Friday September 4, 2015 at 14:00 PM.

Supervisor: Xiaojia Zhao

Graduating Professor: Prof. Richard Curran

An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft Delft University of Technology

Preface

This master thesis report was compiled in partial fulfilment of the requirements for the degree of Master of Science in Aerospace Engineering at Delft University of Technology. The research elaborated in this report is performed in-house at the mentioned university and is 42 ECTS worth.

For establishment of the thesis report the MSc candidate is guided and assisted by several persons. First of all, many credits, appreciation and thanks goes to my supervisor Xiaojia Zhao, who supported me through the whole thesis project even in times when she was extremely busy with her PhD dissertation. Xiaojia has invested time and effort to make sure that I would reach my objective. Secondly I would like to thank my graduating professor Ricky Curran, he has provided me with useful feedback and ideas to complete my thesis. I would also like to thank Dr. Wim Verhagen from ATO department, for his feedback regarding maintenance costs and Prof. Roel Marissen, from materials department for his insight concerning composite material maintenance. I would like to thank Dr. Christos Kassapoglou for his ideas and help for completion of structural analysis part. Last but not least, I would like to thank my family for their support, patience and encouragement through the whole study.

The reader is wished a pleasant and informative read.

Massoud Urdu

July 2015

Executive Summary

The present day aviation market drives the airlines to reduce the life cycle cost (LCC). About 70-85% of commercial aircraft LCC is determined during the design stage of the aircraft (PeriyarSelvam et al., 2013). Aircraft maintenance is a vital process within aircraft operation and it takes around 15% of LCC (Suwondo, 2007; IATA, 2013). In the academic literature there is not a comprehensive maintenance cost estimation method available that addresses the maintenance cost contribution based on the operation parameters and design parameters. However, in order to analyse the aircraft maintenance cost of an airliner, influences from both the aircraft operation parameters and the aircraft design parameters should be investigated and incorporated in the cost estimation. In this research, the aircraft maintenance cost estimation methods are developed by analysing the current maintenance process while considering operation and design parameters.

To estimate the aircraft maintenance cost, several cost estimation methods can be consulted. Maintenance cost estimation can be defined as the process of predicting the cost of all maintenance activities. Maintenance cost is the price paid for the whole process, which is required to perform regular inspections and to bring the aircraft into serviceable condition according to the airworthiness regulations. The current aircraft and its components maintenance is evaluated regarding the MSG-3 philosophy. This philosophy has a task-oriented approach to conduct aircraft maintenance, in which the maintenance tasks are predetermined to avoid in-service failures. The maintenance cost estimation method used in present aviation industry differs from organization to organization. The difference of selecting an appropriate maintenance cost method is based on: available data that is used as input and the degree of accuracy of maintenance cost estimation.

The methodology proposed in this thesis project provides two different methods: Aging Involved Method (AIM) and Interval-Based Method (IBM), these methods are subjected to MSG3 maintenance program. The A330-200 rudder is utilized as a case study. The AIM method estimates the Scheduled Maintenance Labor Cost (SMLC), Unscheduled Maintenance Labor Cost (UNMLC), Scheduled Maintenance Material Cost (SMMC), Unscheduled Maintenance Material Cost (UNMMC) and maintenance overhead cost of a certain aircraft component. This method obtains the mentioned maintenance costs at a certain aircraft age by incorporating the aging factor. The method associates the maintenance costs with aircraft weight estimation which is allied to operational and design parameters. During the AIM analysis, the SMC remains is approximated as a constant while the UNMC increases as a function of increasing aircraft age. This means that the aircraft is anticipated to be taken out of service for maintenance purpose more often when the aircraft becomes older. From sensitivity analysis on the A330 rudder by using the AIM, the main cost drivers are extracted in terms of operation and design parameters; vertical tail surface (design parameter), flight cycles (operation parameter), flight hours (operation parameter) and rudder surface (design parameter).

The Interval-Based Method (IBM) conducts detailed evaluation of the average maintenance labor cost for a particular aircraft component. Firstly, certain aircraft component is

categorized into adjacent sub-parts. The categorization can be made in terms of materials, aircraft part items (spar, skin, rib, and etc.) and the maintenance tasks (as specified in the Maintenance Planning Document (MPD)). The IBM takes the failure rate of a specific component as an input. Initially, the failure rate is assumed to be equal to the reciprocal of the maintenance intervals as stated in the MPD. Then maintenance cost estimation is performed in bottom-to-top manner. However, the failure rate for a specific part item can be determined accurately by performing structural analysis as conducted in sub-section 6.2.2 (Integrated Aircraft Rudder Design & Maintenance) to obtain maintenance intervals. The procedure described in sub-section 6.22 illustrates how a direct link can be made between maintenance cost and aircraft design parameters by considering different failure modes. In this case, for design parameter material, the fatigue damage of a composite skin subject compression stress is exemplified, to obtain maintenance intervals as a consequence of repetitive cyclic loading on the rudder. In other words, a method starting from component load conditions, stress analysis, damage types, till maintenance interval determination has been developed. The intervals calculated from this analysis can replace the intervals extracted from MPD to be the input of IBM, so that a direct link between the component design and operation to its maintenance is built. Three types of composite damages are analysed: delamination, tension/compression failure of facings and shear strength failure of core. And the delamination damage will be maintenance critical first. Further, from the analysis it is found that initial maintenance threshold of the composite skin is at an aircraft age of 12.71YE with a maintenance inspection interval of 3.89YE for the delamination damage.

Table of Contents

Preface iii
Executive Summary iv
Table of Contents vi
List of abbreviations ix
List of symbols xi
List of figures xv
List of Tables xviii
1 Introduction 20
2 Research Scope 22
3 Literature Review 25
3.1 Cost Estimation Methods 25
3.2 Maintenance Process 26
3.3 Maintenance Cost 33
3.4 Composite Material in Aerospace 35
3.5 Design Consideration in Maintenance Cost Estimation 36
4 Model Framework 38
4.1 General Cost Estimation Methods 38
4.1.1 Qualitative Cost Estimation Techniques 39
4.1.2 Quantitative Cost Estimation Techniques 39
4.1.3 General Cost Estimation Models 40
4.2 Maintenance Process Model 42
4.2.1 Maintenance Program Development 43
4.2.2 Airbus's MPD Description 44
4.3 Maintenance Cost Breakdown and its Influence on LCC 48
4.4 Aircraft Maintenance Cost Estimation Methods 53
4.4.1 The Airbus Method 53
4.4.2 Second Order Reliability Method 53
4.4.3 Project-Evaluating Method 54
4.4.4 IATA's Maintenance Task Force 55
4.4.5 Dhillon's Maintenance Labor Cost Estimation Method 57
4.4.6 Liebeck's Maintenance Airframe, Material Cost Estimation Method and Maintenance Overhead Cost 58

4.4.7 Brugidou's Method for UNMC of Structures and Zonal Maintenance 59
4.4.8 Van der Velden Method 60
4.4.9 Roskam Method 61
4.5 MCEM Framework 63
5 Methodology 64
5.1 Aging Involved Method 65
5.1.1 Maintenance Labor Cost Estimation 68
5.1.2 Maintenance Materials Cost Estimation 73
5.1.3 Maintenance Overhead Cost Estimation 74
5.2 Interval-Based Method 75
5.2.1 Scheduled Maintenance Labor Cost Estimation 77
5.2.2 Integrated Aircraft Component Design & Maintenance 79
6 Case Study of A330-200 Rudder 90
6.1 Aging Involved Method 90
6.1.1 Scheduled and Unscheduled Maintenance Labor Cost 92
6.1.2 Scheduled and Unscheduled Maintenance Material Cost 96
6.1.3 Maintenance Overhead Cost 99
6.1.4 Sensitivity analysis of AIM 100
6.2 Interval Based Method 102
6.2.1 Scheduled Maintenance Labor Cost 102
6.2.2 Integrated Aircraft Rudder Design & Maintenance 107
7 Verification and Validation 136
7.1 Verification of Maintenance Cost Analysis Variables 136
7.2 Verification and Validation of AIM 137
7.2.1 Airframe Maintenance Labor Cost Validation by Roskam and van der Velden Method A 138
7.2.2 Airframe Maintenance Labor Cost Validation by Roskam and van der Velden Method B 142
7.2.3 Unscheduled Maintenance Cost Validation using Modified Brugidou Method 143
7.3 Verification and Validation of IBM 149
7.3.1 Validation Between Aging Involved Method and Interval-Based Method for SMLC 149
7.3.2 Verification and Validation of Integrated Component Design & Maintenance 150

8 Conclusions & Recommendations 152
8.1 Conclusion 152
8.2 Recommendations for Further Research 154
References 156
Appendix A MSG-3 Categories 163
Appendix B Failure Effects Evaluation 165
Appendix C Weight and Load Factor Estimation 166
Appendix D Aircraft Part Breakdown 172
Appendix E Wing Structure Breakdown 173
Appendix F Load Cycles per Flight Cycles 174
Appendix G A330-200 Rudder Tasks 178
Appendix H Rudder Scheduled Maintenance Tasks Calculation 182
Appendix I A330-200 Dimensions 187
Appendix J DMC Labor for A330-200 Rudder for AIM 188
Appendix K A330-200 Rudder Material Cost 189
Appendix L MSG-3 Task Selection by Failure Mode 190
Appendix M Detailed A330 Rudder Sketches 191
Appendix N Shear and Moment Diagrams of the Spar 192

List of abbreviations

A/C		Aircraft
AC		Advisory Circular
AC		Aircraft
AD		Airworthiness Directive
ADL		Allowable Damage limits
ADLC		Airframe Direct Labor Cost
AF		Aging Factor
AFPM		Annual Frequency of Preventive Maintenance Tasks
AMM		Aircraft Maintenance Manual
ATA		Air Transport Association
CBS		Cost Breakdown Structure
CDL		Critical Damage Thresholds
CER		Cost Estimation Relationship
CM		Condition-Monitoring
CPCP		Corrosion Prevention and Control Programs
DET	or	Detailed Inspection
DI		
DMC		Direct Maintenance Cost
DOC		Direct Operating Cost
DOC+I		Direct Operating Cost plus Interest
DS		Discard
DSG		Design Service Goal
ETPMT		Elapsed Time for Preventive Maintenance Task
FAA		Federal Aviation Administration
FC		Functional Check/ Flight Cycle
FCs		Annual flight cycle
FH		Flight Hours
FPM		Frequency of Preventive Maintenance Tasks
GAG		Ground-Air-Ground
GV	or	General Visual Inspection
GVI		
HT		Hard Time
IATA		International Air Transport Association
IMC		Indirect Maintenance Cost
IN		Inspection
IR		Inflation Rate
LCC		Life Cycle Cost
LMC		Line Maintenance Cost
LL		Limit Load
LR		Labor Rate
LU		Lubrication
MAC		Mean Aereodyanamic Chord
MaReps		Maintenance Reports
MC		Maintenance Cost
MCEM		Maintenance Cost Estimation Method
MCET		Maintenance Cost Estimation Tool
MEW		Manufacturer Empty Weight
M.H		Man-Hour

MLW	Maximum Landing Weight
MMHs	Maintenance-Man-Hours
Mmo	Maximum operating Mach
MSG	Maintenance Steering Group
MSI	Maintenance Significant Item
MRB	Maintenance Review Board
MRO	Maintenance Repair Organization
MPD	Maintenance Planning Document/Data
MPMT	Mean Preventive Maintenance Time
MTBF	Meant Time Between Failure
MTTF	Mean Time To Failure
MTOW	Maximum Take-off Weight
MZFW	Maximum Zero fuel Weight
NASA	National Aeronautic Space Administration
NDI	Non-destructive Inspection
NE	Number of Equations
NFF	No Fault Found
NR	Number of Reactions
OEW	Operational Empty Weight
OAMP	Operator Approved Maintenance Program
OMP	Operator maintenance Program
OC	On-Condition
OP	Operational Check
OPS	Operations
PiReps	Pilots Report
POD	Probability Of Detection
PSE	Principal Structural Elelement
SB	Service Bulletin
SDI or SI	Special Detailed Inspection
SL	Safety Limit
SMC	Scheduled Maintenance Cost
SMMC	Scheduled Maintenance Material Cost
SSI	Structural Significant Item
SV	Servicing
TMC	Total Maintenance Cost
TMLC	Total Maintenance Labor Cost
UL	Ultimate Load
UNMLC	Unscheduled Maintenance Labor Cost
UNMC	Unscheduled Maintenance Cost
UNMMC	Unscheduled Maintenance Material Cost
VC	Visual Check
WG	Working Group
ZFW	Zero Fuel Weight

List of symbols

a_i	Initial flaw size
a_c	Critical flaw size
a_d	Reliable detectable flaw size
AC_{age}	Aircraft age
AF_y	Aging factor for aircraft year y
$A.R$	Aspect Ratio
$(A.R)_{tail}$	Tail aspect ratio
b	Wing span
b_R	Span of the rudder
b_H	Span of horizontal tail
b_v	Span of the vertical tail
C_{amb}	applied maintenance burden
$C_{component}$	Component maintenance cost
C_{cycle}	Repair cost of life limited part
C_{fix}	Fixed cost
C_{labor}	Labor cost
$C_{labor\ airframe}$	Airframe maintenance labor cost
$C_{labor\ air+sys}$	labor cost of airframe and systems maintenance
$C_{labor,corrective}$	Corrective maintenance labor cost
$C_{labor,preventive}$	Preventive maintenance labor cost
$C_{labor\ component}$	Component maintenance labor cost
$C_{lab/en}$	labor cost engines(s) maintenance
$C_{L_\propto}$	Lift curve slope
C_{mat}	Material cost
$C_{material\ airframe}$	Airframe maintenance material cost
$C_{mat/ap}$	Cost of maintenance materials for the airframe and systems
$C_{material\ component\ y}$	Component material maintenance cost
C_r	Total cost of repair
$r_{labor\ C-Check}$	the maintenance labor rate of the inspector ($€/hr$)
C_R	Rudder chord
$C_{reference}$	The reference cost
C_{rep}	Repair cost
C_S	Total cost of structural
C_{SMM}	Scheduled maintenance material cost
C_{SML}	Scheduled maintenance labor cost
$C_{SML\ component}$	Component scheduled maintenance labor cost
C_{sub}	Subcontracted cost
$\overline{c_t}$	Mean geometric chord of vertical surface (m)
C_{UNMM}	Unscheduled maintenance material cost
$C_{UNM\ airframe\ y}$	Unscheduled Maintenance Cost of the airframe in the year of interest y
C_{UNMM}	Airframe Unscheduled Maintenance material Cost
C_{UNL}	Unscheduled maintenance labor cost
$C_{UNL\ component}$	Component unscheduled maintenance labor cost
$CF_{\$\to€}$	Conversion factor USD to EURO
C_{Vr}	Root chord length of vertical tail
C_{Vt}	Tip chord length of vertical tail

$c.g$	Centre of gravity
C_{Y_v}	Lateral force derivative due to vertical tail v
C_{Y_β}	Lateral force derivative due to angle β
$D_{I_{year=x}}$	Deflator for year =x
DS	Damage Size
DS_i	Damage size at ith inspection interval
DOC_{fin}	Direct operating cost of financing
DOC_{flt}	Direct operating cost of flying
DOC_{lnr}	direct operating cost of landing fees, navigation fees and registry taxes
DOC_{maint}	direct operating cost of maintenance
DOC_{depr}	the direct operating cost of depreciation
f	Frequency (Hz)
F_y	Force in y-direction
$(F_2)_{asy\ thrust}$	Load on the rudder in case of one engine failure (N)
$(F_2)_{LG}$	Load on the rudder due to lateral gust (N)
$(F_2)_{\max \delta_R}$	Load on the rudder due to sudden max rudder input (N)
g	Acceleration due to gravity (m/s^2)
h_y	Amount of hours in a year
IR_y	Inflation rate for certain year
i_h	Tasks interval in hour
I_1	Initial inspection time
FCs	Annual flight cycles
FHs	Annual utilization flight hour
F_y	Forces in y-direction
k	Probability of crack appearance
K_{gt}	Gust alleviation factor
L	Lift
l_v	Distance between aerodynamic centre of the vertical tail to aircraft cg
L_v	Lift force at vertical tail surface
$(L_V)_{\max \delta_R}$	Load on fin due to sudden max rudder input (N)
$(L_v)_{asy\ thrust}$	Load on vertical tail due to asymmetric thrust
$(L_v)_{LG}$	Load on vertical tail due to lateral gust
$(L_v)_{man}$	Load on vertical tail due to yaw manoeuvre
l_H	Distance from airplane c.g to aerodynamic centre of the tail
Lt	Vertical Tail load
$loads_{ap}$	Amount of loads cycle on the rudder during approach of the runway
$loads_{br}$	Amount of loads cycle on the rudder during braking
$loads_{cl}$	Amount of loads cycle on the rudder during climb
$loads_{cr}$	Amount of loads cycle on the rudder during cruise flight
$laods_f$	Number of loads during flight operation on the rudder
$loads_{g_I}$	Number of loads during ground operation (before take-off) on the rudder
$loads_{g_{II}}$	Number of loads during ground operation (after the landing) on the rudder
$loads_{GT}$	Amount of loads cycle on the rudder during ground turning
$loads_{IC}$	Amount of loads cycle on the rudder during initial climb

$loads_{ID}$	Amount of loads cycle on the rudder during initial descent
$loads_{LR}$	Amount of loads cycle on the rudder during landing roll
$loads_{PB}$	Amount of loads cycle on the rudder during pre-flight braking
$loads_{Ro}$	Amount of loads cycle on the rudder during aircraft rotation
$loads_{st}$	Amount of loads cycle on the rudder during standing
$loads_{TD}$	Amount of loads cycle on the rudder during touch down
$loads_{TI}$	Amount of loads cycle on the rudder during taxi-in
$loads_{TOR}$	Amount of loads cycle on the rudder during take-off run
M	Aircraft Mach number
$MMH_{C-Check}$	the maintenance man hours for inspection
MMH_{On}	Maintenance Man Hours on the aircraft
MMH_{off}	Maintenance Man Hours off the aircraft
MAC_W	Mean aerodynamic chord of the wing
$MHR_{map_{bl}}$	Number of airframe man-hours needed per block hour
N	Number of load cycles
N_A	Yawing moment about Z-axis
N_{cg}	Moments about Z-axis taken over cg
N_f	Number of load cycles to failure
N_{normal}	Load factor
N_{ult}	Ultimate load factor
$NDI_{detection\ period}$	Non-Destructive Inspection period
P	Aerodynamic load on the fin-and-rudder
P_{max}	Maximum pressure differential---change it in Pmax in MSc thesis
POD_x	The crack growth group
Pt_g^x	Total structural repair cost in crack group x
R	Range (m)
R_{gy}	Radius of gyration in yaw (m)
R_{yaw}	Yaw rate
$\bar{r}_{inflation}$	Average inflation rate per year in percentage in Europe between 1994-2014
r_{labor}	Labor rate (€/h)
T_L	Thrust of left engine (N)
t_{bl}	Block hour time
t_{cl}	Time to climb
t_{cr}	Time to cruise
t_{de}	Time to descent
t_{flight}	Flight time (FH)
t_{gm}	Ground manoeuvres time (s)
t_{loss}	Loss time (s)
t/c	Average airfoil thickness
s	The aircraft seat capacity
S	Shear Stress (N/m^2)
S_{He}	Surface of the horizontal tail (m^2)
S_V	Surface of the vertical tail (m^2)
S_{rudder}/S_R	Rudder surface (m^2)
S_{wing}	Wing area (m^2)
S_{wg}	Gross wing area (m^2)
SMC_y	Scheduled maintenance cost for certain AC age y
$TMC_{\ shop\ est}$	Total maintenance cost shop estimation

TMC_y	Total maintenance cost for a certain aircraft age y
$UNMC_y$	Unscheduled maintenance cost for certain AC age y
v	Derived gust velocity in horizontal direction (m/s)
V_{bl}	Block speed (m/s)
V_{MC}	Minimum Controllable Speed (m/s)
$Visual_{detection\ period}$	Visual detection period
V_S	Stall Speed (m/s)
W	Aircraft weight (kg)
$W_{Aircraft}$	Aircraft weight (kg)
$W_{airframe}$	Airframe weight (kg)
W_{fus}	Weight of the fuselage (kg)
W_{gear}	Landing gear weight (kg)
$W_{vtail(-rudder)}$	Weight of the vertical tail less the rudder weight (kg)
y_T	Distance between AC c.g and the engine (m)
β	Angle of sideslip (rad)
y_T	Distance between aircraft cg and engine (m)
Δ	Available inspection time (s)
Δ	Skin thickness, by design analysis
ΔI	Inspection interval $= 1/2 \cdot \Delta$
δ_r/δ_R	Rudder deflection angle (deg)
δ_{rmax}	Maximum Rudder deflection angle (rad)
λ_l	Wavelength (m)
$\boldsymbol{\lambda}$	Taper ratio
λ_i	Failure rate for i element
$\emptyset$	Bank angle (rad)
Λ	Sweep angle (rad)
Λ_{ea}	Quarter chord sweep angle (rad)
ρ	Air density (kg/m^3)
σ_U	Average static strength (MPa)
$(\sigma_U)_{Dam}$	Damaged static strength (MPa)
$(\sigma_U)_{Undam}$	Undamaged static strength (MPa)
$\#\ of\ trips$	Number of trips
$\frac{\#LC}{FC}$	Number of loads cycles per flight cycle

List of figures

Figure 1 the pyramid of the MSc research 23
Figure 2 (un)scheduled maintenance reliability vs. service time (Kinnison, 2004) 27
Figure 3 MSG-2 vs. MSG-3 Decision Logic Process (Ackert, 2010) 29
Figure 4 maintenance triggers (aviamech, 2011) 31
Figure 5 OAMP establishment (Ackert, 2010) 33
Figure 6 maintenance process breakdown (Knotts, 1999) 34
Figure 7 maintenance cost per segment (Bulato, 2010) 34
Figure 8 flow diagram of structural design analysis process (Kassapoglou, Design and Analysis of Composite Structures, 2010) 37
Figure 9 Cost Estimation Methods (source: Niazi et al., 2006) 38
Figure 10 Cost Estimation Techniques (Source: Niazi et al., 2006) 39
Figure 11 maintenance program evolution process (Bulato, 2010) 43
Figure 12 OMP development of B737NG by Transavia (Muchiri, 2002) 44
Figure 13 an example of MPD source: (Airbus, 2006) 47
Figure 14 LCC cost breakdown (Thokala, 2009) 48
Figure 15 total operation cost of an aircraft (IATA, 2013) 49
Figure 16 TMC cost breakdown (Khwaja, 2012) 49
Figure 17 manufacturer and airline influence on maintenance cost (Khwaja, 2012) 50
Figure 18 average composition of TMC (Dixon, 2006) 50
Figure 19 DMC compositions (Brugidou, 2007) 51
Figure 20 maintenance cost per FH vs. AC age (Dixon, 2006) 51
Figure 21 effect of age on airframe maintenance costs (Dixon, 2006) 52
Figure 22 Boeing's maturity curve (Dixon, 2006) 52
Figure 23 mission profile definitions (Roskam, 2002) 62
Figure 24 MCEM elements 63
Figure 25 the TMC section that are analysed 64
Figure 26 Aging Involved Method flowchart 65
Figure 27 structure of the model with associated parameters 66
Figure 28 ratio between Unscheduled and scheduled maintenance cost as a function of aircraft age (Suwondo, 2007) 67
Figure 29 ratio between UNMC/SMC 69
Figure 30 error of the developed AF formula compared to observed values 70
Figure 31 IBM and Integrated Component Design flowchart 76
Figure 32 flowchart of Integrated Aircraft Component Design & Maintenance 76
Figure 33 IBM method implementation 77
Figure 34 structural maintenance program development adapted from (Homan, 2008) 80
Figure 35 MSG-3 structural analysis flowchart (Homan, 2008) 81
Figure 36 mission profile A330/A340 (Schmidt et al., 1995) 83
Figure 37 strength vs. damage diameter (adapted from Kassapoglou, 2010) 86

Figure 38 determination of initial inspection time I1 and inspection interval ΔI (Heida and Grooteman, 1998) 88
Figure 39 structural strength and inspection interval (Goranson, 2007) 88
Figure 40 required damage detection reliability for an aircraft (Goranson, 2007) 89
Figure 41 the A330-200 rudder (Tissenier, 2012) 90
Figure 42 the structure of the model for A330-200 rudder 92
Figure 43 limit bank angle A330 (Airbus, 2014a) 93
Figure 44 A330-200 rudder labor cost in terms of SMLC and UNMLC 96
Figure 45 the UNMLC of TMLC of A330-200 rudder 96
Figure 46 A330-200 rudder material cost 97
Figure 47 the A330-200 rudder maintenance cost 98
Figure 48 A330 rudder DMC through AC age 98
Figure 49 rudder MC for scheduled and unscheduled maintenance 99
Figure 50 direct maintenance cost in scheduled and unscheduled MC for labor and material 99
Figure 51 A330 Rudder overhead cost 100
Figure 52 TMC of the rudder as function of AC age 100
Figure 53 sensitivity analysis of parameters w.r.t maintenance labor cost 102
Figure 54 A330-200 Rudder structures, Zonal and System & Component task (Zhao et al., 2014) 103
Figure 55 annual maintenance labor cost for different rudder parts 105
Figure 56 aircraft life (20YE) maintenance labor cost for different rudder parts 105
Figure 57 annual and aircraft life rudder maintenance labor for composites and non-composites 105
Figure 58 annual and AC life maintenance labor cost by different maintenance tasks 106
Figure 59 rudder maintenance labor cost by structures, zonal and systems & component 107
Figure 60 summary of maintenance intervals determination approach 107
Figure 61 A330 rudder main parts (Ward, 2001) 108
Figure 62 sandwich skin 108
Figure 63 example of a spar 109
Figure 64 cylinder torsion bar 109
Figure 65 directional control due to rudder deflection (Sadraey, 2012) 111
Figure 66 a twin engine aircraft with right engine inoperative (Sadraey, 2012) 113
Figure 67 loads on the vertical tail and rudder 114
Figure 68 simplified vertical tail and rudder with associated loads 115
Figure 69 vertical tail and rudder forces and angles 115
Figure 70 rudder 3D representation 117
Figure 71 rudder spar with the attachments 117
Figure 72 FBD of spar with reaction forces and distances 117
Figure 73 superposition diagrams 119
Figure 74 simply supported beam with dimensions and loading 120
Figure 75 Top view representation of spar with M and S 121
Figure 76 Top view representation of rudder with F2, M and S 121
Figure 77 flange crippling (Kassapoglou, Design and Analysis of Composite Structures, 2010) 122

Figure 78 failure modes in composite airframe (Kassapoglou, 2010) 122
Figure 79 rudder force and dimensions 122
Figure 80 rudder distributed force and dimensions 122
Figure 81 rudder with cutting section 123
Figure 82 view AA with forces on the skin 123
Figure 83 AA view with the moment M 123
Figure 84 skin cross-section with strength 124
Figure 85 center of gravity limits A330-200 (Airbus training, 2010) 127
Figure 86 vertical tail load vs. rudder deflection 129
Figure 87 load cycles vs. DS for the honeycomb core, delamination failure 130
Figure 88 determination of maintenance inspection variables for delamination failure mode 133
Figure 89 determination of maintenance inspection variables for tension/compression failure mode 133
Figure 90 determination of maintenance inspection variables for shear strength failure mode 134
Figure 91 the TA activities and time of A330 (Airbus, 2014) 140
Figure 92 direct maintenance cost by segment year 2012 (IATA, 2013) 145
Figure 93 the unscheduled maintenance cost of airframe by Modified Brugidou Method 147
Figure 94 UNMC of A330 rudder 148
Figure 95 the rudder UNMC comparison developed method (case study) and modified Brugidou method 148
Figure 96 cost comparison between AIM and IBM 150
Figure 97 failure effects evaluation (Homan, 2008) 165
Figure 98 standard weight terms and weight groups (Elham, 2013) 166
Figure 99 forces on an aircraft during a level coordinated turn (Cavcar, 2004) 170
Figure 100 load factor vs. bank angle 170
Figure 101 Number of gust load cycles for a F27 and F28 (schijve, 1985) 174
Figure 102 manoeuvre load cycles for F27 and F28 (Schijve, 1985) 175

List of Tables

Table 1 the maintenance checks (EUROCONTROL, 2008) 32
Table 2 Cost Estimation Techniques (source: Niazi et al., 2006) 42
Table 3 utilization of commercial airplanes (Roskam, 2002) 63
Table 4 parameter table 66
Table 5 interpolation of UNMC/SMC 68
Table 6 parameter table for Interval-based Method 78
Table 7 aircraft loads adapted from (Neubauer, 2000) 82
Table 8 inspection planning for damage phase (Goranson, 2007) 83
Table 9 representation and application of operational conditions (Schmidt et al., 1995) 84
Table 10 loads on the aircraft at, GAG (schmidt et al., 1995) 84
Table 11 A30 load matrix for cruise flight, GAG spectrum (Schmidt et al., 1995) 85
Table 12 constants for different type of composite materials (Mallick, 2007) 86
Table 13 the operation and design parameters used as input for MC of A330-200 91
Table 14 parameter list table for A330 rudder SMLC and UNMLC 95
Table 15 parameter list table for A330 rudder for SMMC and UNMMC 97
Table 16 parameter list table for A330 rudder SMLC (IBM) 104
Table 17 annual maintenance labor cost for rudder parts 104
Table 18 aircraft life maintenance cost for rudder parts 104
Table 19 rudder maintenance cost by several task types 106
Table 20 rudder parts with associated materials and failure modes (Homan, 2008) and (Kassapoglou, 2010) 110
Table 21 failures of spar 121
Table 22 typical composite skin failures under moment/forces 125
Table 23 parameters and values for lateral gust load determination 126
Table 24 parameter list for asymmetric thrust 128
Table 25 parameter list for sudden max rudder input load estimation 129
Table 26 loads on the rudder of A330 129
Table 27 parameter list for maintenance interval determination with inputs and outputs 130
Table 28 speed of sound and frequency range for different sandwich materials 132
Table 29 parameter table for maintenance intervals 134
Table 30 maintenance inspection variables expressed in years 134
Table 31 verification table for variables used in weight estimation 136
Table 32 verification data table for maintenance cost results 136
Table 33 verification table of the maintenance cost 137
Table 34 parameter list table for variables and equations used to verify the results 138
Table 35 A330-200 operational parameters (IATA, 2013) 139
Table 36 variables categorization into design pts and operation pts 142
Table 37 validation by Roskam and van der Velden method A and B 142
Table 38 variables and equations used for verification by Method 2 144
Table 39 AF growth rate for airframe by Rand (Dixon, M, 2006) 146
Table 40 number of load cycles to failure for three different failure modes 150
Table 41 threshold and subsequent maintenance inspection intervals 151

Table 42 AIM results 153
Table 43 annual maintenance inspection labor cost of IBM by material categorization 154
Table 44 annual maintenance inspection labor cost of IBM by MSG-3 task categorization 154
Table 45 weight ratio of several civil airplanes (Elham, 2013) 166
Table 46 ratio of each OEW sub-group to MTOW (Elham, 2013) 167
Table 47 number of loads occurrence during take-off and landing (Wells, 1956) 175
Table 48 types of loading and frequencies 177
Table 49 A330 load spectrum for A330 rudder 177
Table 50 structures maintenance task rudder A330, source (Airbus, Maintenance Planning Document (MPD), 2006) 178
Table 51 Zonal Maintenance tasks rudder A330, source (Airbus, Maintenance Planning Document (MPD), 2006) 179
Table 52 System & Component 179
Table 53 spar tasks 182
Table 54 rib tasks 182
Table 55 skin tasks 183
Table 56 actuator attachment tasks 183
Table 57 hinges & actuator fittings/bearing 183
Table 58 hinge arm 184
Table 59 autopilot and flight direction tasks 184
Table 60 mechanical control 185
Table 61 hydraulic actuation 185
Table 62 yaw damper actuation 186
Table 63 electrical flight control 186

1 Introduction

Aircraft maintenance is overhaul, repair, inspection or modification of an aircraft or its component (Ghobbar, 2010), is an indispensable process within aircraft operation. The maintenance cost of a commercial aircraft has a contribution of 10-20% to the Direct Operating Cost (DOC) of an airliner (Wu et al., 2004; IATA, 2013 and Kinnison, 2004). The goal of aircraft maintenance is to provide a fully serviceable aircraft when required by an airline at minimum cost. In the beginning of aviation, maintenance was performed as a ‘’necessary’’ action and the machines and tools required often several hours of maintenance time for every hour of flying. The modern aircraft needs more sophisticated maintenance program to achieve the maintenance goal along with airworthiness regulations. The initial maintenance program is developed during the aircraft design phase. Safety, airworthiness, maintainability and economics are the main trade-off factors of the maintenance program development. A derivative of an existing aircraft maintenance model is often used to determine the maintenance program (Kinnison, 2004). About 70-85% of commercial aircraft Life Cycle Costs (LCC) are determined during the design stage (Wu et al., 2004). And the maintenance cost takes around 15% of LCC (Suwondo, 2007; IATA, 2013). The present day market scenario drives the airlines to reduce their LCC (PeriyarSelvam et al., 2013). Therefore, for an airline it is necessary to know in detail how the maintenance cost is established from both airline operation perspective and design parameters within the scope of LCC. The design parameters such as material and geometry can be the drivers which influence the maintenance cost and the aircraft choice of the airlines.

The purpose of this master thesis is to provide a methodology that estimates maintenance cost and provide information how the maintenance cost is related to operation and design parameters.

It is hypothesized that the *adjustment of the design parameters of an aircraft, such as materials will result in less maintenance cost within the scope of life cycle cost comparing to the present (metal) aircraft.*

In order to develop the methodology, several aircraft maintenance cost estimation methods are analysed and adapted to build a Maintenance Cost Estimation Model (MCEM). The corresponding MCEM estimates the scheduled and unscheduled maintenance cost for Design Service Goal (DSG) of an aircraft with incorporating the aging factor. In this research the DSG is assumed to be 20 years. Further, the influence of a composite part as a design variable is analysed with regarding the maintenance cost. The limiting conditions in this research are the lack of real life data about the maintenance cost for an aircraft part, i.e rudder or wing, to validate the developed methodology. The results provided by the model are verified and validated by adapting other maintenance cost estimation methods and using IATA’s Maintenance Cost Task Force (MCTF).

In the coming chapters (2-8) the structure of the thesis is presented. In chapter 2 the research aims, motives and objectives are discussed and research question and sub-questions are

established. In chapter 3, the relevant literature concerning the topic is in short reviewed. Hereafter in chapter 4 the framework of maintenance cost model is discussed. In chapter 5 the methodology of the maintenance cost model is developed. Subsequently the developed methodology is applied in chapter 6 as a case study to obtain results. Chapter 7 provides verification and validation for the developed methodology and the results obtained in case study chapter. And finally, in chapter 8 conclusions are drawn and recommendations are given for further research.

2 Research Scope

The variation in aircraft design concept has significant impact on maintenance cost associated with material and structural innovations (Ilcewicz et al., 1991). Low production cost and high throughput are characterized in aerospace industry but is it also cost effective at the maintenance phase? The aircraft producers have realised that cost reduction needs to be tackled at the design stage (Thokala, 2009 and Curran et al., 2004). Awareness of the maintenance processes and maintenance costs during the design phase can lead to wiser decisions regarding aircraft maintenance (Knezevic, 1997). If the aircraft operators are aware about the maintenance cost and maintenance ease of an aircraft, a better trade-off can be made between alternative aircraft by arranging their fleet. The design parameters such as geometry and/or material could have direct effect on the maintenance costs (Thokala, 2009 and Kaufmann, 2008). Considering composites as design parameter, it can be seen that the usage in aviation is increasing. In the beginning, late 80s, the composites were used in secondary aircraft structures and now more and more primary structures are built with composites (Flynn et al., 1997; Fox et al., 2005; Deo et al., 2003; Walker et al., 1997 and Kassapoglou, 2010). Current examples are, the structure of Airbus A380-800 exists of 23% composites, the A350XWB has 53% composite structure and the Boeing's Dreamliner 787 has 50% structure weight consisting of composites (Thevenin, 2011). In academic literature the benefits of composites as potential weight in commercial airplanes are reviewed (Kaufman, 2008; Flynn et al., 1997; Thevenin, 2011 and Raman et al., 2003). But what is the relation between composite, as design parameter and maintenance cost? This leads to **the problem definition** of the MSc thesis: what are the consequences of this design parameter, i.e. composites, on the maintenance cost considering aircraft life? In fact, a methodology can be developed together with a maintenance cost model in order to provide the in-depth understanding, within the scope of Life Cycle Cost (LCC) of an aircraft.

Thesis objective: The desired result of this study is a maintenance cost estimation methodology within the life cycle cost, which could be used to show design parameters influence on maintenance cost.

The Research Question that has to be answered is as follows:

How to develop the maintenance cost model, considering essential design parameters?

Several sub-questions are constructed to approach the research question, these **sub-questions** are:

1) *What are the current aircraft/components maintenance processes?*
2) *What are the current maintenance cost estimation methods?*
3) *What are the maintenance cost driving parameters?*
4) *What are the essential design parameters that affect the maintenance cost?*
5) *How are those maintenance cost driving related to the design parameters?*
6) *In what extent does the change in design affects the maintenance process, therefore further affects the maintenance cost?*

After stating the research objective, research question and sub-questions, the **hypothesis is proposed**: *Changing the design parameters of an aircraft, such as implementation of composite materials will result in less maintenance cost than the conventional (metal) aircraft.*

Research Content

In order to provide an answer to the research question, the process of this research is shown in the pyramid graph, Figure 1. The pyramid has 5 steps, it starts at analysing the maintenance processes and it ends at results obtained from the MCEM (down to top process) and providing answers to the research question. At the end, either the hypothesis is accepted or rejected.

Step 1: Maintenance processes

At the 1st step the aircraft and aircraft component maintenance processes are analysed. The differences between old (MSG-2) and current (MSG-3) maintenance philosophy are evaluated. Also, the impact of these processes on maintenance cost is analysed. The questions should be answered during this process are: what is the main reason for adapting or introducing a new maintenance policy, what is the role of design parameters during this transition and how are the airlines affected by maintenance process modification.

Step 2: Maintenance Cost (MC) estimation method and MC driving parameters

The second step in the pyramid research is the analyses of the MC estimation methods and MC main cost drivers. In this step several cost estimation methods are investigated. In addition, more specific, existing maintenance cost estimation methods are elaborated. The cost estimation methods for scheduled maintenance and unscheduled maintenance are analysed separately. The main cost drivers are highlighted.

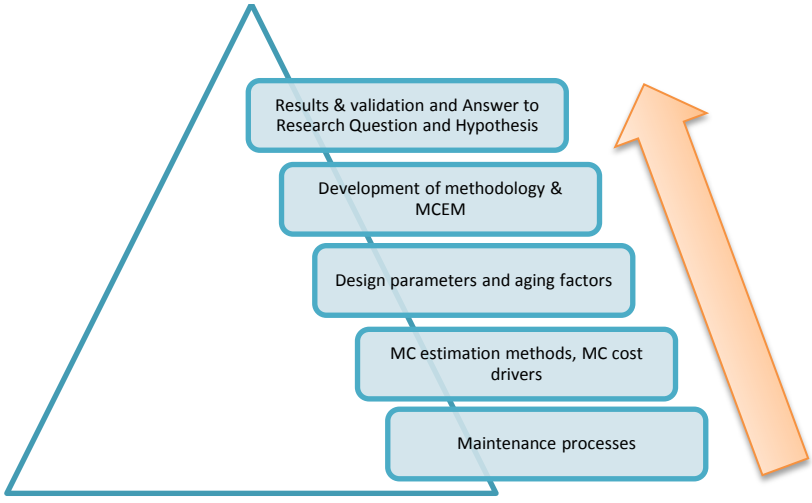


Figure 1 the pyramid of the MSc research

Step 3: Design parameters and Aging Factor (AF)

In this step the influence of design parameters to maintenance process are investigated. General rules and mathematical equations are constructed. The influence of aircraft age on the maintenance cost is analysed. The aging factor versus aircraft life is investigated. A relation should be found, to show how the design parameters together with aircraft age affect the maintenance cost of an aircraft, during service life of 20-years.

Step 4: Methodology & Maintenance Cost Estimation Tool development

Findings from steps 1-3, Maintenance process, MC estimation methods and design parameters & AF are incorporated in a solid methodology regarding maintenance cost. The constructed equations that are built in the methodology are used to develop a model in EXCEL to perform maintenance cost calculations for scheduled and unscheduled maintenance. The influences of composite as design variable and aging factors are also incorporated in the methodology and the model.

Step 5: Results & validation

The constructed equations and methods are performed on a case study, the rudder of A330-200 to obtain results. The results are validated by using other cost estimation methods and experts judgments (KLM). Finally, the research question will be answered and the hypothesis is whether accepted or rejected.

3 Literature Review

In this chapter the relevant academic literature related to the maintenance processes, maintenance cost, the influence of the composite material on the maintenance cost and maintenance cost estimation methods are elaborated. This chapter consists of 5 sections. In section 3.1 the literature concerning cost estimation methods is discussed. In section 3.2 elaboration of maintenance process is shown. Section 3.3 discusses the maintenance cost decomposition. In section 3.4 the composite materials in aerospace are reviewed. The relevant literature that shows the influence design on maintenance is reviewed in section 3.5.

3.1 Cost Estimation Methods

Thokala (2009) defines cost estimation as a process of predicting the cost of a product before all stages of the product development has been executed. Niazi et al. (2006) and Thokala (2009) categorize the cost estimation methods into Qualitative cost estimation techniques and Quantitative cost estimation techniques. *Qualitative cost estimation techniques* are primarily based on a comparison analysis of a new product with the products that have been manufactured previously in order to identify the similarities in the new one. By analysing the similarities, the past data can be incorporated into the new product in order to estimate the costs. The past experience and/or the past design and manufacturing data of an estimator can be used to generate reliable cost estimates. Historical design and manufacturing data for products with known costs may also be used systematically to obtain cost estimates for new product. *Quantitative techniques*, on the other hand, are based on a detailed analysis of a product design, its features, and corresponding manufacturing processes instead of simply relying on the knowledge of an estimator. Therefore, costs are either calculated using analytical function of certain variables representing different product parameters or as the sum of elementary units representing different resources consumed during a whole production cycle. Curran et al. (2004) classifies the cost estimation methods differently. The authors distinguish two types of estimating techniques: (i) Classic estimating technique and (ii) Advanced estimating techniques. Classic techniques are divided into: analogous, parametric and bottom-up estimating techniques. The advanced estimating techniques: Feature-based modelling, fuzzy logic, neural networks, uncertainty and data mining.

Maintenance Cost Estimation Methods

The literature regarding aircraft maintenance cost estimation varies by airline. For example, most of the generated maintenance cost estimation methods are created by using historical data. The historical data that has been used could be airline operations dependent and is often confidential and therefore the method is not published. Xinguang et al. (n.d) analyses the maintenance cost estimation methods and their application in a certain area. The authors also present a cost estimation methods development in aviation. The Boeing company estimates the maintenance cost by using a derivatives of the method ‘’A new method for estimating current and future Transport Aircraft Operating Economics’’ (Khawaja, 2014). This method addresses aircraft related operating cost elements and is based on an in-depth examination of airline operating experiences and relevant operating data. The estimate is based on design features such as take-off gross weight, seat capacity, design range and number of engines

(American Airlines, 1978). The Airbus method described by Wu et al. (2004) calculates Direct Maintenance Cost (DMC) by using maintenance man hour, labor rate and material cost. ‘’The Engineering Method’’ discussed by Suwondo (2007) counts the cost of every item by using of work breakdown structure from bottom to top, and the cost estimating value is gained by accumulating all cost items in the whole maintenance work. It sums all kind of cost for every part or subsystem in each phase such as development, production, operating and support. Addition of the costs results to the total costs based on Cost Breakdown Structure (CBS). Salamanca et al. (2005) describes a method in which the maintenance costs are subdivided into basic expenses units, and then the final cost can be added from bottom to top. To use this method the program flow of the maintenance action should be known. For example, on an engine shop visit, the program flow is divided into three steps: *1) Module cost estimating, 2) labor cost and 3) total costs of a shop visit.* Addition of all the costs in every step results in total maintenance cost for an engine and/or engine component. Wagner and Fricke (2006) established a method to estimate the daily unscheduled line maintenance cost for components. For their estimation they used the power law model. Bruinsma (2009) and Bruigidou (2007) estimates the unscheduled maintenance cost by using Pilot Report (PiReps), Maintenance Report(MaReps), Line Maintenance Cost (LMC), Flight Cycles (FC) and Flight Hours (FH) as input. Liebeck et al. (1995) established general equations, in there NASA contractor report, to estimate airframe labor maintenance cost, material maintenance costs, engine maintenance costs and burden maintenance costs. This method is also called DOC+I (Direct Operating Cost plus interest). The equations are valid for the modern subsonic commercial aircraft. The equations uses manufactures empty weight less the dry-weight of engine, labor rate and engine thrust as inputs. The maintenance costs are calculated per FC and per FH. Liebeck’s equations are adapted by Ross (1998) and applied for wide body aircraft. Later the method is used by Southampton University (2004) to estimate the Direct Operating Cost (Southampton University, 2004). Schaufele et al. (2011) adapted the Liebeck equations by adding the rapid increase in inflation of 1993-2009. One of the arguments of the author is the increased inflation with respect to airline labor cost per unity of productivity. Concerning material cost, Zorgdrager (2013) attempts to provide forecastability in the non-routine material demand by analysing the historical consumption data of parts for certain maintenance tasks, aircraft operational factors and the maintenance program. The probability of material demand and average part quantity per maintenance tasks and material forecast are investigated.

3.2 Maintenance Process

Kinnison (2004) defines maintenance as ‘the process of ensuring that a system continually performs its intended function at its designed-in level of reliability and safety’. Homan (2008) gives slightly different definition of maintenance: ‘All activities subjected to technical systems to be kept in the condition (preventive) or to be brought in the condition which is required to fulfil specified functions’. The need for maintenance is discussed by Kinnison (2004), the author compares maintenance with the process of entropy. The entropy is always increasing as function of time and so are the systems irregularities. This is due to imperfections of the physical world which makes building of a perfect system impossible. A system will degrade in performance through its service life and eventually the system will

break down. Kinnison (2004) shows graphically how the level of reliability is related to service time of a product, Figure 2.

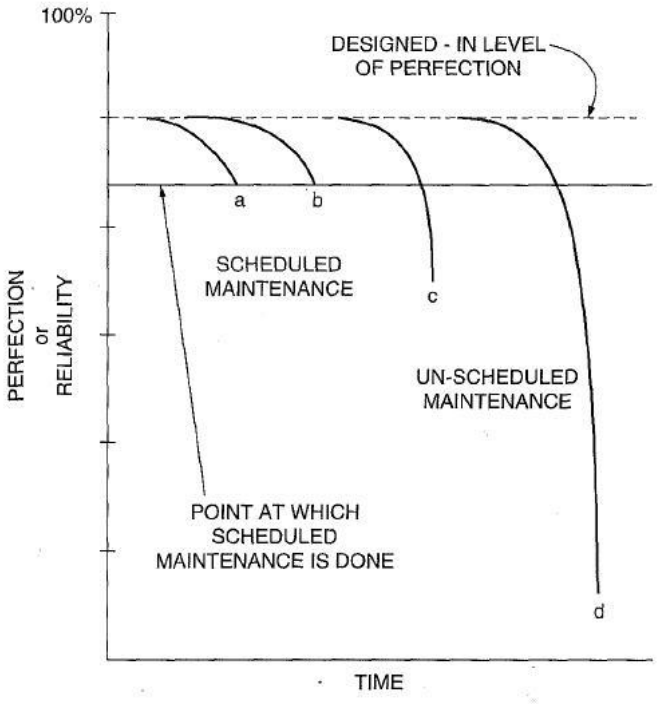


Figure 2 (un)scheduled maintenance reliability vs. service time (Kinnison, 2004)

In Figure 2 the natural decaying process of an item is given with scheduled an unscheduled maintenance at a certain point of time (horizontal axis). The vertical axis represents the item's reliability. As it can be seen from the figure the top of vertical axis, the level of perfection or level of reliability is never reached at 100%. The top horizontal dash line is the designed level of perfection and the second horizontal line with points a and b depicts the points in time when scheduled maintenance should be performed. After the scheduled maintenance with fixed time intervals, the system is restored back to the ''designed in level of perfection''. However, in some cases the system could degrade faster than predicted due undesired circumstances, curve c and curve d. In these cases the system should be restored in a not predetermined fixed time interval to restore the system to the designed level of perfection. In this case the unscheduled maintenance should be performed. The standard developed for aircraft maintenance is described below.

Maintenance Steering Group (MSG) program

In 1968 the Boeing Company started the modern approach to develop maintenance program for the 747 airplane. It was seen as a new era in aviation, the jumbo jets era. Boeing felt that this new era should begin with a more sophisticated approach for maintenance program development due to increase in aircraft complexity (Kinnison, 2004). Teams were organized with representatives from Boeing design and maintenance program groups along with representatives from suppliers, airlines and FAA. Six industry working groups were involved: structures, mechanical systems, engine and auxiliary power plant (APU), electrical and avionics systems, flight controls & hydraulics and zonal. Each group addresses their specific systems in the same way to develop an adequate initial maintenance program. An item is

analysed by using a logic tree to determine its requirements (MSG-1). The MSG-1 developed for 747 was successful, and the approach was modified to MSG-2 for other aircraft such as Lockheed L-1011 and McDonnell-Douglas DC-10 airplanes in 1972. In 1979 the Air Transport Association (ATA) improved MSG-2 into MSG-3 for the new generation aircraft such as 757 and 767. The MSG-2 and MSG-3 are discussed below.

The *MSG-2* is a bottom up approach whereby a component of an aircraft is examined and assigned to one of the primary maintenance processes, Hard-Time (HT), On-Condition (OC) and Condition-Monitoring (CM) (Ghobbar, 2010; Ackert, 2010 and Kinnison, 2004).

Ghobbar (2010) describes the primary maintenance processes (MSG-2) as follow:

Hard-Time: this is defined as a preventive process in which deterioration of an item is limited to an acceptable level. The maintenance actions are carried out periodically according to time in service. This time may be the calendar time, the number of cycles, or the number of landings. For example: engine disks, flap links, and landing gear parts are typical Hard-Time replacement items.

On-Condition: this is also a preventive process, but one in which the item is inspected or tested at specified periods to an appropriate standard in order to determine whether it can continue in service. Typical examples of On-Condition applications are: NDT tests for hydraulic and pneumatic systems, Borescope checks on internal engine parts, and visual inspections on structural items.

Condition-Monitoring: this is not a preventive process, having neither hard-time nor on-condition elements, but one in which information on items is collected from operational experience, then analysed and interpreted on a continual basis as a means to implement corrective procedures. All electronic components and most of the complex electrical or mechanical units are normally part of the CM process.

The *MSG-3* is a task-oriented approach. It uses predetermined maintenance tasks to avoid in-service failures. By using equipment redundancy in-service failures and allowing them to occur without affecting safety and operation. A reliability program is used for certain components or systems whose failure rates are not predictable and for those that have no scheduled maintenance tasks. The current method, MSG-3 is used for developing the scheduled maintenance tasks and intervals which will be acceptable to the a) Manufacturers, b) Regulatory authorities and c) Operators. ATA (1993) provides the MSG-3 content with specified rules, regulations and terminology. Ackert (2010) discusses the shortcoming of MSG-2 comparing to MSG-3:

- MSG-2 did not distinguished maintenance being done for safety reasons and economic reasons
- MSG-2 could not deal effectively with the increasing complexity of aircraft systems
- MSG-2 was to abstract and difficult to manage because it required too many components to be individually tracked
- MSG-2 did not address regulations related to damage tolerance and fatigue evaluation of structures; these are currently accounted for in Corrosion Prevention and Control

Programs (CPCP) and requirements mandated through an Aging Aircraft maintenance program. Primarily due to these shortcomings of MSG-2 the MSG-3 is developed for more complex aircraft, jumbo jets.

In Figure 3 the MSG-3 and MSG-2 logics are reviewed.

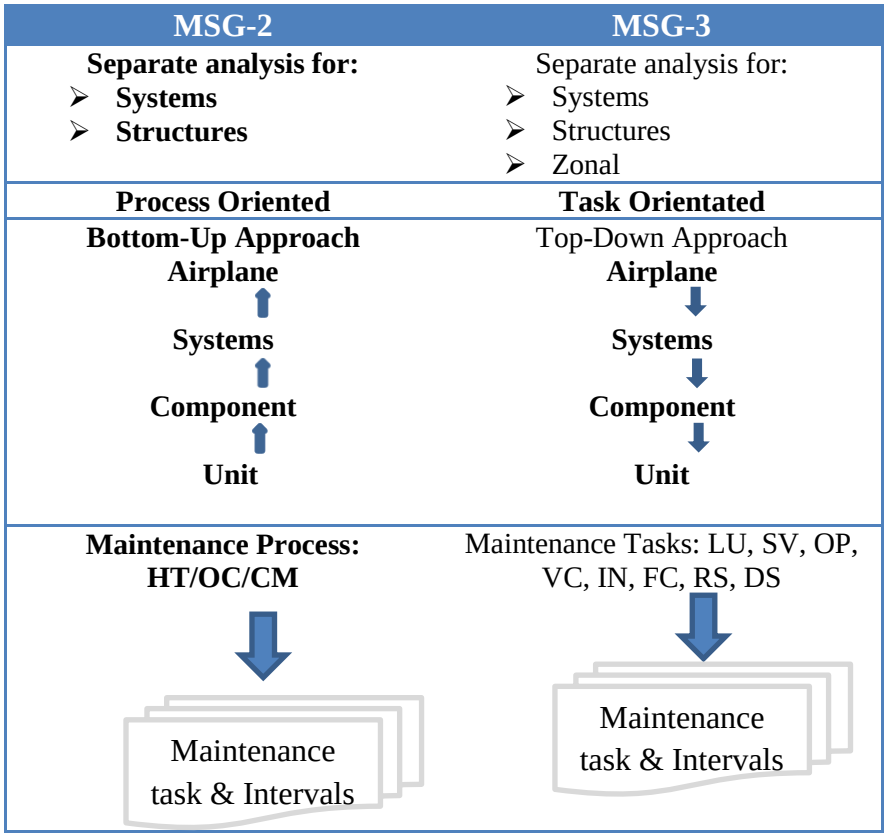


Figure 3 MSG-2 vs. MSG-3 Decision Logic Process (Ackert, 2010)

The terms used in the logic diagram are:

- Lubrication (LU), an act of replenishing oil, grease, or other substances used for the purpose of maintaining the inherent design capabilities by reducing friction and/or conducting away heat.
- Servicing (SV), an act of attending to basic needs of components and/or systems for the purpose of maintaining the inherent design capabilities.
- Operational check (OP), a task to determine if an item is fulfilling its intended purpose. This is a failure-finding task and does not require quantitative tolerances or any equipment other than the item itself.
- Visual check (VC), an observation to determine if an item is fulfilling its intended purpose. This is a failure-finding task and does not require quantitative tolerances.
- Inspection (IN), an examination of an item and comparison against a specific standard.
- Functional check (FC), a quantitative check to determine if each function of an item performs within specified limits. This check may require use of additional equipment. The inspection checks to test functionality are: (i) general visual inspection (visual inspection by human eye),

(ii) Detailed inspection (an intensive visual inspection of a specified detail, assembly or installation using adequate lighting, where necessary inspection aids such as mirrors, hand lenses etc.). (iii) Special detailed inspection (an intensive examination of a specific location with special techniques such as non-destructive inspections (NDI).

- Restoration (RS), the work necessary to return the item to a specific standard. Restoration may vary from cleaning the unit or replacing a single part up to and including a complete overhaul.
- Discard (DS), the removal from service of any item at specified life limit.

Airbus (2006) uses this kind of inspection in Maintenance Planning Document (MPD) to make distinguish between several inspection types. Khwaja (2012) shows the Boeing's IP-44 using MSG-3 tasks and in-service failures to optimize the maintenance planning. The maintenance process is optimized with a continuous feedback from the partner airlines. The author shows that a MPD of an aircraft can be optimized and that could result in cost savings. Knotts (1999) categorizes two types of maintenance processes, the scheduled maintenance (preventive) and un-scheduled maintenance (corrective). *Preventive maintenances* are the actions performed at defined interval to retain an item in a serviceable condition by systematic inspection, detection, replacement of wear out items, adjustment, calibration, cleaning etc. This type of maintenance is carried out at prescribed points in an aircraft's life and equipment's life and is termed scheduled maintenance.

Corrective maintenance is all the actions performed as a result of failure. In this case an item is restored to a satisfactory condition by providing correction of the analysed malfunction and or defect. This type of maintenance may include one or more of the following steps: defect location, defect isolation, disassembly, replacement, reassembly, alignment/adjustment, and testing. This type of maintenance is known as unscheduled maintenance. Homan (2008) gives slightly different definition for preventive (scheduled) and corrective (unscheduled) maintenance. Preventive maintenance: actions before the functional failure of an aircraft or an item. And corrective maintenance: actions after functional failure.

Aviamech (2011) shows the maintenance program development of a new aircraft from scheduled maintenance triggers (maintenance scheduled, calendar time, FH, FC and landings) and unscheduled maintenance triggers (Airworthiness Directives (ADs), Service Bulletins (SBs), modifications, Defects arising and special events), Figure 4

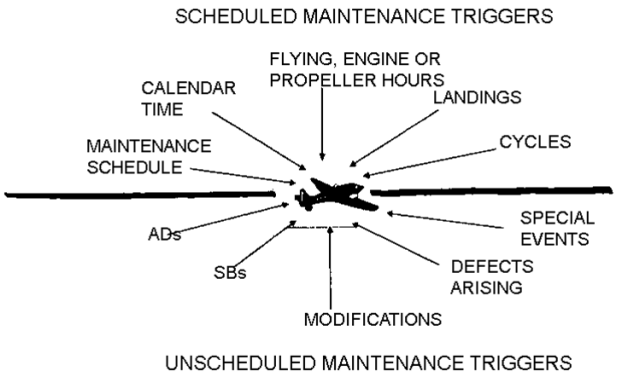


Figure 4 maintenance triggers (aviamech, 2011)

Muchiri (2002) shows graphically how an Operator Maintenance Program is developed for Transavia airlines. Goranson (2007) discusses how the working groups evaluate the Maintenance Significant Items. (Airbus-MDP, 2006) Explains the content of a MPD how it can be read. Homan (2008) discusses the four basic maintenance tasks which are used for initial maintenance program. In more detail, the tasks are Scheduled Inspection, Scheduled Rework (overhaul), Scheduled Discard (replacement) and Scheduled Failure Finding. The scheduled failure findings are certain type of inspection to find 'hidden failures' of a system, see Appendix B for the graph. The source of MSG-3 which comes from the predefined Maintenance Significant Items (MSI) and Structural Significant Items (SSI) are more in detail explained by Homan (2008). Classification of parts or items whether in MSI or SSI are done by a decision tree.

