Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Project

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CG-Travel of Passenger Aircraft

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Abstract

This project deals with the analysis of CG-travel (Center of Gravity travel) of passenger Aircraft. Knowledge has been gained through a literature research which has helped to understand the relations between the different parameters. On ground, the CG travels because of the boarding of passengers and the refueling process. Then the cabin layout and the geometry of fuel tanks have been particularly taken into account. Indeed the position of each passenger and the volume of fuel loaded strongly affect the CG position. The CG margins have a strong impact on the horizontal tail-plane sizing. Rather than developing a separated tool, it has been chosen to include it in PreSTo (Preliminary Sizing Tool). It allows investigating the impact of different inputs on the CG-travel for short, middle and long range airliners with conventional configurations. By using empirical formulas and a minimal number of input data, the CG range, the CG margins and the load and trim sheet are given. These results are given with respect to the MAC (Mean Aerodynamic Chord). They are both accurate and easy to obtain. The computing has been made in a way to allow as many different study cases as possible. Human engineering has also been an important part of this project: it is not needed to have particular computing knowledge to use the software, which has been designed as user friendly as possible. Nevertheless it is to keep in mind that the tool is limited to single deck aircraft and only consider one level of comfort. At the end a comparison of results for two different cabin layouts has been carried out. The reference aircraft has been based on the Airbus A320. Its conventional cabin layout shows 6 seats abreast with only one aisle. Thanks to the tool an alternative design with 2 aisles has been evaluated. The results given for the conventional Airbus A320 have been compared to the real CG margins.

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DEPARTMENT OF AUTOMOTIVE AND AERONAUTICAL ENGINEERING

CG-Travel of Passenger Aircraft

Task for a *Project*

Background

The Center of Gravity (CG) of an aircraft travels according to boarding/disembarking of passengers, loading/unloading of cargo and refueling on ground or fuel consumption during flight. As often the case, the fuel is taken additionally from different aircraft fuel tanks. The calculated CG travel is usually depicted in load and trim sheets. In this way, the required CG-margin can be determined. During aircraft preliminary design, the required CG margin of the projected aircraft influences heavily the wing positioning as well as the sizing of the horizontal tail-plane.

Task

The task includes:

- Literature research
- Description of the interrelations between: CG travelling (CG margin), horizontal tail-plane sizing and wing positioning in aircraft preliminary design
- Gathering of aircraft data in relation to the task performed
- Calculation of the CG travel constrained to aircraft geometry parameters – in general and on the example of selected passenger aircraft
- Calculation of the CG margin constrained to aircraft geometry parameters in general. Calculation of the absolute value of the CG margin with respect to the Mean Aerodynamic Chord (MAC).

The report has to be written in English based on German or international standards on report writing.

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List of Symbols

b	Wingspan
c	Chord
d	Diameter
FS	Front Spar
Gravityx	Component of the gravity vector along the *x*-axis
Gravityy	Component of the gravity vector along the *y*-axis
Gravityz	Component of the gravity vector along the *z*-axis
i	Incidence angle
l	Length
m	Number
Pitch	Seat Pitch
RS	Rear Spar
S	Area
t/c	Relative thickness
u	Vector component along the x-axis of a coordinate system
v	Vector component along the y-axis of a coordinate system
V	Volume
w	Vector component along the z-axis of a coordinate system
x	Position along the x-axis in the aircraft coordinate system
y	Position along the y-axis in the aircraft coordinate system

Greek Symbols

Δ	Range, difference
Λ	Wing sweep
ρ	Density
ν	Dihedral angle

Subscripts

Subscripts for aircraft components

$(\ )_{Aisle}$	Aisle
$(\ )_{Cabin}$	Cabin
$(\ )_{FG}$	Fuselage
$(\ )_{Nose}$	Aircraft Nose
$(\ )_{t}$	Tank
$(\ )_{WG}$	Wing

Subscripts for loads

$(\ )_{PAX}$	Passenger
$(\ )_{f}$	Fuel

Subscripts for cabin layout

$(\ )_{row}$	Row
$(\ )_{sa}$	Seats abreast

Subscripts for wing geometry

$(\ )_{LEMAC}$	From the aircraft nose to the LE of the MAC
$(\ )_{CG\ LEMAC}$	From the CG to the LE of the MAC
$(\ )_{WG\ LEMAC}$	From the CG of the wing group to the LE of the MAC
$(\ )_{k}$	Kink
$(\ )_{MAC}$	Mean Aerodynamic Chord (MAC)
$(\ )_{r}$	Wing root
$(\ )_{t}$	Wing tip
$(\ )_{,i}$	Inner
$(\ )_{,o}$	Outer

Other subscripts

$(\ )_{0}$	Initial
$(\ )_{0\text{-}MAC}$	Initial CG in percent of the MAC
$(\ )_{CG}$	CG
$(\ )_{i}$	Component or element number i

$(\ )_{MTO}$	Max. Take-off
$(\ )_{\mathrm{ML}}$	Max. Landing
$(\ )_{MZF}$	Max. Zero Fuel
$(\ )_{OE}$	Operating Empty

List of Abbreviations

A	Aisle seat
A1	Aisle number 1
A2	Aisles number 2
Aero	Aircraft Design and Systems Group
ALOHA	Aircraft Design for Low Cost Ground Handling
C	Cushion seat
CAD	Computer Aided Design
CG	Center of Gravity
DOC	Direct Operating Cost
HAW	Hochschule für Angewandte Wissenschaften (University of Applied Sciences)
IFL	Institute of Aircraft Design and Lightweight Structures
JAR	Joint Aviation Requirements
LE	Leading Edge
FAR	Federal Aviation Regulations
M1	Middle seat number 1 (the seat next to aisles)
M2	Middle seat number 2 (the seat next to Middle seat number 1)
M3	Middle seat number 3 (the seat which is the most further to aisle)
MAC	Mean Aerodynamic Chord
MLW	Maximum Landing Weight
MTOW	Maximum Take Off Weight
MZFW	Maximum Zero Fuel Weight
OEW	Operating Empty Weight
PrADO	Preliminary Aircraft Design and Optimization
PreSTo	Preliminary Sizing Tool
VBA	Visual Basic for Applications
W	Window seat

Glossary

CG margins

The directives for qualification approval JAR 25 and FAR Part 25 require that the CG lies in a range where the safety is assured. The CG margins have to be furnished in the aeroplane Flight Manual (see **JAR 25 2009**).

> *CS 25.27 Centre of gravity limits*
> *The extreme forward and the extreme aft centre of gravity limitations must be established for each practicably separable operating condition. No such limit may lie beyond –*
> *(a) The extremes selected by the applicant;*
> *(b) The extremes within which the structure is proven; or*
> *(c) The extremes within which compliance with each applicable flight requirement is shown.*

> *CS 25.1583 (c) Weight and loading distribution*
> *The weight and centre of gravity limitations established under CS 25.1519 must be furnished in the aeroplane Flight Manual. All of the following information, including the weight distribution limitations established under CS 25.1519, must be presented either in the aeroplane Flight Manual or in a separate weight and balance control and loading document that is incorporated by reference in the aeroplane Flight Manual;*

CG range

The CG range is defined as the distance between the forward and backward CG margins. It can be presented in terms of both distance-from-datum and percentage of the MAC.

Number of seats abreast

This is the amount of passenger sitting next to each other, or the amount of seats seen in the cross-section. (**Goderis 2008**)

Seat pitch

The seat pitch is the distance between a point on one seat and the same point on the seat in the next row. (**Raymer 1989**)

Seat width

The seat width is defined as the distance from armrest to armrest.

Mean Aerodynamic Chord (MAC)

The MAC is the chord of an equivalent linear tapered, untwisted wing, which gives the same lift and the same pitching moment than the previous wing. The aerodynamic center is transversally located on the MAC. The aerodynamic center can be determined through the following properties: If we take an axis orthogonal to the aircraft plane of symmetry which goes through the aerodynamic center, then the pitching moment coefficient of the wing is constant and independent from the lift. (**Torenbeek 1988**)

Axes of an aircraft

In order to keep some consistence in the many dimensions concerning wing geometry that will be calculated, it is useful to define a coordinate system used for the entire aircraft. Figure 0.1 give a clear representation of the different axes and also gives their name as used in stability definition. (**Coene 2008**)

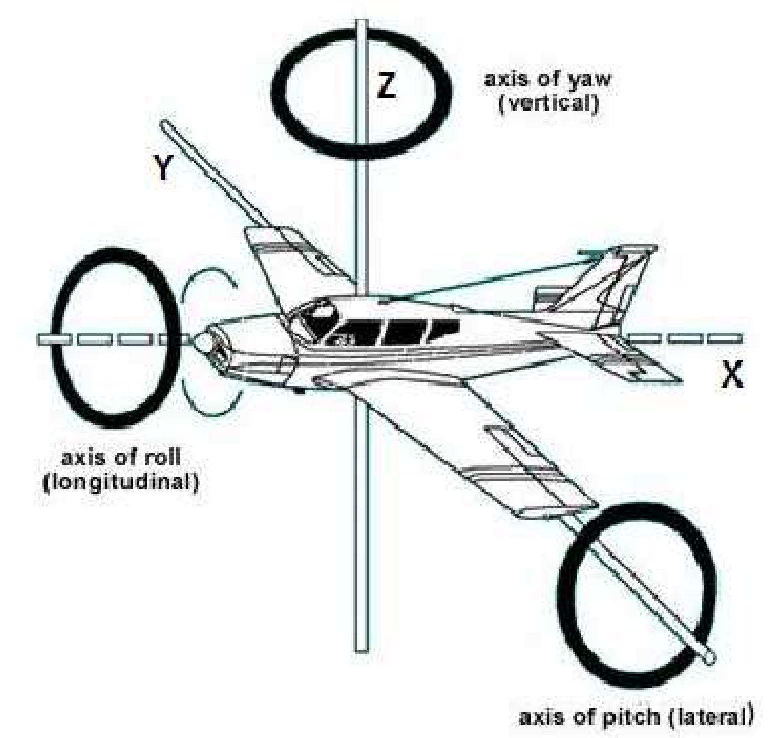


Figure 0.1 Axes of an aircraft (based on **Startflying 2010**)

Dihedral angle

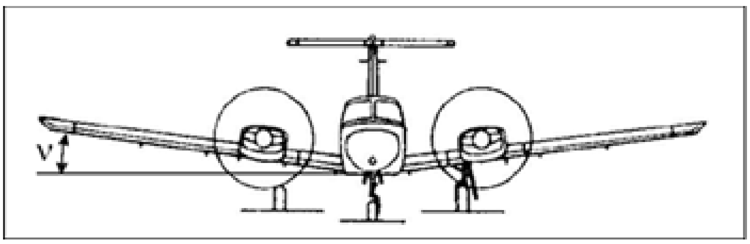


Figure 0.2 Positive dihedral angle v (**Scholz 1999**)

Incidence angle

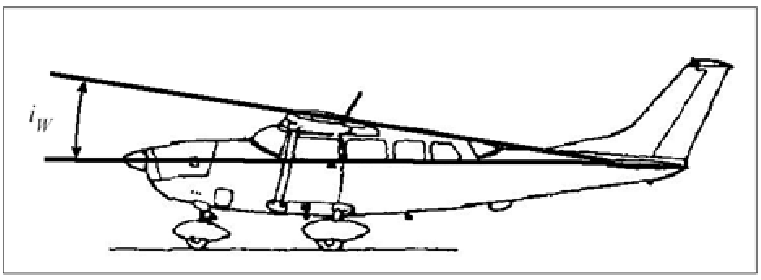


Figure 0.3 Positive incidence angle i_w (**Scholz 1999**)

1 Introduction

1.1 Motivation

Nowadays engineers and designers have recourse to CAD in order to develop new aircrafts in a shorter time. The aim of the tools is to improve the efficiency and minimize the cost through using existing databases and automatic calculation. Using computers is particularly adapted to aircraft design, which is an iterative process. A tool has been developed at HAW Hamburg and is called PreSTo, which stands for Preliminary Sizing Tool. PreSTo is used for educational purposes. It gives the possibility for students to apply the presented process for re-disigns of existing aircraft or notional new ones and learn about the reasons why current aircraft look the way they do (**Seeckt 2010**). Using Excel and macro level, this tool is really helpful to investigate the impact of different inputs during the preliminary sizing. It focuses on short, middle and long range airliners with conventional configurations.

This project, *CG-Travel of Passenger Aircraft*, aims to develop this tool further. It is one of the purposes of PreSTo to give the possibility for student projects to use individual steps of the process of the aircraft design lecture and further handbook data and program them into an aircraft design tool (**Seeckt 2010**). This student project deals also with the bigger research project Aircraft design for LOw cost ground Handling or shortly ALOHA. ALOHA is a joint research project. The duration is 2 years and 4 months. Innovative conventional and unconventional aircraft designs are being investigated and evaluated with respect to ground handling. The aim is to reduce ground handling cost a well as overall DOC. (**Scholz 2007**)

The CG position is of major importance during all flight phases. It affects the stability and the maneuverability. Thus, automatically displaying the load and trim sheet has been identified as an important development. The CG position changes during ground handling processes. During the flight the CG also moves, due to the consumption of the fuel from the different tanks. This is the so-called CG travel. The load and trim sheet gives the CG-range, which is the main parameter to calculate the area of the horizontal tail. Moreover the boarding of passengers, refueling and cargo loading changes the CG. Considering a different cabin layout could lead to different CG margins, and thus to different horizontal tail plane surface area. The new functions that have to be implemented in PreSTo have to work together with the inputs and outputs from earlier design phases. Naturally they will be written in VBA and integrated to the existing *Microsoft Excel* Spreadsheet.

1.2 Definitions

Load and Trim sheet

As required by JAR, the load and trim sheet is a weight and balance control and loading document which could be incorporated by reference in the aeroplane flight manual. (see **JAR 25 2009**)

> *JAR 25.1583 (c) Weight and loading distribution*
> *The weight and centre of gravity limitations established under CS 25.1519 must be furnished in the aeroplane Flight Manual... or in a separate weight and balance control and loading document that is incorporated by reference in the aeroplane Flight Manual.*

Figure 1.1 shows a load and trim sheet. The load and trim sheet contains the valid scope for a combination of aircraft mass and CG position. The CG travel in loading and unloading is also plotted in the load and trim sheet. The load and trim sheet is used for air traffic as well as for aircraft design. (**Scholz 1999**)

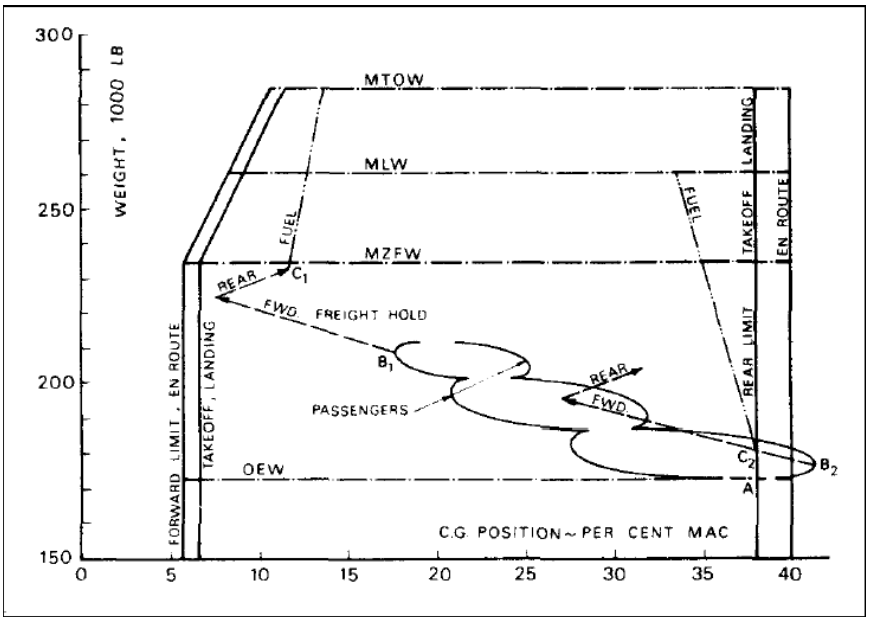


Figure 1.1 Example of a load and trim sheet (**Torenbeek 1988**)

Figure 1.2 shows the curves displayed in a load and trim sheet clearly. This load and trim sheet is a good example of such a diagram for an aircraft having six seats abreast, two cargo holds and three different types of tanks. The loading vectors can be shifted in the load and trim sheet, but usually the boarding of passengers is considered first.

