Aircraft Passenger Comfort Enhancement by Utilization of a Wide-Body Lower Deck Compartment

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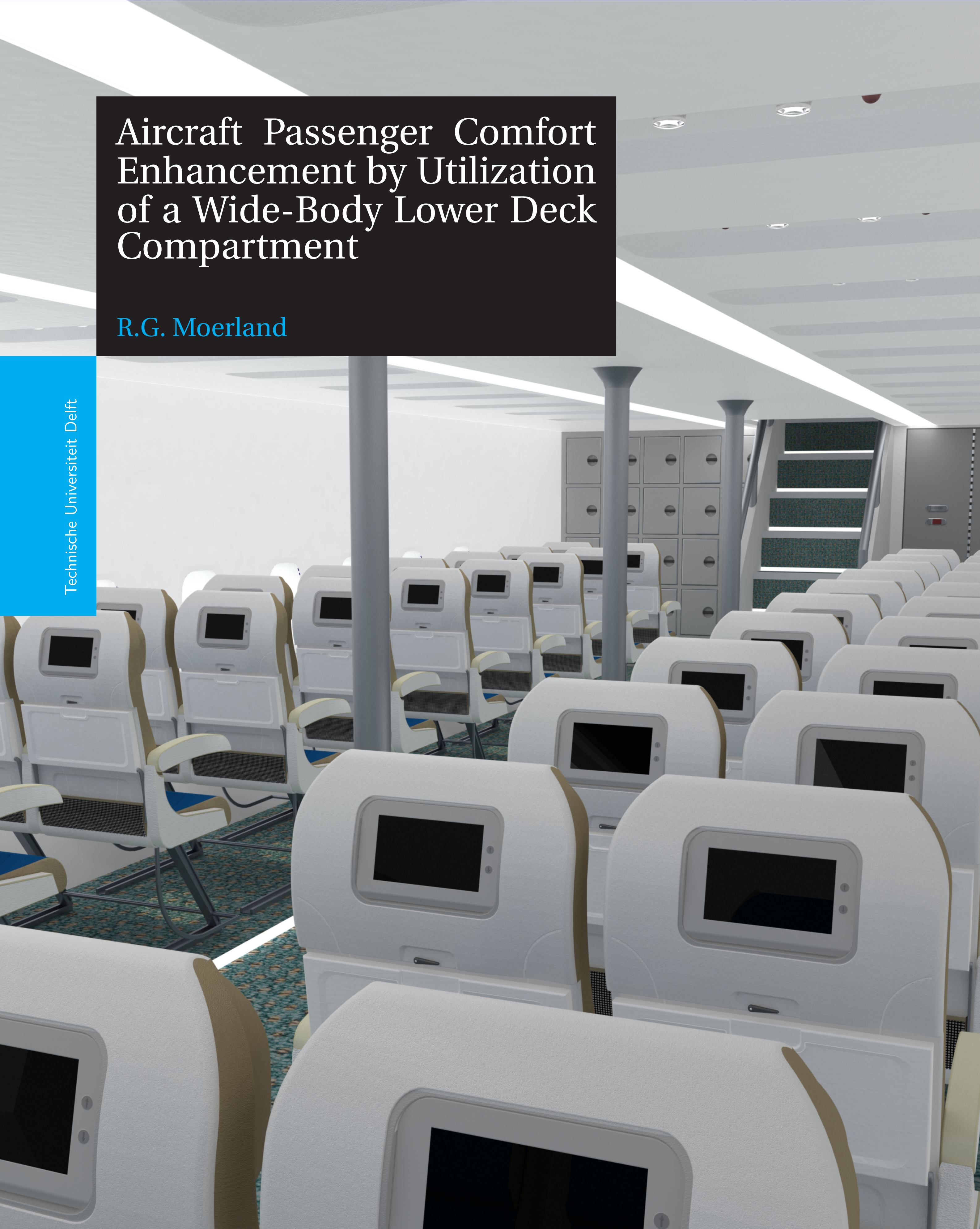

Delft University of Technology

Challenge the future

Aircraft Passenger Comfort Enhancement by Utilization of a Wide-Body Lower Deck Compartment

by

R.G. Moerland

in partial fulfillment of the requirements for the degree of

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SUMMARY

Growing passenger dimensions and the demand for more comfort in the economy class cabin is a trend that is becoming more important during aircraft conceptual design. Based on recent investigations, it is known that current aircraft seat dimensions are not suitable and safe for a large part of the world population. Therefore, a change in aircraft conceptual design thinking, by taking human anthropometry into account, is required. This thesis investigates the opportunity to change the aircraft during conceptual design as well as the opportunity to change current aircraft in order to provide a higher level of passenger comfort and safety. To measure the latter, a comfort model is created, based on scientific research and human dimensions, allowing for the measurement of comfort related to seating configurations, seat characteristics, and cabin dimensions.

By establishing the ideal seat dimensions, it is shown that conceptual aircraft designs for the worldwide 95 percentile passenger require wider, but shorter, fuselages. Using the Initiator as a conceptual design tool, four short-haul and four long-haul aircraft are modeled for a range of seat dimensions. Based on an inside-out aircraft design approach, it is shown that similar aircraft performance characteristics are obtained when designing for the worldwide 95 passenger percentile. Moreover, a similar level of direct operating costs, and hence profitability, is attained. However, designing for the worldwide 99 passenger percentile yields considerably higher fuel burn rates and operating costs. An average increase of 3.9 % among all modeled aircraft is seen for the harmonic fuel burn, leading to an increase of 4.2 % in direct operating costs.