The Maintenance Checks

The tasks defined through the maintenance development process are allocated into scheduled work packages. Tasks with similar intervals are grouped into a certain number of maintenance packages. Each task has its own interval. For the commercial aircraft these intervals range from daily walk-around checks to service checks performed at base maintenance station. In commercial aviation industry these checks are: A-Check, (B-Check) C-Check and D-Check (EUROCONTROL, 2008)

A-Check usually consists of a general inspection of the interior/exterior of the aircraft with certain selected areas. Duration is from biweekly to monthly. Some examples of the A-Checks are: checking and servicing oil, replacement of the filter, lubrication, operational checks (does the equipment meet the intended purpose) and inspections.

C-Check, depending on the operator, airplane type and utilization, is typically scheduled every 12-20 months. Examples of C-check are: functional (quantitative check for an item, whether it meets certain specified accuracy level) and operational system checks, cleaning and servicing, attendance to minor structural inspections and Service Bulletin (SB) requirements.

D-Check or Heavy Maintenance occurs 6-12 years. It is again depending on the airplane type and utilization. By a D-Check the aircraft is taken out of service for several weeks. During

this check the exterior paint is stripped and large parts of the outer panelling are removed, uncovering the airframe, supporting structure and wings for inspection of most SSI. In addition, many of the aircraft's internal components are functionally checked, repaired/overhauled or exchanged.

In Table 1 the maintenance checks are summarized, the location, description (MSG-3 tasks), the duration and the interval of the checks are given.

Table 1 the maintenance checks (EUROCONTROL, 2008)

Check	Location	Description	Duration	Interval
Line/transit	At gate	Daily (before first flight or at each stop when in transit). Visual inspection: fluid level, tires and brakes, emergency equipment. MSG-3 tasks: LU,SV,VC	≈ 1 hour	After the landing before the takeoff
A	At gate	Routine light maintenance: engine inspection MSG-3 tasks: LU,SV,VC, OP	≈ 10 hours whole shit/overnight	every 500 - 800 flight hours or 200 - 400 cycles
B	At gate	If carried out, similar to ''A'' Check but different tasks (may occur between consecutive A checks). MSG-3 tasks: LU,SV,OP,VC,IN,FC,RS,DS	≈ 10 hours to ≈ A day	Every 4-6 months
C	Hangar	Structural inspection of airframe, opening access panels, routine and non-routine maintenance, run-in tests. MSG-3 tasks: LU,SV,OP,VC,IN,FC,RS,DS	≈ 3 days to ≈ 1 week	12 to 20 months
D	Hangar	Major structural inspection of airframe after paint removal, engines, landing gear and flaps removed instruments electronic and electrical equipment removal, interior fittings (seats and panels) removed, hydraulic and pneumatic components are removed. MSG-3 tasks: LU,SV,OP,VC,IN,FC,RS,DS	≈ 1month	6 to 12 years

Ackert (2010) pointed out that every aircraft operator can establish their own maintenance program, which could deviate from the manufacturer, if the airworthiness authorities accepted their maintenance program proposal, so called Operator Approved Maintenance Program (OAMP). This is shown in Figure 5. As it can be seen the OAMP is established not only with MPD but also with Local regulations, Vendor Manuals, Airline Tasks, Airworthiness Directives (AD), Service Letters, and Service Bulletins. Moreover, each individual airline has final responsibility to decide what to do and when to do as far the maintenance requirements are taken into account.

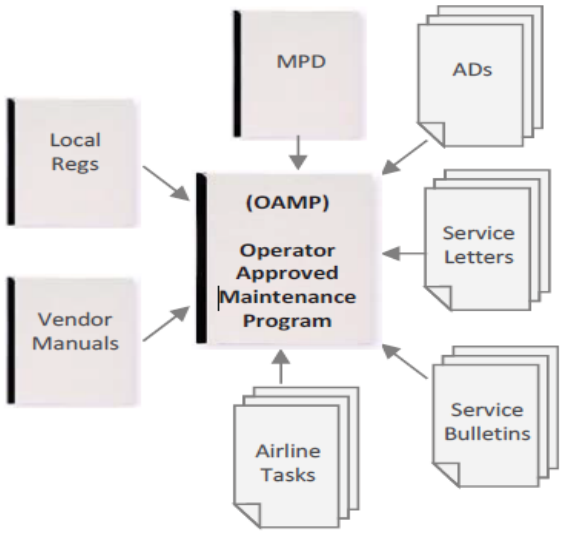


Figure 5 OAMP establishment (Ackert, 2010)

Further Khwaja (2012) mentioned that Boeing's IP-44 which is based on ''statistical intervals''. IP-44 is an optimized maintenance program of Boeing introduced in 2008. In this aircraft maintenance philosophy, the MSG-3 tasks are used with comprehensive data set regarding scheduled and unscheduled maintenance and the maintenance program is optimized in order to reduce maintenance cost. IATA (2013) Maintenance Cost Task Force provides the real-life maintenance costs for several types of aircraft. In this study, 46 airlines participated with a total of 4105 aircraft.

3.3 Maintenance Cost

As stated before, the common goal of the maintenance process is to provide a fully serviceable aircraft by an airline at minimum cost. At present, maintenance cost of a commercial aircraft makes a significant contribution to an aircraft cost of ownership. Maintenance costs typically account for 10-20 % of aircraft operating costs (Wu et al., 2004). Ghobbar (2010), Khwaja (2012), Kinnison (2004), Suwondo (2007), Wu et al. (2004) and Dixon (2006) decomposes Total Maintenance Costs (TMC) into Direct Maintenance Costs (DMC) and Indirect Maintenance Costs (IMC). Direct maintenance costs are the expenditures that are directly performed on the aircraft during the maintenance, meaning the labor and material costs directly performed on the airframe, component and/or powerplant. The indirect maintenance costs are the expenditures which are not directly performed on aircraft during the maintenance. Knotts (1998) makes time breakdown for the maintenance activities in order to analysis how the maintenance time is established.

Figure 6 shows the maintenance process breakdown. Further Knotts (1999) uses the term 'predictive maintenance' for the CM process. The author also shows, for example how predictive maintenance is carried out by either using Hard-Time or On Condition process.

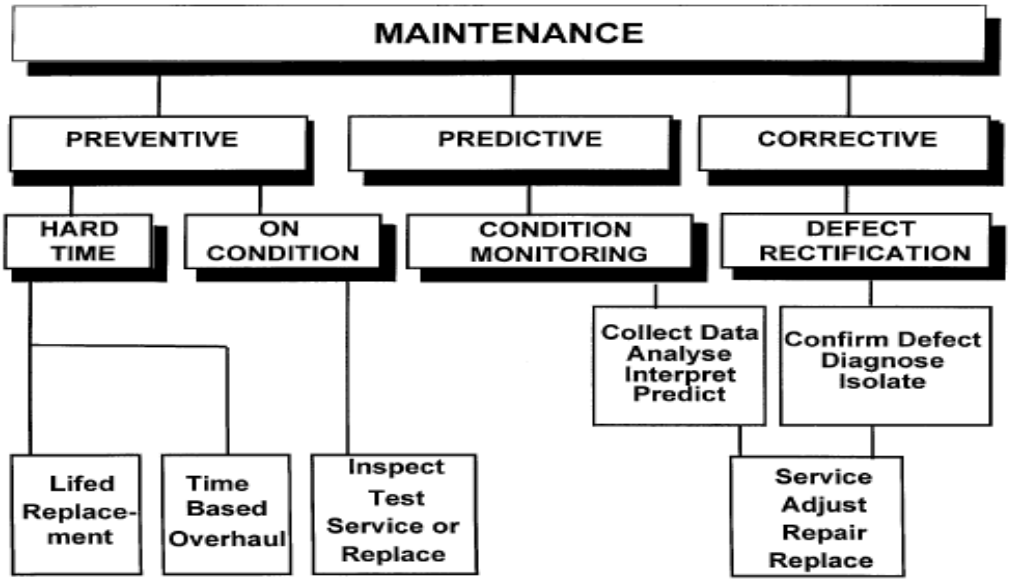


Figure 6 maintenance process breakdown (Knotts, 1999)

In some literature the DMC is broken-down in component maintenance (30%), powerplant maintenance (35%) and airframe maintenance (35%) (Bulato, 2010), see Figure 7

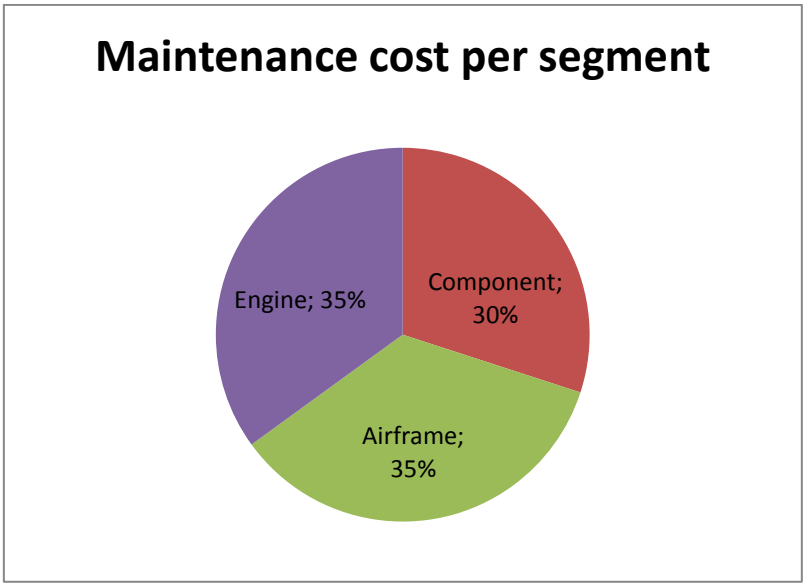


Figure 7 maintenance cost per segment (Bulato, 2010)

Thokala (2009) defines maintenance cost slightly different. The author classifies the maintenance cost into three categories: 1) *variable costs*: costs that vary as a function of utilization and they include fuel costs, labor costs and spare costs. 2) *Fixed costs*: costs include those costs that must be borne by the flight department irrespective of the level of aircraft utilization. These include hangar lease expense, salaries and software services. 3) *Periodic costs*: costs include those overhaul, refurbishment and modernization items, which occur infrequently. The author also made a subdivision of the DMC of an aircraft:

- Airframe

- Engine
- components parts and
- maintenance burden in labor cost, material cost and overhead

Furthermore, the direct maintenance costs can be divided into scheduled maintenance cost and unscheduled maintenance costs (Knezevic, 1997; Knotss, 1999 and Boeing, 2008). The contribution of the unscheduled maintenance cost is higher than the scheduled maintenance costs (Raman et al., 2003). Ghobbar (2008) and Boeing (2008) explains that the unscheduled maintenance costs are higher due to unexpected appearance, the unexpected downtime of aircraft causes higher repair costs, facility costs and spare costs etc.. The unscheduled maintenance cost is dependent on aircraft age (Dixon, 2006; Kinnison, 2004; Suwondo, 2007; Bruinsma, 2009 and Khwaja, 2012).

3.4 Composite Material in Aerospace

In previous section the maintenance cost estimation methods from airline operation perspective are reviewed. In this section and the next section the influence of the design on the maintenance cost is discussed. As state, the composite application as a design parameter is chosen. This section discusses the literature about the composite application in aviation industry, the main advantages and the trends. And the next section, 3.5 the composite material are analysed as a design parameter.

Usually composite materials are made from two or more constituent materials with different material properties. The combined material has different characteristics other than each individual material. The anisotropic property of composites gives the material another character than the metals. More complex designs can be made due to anisotropic material behaviour (Richardson, n.d.). Ilcewicz et al. (1991) identify composite design and manufacturing concepts that have a strong potential for cost and weight savings in aviation. Eaglesham (1998) discusses the early introduction of advanced composites in the aerospace industry. Harris et al. (2001) lists in the NASA report the lessons learned from the composite application in the civil aircraft. Deo et al. (2001) and Raman et al. (2003) argue that composites are used for military aircraft and have potential to reduce life cycle cost. Concerning commercial aircraft, the cost reduction due to application of composite material is mainly in direct operation cost (Deo et al., 2003 and Ye et al., 2005). Furthermore, Deo et al. (2003) shows the trend of composite application in different types of aircraft from various manufacturers till 1995. Fox et al. (2005) analyse the rudder failure of the A300-600 crash. In this case several rudder parts are decomposed and analysed separately. Tenney et al. (2009) discusses in the NASA report the lessons learned and also the future challenges of composites structures in the aerospace till that period. Composite materials are used more and more for the primary structures and not only in the secondary structures (Cairns, 2010 and FAA 2013). However, the composites tend to fail in a different way comparing to metals. New generation large aircraft are designed with composite fuselage and wing structures and repairing of these advanced composite materials requires an in-depth knowledge of composite structures, materials, and tooling. Thevenin (2011) shows the application of composites materials in airbus aircraft. The author discusses in-service experience of composite repairs in current airbus aircraft is discussed. Also the application of composite in new type aircraft like A380 is

shown. FAA (2013) discusses the advantages of advanced composite materials as high strength, relatively low weight, and corrosion resistance. FAA's maintenance technician handbook shows a guide line of how to repair composite materials (US Department of Transportation, 2012). The weight and fuel savings of composites and manufacturing costs are widely discussed in academic literature but there is still less information about their consequence on maintenance cost while there is a clear increase in application of composites in commercial airplanes (Boeing, 2008). Personnel interview with prof. Marissen (2014) reveals that the material storage for the airlines could be the most expensive maintenance activity for the composite maintenance instead of repair time. The same is argued by Thevening (2011) and Tenney et al. (2009).

3.5 Design Consideration in Maintenance Cost Estimation

Kassapoglou (2010) reviews the design and analysis of composite structures. The failure criteria with associated governing equations to predict failure is discussed. The stress-strain equations are provided for composite structural components. The buckling of sandwich structures and plate composite parts, by different types of loadings is analysed. Kassapoglou (2010) states the objective of the structural design process is to create a structure that meets *specific requirements* and has several *desirable attributes*. The design requirements can be: (1) fit, form and function, (2) applied loads, (3) corrosion resistance and resistance to fluids, (4) thermal expansion coefficient placement and (5) frequency placement. *Fit, form and function* the structure has to be designed such that it must fit within the allowable envelope, the intervention with other structure pars should be avoided, must have appropriate material and generic shape to perform its intended function optimally. The structure should also provide attachment points for other structures and if needed also access for intersecting parts such as electrical and hydraulic equipment. *Applied Loads,* the structure that is designed should not fail under expected applied static loads and must have the desired life under applied fatigue loads. In addition, the designed structure must be able to carry certain static and applied fatigue load in presence of damage without affecting the operation safety. *Corrosion resistance, resistance to fluids,* the structure should be designed such to avoid exposure to water or other form of liquids during the service life. *Thermal expansion coefficient placement*, airframe structures are exposed in variant ambient temperature, the structures should be designed such to have low thermal expansion coefficients so that deformations resulting from temperature changes do not compromise the performance of the structure and do not lead to failure. *Frequency placement,* due to vibration of airframe structures with specific driving frequencies, from gusts or engines. The natural frequencies of the main structural modes such as the first few bending and torsional modes must be far from the driving frequencies to avoid deflections and premature failures. Desirable attributes are stated by Kassapoglou (2010) as: minimum weight, minimum cost, low maintenance, irreplaceability across assemblies etc. *Minimum weight,* decreasing the structural weight by increasing the payload weight and or fuel weight. If the increase of payload is not desired the overall size reductions is achieved. *Minimum cost,* this can be the recurring fabrication cost in terms of labor and material and non-recurring cost which will be incurred one time during life cycle cost (development/research). *Low maintenance,* for the customers an attractive attribute to reduce the life cycle cost of the aircraft regarding maintenance cost (inspection, disposition

of problems found and repairs). *Replaceability across assemblies*, it is indirectly dependent with maintenance, means exchanging same parts between two different assemblies without significant rework. It depends on part geometry. This can reduce the repair and maintenance and turn-around time of the aircraft drastically. In Figure 8 a simplified flow diagram of the structural design process is shown. In the figure iteration is shown between specific design requirements and desirable attributes.

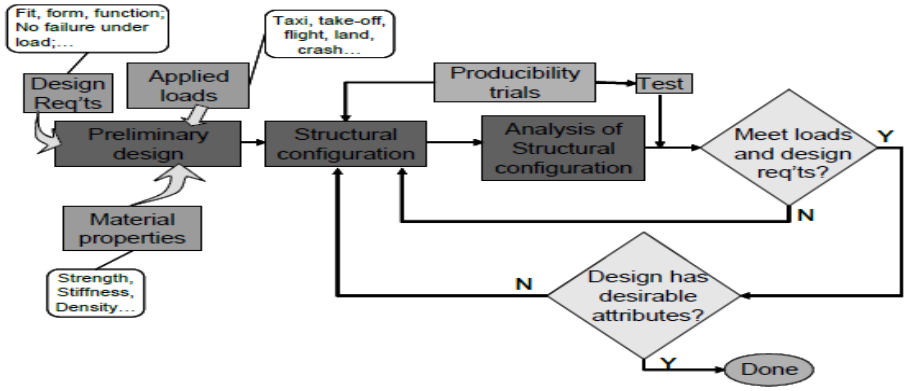


Figure 8 flow diagram of structural design analysis process (Kassapoglou, Design and Analysis of Composite Structures, 2010)

4 Model Framework

In this chapter, the framework of the maintenance cost analysis model is developed based on the studies of the involved modelling techniques in this research. Firstly, the general cost estimation method is classified in Section 4.1. Secondly, the up-to-date maintenance process model is reviewed in section 4.2. Thirdly, in Section 4.3 the maintenance cost breakdown and its influence on Life Cycle Cost (LCC) are extracted. Section 4.4 elaborates couple of aircraft maintenance cost estimation methods. Finally, on the basis of integrating the aforementioned elements, the framework of the Maintenance Cost Estimation Model (MCEM) is introduced in section 4.5.

4.1 General Cost Estimation Methods

In this section various general (product) cost estimation methods are discussed. Cost estimation is defined as the process of predicting the cost of a product before all the stages of the product development have been executed (Thokala, 2009). The classification of cost estimation methods is elaborated as follows; Niazi et al (2006) categorized the cost estimation methods into qualitative and quantitative techniques. *Qualitative cost estimation techniques* are primarily based on a comparison analysis of a new product with the products that have been manufactured previously in order to identify the similarities in the new one. By analysing the similarities, the past data can be incorporated into the new product in order to estimate the costs for example, the past experience and/or the past design and manufacturing data of an estimator can be used to generate reliable cost estimates. Historical design and manufacturing data for products with known costs may also be used systematically to obtain cost estimates for a new product. In general, qualitative methods help obtain rough estimations during the design conceptualization. These techniques can be further categorized into intuitive and analogical techniques see Figure 9.

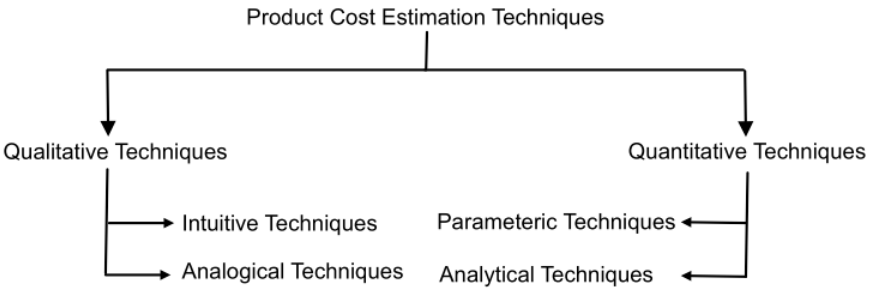


Figure 9 Cost Estimation Methods (source: Niazi et al., 2006)

Quantitative techniques, on the other hand, are based on a detailed analysis of a product design, its features, and corresponding manufacturing processes instead of simply relying on the past data or knowledge of an estimator. Therefore, cost can be estimated using mathematical expressions with variables representing product features with different resources consumed during the production cycle (Niazi et al., 2006). The quantitative methods can be further classified as parametric and analytical techniques see Figure 9.

4.1.1 Qualitative Cost Estimation Techniques

Qualitative Cost Estimation Techniques includes the intuitive and analogical techniques. The intuitive cost estimation techniques are based on using the past experience. A domain expert's knowledge is systematically used to generate cost estimates for parts and assemblies. The knowledge may be stored in the form of rules, decision trees, judgments, etc., at a specific location, e.g., a database to help the end user improve the decision-making process and prepare cost estimates for new products based on certain input information. Niazi et al. (2006) mention two subcategories for the intuitive cost estimation method, see Figure 10.

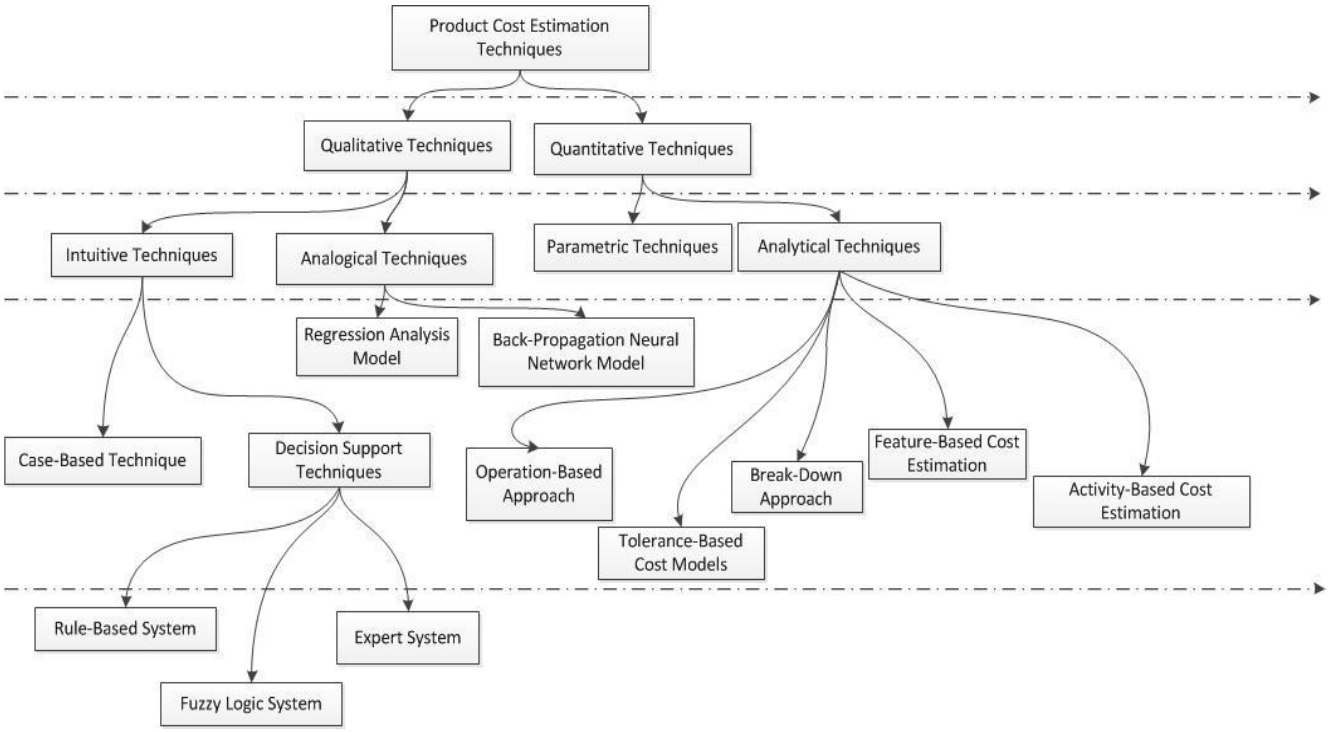


Figure 10 Cost Estimation Techniques (Source: Niazi et al., 2006)

Analogical cost estimation techniques are based on similarity criteria of historical cost data. By knowing the data the estimations can be done.

4.1.2 Quantitative Cost Estimation Techniques

Quantitative Cost Estimation Techniques includes parametric and analytical techniques. Parametric cost estimation techniques are derived by applying the statistical methodologies and by expressing the cost as a function of its variables. This method is effective by knowing the parameters, also called the cost drivers. Parametric cost models are generally used to quantify the unit cost of product.

Analytical techniques decomposes a product into elementary units, operations and activities that represent different resources consumed during the production cycle and expresses the cost as a summation of all these components. This method is subcategorized into five other methods, see Figure 10. In Table 2 all of the cost estimation methods are given again with advantages and limitations.

Curran et al. (2004) classifies the cost estimation method differently than Niazi et al. (2006). The Classification done by Curran et al. (2004) distinguishes two type of estimating techniques: (i) Classic estimating technique and (ii) Advanced estimating techniques. Classic techniques are divided into: Analogous, parametric and Bottom-up estimating techniques. The advanced estimating techniques are: Feature-based modelling, Fuzzy logic, Neural networks, Uncertainty and Data mining.

4.1.3 General Cost Estimation Models

Some cost estimation methods are discussed in common by Niazi et al. (2006), Curran et al. (2004), Catagne et al. (2008) and Thakola (2009). These methods or a derivation of them are often used to generate cost estimation methods. They are summarized in short.

Parametric

Parametric models are derived by applying the statistical methodologies and by expressing cost as a function of its constituent variables. These techniques could be effective in those situations where the parameters, sometimes known as cost drivers, could be easily identified (Niazi et al., 2006). Parametric models are generally used to quantify the unit cost of a given product. According to Castagne et al. (2008), the cost estimation consists of development and application of equations or cost estimation relationships (CERs) that describe the relationships between cost, schedule and measurable attributes of systems. The method is also applied to estimate the cost of design process.

Breakdown Cost Models

According to Niazi et al. (2006), the Breakdown Approach, estimates the total product cost by summing all the costs incurred during the production cycle of a product, including material costs and overheads. The method requires detailed information about the resources consumed to manufacture a product including purchasing, processing, and maintenance details, to estimate the cost for a specific element.

Rule-based Systems

These systems are based on process time and cost calculation of feasible processes from a set of available processes for the manufacturer of a part based on design and/or manufacturing constraints. Such a system reflects these constraints in respective rule class with information in it by an expert in the area. An algorithm is used that helps to establish design and manufacturing constraints. Niazi et al. (2006) shows an example of rule-based algorithm developed for selection and optimization of feasible processes to estimate process time and cost based on parts features.

Feature-Based Cost Estimation

The feature-based cost estimation methodology deals with the identification of a product have cost related features and the determination of the associated costs. These features can be design related such as materials and geometry for specific product. The design features are often used as relational drivers of cost for two reasons, 1) cost functions can be derived for classes of similar objects that serve as key drivers of global cost estimation and are linked to

engineering domain and 2) the designers want to know the cause of cost so that when link to the design features they are able to influence committed cost directly (Curran et al., 2004).

Genetic-Casual Method

Curran et al. (2004) show a methodology to estimate the cost implications of design decisions by integrating cost as a design parameter at an early design stage. The cost estimation model is based on hierarchical basis, the manufacturing cost of aircraft fuselage panels is analysed. The genetic-causal method is used. The drivers of each cost element are identified relative to the process capability. In the model the life cycle cost is computed as a manner of direct operating cost as a function of acquisition cost and fuel burn and coupled with a semi empirical numerical analysis. That was done using the structural integrity of the fuselage shell with respect to material failure and various modes of buckling are determined.

In the model each cost element is computed in relation to its main cost drivers, these being linked to particular genetic identifiers relating to materials, processes and forms. The cost element can be anything that adds cost. The objective is then to define averaged cost equations that depend on the design parameters that do not need detailed analyses at each manufacturing step. The data for the research was collected in the form of bills of material, engineering drawings and engineering process records for the panels that comprise the main fuselage of a regional passenger jet. By using regression analyses the cost equations were developed from the data for each parts family.

Table 2 Cost Estimation Techniques (source: Niazi et al., 2006)

Product Cost Estimation Techniques				Key Advantages	Limitations
Qualitative Cost Estimation Tehcniques	Initutive Cost EStimation Techniques	Case-Based Systems		Innovative Design	Dependence on past cases
		Decision Support Systems	*Rule-based systems*	Can provide optimized results	Time consuming
			Fuzzy logic	Handles uncertainity, reliable estimates	Estimating complex features costs is tedious
			Expert systems	Quicker, more consistent and more accurate results	Complex programing required
	Analogical cost Estimation Techniques	*Regression Analysis*		Simpler method	Limited to resolve linearity issues
		Back propagation neural network model		Deal with uncertain and non-linear problems	Completely data dependant, higher establishment cost
Quantitative Cost Estimation Techniques	Parametric Cost Estimation Techniques			Utilize cost drivers effectively	Ineffective when cost drivers cannot be identified
	Analytical Cost Estimation Techniques	*Operation-based cost models*		Alternative process plans can be evaluated to get optimized results	Time-consuming, require detailed design and process planning data
		Break-down cost models		Easier method	Detailed cost information required about the resources consumed
		Cost tolerance models		Cost effective design tolerances can be identified	Require detailed design information
		Feature-based cost Models		Features with higher costs can be identified	Difficult to identify costs for small and complex features
		Activity-based cost modesl		Easy and effective method using unit activity costs	Require lead-times in the early design stages

4.2 Maintenance Process Model

In this section the maintenance process model is discussed. In the next section maintenance cost as part of aircraft life cycle cost is reviewed (4.3). In sub-section 4.2.1 maintenance program development is discussed and in sub-section 4.2.2 the maintenance planning documents (MPD) is shown by describing the elements of the MPD.

4.2.1 Maintenance Program Development

The tasks selected in the MSG process are published by the airframe manufacturer in an FAA approved document called *maintenance review board* (MRB) report. This report contains the initial scheduled maintenance program (the maintenance checks). The Boeing Company calls their MRB report as Maintenance Planning Data (MPD) and the Airbus calls their MRB document as Maintenance Planning Document (MPD). The documents are often grouped by letter check and by hours, cycles and calendar times. These documents also include information for developing the maintenance program and the planning of maintenance checks. They also provide estimated labor time required for each task (Kinnison, 2004 and ATAA, 1993). This will be reviewed in more detail in sub-section 4.2.2. Development of the MPD is a continuous feedback process between aircraft operators and aircraft manufacturers. An example of aircraft maintenance program is shown in Figure 11. The input of MPD is established by the Industry Steering Committee (ISC). ISC uses the policies and procedures and the analysis of Maintenance Working Groups (MWG) to establish minimum requirements for maintenance tasks. MWG exists of six groups. The working groups of MWG are structures, mechanical systems, engine and auxiliary power plant (APU), electrical and avionics systems, flight controls & hydraulics and zonal. Each group analyses their Maintenance Significant Item (MSI) in the same way to develop an adequate initial maintenance program. An item is analysed by using a logic tree to determine its requirements (Kinnison, 2004). The MWG uses the MSG-3 process to determine adequate maintenance tasks and the task interval for each MSI that are determined by aircraft manufacturer. The output of ISC is provided through Maintenance Review Board Report (MRBR) to MPD. MRBR is the working party of developing the initial minimum maintenance/inspection requirements which form the basis of Operator Maintenance Planning (OMP) (Bulato, 2010). The difference between the MPD and MRB is the labor time and reference of the stated maintenance tasks. MPD provided also the man-hours per task with the reference to Aircraft Maintenance Manual (AMM), or Structural Repair Manual (SRM) or Non-Destructive Testing Manual (NTM). From the output of MPD the operator can establish their own maintenance planning when it is approved by local authorities, as the OMPD.

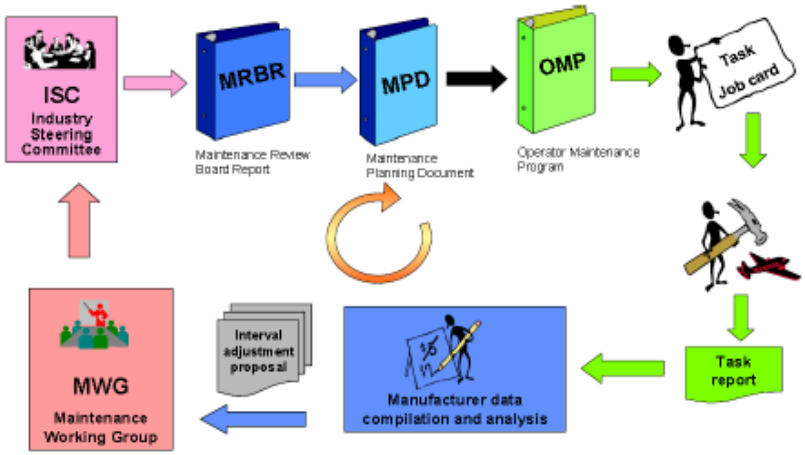


Figure 11 maintenance program evolution process (Bulato, 2010)

Muchiri (2002) shows in Figure 12 how the Transavia's maintenance program is developed for B737-NG aircraft.

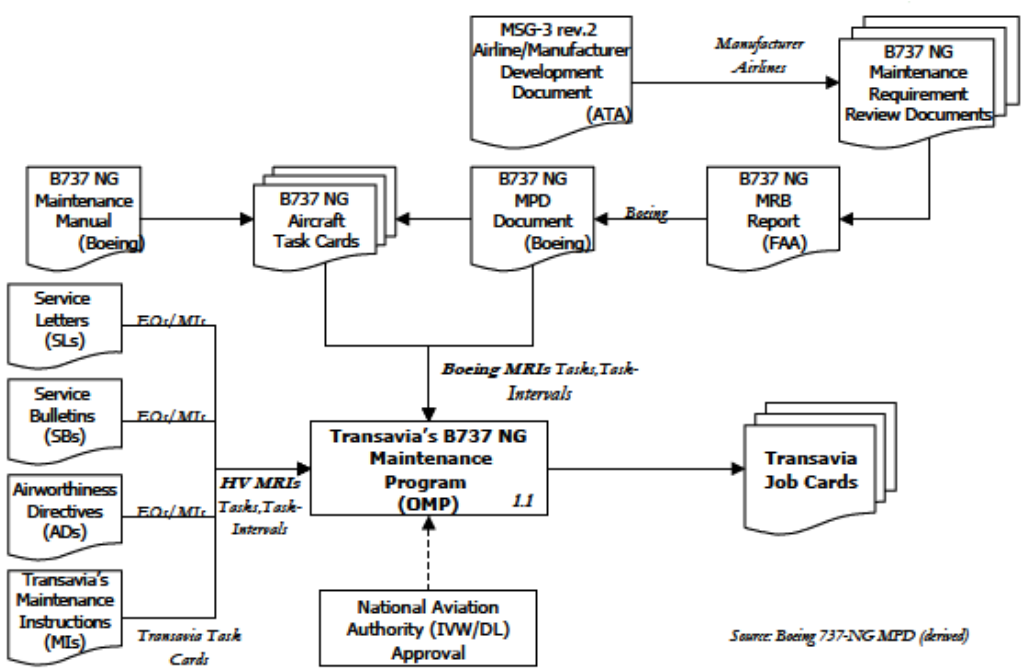


Figure 12 OMP development of B737NG by Transavia (Muchiri, 2002)

As Figure 12 shows the OMP's initial source is the manufactures obligated MPD. The MPD covers all tasks MSI's, tasks determined with the MSG-3 Philosophy. Besides that, the B737NG Task Cards are used as a source to determine Transavia's own maintenance program for B737NG. Service Letters (SLs), Service Bulletins (SBs), Airworthiness Directives (ADs) and Transavia Maintenance Instructions (MIs) form the final steps or provide modification possibilities to the OMP.

SBs and SLs are the manufactures' modification on that product. These modifications could improve the operations, reliability and/or maintenance process of that specific product. The aircraft operator is not compulsory to implement the modification provided by SBs or SLs. On the contrary, the Airworthiness Directives (ADs) are mandatory to be implemented on the aircraft, because the modification is safety related which goes along with airworthiness of the aircraft.

4.2.2 Airbus's MPD Description

The maintenance tasks and their frequencies presented in the MPD for the Systems, APU, Powerplant, Structures and Zonal sections are described as follows (Airbus-MDP, 2006):

- *The Systems, APU and Powerplant Program* sections define the related tasks at the level of individual Maintenance Significant Item (MSI) by considering the failure effects and failure causes.

- *The Structure Program* section defines the necessary inspections for each Structural Significant Item (SSI). The tasks are developed through the evaluation regarding environmental fatigue and accidental damage. In this case a Corrosion Prevention and Control Program (CPCP) is also integrated in the Maintenance Review Board (MRB) and MPD.
- *The Zonal Inspection Program* section defines General Visual Inspection (GVI) of system installations and aircraft structure by zone.

Inspection Intervals

For the Systems and Powerplant Program and the Zonal Program the basic initial inspection check intervals are:

A-Check and multiples	600 FH and multiples
C-Check	18 Months
2C-Check	36 Months/3YE
4C-Check	6 Years (YE)
8C-Check	10 YE

For the Structures Program, the basic initial thresholds and intervals for environmental deterioration related items are listed as follow:

Thresholds: 6 Years and 10 Years
Intervals: 6 Years and 10 Years

The interval units can be expressed in operational units and calendar units:

Operational Units:

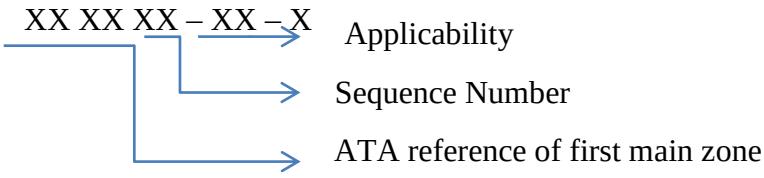
- Flight Hours (FH): elapsed time between wheel lift off and touchdown
- Flight Cycle (FC): A complete take-off and landing sequence
- Cycle (CY): Engine cycles
- APU Hours (AH): APU operation hours

Calendar units

- Hour (HR): One calendar hour elapsed
- Day (24 Calendar hours elapsed)
- Month (MO): One Calendar month
- Year (YE): One Calendar year

Maintenance Tasks

In the MPD the maintenance tasks are presented in a table with task number. When a task applies to two specific main zones which located symmetrically to either side of the aircraft centreline, the tasks is assigned a single task number, but LH and RH zones are indicated in the ‘’zone’’ column. The task number consists of 9 digits and is organized as follows:



- The ATA reference zone shows the system/sub-system or component on which the tasks are performed. The zone number is preceded by the letter code ‘’ZL’’. For the structural, the ATA reference identifies the structural significant item on which the task is to be accomplished and has the same number as the MRB report.
- Sequence number, in general the sequence number is used to distinguish between different tasks relating to the same hardware
- The applicability index identifies the successive developments of a task, introduced by modifications or specific requirement. The technical status or specific requirement associated with each applicability index is specified in the applicability column. As a general rule, tasks with the same first 8 digits in task number have same work description in the Aircraft Maintenance Manual (AMM).

In Figure 13 an example of MPD is shown with the columns: Task Number, Zone, Description, Threshold interval, source code, Reference, Men, Man-hours (M.H) and applicability.

1) Task number
2) Location of the task, identified by zone number(s)
3) Task Title (FWD Passenger overhead comp), Skill Code (Af= Airframe), Task code (General Visual Inspection, GVI) and task description
4) Task preparation(s)
5) Access Panel(s) per position
6) Threshold, Interval
7) Source of the task
8) Aircraft Maintenance Task Oriented Support System (AMTOSS), technical publication, Special Directives References, MRB report etc.
9) Number of men and man-hours (M.H)
10) Man-hours (in hours and hundredth of hours) per preparation
11) Man-hours (in hours and hundredth of hours) per opening/closing access panels per position
12) Task applicability

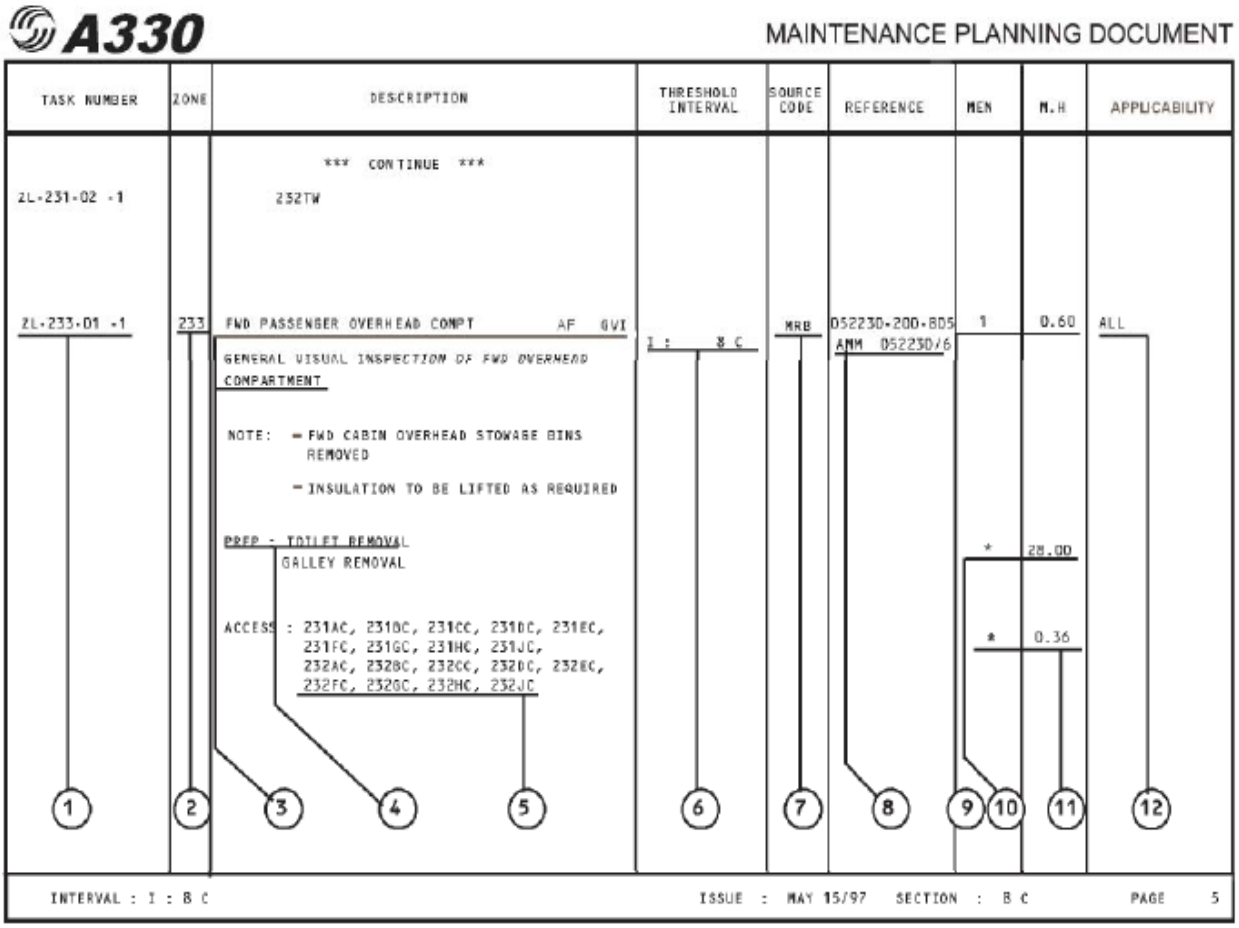


Figure 13 an example of MPD source: (Airbus, 2006)

The task codes such as General Visual Inspection (GVI), Detailed Inspection (DI) and Special Detailed Inspection (SDI) are explained as follows (Airbus-MDP, 2006):

General Visual Inspection (GVI)

The interior or exterior, installation or assembly are visually examined to detect obvious damage failure or irregularity. Generally this inspection is performed from the touching distance unless it is specified in differently. A mirror could be used for areas or surfaces if necessary. This level of inspection is made under normally lightening conditions such as daylight, hangar lighting, flashlight or drop-light and may require removal or opening of access panels or doors. Stands, ladders or other platforms may be used to perform inspection.

Detailed Inspection (DI)

Intensive examination of a specific item, installation or assembly to detect damage, failure or irregularity. A direct source of good lightening is used at an intensity deemed appropriate. Inspection aids could be used such as: mirrors, magnifying lenses etc. surface cleaning and elaborate access procedures may be required.

Special Detailed Inspection (SDI)

An intensive examination of a specific item, installation or assembly to detect damage, failure or irregularity. During this inspection an extensive use can be made of specialized inspection techniques and/or equipment. Elaborate cleaning and substantial access or disassembly procedure may be required. The Non Destructive Testing (NDT) procedures are described in the A330 Non Destructive Testing Manuals (NTM).

4.3 Maintenance Cost Breakdown and its Influence on LCC

The Life Cycle Cost (LCC) of an aircraft can be broken down into (i) Research & development costs, (ii) production & construction costs, (iii) operations & maintenance costs and (iv) retirement & disposal costs, see Figure 14. As stated before, the maintenance costs are roughly 10-20% of the total operation costs (Ghobbar, 2010; American Airlines, 1978; Dixon, M, 2006; Wu et al., 2004; IATA, 2013). In Figure 15 the total operation cost of 46 airlines are shown (study year 2012). In this figure the cost breakdown is explained as:

- Cost of Operations: pilot salaries, station, ground, general administration cost
- Fuel cost
- Aircraft maintenance cost in labor, material, outsourcing and overhead
- AC Ownership in rentals and depreciation
- Distribution ticketing, sales and promotion
- Charges as navigation and landing fees
- Pax services are passenger services like check-in counter, gate agents and cabin crew
- Others costs are the IT and communications, flight equipment insurance load insurance etc.

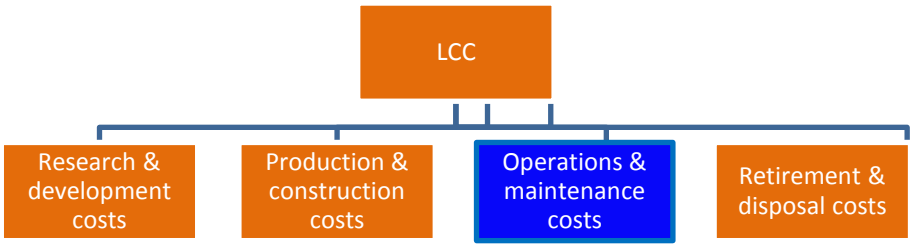


Figure 14 LCC cost breakdown (Thokala, 2009)

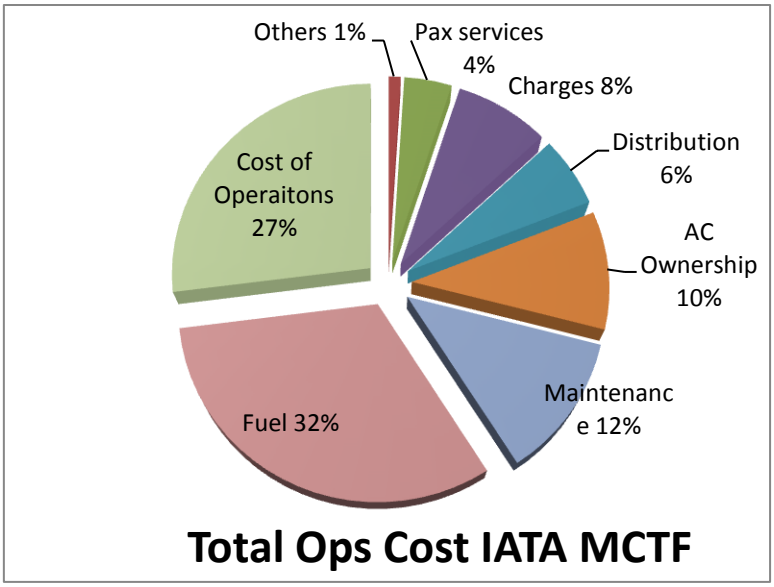


Figure 15 total operation cost of an aircraft (IATA, 2013)

The Total Maintenance Cost (TMC) can be divided into Direct Maintenance Cost (DMC) and Indirect Maintenance Cost (IMC). DMC is the maintenance cost in terms of labor and material which are directly expended in performing maintenance on an aircraft or an item (Ghobbar, 2010). And IMC includes the all the other costs. The IMC costs are for example: administration, supervision, tooling, test equipment, facilities, record keeping etc. In Figure 16 the cost breakdown of TMC is given. In this case the DMC is broken down into airframe maintenance cost and powerplant. The airframe maintenance cost is further divided into access, set-up, task completion, line maintenance, checks, components and defect rectification (Kinnison, 2004). The components refers to those which are constructed the airframe (wing, fuselage and empennage). The engine (powerplant) is divided into engine repair, engine overhaul, life-limited parts and powerplant components.

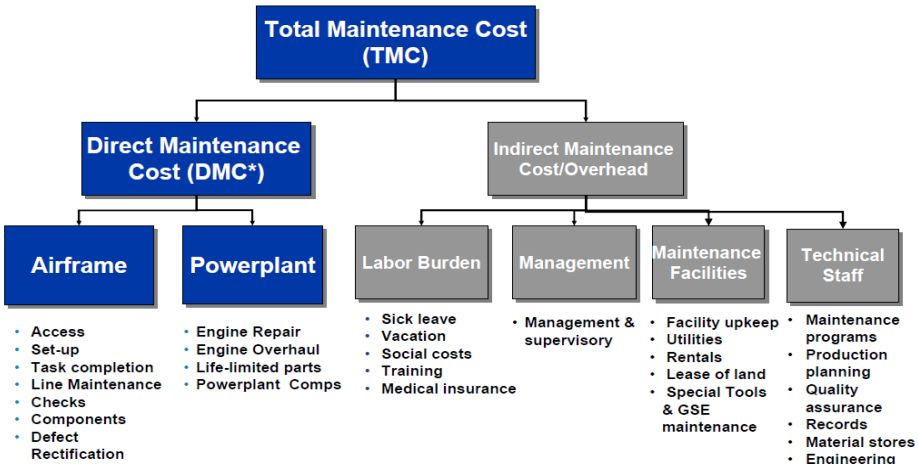


Figure 16 TMC cost breakdown (Khwaja, 2012)

The contribution of the maintenance cost can be seen as 'fixed and variable'. *Fixed* from the perspective of manufacturer, how good the inherent reliability of the airplane is maintainability of the airplane and manufacturer product support. The *variable* from airline

perspective, is airline operations, airline maintenance practices, airline accounting practices and airline support practices related, Figure 17. So the maintenance cost of an aircraft seen from manufacturer point of view has constant behaviour, i.e. the initial maintenance program of a certain type aircraft is the same for every aircraft operator. From the aircraft operator, airline perspective the maintenance cost has a more variable behaviour. In this case the maintenance cost depends on the maintenance capabilities, the aircraft utilization, maintenance policy (outsourcing or in-house maintenance) etc.



Figure 17 manufacturer and airline influence on maintenance cost (Khwaja, 2012)

The cost distribution of TMC in terms of engine maintenance, airframe maintenance and burden (overhead) is given by RAND, Dixon (2006) in Figure 18. The data analysis by Dixon (2006) was from 29 aircraft types from different airlines spanning in 38 years.

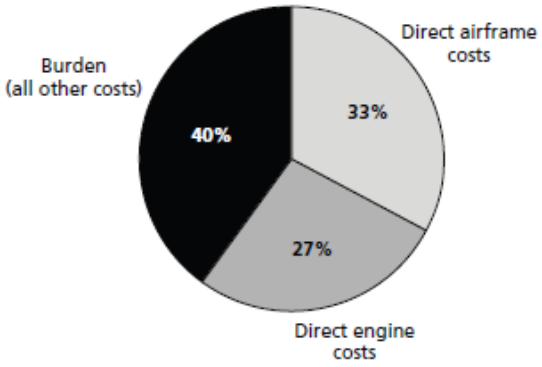


Figure 18 average composition of TMC (Dixon, 2006)

The DMC cost breakdown by Brugidou (2007) is shown in Figure 19. The composition of scheduled and unscheduled maintenance costs is indicated. Inside the circle the contribution of components, powerplant and airframe are also given with percentages for labor (L) and material (M) for each segment. As it can be seen from Figure 19, for an airline the airframe segment is the most labor intensive segment.

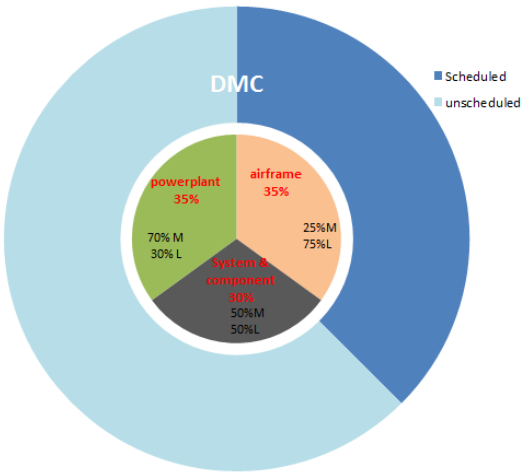


Figure 19 DMC compositions (Brugidou, 2007)

Maintenance cost and aging factor

Several factors, such as aircraft age, utilization, operator, the manufacturer, flight length and environment in which the aircraft operates, have influence on the maintenance costs of an aircraft (Khwaja, 2012). Except the age all other parameters are aircraft operator dependent. The maintenance costs due to aircraft age can be seen as unavoidable cost for every airline independent of their airline operation profile. The RAND (Dixon, 2006) studied influence of aircraft age on maintenance cost. The aircraft age is categorized in three categories: age 0-6, age 6-12 and age 12 years and older (Dixon, 2006). Figure 20 shows the total maintenance cost per flight hour given as a function of aircraft age. In Figure 21 a six-year old aircraft is normalized with a value of 1.0 for total cost per FH. It should be noted that in the figure airframe maintenance costs, engine maintenance costs and overhead costs are included. The airframe maintenance cost shows a more convex behaviour (Dixon, 2006). In Figure 22 the airframe maintenance cost per FH versus the average fleet age is illustrated.

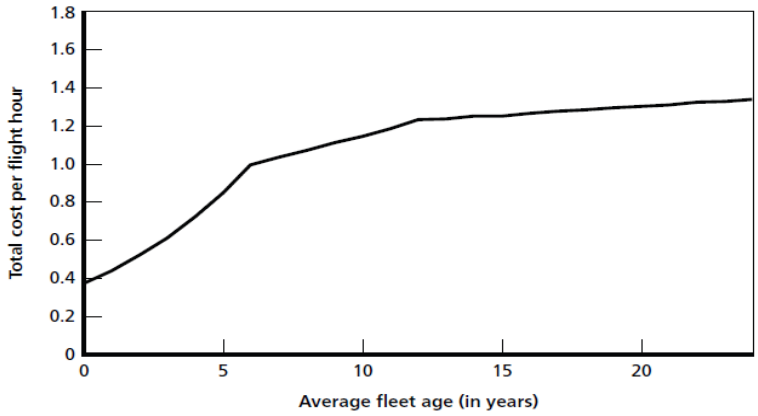


Figure 20 maintenance cost per FH vs. AC age (Dixon, 2006)

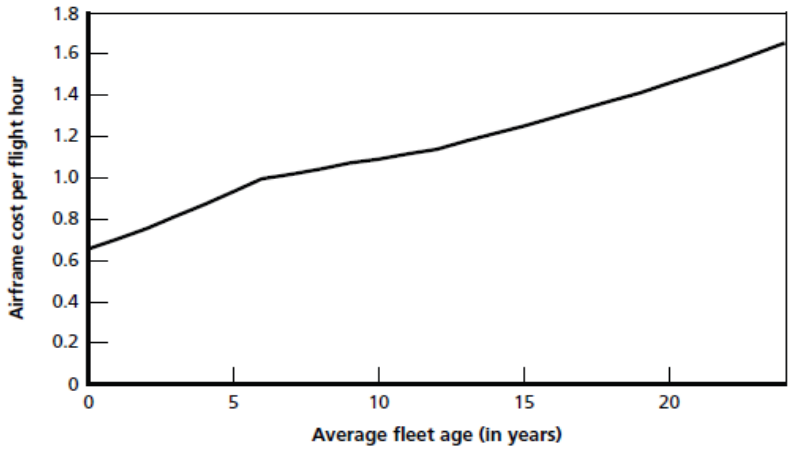


Figure 21 effect of age on airframe maintenance costs (Dixon, 2006)

Boeing developed a maturity curve to express the normalized airframe costs of aircraft of various ages. The aircraft life is categorized in three categories: ‘‘newness period’’ (until the 1st D-check), ‘‘mature period’’ (ends at 2nd D-check) and ‘‘aging period’’ (starts at 2nd D-check). The mature period is used as a reference (is normalized to 1.0) and the costs of various ages can be compared. The aircraft is cheaper to maintain during the newness period and the maturity factor is less than one. The maintenance costs are higher during aging period since the factor is greater than one (see also Figure 20 and Figure 21). The maturity curve is adapted by Dixon (2006) and shown for two categories of aircraft, one is manufactured pre-1980 and the other is manufactured post-1980, see Figure 22.

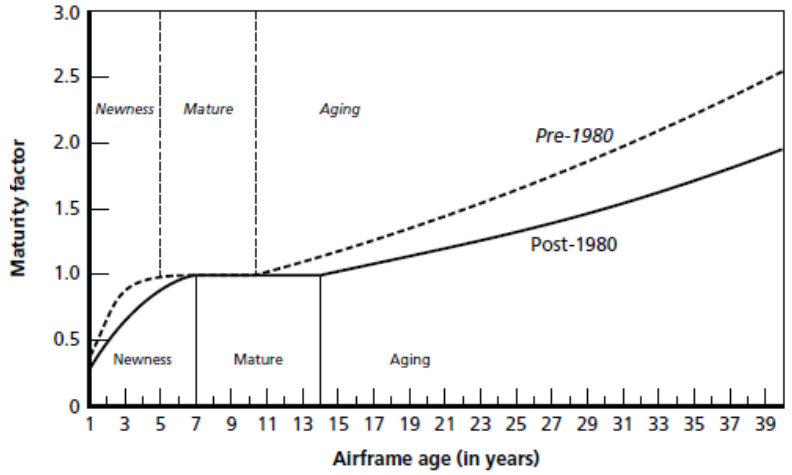


Figure 22 Boeing’s maturity curve (Dixon, 2006)

According to Figure 22 the aging period starts at an age of 11 years for pre-1988 aircraft and at 14 years old for post-1980 aircraft. Bruinsma (2009) argues that the aging period for airbus aircraft starts at an age of 13 years and the maintenance cost increases 1.5% annually. The increase is only noticeable in the unscheduled maintenance cost. The scheduled maintenance cost stays in a constant trend during the aircraft life (DSG) unless there is a modification on the airplane by Airworthiness Directives (AD’s) or Service Bulletins (SB’s). The scheduled maintenance tasks are consistent and are provided by the manufacturer, the MPD or the

operators established OMPD. In the next sub-section, the maintenance program development is reviewed.

4.4 Aircraft Maintenance Cost Estimation Methods

In this section the maintenance cost estimation methods are discussed. These methods are; The Airbus method, the Second Order Reliability method, Engineering method, Project Evaluating Method, method used by IATA's Maintenance Task Force, Dhillon's method, the Liebeck's cost estimation method, Brugidou's method, the American Airline's method "A new method for estimating current and future Transport Aircraft Operating Economics'' that is adapted by van der Velden and finally the Roskam method. These methods are reviewed because they or their adaption are widely used by aircraft operators or manufactures, further the maintenance cost estimation is performed by the methods with different with variables.