The next curves in Figure 1.2 show the cargo loading and refueling. Please notice that the loading sequence is important. When a loading sequence is for example: 1. Passengers, 2. Cargo, 3. Fuel, then the consequence of other loading sequences also have to be checked: 1-3-2, 2-1-3, 2-3-1, 3-1-2. The unloading sequences have also to be considered. (**Scholz 1999**)

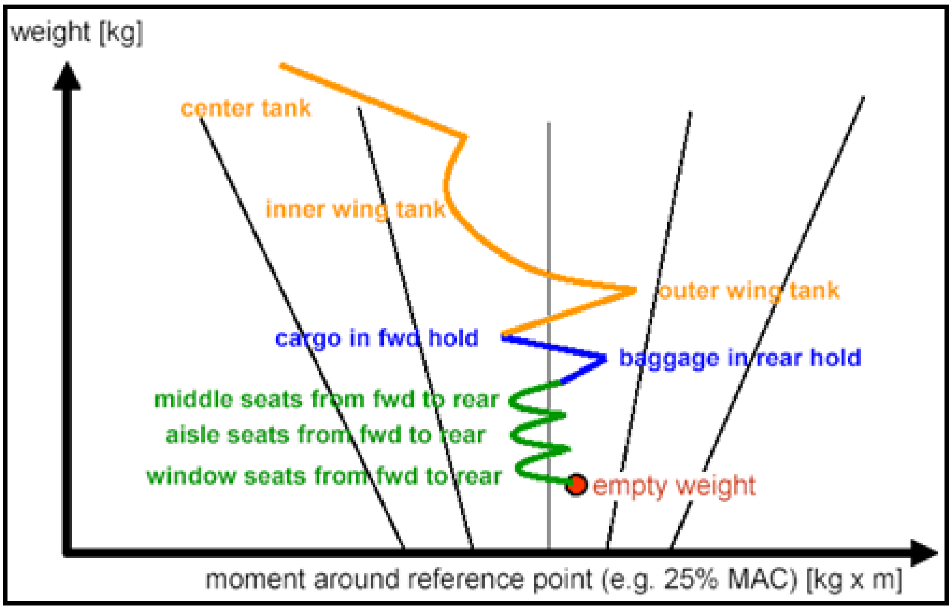


Figure 1.2 Curves composing the load and trim sheet (**Trahmer 2006**)

Potato curves

Figure 1.3 illustrates the model of boarding. The starting point in the diagram is the Operating Empty Mass and the CG at Operating Empty mass. It is assumed that the passengers firstly occupy the window seats (A → C). After the window seats are full, the seats next to the window seats will be occupied (C → D) and after that the seats located next to aisle (D → E). If the backward window seats are occupied first, then the weight and the CG move along the right curve, that is to say for example along the path (A → B2 → C). In case the forward window seat are occupied first, then the left curve will be defined (A → B1 → C) (**Scholz 99**). The curves are called potato curves after their shape.

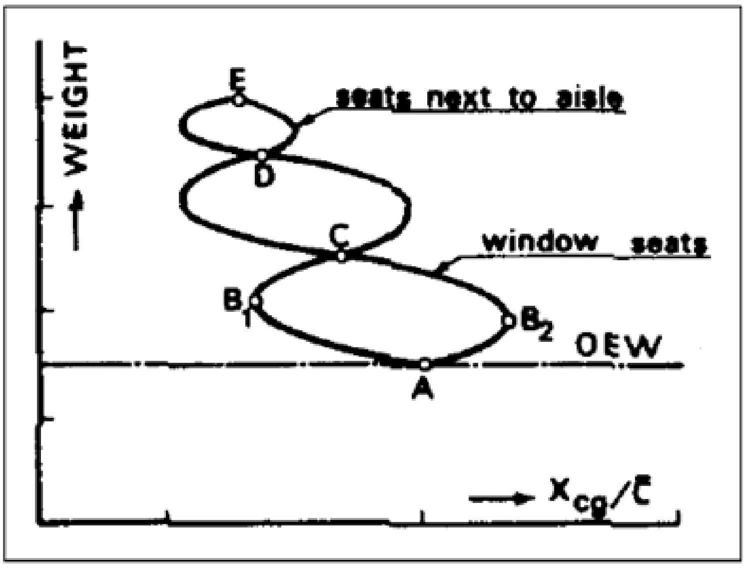


Figure 1.3 Boarding of passengers in the load and trim sheet (**Torenbeek 1988**)

1.3 Objectives

The tool should deliver accurate results with a minimum of input data. The cabin layout and the dimensions of fuel tanks have to match with what can be found on real passenger aircraft. That is why the creation of the tool starts with literature research, which also helps to understand the interrelations between CG margin, horizontal tail-plane sizing and wing positioning. Computing is a big part of this project. The language is Visual Basic for Applications (VBA) which is employed in all *Office* applications. The running time to get the load and trim sheet should be kept as short as possible. It is expected to run in no more than around two or three minutes. The goal is not to be particularly innovative, but rather to create reliable and robust software. Skilful maneuverings should be avoided. The code should deal with common loops and tools used in VBA computation and commented as much as possible to help the understanding of computation. It should be kept understandable and easy to read. Meaningful names have to be chosen and each function has to fulfill only one particular task. Small functions have to be written in order to ensure both logic and efficiency. The different functions would be stored in the same object, in order to keep PreSTo easy to maintain.

Human engineering should not be forgotten and even a non-computer minded person should be able to use the file at the end. For this purpose an easy to use man-machine interface has to be developed. The new *Excel* spreadsheet must look like the other spreadsheets already in the software. Nevertheless it should be possible to run the new functions independently, in order to conduct tests. The interface is in English.

1.4 Structure of the present report

This report is structured in seven chapters and five appendices as follows:

Chapter 2 describes the boarding of passenger process and the cabin layout. This chapter explains how the software works to display the potato curves.

Chapter 3 describes the refueling process and the geometry of the tanks. This chapter explains how the software works to display the curves related to the refueling.

Chapter 4 explains how the curves are finally displayed after the entire calculation is fulfilled.

Chapter 5 describes the CG range obtained and investigates its impact for the design of the tail.

Chapter 6 explains how to install the software and how to launch the calculation.

Chapter 7 compares the tool output with expected results and real values taken from the aircraft A320.

Appendix A Results from the software using the Airbus A320 input data.

Appendix B Load and trim sheet from the Airbus A320 Weight and Balance Manual.

Appendix C Input data for preliminary design of Airbus A320 in Presto.

Appendix D Top view of Airbus A320.

Appendix E This is the CD-ROM containing the Excel tool and the present report as PDF file.

2 Boarding of passengers

2.1 Cabin layout

The passengers are naturally the first thing to think about when it comes to ground handling processes. With freight and fuel they are also a parameter to affect the CG. The cabin layout both has to satisfy technical specifications and abide by the regulations. One of the requirements is feasible ground operations. The aim is to board and disembark in a short time. On airliners the seats are arranged in rows running across the fuselage. Most of the time the seats are forward facing.

Important parameters are seat width and seat pitch. The seat width varies with the class of accommodation. It is linked to the fuselage width and the number of seats abreast. It is defined as the distance from armrest to armrest. The seat pitch varies also with the class of accommodation. It affects the legroom and the thickness of the seatback, which are important parameters of comfort. The seat pitch is the distance between a point on one seat and the same point on the seat in the next row.

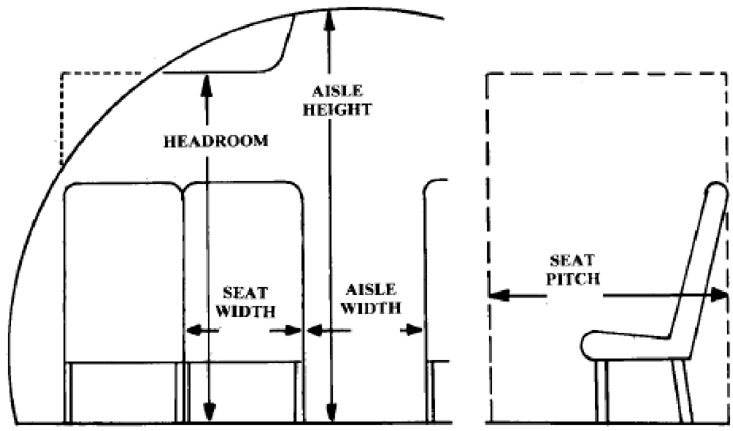


Figure 2.1 Important cabin measurements (**Raymer 1989**)

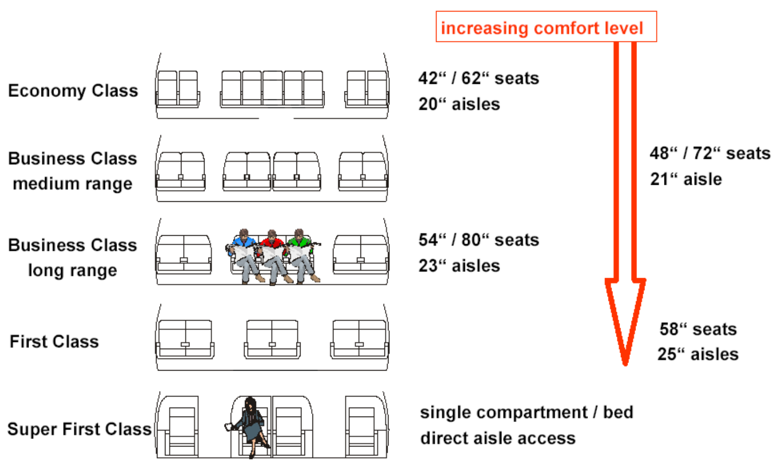


Figure 2.2 Seats and aisles width and comfort level (derived from **Trahmer 2004**)

	First class	Economy	High density/ small aircraft
Seat pitch (in.)	38–40	34–36	30–32
Seat width (in.)	20–28	17–22	16–18
Headroom (in.)	>65	>65	–
Aisle width (in.)	20–28	18–20	≥ 12
Aisle height (in.)	>76	>76	>60
Passengers per cabin staff (international-domestic)	16–20	31–36	≤ 50
Passengers per lavatory (40″ × 40″)	10–20	40–60	40–60
Galley volume per passenger (ft³/pass)	5–8	1–2	0–1

Table 2.1 Typical cabin and seat measurements (**Raymer 1989**)

The number of seats abreast leads to the minimum number of aisles. Aircraft can be described as narrow-body or wide-body. A narrow-body usually deals with a single aisle with seats on either side, with a seats abreast going from 2 to 6. For example on the Beechcraft 1900 there are only individual seats on each side of the aisle. They are usually short and middle range airliners, the most famous being Airbus A320 and Boeing 737. When an aircraft shows more than one aisle it is then described as a wide-body aircraft. At that time not any commercial aircraft has been manufactured with more than two aisles, because it is more efficient to design the aircraft as a double-decker instead. According to JAR 25.817 the number of seats abreast can theoretically run from 3 to 12 with two aisles (**JAR 25 2009**). Practically the smaller number of seats abreast seen in wide-body aircraft is 4 in business class. The Airbus A380 and the Boeing 747 have ten seats abreast in economy class, typically in a 3+4+3 layout. Asymmetrical layouts also exist.

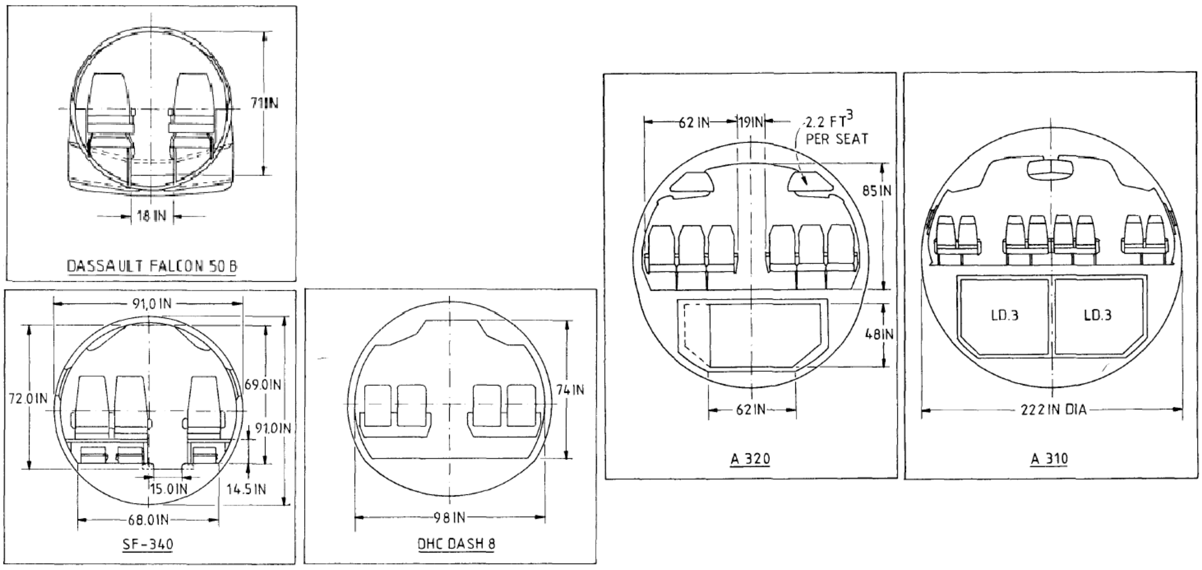


Figure 2.3 Examples of seat layout for different aircraft (**Roskam III**)

A top view of the seat layout is the best way to visualize the inside of a passenger aircraft. A diagram of such seats in an aircraft is called the aircraft seat map. It indicates the basic seating layout, the location of the emergency exits, lavatories and galleys.

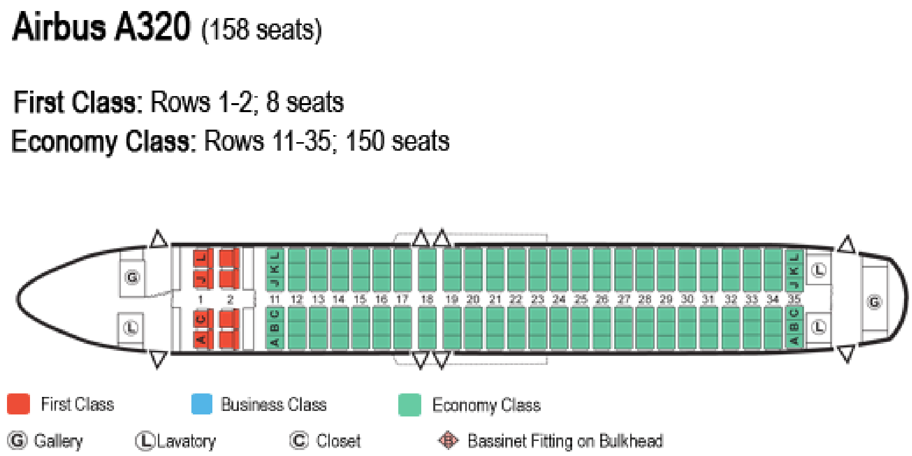


Figure 2.4 Seat map of Airbus A320 (**Air China 2010**)

2.2 Textbook case

The boarding is defined as the entry of passenger onto the aircraft. Boarding starts with entering the aircraft and ends with the seating of each passenger and closure of the doors. The aircraft is described as “in flight” as soon as the doors are closed.

Even if airlines rarely require the passengers to board in a really defined way, there is of course a most efficient way to board. In the textbook case passengers will enter the aircraft and seat first on the seats which are further to the aisles. These seats are window seats and seats in the middle, if they exist. For example the first seats to be occupied for a conventional Airbus A320 will be the window seats at the left and right sides. The cabin floor is assumed to be horizontal during the boarding and disembarking processes.

On many aircraft, the rightmost seats have letter designations H, J and K, skipping the letter I. Another denomination has been chosen in the software. This way the seats always keep the same denomination. Figure 2.6 are different examples of the seat groups according to the layout.