4.4.1 The Airbus Method

The Airbus Method calculates the Direct Maintenance Cost (DMC) with following *Eq. 1* (Wu et al., 2004):

$$DMC = \left(MMH_{on} + MMH_{off}\right) \cdot LR + MC \qquad Eq.\ 1$$

Where;
MMH_{on} is maintenance man hours on aircraft,
MMH_{off} is maintenance man hours off aircraft (out sourced),
LR is labor rate and
MC is material costs

The DMC is calculated generally, more detailed analysis of the cost estimation for several components of an aircraft is needed. A cost breakdown method for several parts/components can be done by using the above expression for each item. Then a summation of those cost estimation can give the total DMC. Usually the off-aircraft MMH refers to the system and components and not to structure or zonal maintenance. In this case the items, components etc. are physically removed from the aircraft and they are whether repaired in the hangar or the work is outsourced to a Maintenance Repair Organization (MRO).

4.4.2 Second Order Reliability Method

According to the developed method by Slamanca et al. (2005) the airframe maintenance cost is calculated as a function of non-destructive inspections, safety and the repair and replacement of crack components. Further the authors claimed that the service lifetime of an aircraft can be extended for a long period by performing inspections, repairs and making feasible replacements with appropriate frequency. However, in some cases, maintenance costs tend to increase and extending aircraft life can become uneconomic. A trade-off between aircraft replacement cost and its maintenance cost need to be performed. The authors estimate the total maintenance cost (TMC) of the airframe with the following equation:

$$TMC = C_r = C_S = k \sum_{x=1}^{h} (C_x \times POD_x \sum_{g=1}^{n} Pt_g^x) + knC_S \qquad Eq.\ 2$$

Where;
C_r is the total repair cost
C_S the total structural cost
$POD_x$is the crack growth group, cracks are categorized into two groups:

I. Cracks between minimum detectable size a_m and 0.03 in, a_1
II. Cracks between a_1 and critical size a_{cr}

Pt_g^x is the structural repair costs, x represents the cracks in group I or II and g is the number of inspection needed to find cracks
k is the probability of the details having crack in a certain group

This method is more based on the structural analysis and it is only limited to the crack inspection, probability of crack detection and repair. The others do not provide information when the examination period for cracks are conducted or during which maintenance task.

4.4.3 Project-Evaluating Method

In this method the maintenance costs are subdivided into some basic expense units, . Then the final cost can be added from bottom to top. The project-evaluating method was created by Boeing to predict maintenance cost after dividing the aircraft in several modules. Regression model is developed with factors that have influence on maintenance level, repair shop, time and operating circumstance (Jian and Hong-fu, 2004). the following aspects should be noticed by apply cost estimation using this method:

1) All expenses of the system should be considered integrally.
2) Various expenses must be strictly defined to avoid calculating repeatedly
3) Cost Breakdown Structure (CBS) should be consistent with the account sheet.
4) Which part is the recurrent fee and which part is not should be clarified.

The workload of the method is relatively heavy. However, this method can provide a comparatively detailed and accurate expenses budgetary estimation and it can also point out the direction of the flow of the expenses. Therefore the method is commonly used to present maintenance cost calculation. The authors Jian and Hong-fu (2004) use the project-evaluating method to calculate the total cost of an engine at a certain repair shop.

The CBS of ‘’shop visit costs’’ are: fixed costs, labor costs, material costs, repair costs, sub-contracted costs, life-limited part cost and trade-in cost.

The programme flow of this maintenance action is divided into three steps: *Module cost estimating, labor cost and total costs of a shop visit.*

1. Module cost estimating. The engine can be divided into several modules. For example: fan, core engine, high-pressure turbine and accessory drive. The related cost forecasting of module i is given as:

$$C_{est\,i} = C_1 \cdot C_2 \cdot C_3 \cdot C_4 \cdot C_{reference}$$
$$= C_1 \cdot C_2 \cdot C_3 \cdot C_4 \cdot [C_{mat} + C_{rep} + C_{sub} + C_{cycle}] \quad \textit{Eq. 3}$$

$$= C_{mat\ i} + C_{rep\ i} + C_{sub\ i} + C_{cycle\ i}$$

Where;
$C_{est\ i}$ is the estimated cost of module i
$C_{reference}$ is the reference cost of module $_i$
C_{mat},C_{sub},C_{rep} and C_{cycle} are the cost of material, subcontract, repair and life-limited part respectively
And c_1, c_2, c_3 and c_4 stand for the influence factors of maintenance level, repair shop, time and operating circumstance respectively.

2. For labor cost Liang and Hong-fu (2004) found that their calculated labor cost is relevant to the cost of material; repair can be sub-contracted at the engine shop. Therefore regression model is used to forecast labor cost based the material cost, repair cost and sub-contract cost. The following equations was found:

$$C_{labor\ i} = b_1 \cdot C_{rep} \cdot b_2 \cdot C_{mat} \cdot b_3 \cdot C_{sub} + a \qquad Eq.\ 4$$

Where, $C_{labor\ i}$ is the labor cost for module i and b_1, b_2, b_3 and a are the coefficients.

3. Total costs of a shop visit are:

$$TMC_{\ shop\ est\ i} = C_{labor\ i} + \sum_{i=1}^{n} C_{est\ i} + C_{fix} \qquad Eq.\ 5$$

Where, $TMC_{\ shop\ est\ i}$ is the Total maintenance cost of a shop visit for module i, $C_{labor\ i}$ the labor cost for module i, $C_{est\ i}$ is the estimated cost for module i, and C_{fix} is the fixed cost.

4.4.4 IATA's Maintenance Task Force

The DMC can be calculated using *Eq. 6*. In this case it is not distinguished who is performing the maintenance, e.g. the airliner or an approved Maintenance Repair Organization (MRO). Thus it is not important whether the maintenance activities are outsourced or performed In-house by the operator (IATA, 2013).

$$\begin{aligned} &Direct\ Maintenance\ Cost \\ &= \sum Line\ Labor \\ &+ \sum Line\ Material + \sum Base\ Labor \\ &+ \sum Base\ Material + \sum Engine\ Labor \\ &+ \sum Engine\ Material + \sum Component\ Labor \\ &+ \sum Component\ Material + \sum Powerplant\ Labor \\ &+ \sum Powerplant\ Material \end{aligned} \qquad Eq.\ 6$$

The difference between Line maintenance and Base maintenance can be described as follow: *Line maintenance* can be defined as maintenance activities on transit, daily, weekly and periodic basis. This type of maintenance mainly consist of visual inspections, lubrications and general servicing of aircraft and does not require to open panels and access doors for detailed inspections. Line maintenance has short downtime periods of 24 hours or less and has small maintenance packages in terms of man-hours.

Base (heavy) maintenance is generally defined as maintenance activities under the C- and D-Checks. In this case the panels and access doors could be disassembled or opened for inspections purposes and necessary repairs can be conducted. Base maintenance is mainly characterised by long downtime periods and large maintenance packages in terms of man-hours. This method shows striking similarities with the Airbus Method. In this case the labor costs and material costs for each aircraft segment is calculated separately and summed up at the end.

For every segment of *Eq. 6* the Direct Labor Cost can be by the following expression

$$Direct\ Labor\ Cost = Manual\ workers \times Average\ Direct\ Labor\ Cost \qquad Eq.\ 7$$

The Average Labor Cost is again given by the formula:

$$Average\ Direct\ Labor\ \ cost = Salary\ \&\ Wages + Social\ Cost \qquad Eq.\ 8$$

The total overhead cost can be estimated by following expression:

$$Total\ Overhead\ Cost = Total\ Labor\ Overhead\ Cost + Total\ Non\ Labor\ Overhead\ Cost \qquad Eq.\ 9$$

The Labor Overhead Cost can be approximated by:

$$Total\ Indirect\ Labor\ Cost\ (overhead) = Non\ Manual\ workers \times Average\ Indirect\ Labour\ Cost \qquad Eq.\ 10$$

$$Average\ Indirect\ Labor\ cost = Salary\ \&\ Wages + Social\ Cost \qquad Eq.\ 11$$

The average Indirect Labor Cost is the summation of salary & Wages and Social Cost of non-manual workers. The Non Labor Overhead Cost of *Eq. 9* can be estimated by the following formula:

$$Total\ Non\ Labor\ Overhead\ Cost = Facilities\ (Utitlities) + Equipment + Communication + Training + Other\ (Insurances\ and\ Taxes) \quad \textit{Eq. 12}$$

4.4.5 Dhillon's Maintenance Labor Cost Estimation Method

The *corrective* labor cost can be obtained by *Eq. 13* (Dhillon, 2002):

$$C_{labor,corrective} = \frac{FH \times r_{labor} \times MTTR}{MTBF} \quad \textit{Eq. 13}$$

In this case the MTTR and MTBF can be expressed by the following equations:

$$MTTR = \frac{\left(\sum_{i=1}^{k} \lambda_i CMT_i\right)}{\sum_{i=1}^{k} \lambda_i} \quad \textit{Eq. 14}$$

The λ_i, failure rate in this case is assumed to be the summation of inspection interval:

$$\lambda = \frac{1}{\sum_{i=1}^{k} ineterval_i} \quad \textit{Eq. 15}$$

$$MTBF = \frac{\sum_{i=1}^{k} interval_i}{k} = \frac{\sum_{i=1}^{k} MTBF_i}{k} \quad \textit{Eq. 16}$$

Where;

r_{labor} is labor rate, i.e. Maintenance cost per hour

MTTR is mean time to repair. It represents the average time required to conduct corrective maintenance.

k is number of units or parts

λ_i is failure rate of unit/part, for $i = 1,2,3, \dots, k$.

CMT_i is corrective maintenance/repair time required to repair unit/part i, $i = 1,2,3, \dots, k$. (hr)

The *preventive* labor cost can be obtained by the following *Eq. 17*:

$$C_{labor,preventive} = \frac{FH \times r_{labor} \times MPMT}{MTTF} \quad \textit{Eq. 17}$$

$$MPMT = \frac{\left(\sum_{i=1}^{k} FPM_i \times ETPMT_i\right)}{\sum_{i=1}^{k} FPM_i} \quad \textit{Eq. 18}$$

$$MTBF = \frac{\sum_{i=1}^{k} interval_i}{k} = \frac{\sum_{i=1}^{k} MTBF_i}{k} \quad \textit{Eq. 19}$$

$$MTTF = \frac{1}{\sum_{i=1}^{k} \lambda_i} \quad \textit{Eq. 20}$$

Where;
MPMT is mean preventive maintenance time. It is an average downtime to conduct scheduled preventive maintenance.
k is total number of preventive maintenance tasks,
FPM_i is frequency of preventive maintenance task i, for $i = 1,2,3, \dots, k$ (n times/hr)
$ETPMT_i$ is elapsed time for preventive maintenance task i, for $i = 1,2,3, \dots, k$. (hr)
MTTF is mean time to failure

4.4.6 Liebeck's Maintenance Airframe, Material Cost Estimation Method and Maintenance Overhead Cost

The Liebeck method estimates the airframe direct labor cost with the following equations (Liebeck et al., 1995):

$$\frac{Maintenance\ Labor\ Hours}{Trip} = \left[1.26 + 1.774\left(\frac{W_{airframe}}{1\times10^5}\right) - 0.1071\left(\frac{W_{airframe}}{1\times10^5}\right)^2\right] \times Trip\ Time + \left[1.614 + 0.7227\left(\frac{W_{airframe}}{1\times10^5}\right) + 0.1204\left(\frac{W_{airframe}}{1\times10^5}\right)^2\right] \quad \textit{Eq. 21}$$

Now the airframe labor cost is given by the following equations:

$$C_{labor\ airframe} = \frac{Maintenance\ Labor\ Hours}{Trip} \times (\#\ of\ trips) \times (r_{labor}) \quad \textit{Eq. 22}$$

Where;
$C_{labor\ airframe}$ is the direct labor cost of the airframe
$W_{airframe}$ is the weight of airframe less the dry weight of the engines
$Trip\ Time$ is the time of the flight in terms of Flight Hours per Flight Cycle (FH/FC)
$\#\ of\ trips$ is number of trips, annual Flight Cycles
r_{labor} is the labor rate in euro/h

Maintenance Material Cost

Also the material maintenance cost can be obtained with the Liebeck's method:

$$\frac{Material\ Cost}{Trip} = \left[12.39 + 29.8\left(\frac{W_{airframe}}{1\times10^5}\right) + 0.1806\left(\frac{W_{airframe}}{1\times10^5}\right)^2\right] \times Trip\ Time + \left[15.2 + 97.33\left(\frac{W_{airframe}}{1\times10^5}\right) - 2.862\left(\frac{W_{airframe}}{1\times10^5}\right)^2\right] \quad \textit{Eq. 23}$$

$$C_{material\ airframe} = \frac{Material\ Cost}{Trip} \times (\#\ of\ trips) \quad \textit{Eq. 24}$$

Where;

$C_{material\ airframe}$ is the direct material cost of the airframe
$W_{airframe}$ is the weight of the airframe
Trip time is the flight duration, in this case it is assumed to be equal to amount of flight hours per flight cycle, $\left(\frac{FH}{FC}\right)$
$\#\ of\ trips\ is$ the number of trips in a certain year

Airframe Applied Maintenance Overhead Cost

The applied airframe maintenance burden or overhead cost can be estimated with the following simple equations:

$$C_{airframe\ overhead} = 2.0 \times C_{labor\ airframe} \qquad \textit{Eq. 25}$$

With $C_{labor\ airframe}$ given by *Eq. 22*, where the maintenance burden cost applied on the airframe consist direct labor cost, material cost and overhead maintenance costs.

4.4.7 Brugidou's Method for UNMC of Structures and Zonal Maintenance

Structural (and zonal) unscheduled maintenance is always performed on-aircraft. It can be performed by line maintenance or base maintenance personnel. In the case of base maintenance the aircraft is taken out of the service and will have certain down time that results for the airliners as a loss of incomes. The defects found by flight crew or during (routine) inspections could result to structures and zonal maintenance. The unscheduled maintenance costs for a certain year can be calculated with the following expression (Brugidou, 2007 and Bruinsma, 2009):

$$C_{UNM\ airframe\ y} = (TCM/FH)_y \times FHs \qquad \textit{Eq. 26}$$

Where;
$C_{UNM\ airframe\ y}$ = the Unscheduled Maintenance Cost of the airframe in the year of interest y
$(TCM/FH)_y$ = the Total Costs due to Pilot Reports (PiReps) and Maintenance Reports (MaReps) per Flight Hour in year of interest y
FHs = the amount of yearly Flight Hour

The term $(TCM/FH)_y$ can be obtained by the following formula:

$$\left(\frac{TCM}{FH}\right) = \frac{LMC/FC}{\#(PiReps + MaReps)/FC} \times \left(\frac{FCs}{FHs}\right) \qquad \textit{Eq. 27}$$

Where;
$\left(\frac{TCM}{FH}\right)$ = the Total Costs due to pilot reports (PiReps) and Maintenance Reports (MaReps) per Flight Hour
LMC/FC = the Line maintenance Costs per Flight Cycle
$\#(PiReps + MaReps)/FC$ = the number of Pilot Report and Maintenance Reports per Flight Cycle
FHs = the yearly aircraft utilization in Flight Hours
FCs = the yearly aircraft utilization in Flight Cycles

Combing *Eq. 26* and *Eq. 27* results in following formula for the Unscheduled Maintenance Cost of the airframe:

$$C_{UNM\ airframe\ y} = \left[\frac{LMC/FC}{\#(PiReps + MaReps)/FC} \times \left(\frac{FCs}{FHs}\right)\right] \times FHs$$

Eq. 28

$$C_{UNM\ airframe\ y} = \frac{LMC/FC}{\#(PiReps + MaReps)/FC} \times FCs$$

The number of Pilot's reports and Maintenance's reports can be determined by analysing the aircraft's logbook or the pilot reports and maintenance reports. The pilot and maintenance reports are constructed per 100 take-offs or 1000 Flight Hours.

4.4.8 Van der Velden Method

The method provided by van der Velden (1997) is an adaption of the American Airlines (1978) method 'A new method for estimation current and future transport aircraft operating economics'. The method predicts the number of labor hours per flight cycle (FC) and the number of labor hour per flight hour (FH). The costs are associated with the number of passengers (seats), the size of the aircraft and the Mach number. Following relation are given for the number of labor hours per FC *Eq. 29* and number of labor hours per FH *Eq. 30*:

$$\left(\frac{MMH}{FC}\right)_{airframe} = [2.14 + 0.0000079\ MTOW + 0.0046\ s]\ \sqrt{M} \qquad \textit{Eq. 29}$$

$$\left(\frac{MMH}{FH}\right)_{airframe} = [3.08 + 0.000032\ W_{airframe} + 0.0041\ s]\ \sqrt{M} \qquad \textit{Eq. 30}$$

Where;
$\left(\frac{MMH}{FC}\right)_{airframe}$ is number of airframe labor hours per FC [h]
$\left(\frac{MMH}{FH}\right)_{airframe}$ is number of airframe labor hours per FH [h]
$MTOW$ is the Maximum Take-off Weight [kg]
s is the aircraft seat capacity [-]
M is the aircraft Mach number [-]
$W_{airframe}$ is the weight of the airframe [kg]
The airframe labor cost are expressed as a function of both $H_{labor/FC_{airframe}}$, $H_{labor/FH_{airframe}}$, aircraft range (R), block speed (V_b) and certain deflator D_l to compensate for the inflation. To compensate for the inflation, for the airframe labor cost the CPI is chosen (van der Velden, 1997) see *Eq. 31* and *Eq. 33*:

$$C_{labor\ airframe} = 15\ D_l \left[\frac{\left(\frac{MMH}{FC}\right)_{airframe}}{R} + \frac{\left(\frac{MMH}{FH}\right)_{airframe}}{V_b}\right] \qquad \textit{Eq. 31}$$

The block speed V_b is defined as function of range (R) in km and time loss t_{loss} and flight time t_{flight} in hour:

$$V_b = \frac{R}{t_{loss} + t_{flight}} \qquad \textit{Eq. 32}$$

The t_{loss} is taken to be 30 minutes. Definition of the deflator is given by the following expression:

$$D_{I_{year=x}} = \frac{CPI\ year\ x}{CPI\ 1994} \qquad \textit{Eq. 33}$$

Year 1994 is used as reference because the method was developed at that year (van der Velden, A, 1997). The method discussed by van der Velden (1997) does not make distinguish between scheduled and unscheduled maintenance cost. The method basically estimates the airframe maintenance labor cost for a certain year.

The maintenance burden cost or overhead cost is estimated by van der Velden method by taking a summation of engine maintenance labor cost and airframe maintenance labor cost:

$$maintenance\ burden = 3\ (C_{labor\ airframe} + C_{labor\ engine}) \qquad \textit{Eq. 34}$$

In this equation also the supervision and inventory management cost are incorporated.

4.4.9 Roskam Method

Roskam (2002) presented a method for estimating the DOC of a commercial airplane in USD/nm. Roskam adapted the so called ATA-method and it can be applied to any type of commercial aircraft. The DOC per nautical mile is given with the following expression:

$$DOC = DOC_{flt} + DOC_{maint} + DOC_{depr} + DOC_{lnr} + DOC_{fin} \qquad \textit{Eq. 35}$$

Where;
DOC_{flt} is the direct operating cost of flying [USD/nm]
DOC_{maint} is the direct operating cost of maintenance [USD/nm]
DOC_{depr} is the direct operating cost of depreciation [USD/nm]
DOC_{lnr} is the direct operating cost of landing fees, navigation fees and registry taxes [USD/nm]
DOC_{fin} is the direct operating cost of financing [USD/nm]

The direct operating cost of maintenance by Roskam (2002), which is for the interest of this report, is broken down in several components, respectively in labor costs of airframe and systems in USD per nautical mile (USD/nm), engine labor cost in USD/nm, cost of maintenance materials for airframe and systems in USD/nm, the maintenance cost of engine materials in USD/nm and the applied maintenance burden (overhead) in USD/nm. The following equation gives the Roskam's Direct Operating cost of Maintenance: DOC_{maint}

$$DOC_{maint} = C_{labor\ air+sys} + C_{lab/en} + C_{mat/ap} + C_{mat/eng} + C_{amb} \qquad \textit{Eq. 36}$$

Where;
DOC_{maint} is the Direct Operating Cost of an aircraft [USD/nm]
$C_{labor\ air+sys}$ is the labor cost of airframe and systems maintenance [USD/nm]

$C_{lab/en}$ is the labor cost engines(s) maintenance [USD/nm]
$C_{mat/ap}$ is the cost of maintenance materials for the airframe and systems [USD/nm]
$C_{mat/eng}$ is the cost of maintenance materials for the engine [USD/nm]
C_{amb} is the applied maintenance burden [USD/nm]

The maintenance labor cost per nautical mile for airframe and systems, $C_{labor\ air+sys}$ can be estimated by:

$$C_{labor\ air+sys} = 1.03\left(MHR_{map_{bl}}\right)(r_{labor})(V_{bl}) \qquad \textit{Eq. 37}$$

Where;
1.03 is the non-revenu factor. It accounts for extra maintenance costs due to flight delays
$MHR_{map_{bl}}$ is the number of airframe man-hours needed per block hour.
r_{labor} is the airplance maintenance labor rate per man-hour [USD/hr].
V_{bl} is the block speed, see *Eq. 39*

The number of maintenance man-hours for airframe per block hour. This is related to the number of maintenance man-hours per flight hour (FH)

$$MHR_{map_{bl}} = \left(MHR_{map_{flt}}\right)\left(\frac{t_{flt}}{t_{bl}}\right) \qquad \textit{Eq. 38}$$

Where;
$MHR_{map_{flt}}$ is number of maintenance man-hours per FH
t_{flt} is flight time, the time between (aircraft is off-the-ground) take-off (aircraft is on-the-ground) and landing [hr]
t_{bl} is the block time, time between aircraft is pushed back for departure and arrival at the gate, simply said, the time between chocks-on and chocks-off. See also Figure 23 for the mission profile definition provided by Roskam (2002).

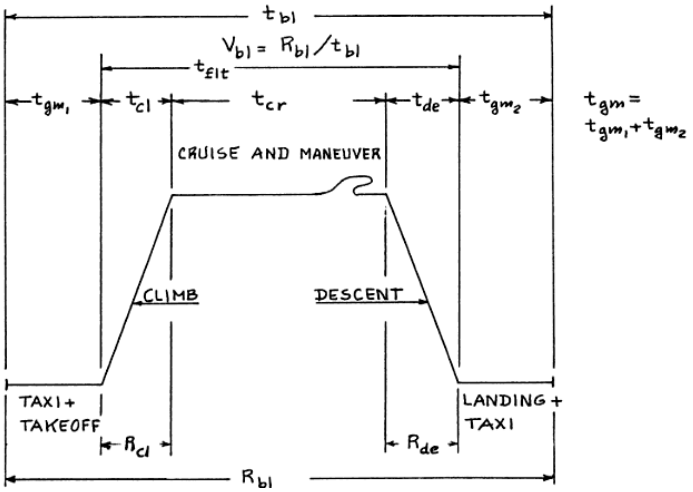


Figure 23 mission profile definitions (Roskam, 2002)

The block speed V_{bl}can be estimated by the following equation:

$$V_{bl} = \frac{R_{bl}}{t_{bl}} \qquad Eq.\ 39$$

Where;
R_{bl} is the block distance measured in nm. It is defined in Figure 23.
t_{bl} is the block time [hr]

Some typical values of block hours per day and annual block times are given by the Roskam (2002) for different types of aircraft in Table 3. As it can be seen from Table 3, annual utilization in terms of block hours for a jet transport aircraft is for long-haul flight between 3600-4400 hours, medium long-haul flight has a block time between 2100-3300 hours and short-haul flights has a block time between 1000-3000 hours.

Table 3 utilization of commercial airplanes (Roskam, 2002)

	Type of Operation		
Airplane type	*Long haul*, $t_{bl} > 5$	*Medium Haul*, $2 < t_{bl} < 5$	*Short Haul*, $0.5 < t_{bl} < 2$
Jet transports	3600-4400	2100-3300	1000-3000
Regional transport	NA	2000-3000	1000-2500
Corporate transports	500-1500	400-1200	300-1000

4.5 MCEM Framework

In the previous sections, the aircraft maintenance process model and the maintenance cost estimation methods were summarized. By considering the aircraft design and maintenance properties, those cost estimation methods are adapted and/or reformulated to construct the Maintenance Cost Estimation Model (MCEM). In this section, the development of MCEM is discussed. The MCEM estimates the DMC and the burden cost of airframe structures, i.e wing, fuselage and empennage. The DMC has been defined in Chapter 3 and Chapter 4 as: the labor cost and the material cost which are directly expended in performing maintenance on an aircraft or an item. And the burden costs are all other expenditures that are used to perform direct maintenance (Ghobbar, 2010). The MCEM elements are shown in Figure 24, which contains the inputs, the cost model and the outputs. The desired outcomes of the MCEM are the maintenance cost estimates in terms of labor, material and burden cost estimations for both scheduled maintenance and unscheduled maintenance. The inputs are the aircraft design and airline flight and maintenance operation parameters. In Chapter 5, the methodology details of the MCEM will be developed further.

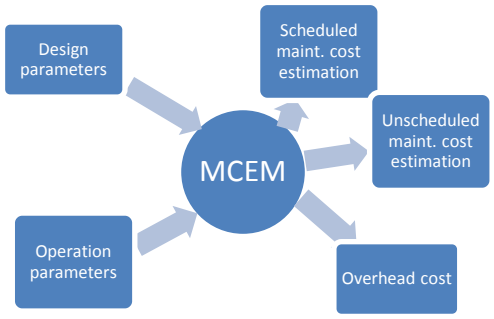


Figure 24 MCEM elements

5 Methodology

Two maintenance cost estimation methods are introduced in this thesis, (i) the Aging Involved Method (AIM) and (ii) Interval-Based Method (IBM). The Aging Involved Method is adapted from the Liebeck's method reviewed in Section 4.4.6. This adapted method is such that it can estimate the DMC and IMC of an aircraft component during the aircraft's DSG. The inputs of the method are those of the weight estimation. An aging factor is incorporated in the method to insure the consequence of the aging process in the maintenance cost estimation. The IBM is developed based on Dhillon's method, shown in Section 4.4.5. The method mainly uses the MSG-3 tasks with their associated maintenance check intervals and the estimated labor hours (Man-hours) as inputs. The maintenance intervals can be obtained from one of the two paths: calculations which associate the geometry sizes, load conditions, structural properties and component failure modes to the specific maintenance interval; data extractions which collect the intervals of maintenance tasks stored in the MPD. In terms of maintenance task man-hours, the data can be obtained from engineering practices or the data stored in MPD for maintenance planning purpose. The IBM developed in this research can estimate the average scheduled maintenance labor cost on yearly basis.

The hierarchical structures of the maintenance cost elements involved in the MCEM are illustrated in Figure 25. On the first horizontal layer, the aircraft components considered by the MCEM are in red. The second horizontal layer shows the maintenance segments. The maintenance labor and material costs, including both scheduled and unscheduled costs for each, are estimated by the MCEM. In general, the MCEM can have design parameters or airline operation parameters as input. Both the scheduled and unscheduled cost estimation composes airframe maintenance labor cost and airframe maintenance material cost, which is then aggregated to the airframe DMC.

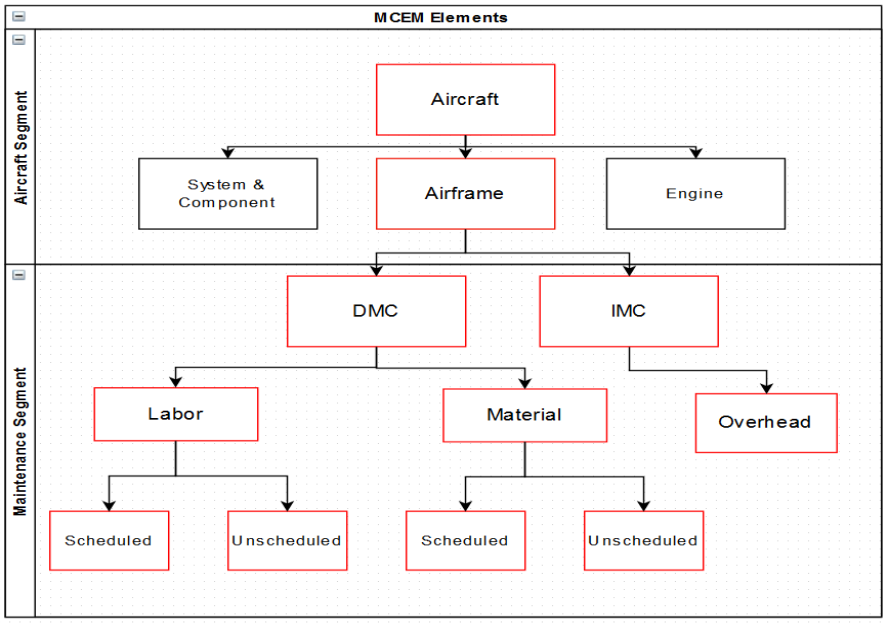


Figure 25 the TMC section that are analysed

5.1 Aging Involved Method

In this section the Aging Involved Method (AIM) is discussed. In Figure 26, the flowchart of the Aging Involved method is depicted. The process starts with analysing the applicable Maintenance Cost (MC) methods, i.e. which component the cost estimation method can estimate - engine MC, system & component or airframe MC, and which cost type the cost estimation method can evaluate - DMC or IMC. Then suitable method or methods is/are chosen, the selection is done by considering the degree that a method can be adopted, the data required as input and feasibility to obtain end results. Subsequently the chosen method is adapted and aging factor is implemented to perform maintenance cost estimation for both scheduled maintenance cost and unscheduled maintenance cost for material and labor. Also the indirect cost, the overhead cost should be estimated. In this phase the method should be able to estimate the maintenance cost for a certain aircraft component i.e. airframe, wing rudder etc. The cost outcomes should be verified and validated, if the results are not verified and validated the process should start again from analysing cost estimation and maintenance cost estimation methods. However, if the method is verified and validated the maintenance cost driving parameters should be extracted. Afterwards sensitivity analysis can be conducted to obtain main cost drivers for both design and operation parameters, than the process of AIM end.

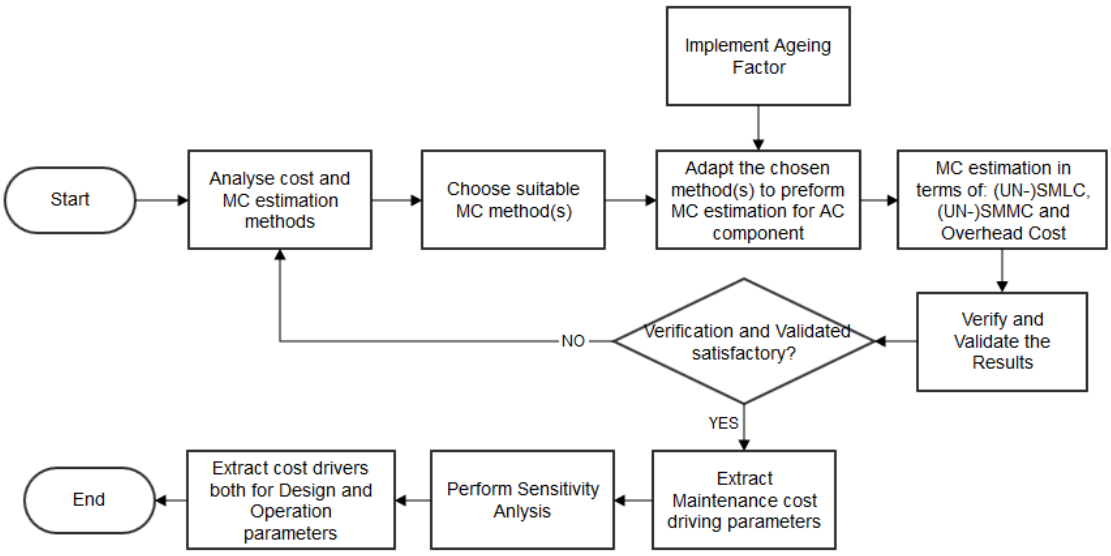


Figure 26 Aging Involved Method flowchart

The hierachical structure of implementing the AIM is shown in Figure 27. It associates the inputs from operation perspective and design perspective to the cost estimation including Scheduled Maintnenance Labor Cost (SMLC), Unscheduled Maintenance Labor Cost (UNMLC), Scheduled Maintenance Material Cost (SMMC) and Unscheduled Maintenance Material Cost (UNMMC). The figure has four horizontal layers. In the top layer (firste layer) of the figure the inputs from operation point of view are given in orange, in the sencond layer the inputs from design perspective in blue. The calculation steps, which are numbered in sequence, serve as pre-processing steps for the actual cost estimation.The developed model shown in the third layer (red) estimates the SMLC, UNMLC, SMMC and UNMMC, which are shown in green in the fourth layer.

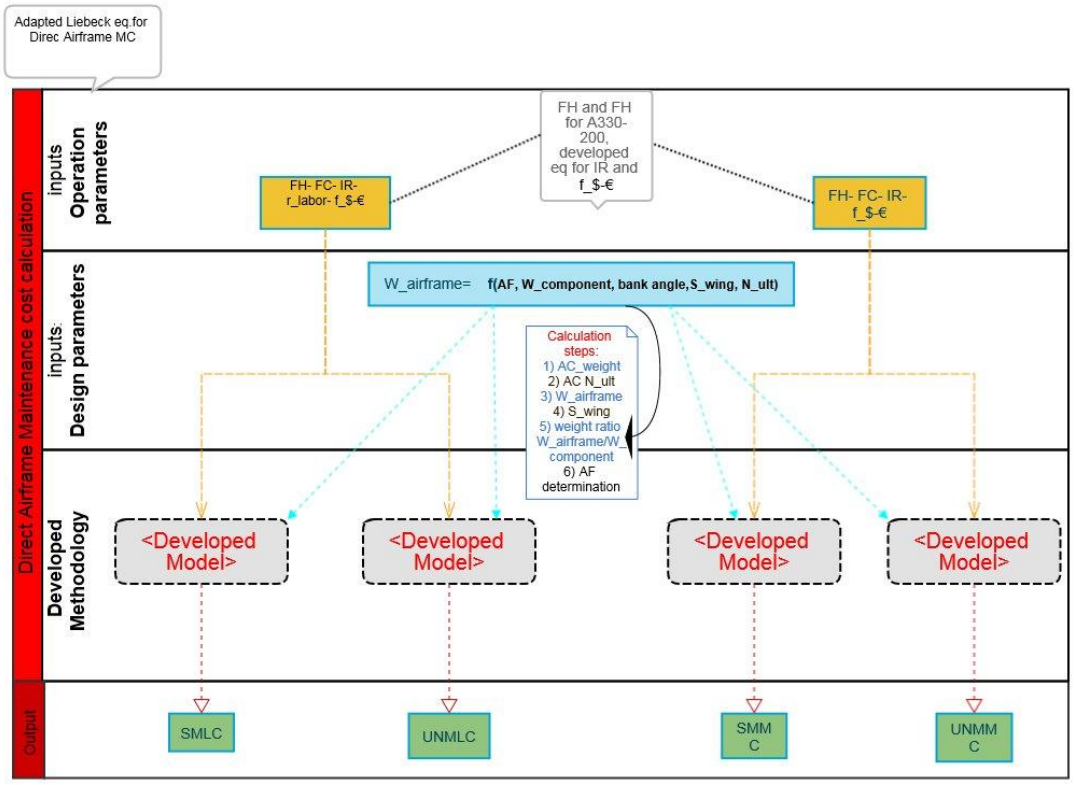


Figure 27 structure of the model with associated parameters

In Table 4 the parameters, equations that will be used in this section are listed in advance. The parameters are categorized into design and operation types associated with their units and equation, table, figure and/or source.

Table 4 parameter table

	Parameter	Unit	Equation/Table/Figure/source
Operation	IR	-	*Eq. 43*, (FXtop, 2013)
	FH	hr	(IATA, 2013)
	FC	-	(IATA, 2013)
	r_{labor}	€/hr	(Zhao et al.,2014)
Design	$W_{airframe}$	kg	Figure 98, Table 45 and Table 46
	AF_y	Variable	*Eq. 43*, Table 5 and Figure 28
	$W_{Aircraft}$	kg	(Airbus, 2006)
	N_{ult}	-	*Eq. 194*
	∅	deg	*Eq. 192*,Figure 99 and Figure 100
	Ratio $\frac{W_{component}}{W_{airframe}}$	-	Figure 98, Table 45, Table 46 and *Eq.32- Eq. 194*
	S_{wing}	m^2	(Airbus, 2006)

The operation parameters like FH and FC are determined from aircraft operator flight profile for a certain type of aircraft. These parameters are needed in yearly basis to perform direct

airframe maintenance cost estimation annually. In this case the labor rate (r_{labor}) and the Inflation Rate (IR) are also considered as operation parameters. The design parameters, which are aircraft characteristics, are determined analytically.

The calculation steps for performing weight estimation for the airframe and airframe component are listed below:

1) AC weight determination in terms of MTOW and other AC weight groups
2) Aircraft ultimate load factor determination (N_{ult})
3) Aircraft characteristics such as wing area(S_{wing}), sweep angle Λ, bank angle $\emptyset$ etc.
4) AC weight breakdown for airframe and components of airframe (wing, tail and landing gear)
5) Weight ratio between component and airframe $\frac{W_{component}}{W_{airframe}}$

The *Eq. 21* and *Eq. 22* estimates the direct maintenance labor cost of an aircraft on annual basis. The equations do not make distinguish between SMC and UNMC. To determine the contribution of SMC and UNMC including Aging Factor (AF) Figure 28 can be used. In the figure, the ratio of UNMC over SMC is given for different aircraft ages. The grey area in this figure represents the upper and lower ratio limits between UNMC and SMC. As it can be seen, the figure shows a higher increase rate after an aircraft age of approximately 14 years. maintenance cost illustrated in the figure represents the total aircraft maintenance cost (incl. airframe, engine, components and burden). Assuming that the figure also holds for the direct maintenance labor cost only, Table 5 is created for different aircraft ages through interpolation of the upper bound and lower bound of the grey area. The Averaged AFs (AVG AF) are then extracted for the AIM.

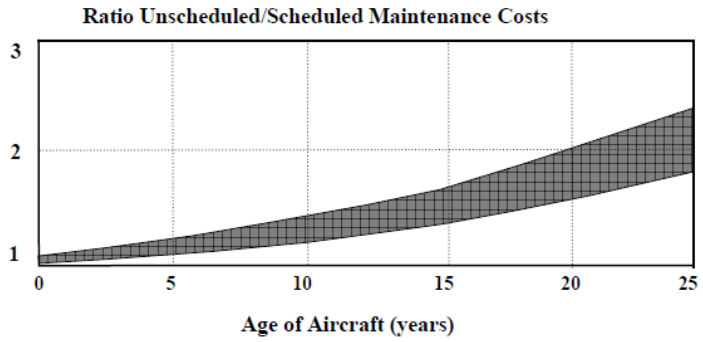


Figure 28 ratio between Unscheduled and scheduled maintenance cost as a function of aircraft age (Suwondo, 2007)

Table 5 interpolation of UNMC/SMC

AC Age	Lower AF	Upper AF	AVG AF
1	0.20	1.10	0.565
2	1.02	1.15	1.085
3	1.03	1.17	1.100
4	1.05	1.19	1.120
5	1.08	1.20	1.140
6	1.10	1.26	1.180
7	1.13	1.30	1.215
8	1.14	1.35	1.245
9	1.15	1.38	1.264
10	1.15	1.40	1.275
11	1.19	1.50	1.345
12	1.20	1.58	1.390
13	1.25	1.60	1.425
14	1.28	1.70	1.490
15	1.30	1.80	1.550
16	1.35	1.85	1.600
17	1.48	1.93	1.705
18	1.52	1.98	1.750
19	1.55	2.00	1.775
20	1.60	2.10	1.850

5.1.1 Maintenance Labor Cost Estimation

To estimate the labor cost for both scheduled and unscheduled maintenance, Liebeck's equations can be used to estimate the labor costs for a certain year (Liebeck et. al, 1995). The Liebeck's equations are applicable to the following conditions:

- Subsonic transport airplanes
- Modern aircraft (entry-into-service(EIS) 2005+)
- Wing design: supercritical divergent trailing edge airfoils
- Advanced composite usage for wing and empennage structure is assumed
- The aircraft has a conventional configuration with pylon mounted wing engine

Aging Factor Determination

To obtain a relation that expresses the maintenance cost as a function of AF, an expression is derived in the form:

$$TMC_y = SMC_y + UNMC_y \qquad Eq.\ 40$$

The subscript y expresses the aircraft age in years. In this case both SMC_y and $UNMC_y$ are considered as the sum of DMC and IMC. The SMC can be assumed to be constant during AC life because the maintenance tasks provided in the MPD will be the same unless an AD or ALI is announced by the authorities or SB is perform by the manufacture. Besides that, only

the labor rate and/or inflation and learning curve of the maintenance personnel of the airline have influences on the SMC during the aircraft life. The change of TMC as a function of aircraft age is mainly due to UNMC (Ackert, 2010; American Airlines, 1978; Boeing, 2008; Brugidou, 2007; Dixon, 2006 and Homan, 2008).

According to Table 5, the $\frac{UNMC}{SMC}$ ratio is constructed as a function of aircraft age. As it can be seen from Figure 28 and Table 5, the ratio between UNMC and SMC is increasing along with the increasing of the aircraft age. To find an expression of AF it is assumed that this increase is only contributed due to aging factor and the increase rate is constant. The aircraft age against average AF of Table 5 is plotted in Figure 29:

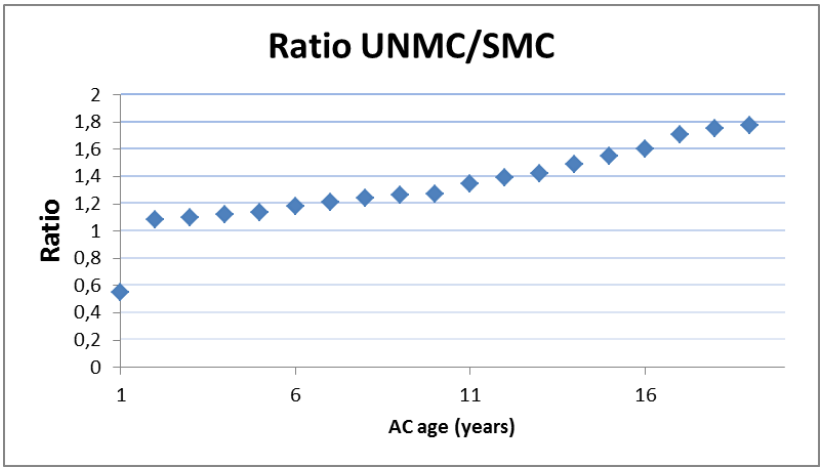


Figure 29 ratio between UNMC/SMC

A The expression is shown in *Eq. 41*:

$$\frac{UNMC}{SMC} = AF = 0.0487 \times AC_{age} + 0.8397 \qquad \textit{Eq. 41}$$

The aging factor is expressed as the increase of ratio between UNMC and SMC:

$$AF_y = \left(\frac{UNMC}{SMC}\right)_y \qquad \textit{Eq. 42}$$

Here the aircraft age AC_{age} is expressed in years as y=1,2,..,20.

Then AF as a function of aircraft life can be expressed as

$$AF_y = 0.0487y + 0.8397 \qquad \textit{Eq. 43}$$

Therefore, the total maintenance cost can be evaluated:

$$TMC_y = SMC_y + AF_y \times SMC_y \rightarrow AF_y = \left(\frac{TMC_y}{SMC_y}\right) - 1 \qquad \textit{Eq. 44}$$

By using *Eq. 43* and Table 5 the error between the developed relation (*Eq. 43*) and the observed quantities can be obtained. In Figure 30 the off-set is given for different aircraft age, the error between average quantities of Table 5 and developed formula is plotted.

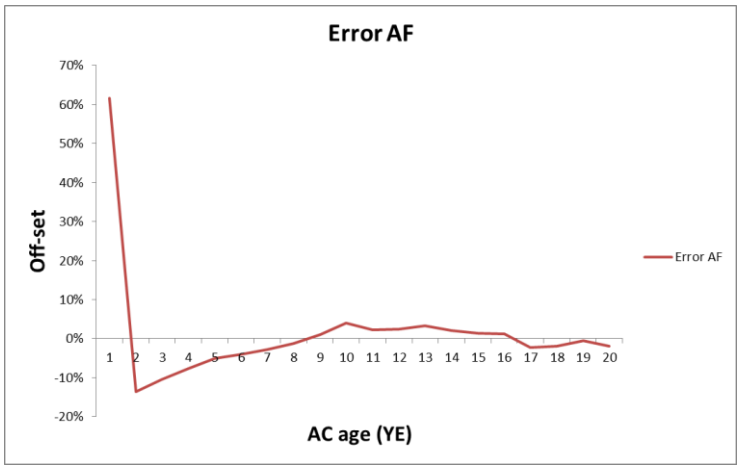


Figure 30 error of the developed AF formula compared to observed values

After aircraft age of 5 years, the deviation is shown less than 5%. It is also assumed that the aging process starts after 5 years.

Direct Airframe Maintenance Cost

Eq. 22 is adapted by implementing the IR contribution and the conversion rate from USD to EUROS, $CF_{\$\to€}$.

$$C_{labor\ airframe\ y} = \left[\frac{Maintenance\ Hours}{Trip} \times (\#\ of\ trips) \times (r_{labor})\right] \times \mathrm{IR}_y \times CF_{\$\to€} \qquad \textit{Eq. 45}$$

The maintenance hours per trip is given in *Eq. 21*. The IR for a specific aircraft age can be given by the following formula:

$$IR_y = \left(1 + \bar{r}_{inflation}\right)^{y-1} = (1 + 1.96\%)^{y-1} \qquad y = 1,2,3 \ldots 20\ years \qquad \textit{Eq. 46}$$

The 1.96% is the average Europe inflation rate per year ($\bar{r}_{inflation}$) between 1994-2014, 20 years like the aircraft DSG (FXtop, 2013), it is assumed that the inflation rate will hold till the end of the aircraft life.

Therefore, the airframe direct labor cost for aircraft life, $C_{labor\ airframe\ y}$ (DSG, 20 years) can be estimated with the following adapted formula:

$$C_{labor\ airframe\ y} = \left[\frac{Maintenance\ Hours}{Trip} \times (\#\ of\ trips) \times (r_{labor})\right] \times (1.0196)^{y-1} \times CF_{\$\to€} \qquad \textit{Eq. 47}$$

The IR is given by *Eq. 46* and $\frac{Maintenance\ Hours}{Trip}$ is given by *Eq. 21*. The developed mathematical expression, *Eq. 47* estimates the direct labor cost for the airframe at certain aircraft age y.

SMLC and UNMLC Decomposition

In this case the contribution of scheduled labor maintenance cost (SLMC, C_{SML}) and unscheduled labor maintenance cost (UNLMC,C_{UNL}) are not discernible in the equation since the estimates the sum of SLMC and UNLMC. In order to estimate the contribution of SMLC and UNMLC separately, two equations (*Eq. 48* and *Eq. 49*) are constructed:

$$C_{labor\ airframe\ y} = (C_{UNL\ y} + C_{SML\ y}) \qquad \textit{Eq. 48}$$

Where;
$C_{labor\ airframe\ y}$ is the airframe direct labor cost for a certain aircraft age y [€]
$C_{UNL\ y}$ is the direct unscheduled maintenance labor cost per certain aircraft age y [€]
$C_{SML\ y}$ is the direct scheduled maintenance labor cost for certain aircraft age y [€]
With y=1,2,..,20

The ratio between UNMC and SMC is given in *Eq. 43*, assuming that this aging factor (AF) also applies to airframe labor cost, the following relation can be constructed:

$$\mathrm{AF_y} = \frac{\mathrm{UNMC_y}}{\mathrm{SMC_y}} = \frac{\mathrm{C_{UNL\,y}}}{\mathrm{C_{SML\,y}}} \qquad \textit{Eq. 49}$$

Eq. 49 is modified to:

$$C_{SML\ y} = \frac{C_{UNL\ y}}{AF_y} \qquad \textit{Eq. 50}$$

Inserting *Eq. 50* into *Eq. 48* , it results:

$$C_{UNL\ y} = \frac{C_{labor\ airframe\ y}}{\left(1 + \frac{1}{AF_y}\right)} \qquad \textit{Eq. 51}$$

Given the total airframe cost is evaluated through *Eq. 47*, Now there are 2 equations (*Eq. 51* and *Eq. 50*) with 2 unknowns ($C_{UNL\ y}$ and $C_{SML\ y}$) so it can be solved. *Eq. 51* can be modified such that the inputs are airframe labor cost per certain aircraft age y, by inserting *Eq. 43* into *Eq. 51*, a relation for the **Unscheduled Maintenance Labor Cost can be obtained:**

$$C_{UNL\ y} = \frac{C_{labor\ airframe\ y}}{\left(1 + \frac{1}{0.0487y + 0.8397}\right)} \qquad \textit{Eq. 52}$$

Where $C_{labor\ airframe\ y}$ is given by *Eq. 45*. The **Scheduled Maintenance Labor Cost** per aircraft age is then:

$$C_{SML\,y} = C_{labor\ airframe\ y} - C_{UNL\,y} \qquad \textit{Eq. 53}$$

Maintenance Labor Cost for Airframe Component

The equations derived in this sub-section are labor costs of both scheduled and unscheduled maintenance cost for the aircraft component at a certain aircraft age. To estimate the DMC for aircraft component i.e. wing, aileron, horizontal tail etc., the assumption is made regarding the maintenance cost distribution based on their weight ratios (the weight of the component over total weight of the airframe). It is assumed that the maintenance cost ratio of a component is the same as its weight:

$$Maintenance\ Cost_{component} = Maintenance\ Cost_{airframe} \times \left(\frac{W_{component}}{W_{airframe}}\right) \qquad \textit{Eq. 54}$$

$$\rightarrow C_{labor\ component\ y} = C_{labor\ airframe\ y} \times \left(\frac{W_{component}}{W_{airframe}}\right)$$

The direct maintenance labor cost for a certain component can also be expressed by applying the weight ratio on *Eq. 47* for the aircraft component:

$$C_{labor\ component\ y} = \left\{\left[\frac{Maintenance\ Hours}{Trip} \times (\#\ of\ trips) \times (r_{labor})\right] \times (IR)^{y-1} \times CF_{\$\rightarrow€}\right\} \times \left(\frac{W_{component}}{W_{airframe}}\right) \qquad \textit{Eq. 55}$$

Where;
$C_{labor\ component\ y}$ is the direct labor cost of the component for AC age y [€]

$\frac{Maintenance\ Hours}{Trip}$ is the maintenance hours per trip given by *Eq. 21*
$W_{airframe}$ is the weight of airframe less the dry weight of the engines [kg]
$W_{component}$ is the weight of the component (wing, tail etc.) [kg]
$\#\ of\ trips$ is number of trips, annual Flight Cycles
r_{labor} is the labor rate in euro/h
IR is the inflation rate
$CF_{\$\rightarrow€}$ is the conversion factor from USD to EUR

Once the labor maintenance cost for component is obtained ($C_{labor\ component}$) the same strategy which have been done for *Eq. 48* to *Eq. 53* can be repeated for the components to get their scheduled maintenance labor cost and unscheduled maintenance labor cost.

The Unscheduled Maintenance Labor Cost for **Component:**

$$C_{UNML\ component\ y} = \frac{C_{labor\ component\ y}}{\left(1 + \frac{1}{0.0487y + 0.8397}\right)} \qquad Eq.\ 56$$

Where, $C_{UNML\ component\ y}$ the unscheduled maintenance labor cost for a component.

The Scheduled Maintenance Labor Cost for **component:**

$$C_{SML\ component\ y} = C_{labor\ component\ y} - C_{UNL\ component\ y} \qquad Eq.\ 57$$

Where, $C_{SML\ component\ y}$ is the scheduled maintenance labor cost for an airframe part e.g. component.

5.1.2 Maintenance Materials Cost Estimation

To estimate the material cost for both scheduled and unscheduled maintenance, equations provided in sub-section 4.4.6 can be employed. The maintenance material costs are estimated for a certain year with a certain aircraft age by *Eq. 23* and *Eq. 24*. In this sub-section the material cost estimation relationships are constructed for both scheduled and unscheduled maintenance material costs for airframe and component through the aircraft life.

To implement the inflation and ageing effects, again the IR and AF are incorporated in *Eq. 24*:

$$\mathrm{C_{material\ airframe_y}} = \left\{\frac{\text{Material Cost}}{\text{Trip}} \times (\#\ \text{of trips})\right\} \mathrm{AF_y} \times \mathrm{IR_y} \times \mathrm{CF_{\$\rightarrow€}} \qquad Eq.\ 58$$

With $\mathrm{C_{material\ airframe_y}}$ the maintenance material cost of the airframe (€), $\frac{Material\ Cost}{Trip}$ is the material cost per trip or FC, given by *Eq. 23*, AF_y is the aging factor for a certain aircraft age, given by *Eq. 43*.IR_y is the inflation rate for interest year, which can be obtained by *Eq. 46*. Moreover, a conversion factor $CF_{\$\rightarrow€}$ is added to convert the costs from USD to EUROS.

In addition, in order to estimate maintenance material cost for a certain component, again the assumption is made that the material cost of a component relative to the airframe has the same ratio as the component weight over the airframe weight. This expression is shown by *Eq. 54* for maintenance labor cost estimation. So similar equation is drawn for material maintenance cost:

$$C_{material\ component\ y} = C_{material\ airframe\ y} \times \left(\frac{W_{component}}{W_{airframe}}\right) \qquad Eq.\ 59$$

Where $C_{material\ component}$ represents the maintenance material cost for a component [€] and $W_{airframe}$ is the weight of component [€].

The same relations as used in *Eq. 49-Eq. 53* can be used to express the maintenance material cost of airframe or component into scheduled maintenance and unscheduled maintenance for a certain aircraft age.

The Unscheduled Maintenance Material Cost for **airframe:**

$$C_{UNMM\ y} = \frac{C_{material\ airframe\ y}}{\left(1 + \frac{1}{0.0487y + 0.8397}\right)} \qquad \textit{Eq. 60}$$

Where;
$C_{UNMM\ y}$ is the unscheduled maintenance material cost of the airframe for a certain aircraft age y [€].
$C_{material\ airframe\ y}$ is the maintenance material cost of the airframe for a certain aircraft age y [€].
y is the aircraft age in years, $y = 1,2,..,20$.

The Scheduled Maintenance Material Cost for **airframe:**

$$C_{SMM\ y} = C_{material\ airframe\ y} - C_{UNM\ y} \qquad \textit{Eq. 61}$$

Here is $C_{SMM\ y}$ the scheduled maintenance material cost for certain aircraft age y [€]

The **Scheduled and Unscheduled Maintenance Material Costs, $C_{UNMM\ y}$ and $C_{SMM\ y}$,** for **components** can be estimated with the following expressions:

$$C_{UNMM\ component\ y} = \frac{C_{material\ component\ y}}{\left(1 + \frac{1}{0.0487y + 0.8397}\right)} \qquad \textit{Eq. 62}$$

$$C_{SMM\ component\ y} = C_{material\ component\ y} - C_{UNMM\ component\ y} \qquad \textit{Eq. 63}$$

Where y is the aircraft age in years, with $y = 1,2,..,20\ years$.

5.1.3 Maintenance Overhead Cost Estimation

The airframe overhead cost at the aircraft age y can be evaluated by modifying *Eq. 25* and inserting it into *Eq. 47*:

$$C_{overhead\ airframe\ y} = overhead\ factor \times C_{labor\ airframe\ y} \qquad \textit{Eq. 64}$$

With $C_{overhead\ airframey}$ the maintenance overhead cost for a certain aircraft age y and $C_{labor\ component\ y}$ the direct maintenance labor cost of component for a certain aircraft age y, given by *Eq. 55*. To estimate airframe overhead and eventually the component overhead expenses, recent data of IATA's MCTF are utilized to obtain a more realistic and applicable value for the overhead factor. Therefore, according to Figure 18, a relation can be developed to obtain the overhead factor of *Eq. 64*. The following relations are extracted:

$$DMC_{airframe} = 33\%\ of\ TMC \qquad \textit{Eq. 65}$$

From the latest MCTF report (IATA, 2013) the overhead cost is approximately 20% of TMC:

$$Overhead = 20\%\ of\ TMC \qquad Eq.\ 66$$

By combining *Eq. 65* and *Eq. 66*, the overhead is expressed as:

$$Overhead = \left(\frac{0.20}{0.33}\right) DMC_{airframe} \qquad Eq.\ 67$$

Eq. 67 gives the overhead as a function of DMC of the airframe ($DMC_{airframe}$). While it is desired to express the overhead costs as a function of airframe maintenance labor cost ($C_{labor\ airframe}$). According to Figure 19, which shows the contribution of the labor and material maintenance cost to the airframe DMC. Labor consists of 75% $DMC_{airframe}$, Therefore, *Eq. 67* can be modified to the following equation:

$$C_{airframe\ overhead\ y} = 0.75\left(\frac{0.20}{0.33}\right) C_{labor\ airframe\ y} \qquad Eq.\ 68$$

In *Eq. 68* the up-to-date overhead factor is $0.75\left(\frac{0.20}{0.33}\right)$. The overhead cost is expressed as a function of airframe labor cost per aircraft age y. To adjust the overhead cost for the component, the weight fraction can be employed in *Eq. 68* or a direct relation can be obtained by using the labor cost of the component:

$$C_{component\ overhead\ y} = 0.75\left(\frac{0.22}{0.33}\right) C_{labor\ component\ y} \qquad Eq.\ 69$$

5.2 Interval-Based Method

In order to analyse the influence of design parameters on aircraft component maintenance cost, the Interval Based Method (IBM) is developed. First, the aircraft is broken down into several parts. Thereafter, bottom-up maintenance cost estimation is performed. This bottom-up analysis allows more detailed maintenance cost estimation and it can be useful to reveal the underlying principle of how the design parameters impact on its maintenance cost. The aircraft main components are divided into: wing, fuselage and empennage. Every component can be broken down into structural parts. An airframe breakdown is given in Appendix D . For example, the empennage is broken down into horizontal tail and vertical tail. The vertical tail plane can be subdivided into rudder, fin and can be further divided in to parts such as skin, ribs, spars, and attachments, *etc*.

The process flow of IBM is illustrated in Figure 31. As depicted in the figure, particularly the middle layer, an analysis work flow is built to integrate the component design & maintenance properties to the framework, which is elaborated in sub-section 5.2.2 in more detail, by zooming into the integrated Aircraft Component Design & Maintenance. The elaborated process flow is shown in Figure 32. First the aircraft component is decomposed into several parts which carry loads, i.e. spar and sandwich skin. Then the materials which are used for those parts are analysed. The failure modes those could occur due to the fatigue, impact and corrosion damages are elaborated. Afterwards, the damage growth versus load cycles or flight

cycles should be determined. The strength reduction due to the damage growth should be found. The maintenance tasks together with the maintenance intervals can be selected based on various failure modes. At the end, the maintenance cost can be estimated for each rudder part based on the selected maintenance tasks.

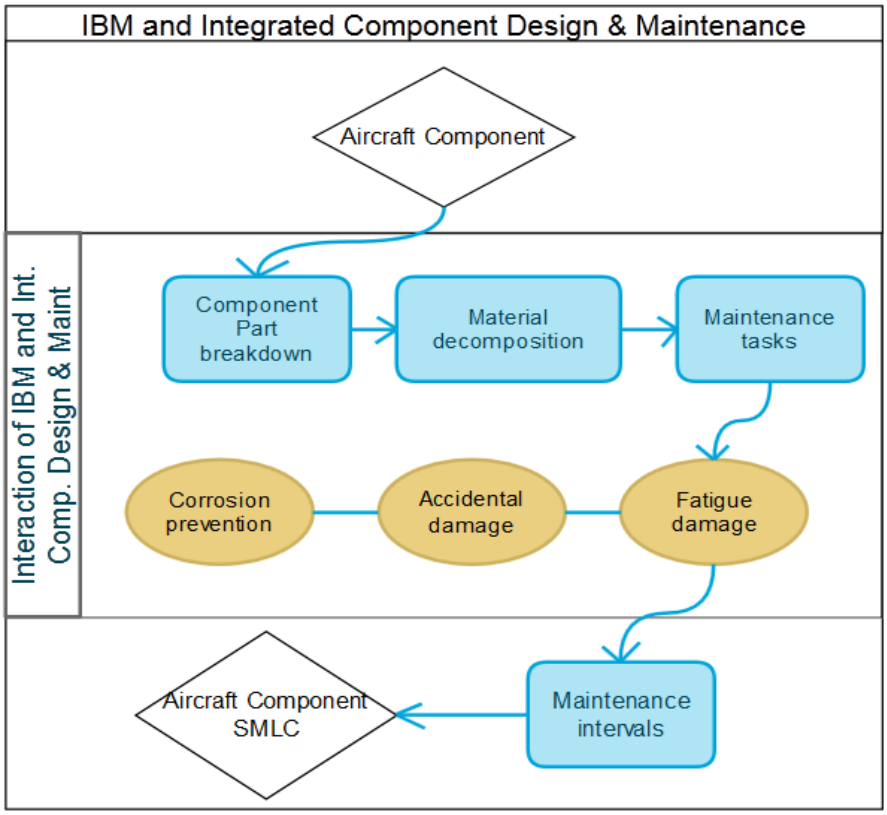


Figure 31 IBM and Integrated Component Design flowchart

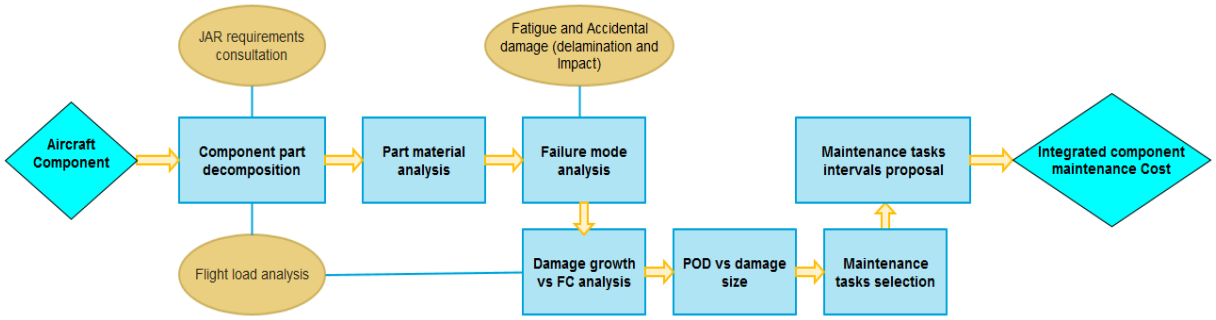


Figure 32 flowchart of Integrated Aircraft Component Design & Maintenance

In Figure 33 a more detailed representation of implementing the IBM method is shown. The figure also illustrates how the IBM is used to generate the cost of maintenance inspections. First, an aircraft component i.e. wing or vertical tail is chosen for maintenance cost estimation. The component is then divided into sub-parts. The material used for each sub-part is extracted. Moreover, a distinction is made for the composite and non-composite components. By taking maintenance task intervals and the associated man-hours into

consideration, the IBM is applied to estimate the SMLC for different parts associated with their specific geometries, materials, and the maintenance characteristics. From another perspective, by grouping various types of maintenance tasks applied on the component, the IBM can also be applied to determine the SMLC of different types of maintenance tasks from MSG-3.

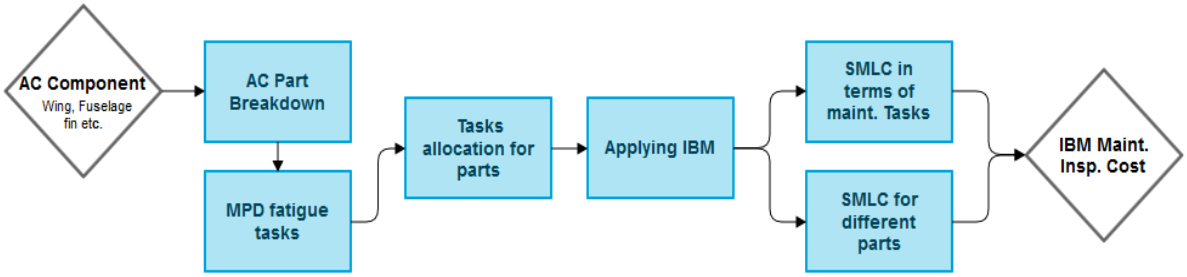


Figure 33 IBM method implementation

The following is done to predict maintenance task intervals based on design parameters specifically for the components made from composite materials:

1) The composite parts of a certain aircraft component are detected; this is done after the aircraft is broken down into several parts.
2) The composite failure modes and defects of the associated composite parts should be analysed.
3) The maximum loads and stresses on the parts of interest should be determined by equations/ diagrams that describe the failures. The flight envelope and regulations should be used to determine the ultimate loads and stresses.
4) After determination of the loads and stresses, the S-N curves will be used to determine the number of cycles to failure.
5) By knowing the failures due to cyclic loading, the MSG-3 tasks can be used to determine the maintenance program in calendar unit if necessary.
6) The results can be implemented in the maintenance cost model (Excel) to obtain maintenance cost estimation based on the design parameters of the composite materials.

5.2.1 Scheduled Maintenance Labor Cost Estimation

The scheduled labor costs are estimated by *Eq. 17* to *Eq. 20*. The parameters, equations and sources used for the Interval-Based Method are shown in Table 6. It should be emphasized that the labor cost estimation by IBM method does not incorporate the aging influence. And the method estimates the average annual maintenance cost per calendar unit.

Table 6 parameter table for Interval-based Method

Parameters	Unit	Equations/source
FH	hr	(IATA, 2013)
FC	-	(IATA, 2013)
r_{labor}	€/hr	(Zhao et al.,2014)
FPM_i	-	MPD A330-200
MTTF	hr	MPD A330-200 and *Eq. 20*
$ETPMT_i$	Hr	MPD A330-200
λ_i	-	MPD A330-200
$AFPM_i$	-	MPD A330-200, *Eq. 182* and *Eq. 183*
$C_{labor,preventive}$	€	*Eq. 17-Eq. 20*

The inputs for *Eq. 17* to *Eq. 20* are taken from the MPD of a specific aircraft, of which the maintenance cost is going to be estimated. The flight hour (FH) is taken from IATA's maintenance task force commentary (IATA, 2013) for a certain aircraft. Further the labor rate (r_{labor}) can be country or company dependent and it is a variable. $ETPMT_i$ is approximated to be equal to the man-hours stated in the column of Man-Hour for a certain maintenance task in the MPD. FPM_i, the frequency of preventive maintenance task, is adopted for the average annual cost calculation. The frequency of the preventive maintenance tasks are given in flight cycles and/or flight hours. Further, the intervals of tasks from MPD are given as a single C-check interval (C) or a multiple C-check intervals (nC). A C-check interval is equivalent to 18 months, which can be further normalized into hours. In order to obtain the number of a specific preventive maintenance task i applied in a year, the following expression is adopted:

$$AFPM_i = \frac{h_y}{i_h} \qquad \textit{Eq. 70}$$

Where;
$AFPM_i$ is the annual frequency of preventive maintenance task i, for $i = 1,2,3,\dots,k$.
h_y is amount of hours in one year (hr)
i_h is the task interval in hour (hr)

The amount of hours in a year is estimated, $h_y = 12 * 30 * 24 = 8640\ hr$, which assumes 30 days each month). So *Eq. 70* can be rewritten as:

$$AFPM_i = \frac{8640}{i_h} \qquad \textit{Eq. 71}$$

The interval conversions from checks to flight hours of i_h are shown below:

Interval in Checks	**Interval in hour, month or year**	i_h **[hr]**
A-Check and multiples	600 FH and multiples	600
C-Check	18 Months	12960
2C-Check	36 Months	2×12960
4C-Check	6 Years	4×12960
8C-Check	10 Years	8×12960

Now the *Eq. 17* can be rewritten to express the preventive (scheduled) maintenance labor cost (SMLC) for a certain inspection task.

$$C_{labor,Scheduled} = \frac{FH \times r_{labor} \times \frac{\left(\sum_{i=1}^{k} AFPM_i \times MMH\right)}{\sum_{i=1}^{k} AFPM_i}}{MTTF} \qquad Eq.\ 72$$

With MMH the amount of man-hours (hr) and $AFPM_i$ given by *Eq. 71*. Mean Time To Failure (MTTF) equals the reciprocal of the summation of all failure rates $\sum \lambda_i$, as indicated in the *Eq. 20*. Approximately, the failure rate λ_i can be assumed to be equivalent to the reciprocal of inspection interval. By extracting maintenance task intervals from MPD, the failure rates can be obtained in terms of C-checks or multiples of C-checks. While in order to determine the actual failure rate λ_i for a specific part, the structural analysis of an aircraft component should be made. After the structural analysis, the maintenance inspection intervals can be determined to provide the maintenance cost estimation instead of the interval data extracted from the MPD. This effort has been elaborated in the sub-section 5.2.2. In this research, attempt has been made to analyse the fatigue behaviour of a component made of composite material under cyclic loading conditions, so that the number of cycles to failure for this aircraft component can be determined. After the examination of the relation between the composite damage growth rate and the number of applied load cycles, the reduction of structural strength can be determined. When the structural strength of the component reaches the threshold for maintenance, maintenance activities need to be performed. The number of load cycles correspondent to the threshold can be extracted to obtain the maintenance interval of the component. In the next sub-section, a methodology is developed to conduct the aforementioned analysis process, which illustrates and emphasizes the aircraft component design properties influence on the maintenance inspection intervals, and eventually their impacts on the maintenance cost.

5.2.2 Integrated Aircraft Component Design & Maintenance

In this sub-section, the attention is laid on the influences of the aircraft design on the maintenance process. In particular, it analyses how the maintenance inspection intervals are determined, and what are the effects of typical damages on the maintenance intervals and eventually on the maintenance cost. It introduces the overall process flow of developing the maintenance program, which is then elaborated in more detail. First, the aircraft component parts which require maintenances are analysed based on MSG-3 regulations. Followed by the analysis of aircraft loads, those are acting on the aircraft component during typical aircraft mission. Thereafter, the number of load cycles for the typical loads in each flight cycle is estimated. Then the composite fatigue damage evaluation is elaborated. Finally, the method which determines the maintenance inspection interval is discussed.

The structural maintenance program can be developed by using the workflow shown in Figure 34. The processes workflow is meant to support the analysis to obtain the maintenance intervals. The processes can be separated in 4 phases. In Phase (1), the aircraft structure parts are analysed. And the materials properties should be extracted (white blocks with black boarder). In Phase (2), the flight envelope, regulations, critical flight conditions with the

associated loads and stresses should be reviewed (grey blocks). In Phase (3), the S-N curves with failure rates of the parts and sub-parts should be determined for fatigue damages (blue blocks) and in phase (4) fatigue, residual stresses etc. should be determined which results to maintenance structural program for the SSI or PSE (red and green blocks).

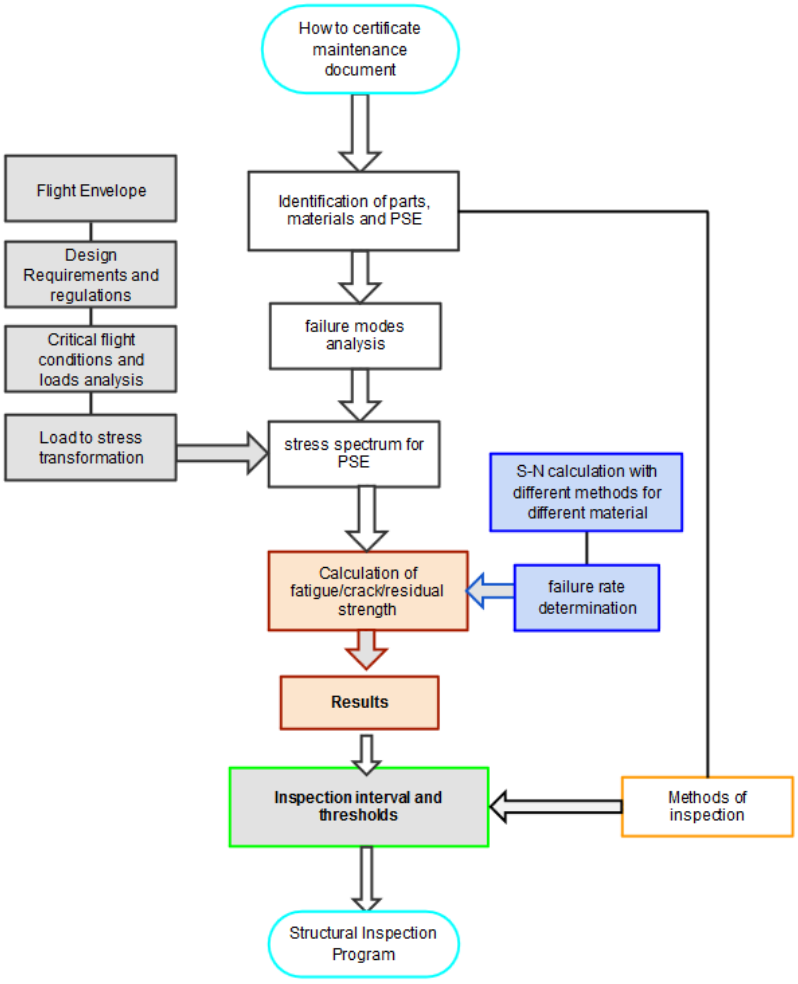


Figure 34 structural maintenance program development adapted from (Homan, 2008)

Structural Significant Items (SSI)

To obtain the structural maintenance program for a particular part, the aircraft is defined in several aircraft zones or areas first. In every zone area, the structural items included are identified. Then the Structural Significant Items (SSI) or the Principal Structural elements (PSE) are distinguished, as shown in Figure 35. SSI is defined by ATA (1993) as any element or aircraft structure that significantly carries flight, ground, pressure or control loads and whose failure could affect the flight safety. SSI (or PSE) contains items whose failure (ATA, 1993):

- Could have safety effect (on ground or in-flight) and/or
- Is undetectable during operations and/or
- Could have significant operational impact and/or
- Could have significant economic impact

Regarding a complete analysis tree of the SSI, the reader is encouraged to consult the MSG-3 analysis (ATA, 1993). The determined SSI parts are subjected to accidental damage, fatigue damage and environmental deterioration analyses that can result in corrosion prevention & control program. At the end of fatigue damage analysis and corrosion prevention & control program, a structural maintenance program can be constructed (Homan, 2008). The accidental damage does not have direct influences on the structural maintenance program because of its stochastic character.

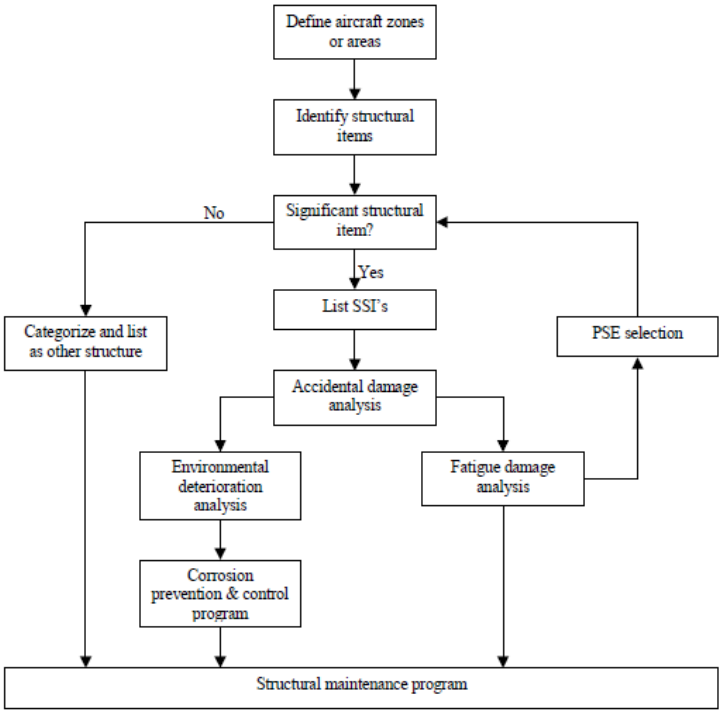


Figure 35 MSG-3 structural analysis flowchart (Homan, 2008)

The SSI/PSE requires mandatory inspections and they are mentioned in MPD as Airworthiness Limitation Items (ALI). The aircraft operator must inspect the ALIs at a predefined interval (Homan, 2008). Examples of PSE are:

- Control surfaces with their attachment hinges and fittings
- Integrally stiffened plates
- Primary fittings
- Principal splices
- Skin or reinforcement around cut-outs or discontinuities
- Skin-stringer combinations
- Spar cabs
- Spar webs

Aircraft Loads

In phase (2), load conditions for the component are examined. The aircraft loads can be divided into three categories: i) quasi-static loads, ii) dynamic loads and iii) fatigue loads. In Table 7 these loads are categorized (Neubauer, 2000).

Table 7 aircraft loads adapted from (Neubauer, 2000)

Quasi-static loads				
Flight loads	**Ground loads**	**Local and internal loads**	**Dynamic loads**	**Fatigue loads**
Symmetric manoeuvres	Take-off	Max/min aerodynamic pressure	buffet	Derived from quasi-static load with dynamics loads
Asymmetric manoeuvres	landing	Local acceleration	Dynamic gust	The frequency should be sufficiently high
Gust loads	Repaired runway	System/bay pressures	Shimmy (undercarriage)	Mostly combination of flight loads with local internal loads or acoustic loads
	Taxing, towing, etc.	Hydrostatic pressures	Acoustic noise	
		Engine pressure	Limit cycle	
			vibrations	

To determine the maintenance inspection interval regarding aircraft load for the fatigue evaluation, the load spectra/stress spectrum of a particular aircraft can be consulted. Load spectrum is the loads those are acting on the aircraft during service time. Knowledge of the loads in terms of frequency (number of load cycles), load sequence and load amplitudes are required. To define a load spectrum correctly, the load application of an aircraft should be known before aircraft's first flight. The load spectrum can contribute to correct proposed maintenance plan regarding the component structure. Two different type of load categories can be distinguished (Homan, 2008):

1. Deterministic loads
2. Stochastic loads

Deterministic loads are loads of which both magnitude and occurrences are known. These loads are well suited to define a load spectrum. Examples of deterministic loads are pressure vessels (e.g. aircraft cabin) and aircraft manoeuvres.

Stochastic loads are of statistical nature, both magnitude and occurrence of such a load at a given time are not predictable. Stochastic loads are random loads of which the statistical data are gathered by long term measurements. An example of stochastic loads is the loads caused by turbulence. It must be noted that many load types have a mixed characters: deterministic by magnitude and stochastic by occurrences.

The modern aircraft is designed using the principle of Damage Tolerance. The DT implies that a damaged structure (due to fatigue, corrosion or accidental damage) to a certain level should be capable to sustain a certain in-service loads before the damage is detected under a pre-defined inspection interval (Goranson, 2007). Fatigue is the material deterioration caused

by repeatedly applied loads (Schijve, 2009). Accidental damage is the physical deterioration of an item caused by impact damage with an object which is not part of the aircraft. Also incorrect executed maintenance procedures can lead to impact damage (e.g. tool drop). Environmental damage on the other hand is the physical deterioration of a part's strength as a result of chemical interaction with the climate or environment (Homan, 2008). The principle inspection planning parameters for fatigue, environmental and accidental damage are shown in Table 8. The damage is categorized in two phases, the damage initiation phase and the damage growth phase. In this analysis only fatigue damage is considered. The inputs, which drives the inspection planning, for both the initiation phase and the growth phase are mainly: cyclic loading (stress), flight cycles/hours and the material that is used, Table 8.

Table 8 inspection planning for damage phase (Goranson, 2007)

Damage phase	Principal inspection planning parameters		
	Fatigue	**Environmental deterioration**	**Accidental**
Initiation	• Design quality • Cyclic stress • Operating environment • Flight cycles	• Corrosion - Operating environment - Protective system • Stress corrosion - Material sensitivity - Sustained stress	• Random discrete event from a cause not normally encountered during fleet operations
Growth	• Material • Geometry • Cyclic stress • Environment • Flight cycles/hours	• Extent of conditions that causes damage initiation • May result in subsequent crack growth if not detected and repaired	• May result in subsequent crack growth if not detected and repaired

Load Cycles (LC) in a Flight Cycle (FC)

Still in phase (2), the number of Load Cycles (LC) should be quantified. The mission profile of a particular aircraft can be used to obtain the relation between flight cycles and load cycles. A typical flight profile is shown in Figure 36 for the A330 Short Range (SR), A340SR and A340 Medium Range (MR).

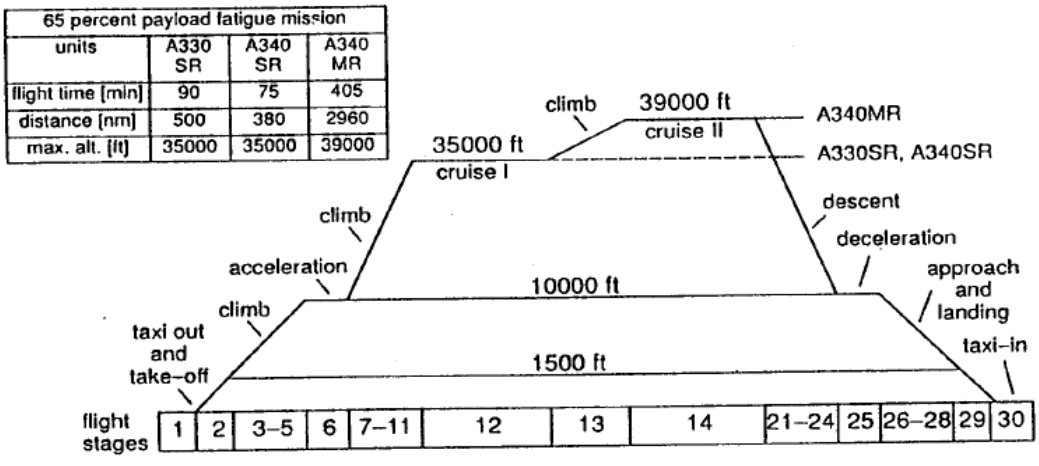


Figure 36 mission profile A330/A340 (Schmidt et al., 1995)

It can be seen from Figure 36 that the mission profile is divided in 30 flight stages. The flight stage starts with take-off and ends with taxi-in. In Table 9 the relevant flight loads and ground loads are listed. The operational basic conditions, the loading component during flight and the load representation are stored in the table. A similar but categorized operational basic load conditions can be seen from Table 10. The load representation can be seen as the occurrence of the loads during ground-flight-ground condition. Some of the occurrences of loads are constant while others (in flight) are stepped spectra. The stepped spectra depend on the flight route with variable flight ranges. Schmidt el al. (1995) has distinguished the different flight types with the letters A-H, as indicated in Table 10.

Table 9 representation and application of operational conditions (Schmidt et al., 1995)

	Operational basic conditions	Loading component	representation
ground	Standing		Steady case
	Taxi-out		Two cycle per flight
	Pre-flight breaking		-
	Ground turning		-
	Taxi-off run		Two cycle per flight
	Rotation		Steady case
flight	Initial climb Climb Cruise I Cruise II Initial descent approach	Vertical gust	Stepped spectra
		Vertical manoeuvre	Stepped spectra
		Lateral gust	Stepped spectra
		Lateral manoeuvre	Stepped spectra
		ΔP	Stepped spectra
		Temperature load	Stepped spectra
ground	Touch down		One cycle per flight
	Landing roll		Two cycle per flight
	Braking		-
	Ground turning		-
	Taxi-in		-

Table 10 loads on the aircraft at, GAG (schmidt et al., 1995)

Application	Basic loads (1G)	Incremental loads
Ground	Standing on ground, taxi-out, take-off run, rotation	Rolling bumps (high speeds) Taxi bumps (low speeds)
Flight	Climb, cruise, approach (up to eleven different flight cases)	Vertical gust Lateral gust Vertical manoeuvre Lateral manoeuvre
Ground	Touch down, landing roll-out, taxi in	Landing (0.61 m/s-1.83 m/s) Rolling bumps (high speeds) Taxi bumps (low speeds)

Table 11 A30 load matrix for cruise flight, GAG spectrum (Schmidt et al., 1995)

Flight type	Frequency of flight type per block	Load cycles per flight	Load cycles per block	Load cycles per life
A	5	41	205	2050
B	7	34	238	2380
C	22	24	528	5280
D	56	16	896	8960
E	130	11	1430	14300
F	380	8	3040	30400
G	1000	3	3000	30000
H	2400	1	2400	24000

To determine the number of LCs in a FC, the mission profile of the aircraft can be employed. This is illustrated by using the rudder on a typical A330 as an example. As shown in Figure 36 and Table 9 to Table 11, mainly the lateral loads and lateral gusts are important (yawing and rolling motions) for the vertical tail including the rudder. The following expression can be developed to calculate the number of LCs per each FC:

$$\frac{\#LC}{FC} = loads_{g_I} + loads_f + loads_{g_{II}} \qquad Eq.\ 73$$

Where;
$\frac{\#LC}{FC}$ is the number of LCs per each FC
$loads_{g_I}$ is the number of loads during ground operation (before take-off) on the component
$laods_f$ is the number of loads during flight operation on the component
$loads_{g_{II}}$ is the number of loads during ground operation (after the landing) on the component

Each segment of *Eq. 73* can be divided in more detail according to the differences of the flight phases shown in Appendix F .

Composite Fatigue Evaluation

In Phase (3), the fatigue stress for the composites can be determined by a different S-N curve than that of metals. The following expression calculates the maximum fatigue stress for composites (Mallick, 2007).

$$S_{max} = \sigma_u(m \log N_f + b) \qquad Eq.\ 74$$

Where;
S_{max} is the maximum fatigue stress
N_f is the number of LCs to failure
σ_u is the average static strength
m, b are constants

Eq. 74 can be rewritten to find the number of cycles to failure, which is also called the fatigue life:

$$N_f = 10^{\left(\frac{S_{max}}{\sigma_U} - b\right)/m} \qquad Eq.\ 75$$

Some typical values for b *and* m in *Eq. 75* are given by Table 12.

Table 12 constants for different type of composite materials (Mallick, 2007)

Material	Layup	m	b
E-glass-ductile epoxy	0°	-0.1573	1.3743
T-300 Carbo-ductile epoxy	0°	-0.0542	1.0420
E-glass-brittle epoxy	0°	-0.1110	1.0935
T-300 Carbon-brittle epoxy	0°	-0.0873	1.2103
E-glass-epoxy	[0°/±45°/90°]	-0.1201	1.1156
E-glass-epoxy	[0°/90°]	-0.0815	0.934

In this research, *Eq. 75* is used to calculate the number of cycles to failure. It is observed from *Eq. 75* that the number of cycles to failure depends on the maximum stress, S_{max} , the b and m (which is assumed as constant values), and the average static strength, σ_U . The maximum stress S_{max} is obtained from the analysis of the critical maximum load. The average values from Table 12 are approximated to 1.09 and 0.10 respectively, representing the constants b and m. The average static strength of the material reduces in presence of the damage. In Figure 37, the ratio of damaged over undamaged strength varies along with the increase of the damage size. In this figure, the ratios of the following damage types are illustrated: impact damage, porosity and delamination.

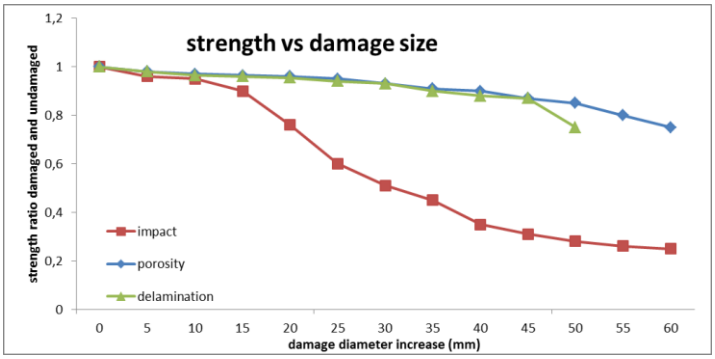


Figure 37 strength vs. damage diameter (adapted from Kassapoglou, 2010)

As it can be seen from the figure the impact damage strength reduces in higher rate than delamination and porosity. According to Figure 37, a group of formula can be developed to express the ratio between undamaged and damaged compression static strength in terms of an increasing damage size. In this case, the damage size refers to the damage diameter increases. A linear approximation is practical for porosity and delamination, while exponential equation is more suitable for impact damage. Therefore, the porosity and delamination damages can be approximated by the following expressions:

$$\left(\frac{(\sigma_U)_{Dam}}{(\sigma_U)_{undam}}\right)_{Porosity} = -0.0037 \times DS + 1.02 \qquad Eq.\ 76$$

$$\left(\frac{(\sigma_U)_{Dam}}{(\sigma_U)_{undam}}\right)_{Delamination} = -0.0038 \times DS + 1.0159 \qquad \textit{Eq. 77}$$

The exponential expression for impact damage is given by:

$$\left(\frac{(\sigma_U)_{Dam}}{(\sigma_U)_{undam}}\right)_{Impact} = 1.1604e^{-0.027 \times DS} \qquad \textit{Eq. 78}$$

Where DS represents the damage size (mm).

These equations are for typical composites such as glass fibre and carbon fibre in the presence of damage. The strength of composite materials in the presence of damage is significantly lower and varies with the damage sizes and damage types, see *Eq. 76-Eq. 78* and Figure 37. It should be noted that for different type of materials and or layups, different behaviours are expected. However, the trends shown in Figure 37 are representative for most composites types (Kassapoglou, 2010). To express the damage directly as a function of damage size (DS) and undamaged compression static strength (σ_U) *Eq. 76* to *Eq. 78* are rewritten to:

$$(\sigma_U)_{Dam_{porosity\ compr.strength}} = (\sigma_U)_{undam_{porosity}} \times (-0.0037 \times DS + 1.02) \qquad \textit{Eq. 79}$$

$$(\sigma_U)_{Dam_{del.compr.strength}} = (\sigma_U)_{undam_{delamination}} \times (-0.0038 \times DS + 1.0159) \qquad \textit{Eq. 80}$$

$$(\sigma_U)_{Dam_{impact\ compr.strength}} = (\sigma_U)_{undam_{impact}} \times 1.1604e^{-0.027 \times DS} \qquad \textit{Eq. 81}$$

Where;
$(\sigma_U)_{undam}$ the undamaged static strength for a certain damage type: impact, delamination or porosity (MPa)
$(\sigma_U)_{Dam}$ is the damaged static strength for certain a certain damage type: impact, delamination or porosity (MPa)

Maintenance Inspection Interval Determination

In phase (4), it analyses the inspection interval concerning the fatigue damage which is caused by cyclic loading, where the Figure 38 and the Figure 39 can be utilized. The relation between the initial inspection intervals, in terms of visual inspection or special detailed inspection by using NDI methods and the damage growth are shown in the figures. The figures are applicable for inspectable structures which are made from DT design principles (Goranson, 2007). According to the DT philosophy, in every structure there are initial failures such as flaws as a consequence of imperfections during the manufacturing phase. It is assumed that the initial flaws are undetectable by NDI methods.

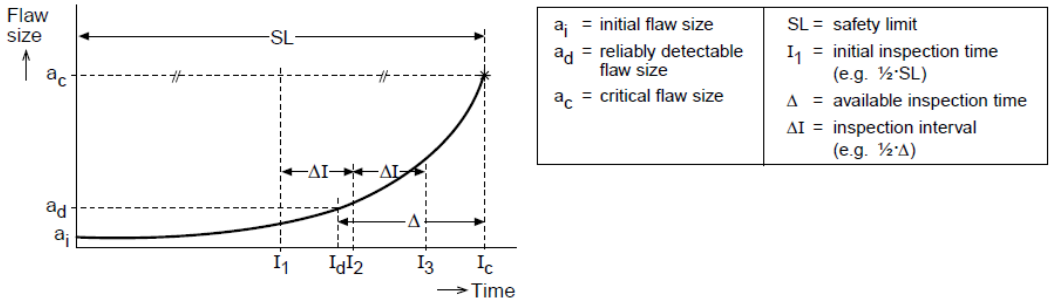


Figure 38 determination of initial inspection time I_1 and inspection interval ΔI (Heida and Grooteman, 1998)

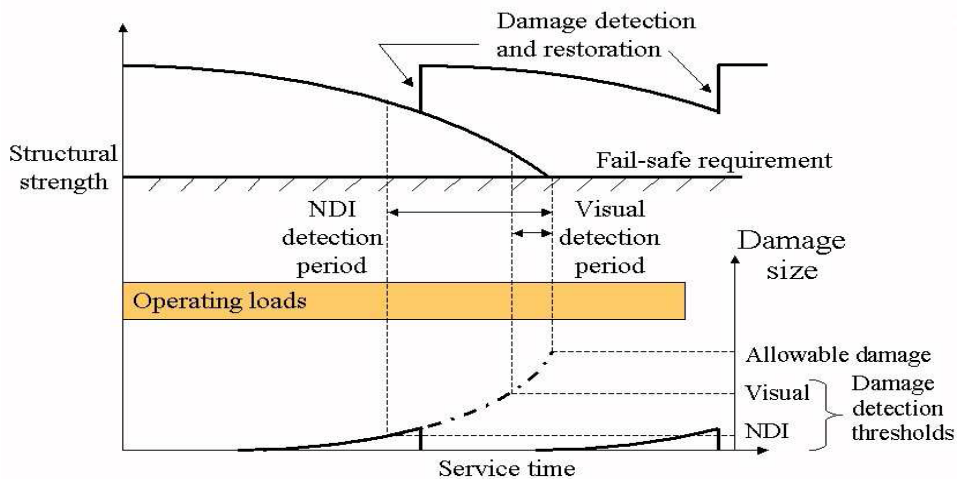


Figure 39 structural strength and inspection interval (Goranson, 2007)

In Figure 39, the structural strength together with damage size is given as a function of aircraft service time. Before structural strength of a structure decreases to fail-safe requirement, the structures should be inspected and restored to its initial state level. In the most cases initial state of the structure is considered to have a reliability of 100% (Kinnison, 2004). The damage detection and restoration point is predetermined by designers according to regulations within a certain level of acceptance. By combining both of the figures, the following rules are extracted:

- Safety Limit (SL), $SL = I_c - I_o$,with I_0 the inspection time at a_0 and is 0
- Initial inspection time $I_1 = \frac{1}{2}SL$
- The available inspection time, $\Delta = I_c - I_d$, where I_c is the critical inspection time and I_D is the flaw reliably detectable inspection time
- The inspection interval $\Delta I = \frac{1}{2}\Delta$. Subsequent the inspection interval is $\Delta I = \frac{I_c - I_d}{2}$
- The second inspection interval $I_2 = I_1 + \Delta I = \frac{1}{2}SL + (I_c - I_d)$
- The third inspection interval $I_3 = I_1 + 2\Delta I = \frac{1}{2}SL + 2(I_c - I_d)$
- j^{th} inspection interval $I_j = I_1 + (j-1)\Delta I$

As it can be seen from the Figure 39, after the detection and restoration the flaw size reaches again its initial size a_i. Further the detection periods for visual inspection and special detailed inspection (NDI detection) can be extracted.

- $NDI_{\text{detection period}} = I_c - I_1$
- $Visual_{\text{detection period}} = I_c - I_{VI}$, where I_{VI} is the threshold for visual inspection detection, it is between I_D and I_C
- $NDI_{\text{detection period}} > Visual_{\text{detection period}}$

The visual damage detection is less expensive than the NDI damage detection (Heida, 2013). Further, in order to find defects during the maintenance inspection for several aircraft parts, designers have to set up confidence levels for inspections, which refers to the reliability of detecting the flaws. This is done to avoid the so called No Fault Found (NFF) which is seen as a waste during the inspection (Goranson, 2007). Moreover, from the safety point of view, it is essential to assure the defects can be found within the SL before the critical flaw size is reached. For a certain inspection type, either NDI or visual inspection, the required detection reliability is shown in Figure 40.

Required detection reliability				
Structure			Cumulative detection probability, %	Equivalent detection opportunities (DTR)
Wing and nacelles	Externally visible areas		94	4
	Areas not externally visible		98	6
	Primary flap structure		99	8
Empennage	Primary structure		98	6
Fuselage	Contribution of cabin differential pressure to total fail-safe stress	<50%	98	6
		≥50%	99.9	10

Figure 40 required damage detection reliability for an aircraft (Goranson, 2007)

6 Case Study of A330-200 Rudder

As mentioned in in the research scope (Chapter 2), the developed methods are applied on the A330-200 rudder component to obtain results. This chapter starts with Section 6.1, in which the AIM is applied to estimate the maintenance labor cost, the material cost and the overhead cost. In addition, a distinction is made in terms of scheduled maintenance cost and unscheduled maintenance cost. At the end of this section, the influences of the maintenance cost drivers, including the operational parameters and the design parameters, are shown by using sensitivity analysis. In Section 6.2, the IBM is applied to determine the scheduled maintenance labor cost for the specific rudder parts and the associated maintenance tasks. Subsequently, in the Sub-section 6.2.2 the analyses of the integrated aircraft component design & maintenance, which is a part of the IBM method, is exemplified. It illustrates the detailed procedure of obtaining maintenance task intervals for the fatigue damage cause by compression loading conditions. In the meantime, it emphasizes the influence of the design variables, such as the component geometric size and its composite material properties, on the maintenance interval, and further on the maintenance cost.

The A330-200 rudder is mainly made from composite materials. The inner and outer skin, the upper and the lower ribs, and the spars are Carbon Fibre Reinforced Polymer (CFRP). The core of the skin is made from Nomex honeycomb. Only the hinge, actuator arm and fittings are not composite. Figure 41 shows the A330-200 rudder and its material list.

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

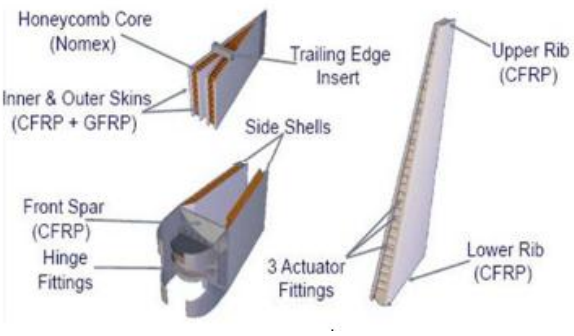


Figure 41 the A330-200 rudder (Tissenier, 2012)

6.1 Aging Involved Method

In this section the AIM is used to produce results for the A330-200 rudder. Before presenting the equations and results which estimate the scheduled and unscheduled maintenance costs, the parameters of interest are shown in Table 13. The variables stated in this table will be used to estimate the weight and the cost of the rudder; these parameters are aircraft characteristics, so called the design parameters. The airline operation parameters are provided as well in the table. The sources and corresponding reference of each variable are shown in the last column.

Table 13 the operation and design parameters used as input for MC of A330-200

Variable	Description	Value [unit]	Source/Reference
MTOW	Max. Take-off Weight	230 000 kg = 507063 lbs	(A330 Flight deck and systems briefing for pilots, 1999)
$W_{airframe}$	Weight of airframe	57897 kg=127641 lbs	Figure 98, Table 45 and Table 46
S_V	Vertical tail surface	47.60 m^2 = 512.92 ft^2	(Jenkinson et al., 2001)
$\frac{W_{rudder}}{W_{airframe}}$	Ratio between rudder weight and airframe weight	0.0148 (1.48%)	Figure 98, Table 45, Table 46 , *Eq.32- Eq. 194*, and *Eq. 85- Eq. 90*
N_ult	Ultimate load factor	3,84	*Eq. 82*, (Cavcar,(2004) and (A330/A340 flight crew training manual, 2002)
b_v	Span of vertical tail	9.44 m = 30.96 ft	Appendix I and (Jenkinson et al., 2001)
$(t/c)_{avg}$	Average airfoil thickness	0.082	*Eq. 83* Ciornei (2005) and Torenbeek (1988) equations and Liebeck (1995)
S_{wg}	Gross wing surface	361.10 m^2= 3892.357 ft^2	(Airbus, 2014) and (Jenkinson et al., 2001)
Λ_{ea}	¼ chord sweep	45°	(Liebeck et. al, 1995) and (Jenkinson et al., 2001)
S_{rudder}	Rudder surface area	13.86 m^2	Appendix I
$(A.R)_{tail}$	Aspect ratio tail	1.87 A.R = $(b_v)^2/S_v$	(Jenkinson et al., 2001)
$\boldsymbol{\lambda}$	Taper ratio= length of tip chord/Root chord	0.350	(Jenkinson et al., 2001)
r_{labor}	Labor rate	43.5 euro/hour	(Zhao et al., 2014)
IR	Inflation rate	1.96% , 1.0196	*Eq. 43* (FXtop, 2013)
FH	Flight Hour	4088 hr	(IATA, 2013)
FC	Flight Cycle	951	(IATA, 2013)
AF_y	Aging Factor	variable	*Eq. 43*, Table 5 and Figure 28

Figure 27 shown in section 5.1 can be expanded by adding the specific design parameters for rudder maintenance cost estimation as shown in Figure 42. In Sub-section 6.1.1 to 6.1.3, the research obtains the SMLC, UNMLC, SMMC, UNMMC and overhead costs, which are outputs stated in Figure 42. The Table 13 and the Figure 42 can be referenced as a road map which leads to the implementation towards its final outputs.

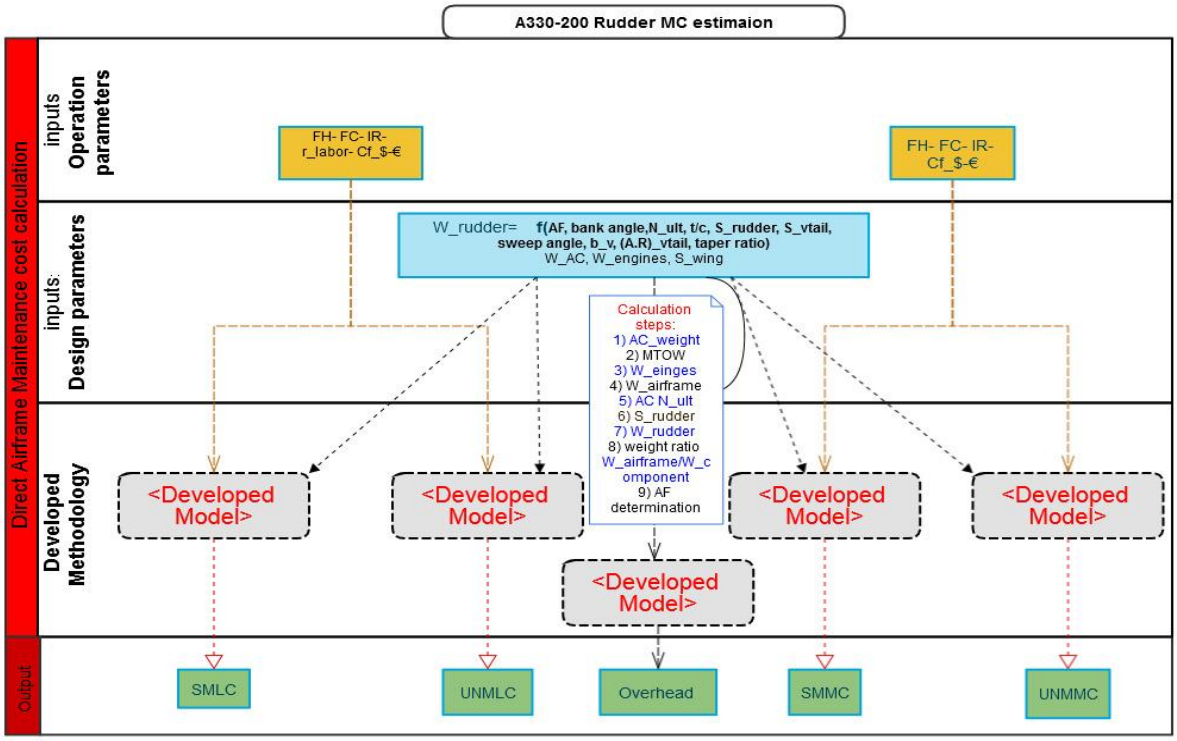


Figure 42 the structure of the model for A330-200 rudder

6.1.1 Scheduled and Unscheduled Maintenance Labor Cost

To estimate the direct labor cost of the A330-200 rudder, the calculations using the developed equations provided in Section 5.1 are conducted. In this section, the procedures of rudder weight determination as well as the SMLC and USMLC estimations are provided. First the ultimate load factor and airfoil thickness are determined before determining the rudder weight using the equations provided in Appendix C . After rudder weight determination, a parameter list table is provided, Table 14, in which the variables, results/values and sources/equations are listed for the SMLC and UNMLC.

First the ultimate load factor is determined by (Appendix C) *Eq. 192*, Figure 100 and *Eq. 194* for the A330 rudder, if the bank angle of the airplane is known. In Figure 43 the bank angle limit for the A330 aircraft is given. As it can be seen from the Figure 43 the limit bank angle for A330 is 67°. Further from Figure 100, we can see that the load factor increases with increase of the bank angle ∅.

$$N_{ult} = \frac{1}{\cos 67°} \times 1.5 = 3.84 \qquad \textit{Eq. 82}$$

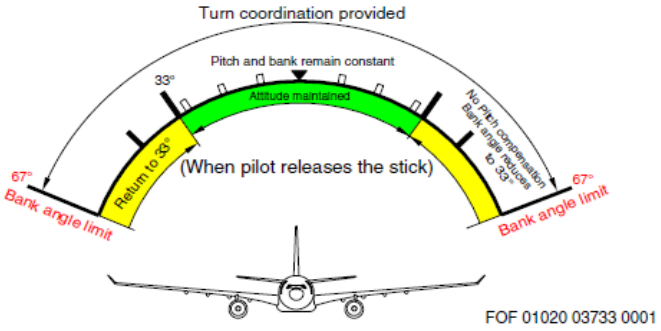


Figure 43 limit bank angle A330 (Airbus, 2014a)

After the determination of the load factor the airfoil thickness t/c can be calculated for the A330 using *Eq. 189* (Appendix C). The operating Mach number for A330-200 is $M = 0.86$ (Airbus, 2014b) and M^*= 1.0 inserting (for peaky conventional airfoils (Torenbeek, 1988)) these values in *Eq. 83* the average airfoil thickness is obtained:

$$\frac{t}{c} = 0.0823 \qquad \textit{Eq. 83}$$

To estimate the rudder weight, *Eq. 85* and the variables from Table 13 and Appendix I are used.

The vertical tail weight without rudder weight is shown in *Eq. 184*:

$$\begin{aligned} W_{vtail(-rudder)} &= 2.62 \times 569.11 + 1.5 \\ &\times 10^{-5}\left[\frac{3.84\,(30.96)^3\left(8.0 + 0.44\,\frac{507063}{3892.4}\right)}{0{,}0823\,cos^2 45°}\right] \\ &= 4058\,[Ibs] = 1841\,[kg] \end{aligned} \qquad \textit{Eq. 84}$$

Additionally, it is stated by Standford (2014) that the rudder weights 60% more per unit area than the vertical tail without rudder. A general equation can be developed for rudder weight determination, *Eq. 85*:

$$W_{rudder} = \left[1.60 \times \frac{W_{vtail(-rudder)}}{S_V}\right] \times S_{rudder} \qquad \textit{Eq. 85}$$

Inserting the outcome of *Eq. 84* and associated values from Table 13 into developed *Eq. 85* results into rudder weight, W_{rudder} of:

$$W_{rudder} = 856.45\,[kg] \qquad \textit{Eq. 86}$$

The rudder labor cost over the airframe labor cost is assumed to comply with the same ratio as the rudder weight over airframe weight. With *Eq. 21* and *Eq. 45* the airframe labor cost can be obtained for the A330. The manufacture's empty weight (*MEW*) is subject to (Figure 98):

$$MTOW = MLW + MZFW + OEW + MEW \qquad \textit{Eq. 87}$$

Where;
$MTOW$ is the maximum take-off weight
MLW is the maximum landing weight
$MZFW$ is the maximum zero fuel weight
OEW is the operational empty weight
MEW is the manufacture empty weight

Furthermore, in Table 46, Elham (2013) provides weight ratios for a couple of airplane types:

A330-200	**Ratio/weight**
$\frac{OEW}{MTOW}$	0.296
Tail	0.015
Weight engine	2 x 5091.62 kg (CF6-80E1)

From Table 46 it can be observed, ratio between $\frac{OEW}{MTOW} = 0.296$ for an A330-200. The *MEW* can be estimated (Figure 98 (Appendix C), Table 45 and Table 46).

$$MEW = OEW - operator\ items \qquad \textit{Eq. 88}$$

Eq. 88 can be modified in order to use the *Eq. 21* and *Eq. 45*:

$$W_{airframe} \approx 0.296\ MTOW - operator\ item - engines\ weight \qquad \textit{Eq. 89}$$

Where;
MEW is the manufacturer empty
$0.296\ MTOW$ is the ratio of airframe weight and maximum take-off weight
$operator\ item$ are the items which belongs to operator as:

- Unusable fuel
- Oil for engines, IDG and APU
- Water for galleys and toilets
- Aircraft documents and tool kits
- Passenger seats and life vests
- Galley structure and fixed equipment
- Catering removal and catering allowance
- Emergency equipment
- Crew and baggage

$W_{airframe}$ is the weight of the airframe weight without the dry weight of the engines [kg]
Engines weight is the weight of 2 turbofan engines of A330-200 assuming the engines are the GE CF6-80E1, each engine weights 5091.62 [kg] (General Electric, 2014)
Assuming the operator's items are zero, the airframe weight is estimated:

$$W_{airframe} \approx 57897\ [kg] \qquad \textit{Eq. 90}$$

Now *Eq. 21* and *Eq. 45* for an aircraft age, y=1 can be used to estimate airframe direct maintenance labor cost by inserting the result found in *Eq. 90*:

$$C_{labor\ airframe\ y} = 916336\ USD\ or\ 707718\ EURO \qquad Eq.\ 91$$

Now the airframe direct maintenance labor cost is estimated for an aircraft which has been operated for 1 year.

Eq. 47 can be used to determine the airframe direct maintenance labor cost for aircraft life (DSG) of 20 years. *Eq. 46* and *Eq. 43* provides the relation and rules to estimate inflation rate (IR) and Aging Factor (AF) as a function of aircraft age y. It should be noted that the IR is assumed to be constant (1.96%) as the Europe's average annual inflation increase in the past 20 years (1994-2014 (FXtop, 2013)). With *Eq. 54* the direct maintenance labor cost of the rudder can be estimated for a certain aircraft age. To distinguish the rudder maintenance labor cost in SMLC and UNMLC, respectively *Eq. 53* and *Eq. 54* can be used. All the variables and equations used for rudder maintenance labor cost estimation are summarized in Table 14 with sources and values.

Table 14 parameter list table for A330 rudder SMLC and UNMLC

Variable	Result/Value	Equation/Table or Source
$W_{airframe}$	57897 (kg)	*Eq. 90*
$W_{vtail(-rudder)}$	1841 (kg)	*Eq. 84*
W_{rudder}	856 (kg)	*Eq. 85* and *Eq. 86*
r_{labor}	43.5 (€/hr)	(Zhao et al.,2014)
IR	1.96% or 1.0196	*Eq. 46* (FXtop, 2013)
FH	4088 (hr)	(IATA, 2013)
FC	951 cycles	(IATA, 2013)
AF_y	Variable	*Eq. 43*, (Dixon, 2006)
$CF_{\$\rightarrow€}$	0.77223[1]	(Wisselkoers, 2014)
$C_{labor\ airframe\ y}$	707718 (€)	*Eq. 91*
$C_{labor\ rudder\ y}$	10496 (€)	*Eq. 54* and *Eq. 55*
Ratio $\frac{W_{rudder}}{W_{airframe}}$	1.48% or 0.0148	*Eq. 90*, *Eq. 85* and *Eq. 86*
$C_{SML\ rudder\ y}$	6754 (€)	*Eq. 57*
$C_{UNML\ rudder\ y}$	3715 (€)	*Eq. 56*
Weight operator items	0 (kg)	*Eq. 90*

By using the variables and equations provided in Table 14 the scheduled and unscheduled maintenance labor costs for the A330-200 rudder are obtained. In Figure 44 the results are shown. In the vertical axis the cost in euros are depicted and in the horizontal axis the aircraft age. The scheduled maintenance labor cost (SMLC) is shown in red while the unscheduled maintenance labor cost (UNMLC) is illustrated in blue. As it can be seen from Figure 44 the rudder SMLC for an aircraft age of 1 year is 5544€ while UNMLC is 4925€. For an aircraft age of 20 years the SMLC contributes to 5380€ and UNMLC is 9758€. And by summing the red and blue bars, the total direct labor maintenance cost can be seen for different aircraft age.

[1] Conversion factor USD-EURO of 8 September 2014

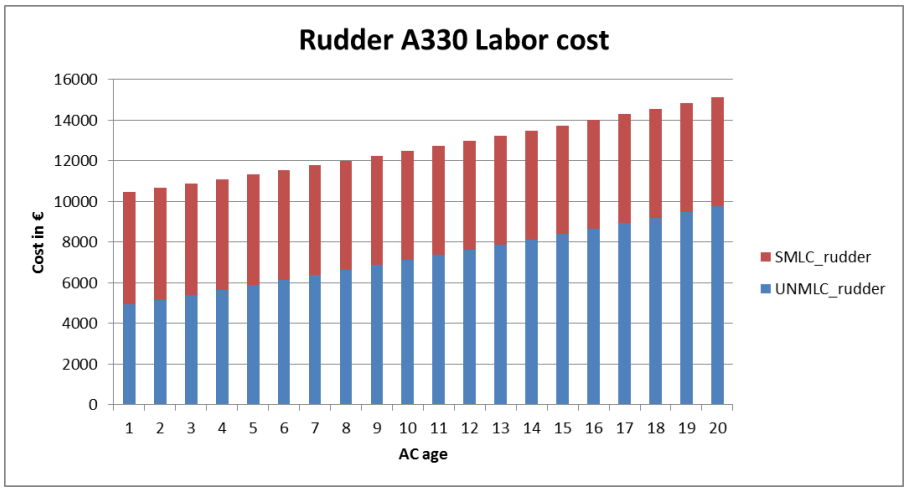


Figure 44 A330-200 rudder labor cost in terms of SMLC and UNMLC

In Figure 45 the percentage of UNMLC over total maintenance labor cost (TMLC) is given as a function of aircraft age. As shown in the figure, the graph has more and less a linear growth. It shows the percentage of UNMLC is 47% at an aircraft age of 1 year and almost 65% at an aircraft age of 20 years. This figure shows a linear increase of the UNMLC over TMLC due to aging factor.

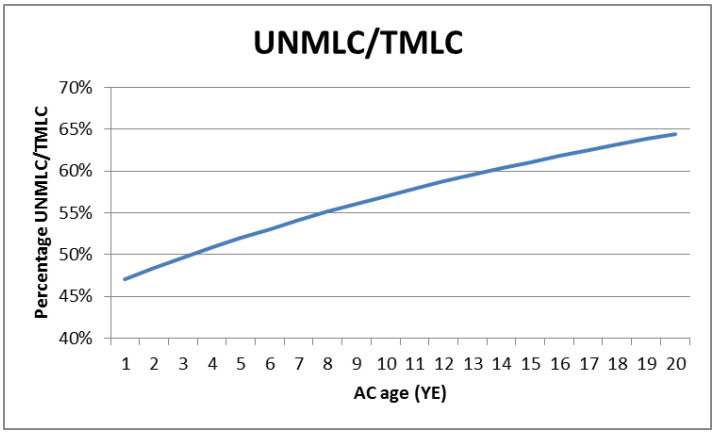


Figure 45 the UNMLC of TMLC of A330-200 rudder

6.1.2 Scheduled and Unscheduled Maintenance Material Cost

The material cost is estimated in the same manner as the maintenance labor cost shown in the previous sub-section. In Table 15 the variables, Result/values and equations or sources are listed for the maintenance material cost determination. The results shown in the table are estimations based on an aircraft age of 1 year (y=1). The equations provided in the *equation/Table or source* column provides guidelines to the associated formulas which are used to obtain the results.

Table 15 parameter list table for A330 rudder for SMMC and UNMMC

Variable	Value/Result	Equation/Table or Source
$W_{airframe}$	57897 kg	*Eq. 90*
$W_{vtail(-rudder)}$	1841 (kg)	*Eq. 84*
W_{rudder}	856 (kg)	*Eq. 85* and *Eq. 86*
r_{labor}	43.5 (€/hr)	(Zhao et al.,2014)
IR	1.96% or 1.0196	*Eq. 46* (FXtop, 2013)
FH	4088 (hr)	(IATA, 2013)
FC	951	(IATA, 2013)
AF_y	Variable	*Eq. 43*, (Dixon, 2006)
$CF_{\$\rightarrow€}$	0.77223[2]	(Wisselkoers, 2014)
$C_{material\ airframe\ y}$	259180 (€)	*Eq. 23*,*Eq. 24* and *Eq. 58*
$C_{material\ rudder\ y}$	3834 (€)	*Eq. 59*
Ratio $\frac{W_{rudder}}{W_{airframe}}$	1.48% or 0.0148	*Eq. 90*, *Eq. 85* and *Eq. 86*
$C_{SMM\ rudder\ y}$	6754 (€)	*Eq. 63*
$C_{UNMM\ rudder\ y}$	3715 (€)	*Eq. 62*
Weight operator items	0 (kg)	*Eq. 90*

The maintenance material cost for scheduled and unscheduled maintenance is depicted by Figure 46. The vertical axis depicts the cost in euros and the horizontal axis represents the aircraft age. As it can be seen from the figure the Scheduled Maintenance Material Cost (SMMC) for an aircraft age of 1 year is 2030€ (red bar) and Unscheduled Maintenance Material Cost (UMMC) is 1804€ (blue bar). For an aircraft of 20 years, the SMMC is 2030€ and 3574€. The SMMC is more and less constant during aircraft life. It is 60€ higher in the beginning than the cost at the end of the aircraft life. One of the reasons can be the error in the interpolation of the Figure 28 and the second reason could be the assumption of constant (lower) inflation rate of 1.96%.