Figure 2.5 Seats and aisles denominations for the loading process

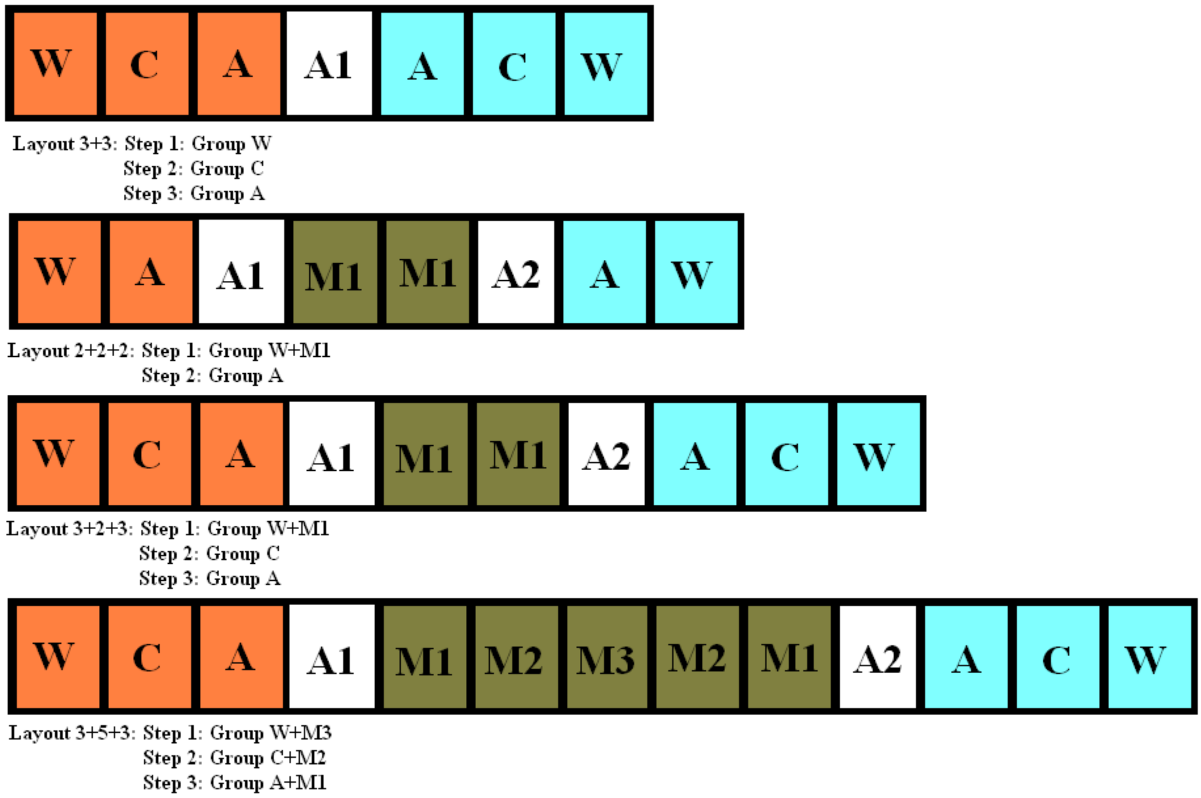


Figure 2.6 Loading process and seat groups for different seat layouts

2.3 Equations

Each new passenger sitting will make the CG travelling. The travel depends on the seat location, the mass of the passenger and the mass of the whole aircraft (equipments, passengers already seated and cargo already loaded).

$$\Delta x_{CG} = x_i . \frac{\Delta m_i}{\sum m_i} \qquad (2.1)$$

Δx_{CG} is the travel of the CG. x_i is the algebraic distance from the position of the added mass Δm_i to the actual position of the CG. m_i is the mass of the component *i*. It may be noticed that when passengers board from front to rear the CG will move forward first. After the row to be occupied reaches a point backward to the actual position of the CG, then the CG begins to move backward. It is the contrary when passengers board from rear to front. It could happen that the CG does not move if one passenger take a seat exactly at the actual position of the CG (case $x_i = 0$).

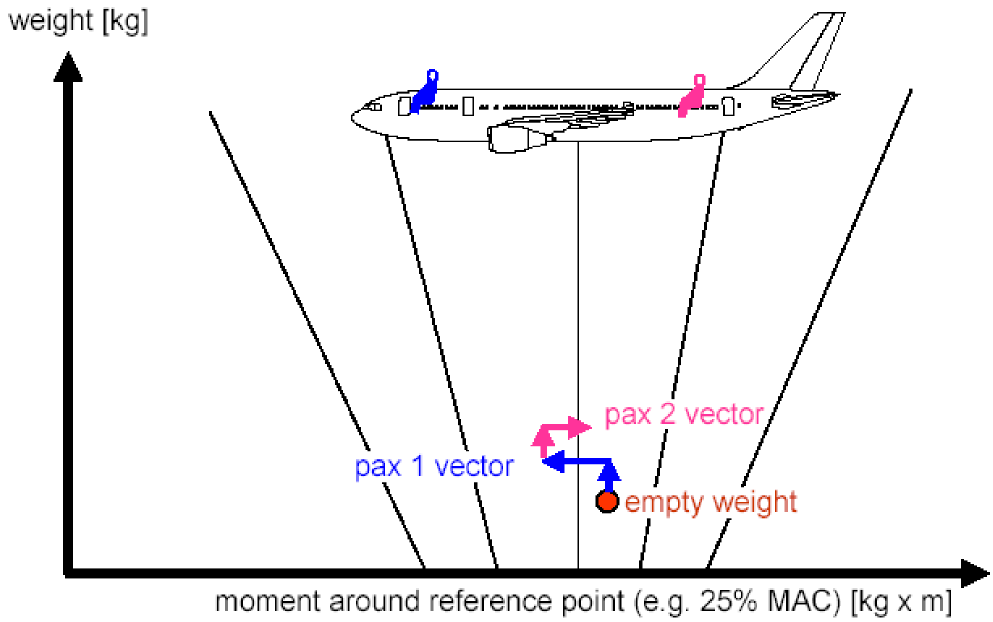


Figure 2.7 Typical Vectors for boarding of passenger at the front of the CG (passenger 1) and boarding of passenger at the back of the CG (passenger 2) (derived from **Trahmer 2006**)

$$x_{LEMAC} = x_{FG} - x_{CG,LEMAC} + \frac{m_{WG}}{m_{FG}}(x_{WG,LEMAC} - x_{CG,LEMAC}) \tag{2.2}$$

Equation (2.2) is to get the distance x_{LEMAC} from the aircraft nose to the leading edge of the MAC. It is useful to define the wing position. Knowing the MAC it is also possible to get the distance from the aircraft nose to the CG of the whole aircraft. $x_{CG,LEMAC}$ is the distance from the leading edge of the MAC to the CG. m_{WG} and m_{FG} are respectively the mass of the wing group and the mass of the fuselage group. $x_{WG,LEMAC}$ is the distance between the leading edge of the MAC and the CG of the wing group. The last parameter is x_{FG}, which is the distance between the aircraft nose and the CG of the fuselage group.

2.4 Inputs

On Excel the spreadsheets can be adapted to a wide range of needs. They can contain buttons, drop-down menus, listboxes or textfields. Concerning the present application such possibilities have been used to help the user. The proper fields can be directly filled. Nevertheless the information will not be verified by the software, so it is the own responsibility of the user to insert correct values.

The aim is to get as much input as possible from the earlier design stages in order to reduce the workload of user and minimize the time needed to analyze a new aircraft design. The cells filled with inputs coming from previous phases are colored in light grey whereas the required inputs should be typed in white cells. The software can not run properly if these inputs are not indicated. The number of passengers, the number of seats and the number of aisles can come directly from the spreadsheet dealing with the cabin design.

1.	Preliminary sizing data		
Number of passengers	n_{PAX}	70	[passenger]
Max. Take-off mass	m_{MTO}	20467	[kg]
Max. landing mass	m_{ML}	19853	[kg]
Max. zero fuel weight	m_{OE}	17725	[kg]
Operating empty mass	m_{OE}	11073	[kg]

Figure 2.8 Inputs from the preliminary sizing

Inputs from the cabin design are really useful to know the cabin layout (Figure 2.9). The rows in the cabin could be located accurately, since the cabin length, the nose length and the seat pitch are given.

2.	Cabin design		
Cabin length	l_{Cabin}	14,750	[m]
Nose length	l_{Nose}	4,00	[m]
Seat abreast	N_{sa}	4	[seat]
Seat pitch	Pitch	0,700	[m]
Aisles	N_{aisles}	1	[aisle]
Rows	N_{rows}	17,5	[row]

Figure 2.9 Inputs from the cabin design

The number of seats abreast is the indicator for the class of accommodation. However the previous input does not state the number of seats on the left and right sides and in the middle. The previous design phases do not give more information to know how the passengers will enter the aircraft. For example 9 seats abreast, which required a twin aisle configuration, can be either 3+3+3 or 2+5+2. Such a difference will of course affect the boarding process. The load and trim sheet directly depends on the possibility for the passengers to access the seats. Another input is then needed to get a better definition of the seat layout (Figure 2.10). The number of seats in each group will have to be entered by the user. This way it would be possible to know exactly which seats will be occupied first, assuming that the passengers board like in the textbook case.

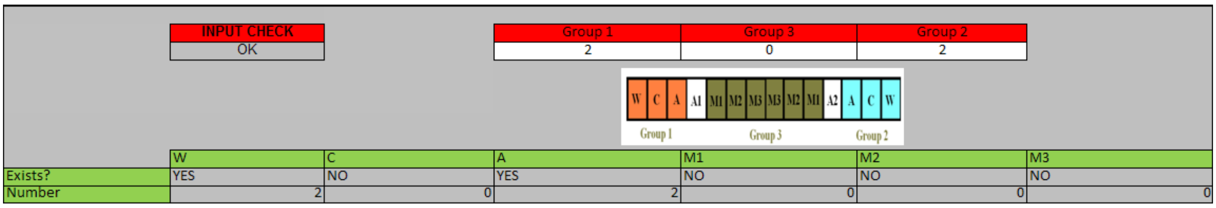


Figure 2.10 Manual inputs to define the seat layout

In order to avoid mistakes a cell indicates if the input matches with the number of seats abreast and the number of aisle previously indicated. Thanks to new inputs it is possible to know the exact number of window seats, cushion seats, aisles seats, as well as the number of middle seats. These numbers are written in a dedicated table: the macro runs automatically each time a white cell has been modified.

The passenger data is strictly reduced to the mass (Figure 2.11), which depends on the flight range. It is perfectly understandable that travelers have heavy luggage when they fly far from home, because they usually stay longer at the destination place. The dedicated input is the answer of the question "Is the flight short and middle range?" and takes either the values "Yes" or "No". Only these two possibilities are available in the listbox. The average mass of a passenger and luggage are defined in Table 2.2. The mass of the aircraft will be increased by 93.0 kg or 97.5 kg for each passenger seating depending on the average range. It is assumed that each luggage is placed at the same longitudinal position than its owner. The value to be considered in the spreadsheet is chosen according to the user's choice.

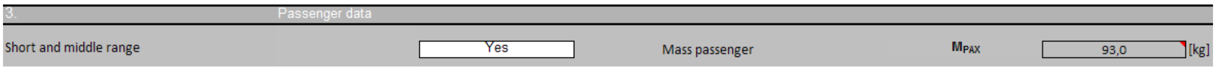


Figure 2.11 Manual input to get the average mass of passenger and luggage

	Short and middle range	Long range
Passenger average mass	79.4 kg	79.4 kg
Luggage average mass	13.6 kg	18.1 kg
Total	93.0 kg	97.5 kg

Table 2.2 Average mass of passenger and luggage (Derived from **Roskam I**)

In order to calculate the CG travel it is first needed to know the CG position at operating empty mass. Unfortunately this position has not been calculated in any previous design phase. It is not the purpose to calculate this position since the present project only cares about the CG travel. Nevertheless originate values are needed and that is the reason why something had to be done anyway.

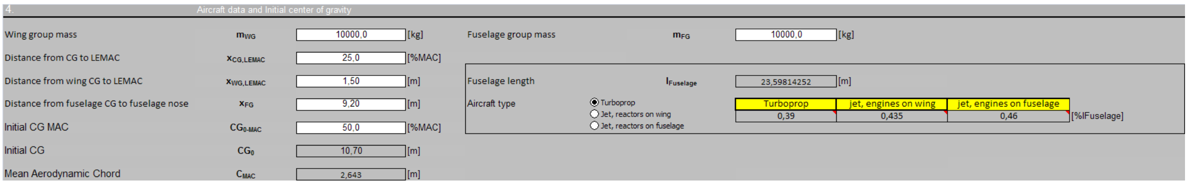


Figure 2.12 Input dedicated to the estimation of CG position at operating empty mass

The location of the CG at Operating Empty Weight will be determined by using equation (2.2). The user would have to indicate the masses of the wing group and fuselage group since they are not given from the previous design phases. The next manual input is $x_{CG\ LEMAC}$ in percentage of MAC. This value is really important because it is actually the abscissa of the point at Operating Empty weight. For a rectangular wing the aerodynamic center is located at 0.25%MAC. Since the aerodynamic center is the point where the pitching moment coefficient is constant it is usually aimed to place the CG at Operating Empty Weight on this location. $x_{WG,LEMAC}$ is also to be indicated manually. x_{FG} can be found tanks to indications given by (**Torenbeek 1988**). The needed information is stored in the spreadsheet. The user simply has to indicate the aircraft configuration. Admittedly the result is not as accurate as it could be, but the correct value should come from another design phase in the future. The development of a new macro calculating the CG position is a time-consuming work.

2.5 Functions and outputs

Then the boarding of passengers can be simulated. It is always the first function to run in order to get the load and trim sheet. The first step of this function is to clean the tables previously created. It does not really make sense to have a number of seats which is not divisible by the number of seats abreast. One of the specifications of this software is to give a correct result with the general cases. Other studies for the particular cases can be done to get more detailed results. Then the software will always assume that the number of passengers is the next upper number divisible by the number of seats abreast.

At the beginning it is assumed that the CG will travel in a range from -50 to +150%MAC. The abscissa values are the first to be written in the table, with a step of 0.25%MAC between two values. It means that for each passenger seating (or each group of passenger, depending on the cabin layout) a precision of 0.25%MAC can be achieved.

Further on the MTOW, MLW, MZFW and OEW are entered in the table. These curves can be easily displayed since they are horizontal curves in the loading diagram. These values are fixed values for a defined aircraft design and there is no need of any calculation to get the curves.

The cabin layout is defined as follows. Each row of seats is considered after the other. The last row is considered to be at the most backward position in the cabin, with an offset of 0.1 m in order to allow the backseat to recline. The CG of each passenger is supposed to be 0.1 m from the most rear point of the seat. The seat pitch is added to the previous position in order to get the position of the next forward row. It may be noticed that the emergency exists, toilets and galleys are not taken into account.

The curves for the passengers to enter the aircraft and seat at the first available seat beginning from the front and beginning from the back are interesting curves to plot. Indeed they can be compared to the load and trim sheet with passengers sitting as described in the textbook case. They are the most critical curves, and then the case described by these curves is to be avoided as much as possible by the airlines. The boarding process is divided in groups of seats. There are as many curves to display as groups of seats. The seats will be occupied from the nose to the rear of the aircraft, or from the rear to the nose. This will give two different curves, which draw one so-called potato. Once all seats belonging to the first group are occupied, then passengers board to seat on the seats belonging to the second group. These steps continue until there is not any seat available in the cabin. The module `Load_passengers` deals with this algorithm. The number of window seats, aisle seats and cushion seats, as well as the number of seats in the middle are caught from the spreadsheet. For each group of seat there are one curve for loading of passengers from front to rear and one curve for loading of passengers from rear to front to be drawn.

The different points correspond to the actual position of the CG in abscissa and the mass of the aircraft in ordinate. Each row is considered after the other and the number of points to display is equal to the number of seat groups multiplied by the number of rows. For example, 3 x 27 rows = 81 points for a single class conventional Airbus A320. Since there are two curves (loading from rear to front and loading from front to rear), it makes 162 points altogether. The ways to get the different points of these curves are similar, only the order of rows to consider will be different. This difference is taken into account thanks to the functions `Load_passengers_front_to_rear` and `Load_passengers_rear_to_front`.

Each new seat to be occupied will lead to a small travel of the CG. This travel is determined through equation (2.1). At the beginning of the loading process the mass is the operating empty mass. The mass of the aircraft will be increased for each new passenger sitting. This gives the absolute position of the CG measured from the aircraft nose. Knowing the MAC and the position of the CG at the operating empty mass it is then possible to get the relative position of the CG in percent of the MAC. The calculated values are stored in arrays.

The next step is to transfer these values into the Excel spreadsheet in order to plot the curves at the end. The table runs from -50% to +150% of the MAC. Since the tool is developed to evaluate new designs, it may happen that the values are outside these boundaries. In such a case the boundaries will be automatically extended to the smaller and higher values needed.

At the end of the functions the titles of the columns are written in accordance with the group of seat considered. These titles are important because they will be further used to write the legend of the load and trim sheet. Moreover the user may directly refer to the table in order to get a better idea of the plotted points. The points of each potato curve are stored in four different columns:

- Seats rear to front rear
- Seats rear to front front
- Seat front to rear front
- Seat front to rear rear

Where 'Seats' can be the following string, depending on the number of seats abreast and the seat layout:

- W
- A
- C
- M1
- M2
- M3
- W and M1
- W and M2
- W and M3
- A and M1
- A and M2
- C and M2
- C and M1

These names may change after the entire calculation is fulfilled, as explained in Chapter 4. The actual position of the CG and the mass of the aircraft are stored for the next group of seats to be considered or as origin for the coming refueling process analysis if the entire boarding process has been fulfilled.