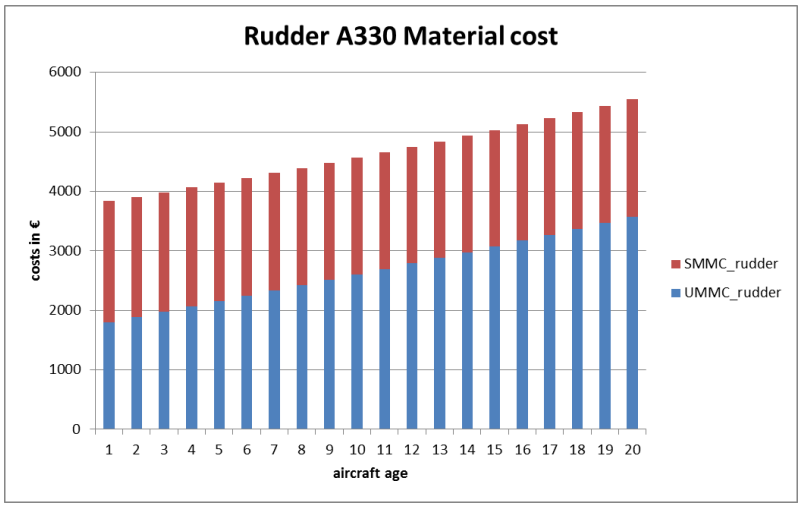


Figure 46 A330-200 rudder material cost

[2] Conversion factor USD-EURO of 8 September 2014

In Figure 47, the overview of the rudder MC (excluding the overhead cost) is depicted. SMLC is shown in blue, the UNMLC is in red, the SMMC is in green and the UNMMC in grey. The costs of the scheduled maintenance for both labor and materials show an approximately constant behaviour, while the costs of the unscheduled maintenance for both labor and material are increasing through the aircraft age.

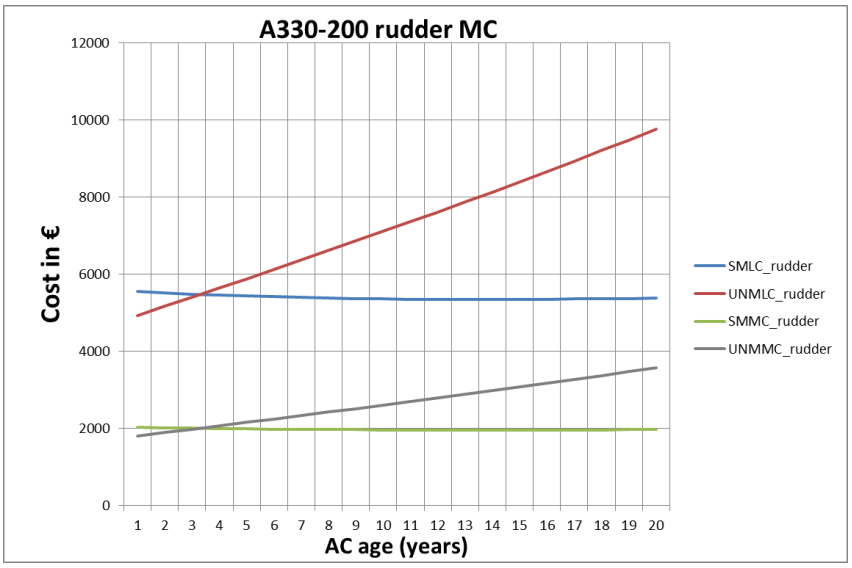


Figure 47 the A330-200 rudder maintenance cost

In Figure 48 the overview of the Direct Maintenance Cost (DMC) of the rudder is given through the aircraft life. Figure 48 shows the DMC of the rudder by material cost (yellow) and labor cost (light blue). It can be seen that the ratio between labor and material is approximately 3:1.

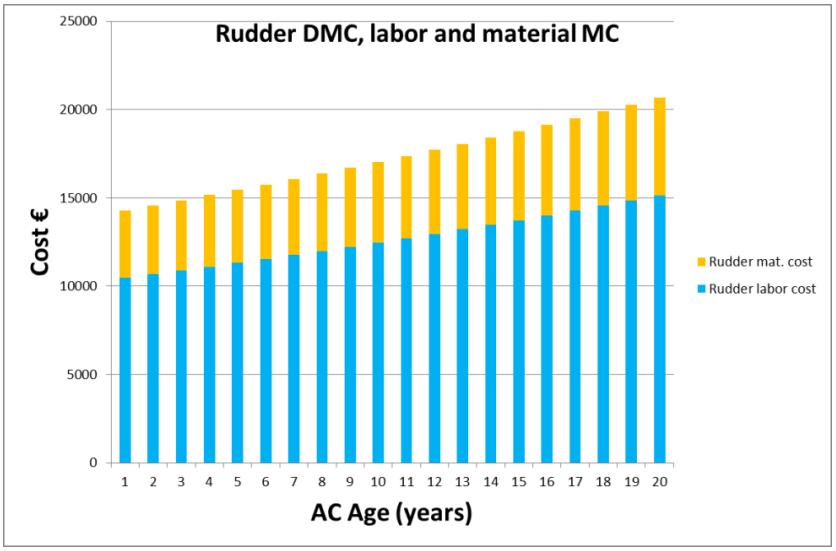


Figure 48 A330 rudder DMC through AC age

The DMC of the rudder by SMC and UNMC as the increase of the aircraft age is given in Figure 49. The red line represents the cost ratio of SMC over DMC and the green line illustrates the cost ratio of UNMC over DMC. The intersection of the lines are around 3.5 years, from that point the UNMC is higher than the SMC. At the end of DSG the UNMC over

DMC is approximately 65% while SMC contributes 35%. It should be noted the SMC and UNMC in this case al only the direct expenditures in labor and material.

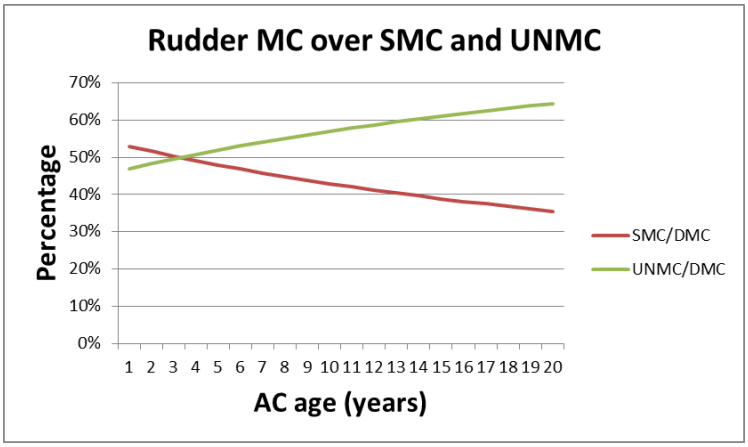


Figure 49 rudder MC for scheduled and unscheduled maintenance

In Figure 50 the average percentages of direct maintenance labor cost and direct maintenance material cost for the A330-200 is given by the outer circle. The inner circle shows the ratio of SMLC/DMC, UNMLC/DMC, SMMC/DMC and UNMMC/DMC as percentages. It is found, the UNMLC contributes the most of the DMC (42%) and the SMMC contributes the least of the DMC (12%).

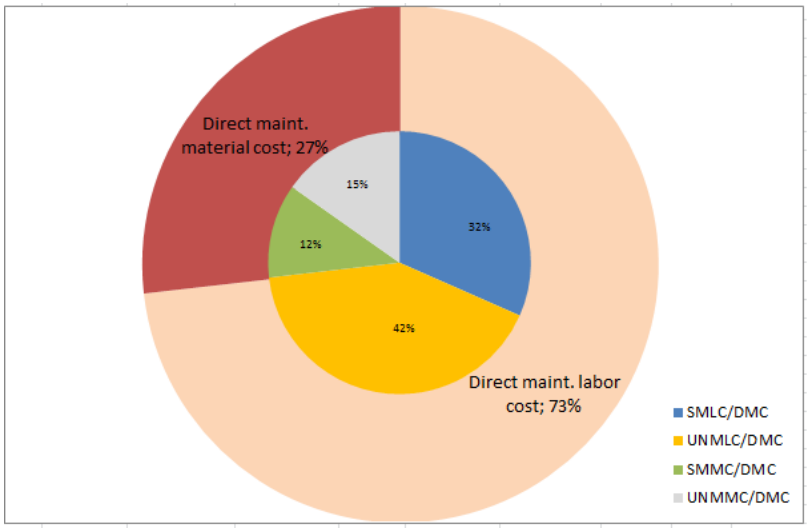


Figure 50 direct maintenance cost in scheduled and unscheduled MC for labor and material

6.1.3 Maintenance Overhead Cost

To estimate the maintenance overhead cost of the rudder, which are the Indirect Maintenance Cost (IMC) induced during the maintenance process for a certain aircraft age y, *Eq. 69* can be used. The overhead cost for the rudder is given in Figure 51 for increasing aircraft age. As it can be observed from *Eq. 69*, the same parameter list tables (Table 14 and Table 15) provided in Sub-section 6.1.1and 6.1.2 can used for maintenance overhead cost estimation.

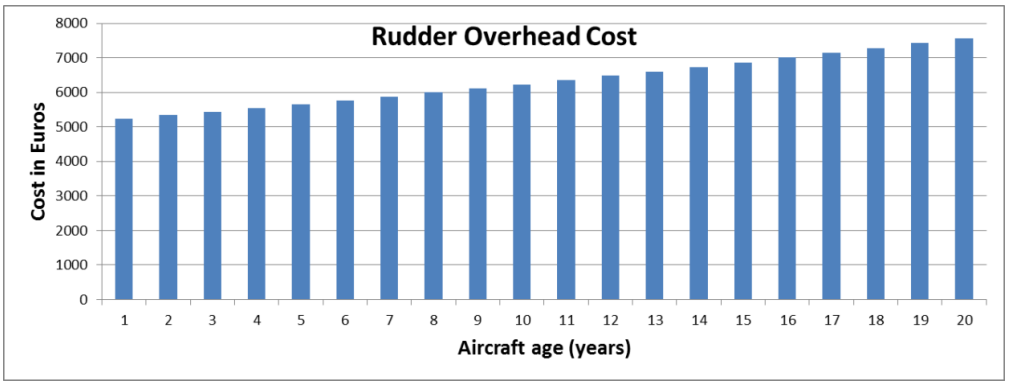


Figure 51 A330 Rudder overhead cost

Since the overhead maintenance cost and DMC are obtained for the rudder, the TMC in terms of DMC and IMC can be plotted as along with the change of the aircraft age. In Figure 52, the TMC of the rudder is shown. As it can be seen from the figure both the overhead cost and the DMC are increasing along with increasing aircraft age. Approximately the DMC is three times higher than the overhead cost.

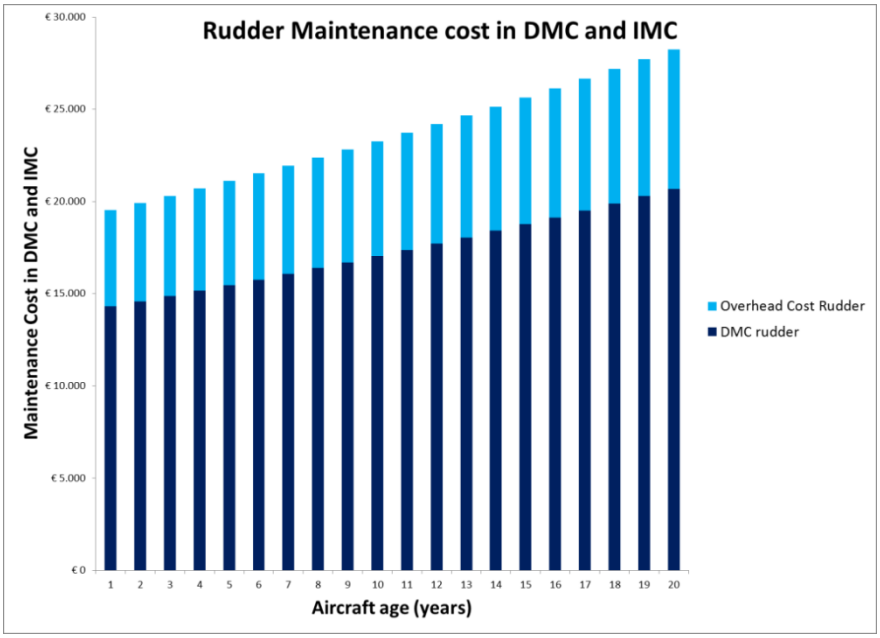


Figure 52 TMC of the rudder as function of AC age

6.1.4 Sensitivity analysis of AIM

In this sub-section, the sensitivity analysis is performed on the AIM. Sensitivity analysis aims at investigating the effect of changes of the design parameters and airline operation parameters on the outcome. The outcomes of case study are used. The design parameters and operation parameters used by maintenance cost estimation can be found by consulting chapter 5 and chapter 6 . In the table below the parameters are again summarized which are used for determination of the DMC of the rudder

	Parameters	Initial value
Design	N_{ult}	3.84
	t/c	0.08
	S_v	513 (ft^2)
	b_v	31 (ft)
	S_{wing}	3892 (ft^2)
	$MTOW$	507063 (lbs)
	S_{rudder}	149 (ft^2)
Operation	FH	4088 (hr)
	FC	951 (cycles)

The sensitivity analysis is only performed on the direct maintenance labor cost of the rudder. Moreover, this is done to avoid duplicate work while the same system of equations with both design parameters and operation parameters are used for determination of rudder weight. See also the set of equations derived in section 5.1 and chapter 6 . The same outcomes will be determined if the sensitivity analysis is performed to direct maintenance material cost. The maintenance labor cost is computed by increasing the design and operation parameters with 5%. The initial value of every parameter is increased till 100% from the initial value in steps of 5% $(1.05 \times initial\ value, 1.10 \times inital\ value, 1.15 \times initial\ value, etc.)$ till 100%. Chapter 6 can be reviewed to see how these initial values are obtained. Every parameter is increased independently while other parameters are kept constant, then the maintenance labor cost of the rudder is calculated. The increase of maintenance labor cost is obtained in percentage. The initial maintenance labor cost of the rudder can be found in *Eq. 54*, Figure 44 and Table 14 and is equal to €10466. In Figure 53 the graph of sensitivities are shown. In this figure the parameters are increased stepwise in percentage and are shown in horizontal axis. In vertical axis, it shows the increase of maintenance labor cost in percentage. It is found that the span of vertical tail b_v from the design parameters has the largest influence on the rudder maintenance labor cost. . And the FC and FH from the operation parameters have the most impact on the maintenance labor cost. The contribution of ultimate load factor (N_{ult}) and average airfoil thickness (t/c) are at the least level.

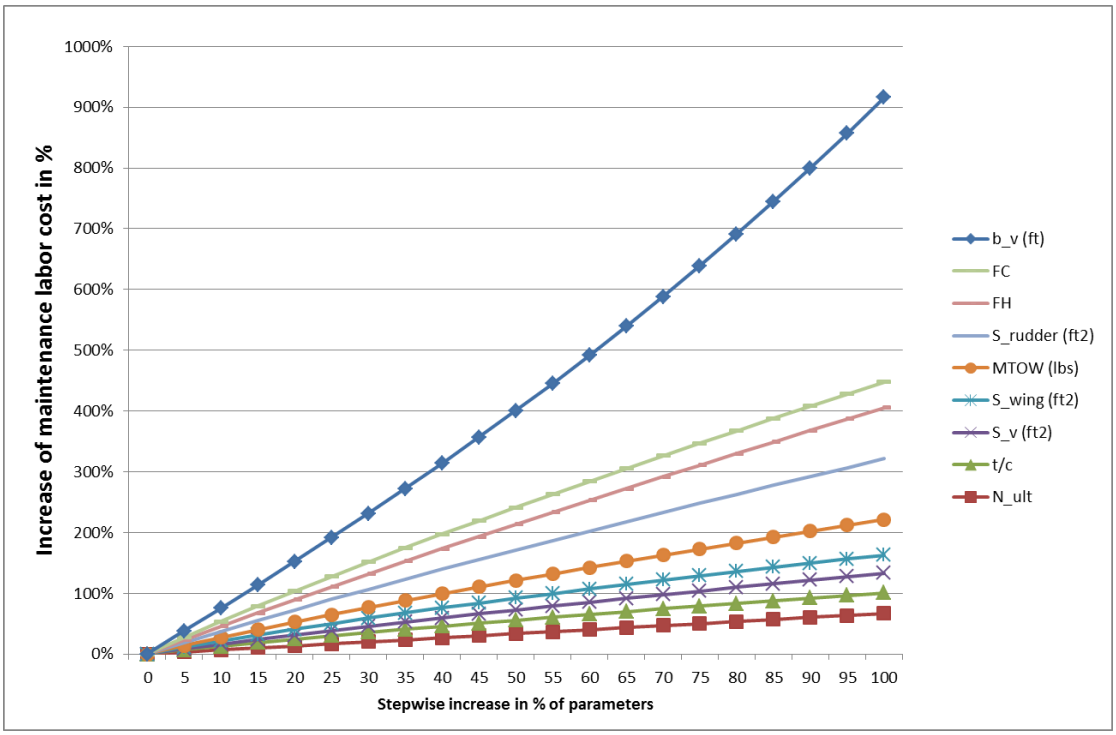


Figure 53 sensitivity analysis of parameters w.r.t maintenance labor cost

6.2 Interval Based Method

In order to estimate the maintenance cost of the A330-200 rudder, maintenance intervals for all failure modes of the rudder parts should be determined. Since it requires a large amount of data to determine the intervals, the effort of adopting MPD data of maintenance intervals are made instead of complying the aforementioned steps of deriving the intervals for each rudder parts. In Appendix F the associated rudder tasks are given for Structures, Zonal and System & Components. In Table 50, Table 51 and Table 52, the structures, zonal and system & components maintenance tasks are shown respectively. The assigned tasks regarding the rudder maintenance of an A330 are shown in Table 50, Table 51 and Table 52. The task description, interval, Man-Hours (M.H), reference, task number and type of inspections are given in the tables. The M.Hs are also given for the opening/closing of the access panels per position if needed for some of the maintenance tasks. The M.H per preparation is also given for some other tasks. In this case a "*'' sign is shown in Table 50. The reference of the tasks refers to the items in the Aircraft Maintenance Manual (AMM) where the detailed maintenance activities are discussed.

6.2.1 Scheduled Maintenance Labor Cost

Using the information from the Airbus MPD as indicated in 0, the rudder is broken-down into several parts and the associated maintenance tasks, M.H are extracted. The A330-200 rudder parts are shown in Figure 41 and Figure 54. Furthermore, the tasks, which are applicable to structures program, zonal program and systems & components program, are also illustrated. The part breakdown for structures and zonal program are: spar tasks, rib tasks, skin (side panel) tasks, actuator attachment tasks, hinges & actuator fittings/bearings and hinge arm tasks. The light purple coloured parts are made from composites and grey parts are non-composite parts. In addition, the shown tasks are also coloured from red to dark pink for

different tasks types, as indicated on the top right side of the Figure 54. Every task number is shown in a rectangular box in orange, green or blue, the colours represent the different type of inspections: GVI, DI or SDI. The M.Hs are given for each task. The inspection intervals for all the structures maintenance tasks are 6 Years (6YE) and for Zonal are: 1C, 4C and 8C (1C is equivalent to 18 months). The total M.Hs for both structures and zonal are calculated in calendar year (YE). The system & component considered by this analysis are: autopilot/flight direction, mechanical control, hydraulic actuation, yaw damper actuation and electric flight control.

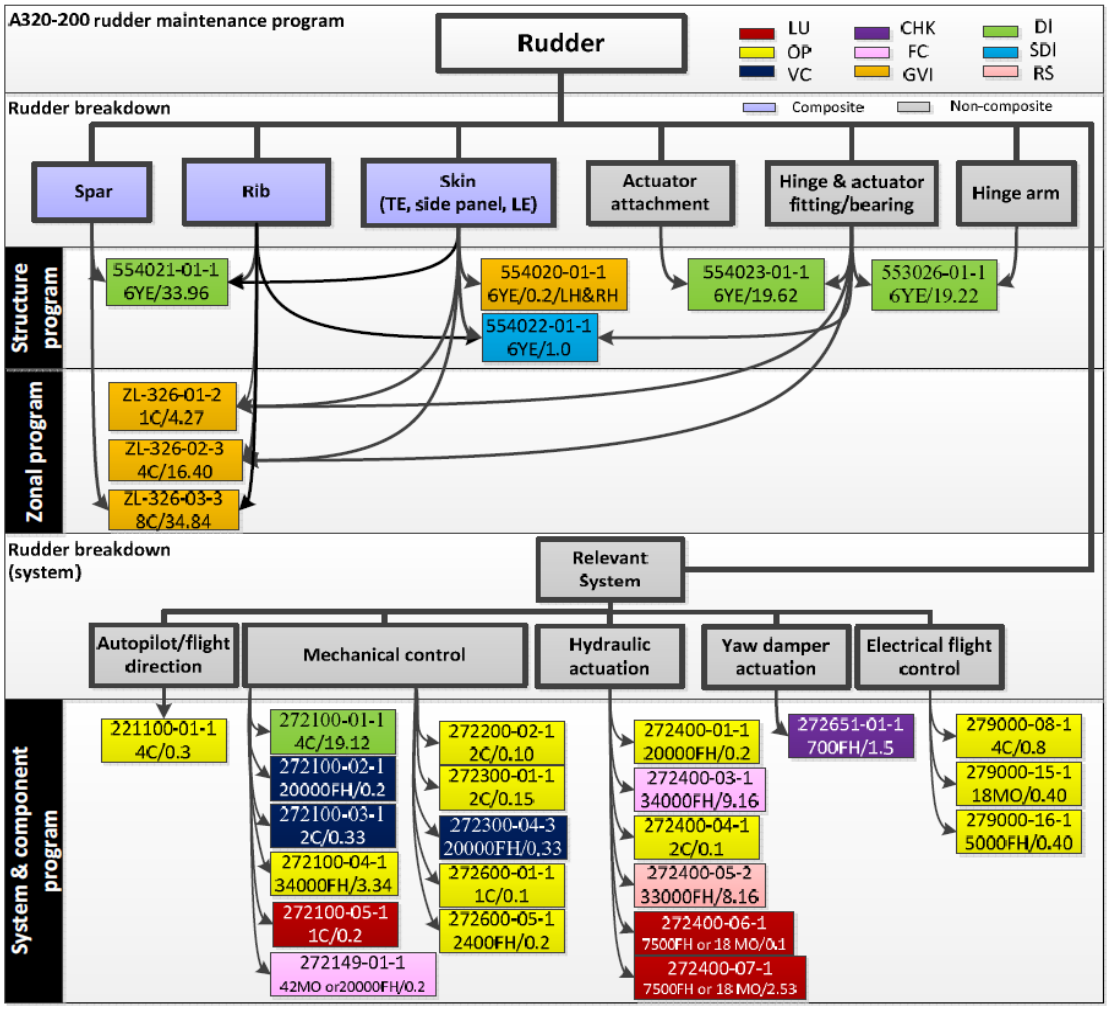


Figure 54 A330-200 Rudder structures, Zonal and System & Component task (Zhao *et al.*, 2014)

Results of SMLC of A330 Rudder

To estimate the labor maintenance cost for the several part of rudder, *Eq. 17-Eq. 20* and *Eq. 70* and *Eq. 71* are used. The results are shown for different parts as illustrated in Figure 54 in Table 53 to Table 63 in Appendix H . The annual flight hour (FHs) is taken from the IATA's Maintenance airline cost commentary (IATA, 2013) for the Airbus A330-200 and is equal to 4088 hours. And the annual flight cycle is (FCs) is 951. Further the labor rate is assumed to be 43.5 euro/hour (Zhao, 2014). The following parameter list table, Table 16 summarize the variables, results/values and equations/sources that are used for SMLC estimation.

Table 16 parameter list table for A330 rudder SMLC (IBM)

Variable	Result/Value	Equation/Table or Source
FH	4088 (hr)	(IATA, 2013)
FC	951 (cycles)	(IATA, 2013)
$\mathbf{r_{labor}}$	43.5 (€/hr)	*Eq. 17*, *Eq. 72* and (Zhao et al.,2014)
MTTF	Variable	(Airbus, 2006), *Eq. 20* and *Eq. 72*
$\boldsymbol{FPM_i}$	variable	MPD A330-200 (Airbus, 2006)
MTTF	hr	(Airbus, 2006), *Eq. 20* and *Eq. 72*
$\boldsymbol{ETPMT_i}$	hr	MPD A330-200 (Airbus, 2006)
$\boldsymbol{\lambda_i}$	-	MPD A330-200 (Airbus, 2006)
$\boldsymbol{AFPM_i}$	-	*Eq. 70*, *Eq. 71* and (Airbus, 2006)
$\mathbf{C_{labor,preventive}}$	Variable Table 17, Table 18 and Figure 55-Figure 59 (€)	*Eq. 72* and (Airbus, 2006)

Labor costs distribution by parts and by materials

Using Figure 54 and *Eq. 17- Eq. 20*, *Eq. 70* and *Eq. 71* distinction can be made between several rudder parts and composites. The dark blue represents here composite materials and light blue non-composites parts.

Composites

Non-Composites

In Table 17 and Table 18 the average annual maintenance labor cost and the average maintenance labor cost for aircraft life of 20 years, for rudder parts are shown. In this case the aging factor is not incorporated in the maintenance labor cost estimation, while it is assumed that the mentioned inspection tasks in the A330-200 MPD does not change for the aircraft life. Further the labor rate is assumed to be constant to 43.5 euro/hour.

Table 17 annual maintenance labor cost for rudder parts

Annual Maintenance Labor cost for rudder parts (€)								
Parts	Spar	Ribs	Skin	Actuator attachment	hinge&actuator fitting/bearing	hinge arm	Systemz& components	Total
$C_{labor\ rudder\ y=1}$	108	108	84	34	145	33	507	1019

Table 18 aircraft life maintenance cost for rudder parts

Aircraft life Maintenance Labor cost for parts (€)								
Parts	Spar	Ribs	Skin	Actuator attachement	hinge&actuator fitting/bearing	hinge arm	System& components	Total
$C_{labor\ rudder\ y=20}$	2617	2617	2029	814	3517	789	12276	23641

The results are graphically shown in Figure 55 and Figure 56. In Figure 57 the contribution of materials, composites and non-composites are illustrated with the associated maintenance labor costs. The left vertical axis stands for the annual costs and the right vertical axis represents the aircraft life costs.

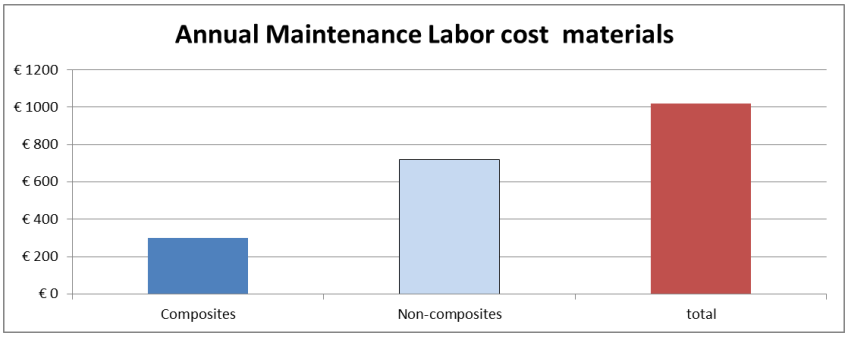


Figure 55 annual maintenance labor cost for different rudder parts

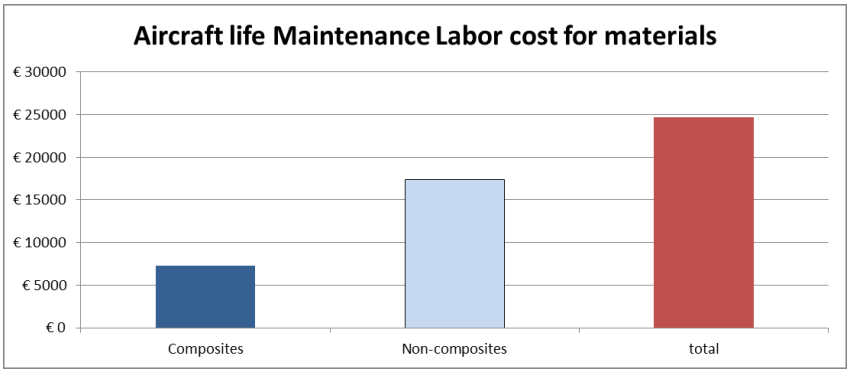


Figure 56 aircraft life (20YE) maintenance labor cost for different rudder parts

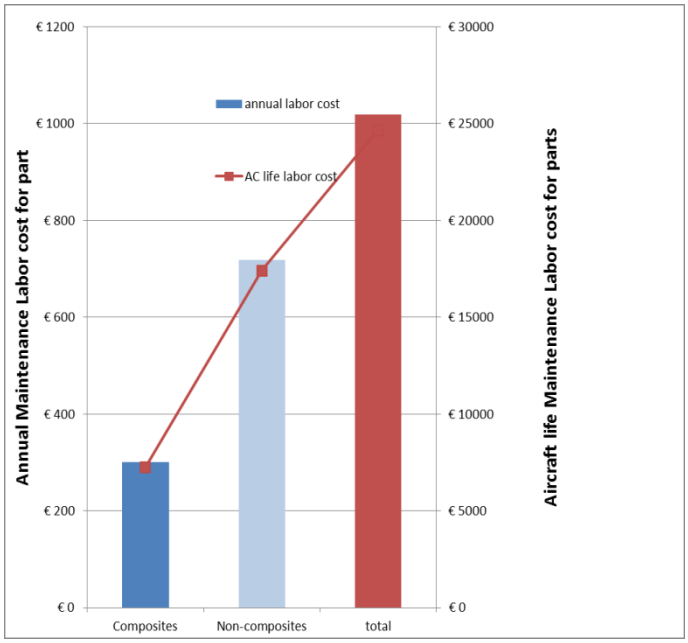


Figure 57 annual and aircraft life rudder maintenance labor for composites and non-composites

From the Figure 57 the total labor maintenance cost for the A330-200 rudder is approximately 1800 euros each year (left vertical axis) and around 35000 euros for an aircraft life (right vertical axis).

The maintenance labor cost by maintenance tasks

The labor cost can also be estimated for several maintenance tasks using *Eq. 17* to and *Eq. 70* and *Eq. 71* separately the results are shown in Figure 58.

Table 19 rudder maintenance cost by several task types

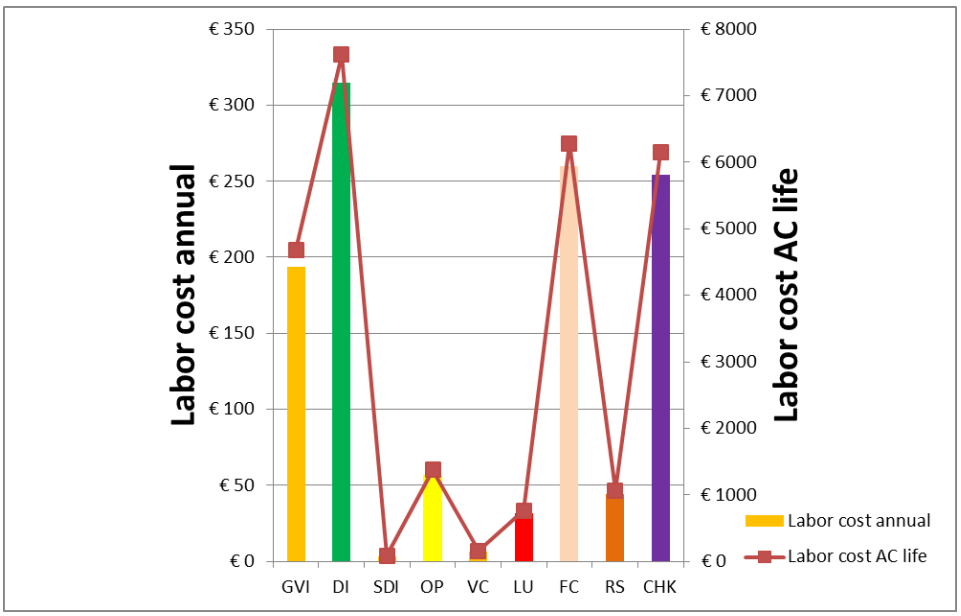


Figure 58 annual and AC life maintenance labor cost by different maintenance tasks

As it can be seen, the most labor intensive maintenance tasks are DI, GVI, FC and CHK. However, the difference between GVI, VC and CHK are not really clear in the MPD of A330. GVI is applicable for structures check while VC and CHK are applied for systems & components, CHK can be:

- Check for condition, leaks, circuit continuity,
- Check fluid reserve on item,
- Check tension and pointer,
- Check fluid level,
- Check detector, Check charge pressure,
- Remove and check, Check torque, Leak Check

Maintenance labor costs in terms of structures, Zonal and System and Component

The labor maintenance cost in terms of structures, zonal and system & component is given in Figure 59. In this graph the contribution of each maintenance segment is shown in percentage. From Figure 59 it is clear that the systems & components are more labor intensive than the structures and zonal, it accounts for approximately 45% of the total labor maintenance cost

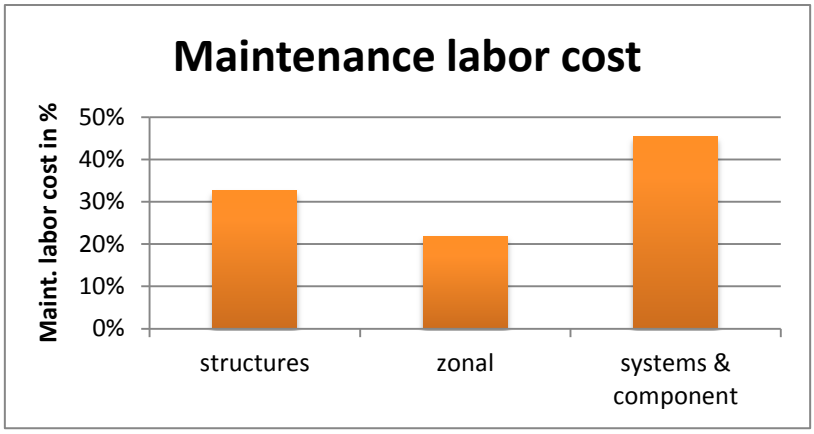


Figure 59 rudder maintenance labor cost by structures, zonal and systems & component

6.2.2 Integrated Aircraft Rudder Design & Maintenance

In this sub-section rudder maintenance intervals are obtained. The method elaborated in sub-section 5.2.2 will be used to gain estimates for the A330-200 rudder in terms of maintenance intervals and eventually SMLC for certain maintenance task. In Figure 60 the process of the maintenance interval determination for the rudder is shown. In the first layer of the swim lane, the three load cases will be analysed. In the second layer the rudder parts with corresponding materials are illustrated. The typical failure mode for fatigue and accidental damage are shown in the third layer and at the fourth layer the maintenance intervals will be determined for impact and delamination damage.

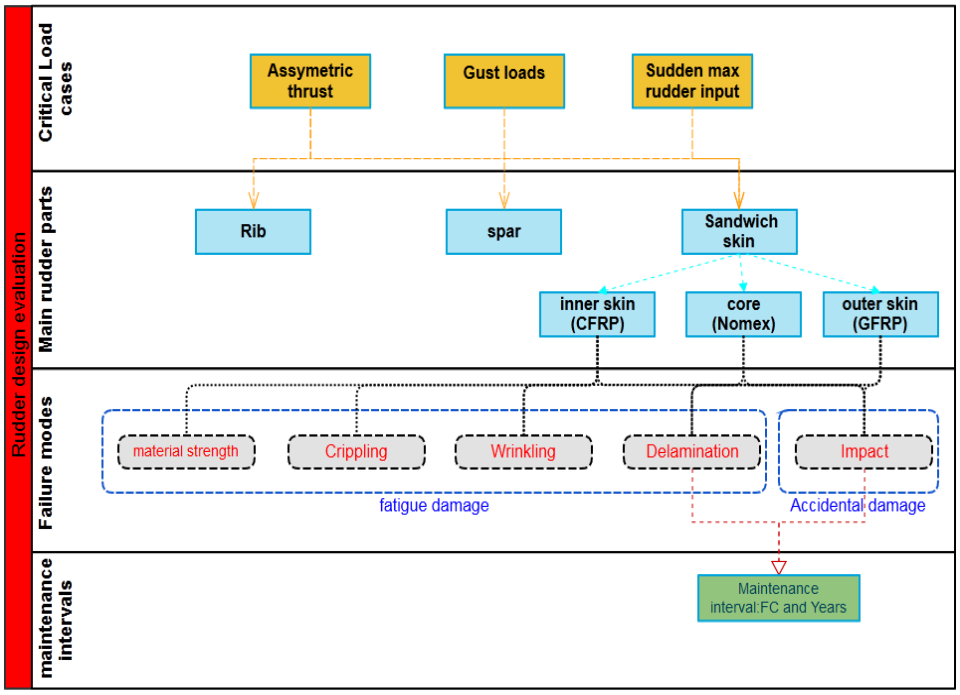


Figure 60 summary of maintenance intervals determination approach

As illustrated in Figure 60 the loads on the rudder are determined for the three cases: asymmetric thrust, lateral gusts and sudden maximum rudder input. It should be noted that Figure 60 is created specifically for the rudder case, and it uses the flowchart shown in Figure 32 in section 5.2. In the following sub-section the sequence of Figure 32 and Figure 60 are

used to approach the results. First, in sub-section 6.2.1.1 the aircraft component part, the rudder is decomposed into several sub-parts and the failure modes are analysed. Secondly, in sub-section 6.2.1.2 and 6.2.1.3 the load analysis and stress analysis are performed for the three load cases for different rudder components. In sub-section 6.2.1.4 the result of the load and stress analysis of the rudder is shown. And finally, in sub-section 6.2.1.5 the maintenance interval determination is shown for the A330-200 skin, which completes Figure 32 and Figure 60.

6.2.1.1 *A330 Rudder Parts, Materials and Failure Modes*

In Figure 61, the A330 rudder is shown with the main components. The rudder has a Carbon Fibre Reinforced Polymer (CFRP) inner skin and Glass Fibre Reinforced Polymer (GFRP) outer skin. Further, the honeycomb core of the sandwich skin is made from Nomex.

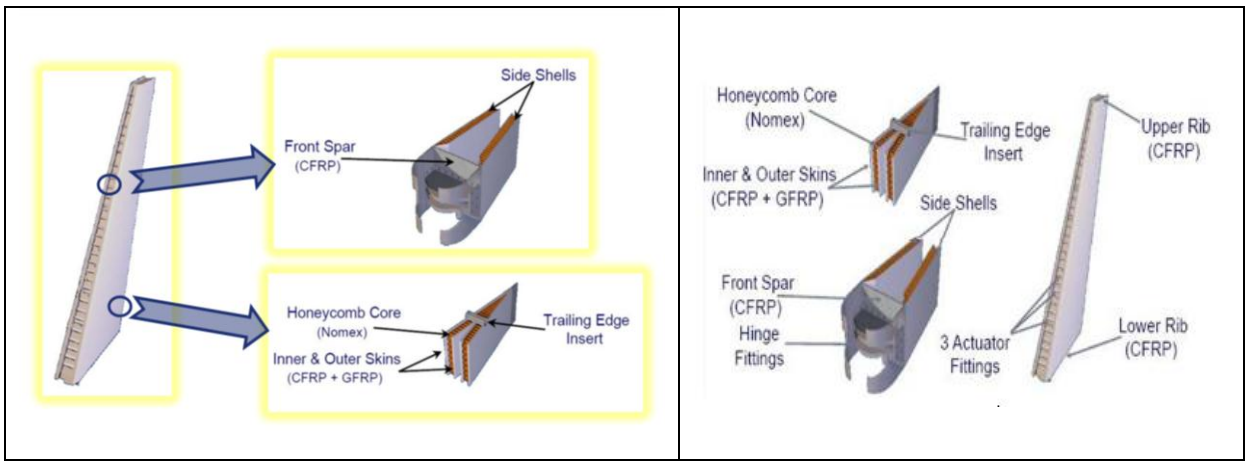


Figure 61 A330 rudder main parts (Ward, 2001)

The function of the main rudder parts, sandwich, spars and ribs are described below. The load carrying capabilities are discussed.

Sandwich skin

A monotonic structure, sandwich structure in which no stringers are needed, has a smooth structure. In Figure 61 a sandwich structure is shown to illustrate the concept in more detail.

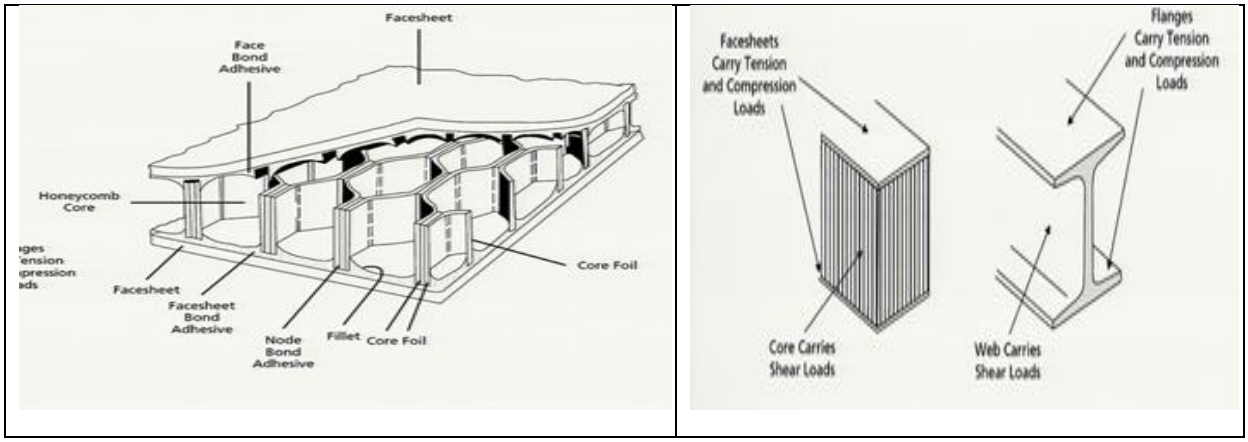


Figure 62 sandwich skin

The face sheets carry tension and compression loads, the core carries shear loads.

Ribs

Ribs has the following functions in a structure; it maintains the design aerodynamic profile of a wing or rudder, the ribs transfers aerodynamic and/or fuel loads on skin to structure, it provide stability against panel buckling, introduces local load into the structure and the ribs can provide sealing for the integral fuel tank (Alderliesten, 2013)

Spars

The function of the spar is to carry bending loads which are created from aerodynamic forces (wing). The basic form of a spar is the I-beam, the spar consists of spar caps called flanges and the web which is a plate. In Figure 63 an example of a spar shown.

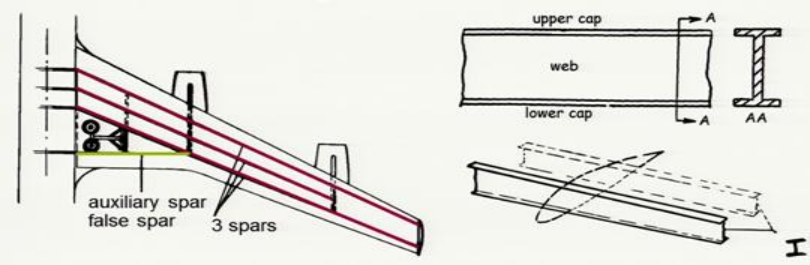


Figure 63 example of a spar

Another type of spar is the tubular spar, which have the best resistance against torsion, shown in Figure 64

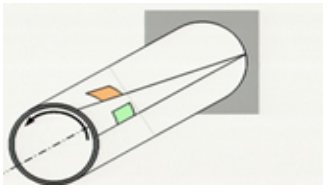


Figure 64 cylinder torsion bar

In Table 19 the rudder parts, the materials used and the composite failures are shown.

Table 20 rudder parts with associated materials and failure modes (Homan, 2008) and (Kassapoglou, 2010)

Part		Material	Function	Failure mode
Side shell	Inner Skin (facesheet)	CFRP	• Carry in plane loads and out-of-plane bending moments, • provide bending stiffness (because of their distance to neutral axis)	➢ Impact with foreign Object ➢ Material strength, core and facesheet disbanding (Adhesive) ➢ Wrinkling ➢ (Intercellular) Buckling ➢ Shear crimping ➢ The imperfections in the manufacturing process (Delamination)
	core	Nomex Honeycomb	• Provide distance between facesheets. • Transfers shear between the facesheets. • Provides shear rigidity and stabilizes the facesheets if they are loaded to stress level higher the limits imposed by general buckling of thin plates core and facesheet disbonding	➢ Impact with foreign Object ➢ Material strength, core and facesheet disbanding (Adhesive) ➢ Wrinkling ➢ (Intercellular) Buckling ➢ Shear crimping ➢ The imperfections in the manufacturing process (Delamination)
	Outer skin (Facesheet)	CFRP	• Carry in plane loads and out-of-plane bending moments, • provide bending stiffness (because of their distance to neutral axis)	➢ Impact with foreign Object ➢ Material strength, core and facesheet disbanding (Adhesive) ➢ Wrinkling ➢ (Intercellular) Buckling ➢ Shear crimping ➢ The imperfections in the manufacturing process (Delamination)
(Front) Spar		CFRP		➢ Material strength (notched strength) ➢ Crippling of flanges ➢ Crippling of reinforcements around cutouts ➢ The imperfections in the manufacturing process
Lower & upper Rib		CFRP		➢ Material strength (notched strength) ➢ Crippling of flanges ➢ Crippling of reinforcements around cutouts ➢ The imperfections in the manufacturing process
Fittings		Non-composite	Connecting adjacent parts	➢ Material strength ➢ Lug failure ➢ Bearing failure ➢ delamination

6.2.1.2 *Critical Load Analysis on the Vertical Tail*

To estimate the loads and eventually the stresses on the rudder (and vertical tail) three cases are analysed using JAR 25.351 (JAA, 1989). The cases are: (i) Asymmetric thrust, (ii) maximum rudder deflection and (iii) lateral gusts. The rudder is used for directional control of the aircraft. When the rudder is deflected to a certain deflection angle δ_r a horizontal lift force (L_v) is created at the vertical tail surface, see Figure 65. This lift force causes a yawing moment (N_A) about the aircraft's centre of gravity (c.g.), about aircraft z-axis (from the top view as Figure 65 the z-axis is going through the c.g). Therefore, the rudder is used to control the aircraft about its z-axis (Sadraey, 2012).

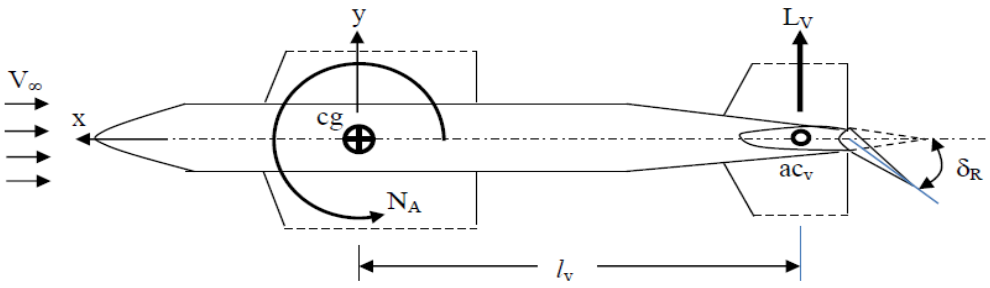


Figure 65 directional control due to rudder deflection (Sadraey, 2012)

Because the vertical tail is located above the aircraft c.g. of the aircraft, the side force L_v on the vertical tail surface causes an intended rolling moment. Therefore, the lateral (aircraft rotation about the aircraft's x-axis) and directional dynamics are frequently coupled. The rudder deflections to the right and to the left are the same. Rudder deflection to the left of the pilot is considered as a positive rudder deflection which generates a positive side force in the y-direction of the aircraft. However, this positive rudder deflection causes a negative yawing moment in z-direction (i.e. counter clockwise), see Figure 65. The side-force L_v is a function of dynamic pressure, vertical tail surface area and the direction of the vertical tail lift, i.e.$(L_v)_{asy\ thrust} = f(\overline{q}, S_V, direction)$.

The design requirement of the rudder is mainly driven by directional control and directional trim ($\sum F_y = 0\ and\ \sum N_{cg} = 0$). Directional control means controlling the aircraft about the z-axis. The directional control is primary governed by the yaw rate (R_{yaw}) and the directional trim by the maximum rudder deflection (δ_{rmax}). The FAA/EASA regulations for the rudder about yawing and manoeuvring conditions of the rudder are discussed below.

Lateral gust

In un-accelerated flight the aircraft is assumed to encounters gusts normal to the plane of symmetry. The gust loading on the vertical tail surface must be computed as follows (JAA, 1989):

$$(L_v)_{LG} = \frac{K_{gt}\ v\ V\ C_{L_\propto} S_v}{498} \qquad Eq.\ 92$$

Where;
$(L_v)_{LG}$ is vertical tail load due to lateral gust (N)

$K_{gt} = \frac{0.88\,\mu_{gt}}{5.3+\mu_{gt}}$ is gust alleviation factor

$\mu_{gt} = \frac{2W}{\rho \bar{c_t} g C_{L_\alpha} S_v}\left(\frac{R_{gy}}{l_v}\right)^2$ is lateral mass ratio

v is derived gust velocity in horizontal direction (m/s)

ρ is the air density (kg/m^3)

W is the aircraft weight (kg)

S_V is the of vertical tail area (m^2)

$\bar{c_t}$ is the mean geometric chord of vertical surface (m)

C_{L_α} is lift curve slope

R_{gy} is the radius of gyration in yaw (rad/s)

l_v is the distance from aeroplane c.g. to lift centre of vertical surface (m)

g is the acceleration due to gravity (m/s^2)

V is aeroplane equivalent speed (m/s)

The limit loads (LL) are the maximum loads expected during the normal flight envelope. During these loads no deformation on the surface occurs. The ultimate loads (UL) are beyond the limit loads:

$$UL = 1.5\,LL \qquad \textit{Eq. 93}$$

Till the ultimate loads no breaking of the surface occurs. The criteria are defined for roll and yaw axis. When achieving those lateral axis manoeuvre criteria, limit loads may not be exceeded. This results in dimensioning the structural design of the surfaces such as the fin and the rudder.

Asymmetric thrust

The A330-200 is a twin engine aircraft; both of the engines are not located along fuselage centreline, (Airbus, 2014). If one of the engines is operative this will result in an asymmetric thrust. This asymmetric thrust will cause an undesirable yawing motion which must be met by the rudder in order to achieve directional trim. The rudder most be powerful enough to overcome the yawing moment produced by the operative engine, Figure 66 as an example. In this case the right engine is failed and the aircraft yaws to the right.

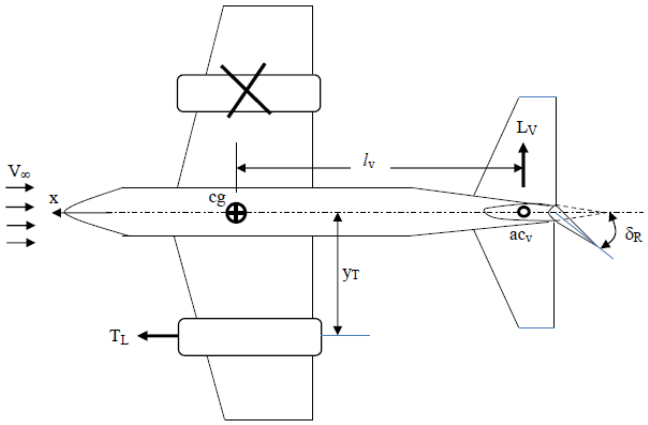


Figure 66 a twin engine aircraft with right engine inoperative (Sadraey, 2012)

Because of the rudder deflection δ_R side-force is generated which causes a moment about c.g. of the aircraft in the opposite direction (aircraft yaws to the left). FAR 25.149 states that a multi-engine aircraft should be controllable at minimum controllable speed, (V_{MC}), further this speed may not exceed 1.13 stall speed (V_S) (JAA, 1989). The rudder must be able to overcome the yawing moment produced by asymmetric thrust. The following expression can be derived.

$$\sum N_{cg} = 0 \rightarrow T_L y_T = -L_V l_v \qquad \textit{Eq. 94}$$

Where; T_L is the power of an A330-200 engine in N
y_T the distance between cg and the engine locations in m
$l_v$the distance between aerodynamic centre of the vertical tail to the cg of the aircraft in m
L_V the side-force action on the vertical tail due to rudder deflection in N

So the yawing moment N_A (Figure 66) due to rudder deflection should equal to asymmetric power condition:

$$N_A = -T_L y_T = (L_V l_v) \qquad \textit{Eq. 95}$$

The side-force on the vertical tail can be obtained:

$$L_V = \frac{-T_L y_T}{l_v} \qquad \textit{Eq. 96}$$

Sudden maximum rudder input

The aerodynamic load on the fin-and-rudder during a lateral manoeuvre (rotation about z-axis of an aircraft) can be obtained by (Puttock, 1956):

$$(L_V)_{\max \delta_R} = \left(-B\beta - C\frac{d\beta}{d\tau} + a_2\delta_R\right)J \qquad \textit{Eq. 97}$$

Where;

$$J = \frac{1}{2}\rho V^2 S_v \qquad C = \frac{1}{\mu_1}a_1 \qquad B = \left(1 + \frac{C_{Y_\beta}}{\mu_1}\right)a_1 \qquad \mu_1 = \frac{W}{g\rho S l_v} \qquad a_1 = -\frac{\partial C_{Y_v}}{\partial \beta} \qquad a_2 = \frac{\partial C_{Y_v}}{\partial \delta_R}$$ and

Where;
$(L_v)_{man}$ is the load on fin-rudder due to yawing manoeuvre (N)
ρ is the density (N/m^2)
V is the EAS m/s
S_v is the vertical tail surface (m^2)
C_{Y_β} is the lateral force derivative due to angle β
W is the aircraft weight (kg)
g is the earth's gravitational acceleration (m/s^2)
β is the angle of sideslip (°)
δ_R is the rudder angle deflection (°)
C_{Y_v} lateral force derivative due to vertical tail surface v

6.2.1.3 *Stress Determination of the Skin and Spar Due to Applied Load L_V*

The load that is acting on the vertical tail, L_V should be determined for fin and rudder separately. In Figure 67 the forces that are acting on the vertical tail plane and the rudder shown on the left. The right picture represents forces on the tail and rudder after rudder deflection by a certain angle δ_R. F_1 and F_2 represents forces on the vertical tail and rudder separately at the center of pressure (CP), so F_1 is the force on the vertical tail without the contribution of the rudder. h_1 and h_2 represents the associated distances to point of action of the side force L_V. For the simplicity it is assumed that the forces are carried by the rudder spar and sandwich skin of the rudder.

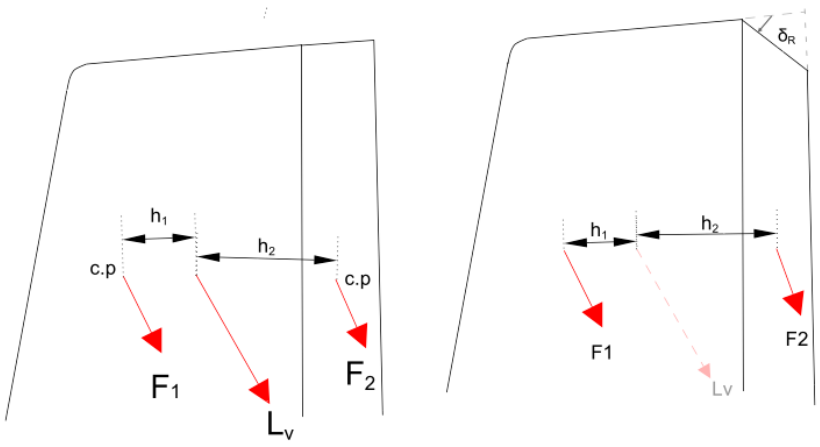


Figure 67 loads on the vertical tail and rudder

To determine the forces on the rudder parts, first the applied load L_v on the vertical tail plane, including the rudder should be translated into two separate forces, namely F_1 on the fin without the rudder and F_2 force that is acting on the rudder surface. In Figure 68 the combination of the rudder and the vertical tail is shown again in a simplified drawing.

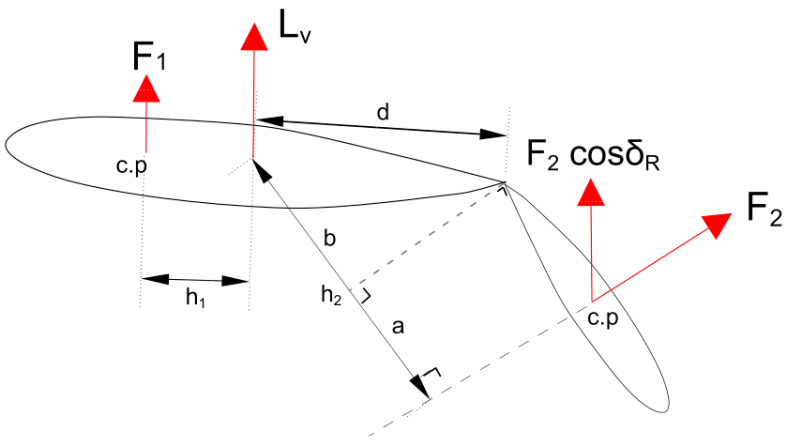


Figure 68 simplified vertical tail and rudder with associated loads

Following equations can be derived by analysing respectively Figure 67 and Figure 68, for the rudder un-detached case and detached case:

$$F_1 + F_2 = L_v \qquad \textit{Eq. 98}$$

$$F_1 + F_2 \cos\delta_R = L_v \qquad \textit{Eq. 99}$$

By taking the moments about point of action of L_v:

$$F_1 h_1 = F_2 h_2 \qquad \textit{Eq. 100}$$

With F_1 is the net aerodynamic force on the vertical stabilizer without the rudder. h_2 can be expressed in terms of the rudder deflection and the point of action of the side force L_v by using Figure 69.