Even the potato curves obtained at the end are really closed to what can be obtained for a realistic aircraft, there are still limitations to use a general tool like the present one. Indeed only one seat pitch is given, which means that the cabin layout will always be considered with a single level of comfort. When using the tool it is to keep in mind that it is limited to single deck aircraft. This is also the case in the previous design phases. The last difference between the software and realistic aircraft is the number of seats abreast which differs in the tail, compared to the rest of the cabin. Also it may happen that there is no seat in some location because space is occupied by toilets, galleys or aisles for emergency exits.

3 Refueling

Figure 3.1 Refueling at Helsinki Vantaa international Airport

3.1 Fuel tanks

The wing design of common passenger aircrafts is made of spars and ribs. The stringers support the wing panels and give the shape of the airfoil. The load carrying material is distributed over the whole structural chord in conjunction with two or more spar webs. The fuel tanks are usually located in the wing box, which lies between the front and rear spars (**Berry 2008**).

Most aircraft fuel systems consist of several tanks due to space, slosh, CG management and safety reasons. The general layout consists of one or more boost pumps that feed the engines from a collector tank, usually a fuselage tank placed close to the CG. The fuel can be transferred from one tank to another by gravity or using pumps, depending on the fuel system architecture (**Gavel 2004**). There are three main types of fuel tanks; discrete, bladder and integral tanks (**Raymer 1989**). Integral tanks are very widespread in modern passenger aircraft.

Due to the complexity of modern aircraft, the location of the different tanks results of a compromise. They are placed to allow a reasonable CG Management. The shape of the tank should ensure that the fuel can be pumped out of the tank with a minimum of residual fuel.

Most of the case the previous requirements lead to place the tanks in the center wing box and in the wing box. The size of the tanks of large aircraft does not allow refueling by gravity. Pressure refueling through sealed connectors is used. The desire to keep turnaround times short gives requirements of high refueling flow rates (**Gavel 2004**).

The relation between the CG and the aerodynamic center is vital to the aircraft stability control. Tanks are usually used during flight to manage the CG by pumping fuel aft or forward. Some aircraft, such as Airbus A380, are fitted with a tank in the horizontal tail box (**Gavel 2004**).

Looking at diagrams from Aircraft recovery manuals, aircraft are equipped with different tanks. The center wing box may be filled with fuel, and the tank called center tank. Usually the major part of the fuel is stored in the wing. The tanks which are closer to the fuselage are referred to inner tanks, while the tanks next to the tip are referred to outer tanks. If there is no separation between the tanks, then the big tank is simply named wing tank. There can also be surge tanks and vent tanks in the wing.

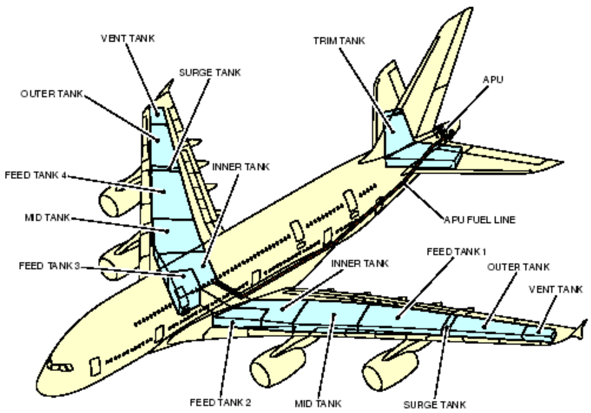


Figure 3.2 Fuel tanks of Airbus A380 (**Airbus 2010**)

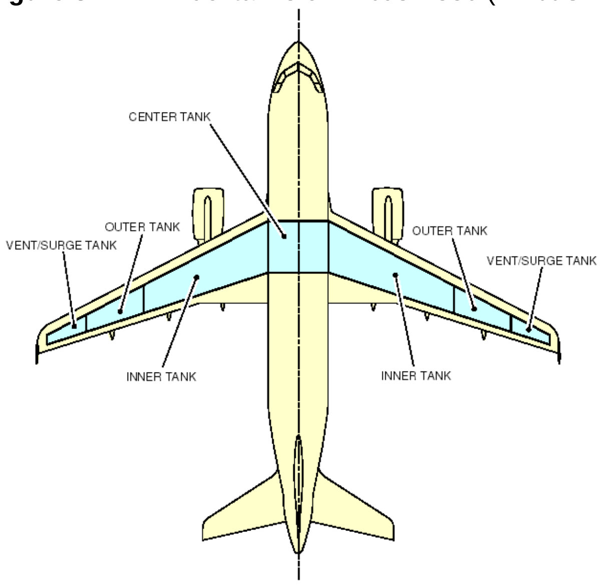
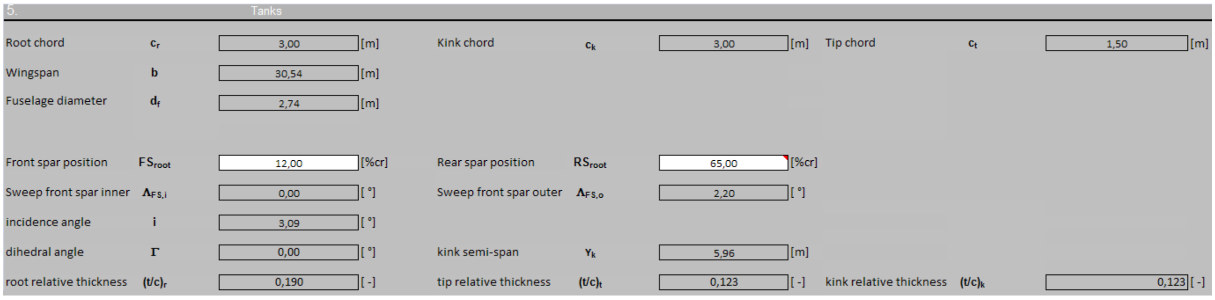


Figure 3.3 Fuel tanks of airbus A319 (**Airbus 2010**)

3.2 Inputs

The inputs to draw the curves concerning the refueling give all the needed information to determine the geometry of the tank. Actually the only manual input concerns the positions of the front and rear spars. The other inputs come all from the wing design.



5.		Tanks									
Root chord	c_r	3,00	[m]	Kink chord	c_k	3,00	[m]	Tip chord	c_t	1,50	[m]
Wingspan	b	30,54	[m]								
Fuselage diameter	d_f	2,74	[m]								
Front spar position	FS_{root}	12,00	[%cr]	Rear spar position	RS_{root}	65,00	[%cr]				
Sweep front spar inner	$\Lambda_{FS,i}$	0,00	[°]	Sweep front spar outer	$\Lambda_{FS,o}$	2,20	[°]				
incidence angle	i	3,09	[°]								
dihedral angle	Γ	0,00	[°]	kink semi-span	Y_k	5,96	[m]				
root relative thickness	$(t/c)_r$	0,190	[-]	tip relative thickness	$(t/c)_t$	0,123	[-]	kink relative thickness	$(t/c)_k$	0,123	[-]

Figure 3.4 Inputs used for the fuel tank definition

3.3 Definition of tanks in the Excel tool

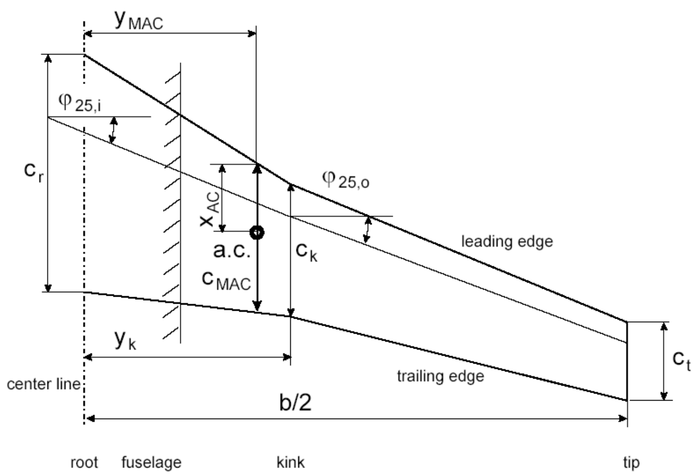


Figure 3.5 Geometry of a double trapezoidal wing (**Scholz 1999**)

All wing tanks for aircraft with trapezoidal wings and double trapezoidal wings (Figure 3.5) can be defined properly. The tanks are seen as a volume between 6 different plane areas. The eight corners of these volumes are the points A, B, C, D, E, F, G and H. The positions of the points are defined in the coordinate system of the tank. The point A is always the origin of the previous coordinate system. The position of each point is defined as follows:

For the right wing tank:

	Position along x-axis	Position along y-axis	Position along z-axis
A	0	0	0
B	Distance between front spar and rear spar at wing root	0	0
C	Distance between front spar and rear spar at wing root	-Thickness at wing root x sin(-dihedral)	Thickness at wing root x cos(dihedral)
D	0	-Thickness at wing root x sin(-dihedral)	Thickness at wing root x cos(dihedral)
E	0.5 x (wingspan - fuselage diameter) x sin(sweep front spar)	0.5 x (wingspan - fuselage diameter)	0
F	0.5 x (wingspan - fuselage diameter) x sin(sweep front spar) + distance between front spar and rear spar at wing tip	0.5 x (wingspan - fuselage diameter)	0
G	0.5 x (wingspan - fuselage diameter) x sin(sweep front spar) + distance between front spar and rear spar at wing tip	0.5 x (wingspan - fuselage diameter)	Thickness at wing tip x cos(dihedral)
H	0.5 x (wingspan - fuselage diameter) x sin(sweep front spar)	0.5 x (wingspan - fuselage diameter)	Thickness at wing tip x cos(dihedral)

Table 3.3 Definition of the corner positions for the right wing tank

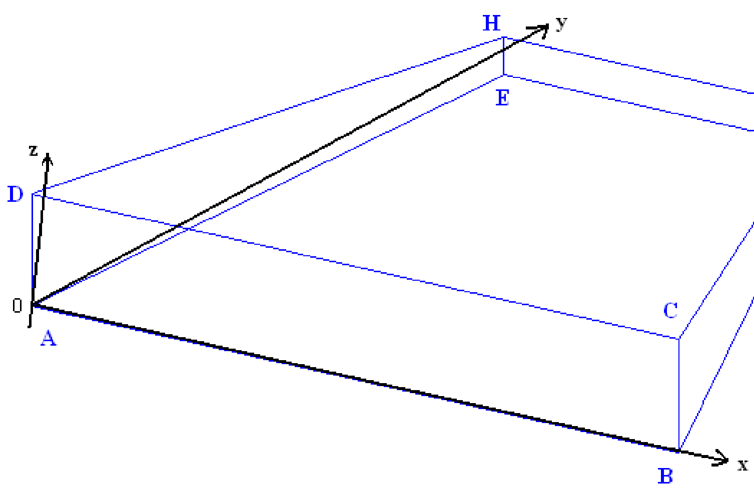


Figure 3.6 Definition of the right wing tank

For the center tank:

	Position along x-axis	Position along y-axis	Position along z-axis
A	0	0	0
B	Distance between front spar and rear spar at wing root	0	0
C	Distance between front spar and rear spar at wing root	Thickness at wing root x sin(-dihedral)	Thickness at wing root x cos(dihedral)
D	0	Thickness at wing root x sin(-dihedral)	Thickness at wing root x cos(dihedral)
E	0	Fuselage diameter	0
F	Distance between front spar and rear spar at wing root	Fuselage diameter	0
G	Distance between front spar and rear spar at wing root	Fuselage diameter - Thickness at wing root x sin(dihedral)	Thickness at wing root x cos(dihedral)
H	0	Fuselage diameter - Thickness at wing root x sin(dihedral)	Thickness at wing root x cos(dihedral)

Table 3.4 Definition of the corner positions for the center tank

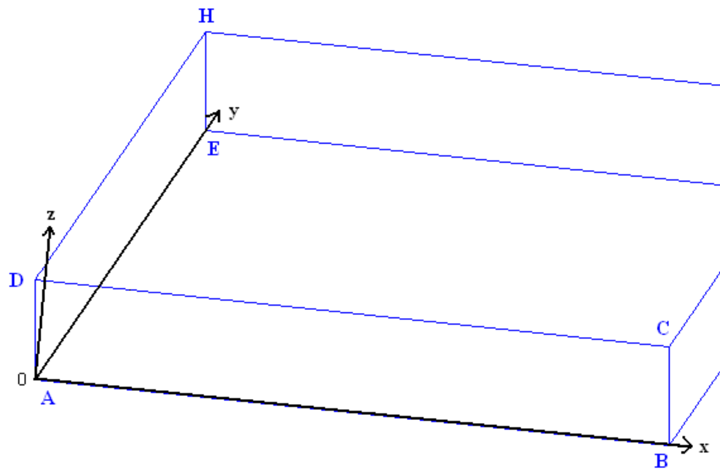


Figure 3.7 Definition of the center tank

To simplify the running of the software and make it useful to evaluate the general design of an aircraft it has been chosen to consider only two different types of tanks. The wing tank is located in the wing between the front spar and rear spar. It is assumed that this tank goes from the wing root to the wing tip. Its upper and lower surfaces are the skin of the wing. Since the calculation time is already important it has been chosen to not consider the kink. This would have lead to three different types of tanks instead of two and actually the front and rear spars are not affected by the kink on many wing designs (it is the case on Airbus A320 and Airbus A340 for example). Indeed, the kink is usually designed as a storage area for the retracted landing gear. The thickness is considered to decrease linearly from the root to the tip. Then the upper and lower sides of the wing tanks are two plane areas. The center tank also lies between the front and rear spars along the longitudinal axis, the two wing root ribs along the transversal axis and the upper and lower skins of the wing along the vertical axis. The center tank is then defined exactly as the center wing box. The top view of the wing and the tanks can be seen the *Excel* sheet (figure 3.8). The view is directly updated when input is changed (there is no function to run).

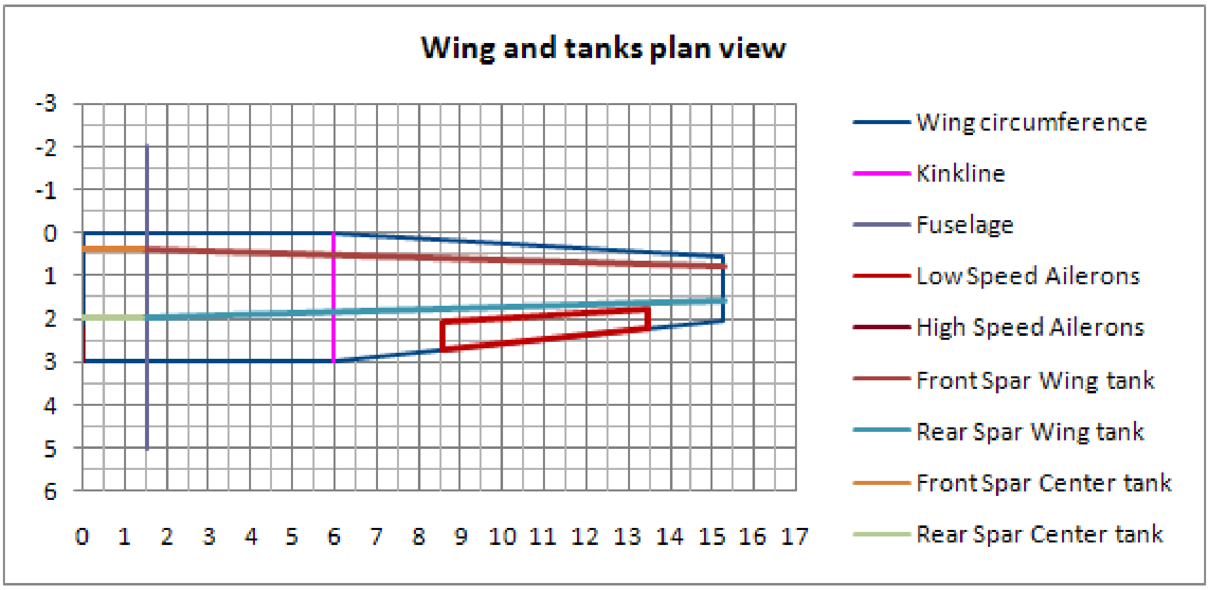


Figure 3.8 Wing and tanks plan view

The attachment of the Wing to the fuselage shows two angles: the dihedral angle (Figure 0.4) and the incidence angle (Figure 0.5). These angles have to be considered because the top surfaces of the fuel inside the tanks depend on their values.

During the refueling the aircraft is steady and the only forces acting on the fuel in the tanks are the weight and the force of the tank acting on the liquid particles. Then the fuel top surface will be orthogonal to the gravity vector. As a liquid, the fuel will naturally take the shape of the tank.