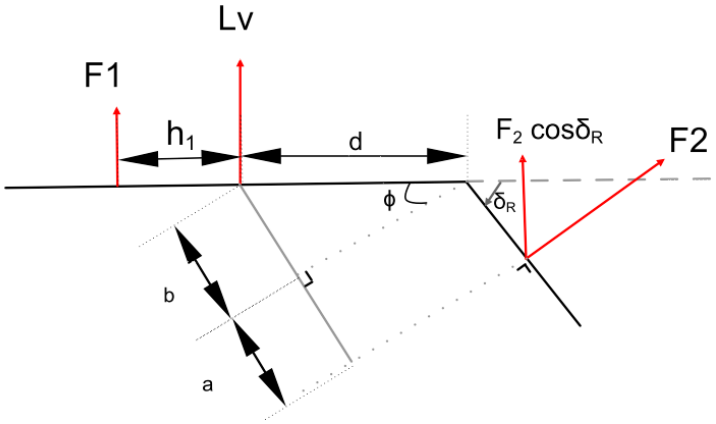


Figure 69 vertical tail and rudder forces and angles

Using the Figure 69 following equations can be constructed to express rudder force in terms of rudder deflection angle:

$$h_2 = a + b \qquad \textit{Eq. 101}$$

$$b = d\ \sin\varphi \qquad \textit{Eq. 102}$$

$$\varphi = 180° - 90° - \delta_R = 90° - \delta_R \qquad \textit{Eq. 103}$$

$$\sin\varphi = \sin 90 - \delta_R = \cos\delta_R \qquad \textit{Eq. 104}$$

Inserting *Eq. 104* into *Eq. 102* results:

$$b = d\ \cos\delta_R \qquad \textit{Eq. 105}$$

Assuming that the force on the rudder acts on the quarter chord of the rudder (where the spar is located) with a distance from the hinge point, the following yields:

$$a = \frac{c_{rudder}}{4} \qquad \textit{Eq. 106}$$

By inserting *Eq. 106* and *Eq. 105* into *Eq. 101* results:

$$h_2 = \frac{c_{rudder}}{4} + d\ \cos\delta_R \qquad \textit{Eq. 107}$$

Inserting *Eq. 84* into *Eq. 100*:

$$F_1 h_1 = F_2\left(\frac{c_{rudder}}{4} + d\ \cos\delta_R\right) \qquad \textit{Eq. 108}$$

Maniuplating *Eq. 108* and *Eq. 100* yields to an expression for the force F_2:

$$F_2 = \frac{L_v h_1}{(h_1 + d)\cos\delta_R + (\frac{c_{rudder}}{4})} \qquad \textit{Eq. 109}$$

From *Eq. 109* follows that F_2 is maximum when $\cos\delta_R$ reaches zero, that means $\delta_R = 90°\ (or - 90°)$. But from maintenance airport planning document of A330-200 (Airbus, 2014) it is given that the maximum rudder deflection $\delta_R = \pm 31.6°$. Now the rudder force can be determined, the stresses in the rudder parts can be computed as well. In Appendix M a detailed sketch of the A330 rudder is shown in top view and sideview representation. The associated figure is used to draw the simplified rudder representative for the analysis of the rudder forces in spar and skin.

The forces on the rudder spar

The forces of the vertical tail are translate to the rudder due to attachments of rudder to the vertical tail. In total there are 7 attachaments, the attachements are integrated in the rudder spar. A 3D representation of the rudder with attachements are shown in the Figure 70.

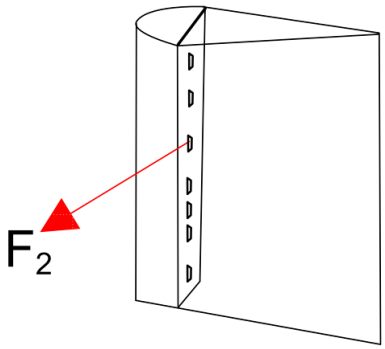


Figure 70 rudder 3D representation

The rudder spar with the attachments and the force F_2 are shown simplified in Figure 71 and a Free-Body-Diagram (FBD) and distances are depicted in Figure 72. The attachments are considereed to be hinges. However, the only exernal force applied on the spar is the F_2 in upward direction, so it is considered that forces in x-direction cancelles each other and are not further taken into the account during the analysis.

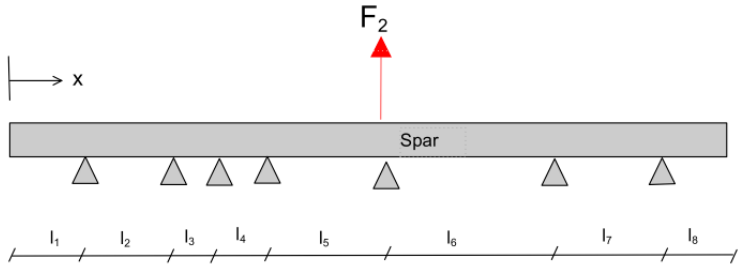


Figure 71 rudder spar with the attachments

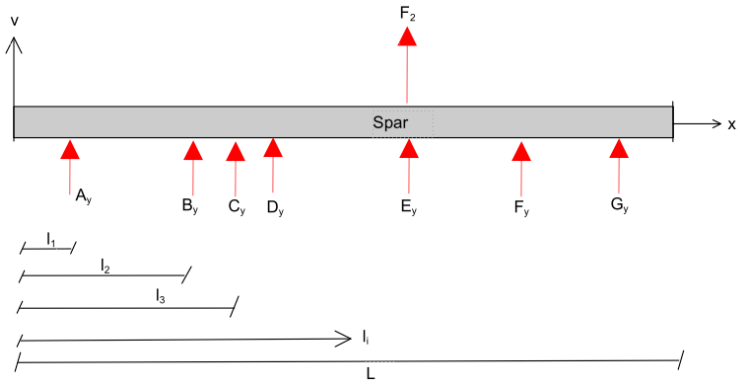
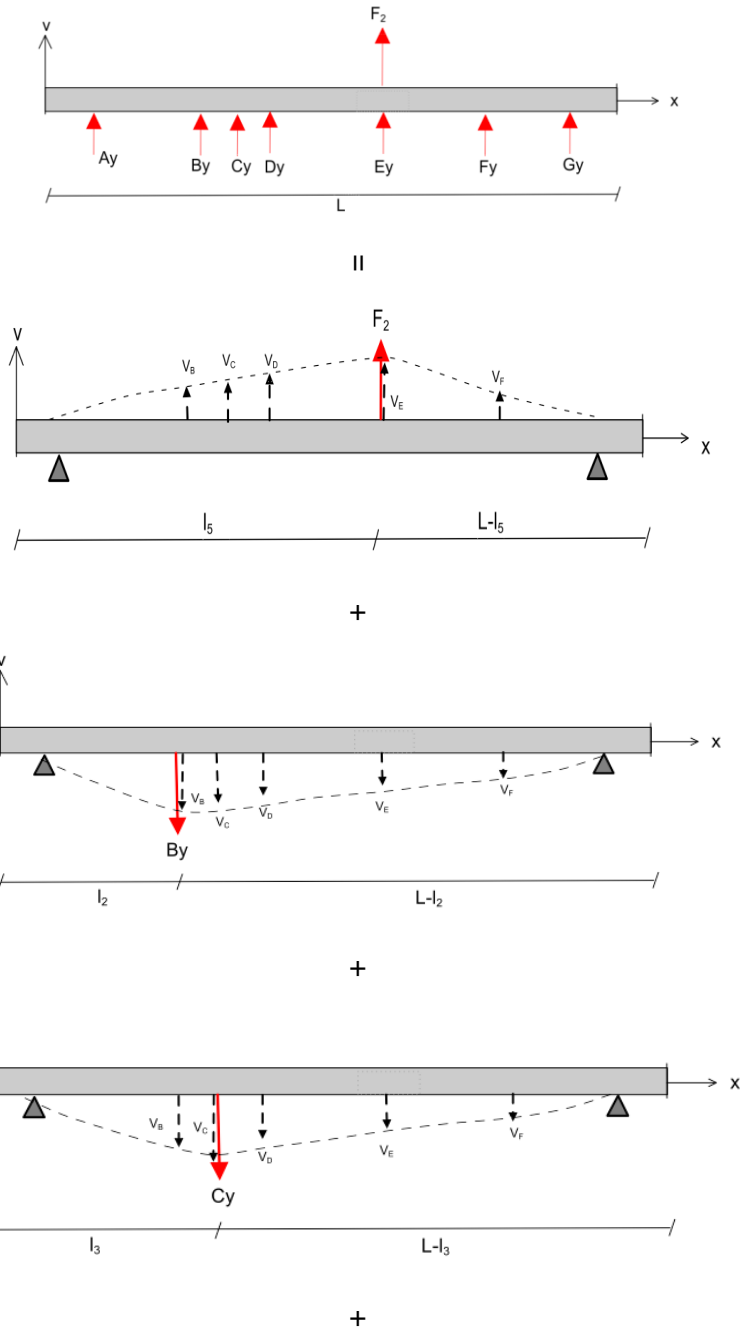


Figure 72 FBD of spar with reaction forces and distances

As it can be seen from Figure 72, the structure is statically indeterminate, number of reactions (NR) is more than number of equations, $\sum F_y \; and \; \sum M$ (NE), $NR > NE$, the number of unknown reaction forces are 7 $(A_y - G_y)$. From Figure 72 the maximum S should be determined as a function of x and maximum M as function of x. Once the reaction forces are determined the maximum moment M and the maximum shear stress S can be obtained. In the following analysis the reaction forces of the rudder attachments are determined.

Reaction forces of rudder attachments

As it can be seen from Figure 72 there are 7 unknowns and 2 equations ($\sum F_v \; and \; \sum M$) which results to a statically indeterminacy to the degree of five. To obtain the reaction forces, the method of superposition is used. Forces $B_y, C_y, D_y, E_y \; and \; F_y$ are taken as the redoundant forces. In Figure 73 the superposition diagrams are shown.



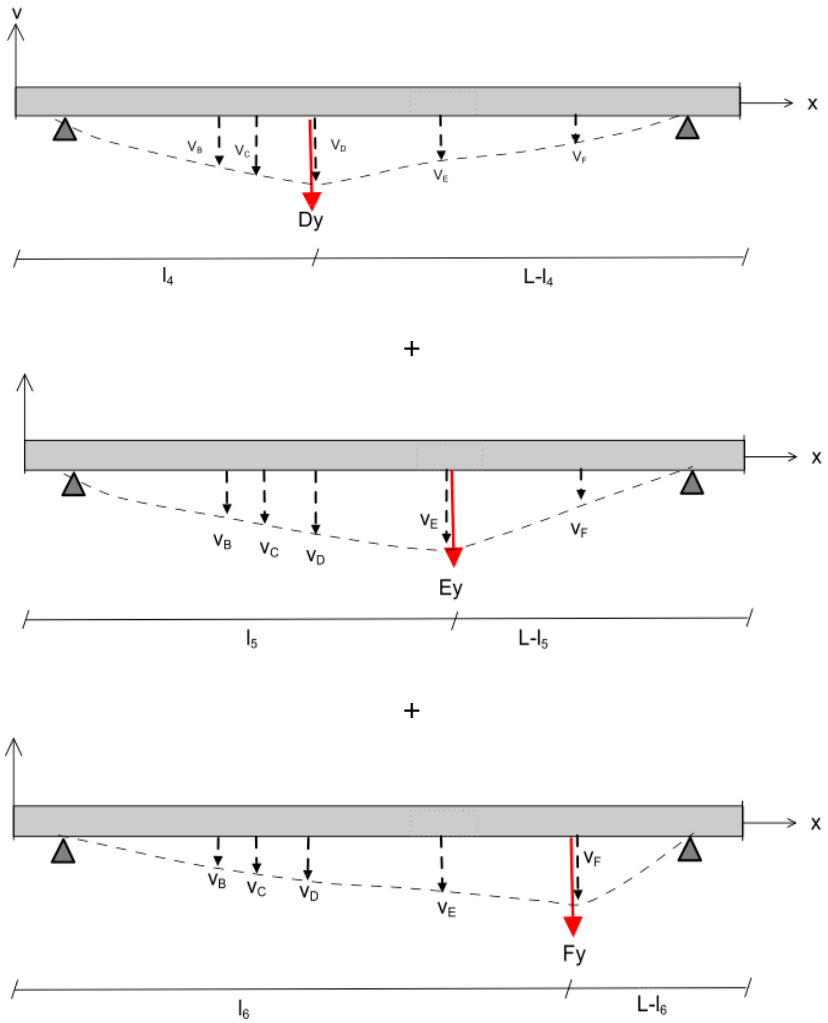


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Figure 73 superposition diagrams

Using superposition diagrams (1-6) of the Figure 73 compatibility equations can be produced. In these equations the vertical displacements of the spar is shown, v_A, v_B, v_C, v_D, v_E *and* v_F which are also indicated in Figure 73. The compatibility equations are (deflection downward is regarded to be positive (↓ +):

$$0 = -v_B + v'_B + v''_B + v'''_B + v''''_B + v'''''_B \qquad \textit{Eq. 110}$$

$$0 = -v_C + v'_C + v''_C + v'''_C + v''''_C + v'''''_C \qquad \textit{Eq. 111}$$

$$0 = -v_D + v'_D + v''_D + v'''_D + v''''_D + v'''''_D \qquad \textit{Eq. 112}$$

$$0 = -v_E + v'_E + v''_E + v'''_E + v''''_E + v'''''_E \qquad \textit{Eq. 113}$$

$$0 = -v_F + v'_F + v''_F + v'''_F + v''''_F + v'''''_F \qquad \textit{Eq. 114}$$

In equations *Eq. 90* to *Eq. 149*, it is assumed that the displacements at hinges are zero. To avoid relative time consuming and relatively complicated methods as integration method and moment-area-method, appendices and tables can be used to estimate the reaction forces. By stating the compatibility equations, there appear more unknowns, $v_i^{'j}$ see *Eq. 90-Eq. 149*. In

total 30 new unknowns are produced. As mentioned before, by using the tables for different type of loading (unsymmetrical) on a simply supported beam the deflections can be determined. The results are shown in Appendix N .

By using the first diagram of Figure 73, equations, *Eq. 115-Eq. 154* can be generated. To determine the deflections appendix C of Hibbeler (2005) is used, with a general formula as: $v_i = -\frac{Pbx}{6EI\,L}(L^2 - b^2 - x^2)$, see Figure 74 that illustrates the simply supported beam with the loading and dimensions.

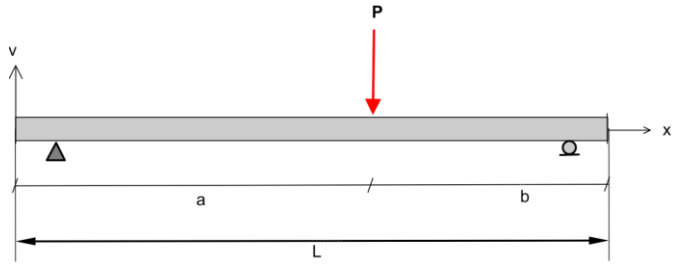

Figure 74 simply supported beam with dimensions and loading

$$v_B = \frac{F_2(L-l_5)l_2}{6EIL}(L^2 - (L-l_5)^2 - l_2) \qquad \textit{Eq. 115}$$

$$v_C = \frac{F_2(L-l_5)l_3}{6EIL}(L^2 - (L-l_5)^2 - l_3) \qquad \textit{Eq. 116}$$

$$v_D = \frac{F_2(L-l_5)l_4}{6EIL}(L^2 - (L-l_5)^2 - l_4) \qquad \textit{Eq. 117}$$

$$v_E = \frac{F_2(L-l_5)l_5}{6EIL}(L^2 - (L-l_5)^2 - l_5) \qquad \textit{Eq. 118}$$

$$v_F = \frac{F_2(L-l_5)l_6}{6EIL}(L^2 - (L-l_5)^2 - l_6) \qquad \textit{Eq. 119}$$

In the same manner expressions can be provided for the other unknowns, $v_i', v_i'', v_i''', v_i'''' \; and \; v_i''''$. By inserting these results into *Eq. 110* to *Eq. 114* the system of equations for the unknowns can be solved eventually with the interested reactions forces. In fact, a model is developed in Maple to obtain the unknowns. A matrix in the form, $Ax = B$ is developed. With A (5x5) matrix, x (5x1) matrix contributing the unknowns and B also (5x1) matrix. In the maple code is provided. The computed shear and moment diagrams can be used to obtain the maximum shear and moment on the rudder spar, shown in Appendix N .

In Figure 75 and Figure 76 are topview representation of the spar given with the moment M, the force F_2 and the shear stress S. The associated dimensions are indicated in the figure as well.

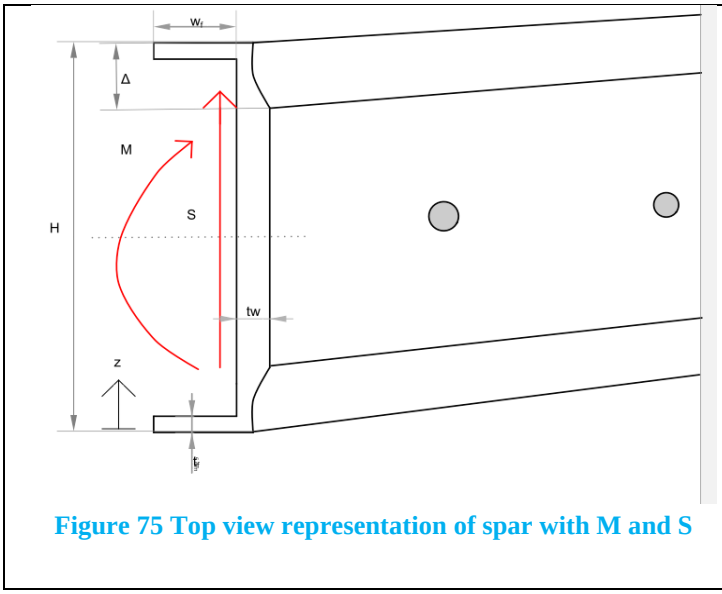

Figure 75 Top view representation of spar with M and S

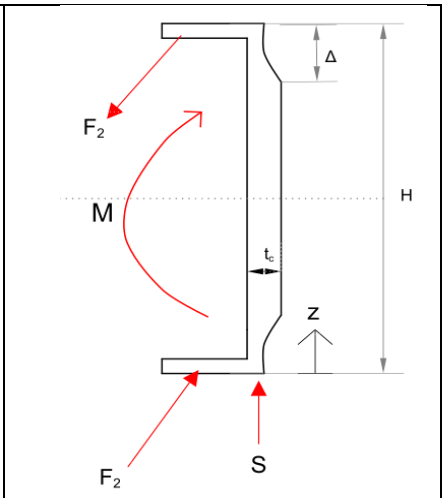

Figure 76 Top view representation of rudder with F_2, M and S

M becomes a force couple, there is no resultant force. The rudder force, F_2 from the moment can be obtained as:

$$M = F_2 H \rightarrow F_2 = \frac{M}{H} \qquad \textit{Eq. 120}$$

To design tap and bottom flange neglect contribution of flange to shear. All of S is taken as a quatratic distribution along H.

$$\tau_{max} = \frac{3}{2}\frac{S}{A} \; at \frac{H}{2} \qquad \textit{Eq. 121}$$

The area of A is equal to:

$$A = 2t_{wall}(H - 2\Delta) \qquad \textit{Eq. 122}$$

Δ is the skin thickness. Typical spar failures for the flange and web are listend in Table 21.

Table 21 failures of spar

	Type of failure	Under force or moment
Flange	No material failure	$A_y - G_y = \frac{M}{L}$
	No crippling failure	$A_y - G_y = \frac{M}{L}$
Web	No material failure	τ_{max}
	No shear buckling	$\tau_{avg} = \frac{S}{A}$

It should be noted that for the flange failue the highest shear load ($A_y - G_y$) should be used. Kassapoglou (2010) describes crippling failure as a stability failure where the flange locally buckles and then collapses. In Figure 77 this shown, under compressive loads, the flanges can

buckle locally with a half-wavelengt l. The buckled flanges cannot carry the maximum loads due to crippling and the post buckled regime will fail. If the loads cannot be transferred to the surrounded members the entire crossection will collapse.

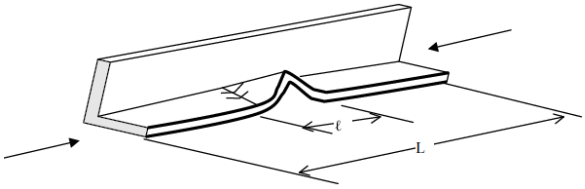

Figure 77 flange crippling (Kassapoglou, Design and Analysis of Composite Structures, 2010)

Crippling is the most common failure modes in composite airframes. In Figure 78 it can be seen that crippling is 25% of failure causes in a composite airframe.

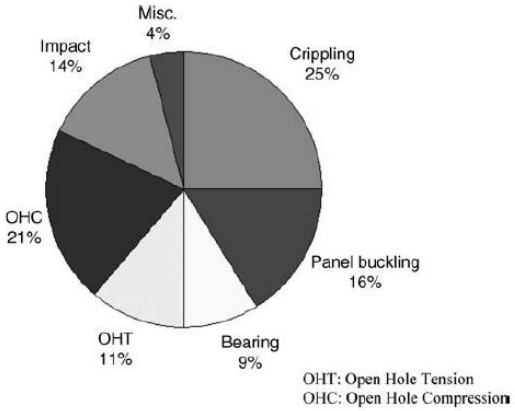

Figure 78 failure modes in composite airframe (Kassapoglou, 2010)

Forces on the rudder skin

The forces on the sandwich skin will be elaborated by using the conservative design approach. The left hand-side of the rudder will be called the inboard and the right hand-side the outboard side. This is indicated in Figure 79 and Figure 80. The distribution force

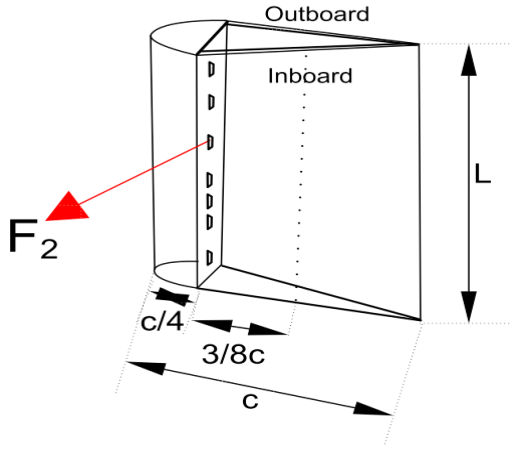

Figure 79 rudder force and dimensions

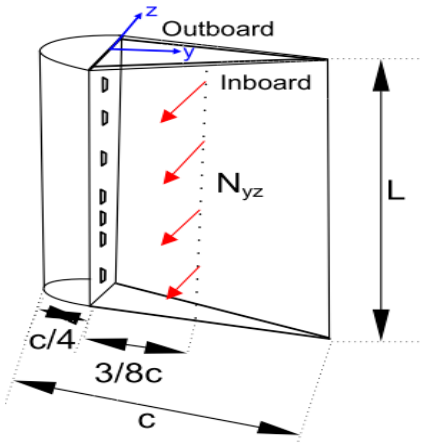

Figure 80 rudder distributed force and dimensions

The distributed force N_{yz} is equal to the rudder force F_2 over rudder length, L:

$$N_{yz} = \frac{F_2}{L} \qquad Eq.\ 123$$

In Figure 81 and Figure 82, the view of AA is shown with the associated force F_0 as shown in Figure 82. Each face sheet on inboard or outboard side carries $\frac{F_0}{2}$.

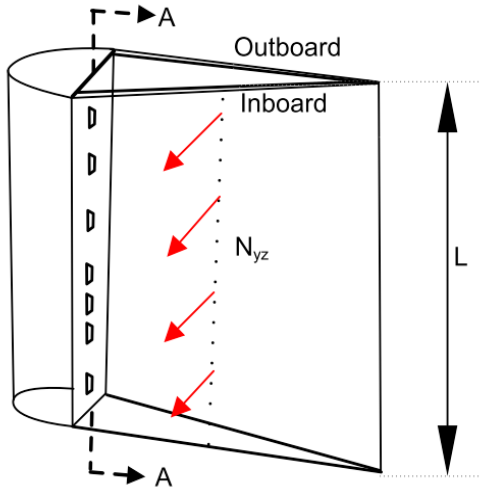

Figure 81 rudder with cutting section

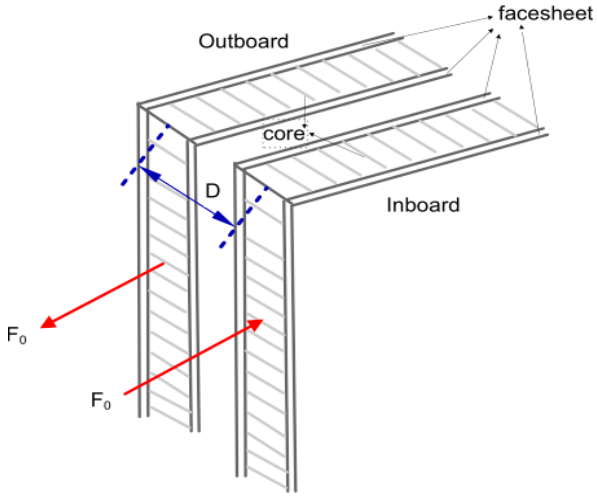

Figure 82 view AA with forces on the skin

To compute or obtain and expression for F_0 Figure 83 can be used in which the moment M is given as a force couple. Following relation are needed to obtain an expression for F_0.

$$M = F_2 \frac{3}{8} c \qquad Eq.\ 124$$

Taking the moment at the centre either of inboard or outboard skin with a distance D, the following yields:

$$F_0 D = M \qquad Eq.\ 125$$

Combining *Eq. 157* with *Eq. 156* results in an expression of F_0 as a function force F_2, distance D between the two skins:

$$F_0 = F_2 \frac{3c}{8D} \qquad Eq.\ 126$$

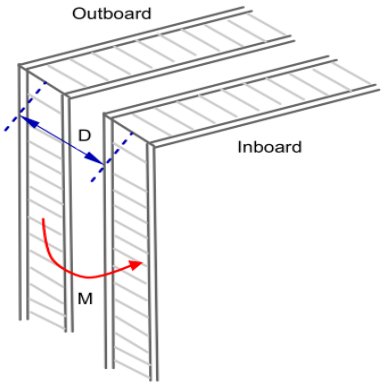

Figure 83 AA view with the moment M

The shear strength in the core of the sandwich skin can be obtained by analysing Figure 84.

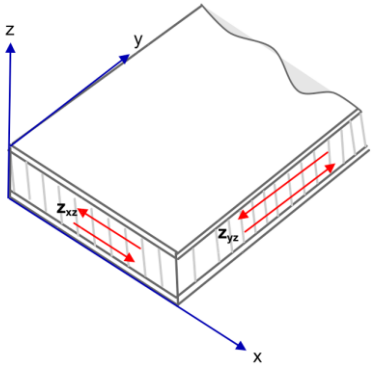

Figure 84 skin cross-section with strength

The composite materials are designed such that one direction (Z_{xz}) is stronger than the other direction (Z_{yz}), anisotropic behaviour. This has to do with the orientation of the core. This material property is called the ribbon material property (Kassapoglou, Design and Analysis of Composite Structures, 2010). The designers analyse the direction in which high loads are applied and then the ribbon material property is applied. Usually, the following can be approximated for ribbon material property. (Assuming that Z_{xz} is higher than Z_{yz}): $Z_{xz} = 2\,Z_{yz}$. Although, Z_{xz} can be expressed as a function of F_2 by the following expression (Kassapoglou, Personal Interview, 2015):

$$Z_{xz} = \frac{F_2}{2\,t_{core}\,L} \qquad \textit{Eq. 127}$$

Where;
Factor 2 is added for the skins, outboard and inboard skin.
L is the length of the spar/rudder [m]
t_{core} is the core thickness [m]

To determine face sheet failure, Figure 82 can be consulted. The outboard skin is assumed to be in tension while the inboard skin is under compression force. Each face sheet (4 in total) is under $\frac{F_0}{2}$. With F_0 given by *Eq. 126*. Wrinkling failure can be determined by using the following formula (Kassapoglou, Design and Analysis of Composite Structures, 2010):

$$N_x wrinkling = 0.43\left(E_c G_z E_f\right)^{\frac{1}{3}} \qquad \textit{Eq. 128}$$

Where;
E_c is the core stiffness (ontof-plane)
G_z is the shear modulus of core in xz-direction
E_f is the facesheet Young's modulus

In Table 22 typical skin failures are shown with the associated forces and moments together with material properties that cause failure.

Table 22 typical composite skin failures under moment/forces

	Type of failure	Under force or moment
Facesheet	Facesheet under tension/compr	$F_0 = \frac{M}{L}\ or\ F_0 = F_2\frac{3c}{8D}$
	wrinkling	$N_x wrinkling = 0.43 t_f \left(E_c G_{xy} E_f\right)^{1/3}$
Core	Shear strenght failure	$Z_{xy} and\ Z_{xz}$
	No shear buckling	$\tau_{avg} = \frac{S}{A}$

In Figure 60 a summary of the maintenance interval determination for the rudder is shown. In the first layer of the swim lane the three cases are indicated that will be analysed. In second layer the rudder parts with corresponding materials are illustrated. The typical failure mode for fatigue and accidental damage are shown in third layer and at the fourth layer the maintenance intervals will that will be determined for impact and delamination damage is illustrated.

In the following sub-section the results for the three critical load cases described are computed (Figure 32 and Figure 60). The obtained results are for the vertical tail load L_V and the rudder load F_2.

6.2.1.4 *Results of Critical Load Cases and Stress Analysis of the Rudder*

For every load case a parameter table, which is used to determine the result, is shown. If the value of a variable could not be obtained, assumptions are made and indicated in the table. The parameters list, result/values and their references are shown in Table 23. The parameters are on a high level and are used for the load cases determination.

Table 23 parameters and values for lateral gust load determination

Parameter	Result/Value	Equation/Source
$\boldsymbol{\rho}$	$1.225\ kg/m^3$	-
$\boldsymbol{\bar{c}_t}$	$\bar{c}_t = = \frac{S}{b} = \frac{47.65}{10.41} = 4.58$ (m)	Elsevier, 2015
$\boldsymbol{A.R}$	9.126	Elsevier, 2015
$\boldsymbol{g}$	$9.81\ (m/s^2)$	-
$\boldsymbol{V}$	$281\ (m/s)$	Airbus, 2007
$\boldsymbol{b}$	$58\ (m)$	Elsevier, 2015
$\boldsymbol{W}$	$230000\ (kg)$	Airbus, 2007
$\boldsymbol{v}$	$100kt/nm = 27.75\ (m/s)/km$	Airbus, 2007
$\boldsymbol{l_v}$	$22.24\ (m)$	*Eq. 132*
$\boldsymbol{S}$	$361.10\ (m^2)$	Jenkinson et al., 2001
$\boldsymbol{S_v}$	$47.65(m^2)$	Jenkinson et al., 2001
$\boldsymbol{C_{L_\propto}}$	7.97	*Eq. 129*
$\boldsymbol{R_{gy}}(=\frac{\boldsymbol{V}}{\boldsymbol{r}})$	$\frac{281}{0.276} = 1018$(m)	Assumption max rudder extension in 2 seconds, $r = 0.276\ rad/s$
$\frac{\boldsymbol{c_{rudder}}}{\boldsymbol{4}}$	$0.41\ (m)$	Elsevier, 2015
$\boldsymbol{S_r}$	$13.86\ (m^2)$	Estimated from Appendix I , Appendix M and Elsevier, 2015
$\boldsymbol{d}$	$2.61\ (m)$	Estimated from Appendix I , Appendix M and Elsevier, 2015
$\boldsymbol{h_1}$	$0.41\ (m)$	Estimated from Appendix I , Appendix M and Elsevier, 2015

Lateral gusts

To obtain the load action on the rudder from lateral gust first *Eq. 92* can be used than this load can be translated into the rudder load by *Eq. 109.* First the lift curve slope ($C_{L_\propto}$) and radius of gyration (R_{gy}) should be determined while the other parameter of *Eq. 92* can be obtained from A330 manuals (Table 23).

The lift curve slope can be obtained by Prandtl-Glauert expression (Kroo, 1995):

$$C_{L_\propto} = \frac{2\pi A.R}{\left(A.R\sqrt{1-M^2}+2\right)} \qquad \textit{Eq. 129}$$

With A.R stands for the aspect ratio and M represents the Mach number. The radius of gyration given in rad/s is the maximum rudder angel deflection (Rad) in certain amount of time. In this case it is assumed that the rudder is deflected in two seconds to the maximum allowable deflection of 31.6 °.
Inserting the results of Table 23 into *Eq. 92*, the vertical tail load due to gusts can be obtained:

$$(L_V)_{LG} = \frac{0.88 \times 27.75 \times 281 \times\ 7.97 \times 47.65}{498} = 5122\ N \qquad \textit{Eq. 130}$$

Using Eq. 109 the rudder load can be computed for the lateral gusts, $(F_2)_{LG}$:

$$(F_2)_{LG} = \frac{5122 \times 0.41}{(0.41 + 2.61)\cos 31.6 + (0.41)} = 704\ N \qquad \textit{Eq. 131}$$

It should be noted that in this case the rudder is assumed to be fully deflected.

Asymmetric thrust

The A330-200 aircraft have different types of engine installed, like PW4000, Rolls-Royce Trent 700 or GE CF6-80E1. All of them have different thrusts. In this analysis it assumed that the A330-200 is flying with the CF6-80E1 series turbofan with each engine having a thrust of $303.3 \times 10^3\ N$ (Airbus, 2014). To determine the dimensions of l_v and y_T Appendix I is used. For the distance between the engine and the centre of gravity it assumed that the A330-200 is symmetric about xz-plane. So cg lies in the middle of aircraft and distance between cg to the engine is, $y_T = \frac{18.74}{2} = 9.37m$. To estimate l_v, more data is required and some assumptions should be made. The center of gravity of an aircraft can have different positions regarding the flight phase and weight of aircraft. In Figure 85 the cg limits of A330-200 are shown for different aircraft weights and flight phases.

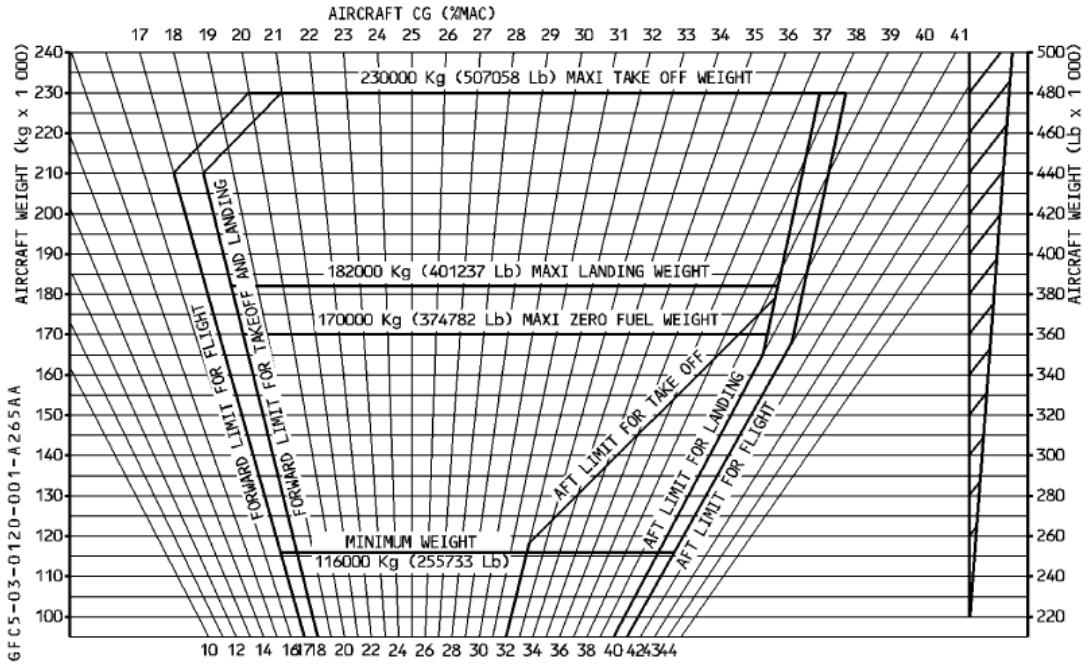

Figure 85 center of gravity limits A330-200 (Airbus training, 2010)

- cg limits are given in percentage of the Mean Aerodynamic Chord (MAC) length aft of the leading edge
- the MAC or reference chord length is 7.27 m, it is 24.96 m aft of the aircraft nose

- the cg must be always within these limits regardless of fuel load

Assuming a cg location at 28%MAC and using Figure 85 (upper) the cg location (x-axis) can be estimated from the nose of the aircraft: $cg = 24.96 + (0.28 \times 7.27) = 27m$. The chord length of the vertical tail root including the rudder, C_{V_r}(see Appendix I) is 8.63m. Assuming the aerodynamic centre of the vertical tail is located at 25% C_{V_r} , the l_v can be estimated:

$$l_v = 47.09 + (0.25 \times 8.58) - 27 = 22.24m \qquad \textit{Eq. 132}$$

Now the results of *Eq. 132* and other parameters are listed in Table 24:

Table 24 parameter list for asymmetric thrust

Parameter	Result/Value	Equation/Reference
$\boldsymbol{T_L}$	303.3×10^3 (N)	(Airbus, 2014)
$\boldsymbol{y_T}$	9.37 (m)	Estimated from Appendix I
$\boldsymbol{l_v}$	22.24 (m)	*Eq. 133*

Inserting the values of Table 24 into *Eq. 96* the load on the vertical tail due to asymmetric thrust can be computed:

$$(L_V)_{Asy\ thrust} = \frac{-303.3 \times 10^3 \times (-9.37)}{22.24} = 127784\ N \qquad \textit{Eq. 134}$$

Using again *Eq. 109* the rudder load due to asymmetric thrust can be determined with max rudder deflection:

$$(F_2)_{asy\ thrust} = \frac{127784 \times 0.41}{(0.41 + 2.61)\cos 90 + (0.41)} = 17568\ N \qquad \textit{Eq. 135}$$

Sudden maximum rudder input

To determine the manoeuvre loads on the rudder *Eq. 97* can be consulted. Although, first the angle of side slip β can be approximated by the following formula (Mulder et al., 2011):

$$\beta = \arcsin\frac{v}{V} \approx \frac{v}{V} = \frac{27.75}{281} \approx 0.10 \qquad \textit{Eq. 136}$$

Where, v is the velocity of the air and V is the speed of the airplane. Further Puttock (1956) argues that the term $\frac{d\beta}{d\tau}$ can be neglected in the case of load affection by rudder deflection. So the *Eq. 97* can be reproduced to:

$$(L_V)_{\max \delta_R} = (-B\beta - C + a_2\delta_R)\,J \qquad \textit{Eq. 137}$$

Typical values for the constants a_1, a_2 and B for commercial aircraft are given by Puttock (1956) as: $a_1 = 2.50$, $a_2 = 1.8$ and $B = 2.527$. The result of the load P as function of the rudder deflection δ_R is plotted in Figure 46. It should be noted that the other variables in *Eq.*

137 are regarded to be constant. For a maximum rudder deflection of $\delta_R = 31.6°$ the load P on the fin and rudder is equal to $141726730\ N$. The parameters used for estimation are listed in Table 25.

Table 25 parameter list for sudden max rudder input load estimation

Parameter	Value	Equation/Reference
$\boldsymbol{T}$	$303.3 \times 10^3\ (N)$	(Airbus, 2014)
$\boldsymbol{V}$	$281\ (m/s)$	Estimated from Appendix I
$\boldsymbol{S_v}$	$52.87\ (m^2)$	*Eq. 138*
$\boldsymbol{W}$	$230000\ (kg)$	
$\boldsymbol{g}$	$9.81\ (m/s^2)$	–
$\boldsymbol{l_v}$	$22.24\ (m)$	*Eq. 139*
$\boldsymbol{J}$	2556984	*6.2.1.2*
$\boldsymbol{C}$	1.91	*6.2.1.2 and* (Puttock, 1956)
$\boldsymbol{a_1}$	2.5	(Puttock, 1956)
$\boldsymbol{B}$	2.527	(Puttock, 1956)

Using *Eq. 135*, *Eq. 109* and Table 25 the rudder load can be obtained.

$$(F_2)_{\max \delta_R} = \frac{141726730 \times 0.41}{(0.41 + 2.61)\cos 90 + (0.41)} = 19817085\ N \qquad \textit{Eq. 140}$$

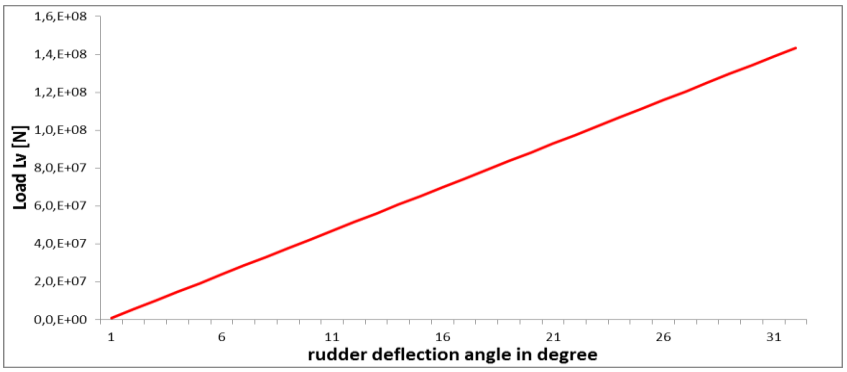

Figure 86 vertical tail load vs. rudder deflection

For different load cases, the rudder loads are determined. The end results are listed in Table 26. However, for fatigue evaluation the frequency of loads per flight cycles are required to determine maintenance intervals. In Appendix F the amount of load cycles per flight cycles (FC) are determined and the obtained results are listed in Table 26 as well.

Table 26 loads on the rudder of A330

Loading type	Magnitude	frequency
Lateral gust loads $(F_2)_{LG}$	$704\ N$	90
Asymmetric thrust $(F_2)_{asym\ thrust}$	$17568\ N$	90
Manoeuvre load/Sudden max rudder input $(F_2)_{\max \delta_R}$	$19817085\ N$	≈ 0

6.2.1.5 *Maintenance Interval Determination for A330 Skin*

The graph of the damage size as a function of the load cycles can be created using *Eq. 75*. In this case the load cycles is determined for various damage sizes, DS_i. Table 27 can be used as guidance of the input parameters, results/value and equations/references.

Table 27 parameter list for maintenance interval determination with inputs and outputs

Parameter	Value/Result	Equation/Reference
N_{f_0}	4.35×10^6	*Eq. 141* and Figure 87
N_{f_i}	$variable$	Figure 87
N_i	$variable$	Figure 87
λ_l	$10\ (mm)$	*Eq. 142*
a	$2800(GFRP)\ and\ 3100\ (CFRP)$ m/s	Table 28
f	$2.8 \times 10^5(GFRP) and\ 3.1 \times 10^5(CFRP)\ (Hz)$	*Eq. 144 and Eq. 145*

First, the number of cycles to failure $N_{f_{DS=0}}$ for a damage size of $DS = 0mm$ is estimated. Then for every damage size, DS_i the number of cycles to failures $N_{f_i}(DS_i)$, are obtained with $i = 10, 20, \dots, 90mm$. Finally the $N_{f_{DS=0}}$ is subtracted by every $N_{f_i}(DS_i)$ to obtain the allowable load cycles as a function of damage size, this is shown in *Eq. 141*. Finally, the results are plotted in Figure 87 for delamination failure mode.

$$N_{f_0}(DS = 0),\ N_{f_i}(DS = i) \rightarrow N_i(DS) = N_{f_0} - N_{f_i} \qquad \textit{Eq. 141}$$

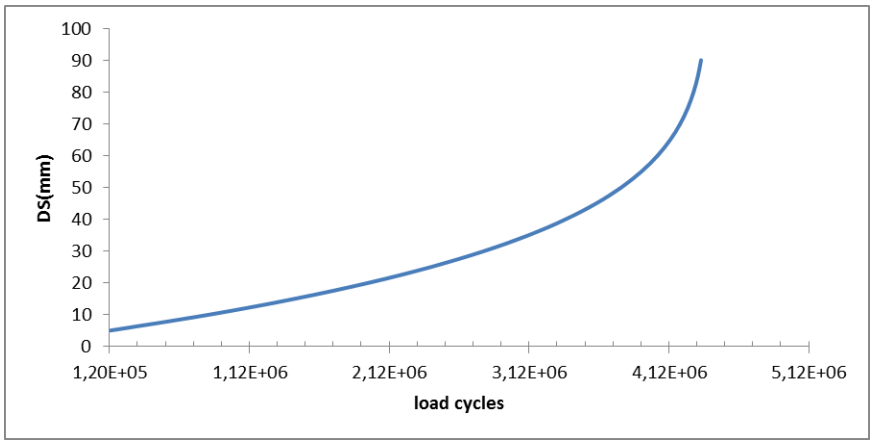

Figure 87 load cycles vs. DS for the honeycomb core, delamination failure

Using the rules generated in sub-section 5.2.2 and using figures, Figure 37 and Figure 38, the maintenance intervals for the sandwich skin can be developed. First Figure 37 and Figure 87 are combined to specify the values of the inspection variables. Then the inspection time can be determined in load cycles. After the determination of the inspection time in load cycles the inspection time can be converted to calendric years. However, the inspection variable I_d is

dependent on the NDI method used to locate failures. The NDI methods that are recommended by Airbus (Urdiroz, 2007) are the Ultrasonic Test (UT), Thermography or X-ray. The preferred NDI method of the mentioned three is UT. The Probability of Detection (POD) of the damage has a significant effect on the wavelength of the ultrasound. The following formula describes the wavelength.

$$\lambda_l = \frac{a}{f} \qquad \textit{Eq. 142}$$

Where;
λ_l is the wavelength (m)
a the velocity of sound in certain medium (m/s)
f is the frequency (Hz)

A general rule of thumb to detect discontinuities is that the wavelength λ_l should be less than one-half of the damage size to be detected.

$$\frac{1}{2}DS > \lambda_l \rightarrow DS > 2\lambda_l \qquad \textit{Eq. 143}$$

As it can be seen from *Eq. 142* the wavelength is inversely proportional to the frequency. The velocity of the ultrasound is constant and it is a material property. The sensitivity and resolution of the UT method increases by increasing the frequency f, thus by decreasing the wavelength λ_l, sensitivity and resolution increases. Sensitivity is the ability to detect small discontinuities. Resolution is the ability of the NDI method to locate discontinuities that are close to each other within the material or located near the part surface. To detect damages in the core the UT should pass through the inner skin and also through the outer skin. Speed of sound in CFRP is 3100 m/s (Hillger et al., 2002). The frequency of UT method can be determined by using *Eq. 142* and assuming to locate delamination damage with a size of 20mm, $\lambda_l < 10mm$:

$$f = \frac{a}{\lambda_l} = \frac{3100}{0.01} = 3.1 \times 10^5 Hz \qquad \textit{Eq. 144}$$

So to have a chance to detect the damages with a size of $DS \geq 20mm$ the frequency of the ultrasound should be higher than, $f \geq 3.1 \times 10^5 Hz$. However, the frequency range used in UT NDI methods is around 0.5 MHz to 2.25 MHz (Nelligan, 2014), so the calculated frequency in *Eq. 144* is less below the standard range which is applied in UT methods. The same equation, *Eq. 142* can be used to determine the frequency of the GFRP. The speed of sound in GFRP is around 2800 m/s (Wrobel, 2007). The frequency to locate delamination damage with $DS \geq 20mm$ for the outer skin can be calculated again with *Eq. 142*:

$$f = \frac{a}{\lambda_l} = \frac{2800}{0.01} = 2.8 \times 10^5 Hz \qquad \textit{Eq. 145}$$

In order to detect damages in the Nomex core frequency of the UT method should be between $5 \times 10^4 Hz - 8 \times 10^5 Hz$ (Hillger et al., 2002). So the UT frequency range of 0.5

MHz to 2.25 MHz satisfies for the 3 different material types of the rudder (inner skin- core-outer skin) to locate damages. Whitehead (1990) argues that the region of Barely Visible Impact Damage (BVID) is approximately between 35mm-41mm. BVID is defined by Fawcett an Oakes (2006) as small damages which may not be found during heavy/base maintenance general visual inspections during typical lighting conditions from a distance of 1.5m. However, the damage can be located by NDI inspection. In Figure 88 the a_d *or* DS_d is set to 35mm. Whitehead (1990) suggest that the damages (impact and delamination) can be easily detected after a damage size of 58mm. In the table below the frequency range and speed of sound for various skin materials is summarized for the UT method.

Table 28 speed of sound and frequency range for different sandwich materials

Material	Speed of sound (m/s)	Frequency range (MHz)
CFRP	3100	0.5-2.25
GFRP	2800	0.5-2.25
Core	-	0.05-0.8

Using the rules generated in section 5.2.2 and using figures, Figure 37 and Figure 38, the maintenance intervals for the sandwich skin can be developed for delamination, tension/compression and shear core failure.

Delamination failure mode

In Figure 88 the product of Figure 37 and Figure 87 is shown. The numeric values can be obtained from this figure.

- Safety Limit, $SL = I_c - I_0 = 4.35 \times 10^6 - 0 = 4.35 \times 10^6$ *number of load cycles*
- $I_1 = \frac{1}{2}SL = \frac{1}{2} \times 4.35 \times 10^6 = 2.185 \times 10^6$ *number of load cycles*

Now the Δ and ΔI can be estimated and are indicated in Figure 88.

- The available inspection time, $\Delta = I_c - I_d = 4.35 \times 10^6 - 3.02 \times 10^6 = 1.33 \times 10^6$ of load cycles
- Subsequent inspection interval $\Delta I = \frac{1}{2}\Delta = \frac{1}{2} \times 1.33 \times 10^6 = 6.65 \times 10^5$ load cycles
- The second inspection interval $I_2 = I_1 + \Delta I = \frac{1}{2}SL + (I_c - I_d) = 2.18 \times 10^6 + 6.65 \times 10^5 = 2.84 \times 10^6$ load cycles
- $\text{Visual}_{\text{detection period}} = I_c - I_{VI}$, to obtain I_{VI} the damage size $DS_{VI} = 58\text{mm}$ is used. $\text{Visual}_{\text{detection period}} = 4.35 \times 10^6 \times 10^6 - 4.00 \times 10^6 = 0.35 \times 10^6$ load cycles
- Condition: $\text{NDI}_{\text{detection period}} > \text{Visual}_{\text{detection period}}$
- j^{th} inspection interval $I_j = I_1 + (j-1)\Delta I$

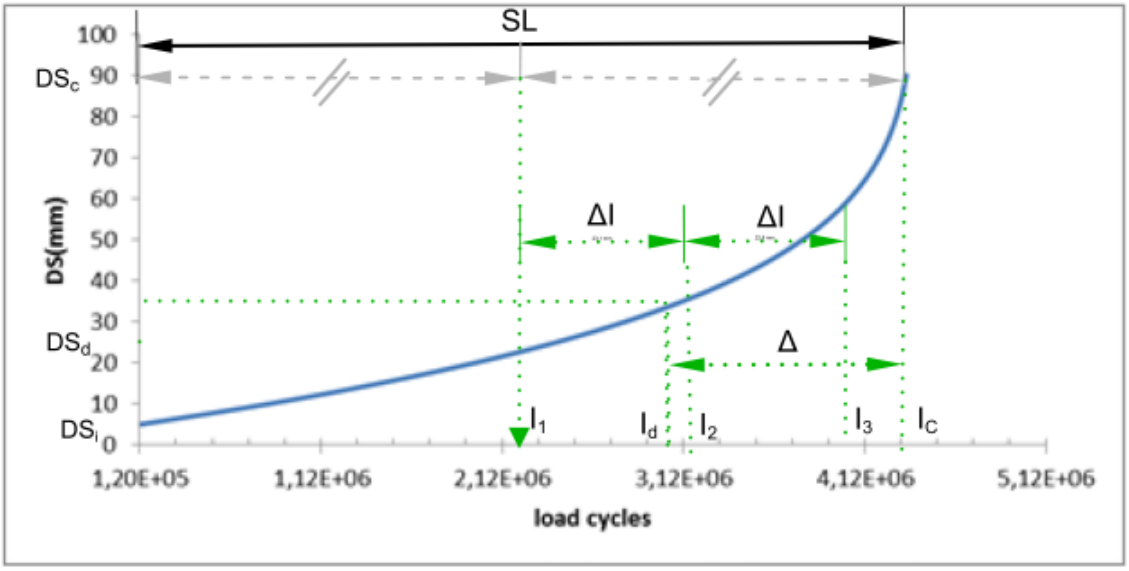

Figure 88 determination of maintenance inspection variables for delamination failure mode

Tension compression failure of face sheets

Using *Eq. 141* and rules generated in sub-section 0 the Figure 89 is created for tension/compression failure of the facings. Maintenance inspection variable for tension/compression failure are:

- $SL = I_c - I_0 = 2.71 \times 10^7 - 0 = 2.71 \times 10^7\ number\ of\ load\ cycles$
- $I_1 = \frac{1}{2}SL = \frac{1}{2} \times 2.71 \times 10^7 = 1.36 \times 10^7\ number\ of\ load\ cycles$
- $\Delta = I_c - I_d = 2.71 \times 10^7 - 1.78 \times 10^7 = 0.93 \times 10^7$
- Subsequent inspection $\Delta I = \frac{I_c - I_d}{2} = \frac{0.93 \times 10^7}{2} = 1.13 \times 10^7\ load\ cycles$
- j^{th} inspection interval $I_j = I_1 + (j-1)\Delta I$

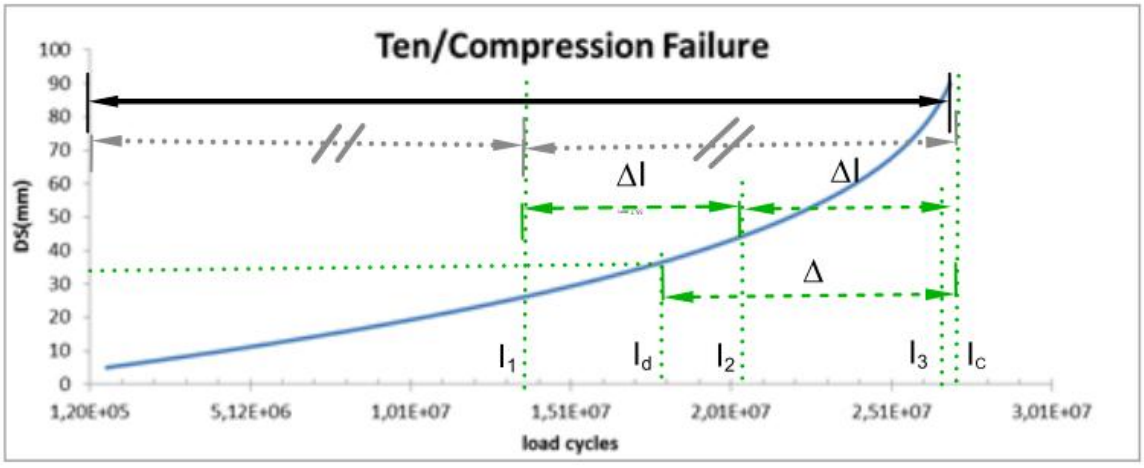

Figure 89 determination of maintenance inspection variables for tension/compression failure mode

Shear strength failure of core

Same approach is used to determine maintenance inspection intervals for shear strength failure of the Nomex core. The results are depicted in Figure 90.

- $I_c - I_0 = 8.62 \times 10^6 - 0 = 8.62 \times 10^6$ *number of load cycles*
- $I_1 = \frac{1}{2}SL = \frac{1}{2} \times 8.62 \times 10^6 = 4.31 \times 10^6$ *number of load cycles*
- $\Delta = I_c - I_d = 8.62 \times 10^6 - 5.85 \times 10^6 = 2.77 \times 10^6$
- Subsequent inspection $\Delta I = \frac{I_c - I_d}{2} = \frac{8.62 \times 10^6 - 5.85 \times 10^6}{2} = 1.39 \times 10^6$ *load cycles*
- j^{th} inspection interval $I_j = I_1 + (j-1)\Delta I$

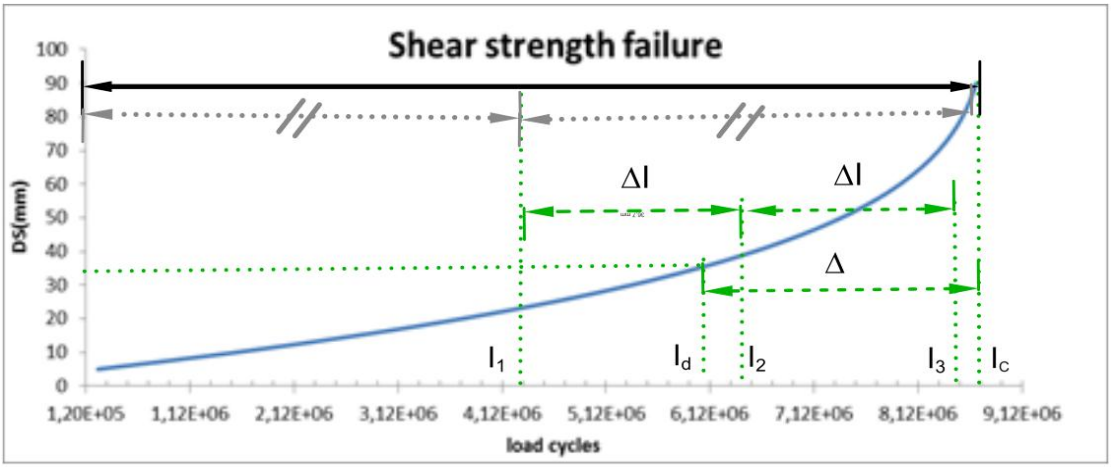

Figure 90 determination of maintenance inspection variables for shear strength failure mode

The inspection intervals are estimated in load cycles that can converted to years. Following parameter table is therefore created:

Table 29 parameter table for maintenance intervals

Number of FC per year, FCs	Number of load cycles per FC	Number of load cycles per year
951 (IATA, 2013)	180 (Table 26)	171180

The obtained maintenance inspection variables for the 3 analysed failure modes: delamination (disbanding of core and face sheets), tension/compression failure of the facings and shear strength failure of the core can be expressed in calendric years in Table 30.

Table 30 maintenance inspection variables expressed in years

Delamination		*Tension/compression failure*		*Shear strength failure core*	
Variable	**Unit in Years**	**Variable**	**Unit in Years**	**Variable**	**Unit in Years**
I_c	25.41	I_c	158.31	I_c	50.36
I_d	17.64	I_d	103.98	I_d	34.17
I_1	12.71	I_1	79.16	I_1	25.18
Δ	7.77	Δ	54.33	Δ	16.19
ΔI	3.89	ΔI	27.17	ΔI	8.09
I_2	16.60	I_2	133.49	I_2	33.27
I_3	20.49	I_3	160.66	I_3	41.36

From Table 30 it can be concluded that delamination failure is prior than other failure modes. The critical inspection time I_c is 25.41 years. This suggests that delamination failure could occur after 25.41 years at the skin core. To avoid delamination failure, sandwich skin should

be inspected and restored. The detectable inspection time expressed in years, is $I_d = 17.64$ years. So the rudder has for that specific failure mode available inspection time (Δ) of 7.77 years before failure can occur. Further the subsequent inspection interval (ΔI) of the delamination is every 3.89 years. As it can be seen from Table 30 for tension/compression failure and shear strength failure the initial inspection times (I_1) are above the aircraft life-cycle (20 YE). For delamination failure the skin should be inspected in total three times (at AC age 12.71YE, 16.60YE and 20.00YE), if I_3 is rounded to 20.00YE. As discussed in section 6.2 the maintenance intervals of A330 are given in C-checks (C to 8C) with C is equal to 18 months. Therefore, to express the determined maintenance intervals in C-checks, the initial maintenance interval (I_1) can be conducted at 8C with subsequent maintenance interval of 2C. The maintenance cost of this maintenance inspection can be estimated in AC life:

$$MC_{C-checks_{delamination}} = 3 \times \left(MMH_{C-Check} \times r_{labor_{C-Check}}\right) \qquad \textit{Eq. 146}$$

Where;
$MMH_{C-Check}$ the maintenance man hours for inspection
$r_{labor_{C-Check}}$ the maintenance labor rate of the inspector ($€/hr$)

It should be noted, the obtained maintenance intervals and expression that estimate maintenance cost is obtained from fatigue perspective. As discussed in section 4.2 the maintenance program or maintenance intervals as stated in the MPD are determined also from other triggers. These triggers can be the past experience of aircraft manufactures and airlines, defects arising from existence models, AD's SB's modification etc.

7 Verification and Validation

In this chapter verification and validation are provided for the methodology, which is developed in chapter 5 and used in chapter 6 . The values obtained for variables and cost estimation results in previous chapter, are first verified with the numerical quantities provided in academic literature and real life data from Maintenance Cost Task Force (MCTF) of IATA (IATA, 2013). After verification of the results, the developed methodologies are validated by other maintenance cost estimation methods. The methods used for validation are adjusted such to allow estimation for aircraft life. Three validation methods are used: Roskam and van der Velden method A and method B. The unscheduled maintenance cost estimation is validated by using modified equations of Brugidou method, which was elaborated in sub-section 4.4.7.

7.1 Verification of Maintenance Cost Analysis Variables

In table below the variables used for weight estimation is given. The associated equation number, obtained values, sources used are verified and the corresponding error is given in percentage.

Table 31 verification table for variables used in weight estimation

Variable	Equation	Obtained Value	Validation value	Source	Error
Airfoil thickness $\frac{t}{c}$	*Eq. 83*	0.0823	0.10	(Liebeck et al., 1995)	17%
Span of vertical tail b_v	*Eq. 84*	9.40 m	9.44 m	(Jenkinson et al., 2001)	0,42%
Vertical tail weight incl. rudder W_{vtail}	*Eq. 84-Eq. 85*	2697 kg	0.8-1.2% of MTOW = 1840kg-2790kg	(Elham, 2013), (Liebeck et al., 1995)	-
Rudder surface S_{rudder}	*Eq. 84-Eq. 85*	13.86 m^2	14.78 m^2	(Jenkinson et al., 2001) and (Sadraey, 2012)	6.64%

Figure 18 and Figure 19 provide the percentages of the following aircraft segments: airframe maintenance cost, engine maintenance cost of and burden cost (all other costs) over total maintenance cost. The airframe, component and powerplant cost are also shown as a percentage of DMC. In the table below the percentages are depicted.

Table 32 verification data table for maintenance cost results

Segment (Rand)	**Maintenance cost segment of TMC**	**Segment (IATA)**	**Maintenance cost segment of TMC**	**Segment (Brugidou)**	**Maintenance cost segment of TMC**		
Direct airframe	33%	**Airframe**	36%	**Airframe**	35%	*Labor* *Material*	*75%* *25%*
Direct engine	27%	**Component**	23%	**Component**	30%	*Labor* *Material*	*50%* *50%*
Burden	40%	**Powerplant**	41%	**Powerplant**	35%	*Labor* *Material*	*30%* *70%*

The obtained labor cost and material cost for the A330 rudder can also be verified with the ratios in Table 32 above. As it can be seen from the table, the airframe maintenance cost are

around 33%-36%. To verify the results of chapter 6 (case study), the average annual maintenance cost for a certain aircraft age is needed as a reference. IATA's Maintenance Cost Task Force (MCTF) evaluates every year around 46 airlines with approximately 4100 aircraft for their cost analysis. For the analysis of fyscial year 2012 the average age of the aircraft were 10 years and maintenance cost was 3.4 million USD per aircraft which is equal to 2.63 millon EUROS[3]. In order to estimate rudder maintenance costs in terms of labor and material total airframe cost was estiamted as well, Appendix J and Appendix K . Assuming the TMC of a A330-200 rudder also consist of 2.63 million EUROS per aircraft per year with an aircraft age of 10 years the obtained airframe maintenance cost over TMC can be derived to verify the results (Appendix J and Appendix K). In the table below the verification table of the obtaine results are shown:

Table 33 verification table of the maintenance cost

	Segement	Obtained result (€)	Source	Verification result	Off-set
Airframe	Labor	842808	Table 32	710100	15.7%
	material	308653	Table 32	236700	23.3%

The ratio between airframe maintenance labor cost over DMC airframe and airframe maitnenance material cost over DMC airframe are:

$$\frac{C_{labor\ airframe}}{DMC_{airframe}} = \frac{710100}{(710100 + 236700)} = 73\% \qquad \textit{Eq. 147}$$

$$\frac{C_{material\ airframe}}{DMC_{airframe}} = \frac{236700}{(710100 + 236700)} = 27\% \qquad \textit{Eq. 148}$$

Comparing the results of *Eq. 147* and *Eq. 148* with Table 32, which shows contribution of labor maintenance cost over DMC and material maintenance cost over DMC, respectively 75% and 25%. It can be concludded that the results of *Eq. 147* and *Eq. 148* deviate with 2%.

7.2 Verification and Validation of AIM

In this section the validation of the Aging Involved Method which was provided in chapter 5 and practiced in chapter 6 is discussed. The outcomes of airframe labor cost are validated by two method of Roskam and van der Velden, A and B. In these methods the equations both of Roskam (2002) and van der Velden (1997) method are combined and used to validate the labor costs. The Roskam and van der Velden method A is elaborated in sub-section 7.2.1 and method B in sub-section 7.2.2. The aging factor and the unscheduled maintenance cost estimation are validated by Modified Brugidou Method shown in sub-section 7.2.3. In Table 34 a parameter list table is given for variables, equations/sources and results.

[3] Cost analysis for fiscal year 2012 and rate of exchange (USD-Euro) of 8th September 2014 is used

Table 34 parameter list table for variables and equations used to verify the results

Variable	Equation/Source	Result/ Value
$C_{lab\ air+sys}$	*Eq. 38* and *Eq. 154*	1700221 (€)
$C_{labor\ airframe}$	*Eq. 161*	784718 (€)
$MHR_{map_{flt}}$	*Eq. 149*, *Eq. 150* and *Eq. 155*	27.79 (hr)
FH (t_{flt})	(IATA, 2013), Constant	4088 (hr)
FC	(IATA, 2013), Constant	951(cycles)
r_{labor}	(Zhao et al.,2014), Constant	43.5 (€/hr)
$\frac{C_{airframe}}{C_{sys\&com}}$	*Eq. 156*,*Eq. 157*, *Eq. 158* and Figure 19	$\frac{0.30}{0.35}$
$CF_{\$\rightarrow€}$	(Wisselkoers, 2014)	0.77223[4]
V_{bl}	*Eq. 39* and *Eq. 151* and Figure 23	1365 (nm/hr)
t_{bl}	*Eq. 152*, *Eq. 153* and Figure 23	5.3 (hr)
R_{bl}	*Eq. 39* , Figure 23 and (Airbus, 2014)	7236 (nm)
TAT	Figure 91	1 (hr)
M	*Eq. 29*, *Eq. 30* and (Airbus, 2014b)	0.86
$W_{airframe}$	*Eq. 90*	57897 (kg)
MTOW	(Airbus, 2014)	230000 (kg)

7.2.1 Airframe Maintenance Labor Cost Validation by Roskam and van der Velden Method A

The results obtained by Aging Involved method are validated by van der Velden method and Roskam, shown in respectively in sub-section 4.4.8 and sub-section 4.4.9. This method is an adoption of the American Airlines method: "A New Method for Estimating Current and Future Transport Aircraft Operating Economics''.

Now the van der Velden method is used to estimate the MMH/FH and MMH/FC in order to estimate airframe labor cost, using *Eq. 29* and *Eq. 30* and using the aircraft characteristics shown below (Airbus, 2014b).

characteristic	Mmo (max.operating mach) (M)	Max. Seat capacity (s)	MTOW [kg]	$W_{airframe}$ $[kg]$
A330-200	0.86	380	230000	57897

[4] Conversion factor USD-EURO of 8 September 2014

$$\left(\frac{MMH}{FH}\right)_{airframe} = [3.08 + 0.000032 \times 57897 + 0.0041 \times 380]\sqrt{0.86} = 6.74\ hr \quad \textit{Eq. 149}$$

$$\left(\frac{MMH}{FC}\right)_{airframe} = [2.14 + 0.0000079 \times 230\,000 + 0.0046 \times 380]\sqrt{0.86} = 5.29\ hr \quad \textit{Eq. 150}$$

Using again the operational parameters as stated by IATA's Maintenance Cost Task Force (MCTF):

Table 35 A330-200 operational parameters (IATA, 2013)

Operational parameter	FH	FC
A330-200	4088	951

Using *Eq. 37* and *Eq. 38* the maintenance labor cost for airframe and systems can be estimated. In order to use *Eq. 37* and *Eq. 38* first expressions are needed for time units, using Figure 23 it can be derived:

$$t_{flt} = t_{cl} + t_{cr} + t_{de} \quad \textit{Eq. 151}$$

Where;
t_{flt} is the flight time, FH [hr]
t_{cl} is the time to climb [hr]
$t_{cr}$is the cruise time [hr]
t_{de} is the time to descent [hr]

Similar the block time t_{bl} can be expressed:

$$t_{bl} = t_{gm} + t_{cl} + t_{cr} + t_{de} \quad \textit{Eq. 152}$$

Where t_{gm} is the time spent in ground manoeuvres, so the turnaround time (TAT) of certain aircraft, *Eq. 153* can be rewritten as:

$$t_{bl} = FH + TAT \quad \textit{Eq. 153}$$

The TAT estimation of the A330 is shown in Figure 91. As it can be seen the TAT is approximately 60 minutes.

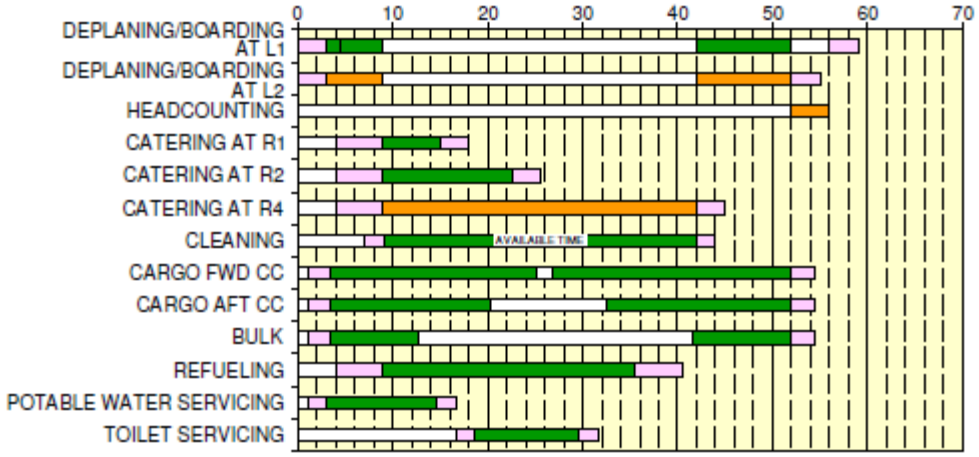

Figure 91 the TA activities and time of A330 (Airbus, 2014)

Inserting *Eq. 153*, *Eq. 38* into *Eq. 37* yields to maintenance labor cost for airframe and systems:

$$C_{labor\ air+sys} = 1.03\left(\left(MHR_{map_{flt}}\right)\left(\frac{t_{flt}}{t_{bl}}\right)\right) \times (r_{labor})(V_{bl}) \qquad Eq.\ 154$$

Where;
1.03 is the non-revenu factor. It accounts for extra maintenance costs due to flight delays
$MHR_{map_{flt}}$ is number of maintenance man-hours per FH, *Eq. 155*
t_{flt} is FH
t_{bl} is the block time [hr] defined in *Eq. 153*
r_{labor} is the labor rate [$/hr]
V_{bl} is the block speed [nm/hr], see *Eq. 39*

$$MHR_{map_{flt}} = \left(\frac{MMH}{FH}\right) + \left(\frac{MMH}{FC}\right)\left(\frac{FC}{FH}\right) \qquad Eq.\ 155$$

Where;
$\left(\frac{MMH}{FH}\right)$ is the maintenance man-hour per flight hour given by *Eq. 149*
$\left(\frac{MMH}{FC}\right)$ is the maintenance man-hour per flight cycle given by *Eq. 150*
$\left(\frac{FC}{FH}\right)$ is the ratio between flight cycle and flight hour given by Table 35

Since *Eq. 154* estimates maintenance labor cost of airframe as well as systems. The equations should be modified in order to estimate only the maintenance labor cost of airframe. From Figure 19 the following relation can be extracted:

$$DMC = (35\%)\ Powerplant + (30\%)\ System\ \&\ Component + (35\%)\ Airframe \qquad Eq.\ 156$$

So the contribution of components maintenance cost, $C_{component}$ and airframe maintenance cost, $C_{airframe}$ relative to the direct maintenance cost (DMC) is:

$$C_{airframe} = 0.35 \times DMC$$

$$C_{sys\&com} = 0.30 \times DMC \qquad \textit{Eq. 157}$$

The following relation can be made between airframe and component maintenance cost:

$$\frac{C_{airframe}}{C_{sys\&com}} = \frac{0.30 \times DMC}{0.35 \times DMC} = \frac{0.30}{0.35} \rightarrow$$

$$C_{sys\&com} = \left(\frac{0.35}{0.30}\right) C_{airframe} \qquad \textit{Eq. 158}$$

Eq. 154 can be rewritten as:

$$C_{labor\ air+sys} = C_{airframe} + C_{sys\&com} \qquad \textit{Eq. 159}$$

Inserting *Eq. 158* into *Eq. 159*:

$$C_{labor\ air+sys} = C_{airframe} + \left(\frac{0.35}{0.30}\right) C_{airframe} \rightarrow$$

$$C_{labor\ air+sys} = C_{airframe}\left[1 + \left(\frac{0.35}{0.30}\right)\right] \qquad \textit{Eq. 160}$$

Expressing airframe maintenance cost as a function of airframe maintenance labor cost and system maintenance labor cost:

$$C_{labor\ airframe} = \frac{C_{labor\ air+sys}}{\left[1 + \left(\frac{0.35}{0.30}\right)\right]} \qquad \textit{Eq. 161}$$

With $C_{lab\ air+sys}$ given by *Eq. 154*.

By using *Eq. 154* and Table 34, the annual maintenance labor cost for airframe of A330-200 is by adapted Roskam (2002) and van der Velden (1997) method is 784718€. Comparing this result with relations developed in chapter 4, *Eq. 45*, *Eq. 91* and *Eq. 55* and the results computed in chapter 5 (Aging Involved Method), the off-set is (for aircraft age, y=1year):

$$\frac{784718 - 707718}{707718} \times 100\% = 11\%$$

Further in Table 36 the variables are categorized into design and operation parameters (pts).

Table 36 variables categorization into design pts and operation pts

Variable	Design pts	Operation pts
$MHR_{map_{flt}}$		✓
FH (t_{flt})		✓
FC		✓
V_{bl}	✓	✓
t_{bl}	✓	✓
R_{bl}	✓	✓
TAT	✓	✓
M	✓	
$W_{airframe}$	✓	
MTOW	✓	✓

7.2.2 Airframe Maintenance Labor Cost Validation by Roskam and van der Velden Method B

A second method to verify the results can be developed by using *Eq. 149*, *Eq. 150* and *Eq. 155*. The maintenance labor cost for airframe and systems can be estimated by the following relation:

$$C_{labor\ air+sys} = \left(\frac{MMH}{FH}\right) \times FH_i \times r_{labor} \qquad Eq.\ 162$$

Where;
$\left(\frac{MMH}{FH}\right)$ is the maintenance man-hours per flight hour
FH_i is the flight hours for a certain year i (or aircraft age)
r_{labor} is the labor rate in €/hr

Using the data provided by Table 34 and the mentioned equations, the maintenance labor cost for airframe can be obtained (for aircraft age, y= 1 year:

$$C_{labor\ airframe} = 653888\ €$$

Comparing this result with the case study maintenance labor cost of airframe (707718 €) and computing the deviation:

$$\frac{653888 - 707718}{707718} \times 100\% = 7.6\%$$

Table 37 validation by Roskam and van der Velden method A and B

	Method	$C_{labor\ airframe}$ (€)	Off-set
Own method	Aging Involved method	707718	-
Verification method	Roskam and van der Velden A	784718	11%
	Roskam and van der Velden B	653888	-7.6%

7.2.3 Unscheduled Maintenance Cost Validation using Modified Brugidou Method

The Brugidou (2007) equation as simplified in *Eq. 28* estimates the unscheduled maintenance cost of structures and zonal tasks (on-aircraft maintenance). The simplified equation estimates the UNMC for a certain year of interest with at a certain aircraft age. To estimate the UNMC of a certain aircraft part (wing, horizontal tail, vertical tail etc.) *Eq. 28* has to be modified and the contribution of airframe component should be implemented. Furthermore, to estimate the UNMC during life cycle of the aircraft or to Design Service Goal (DSG) of the 20 years the aging factor (AF) should be implemented as well. Further the average inflation rate (IR) is incorporated in *Eq. 28* by the *LMC* to compensate for the inflation. The adapted form of *Eq. 28* is given below:

$$C_{UNM\ airframe\ y} = \left[\frac{LMC/FC}{\#(PiReps + MaReps)/FC} \times \left(\frac{FCs}{FHs}\right)\right] \times FHs \rightarrow$$

$$C_{UNM\ airframe\ y} = \frac{LMC/FC}{\#(PiReps + MaReps)/FC} \times FCs \qquad \textit{Eq. 163}$$

As stated in this section the aging of an aircraft should be considered as well by the maintenance cost estimation. The yearly aging growth factor (AF_y) per aircraft age should be incorporated in equation as well to determine the life cycle unscheduled maintenance cost.

$$C_{UNM\ airframe\ y} = \left\{\frac{(LMC/FC)\times IR_y}{\#(PiReps+MaReps)/FC} \times FCs\right\} \times AF_y \qquad \textit{Eq. 164}$$

Where;

$C_{UNM\ airframe\ y}$ is the unscheduled maintenance cost of the airframe [€]

$\#(PiReps + MaReps)/FC$ is the number of Pilot and Maintenance Reports per flight cycle

LMC is the line maintenance cost [€]

AF_y is the Aging Factor for certain aircraft age y

AC_{age} is the aircraft age [years]

IR_y is the inflation rate for certain year

Eq. 62 estimates the unscheduled maintenance cost of the airframe for certain aircraft age. In order to estimate the unscheduled maintenance cost of an aircraft component *Eq. 62* is modified:

$$C_{UNM\ component\ y} = \left\{\left[\frac{(LMC/FC) \times IR_y}{\#(PiReps + MaReps)/FC} \times FCs\right] \times AF_y\right\} \times \left(\frac{W_{component}}{W_{airframe}}\right) \qquad \textit{Eq. 165}$$

Where;

$C_{UNM\ component\ y}$ is the unscheduled maintenance cost for a an aircraft part component (wing, vtail, rudder etc.) [€]

$\left(\frac{W_{component}}{W_{airframe}}\right)$ is the weight ratio between airframe weight and component weight

In order to validate the aging factor (AF) and ratio used for unscheduled maintenance cost and scheduled maintenance cost the Modified Brugidou Method can be consulted. This method is derived in this sub-section, the equations Eq. 163 - Eq. 165 estimates the Unscheduled Maintenance Cost on the airframe ($C_{UNM\ airframe\ y}$). The modified equations estimates unscheduled maintenance cost in terms of labor, material and overhead costs (burden cost) for a certain year:

$$C_{UNM\ airframe\ y} = C_{UNM\ labor\ y} + C_{UNM\ material\ y} + C_{UNM\ overhead\ y} \qquad Eq.\ 166$$

Table 38 provides the variables with the sources or tables that are used by the Modified Brugidou Method:

Table 38 variables and equations used for verification by Method 2

Variables	Equation/source
LMC	*Eq. 163-Eq. 165*, *Eq. 171* and Figure 92
FC	Table 35
FH	Table 35
$\#(\boldsymbol{PiReps + MaReps})$	*Eq. 163-Eq. 165* and *Eq. 175*

IATA's MCTF can be used to obtain numerical and real life values for FC, FH and LMC of A330-200 aircraft. To estimate $\#(PiReps + MaReps)$ back calculation is needed. Following relation is constructed such to obtain $\#(PiReps + MaReps)$:

$$\#\ PiReps + MaReps = \frac{LMC}{UNMC_{On\ A/C\ y}} \times FC \qquad Eq.\ 167$$

Figure 92 shows the LMC, engine, base and system & component direct maintenance costs per FH. DMC is collaboration of the directly expended labor and material on airframe, system & component and engine:

$$DMC = DMC_{airframe} + DMC_{syst\ \&\ comp} + DMC_{engine} \qquad Eq.\ 168$$

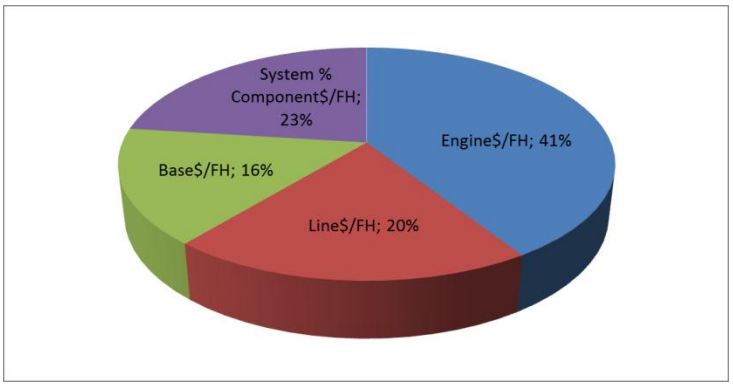

Figure 92 direct maintenance cost by segment year 2012 (IATA, 2013)

Further IATA provides total maintenance cost per aircraft per year and it is equal to 3.4 million USD (2.63 million EURO)[5]. The ratio of DMC over TMC is 60% (Figure 18) and LMC contribution to DMC is 20% (Figure 92). So the DMC and LMC can be estimated:

$$DMC = 0.60 \times 2.63\ million\ € = 1575563\ € \qquad \textit{Eq. 169}$$

$$LMC = 0.20 \times 1575563€ = 315113\ € \qquad \textit{Eq. 170}$$

It should be noted that these values are estimations for fiscal year 2012 per aircraft with an average aircraft age of 10 years. Using the developed *Eq. 42* in section 5.1 the ratio between Scheduled Maintenance Cost (SMC) and Unscheduled Maintenance Cost (UNMC) for certain aircraft age y can be used to obtain the ratio $\left(\frac{UNMC}{SMC}\right)_y$:

$$\left(\frac{UNMC}{SMC}\right)_{10} = \left(0.0487 \times AC_{age} + 0.8397\right) = (0.0487 \times 10 + 0.8397) = 1.33 \qquad \textit{Eq. 171}$$

The TMC calculated by IATA is sum of scheduled and unscheduled maintenance cost and by inserting the results of *Eq. 171* yields to the following expression (it is assumed that SMC and UNMC are both for DMC and IMC):

$$TMC = SMC + UNMC = SMC + 1.33\,SMC = 2.65\ million\ € \qquad \textit{Eq. 172}$$

From *Eq. 172* and *Eq. 171* the SMC and UNMC can be estimated:

$$SMC = 1127012\ €$$

$$UNMC = 1498926\ € \qquad \textit{Eq. 173}$$

[5] AC maintenance cost calculation of physical year 2012 with an average AC age 10 years, conversion factor USD-EURO of 8 September 2014 is used

The estimated UNMC in *Eq. 173* contains airframe, engine and system & component maintenance costs. By using Figure 92 the airframe unscheduled maintenance cost can be estimated for an aircraft age of 10 years:

$$C_{UNM\ airframe} = (0.20 + 0.16) \times 1498926\ € = 539614\ € \qquad \textit{Eq. 174}$$

Now the # (PiReps + MaReps) can be estimated by inserting outcomes of *Eq. 174*, *Eq. 170* and values from Table 38 into *Eq. 167*:

$$\#\ (PiReps + MaReps) = \frac{315113}{539614} \times 951 = 556 \qquad \textit{Eq. 175}$$

The $\#\ PiReps + MaReps$ are estimated for an aircraft age of 10 years. The influence of AF is considered in unscheduled maintenance airframe cost estimation. Table below shows the airframe aging factor growth rate for different aircraft ages (Dixon, M, 2006).

Table 39 AF growth rate for airframe by Rand (Dixon, M, 2006)

AC_{life} / $Aging\ Factor_{rand}$	Airframe
Young $(\mathbf{1 < y > 6\ years})$	1%
Mature $(\mathbf{6 < y > 12\ years})$	2.3%
Aging $(\mathbf{y > 12\ years})$	3.1%

Moreover, the # $(PiReps + MaReps)$ for different aircraft age is assumed to be constant. The LMC (*Eq. 170*) is obtained for different aircraft age by implementing the inflation rate, *Eq. 46*. The computed outcome by *Eq. 170* and aircraft age of 10 years is taken as initial aircraft age. From this aircraft age the life cycle (DSG) unscheduled maintenance cost is estimated by method 2. An example how the LMC is estimated for aircraft ages, y < 10 years and y > 10 years is shown below:

For y = 9:

$$LMC_{y=9} = \frac{LMC_{y=10}}{IR_{y=10}} \rightarrow LMC_y = \frac{LMC_{y+1}}{IR_{y+1}} \qquad \textit{Eq. 176}$$

For y = 11:

$$LMC_{y=11} = LMC_{y=10} \times IR_{y=10} \qquad \textit{Eq. 177}$$

Now to estimate the unscheduled maintenance airframe cost, $C_{UNM\ airframe}$ for different aircraft age with implementing AF (Table 39) *Eq. 28* can be adopted:

$$C_{UNM\ airframe\ y} = \frac{LMC/FC}{\#(PiReps + MaReps)/FC} \times FC_y \times AF_y \qquad \textit{Eq. 178}$$

$$AF_{y+1} = 1 \times AF_y \; for \; 1 \leq y < 6 \; years$$

$$AF_{y+1} = 1.023 \times AF_y \; for \; 6 \leq y < 12 \; years \text{ and}$$

$$AF_{y+1} = 1.031 \times AF_y \; for \; y \geq 12 \; years$$

Where;
$C_{UNM\ airframe\ y}$ is the unscheduled maintenance airframe cost for aircraft age y [€]
LMC/FC is the Line Maintenance Cost per Flight Cycle [€]
$\#(PiReps + MaReps)/FC$ is the number of Pilot and Maintenance Reports per Flight Cycle
FC_y is the utilization of amount of Flight Cycles per aircraft age y
AF_y is the Aging Factor defined in Table 39
With $y = 1,2, \ldots ,20 \; years$

The results are shown in Figure 93 in blue bars. At it can be seen from the figure the costs are more and less linearly increasing. The unscheduled maintenance cost for the airframe contributes in at an aircraft life, y = 1 around 450000 euros while for an aircraft age y = 20 it is approximately 950000 euros. Further the red line in this figure indicates the unscheduled maintenance airframe cost estimation by Aging Involved Method. Comparing both of the results there is an average of 5.34% off-sets between the two developed methods.

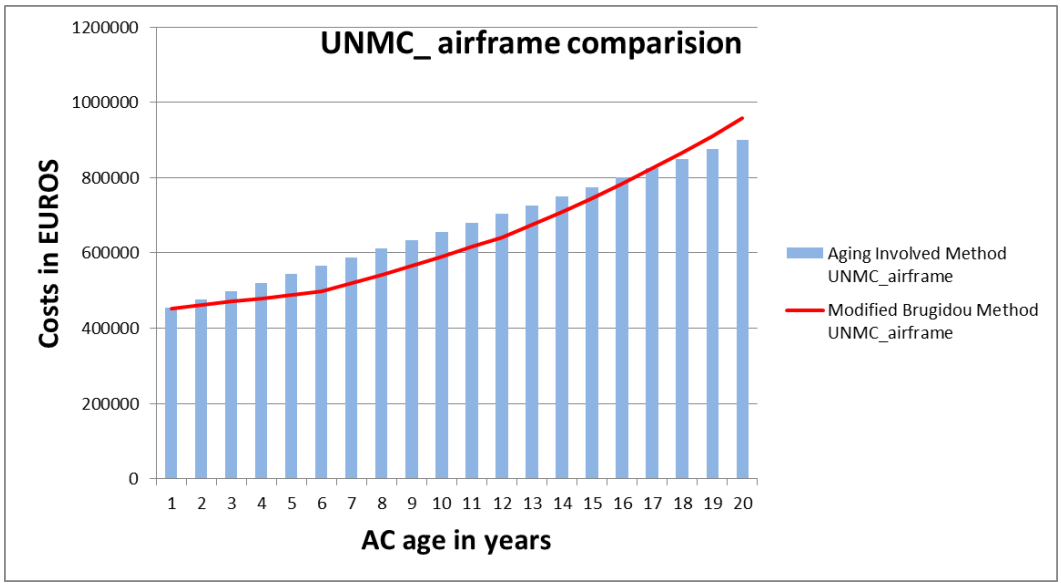

Figure 93 the unscheduled maintenance cost of airframe by Modified Brugidou Method

To estimate the unscheduled maintenance cost (UNMC) of the rudder *Eq. 165* can be used. After estimation of the $C_{UNM\ rudder\ y}$ for certain aircraft life the contribution of labor and material unscheduled maintenance cost is estimated. The results are shown in Figure 94 below. The bars in blue indicate the unscheduled maintenance labor cost and the bars in red illustrate the unscheduled maintenance material cost. Figure 94 is also used to labor and material unscheduled maintenance cost.

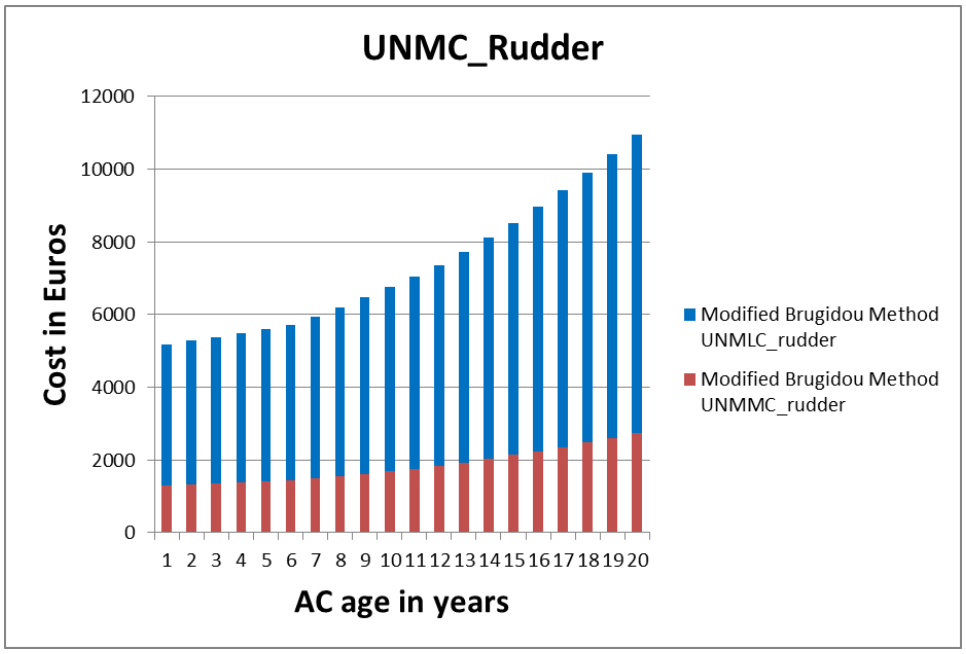

Figure 94 UNMC of A330 rudder

The results of Aging Involved Method and Modified Brugidou Method are plotted in Figure 95 below. As it can be seen from the figure, the blue line indicates the UNMLC of Aging Involved Method (case study), green line the UNMLC of Modified Brugidou Method, the red line indicates UNMMC of Aging Involved Method and the purple line illustrates the UNMMC of Modified Brugidou Method. The off-set between UNMC of the rudder between Aging Involved Method and Modified Brugidou Method contributes 26%. One of the reason for the off-set of 26% can be assumption of constant pilot reports per flight cycle ($\#(PiReps + MaReps)/FC$) that shifts the line of $UNMLC_{rudder}$ and $UNMMC_{rudder}$ downwards, see Figure 95.

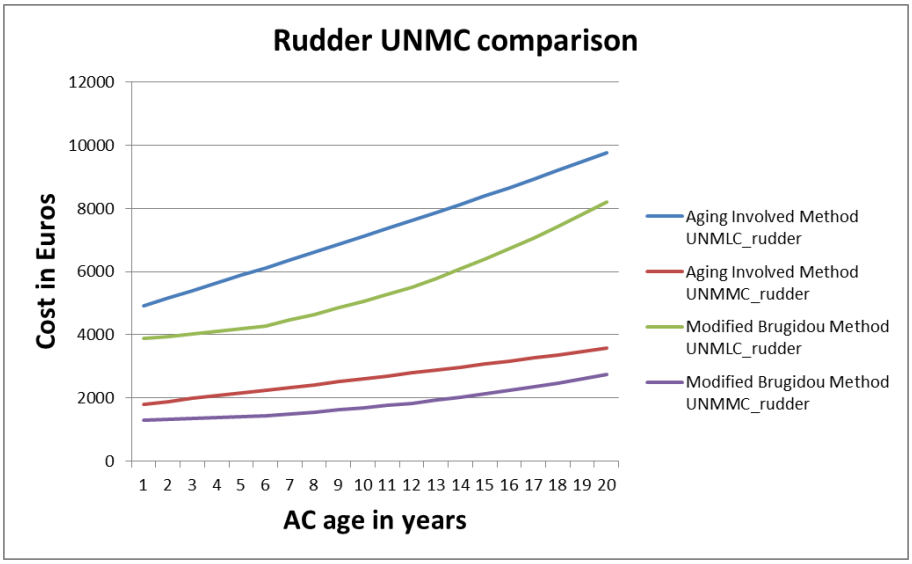

Figure 95 the rudder UNMC comparison developed method (case study) and modified Brugidou method

7.3 Verification and Validation of IBM

In this section the verification and validation of the IBM and the integrated component design & maintenance for interval determination are provided. In subsequent sub-sections, 7.3.1, the validation of IBM and AIM is elaborated. And respectively in sub-section 7.3.2 the verification and validation is provided of the integrated component design & maintenance

7.3.1 Validation Between Aging Involved Method and Interval-Based Method for SMLC

Before presenting the validation results it should be noted that the Aging Involved Method does not make any distinction between line and base maintenance labor cost. The method simply estimates the direct labor cost for a certain aircraft age. Figure 92 is used to express a relation between Line Maintenance Cost (LMC) and Base Maintenance Cost (BMC).

$$BMC = 0.16\, DMC \qquad \textit{Eq. 179}$$

$$LMC = 0.2\, DMC \qquad \textit{Eq. 180}$$

Combining *Eq. 179* and *Eq. 180* yields to:

$$LMC = 1.25\, BMC \qquad \textit{Eq. 181}$$

And the direct maintenance labor cost estimated by AIM is simply summation of both LMC and BMC for certain aircraft age in a certain year. Assuming the same relation as *Eq. 181* also holds for the maintenance labor cost estimation of AIM, the contribution of BMC for the labor can be obtained for scheduled maintenance labor cost. Using the last column of Appendix J the SMLC for base maintenance is approximated for the Aging Involved Method. In Figure 96 the validation graph between the two methods is shown. The green bar represents SMC for AIM and the red line represents the IBM cost. For both the cost results is shown as a function of the aircraft age. The average off-set for the AC life of 20 years is 41%. This large off-set can be explained due to fact that IBM uses the minimum applicable maintenance man hours (MMH) that is directly applied to perform certain maintenance tasks. By cost estimation with IBM, the MMH are directly subtracted from the MPD than maintenance cost of the rudder is estimated. Although, the literature regarding maintenance cost estimation by AIM does not provide information how the MMHs are estimated. The MMHs could be recorded by AIM on daily, weekly, monthly or yearly basis of the employees that were physical attended at the maintenance repair shop or hangar without all the time conducting directly maintenance. This could be one of the reasons that the cost estimation performed by AIM is higher than the IBM. Further, cost outputs of IBM is regarded as constant through aircraft age, the inflation rate is not incorporated and the aging factor is not implemented in the scheduled maintenance labor cost estimation. Simply, it is assumed that the content of MPD does not change through years. In fact the, the content of MPD can be modified through AD's, SB's and ALI's (Airbus, 2014; Airbus, Maintenance Planning Document (MPD), 2006; Ghobbar, 2010).

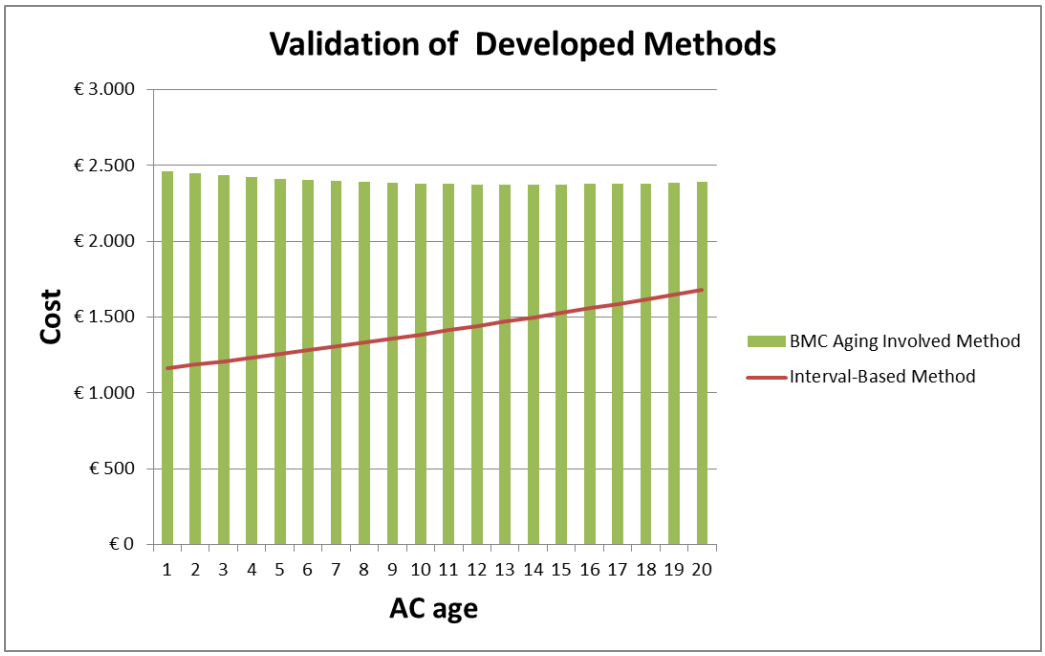

Figure 96 cost comparison between AIM and IBM

7.3.2 Verification and Validation of Integrated Component Design & Maintenance

In this sub-section the verification and validation of the integrated component design & maintenance is provided. First the result of the fatigue failure behaviour is validated, then the A330 MPD is used to validate the determined maintenance intervals. The obtained number of load cycles to failure for three types of composite damages: delamination, tension/compression failure facings and shear strength core failure are listed in Table 40.

Table 40 number of load cycles to failure for three different failure modes

Type of failure	Delamination	Tension/compression facings	Shear strength core
$\boldsymbol{N_f(DS)}$	6.35×10^6	2.71×10^7	8.62×10^6

In Table 40 the number of load cycle to failure (N_f) can be obtained by increasing the damage size (DS) to infinity. Mallick (2007) suggests that the number of load cycles to failure for typical composite materials are around 10^7. All of the estimated values N_f as well as I_c $(or\ N_c)$ are around 10^7. It can be concluded that the computed results are in the order of 10^7 (or less for delamination) and are quite realistic. Further the shape of the obtained graphs, as shown in Figure 87, Figure 88, Figure 89 and Figure 90 are quite similar to Figure 38 and Figure 39, which shows the failure behaviour of a material due to fatigue loading. However, it should be emphasized that not all of the composite material failure graphs (S-N curves) will have the same behaviour as depicted in Figure 87, Figure 88, Figure 89 and Figure 90.

The end results in terms of maintenance intervals can be validated by using the A330 MPD. In this case the maintenance intervals for the Detailed Inspection (DI) and Special Detailed Inspection (SDI) will be compared to the determined results as elaborated in sub-section 6.2.1.5. In Figure 54 (section 6.2) the aircraft maintenance tasks of A330 rudder is shown. As

it can be seen from Figure 54 there are two maintenance inspection tasks for the skin, with the corresponding task numbers 554022-01-1 (in blue) and 554021-01-1 (in green). The associated SDI task is beside the skin also applicable for the hinge & actuator fitting/bearing, rib and spar. And the DI task is also applicable for spar and rib. According to the MPD the threshold interval or the initial interval of this task is 6 year and the subsequent maintenance inspection interval is every 6 year. The computed initial inspection interval and subsequent maintenance interval for the DI and SDI method are listed in Table 41.

Table 41 threshold and subsequent maintenance inspection intervals

Delamination		*Tension/compression failure*		*Shear strength failure core*	
Variable	**Unit in Years**	**Variable**	**Unit in Years**	**Variable**	**Unit in Years**
I_1	12.71	I_1	79.16	I_1	25.18
ΔI	3.89	ΔI	27.17	ΔI	8.09

As already concluded in sub-section 6.2.2 the tension/compression failure of the face sheets and shear strength failure of the core does not have a significant impact on the maintenance inspection interval of the rudder skin. But for the delamination failure the threshold inspection interval is 12.71 year and subsequent inspection interval is 3.89 year. Although it can be concluded that other parts with certain typical failure modes can fail due to fatigue damage earlier than delamination damage examined in this case. While in the MPD, the DI and SDI inspection intervals are applicable for different rudder parts as well. Moreover, the obtained initial inspection intervals and subsequent DI and SDI inspections intervals do not conflict with mentioned SDI inspection time of the A330 rudder. In other words, obtained inspection intervals are larger in magnitude than MPD inspection interval, which suggests that during the provided maintenance inspection intervals there is no failure of the A330 rudder.

8 Conclusions & Recommendations

In this chapter, conclusions are drawn from the findings. And it is followed by the recommendations for further research. In section 8.1 the conclusion is given by reviewing the research goal and the sub-questions. And in section 8.2 the recommendations are provided based on the research analyses.

8.1 Conclusion

In chapter 2, research objective, research question together with the sub-questions was introduced. In that respect, a hypothesis was proposed.

The research question of this thesis was: *How to develop the maintenance cost model, considering essential design parameters?*

The sub-questions which made the approach to the research question more feasible were:

1) *What are the current aircraft/components maintenance processes?*
2) *What are the current maintenance cost estimation methods?*
3) *What are the maintenance cost driving parameters?*
4) *What are the essential operation and design parameters that affect the maintenance cost?*
5) *How are those maintenance cost driving related to the design parameters?*
6) *In what extent does the change in design affects the maintenance process, therefore further affects the maintenance cost?*

In conclusion, the answer to the sub-questions and eventually the research question can be obtained by reviewing chapter 4 to chapter 7. Firstly, general conclusions to this project are summarized as follows, which are the answers to the sub-questions:

The current aircraft and aircraft components maintenance process is evaluated regarding the MSG-3 philosophy. The methodology has a task-oriented approach to perform maintenance, in which the maintenance tasks are predetermined to avoid in-service failures. A reliability program is used for components or systems whose failure rates are not predictable and for those that have non-scheduled maintenance tasks. The current MSG-3 program is used for developing the scheduled maintenance tasks and intervals, which will be accepted by manufacturers, regulatory authorities and operators.

The maintenance cost estimation methods used currently differ from organization to organization, and it is dependent on the type of maintenance cost that has to be determined and the data available that can be used as input. One of the most famous maintenance cost estimation method is the DOC+I method established by Liebeck et al., (1995). By using this method the weight of aircraft, the amount of flight cycles and the flight hours are used as inputs. Another example maintenance cost estimation method by Boeing, an adoption of 25 years old study called “A new method for estimating current and future Transport Aircraft Operating Economics” (Khwaja, 2014). Examples of more detailed maintenance cost estimation are the second order reliability method (airframe structure), which uses non-

destructive inspection of cracks as an input, and the Dhillon's method (aircraft component level), which uses failure rates, maintenance man hours primarily as inputs.

Secondly, to answer the research question, a methodology is developed to estimate the maintenance cost of an aircraft and its components as a function of operation and design parameters. Two maintenance cost estimation methods are developed: AIM and IBM, which are provided in chapter 5. The AIM method estimates the Scheduled and Unscheduled Maintenance Labor Cost (SMLC and UNMLC), Scheduled and Unscheduled Maintenance Material Cost (SMMC and UNMMC) and maintenance overhead cost by taking the aging factor into the account. On the other hand, the IBM conducts detailed inspection of average maintenance labor cost by categorization. The categorization can be made in terms of materials, aircraft part items (spar, skin, rib, and etc.) and maintenance tasks. Afterwards, a bottom-to-top maintenance labor cost estimation is performed, based on the maintenance intervals and man-hours, which are extracted from the MPD. In order to obtain a direct link between design and operation parameters, and maintenance intervals, a method starting from component load conditions, stress analysis, damage types, till maintenance interval determination has been developed, called integrated component design & maintenance.

Thirdly, the developed methods are applied on the composite rudder of an A330-200 aircraft as a case study to obtain cost outputs. From the development of AIM, costs estimations in terms of SMLC, UNMLC, SMMC, UNMMC and overhead cost (or IMC) for the A330 rudder are listed in Table 42. From the table it can be concluded that the direct scheduled maintenance cost in terms of labor and material remain constant throughout the aircraft life. While the direct unscheduled maintenance cost in terms of labor and material are increasing along with the increase of the aircraft age. Therefore, it can be seen from the AIM analysis that the aging factor has only influence on the scheduled maintenance cost. A sensitivity analysis was conducted (chapter 6) to analyse the influence of the operation and design parameters on the maintenance cost. According to the analysis, it is found that the design parameters such as vertical tail surface and the rudder surface have the most influences on the maintenance cost. This is followed by the operational parameters, flight cycles and flight hours, which also have significant impact on the maintenance cost.

Table 42 AIM results

	Maintenance segment	SMLC(€)	UNMLC(€)	SMMC(€)	UNMMC(€)	IMC(€)
AC age	$y = 1$	5540	4920	2030	1800	5240
	$y = 20$	5400	9760	2000	3570	7570

The IBM enables detailed inspection of average maintenance labor cost for a particular aircraft component with associated material (composite) at a certain aircraft age. The IBM method allows detailed maintenance cost estimation of an aircraft component in a bottom-to-top manner. In this case the failure rate of a specific component and the MMH are taken as inputs. The direct scheduled maintenance labor costs are determined on the basis of the

aircraft part material categorization and maintenance tasks categorization, shown in Table 43 and Table 44.

Table 43 annual maintenance inspection labor cost of IBM by material categorization

Annual Maintenance Labor cost for materials			
materials	Composites	Non-composites	total
Labor cost	300	719	1019

Table 44 annual maintenance inspection labor cost of IBM by MSG-3 task categorization

Maintenance Labor cost for tasks									
Parts	GVI	DI	SDI	OP	VC	LU	FC	RS	CHK
Labor cost annual	193	315	3	57	6	32	260	44	254

By performing structural analysis, as shown in sub-section 6.2.2 (Integrated Aircraft Component Design & Maintenance) the inspection intervals of a specific aircraft component (spar, skin or rib etc.) can be determined for different failure modes. The determination of the inspection intervals as such provides the possibility to directly link the aircraft design parameters to the maintenance cost. From the Integrated Aircraft Component Design & Maintenance of the IBM, it is found that the delamination failure, tension/compression failure of facings and shear strength failure of the core, of a composite skin of the A330 rudder does not have a significant effect on the maintenance interval, further on the maintenance cost. For example, considering the aircraft DSG of 20 years, the maintenance threshold inspection intervals is 12.71YE with subsequent inspection intervals of 3.89YE. The repetitive cyclic fatigue loading has the most influence on the delamination failure in this case.

8.2 Recommendations for Further Research

The developed methodology provides an insight of how the maintenance cost can be linked to the aircraft design and the aircraft operation. For further research, it is extremely recommended to conduct research with cooperation of aircraft manufacturer and aircraft operator which performs maintenance activities. Then the researcher will have more possibility to real life data concerning the maintenance cost of an aircraft component. Moreover, the inputs of experienced maintenance mechanics/technicians/crew can be taken into the cost modelling. In that case, his or her experience regarding the maintenance of a part made from composite or conventional metal materials can be analysed and incorporated in the maintenance cost estimation.

The philosophy behind the maintenance interval determination, which is done by the maintenance working groups (MWG) of structures, should be reviewed, from the perspective of aircraft manufacturer. This can be done by examining the maintenance policies, procedures and interviewing the anticipated members of MWG. It is recommended for aircraft operator's maintenance department to make effort on the data collection regarding maintenance cost. Those data should be extracted for each aircraft and its component respectively. Therefore the real life maintenance cost data can be compared with forecasted maintenance cost.

The elaborated method together with maintenance cost estimation results can be improved as well. In this thesis project, in order to achieve the thesis objective several assumptions are

made regarding aircraft dimensions, stability coefficients, LC/FC analysis and structural analysis etc. These assumptions are made due to lack of data and have consequences on the accuracy of final results.

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Appendix A MSG-3 Categories

The MSG-3 categories which are applicable for airframe systems and powerplants, Structures and zonal are described below:

- *Airframe systems and Powerplant tasks*

A progressive logic diagram is used for determining the maintenance program for systems/powerplant (including the components and APU's). The logic diagram is the basis for evaluation technique which is applied to each Maintenance Significant Item (MSI). The item's functional failures and failure causes are the root of the evaluations. In order to apply the MSG-3 logic to an item, first the aircraft's significant systems and components must be identified. The process of identifying MSI is a conservative process, whereby engineering judgment is used on the anticipated consequences of failure.

MSI's are identified by manufacturer and distributed to the Working Groups (WG) and whose failure (ATAA, 1993):

a) Could affect safety (on ground or in flight) and/or,
b) Could be undetectable or are not likely to be detected during operations, and/or,
c) Could have significant operational impact, and/or,
d) Could have significant economic impact.

The initial list of MSI is prepared by manufacturer and is distributed to the Working Groups (structures, mechanical systems, engine and auxiliary power plant, electrical and avionics systems, flight controls and hydraulics and zonal). After the selection process of MSI's the following should be identified for each MSI:

a) Functions – the normal characteristic actions of an item
b) Functional failure(s) – how an item fails to perform its function
c) Failure Effect(s) – what is the result of a functional failure
d) Failure cause(s) – why the functional failure occurs

The identification of tasks and interval are defined using the procedures discussed above. Both the economic and safety related tasks are included to produce initial scheduled maintenance program.

- *Maintenance tasks for structural items*

Three sources of structural deterioration are applicable for airplanes:

- Environmental deterioration, the physical deterioration of an item's strength or resistance to failure as a result of chemical interaction with its climate or environment. Environmental deteriorations may be time dependent.
- Accidental damage, the physical deterioration of an item caused by contact or impact with an object or influence that is not a part of the airplane, or damage as a result of

human error that occurred during manufacturing, operation of the vehicle or performance of maintenance.

- Fatigue damage, the initiation of a crack or cracks due to cyclic loading and subsequent propagation of such cracks.

FAA (2012) establishes in the Advisory Circular document (AC 121-22C) the structural program rules. In this document also the structural program contains requirements how to maintain composite structural detail, elements or assemblies.

1) All aircraft in an operator's fleet or group of operators' fleets are subjected to requirements including external and internal inspections. For both external and internal inspections, structural sampling and age-exploration programs are included such as: corrosion prevention and control programs and additional supplemental structural inspections that may require for fatigue-related items. The check intervals for structural inspection program can be expressed in calendar time, flight cycles or flight-hours.
2) The structural program of an aircraft should include the necessary requirements how to maintain composite structural details, elements or assemblies. The failure of those that affect the structural integrity which is necessary for the safety of the aircraft. Composite structures may be damaged by accidental impact or aging deterioration and the taking into account that composite structures degraded differently than metals. Composite structure will be analysed to create a minimum initial scheduled maintenance requirements. All the structural items regarded composites will be categorized either as structural significant items (SSI) or as other structure.

- *Zonal maintenance tasks*

The zonal maintenance program ensures that all systems, components and installation contained within specified zone on the aircraft receive adequate surveillance to determine the security of installation and general condition. A number of general visual inspections tasks are packaged into a program. These are generated against items in the system's maintenance program into one or more zonal surveillance tasks.

Appendix B Failure Effects Evaluation

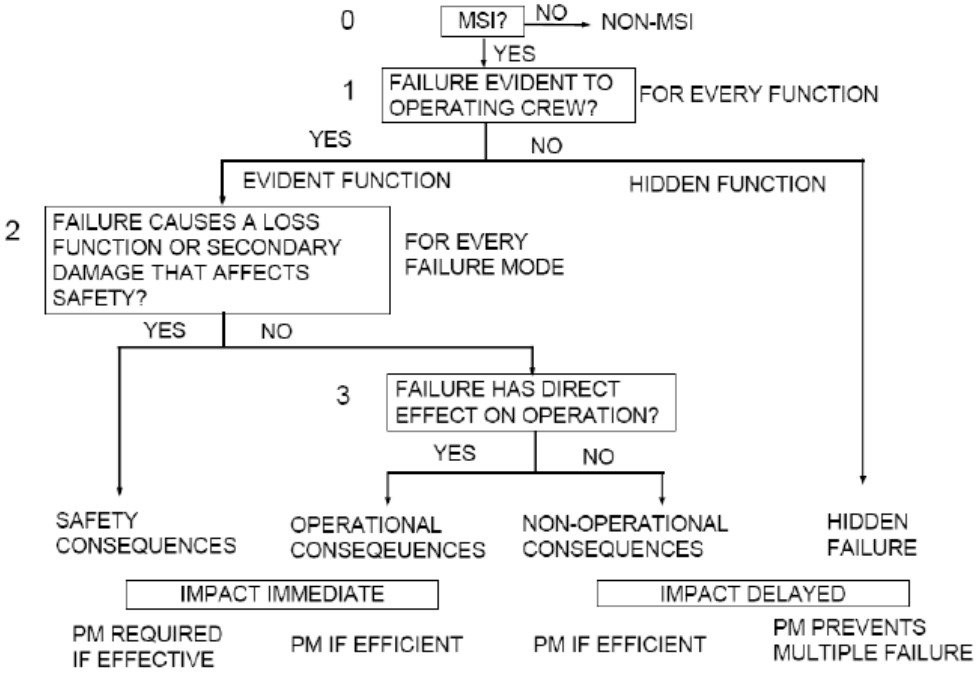


Figure 24: Failure effects evaluation.

Figure 97 failure effects evaluation (Homan, 2008)

Appendix C Weight and Load Factor Estimation

Weight Estimation

To obtain the Manufacture Empty Weight (MEW), weight classification of an aircraft should be done. The weight of an aircraft can be classified into several terms. The most common are: the Maximum Take-off Weight (MTOW), the total weight of the aircraft just before the flight. Operational Empty Weight (OEW), the weight of payload and the fuel. The MEW is the total weight of aircraft's structure including the powerplants, systems and furnishings. In Figure 98, the standard weight terms and weight main groups are shown as standardized by Airbus (Elham, 2013).

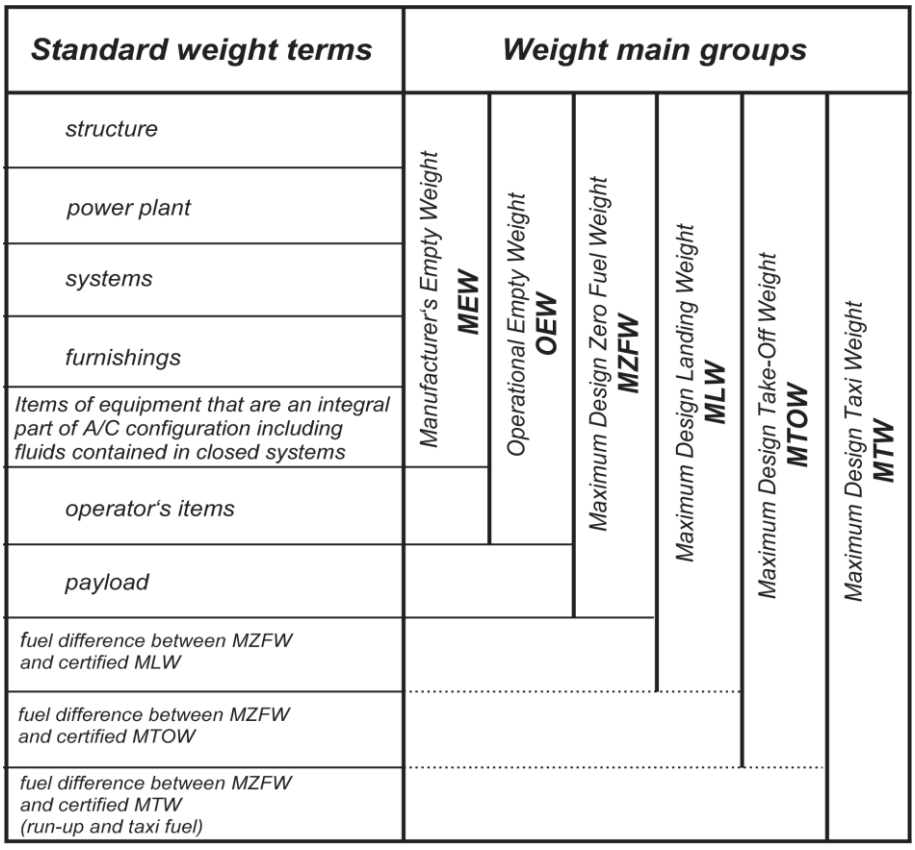


Figure 98 standard weight terms and weight groups (Elham, 2013)

For several aircraft the ratio of weight estimation is given by Elham (2013) in Table 45.

Table 45 weight ratio of several civil airplanes (Elham, 2013)

Airplane	$\frac{OEW}{MTOW}$	$\frac{max.W_{fuel}}{MTOW}$	$\frac{max.W_{payload}}{MTOW}$	Design range (nmi)
A330-200	0.562	0.256	0.261	2700
A330-300	0.545	0.358	0.223	4500
B737-200	0.528	0.341	0.295	1900

The airframe can be subdivided into wing, fuselage, tail, landing gear and engine nacelles. The weight ratio of each OEW of MTOW for sub-groups is given. Table 5 shows the A320-200 as an example.

Table 46 ratio of each OEW sub-group to MTOW (Elham, 2013)

A320-200	Airframe structure (%)	Propulsion (%)	System and equipment (%)
Wing	11.8	-	-
Fuselage	12	-	-
Tail	1.5	-	-
Landing gear	3.1	-	-
pylons	1.2	-	-
Total	29.6	9.8	18

Every subgroup can again be broken down into several components. In Appendix E the wing structure is broken down into two categories: primary structure (skins panels, spars web and flanges, ribs etc.) and secondary structure (trailing edge: flap structure, ailerons, spoilers etc. and leading edge). In order to estimate the maintenance cost of an aircraft component the weight estimation of certain component is needed as in input for the model, see Figure 27.

Standford (2014) estimates the weight of aircraft components, wing, horizontal tail, vertical tail, landing gear and fuselage. Below the equations for the component weight estimations are provided.