Unfortunately there is no data available concerning the ribs from the earlier design phases. These parts naturally occupy a certain volume inside the wing, which should be considered in order to get a better result. This problem is partly solved in the volume calculation because some elementary cubes will not be considered as long as one of its corners is outside the defined tank.

3.4 Equations

The CG travel is determined through equation (2.1) previously used in Chapter 2.

$$\Delta x_{CG} = x_i.\frac{\Delta m_i}{\sum m_i} \tag{2.1}$$

The basic idea to get the CG in a tank is to mesh the tank after the height points A,B,C,D,E,F,G and H have been properly defined. Each elementary volume is a small cube, which can belong to the fuel tank or not. It has a defined size along the three different axes. The position of the small cubes will be compared to the eight sides of the tank. It would be possible to sum up the volumes belonging to the tank in order to get the whole volume of fuel loaded as a result. The CG of the tank is calculated after knowing the position of the Centers of Gravity of all elementary volumes through equation (2.2).

$$x_{CG} = \frac{\sum m_i.x_i}{\sum m_i} \tag{2.2}$$

The fuel is a homogeneous liquid. It is then possible to calculate the mass of fuel as long as the volume and the density are known. The most commonly used fuel for commercial aviation is Jet A-1 which is produced to a standardized international specification. The density of this commercial aviation fuel is ρ_f = 0,785 kilogram per liter. With V_f the volume of fuel in cubic meter the mass of fuel is then determined using the following Equation.

$$m_f = \rho_f.V_f = 0{,}775.V_f \tag{2.3}$$

Due to the dihedral angle and incidence angle and because usually the lower side of the tanks is not orthogonal to the gravity vector, it is required to use matrix calculation to move from the aircraft coordinate system into the coordinate system of the tank. The vector $(u, v, w)$is expressed in the aircraft coordinate system and the vector (u_t, v_t, w_t) is expressed in the tank coordinate system.

$$[u_t \quad v_t \quad w_t] = [u \quad v \quad w]\begin{bmatrix} \cos i_w & 0 & \sin i_w \\ 0 & 1 & 0 \\ -\sin i_w & 0 & \cos i_w \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \nu & -\sin \nu \\ 0 & \sin \nu & \cos \nu \end{bmatrix} \tag{2.4}$$

3.5 Functions

In order to plot the curves it is needed to get the CG position for different volumes of fuel transferred in the tank. The first tanks to be filled are the wing tanks. Thus the first function to run is `Load_fuel_wing_tanks`. The second function is called `Load_fuel_center_tank` and runs the calculation for refueling the center tank. Apart from the definition of the tanks geometry, the two functions have a common way to run. The main difference is actually that the values obtained at the end of the function `Load_fuel_wing_tanks` are stored because they will be used as origin values for the function `Load_fuel_center_tank`.

The equation of a plane is $au + bv + cw + d = 0$. Thus a system of three equations and four unknowns has to be solved. The parameters to solve the system are the position of three points defining the surface along the x-axis, y-axis and z-axis. When the positions of three points A,B and C belonging to the plane are known, then the solution *(a,b,c,d)* is given by:

$a = (vAb \times wAc) - (wAb \times vAc)$
$b = -(uAb \times wAc) + (wAb \times uAc))$
$c = (uAb \times vAc) - (vAb \times uAc)$
$d = -Ua \times a - Va \times b - Wa \times d$

with: $uAb = Ub - Ua$
$vAb = Vb - Va$
$wAb = Wb - Wa$
$uAc = Uc - Ua$
$vAc = Vc - Va$
$wAc = Wc - Wa$

The equations of the eight planes ABC, ADH, CDH, BCG, ABF and EFG are of major importance because they are useful to test if a point is located inside or outside the tank. Indeed each tank is defined as the volume which fulfills all the following criteria (forward and backward, right and left and under and above are taken in the tank coordinate system):

- The volume is backward to the plane ADH
- The volume is forward the plane BCG
- The volume is right to the plane ABC
- The volume is left the plane EFG
- The volume is under the plane CDH
- The volume is above the plane ABF

The gravity vector has to be written in the coordinate system of the tank because it allows much simpler calculation. At the end the CG position for each tank would be written back into the aircraft coordinate system by multiplying the position vector by rotation matrices.

In order to allow the user to have a better idea about how the tanks look like, it is possible to plot the tanks in three dimensions. Dedicated freeware software called *Gnuplot* is used for this purpose. *Gnuplot* is a portable command-line driven program that can generate two- and two-and three-dimensional plots. The source code is copyrighted but freely distributed. It can be easily downloaded from the official website www.gnuplot.info. Plotting the tanks has been really useful during the development of the software to check their geometries. Two text files are created automatically when the functions `Load_fuel_wing_tanks` and `Load_fuel_center_tank` run. The text files are named tankW.txt and tankC.txt and are respectively used to plot the right wing tank and the center tank. Please be sure to write the path of the folder where the text files should be stored as initial value for the variable `path` in the function `create_text_file`. The text file is formatted to be used with *Gnuplot*: the positions of the eight points A, B, C, D, E, F, G and H are written in columns. The columns 1, 2 and 3 respectively contain the positions along the x-axis, y-axis and z-axis. The date of creation of the file is also indicated.

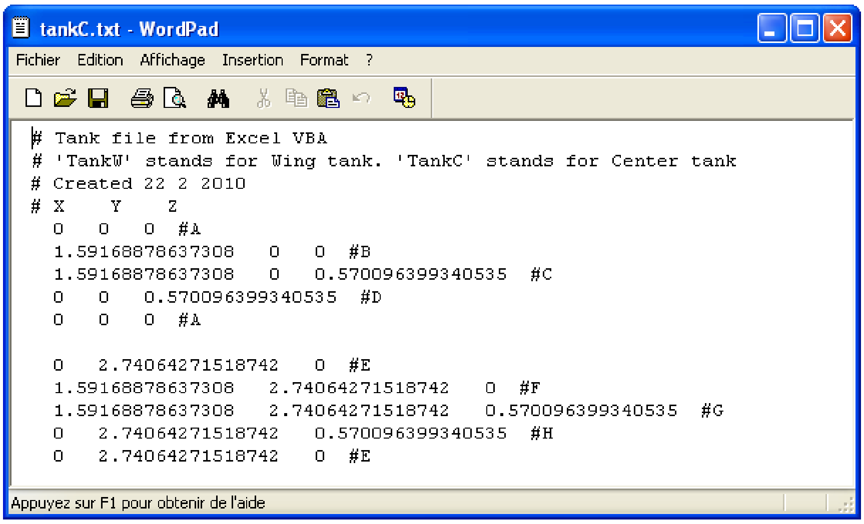


Figure 3.9 Text file created automatically by the software

It is to notice that *Gnuplot* should always be launched from the same folder where the text file to plot is stored, otherwise the files can not be found. The plotting can be launched through command lines, to be written by the user in the *Gnuplot* command window. The command `set parametric` is required to use a parametric plot. The command `splot` takes the name of the file as parameter. The view can be changed with the command `set view angle1, angle2` will change the orientation of the plot. More functions are available in *Gnuplot*. They can of course be used to improve the display, but are not of major importance for the present project. More information about using *Gnuplot* can be found in the *Gnuplot* manual.

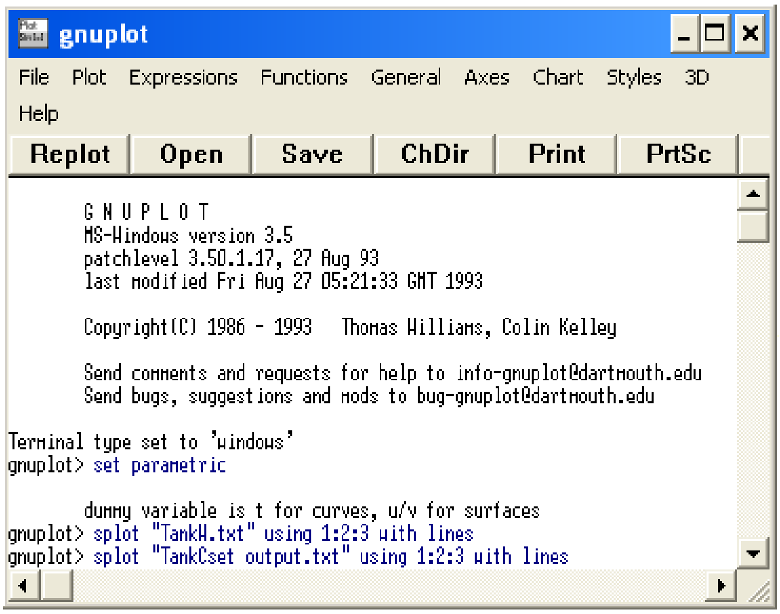


Figure 3.10 Command lines to plot the right wing tank and the center tank in *Gnuplot*

Then comes the simulation of the refueling proper. The volume will first be meshed, that is to say divided in many small elementary cubes. Mathematically a volume is made of an infinite number of points. That is the reason why engineers use meshes, which allows to reduce the amount of data and to get accurate results in relatively short running time. A meshed volume will be defined with a finite number of points. The data concerning each elementary cube, such as the positions along the different axes, is stored in arrays. In order to limit the running time it is aimed to mesh with cubes having a proper size. The size should not be either too small, because the running time would then be too long, or too big, because the result has to be accurate at the end. To do so the bigger distances between two points of the tank on the three axes are needed. They are determined by easy comparison since the sides of the tank are plane areas. It has been chosen to mesh the tanks with 20 elements along the x-axis, 100 elements along the y-axis and 20 elements along the z-axis, which gives 40000 elementary cubes altogether. This number always stays the same and does not depend on the wingspan, thickness or chord. This way the size of the aircraft does not affect the size of the arrays.

Next is to determine if each elementary cube among the 40000 is actually inside or outside the volume occupied by the fuel transferred in the tank. That is the point where the equations of the different sides of the tank are useful. Moreover it is required to get the equation of the top surfaces of the fuel. The refueling process for each tank will be considered at 20 different moments, which show 20 different top surfaces. It is to determine the lower top surface, which corresponds to the first point to be plotted in the load and trim sheet and the upper top surface. All the other top surfaces are obtained by adding 1/20 of the total distance between the lower and the higher top surfaces. Like previously said the fuel top surfaces are all orthogonal to the gravity vector. The equations of top surfaces have the same form like the equations of any other surface: $ux+ vy + wz + d = 0$. If the coordinate system is orthonormal, then a plane having as equation $ux + vy + wz + d = 0$ is orthogonal to the vector (u,v,w). It means that the surfaces having as equation *(Gravityx x x + Gravityy x y + Gravityz x z) + d = 0*, with *Gravityi* being the component of the gravity vector along the *i*-axis (*i* can be *x*, *y* or *z*), are all orthogonal to the gravitation vector. As a result, such surfaces are all fuel top surfaces during the refueling process and getting all of these surfaces is simply done through changing the value of the parameter d. d is minimal or maximal for the minimal or maximal values of *x*, *y* and *z*, according to the sign of the gravity vector coordinates. The minimal value of *x*, *y* and *z* has to be used if the gravity vector is directed backwards, to the right direction or downward. The maximal value of *x*, *y* and *z* has to be used if the gravity vector is directed forward, to the left direction or upward.

When all the 20 different top surfaces are defined it is possible to evaluate the volume of fuel loaded and CG position for each of the 20 moments. Three for loops are used in order to consider all the 40000 elementary cubes. Each loop runs along one axis. An elementary cube is considered not to belong to the volume of fuel loaded if at least one of the following requirements is fulfilled (forward and backward, right and left and under and above are taken in the tank coordinate system):

- The cube is upper to the top surface of the fuel (the ordinate of the elementary cube is upper than the ordinate of the fuel surface)
- The cube is at the left of the face ABCD (the depth of the elementary cube is lower than the depth of the point on the face which has the same abscissa and ordinate)
- The cube is higher than the face CDHG (the ordinate of the cube is higher than the ordinate of the point on the face which has the same abscissa and depth)
- The cube is forward to the face BCGF (the abscissa of the point is higher than the abscissa of the point on the face which has the same ordinate and depth)
- The cube is lower than the bottom face ABFE (the ordinate of the cube is lower than the ordinate of the point on the face which has the same abscissa and depth)
- The cube is at the right of the face EFGH (the depth of the point is higher than the depth of the point on the face which has the same abscissa and ordinate).

If the test leads to the conclusion that the elementary cube has to be considered as a fuel cell, then the volume of the elementary cube can be added to the volume previously calculated and its position is added to the arrays, which will allow the coming calculation of the CG position. At the end the position of all the elementary cubes containing fuel are stored in the arrays. The actual CG is then determined through Equation (2.2). Since the fuel is a homogeneous liquid, then the CG can be calculated as the mean position of the elementary cubes. This is done by the function `determine_centroid`, which takes the arrays and the number of elementary cubes as parameters. The weight is easily determined after the density and the volume are known. The previous steps have to be achieved with all the 20 considered fuel surfaces.

Concerning the wing tanks only the right wing tank is considered for the calculation. Since the aircraft is assumed to be parked on horizontal ground and the aircraft presents plane symmetry along the longitudinal axis, then the CG for the left and right wing tank lies on this plane. The position along the longitudinal axis is the same if we consider only the right tank or the left and right tanks. The weight for the both tanks is simply twice the weight of the right tank. There is no such consideration to lead for the center tank since the whole center tank is considered in the function `Load_fuel_center_tank`.

Knowing the Centre of Gravity position and the mass for the different volumes of fuel loaded, it is now possible to get the 20 points to be displayed in the load and trim sheet. The CG must now be written back in the aircraft coordinate system. At this step the different volumes of fuel added between two moments of the refueling process are simply a certain mass added at a certain point.

The different CG positions relatively to the MAC are calculated exactly in the same way like the boarding of passengers. The values are entered in the *Excel* spreadsheet and once again the lower and higher values of the position relatively to the MAC may be automatically extended if needed.

On the contrary to the loading of passengers which shows different groups of seats depending on the seat layout, the columns concerning the fuel tanks are always denominated with the same titles. Indeed it is assumed that the aircraft in PreSTo is always fitted with two wing tanks and one center tank.

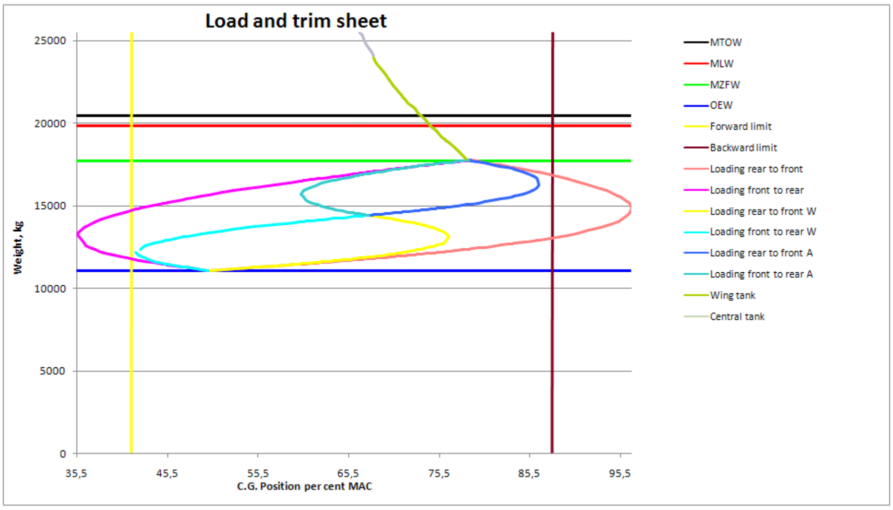


Figure 3.11 Refueling curve taking the last point of passenger boarding as origin

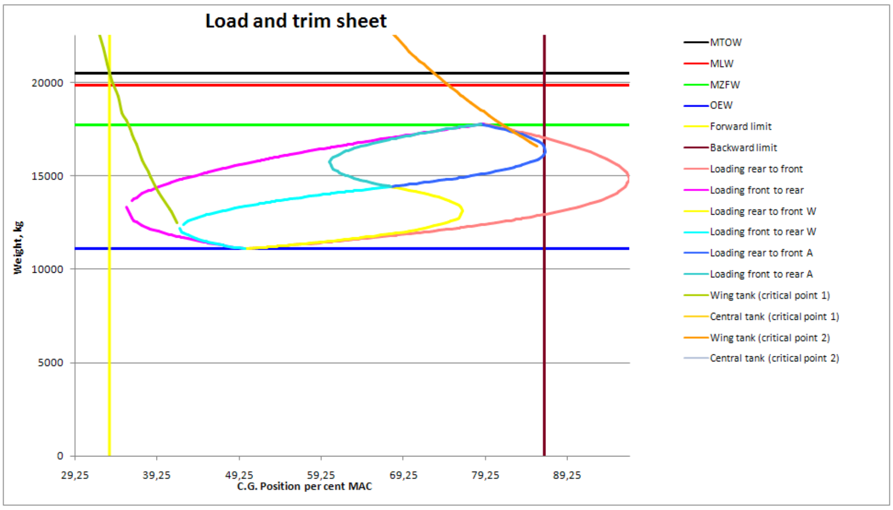


Figure 3.12 Refueling curves taking the two critical points as origins

There are four curves concerning the refueling process to display, two curves for each type of tanks. Indeed at the end of the boarding process there are two critical points to consider. Looking at the figures above it is possible to remark that the CG limits were 42%MAC and 86.5% MAC in the first case. The forward limit has moved to 33.75%MAC in the second case. The inputs did not change from one case to another. The two critical points can be found in the spreadsheet. The function `Limits_before_fuel` runs along the table to get them.