Wing

$$W_{wing} = 4.22\,S_{wg} + 1.642 \times 10^{-6}\frac{N_{ult}b^3\sqrt{TOW\ ZFW}(1+2\lambda)}{(t/c)_{avg}cos^2\Lambda_{ea}S_{wg}(1+\lambda)} \qquad \textit{Eq. 182}$$

Where;
W_{wing} is the weight of the wing [Ibs]
S_{wg} is the gross wing area [ft^2]
N_{ult} is ultimate load factor [-]
TOW Take-off Weight [Ibs]
ZFW is the Zero Fuel Weight [lbs]
t/c is the average airfoil thickness
$\Lambda_{ea}$is the sweep angle of the wing [deg]
b is the wing span [ft]
λ is the ratio between chord length of tip and chord length of root, taper ratio [-]

Horizontal tail

The horizontal tail weight including the elevator weight is similarly estimated by *Eq. 183*:

$$W_{horiz} = 5.25\,S_{He} + 0.8 \times 10^{-6}\frac{N_{ult}b_H^3\,TOW\,MAC_W\sqrt{S_{He}}}{(t/c)_{avg}cos^2\Lambda_{ea}l_H\,S_{Hg}^{1.5}} \quad \textit{Eq. 183}$$

Where;
W_{horiz} is the weight of horizontal tail [lbs]
S_{He} is the surface of the horizontal tail [ft^2]
N_{ult} is the ultimate load factor [-]
MAC_W is the mean aerodynamic chord of the wing [-]
TOW Take-off Weight [lbs]
t/c is the average airfoil thickness
$b_H$is the span of the horizontal tail [ft]
l_H is distance from airplane c.g to aerodynamic center of the horizontal tail [ft]
$\Lambda_{ea}$is the sweep angle of the wing [deg]

Vertical Tail and rudder

The vertical tail without the rudder weight is given by *Eq. 184*. Further it may be assumed that the rudder weighs 60% more per unit area. The formula below is for conventional tails (without engines on tail). Further S_V is the vertical tail area including the rudder surface.

$$W_{vtail(-rudder)} = 2.62\,S_V + 1.5 \times 10^{-5}\left[\frac{N_{ult}b_v^3\left(8.0 + 0.44\,\frac{MTOW}{S_{wg}}\right)}{(t/c)_{avg}\,cos^2\Lambda_{ea}}\right] \quad \textit{Eq. 184}$$

Where:
W_{vtail} is Weight vertical tail [lbs]
MTOW is Maximum Take-off weight [lbs]
S_V is area vertical tail [ft^2]
N_{ult} is ultimate load factor (normal load factor multiplied by safety factor, see *Eq. 194*) [-]
b_v is span of the vertical tail [ft]
$(t/c)_{avg}$is average airfoil thickness [-]
S_{wg} is gross wing area [ft^2]

Fuselage

Fuselage weight is based on gross fuselage wetted area (without cut-outs for fillets or surface intersections and upon a pressure-bending load parameter). The fuselage weight is obtained through *Eq. 185*:

$$W_{fus} = (1.051 + 0.102\ \times I_{fus})S_{fus} \quad \textit{Eq. 185}$$

The pressure index $I_p$and bending index I_b can be determined by eq40 and eq41 respectively:

$$I_p = 1.5 \times 10^{-3} \times P_{max} \times B \quad \textit{Eq. 186}$$

$$I_b = 1.91 \times 10^{-4} N \times W \times \frac{L}{H^2} \quad \textit{Eq.}$$

Where;
P_{max} is the maximum pressure differential [lb/ ft^2]
B is the fuselage width [ft]
H is the fuselage height [ft]
L is the fuselage length [ft]
N is the limit load factor at ZFW [-]
W is the ZFW – weight of wing and wing mounted engines, nacelles and pylons [lbs]

When the fuselage is pressure dominated ($I_p > I_b$),then $I_{fus} = I_p$
When the fuselage is not pressure dominated ($I_p < I_b$), then $I_{fus} = \left(I_p^2 + I_b^2\right)/(2I_p)$

Landing gear

The landing weight is about 4% of the Take-Off Weight (TOW):

$$W_{gear} = 0.04\,TOW \qquad \textit{Eq. 188}$$

This weight is including structure, actuating systems and the tires and its supports. The tire component is approximately 39% of the total gear weight.

Airfoil thickness

The average airfoil thickness (t/c) of a subsonic commercial aircraft, which are used in Eq.32, *Eq. 183* and *Eq. 184* can be calculated by following expression (Ciornei, 2005; Torenbeek, 1988):

$$\frac{t}{c} = 0.30\left[\left(1 - \left\{\frac{5 + M^2}{5 + (M^*)^2}\right\}^{3.5}\right)\frac{\sqrt{1 - M^2}}{M^2}\right]^{\frac{2}{3}} \qquad \textit{Eq. 189}$$

Where: M is the Mach number of the aircraft

M^*= 1.0 for conventional airfoils; maximum t/c around 0.30c
M^*= 1.05 for high-speed (peaky) airfoils (1960-1970) technology
M^*= 1.12-1.15 for supercritical airfoils

Calculation of Load Factor and Ultimate Load Factor

The load factor which is used in Eq.32, *Eq. 183*, *Eq. 184* and *Eq. 187* is expressed in the *Eq. 190*. Load factor is a structural design parameter of an aircraft. It is a measure of the bearing capability of a structure. Therefore, the maximum load factor is a manoeuvring and performance limit. The limit load factor is the highest load factor which an aircraft can experience during its lifetime. The load factor is described in a steady, coordinated turn of the flight phase. During a steady, coordinated turn the lift is balanced by the weight of the airplane to keep constant altitude (Cavcar, 2004):

$$L\cos\emptyset = \mathrm{W} \qquad \textit{Eq.}$$

During a steady coordinated turn, with a certain bank angle ∅, the lift required to balance aircraft weight W, to keep altitude constant, The ratio between lift to weight is:

$$\frac{L}{W} = \frac{1}{\cos \emptyset} \qquad \text{Eq. 191}$$

In Figure 99 the bank angle ∅ is shown in a coordinated turn.

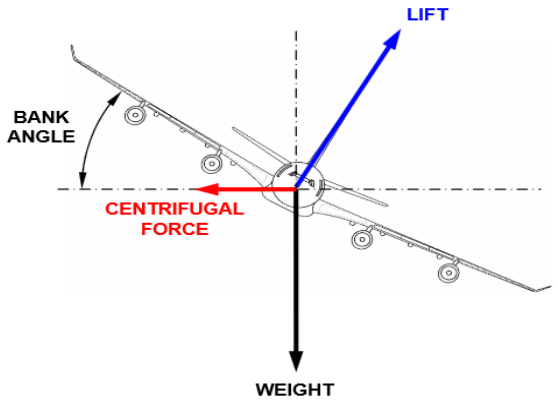


Figure 99 forces on an aircraft during a level coordinated turn (Cavcar, 2004)

As it can be seen from Figure 99 the lift is greater than the weight in banked turn, because cos ∅ < 1 the ratio of lift to weight is the normal load factor:

$$N = \frac{L}{W} = \frac{1}{\cos \emptyset} \qquad \text{Eq. 192}$$

The limit of aircraft bank angle is usually given in aircraft manual. For the airbus aircraft the limits of the bank angle is given in the Aircraft Characteristics Airport and Maintenance Planning document (Airbus, 2014). The load factor is a function of the bank angle ∅. This is shown in Figure 100.

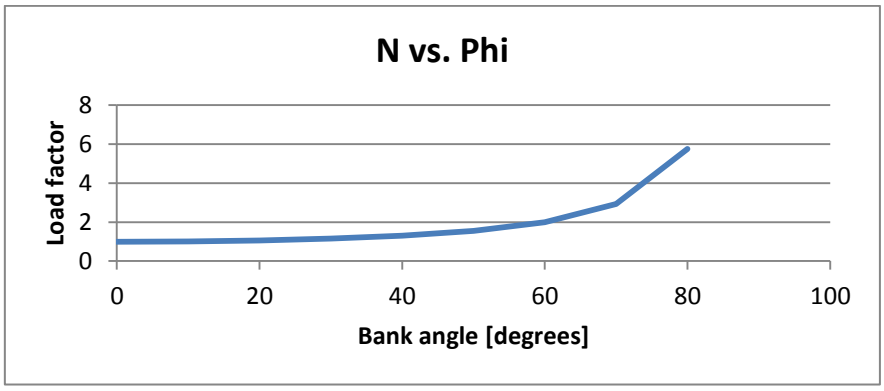


Figure 100 load factor vs. bank angle

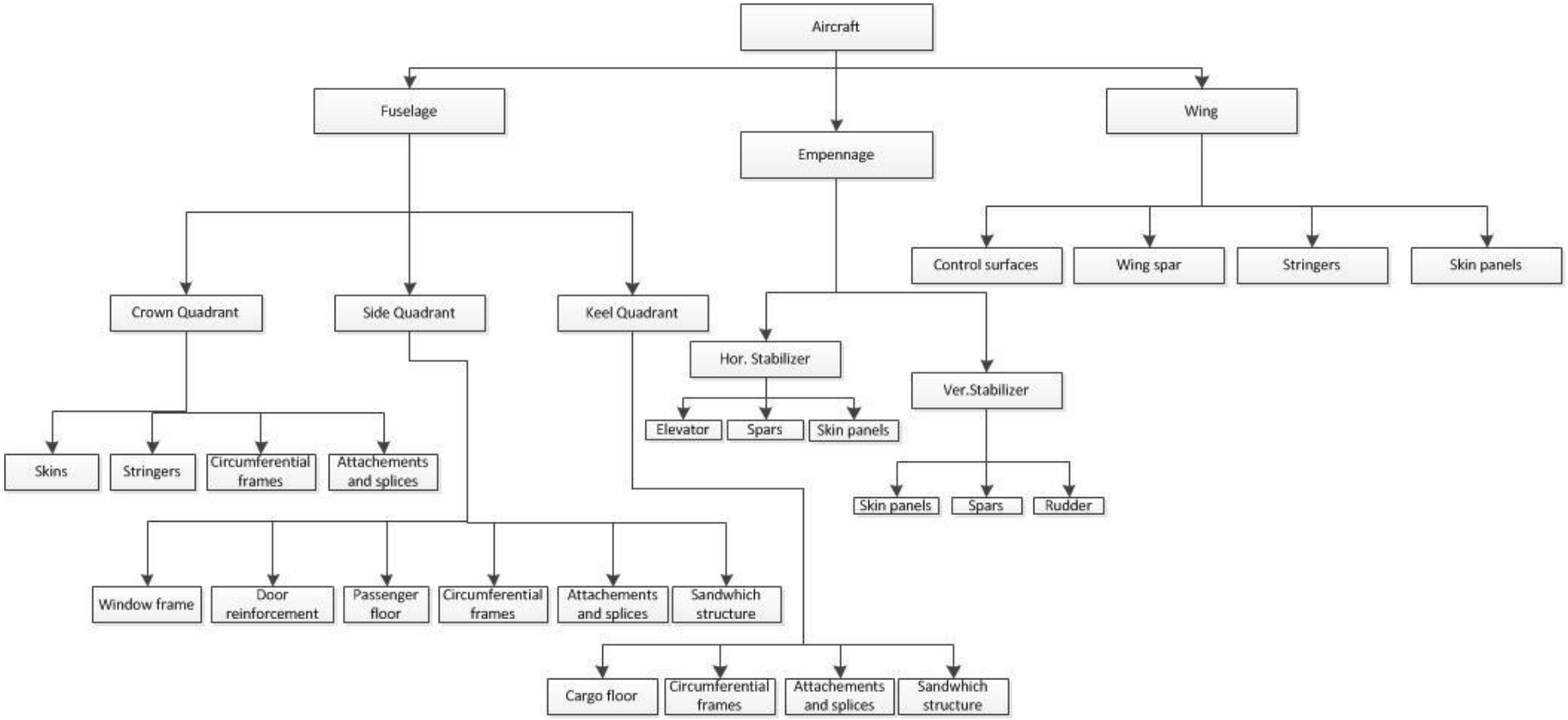
To calculate the ultimate load factor, the following relation is used:

$$N_{ult} = N_{normal} \times safety\ factor \quad \textit{Eq. 193}$$

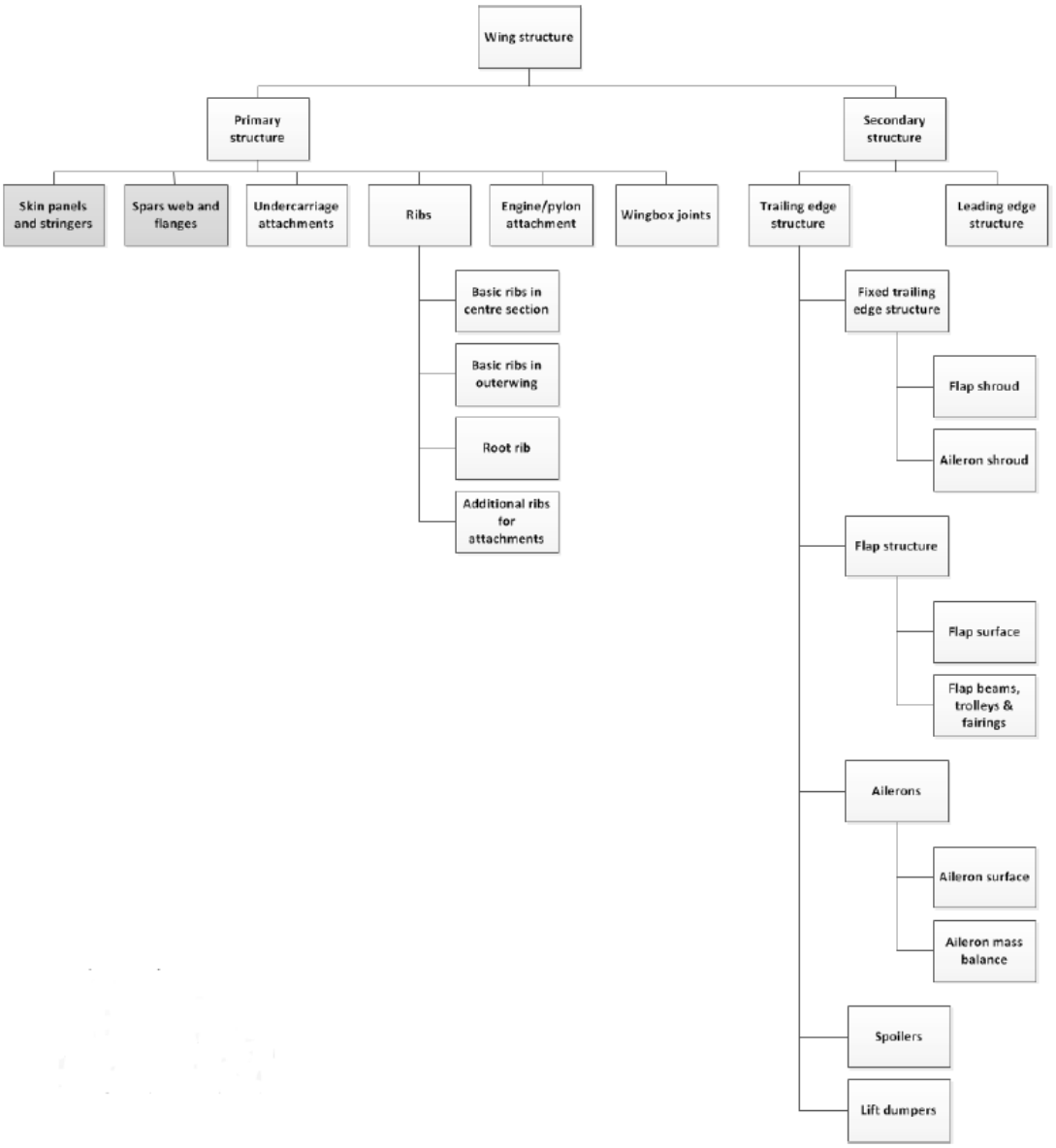
The safety factor is 1.5 (Flynn et al., 1997), *Eq. 193* becomes:

$$N_{ult} = N_{normal} \times 1.5 \quad \textit{Eq. 194}$$

Appendix D Aircraft Part Breakdown



Appendix E Wing Structure Breakdown



source: (Elham, 2013)

Appendix F Load Cycles per Flight Cycles

After determining, the frequency of these loads during the GAG or mission profile of the aircraft, the magnitude of the loads should be obtained. First the frequency of the lateral gust loads is determined than the frequency of manoeuvre loads.

The frequency of gust loads can be determined by using Figure 101. In this figure the amount of 4000 flights are categorized into 9 categories (A-J). In the second column the number of flight cycles is listed for each of the categories. In the last column the total number of load cycles per FC is listed. To obtain the number of load cycles per flight cycles following is done; number of flights (A-J) in block of 4000 flights (second column) are multiplied by total number of cycles per flight (last column). The numbers in brackets are not used. Eventually the number of loads cycles per flight cycle is equal to 90, $\left(\#\frac{LC}{FC}\right)_{gusts} = \frac{359665}{4000} = 90.$

Flight type	Number of flights in one block of 4000 flights	Number and magnitude S_a/S_{mf} of amplitude level										Total number of cycles per flight
		I 1.60	II 1.50	III 1.30	IV 1.15	V 0.995	VI 0.84	VII 0.685	VIII 0.53	IX 0.375	X 0.222	
		Number of cycles per flight										
A	1	1	1	1	4	8	18	64	112	391 (391)	900 (0)	1500 (600)
B	1		1	1	2	5	11	39	76	366 (385)	899 (0)	1400 (520)
C	3			1	1	2	7	22	61	277 (286)	879 (0)	1250 (380)
D	9				1	1	2	14	44	208 (208)	680 (0)	950 (270)
E	24					1	1	6	24	165 (168)	603 (0)	800 (200)
F	60						1	3	19	115 (107)	512 (0)	650 (130)
G	181							1	7	70 (72)	412 (0)	490 (80)
H	420								1	16 (16)	233 (23)	250 (40)
I	1,090									1 (1)	69 (4)	70 (5)
J	2,211										25 (2)	25 (2)
Total number of cycles per block of 4000 flights		1	2	5	18	52	152	800	4170	34800 (34800)	358665 (18442)	
Cumulative number of load cycles per block of 4000 fl.		1	3	8	26	78	230	1030	5200	40000	398665 (58442)	

Figure 101 Number of gust load cycles for a F27 and F28 (schijve, 1985)

To determine the number of manoeuvre load cycles per flight cycle (so called FALSTAFF), again Schijve (1985) can be used, Figure 102. The flights are divided in 32 levels. In total there are 17983 peaks in blocks of 200 flights. So the total number of load cycles per flight is: $\left(\#\frac{LC}{FC}\right)_{manoeuvre} = \frac{17983}{200} = 90$

level	block of 200 flights			
	FALSTAFF		short FALSTAFF	
	no of peaks	no of throughs	no of peaks	no of throughs
32	2	0	2	0
31	0	0	0	0
30	7	0	7	0
29	10	0	10	0
28	24	0	23	0
27	45	0	44	0
26	76	0	74	0
25	104	1	101	0
24	193	2	183	1
23	233	3	213	1
22	404	4	377	1
21	533	12	484	2
20	640	23	540	3
19	954	37	805	10
18	987	69	803	20
17	1151	135	868	35
16	1282	234	943	85
15	1999	327	1304	143
14	4145	511	1398	228
13	4058	716	218	377
12	493	1445	9	750
11	43	4387	0	1640
10	0	6711	0	2871
9	0	1941	0	1457
8	455	543	445	500
7	155	36	155	36
6	0	508	0	508
5	0	327	0	327
4	0	6	0	6
3	0	1	0	1
2	0	2	0	2
1	0	2	0	2
Σ	17983	17983	9006	9006

Figure 102 manoeuvre load cycles for F27 and F28 (Schijve, 1985)

Table 47 number of loads occurrence during take-off and landing (Wells, 1956)

Case	# of load occurrences, mean
Forward Fuselage station: take-off	24.5
Forward Fuselage station: Landing	45.9
Rear Fuselage station: Take-off	18.74
Rear Fuselage station: Landing	35.7

Assuming the load cycles per flight cycle as well as for gust load and manoeuvre loads also apply for the A330 (due to lack of data about the A330). Than the total loads cycles (due to manoeuvre and gusts) per flight cycles are 180. In Table 11 the total number of load cycles for a cruise flight can be obtained, $\left(\#\frac{LC}{FC}\right)_{cruise} = \frac{138}{8} \approx 18$. Using *Eq. 73* following can be constructed for ground phase 1, flight phase and ground phase II loads:

$$loads_{g_I} = loads_{st} + loads_{TO} + loads_{PB} + loads_{TOR} + loads_{Ro} \qquad Eq.\ 195$$

Where;

$loads_{st}$ is amount of loads cycle on the rudder during standing

$loads_{TO}$ is amount of loads cycle on the rudder during Take-off run

$loads_{PB}$ is amount of loads cycle on the rudder during pre-flight braking

$loads_{TOR}$ is is amount of loads cycle on the rudder during take-off run

$loads_{Ro}$ is amount of loads cycle on the rudder during aircraft rotation

The same can be done for load cycles during flight operations:

$$laods_f = loads_{IC} + loads_{cl} + loads_{cr} + loads_{ID} + loads_{ap} \qquad Eq.\ 196$$

Where;

$loads_{IC}$ is amount of loads cycle on the rudder during initial climb

$loads_{cl}$ is amount of loads cycle on the rudder during climb

$loads_{cr}$ is amount of loads cycle on the rudder during cruise flight

$loads_{ID}$ is amount of loads cycle on the rudder during initial descent

$loads_{ap}$ is amount of loads cycle on the rudder during approach of the runway

At last the same similar expression can be developed for ground stage II (after the landing):

$$loads_{g_{II}} = loads_{TD} + loads_{LR} + loads_{br} + loads_{GT} + loads_{TI} \qquad Eq.\ 197$$

Where;
$loads_{TD}$ is amount of loads cycle on the rudder during touch down
$loads_{LR}$ is amount of loads cycle on the rudder during landing roll
$loads_{br}$ is amount of loads cycle on the rudder during braking
$loads_{GT}$ is amount of loads cycle on the rudder during ground turning
$loads_{TI}$ is amount of loads cycle on the rudder during taxi-in

Most of the terms in *Eq. 195* and *Eq. 197* can be considered to be zero for the rudder, because the loads on the rudder are negligible during most of the ground operations, because the rudder is not used to manoeuvre during the ground operations. The following variables are considered zero for ground operation before the take-off ($loads_{g_I}$): $loads_{st} = loads_{PB} = loads_{TOR} = 0$. For variables of loads on the rudder after the touch down ($loads_{g_{II}}$), following are considered to be zero: $loads_{LR} = loads_{br} = loads_{TI} = 0$. So *Eq. 195* and *Eq. 197* can be reproduced as: the load cycles can be obtained for ground phase I and ground phase II.

$$loads_{g_I} = 2\ load\ cycles + 2\ load\ cycles \qquad Eq.\ 198$$

$$loads_{g_{II}} = 1\ laod\ cycle + 2\ load\ cycles \qquad Eq.\ 199$$

So the remaining load cycles of $180 - 18 - 2 - 2 - 1 - 2 = 155$ per flight are for initial climb, climb, initial descent and approach. Form Table 47 the relation between touch down and take-off was given as: $loads_{TD} = 2 \times loads_{TO}$. Assuming the same factor applies to:

$$(loads_{IC} + loads_{cl}) = 0.5\ (loads_{ID} + loads_{ap}) \qquad Eq.\ 200$$

And

$$155 = loads_{IC} + loads_{cl} + loads_{ID} + loads_{ap} \qquad Eq.\ 201$$

So combining *Eq. 200*and *Eq. 201* results in:

$$loads_{IC} + loads_{cl} \approx 52\ load\ cycles\ per\ flight \qquad Eq.\ 202$$

And

$$loads_{ID} + loads_{ap} = 103\ load\ cycles\ per\ flight \qquad Eq.\ 203$$

In previous calculation both the gust loads and the manoeuvre loads are incorporated. Now Table 9 and Table 26 can be updated:

Table 48 types of loading and frequencies

Loading type	Magnitude	frequency
Lateral gust loads $(F_2)_{LG}$	704 N	90
Asymmetric thrust $(F_2)_{asym\ thrust}$	17568 N	≈ 0
Sudden max rudder input $(F_2)_{\max \delta_R}$	19817085 N	90

Table 49 A330 load spectrum for A330 rudder

	Operational basic conditions	Loading component	representation	frequency
ground	Standing		Steady case	4
	Taxi-out		Two cycle per flight	
	Pre-flight breaking		-	
	Ground turning		-	
	Taxi-off run		Two cycle per flight	
	Rotation		Steady case	
flight	Initial climb		Stepped spectra	173
	Climb		Stepped spectra	
	Cruise I		Stepped spectra	
	Cruise II		Stepped spectra	
	Initial descent		Stepped spectra	
	approach		Stepped spectra	
ground	Touch down		One cycle per flight	3
	Landing roll		Two cycle per flight	
	Braking		-	
	Ground turning		-	
	Taxi-in		-	

Appendix G A330-200 Rudder Tasks

Table 50 structures maintenance task rudder A330, source (Airbus, Maintenance Planning Document (MPD), 2006)

Task No.	zone	Description (Structures)	Task type	Threshold Interval	Men	Man hour
553026-01-1	325	Main structure DETAILED INSPECTION OF RUDDER HINGE ARMS AND SUPPORT FITTINGS AND ACTUATOR SUPPORT FITTINGS	DI	T: 6 YE I: 6 YE	1 *	0.60 18.42
554020-01-1	300	Rudder GENERAL VISUAL INSPECTION OF RUDDER SIDE PANELS INCLUDING TRAILING EDGE, EXTERNAL SURFACE LH/RH.	GVI	T: 6 YE I: 6 YE	1	0.20
554021-01-1	326	Rudder DETAILED INSPECTION OF RUDDER FRONT SPAR FORWARD FACE AND INTERNAL STRUCTURE AS FAR AS VISIBLE. PREP ACCESS	DI	T: 6 YE I: 6 YE	1 * *	0.30 0.02 33.64
554022-01-1	300	Rudder SPECIAL DETAILED INSPECTION OF RUDDER SIDE PANELS IN THE FOLLOWING AREAS: MRB REFERENCE - 40 MM STRIP, 430 MM FWD OF TRAILING EDGE FROM 554022-01-1 BOTTOM TO 4280 MM HEIGHT. - 170 MM STRIP, AFT OF THE LEADING EDGE, FROM RUDDER NOSE RIBS 3 TO 10, INCLUDING HOISTING POINTS 1, 2 AND 3.- AREAS DIRECTLY AFT OF THE LEADING EDGE AT BEARING LOCATIONS 1, 6 AND 7.	SDI	T: 6 YE I: 6 YE	1	1.00
554023-01-1	325 326	Main structure DETAILED INSPECTION OF RUDDER HINGE FITTINGS AND ACTUATOR ATTACHMENTS. ACCESS	DI	T: 6 YE I: 6 YE	1 1 *	0.60 0.60 18.42

Table 51 Zonal Maintenance tasks rudder A330, source (Airbus, Maintenance Planning Document (MPD), 2006)

Task No.	zone	Description (Zonal)	Task type	Threshold Interval	Men	Man hour
ZL-326-01-2	326	Rudder GENERAL VISUAL INSPECTION OF RUDDER (AREA OF BEARINGS 2, 3, 4 AND 5) ACCESS	GVI	I: 18 MO	1 *	0.40 3.87
ZL-326-02-3	326	Rudder GENERAL VISUAL INSPECTION OF RUDDER(AREA OF BEARINGS 1 TO 8) ACCESS	GVI	I: 6 YE	1 *	0.40 16.00
ZL-326-03-3	326	Rudder GENERAL VISUAL INSPECTION OF RUDDER (FRONT SPAR FWD FACE AND INTERNAL STRUCTURE AS FAR AS MRB REFERENCE VISIBLE)	GVI	I: 10 YE	1 *	0.60 34.24

Table 52 System & Component

Task No.	zone	Description (system & component)	Task type	Threshold Interval	Men	Man hour
221100-01-1	210	Autopilot/flight direction OPERATIONAL CHECK OF AUTOPILOT ENGAGEMENT AND LOCKING DEVICES OF SIDE STICK CONTROLLER AND RUDDER PEDALS	OP	I: 6 YE	1	0.3
272100-01-1	100	Rudder mechanical control DETAILED INSPECTION OF RUDDER MECHANICAL CONTROL (excluding fin)	DI	I: 6 YE	1 *	2 17.12
272100-02-1	325	Rudder mechanical control VISUAL CHECK OF RUDDER MECHANICAL CONTROL IN FIN	VC	I: 20000 FH	1	0.2

272100-03-1	121	Rudder mechanical control CHECK POINTER OF CABLE TENSION REGULATOR WITHIN LIMITS	VC	I: 36 MO	1 *	0.3 0.03
272100-04-1	325	Rudder mechanical control OPERATIONAL CHECK OF CENTERING MECHANISM	OP	I: 34000 FH	1 *	1.00 2.34
272100-05-1	210	Rudder mechanical control LUBRICATION OF THE RUDDER PEDALS ADJUSTMENT MECHANISM	LU	I: 18 MO	1	0.20
272149-01-1	325	Rudder mechanical control FUNCTIONAL CHECK FOR RUDDER SERVO-CONTROLS SYNCHRONIZATION FOLLOWED BY SPRING-ROD REMOVAL FOR WORKSHOP CHECK	FC	I: 42 MO OR 20000 FH	1 *	1.00 1.60
272200-02-1	210	Rudder mechanical control OPERATIONAL CHECK OF TRIM ACTUATOR STANDBY CHANNEL	OP	I: 36 MO	1	0.10
272300-01-1	210	Rudder mechanical control OPERATIONAL CHECK OF RUDDER AND PEDALS TRAVEL LIMITATION UNITS STANDBY CHANNEL	OP	I: 36 MO	1	0.15
272300-04-3	311	Rudder mechanical control VISUAL CHECK TO CONFIRM INTEGRITY OF CONTROL ROD (ITEM 220 IN IPC 272147-1A) IN PTLU LINKAGE	VC	I: 20000 FH	1	0.20
272400-01-1	210	Rudder hydraulic actuation OPERATIONAL CHECK OF RUDDER SERVO CONTROL WITH INDIVIDUAL HYDRAULIC SYSTEMS	OP	I: 700 FH	1	0.10
272400-03-1	325	Rudder hydraulic actuation CHECK RUDDER SERVO CONTROL AND HINGE BEARINGS FOR EXCESSIVE PLAY AND GENERAL CONDITION	FC	I: 34000 FH	2 *	2.00 5.16
272400-04-1	210	Rudder hydraulic actuation OPERATIONAL CHECK OF RUDDER SERVO CONTROL JAMMING DEVICE	OP	I: 36 MO	1	0.10
272400-05-2	325	Rudder hydraulic actuation REMOVE RUDDER SERVO CONTROL FOR	RS	I: 33000 FH	1 *	3.00 5.16

		WORKSHOP CHECK OF INTERNAL SEALS				
272400-06-1	325	Rudder hydraulic actuation LUBRICATION OF RUDDER SERVO CONTROL TAILSTOCK ROLLER BEARING (RUDDER SIDE)	LU	I: 7500 FH OR 18 MO	1	0.10
272400-07-1	325	Rudder hydraulic actuation LUBRICATION OF RUDDER HINGE BEARING NO 6	LU	I: 7500 FH OR 18 MO	1 *	0.10 2.43
272600-01-1	210	Rudder mechanical control OPERATIONAL CHECK OF YAW DAMPER SERVO ACTUATOR STANDBY SERVO LOOP	OP	I:18 MO	1	0.10
272600-05-1	210	Rudder mechanical control OPERATIONAL CHECK OF BACK-UP YAW DAMPER BY BITE	OP	I: 2400 FH	1	0.20
272651-01-1	310	Yaw damper actuation INSPECTION OF RUDDER YAW DAMPER SERVO-ACTUATOR (ACTIVE POSITION) FOR LEAKAGE (FIN 19CS1)	CHK	T:10000 FH OR 10000 YAW DAMPER SERVO-ACTUATOR FH SINCE NEW I: 700 FH	1	1.5
279000-08-1	210	Electrical flight control system (EFCS) OPERATIONAL CHECK OF RETURN TO LOW SPEED CONFIGURATION OF RUDDER AND PEDAL TRAVEL LIMITATION UNITS	Op	6 YE	2	0.40
279000-15-1	210	Electrical flight control system (EFCS) OPERATIONAL CHECK OF FCSC1 RUDDER SERVO LOOP	OP	I: 18 MO	1	0.40
279000-16-1	210	Electrical flight control system (EFCS) OPERATIONAL CHECK RUDDER ELECTRICAL BACK UP	OP	I: 5000 FH	1	0.40

Appendix H Rudder Scheduled Maintenance Tasks Calculation

Table 53 spar tasks

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
554021-01-1	DI	24528	11,32	4088	43,5	1,93E-05	0,17	1.89
ZL-326-03-3	GVI	49056	17,42	4088	43,5	9,65E-06	0,17	2,90
Total		73584	28,74			2,89E-05	0,33	4,79

Spar	
Maintenance Labor Cost	
MTTF [hr]=	34560,00
MPMT=	14,37
C_labor=	108,14
C_labor_AClife=	2162,70

Table 54 rib tasks

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
554021-01-1	DI	51840	11,32	4088	43,5	1,93E-05	0,17	1,89
ZL-326-01-2	GVI	12960	1,42	4088	43,5	7,72E-05	0,67	0,95
ZL-326-02-3	GVI	51840	5,47	4088	43,5	1,93E-05	0,17	0,91
ZL-326-03-3	GVI	103680	17,42	4088	43,5	9,65E-06	0,08	1,45
554022-01-1	SDI	51840	0,33	4088	43,5	1,93E-05	0,17	0,06
Total		272160	35,96			1, 45E-04	1,25	5,25

ribs	
Maintenance Labor Cost	
MTTF [hr]=	6912,00
MPMT=	4,20
C_labor=	108,14
C_labor_AClife=	2162,70

Table 55 skin tasks

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
554021-01-1	DI	51840	11,32	4088	43,5	1,93E-05	0,17	1,89
ZL-326-01-2	GVI	12960	1,42	4088	43,5	7,72E-05	0,67	0,95
ZL-326-02-3	GVI	51840	5,47	4088	43,5	1,93E-05	0,17	0,91
554020-01-1	GVI	51840	0,20	4088	43,5	1,93E-05	0,08	0,02
554022-01-1	SDI	51840	0,33	4088	43,5	1,93E-05	0,17	0,06
Total		220320	18,74			1,54E-04	1,25	3,82

Skin	
Maintenance Labor Cost	
MTTF [hr]=	6480,00
MPMT=	3,06
C_labor=	83,84
C_labor_AClife=	1676,80

Table 56 actuator attachment tasks

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor]	λ_i	FPM_j	FPM x ETPMT_i
554023-01-1	DI	51840	9,81	4088	43,5	1,93E-05	0,17	1,64
Total		51840	9,81			1,93E-05	0,17	1,64

actuator att.	
Maintenance Labor Cost	
MTTF [hr]=	51840,00
MPMT=	9,81
C_labor=	33,65
C_labor_AClife=	673,03

Table 57 hinges & actuator fittings/bearing

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
ZL-326-01-2	GVI	12960	1,42	4088	43,5	7,72E-05	0,67	0,95
ZL-326-02-3	GVI	51840	5,47	4088	43,5	1,93E-05	0,17	0,91
553026-01-1	DI	51840	9,51	4088	43,5	1,93E-05	0,17	1,59
554023-01-1	DI	51840	9,81	4088	43,5	1,93E-05	0,17	1,64
554022-01-1	SDI	51840	0,33	4088	43,5	7,72E-05	0,17	0,06
Total		220320	26,54			2,12E-04	1,33	5,14

Hinges & act. Fittings/bng	
Maintenance Labor Cost	
MTTF [hr]=	4712,73
MPMT=	3,85
C_labor=	145,34
C_labor_AClife=	2906,74

Table 58 hinge arm

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
553026-01-1	DI	51840	9,51	4088	43,5	1,93E-05	0,17	1,59
Total		51840	9,51			1,93E-05	0,17	1,59

Hinge arm	
Maintenance Labor Cost	
MTTF [hr]=	51840
MPMT=	9,51
C_labor=	32,62
C_labor_AClife=	652,45

Rudder System & Components maintenance tasks

Same method can be applied to Systems & Component maintenance tasks using previously defined equations.

Table 59 autopilot and flight direction tasks

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
221100-01-1	OP	51840	0,3	4088	43,5	1,93E-05	0,17	0,05
Total		51840	0,3			1,93E-05	0,17	0,05

autopilot/flight direction	
Maintenance Labor Cost	
MTTF [hr]=	51840,00
MPMT=	0,30
C_labor=	1,03
C_labor_AClife=	20,58

Table 60 mechanical control

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
272100-01-1	DI	51840	19,12	4088	43,5	1,93E-05	0,17	3,19
272100-02-1	VC	20000	0,2	4088	43,5	5,00E-05	0,20	0,04
272100-03-1	VC	25920	0,33	4088	43,5	3,86E-05	0,33	0,11
272100-04-1	OP	34000	3,34	4088	43,5	2,94E-05	0,12	0,40
272100-05-1	LU	12960	0,2	4088	43,5	7,72E-05	0,67	0,13
272149-01-1	FC	20000	2,6	4088	43,5	5,00E-05	0,20	0,52
272200-02-1	OP	25920	0,1	4088	43,5	3,86E-05	0,33	0,03
272300-01-1	OP	25920	0,15	4088	43,5	3,86E-05	0,33	0,05
272300-04-3	VC	20000	0,21	4088	43,5	5,00E-05	0,20	0,04
272600-05-1	OP	12960	0,1	4088	43,5	7,72E-05	0,67	0,07
272600-05-1	OP	2400	0,2	4088	43,5	4,17E-04	1,68	0,34
Total		251920	26,55			8,85E-04	4,90	4,92

mechanical control	
Maintenance Labor Cost	
MTTF [hr]=	1129,39
MPMT=	1,00
C_labor=	157,95
C_labor_AClife=	3159,05

Table 61 hydraulic actuation

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
272400-01-1	OP	51840	0,2	4088	43,5	1,93E-05	0,17	0,03
272400-03-1	FC	34000	7,16	4088	43,5	2,94E-05	0,12	0,85
272400-04-1	OP	25920	0,1	4088	43,5	3,86E-05	0,33	0,03
272100-05-2	RS	33000	8,16	4088	43,5	3,03E-05	0,12	1,00
272400-06-1	LU	12960	0,1	4088	43,5	7,72E-05	0,67	0,07
272400-07-1	LU	29808	2,53	4088	43,5	3,35E-05	0,67	1,69
Total		187528	18,25			2,28E-04	2,07	3,67

hydraulic actuation	
Maintenance Labor Cost	
MTTF [hr]=	4380,32
MPMT=	1,77
C_labor=	71,76
C_labor_AClife=	1435,15

Table 62 yaw damper actuation

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
272651-01-1	CHK	700	1	4088	43,5	1,43E-03	12,34	18,51
Total		**700**	**1**			**1,43E-03**	**12,34**	**18,51**

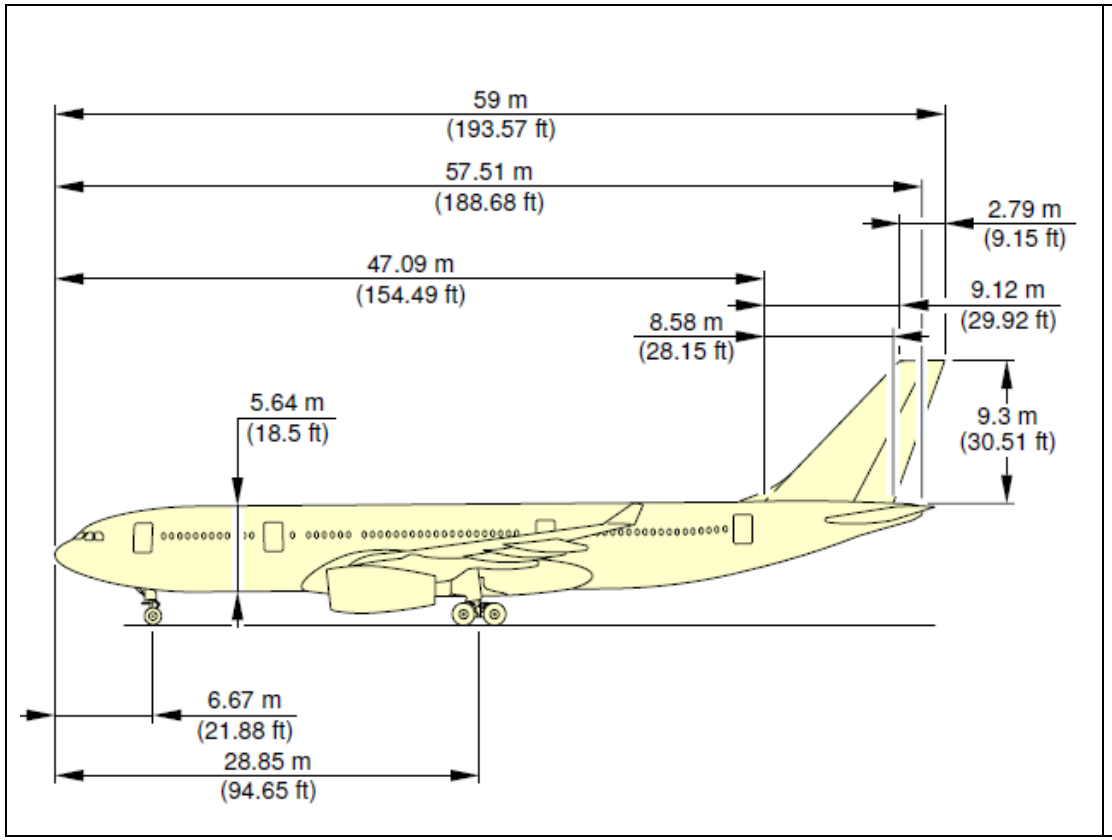
yaw damper actuation	
Maintenance Labor Cost	
MTTF [hr]=	700,00
MPMT=	1,00
C_labor=	254.04
C_labor_AClife=	7621.20

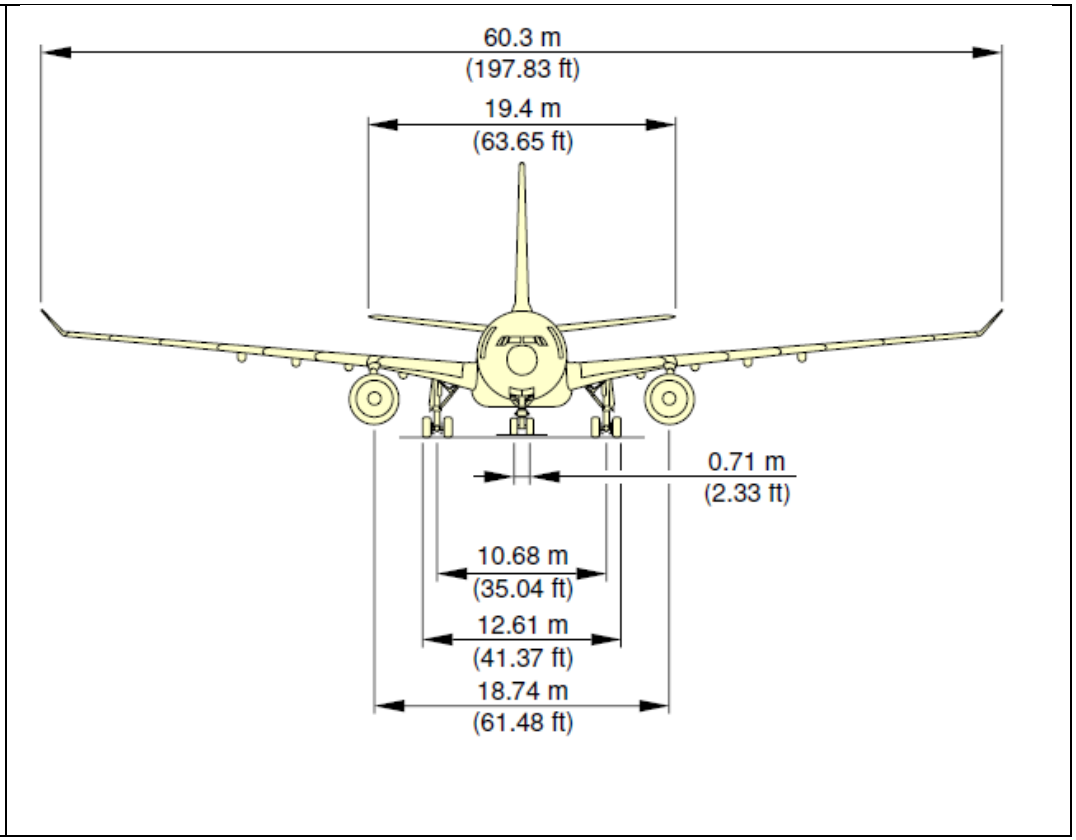
Table 63 electrical flight control

Task #	Inspection	Interval(hr)=MTBF_i	M/H (CMT)=ETPMT_i	FH	r_labor	λ_i	FPM_j	FPM x ETPMT_i
279000-08-1	OP	51840	0,8	4088	43,5	1,93E-05	0,35	0,28
279000-15-1	OP	12960	0,4	4088	43,5	7,72E-05	1,41	0,56
279000-16-1	OP	5000	0,4	4088	43,5	2,00E-04	1,73	0,69
Total		69800	1,6			2,96E-04	3,49	1,54

electrical flight control	
Maintenance Labor Cost	
MTTF [hr]=	3373,24
MPMT=	0,43
C_labor=	22,46
C_labor_AClife=	449,18

Appendix I A330-200 Dimensions





Source (Airbus, 2006)

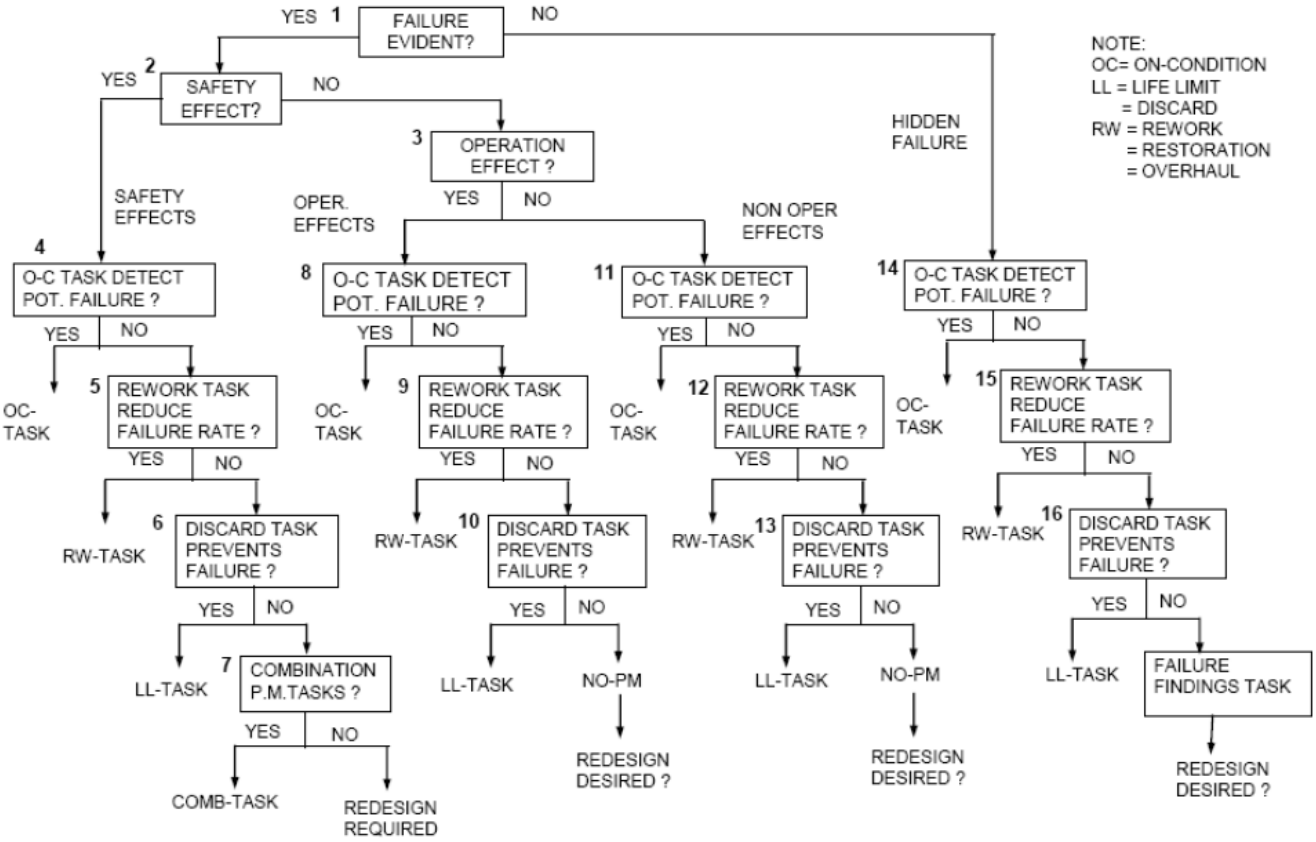
Appendix J DMC Labor for A330-200 Rudder for AIM

AC Age	AF_y	Airframe maint. labor cost (€)	UNMLC airframe(€)	Rudder maintenance labor cost(€)	UNMLC rudder (€)	SMLC rudder (€)
1	0.89	707718	332947	10469	4925	5544
2	0.94	721590	349079	10674	5164	5510
3	0.99	735733	365236	10884	5403	5481
4	1.03	750153	381437	11097	5642	5454
5	1.08	764856	397702	11314	5883	5431
6	1.13	779847	414048	11536	6125	5411
7	1.18	795132	430493	11762	6368	5394
8	1.23	810717	447053	11993	6613	5380
9	1.28	826607	463742	12228	6860	5368
10	1.33	842808	480575	12467	7109	5358
11	1.38	859327	497566	12712	7360	5351
12	1.42	876170	514729	12961	7614	5347
13	1.47	893343	532075	13215	7871	5344
14	1.52	910853	549618	13474	8130	5344
15	1.57	928705	567370	13738	8393	5345
16	1.62	946908	585341	14007	8659	5349
17	1.67	965468	603544	14282	8928	5354
18	1.72	984391	621989	14562	9201	5361
19	1.77	1003685	640688	14847	9478	5370
20	1.81	1023357	659652	15138	9758	5380

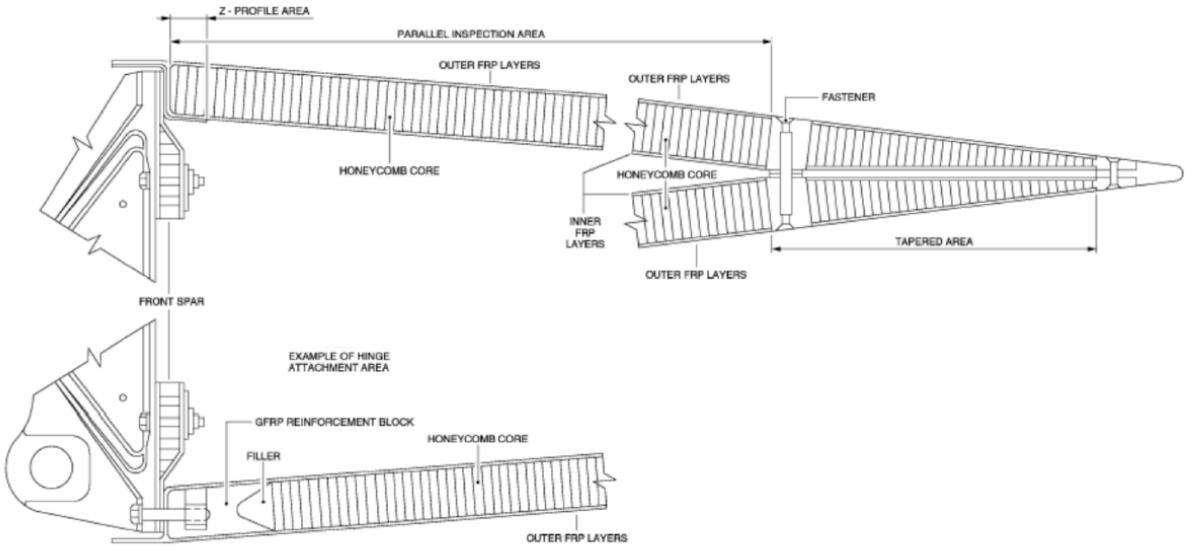
Appendix K A330-200 Rudder Material Cost

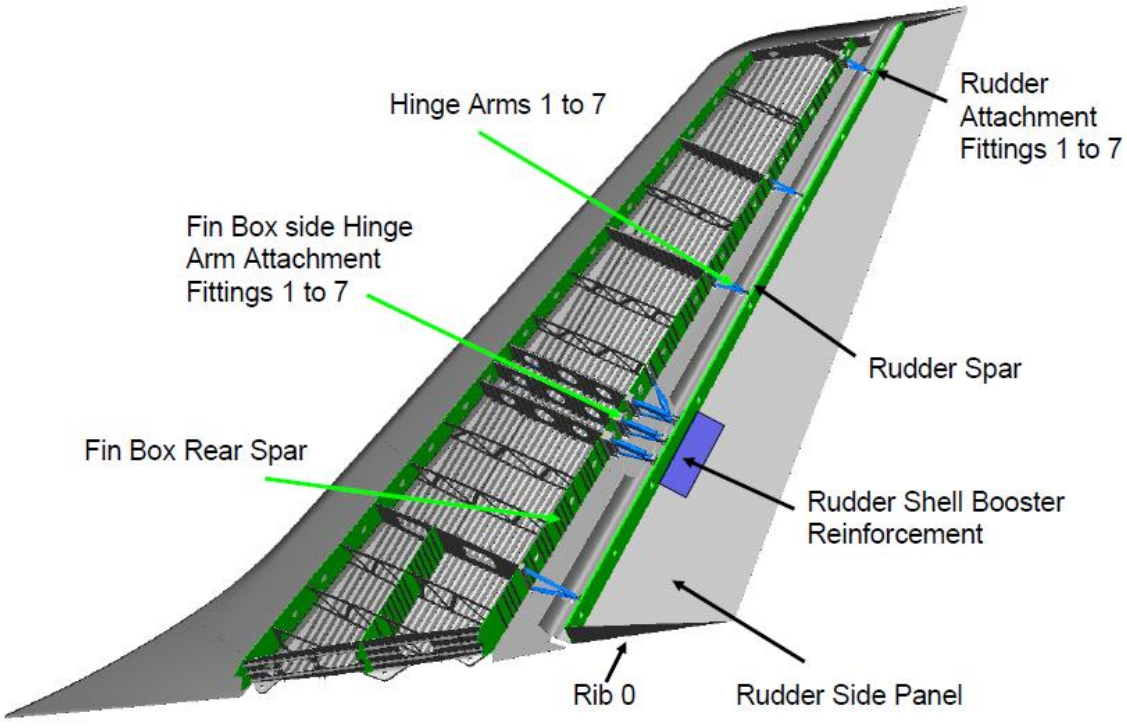
AC Age	AF	Total aiframe material cost(€)	Rudder mat.Cost, y	UMMC rudder	SMMC rudder
1	0.89	259180	3834	1804	2030
2	0.94	264260	3909	1891	2018
3	0.99	269439	3986	1979	2007
4	1.03	274720	4064	2066	1997
5	1.08	280105	4144	2155	1989
6	1.13	285595	4225	2243	1982
7	1.18	291193	4308	2332	1975
8	1.23	296900	4392	2422	1970
9	1.28	302719	4478	2512	1966
10	1.33	308653	4566	2603	1962
11	1.38	314702	4655	2696	1960
12	1.42	320870	4747	2788	1958
13	1.47	327159	4840	2882	1957
14	1.52	333572	4934	2977	1957
15	1.57	340110	5031	3074	1957
16	1.62	346776	5130	3171	1959
17	1.67	353573	5230	3270	1961
18	1.72	360503	5333	3370	1963
19	1.77	367569	5437	3471	1966
20	1.81	374773	5544	3574	1970

Appendix L MSG-3 Task Selection by Failure Mode



Appendix M Detailed A330 Rudder Sketches

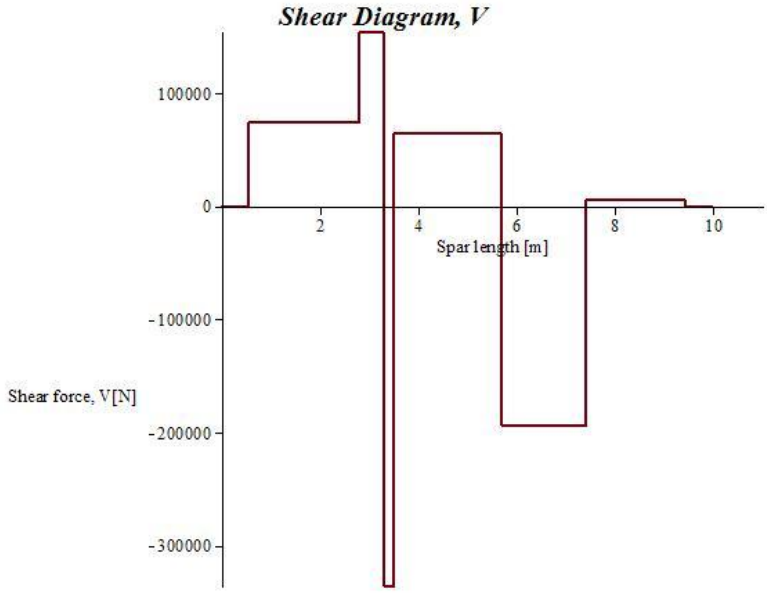




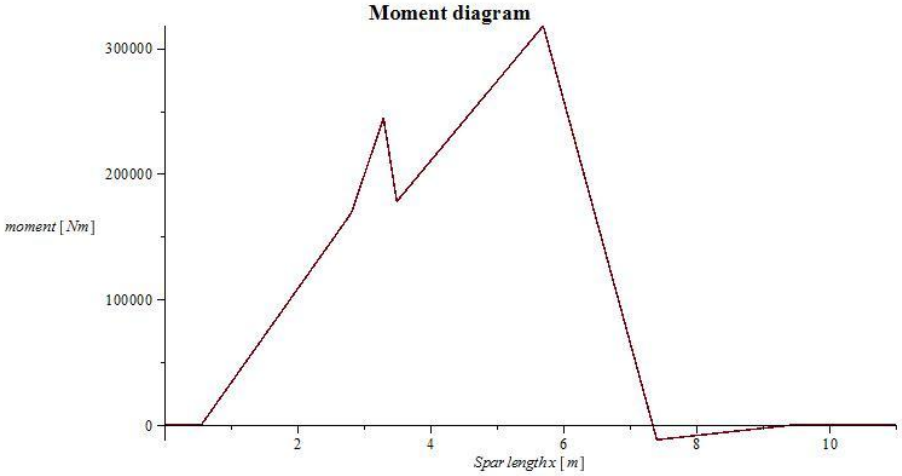
(Hicken, 2007)

Appendix N Shear and Moment Diagrams of the Spar

Shear and moment diagrams for the asymmetric case of the rudder spar, evaluated by Maple.



Maximum shear = 335946 N



Maximum moment = 317999 Nm