4 Display of the load and trim sheet

There are still functions to run in order to make the load and trim sheet good looking once all the points to display are stored in the *Excel* spreadsheet.

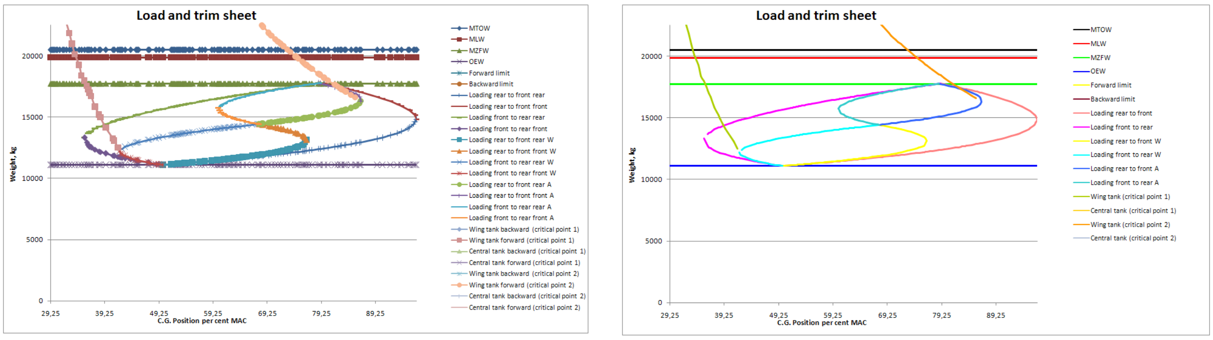


Figure 4.1 Improvement of the display through the function `Display`

As previously written the table contains values which run at least from -50%MAC to +150%MAC. At the end of the calculation there are many empty rows in the tables because it is truly possible that the CG travels only in a much smaller range (usually it actually travels between +20% and +60% MAC). Then the first step of this new function is to delete the rows which do not contain any information after column E.

The function `Display` also writes new values in the table to avoid empty cells. Indeed *Excel* can not display a curve if a column is filled with empty cells between two points to display. Excel would not bind the points. For example, in the present case, only 20 points would be plotted for the wing tanks instead of a beautiful curve. One may think to simply delete the rows instead of writing new values to avoid discontinuous curves, but ordinate values of points may be written in some columns. Thus it has been chosen to fill the empty rows using linearization. It is possible to use a simple linearization (Figure 4.2) because there are enough points perfectly known from the previous calculation. Then the difference is not so big between a curve with some straight lines between well defined point and a perfect round curve. Plotting a second degree curve could have been possible, but it unfortunately costs too much running time for a not much better result.

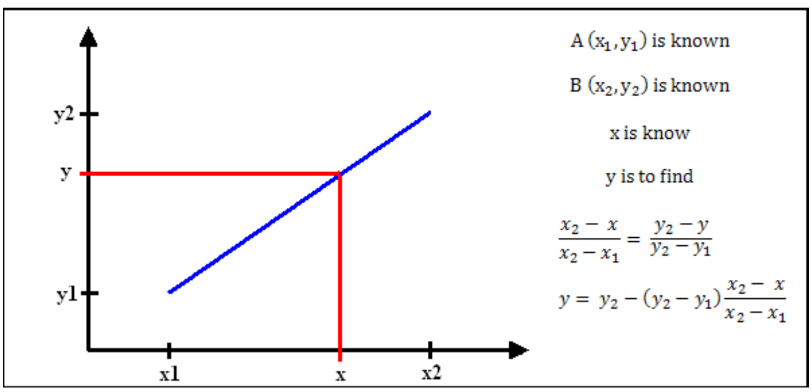


Figure 4.2 Basic Equation used to get the ordinates to fill empty cells.

The axis limits may vary from one study to another because the inputs from the earlier design phases are prior to change. Thus they can not be fixed values and have to adapt to each new study. The function `Display` aims to get the two CG margins and adapts the graph to these margins. The limits for the ordinate will always be 0 kg for the smaller axis limit and MTOW + 5000 kg for the higher axis limit.

Since each left and right curves of the potato curves are actually made of two different curves, then changing the colors of the curves is a good way to make the load and trim sheet less messy. This is particularly true for studies dealing with aircraft having bigger number of seats abreast. Indeed *Excel* automatically plot curves with a different color.

The legend has also to be modified because there are two entries for each left and right sides of each potato curve. Then one entry has to be deleted. The name of the remaining entry would also be changed to match with the entire left or right curve: there is no aim to describe only one part of the curve anymore.

5 Impact on the empennage

5.1 CG margins

The location of the CG is really important for the flight capability. The forward CG limit is responsible for the aircraft maneuverability and the backward CG limit is responsible for the aircraft stability.

The CG has to stay within the envelope plotted on the load and trim sheet. The aircraft can not be operated if the actual CG is outside this envelope.

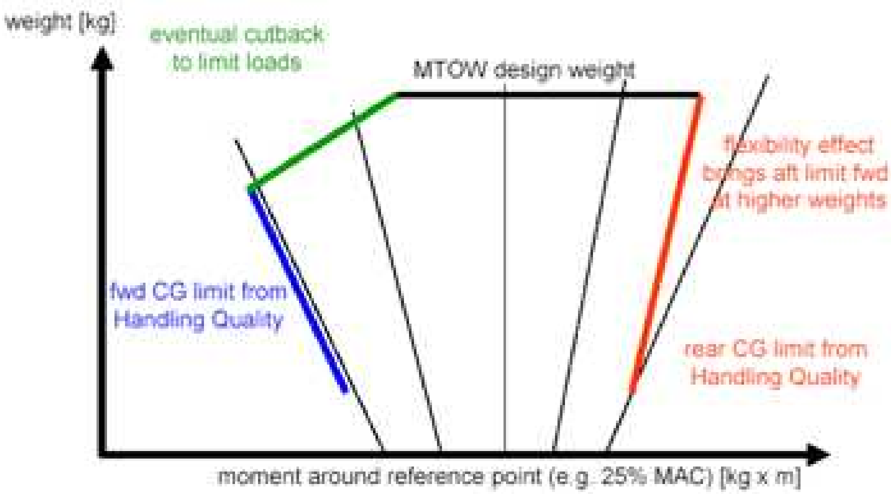


Figure 5.1 CG envelope (**Trahmer 2006**)

This envelope defines the forward and backward CG limits respectively from the maneuverability and stability requirements. The higher possible mass is the maximum take off mass, which is the weight at which the pilot of the aircraft is allowed to attempt to take off (**Goderis 2008**). This mass determines the top of the envelope. The tool aims to display this envelope, but is not able to consider cutbacks or flexibility effects at higher weights.

5.2 Function to get the CG margins

The last function run by the software is the function `Limits`. The purpose of this function is to find the forward and backward CG limits and to plot the two vertical curves corresponding to these limits.

The function basically runs along the table contained in the *Excel* spreadsheet in order to find the abscissas of the most right and most left points. Since the aircraft can not take off with a higher mass than the maximum take off mass, then the points having higher ordinate than this mass are not considered.

The tests on each row of the table are simply fulfilled through if functions.

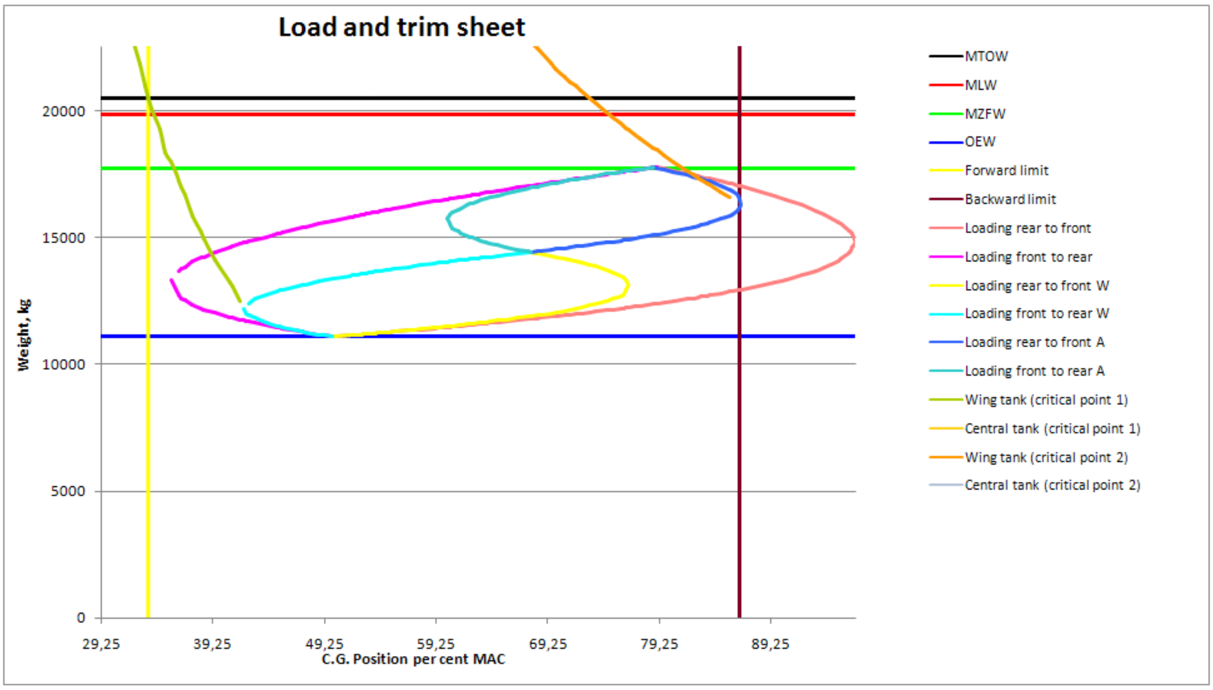


Figure 5.2 Load and trim sheet from the tool with the forward and backward margins

RESULTS:	
CG-range Δx	52,75 % along the MAC
Forward limit	33,75 %MAC
Backward limit	86,5 %MAC

Figure 5.3 Final results

5.3 V-Diagram

The present tool does not include the functionality of plotting the so-called V-diagram. Nevertheless the final results are of great use to determine the required horizontal tail area, which can be done thanks to the V-diagram. The V-diagram takes the maneuverability and the stability into consideration. The function of the empennage is to create yawing and pitching moments. The horizontal tail is responsible for the trimming, the stability and the maneuverability around the axis of pitch. There are other methods to create a pitching moment, but the most common is to deflect the horizontal tail. The area of this part is the parameter which most affects the pitching moment.

The requirements on maneuverability and stability lead both to a required dimensionless horizontal tail area S_H/S_{WG}. The two straight lines are plotted on a common diagram, which is the V-diagram (Figure 5.4). The required CG range Δx comes directly from the load and trim sheet and will lead to the minimal acceptable value of S_H/S_{WG} (**Scholz 1999**). The smaller is the CG range and the smaller can be the horizontal tail, which also means an aircraft less expensive to manufacture and easier to maintain.

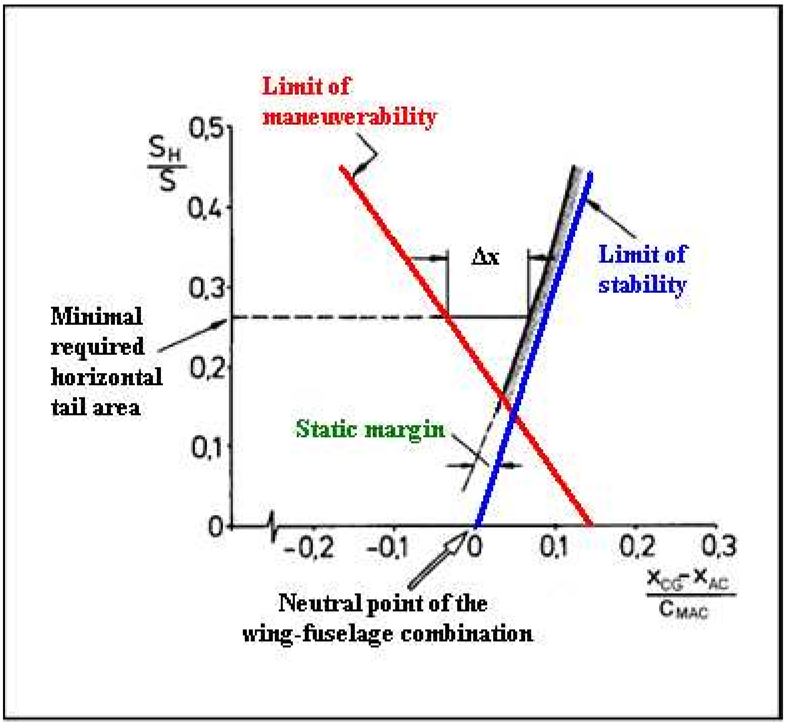


Figure 5.4 V-Diagram (derived from **Hafer 1993**)

6 How to use the software

The installation can be done properly through copy and paste of the Excel file. The only prerequisite is that *Excel* 2003 is installed on the computers which will run the software. At the beginning this tool has been developed to run on *Excel* 2003. The compatibility with previous versions of *Excel* can not be guarantied. Please copy and paste the file where it is wished to be stored. It is recommended to keep the original file as a back-up file, which contains the original settings. The file can be renamed without any problem.

Once all the inputs values are entered two different buttons can be used to run the calculation and get the load and trim sheet. The first button will only lead to the plotting of curves concerning the boarding or disembarking process. This button can be useful to get intermediate results. Indeed the refueling process calculation can run up to 4 or 5 minutes and it would be useless to wait such time if the user only cares the potato curves. The second button is dedicated to run the entire calculation.

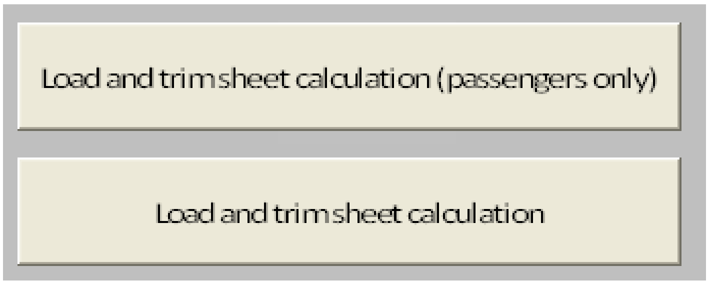


Figure 6.1 Buttons to launch either the passenger loading calculation or the whole calculation

In some extent the functions linked to the two buttons are the main functions of the application. The first button but will make the functions `Load_Passengers` and `Display` running in a row. Clicking on the second button will launch the entire calculation through the following functions:

- `Load_Passengers`
- `Limits_before_fuel`
- `Load_fuel_wing_tanks`
- `Load_fuel_center_tank`
- `Display`
- `Limits`

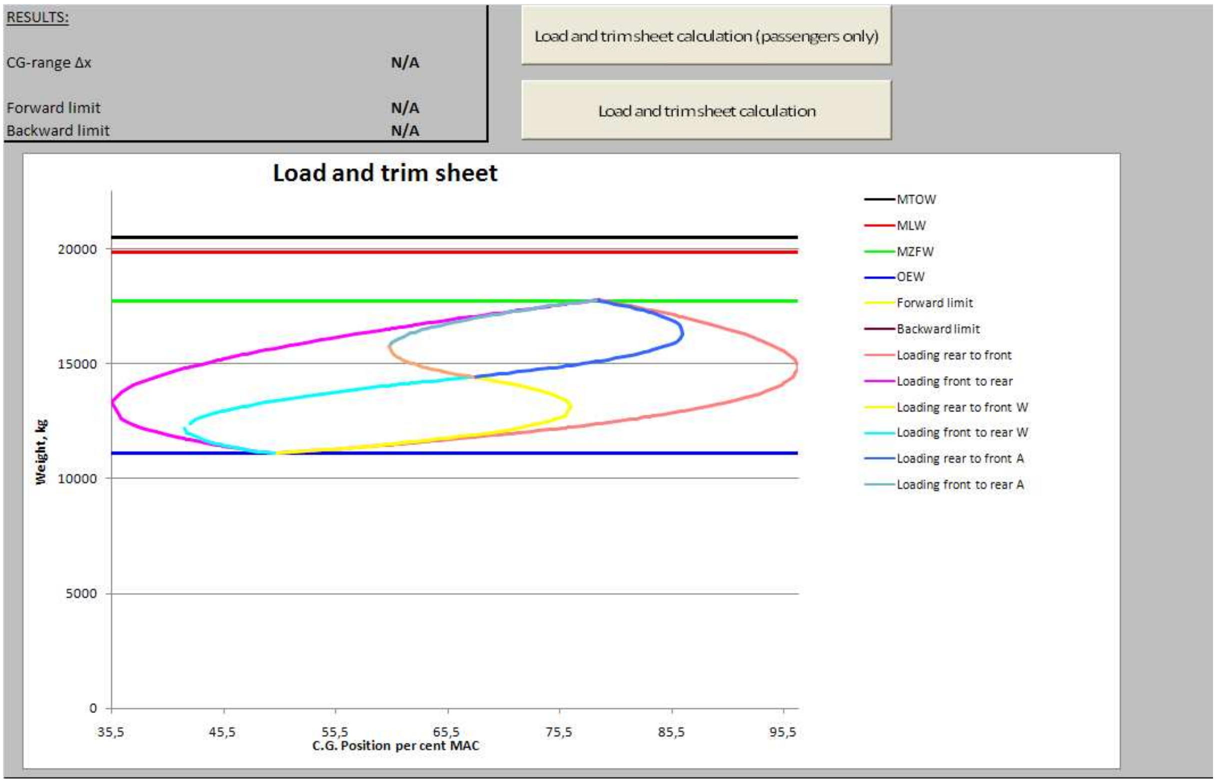


Figure 6.2 Results given from the short calculation (passengers only)

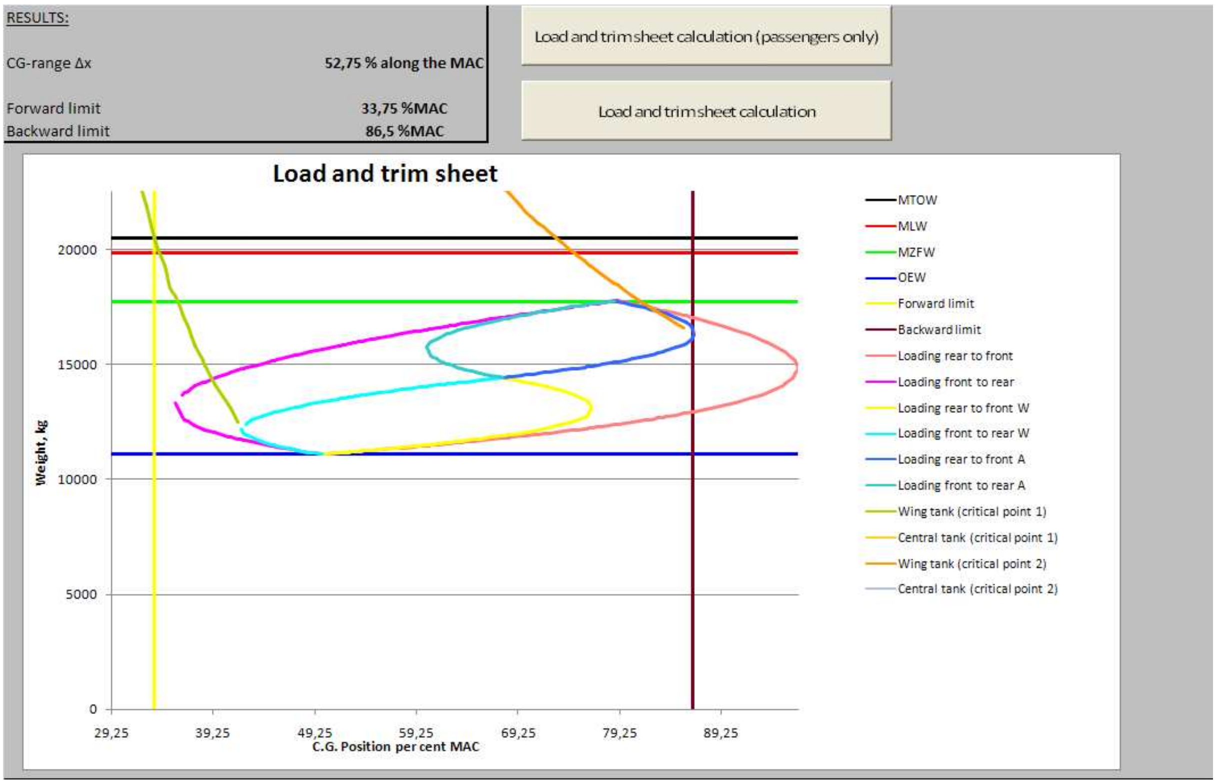


Figure 6.3 Results given from the entire calculation

7 Examples

7.1 Impact of the aircraft configuration

If the cabin is equally balanced over the MAC then all loading vectors are nearly vertical (**Trahmer 2006**). It should give a moderate CG range (lower value of Δx). That is one of the reasons why most of the passenger aircraft are designed with engines under the wing instead of engines attached to the fuselage tail.

If the cabin and cargo hold are more forward than 25% of the MAC, then all loading drives the CG forward (**Trahmer 2006**). This can be seen for most cases of aircraft having engines on fuselage.

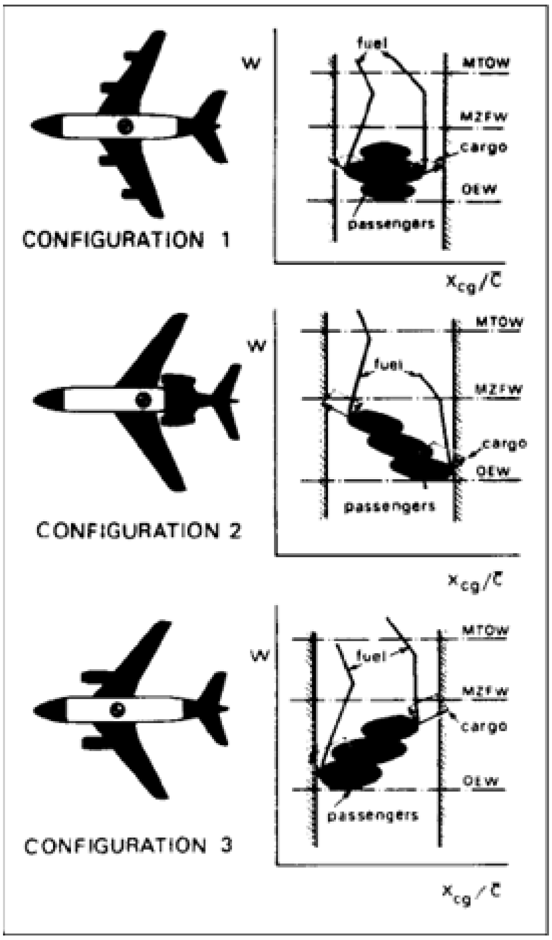


Figure 7.1 Impact of the aircraft configuration on the CG travel (**Torenbeek 1988**)

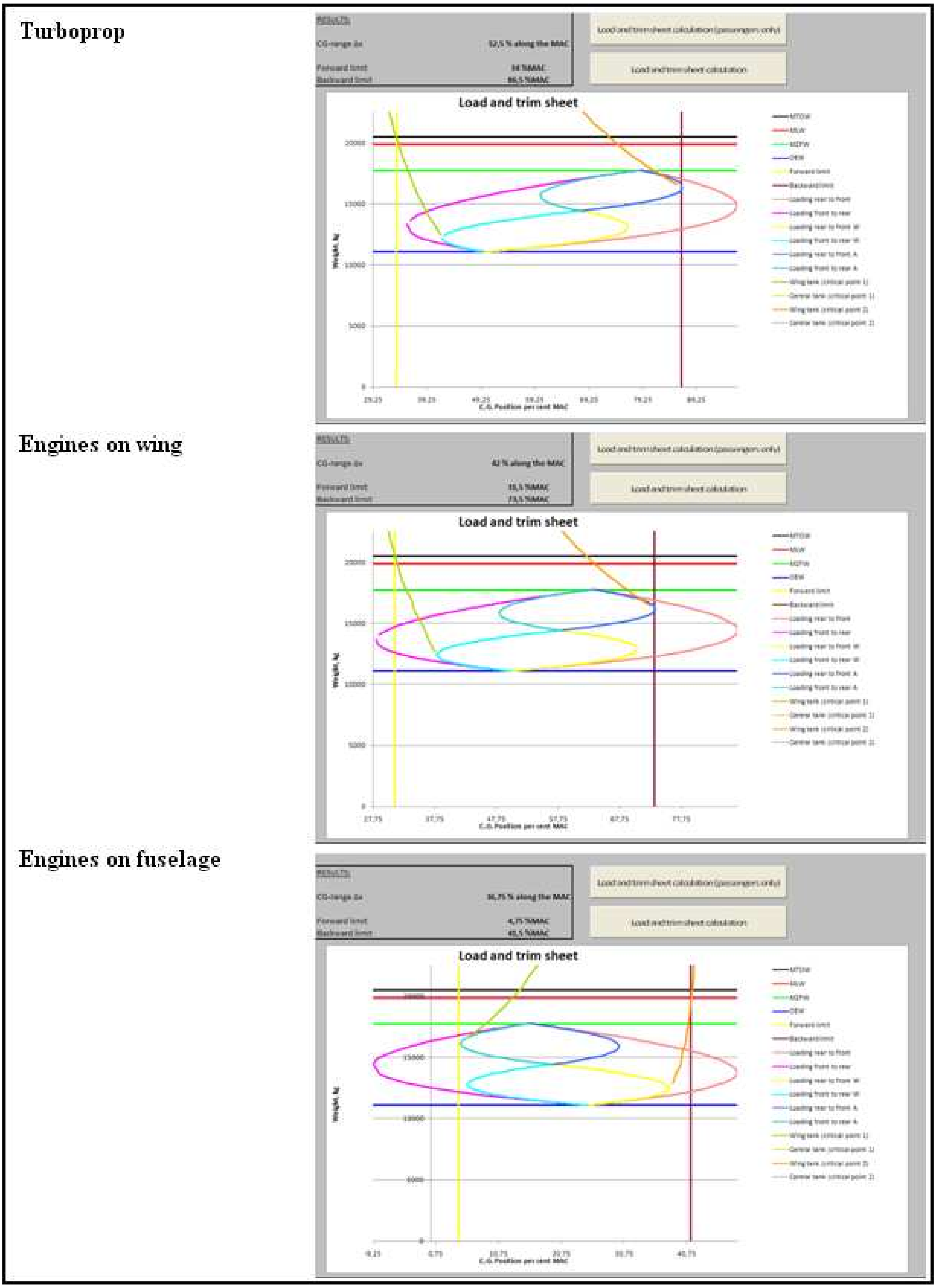


Figure 7.2 Impact of the aircraft configuration in the *Excel* tool

On Figure 7.2 the plotted potato curves show the expected shapes. Loading situation for aircraft configuration with engines on fuselage spreads the CG from aft at empty weight to forward when fully loaded. It is the contrary if the aircraft is fitted with engines under the wing.

7.2 Airbus A320 design in PreSTo

The new tool extends the program PreSTo one step further. It is now possible to get the load and trim sheet of a completely new design. The result can be generated really fast thanks to the functionalities already included in PreSTo.

Comparing the results given by the tool and the load and trim sheet from aircraft manufacturers is a way to validate the computing. The reference aircraft would be Airbus A320 because this aircraft is Airbus's best-selling aircraft to date and it is operated by many low cost companies. The Airbus A320 is designed as a single aisle aircraft with a 3+3 layout.

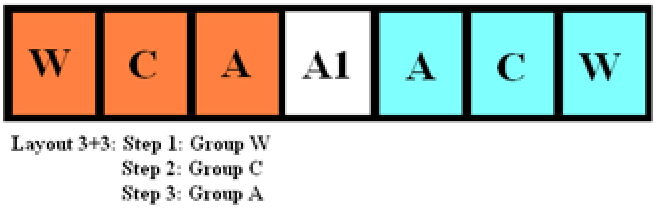


Figure 7.3 Cabin layout A320 conventional design

The first design phases already included in PreSTo will allow generating the data to generate the load and trim sheet of an aircraft which is really similar to A320. The tool gives the possibility to get an idea of the load and trim sheet of such an aircraft, even many design values are still unknown. The only values given are presented in **Appendix C**. The main cabin of A320 can accommodate a maximum of 179 passengers in a high density layout (**Airliners 2010**). According to **Raymer 89** the smaller seat pitch is 30 in. Since the program can only consider a single level of comfort, the best is to run it this way.

Thanks to PreSTo the values for MTOW, MLW, MZFW and OEW are easily determined when the design point is properly chosen. Before verifying the validity of the new functions, it is required to check the validity of the data itself. The values from the first design phases (preliminary sizing, fuselage and wing design) are compared to values from the multidisciplinary aircraft design tool PrADO and **Jane's 08-09**. Then it is time to use the new functionality of PreSTo. The inputted values can be seen in **Table 7.1**. The output can be compared to the real values in **Table 7.2**. The results from PreSTo are presented in **Appendix A** and the real values can be read in the load and trim sheet in **Appendix B**.

Parameter	Symbol	Value	Unit	Reference
Number of passengers	n_{PAX}	179	[passenger]	**Airliners 2010**
Max. Take-off mass	m_{MTO}	74208	[kg]	PreSTo (previous design phase)
Max. landing mass	m_{ML}	65155	[kg]	PreSTo (previous design phase)
Max. zero fuel mass	m_{OE}	58129	[kg]	PreSTo (previous design phase)
Operating empty mass	m_{OE}	41482	[kg]	PreSTo (previous design phase)
Cabin length	l_{Cabin}	28,095	[m]	PreSTo (previous design phase)
Nose length	l_{Nose}	5,24	[m]	PreSTo (previous design phase)
Seat abreast	N_{sa}	6	[seat]	**Airbus**
Seat pitch	*Pitch*	0,762	[m]	**Raymer 89**
Aisles	N_{aisles}	1	[aisle]	**Airbus**
Rows	N_{rows}	29,8	[row]	Own calculation
Seats group 1		3	[seat]	**Airbus**
Seats group 2		0	[seat]	**Airbus**
Seats group 3		3	[seat]	**Airbus**
Short and middle range		Yes		Appendix C
Wing group mass	m_{WG}	24180,0	[kg]	Own calculation
Fuselage group mass	m_{FG}	75801,9	[kg]	Own calculation
Distance from CG to LEMAC	$x_{CG,LEMAC}$	12,0	[%MAC]	Measure on top view drawing
Distance from wing CG to LEMAC	$x_{WG,LEMAC}$	1,29	[m]	Measure on top view drawing
Distance from fuselage CG to fuselage nos	x_{FG}	17,30	[m]	Measure on top view drawing
Initial CG MAC	$CG_{0\text{-}MAC}$	12,0	[%MAC]	Measure on top view drawing
Initial CG	CG_0	15,91	[m]	Measure on top view drawing
Mean Aerodynamic Chord	C_{MAC}	4,190	[m]	PreSTo (previous design phase)
Engines on Wing				**Airbus**
Root chord	c_r	6,00	[m]	PreSTo (previous design phase)
Kink chord	c_k	5,50	[m]	PreSTo (previous design phase)
Wingspan	b	33,91	[m]	**Jane's 08-09**
Tip chord	c_t	1,50	[m]	PreSTo (previous design phase)
Fuselage diameter	d_f	4,00	[m]	Measure on top view drawing
Front spar position	FS_{root}	13,00	[%cr]	Measure on top view drawing
Rear spar position	RS_{root}	59,00	[%cr]	Measure on top view drawing
Sweep front spar inner	$L_{FS,i}$	27,00	[°]	Measure on top view drawing
Sweep front spar outer	$L_{FS,o}$	27,00	[°]	Measure on top view drawing
incidence angle	i	2,78	[°]	PreSTo (previous design phase)
dihedral angle	G	4,50	[°]	PreSTo (previous design phase)
kink semi-span	Y_k	6,26	[m]	PreSTo (previous design phase)
root relative thickness	$(t/c)_r$	0,190	[-]	PreSTo (previous design phase)
tip relative thickness	$(t/c)_t$	0,123	[-]	PreSTo (previous design phase)
kink relative thickness	$(t/c)_k$	0,123	[-]	PreSTo (previous design phase)

Table 7.5 Inputted values A320 conventional design

	Output	Real value
CG range Δx	52.25%MAC	32%MAC (flight)
Forward limit	10.00%MAC	13 to 19%MAC
Backward limit	62.25%MAC	36% to 45%MAC

Table 7.2 Comparison between outputted values and real values A320 conventional design (see Figure B.1)

7.3 Alternative Airbus A320 design in PreSTo

Six seats abreast can lead to several cabin layouts, which all abide by the regulations. On single aisle passenger aircraft there is no choice and the seat layout will be 3+3. It is getting much more complicated when considering more that one aisle: the seat layout can be 2+2+2, 1+4+1 or even unsymmetrical 1+2+3 among others. Thanks to the tool it is possible to easily evaluate an alternative design. It is aimed to find if the new design will help to minimize the CG travel.

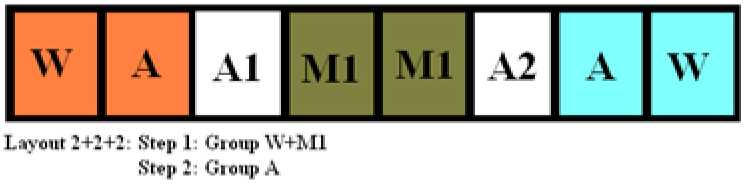


Figure 7.4 Cabin layout A320 alternative design

Once all the data concerning the classic design of Airbus A320 are entered, it takes only few seconds to modify it to take the new cabin layout into account. The only input to modify is the number of aisles N_{aisles}. Two aisles are entered instead of one and the number of seats per seat group is given to match with a 2+2+2 layout.

	Output
CG range Δx	53.75%MAC
Forward limit	8.50%MAC
Backward limit	62.25%MAC

Table 7.3 Outputted values A320 alternative design

7.4 Comparison of results

In order to validate the software, it is needed to look first at the results for the A320 with a conventional design. The outputs is rather close to the real values for the forward CG limit, but show 20%MAC difference for backward CG limit. The forward limit is given as 10.00% MAC and the backward limit has been determined to be 62.25% MAC. If we consider the limits in flight, then the difference with the real values are only 3%MAC in the first case. From the *Excel* tool the CG may move along 52%MAC, which is quite far to the real value of 32%MAC. That means the tool may lead to a bigger horizontal tail area than necessary. The difference can be blamed on the fact that the galleys and lavatories are not considered by the software.

The best advantage to design the A320 as a twin aisle passenger aircraft would be a shorter turn around time because the passengers can have a better access to their seat. This is actually the reason why the load and trim sheet contains only two potato curves instead of three. Also a twin aisle aircraft would allow a better comfort.

Unfortunately, when looking at the results given by the software for the alternative design, it seems that two aisles do not help to reduce the CG range. Indeed two aisles allow more people to seat at the same time and this makes the lower potato curve a bit wider. Then the CG range drops from 52.25%MAC to 53.75%MAC. This implies that the alternative design would probably require a bigger horizontal tail, which may penalize the entire aircraft performances. Moreover having two aisles would require a larger fuselage. This will badly affect the wetted area and the aerodynamic properties. The outputted values concerning the alternative design can unfortunately not be compared to any real value, since not any twin aisle A320 has been ever built.

Summary

This project deals with the analysis of CG-Travel of passenger Aircraft.

The first goal was to conduct a literature research in order to understand the interrelations between the CG margins, the horizontal tail-plane sizing and the wing positioning.

The passenger loading has also a great impact of the mass distribution along the longitudinal axis. Thus, the different possible cabin layouts have been studied. The relation between the seats layout, the number of aisles and the boarding of passengers has been explained. It has a direct impact on the load and trim sheet, and more precisely on the potato curves.

The refueling has also been considered. Indeed, the fuel tanks geometry, the wing sweep, the dihedral angle and the incidence angle make the CG travelling during the refueling process. Different aircraft have been considered in order to analyze the geometry of their fuel tanks.

Rather than developing a separated tool, it has been chosen to include it in PreSTo. This allows investigating the impact of different inputs on the CG travel for short, middle and long range airliners with conventional configurations. Thus a new spreadsheet has been included in PreSTo. Input values dedicated to the drawing of the load and trim sheet need to be given by the user. The new functions have been developed with the language VBA. The tool can give the CG range and the CG margins after only few minutes running. The results could be really useful for the next design phases, such as the design of the tail. The results are given with respect to the MAC.

A calculation has been conducted for a reference aircraft based on the Airbus A320. Two cabin layouts have been considered. The Airbus A320 is a single aisle aircraft with 6 seats abreast (conventional design). The alternative design, which has been evaluated, is a twin aisle aircraft with the same number of seats abreast. The results have been the load and trim sheet and the CG margins. Looking at these results we can conclude that the tool works properly even some output values are closer to the reality than others. This can be blamed on the fact that the galleys and lavatories are not considered by the software. Also the geometry of fuel tanks can rarely match the exact geometry. Indeed, the earlier design phases draw the wing geometry, but they do not give any indication about spars and ribs. A statistical research to compare the results given by the tool and load and trim sheets from the aircraft manufacturers would allow judging the results in a more objective way.

Acknowledgements

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In addition I also would like to thank the International office at the engineering school ESTACA in France. It could not have got the opportunity to study in Hamburg during Winter Semester 2009/2010 without them. Last but not least, I would like to express my gratitude to Doris Peterschmitt and Aloisia Bischoff, German teachers at ESTACA. They gave me the willingness to go in Germany and to improve my German knowledge.

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Appendix A Results from Airbus A320 Study in PreSTo

A.1 Results A320 conventional design (Single aisle 3+3)

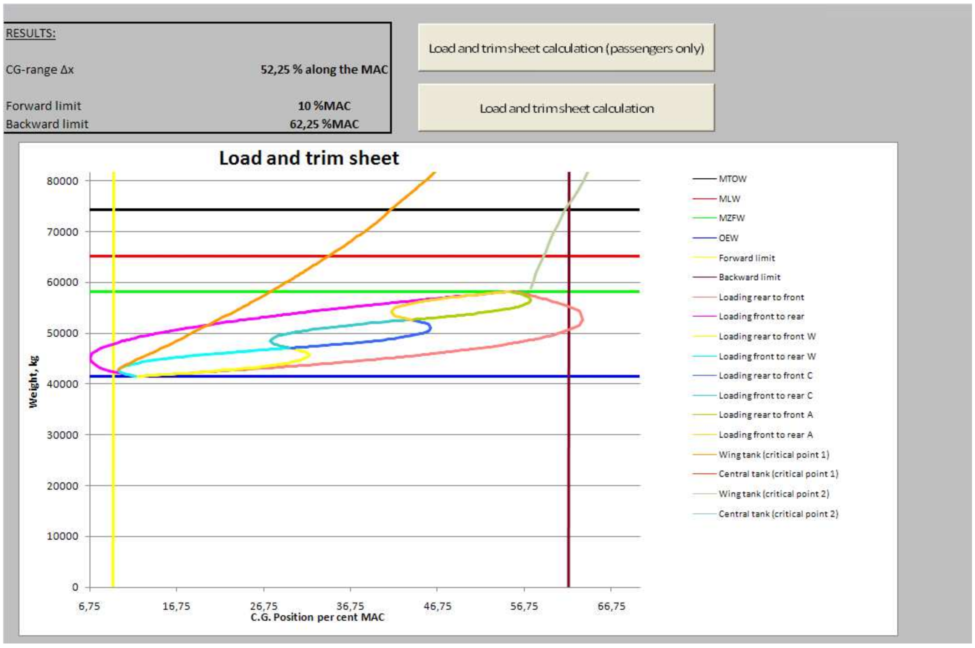

Figure A.1 Results A320 conventional design

A.2 Results A320 alternative design (Twin aisle 2+2+2)

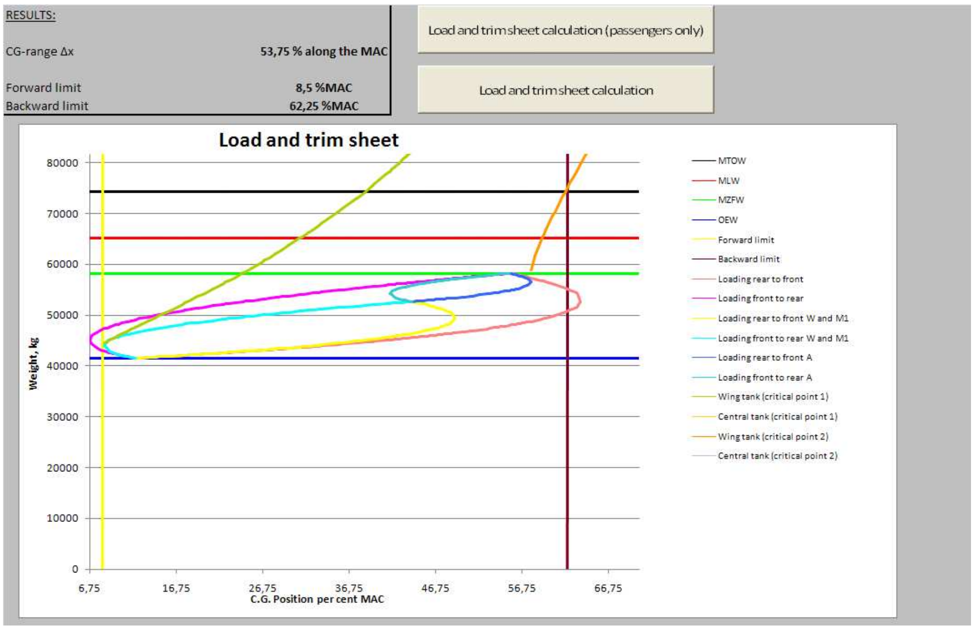

Figure A.2 Results A320 alternative design

Appendix B Load and trim sheet of Airbus A320

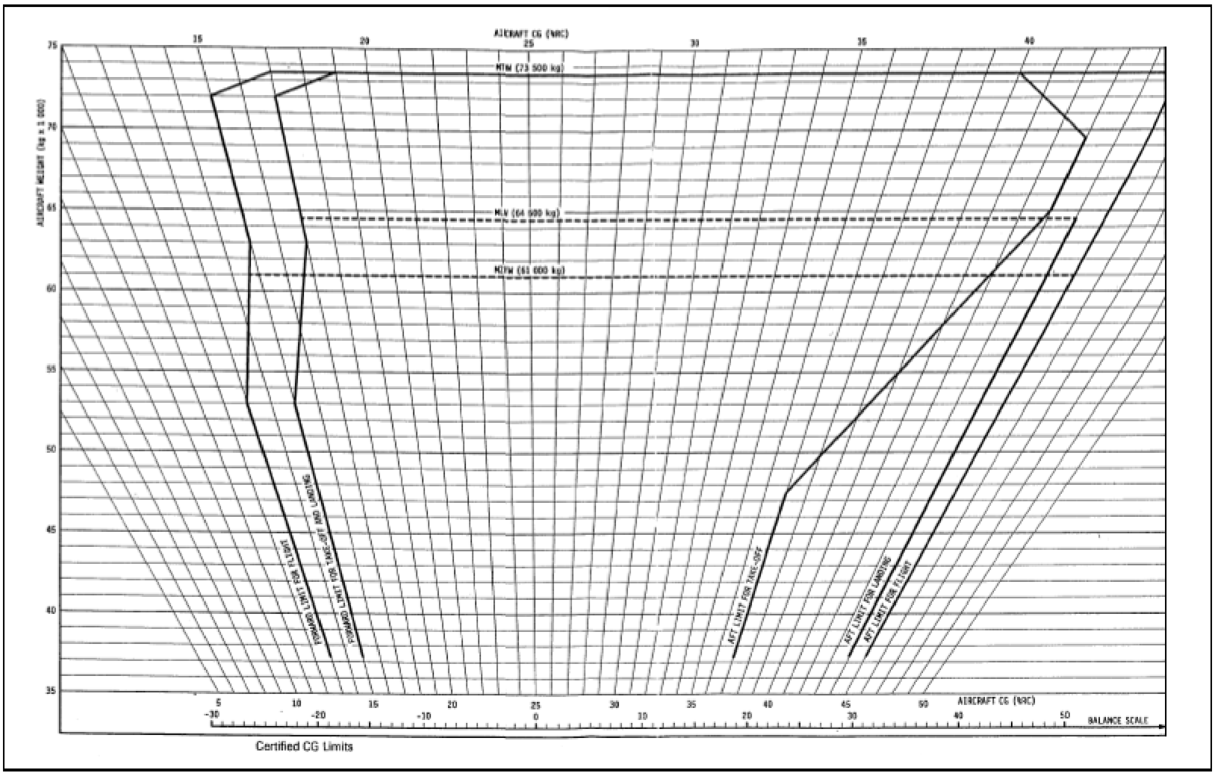

Figure B.1 Load and trim sheet of Airbus A320 (**Airbus 2010**)

Appendix C Input data for preliminary design of Airbus A320 in Presto

- Payload: 150 passenger plus 5674 kg cargo
- Design range: 3273 km at M_{CR} = 0.76; fuel reserves: domestic
- Take-off field length: 2195.7 m
- Landing field length: 1906.4 m
- Wing aspect ratio: 9.396
- Engine by-pass ratio μ of the CFM-56 engines: 6.0
- Specific fuel consumption c of the engines: 16.19 mg/(Ns)
- The operating empty mass accounts to 55.9 % of the maximum take-off mass
- The maximum landing mass accounts to 87.8 % of the maximum take-off mass
- Maximum lift coefficient at take-off: 2.57
- Maximum lift coefficient at landing: 2.57
- Lift independent drag coefficient: 0.025
- Oswald efficiency factor during cruise assumed to be 0.85
- Relative wetted area: 6.474.
- Equivalent surface friction coefficient $\overline{c_f}$ = 0.003
- All calculations have to be accomplished at 0 ft MSL ISA conditions
- Certification basis: FAR Part 25
- Fuel density: 800 kg/m³

Appendix D Top view of Airbus A320

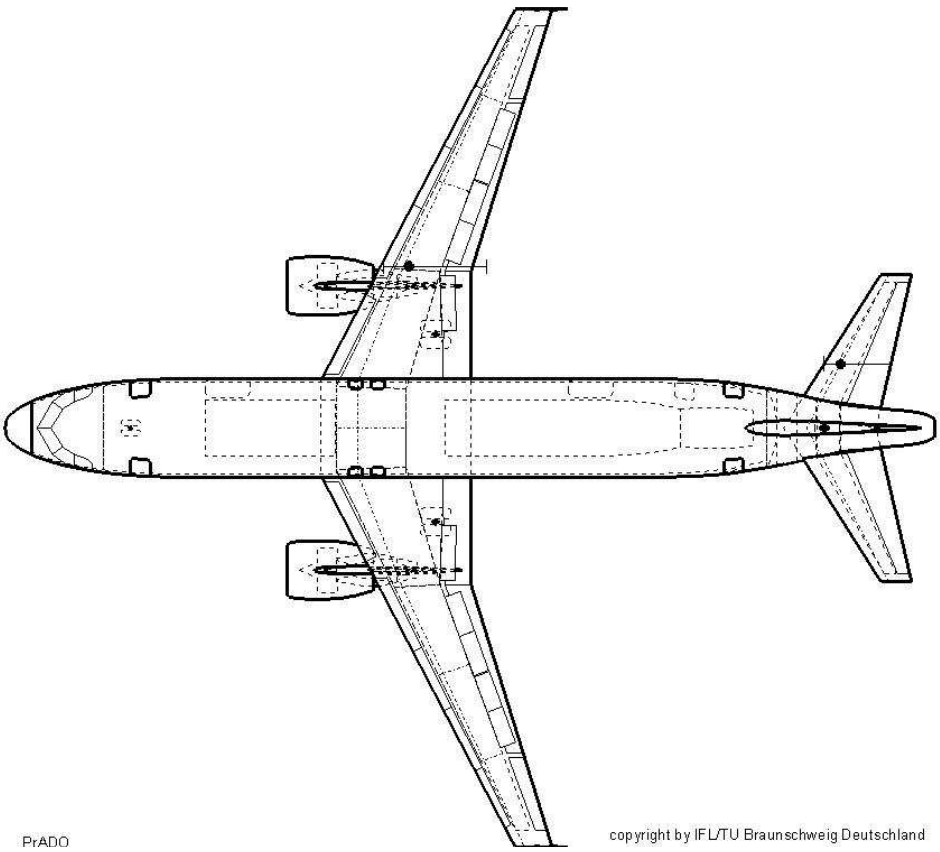

Figure D.1 Top view of Airbus A320 out of PrADO (**Heinze 2004**)

Appendix E CD-ROM

This is the CD-ROM containing the Excel tool and the present report as PDF file.