Considering existing aircraft, use is made of an outside-in aircraft design approach to assess a set of performance characteristics. Based on an average utilization of 37 % of the cargo space in commercial transport aircraft, a potential is shown for a different utilization of the aircraft lower deck, allowing the airline to provide more passenger comfort while retaining a similar level of profitability.
Using the Airbus A340-300 as reference aircraft, it is shown that the placement of passengers in the lower hold is feasible from a regulatory, ergonomical, economical, and structural point of view. Based on a reference three-class layout with 267 passengers, it is shown that a lower deck seating compartment provides an increase of 14.6 % in the number of passengers when similar seat properties are used as on the main passenger deck. The installment of additional furnishing and required structural reinforcements results in a decrease of 12 % in maximum structural payload weight. Nevertheless, it is shown that the placement of passengers in the lower deck yields higher profitability rates for the airline when compared to the carriage of additional freight.
Secondly, the placement of lavatories and galleys in the aircraft lower deck is investigated, allowing for a maximum increase of 13 % in passenger seats. To allow for the installment of galley lift systems, staircases, and required safety measures, a decrease of 6.27 % in maximum structural payload is attained. By subsequently increasing seat characteristics on the main deck, an increase of 12 % in passenger comfort is achieved for the worldwide 95 passenger percentile. The airline profitability level associated to this comfort layout in turn relates to an average carriage of 5300 kg of freight during the aircraft service life, being equal to the current average. For both the lower deck seating and service utilization, it is concluded that the flying experience of the passenger is increased, while a similar level of airline and manufacturer profitability is obtained. Aircraft lower deck utilization can therefore be seen as a feasible replacement for conventional aircraft configurations.

Acknowledgements

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R.G. Moerland
Delft, January 2013

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Nomenclature

Latin Symbols

A	Cross-Sectional Area	m^2
A_G	Galley Area	m^2
A_L	Lavatory Area	m^2
bkl	Buttock-Knee Length	m
C	Cost	US$
c	Comfort Correlation Coefficient	-
C_D	Drag Coefficient	-
C_L	Lift Coefficient	-
d	Diameter	m
E	Modulus of Elasticity	Pa
g	Gravitational Acceleration	$\frac{m}{s^2}$
h	Height	m
I	Area Moment of Inertia	m^4
j	Maximum Applicable Load Factor	-
l	Length	m
LQ	Luggage Quantity	-
LU	Lavatory Utilization	$\frac{pax}{lav}$
LV	Luggage Volume	$\frac{kg}{m^3}$
n	Prescribed Structural Safety Factor	-
N_c	Number of Crew	-
N_Z	Maximum Load Factor including Safety Factor	-
P	Applied Load	N
pax	Number of Passengers	-
pc	Piece	-
R	Range	km
r	Radius	m
S	Surface Area	m^2
sp	Seat Pitch	m
V	Volume	m^3
V_D	Dive Speed	$\frac{m}{s}$
V_{SL}	Stall Speed in Landing Configuration	$\frac{m}{s}$
W	Weight	kg
w	Width	m
wb	Overall Passenger Well-Being	-

Greek Symbols

δ	Deflection	m
ΔP	Pressure Differential	Pa
ρ	Density	$\frac{\mathrm{kg}}{\mathrm{m}^3}$

Subscripts

att	Cabin Attendant
cab	Cabin
c	Crew
eff	Effective
$furn$	Furnishing
fus	Fuselage
fwd	Forward
F	Fuel
$misc$	Miscellaneous
nac	Nacelle
ref	Reference
TO	Take-Off
wet	Wetted
ZF	Zero-Fuel

Abbreviations

ACAPS	Aircraft Characteristics for Airport and Maintenance Planning
BC	Business Class
BWB	Blended-Wing-Body
CAD	Computer-Aided Design
CC	Cabin Configurator
CG	Center of Gravity
CRA	Chair Replacement Algorithm
CRP	Cushion Reference Point
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOC	Direct Operating Costs
ECP	Economy Premium Class
EC	Economy Class
ER	Extended Range
FAA	Federal Aviation Authority
FAR	Federal Aviation Regulations
FC	First Class
GWP	Global Warming Potential
IOC	Indirect Operating Costs

LCC	Low Cost Carrier
LDGL	Lower Deck Lavatory and Galley
LDS	Lower Deck Seating
LE	Leading Edge
LF	Loading Factor
MLW	Maximum Landing Weight
MTOW	Maximum Take-Off Weight
OEW	Operating Empty Weight
SAAA	Service Area Addition Algorithm
SFC	Specific Fuel Consumption
TCDS	Type Certificate Data Sheet
TLR	Top Level Requirement
TOC	Total Operating Costs

1
INTRODUCTION

A comparison between the average size of an Economy Class (EC) aircraft seat and the growth trend of human dimensions over the last decades [1], as illustrated in Figure 1.1, shows a contradictory trend in commercial transport aircraft cabin design and is illustrative for the current passenger comfort perception.

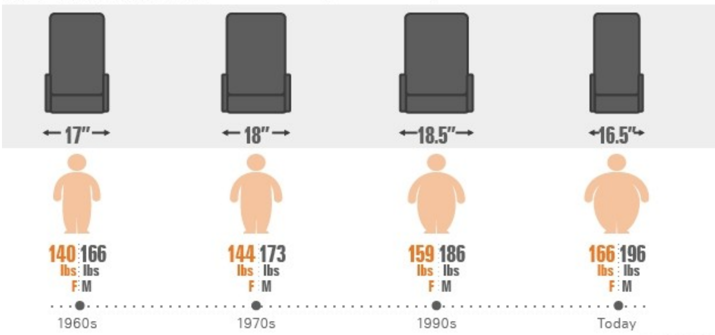


Figure 1.1: The contradicting trend between aircraft seat size and human dimensions [1]

Over the last two decades, the aircraft industry has shown a tendency to fit as many passengers as possible in the EC cabin, thereby trying to increase the overall number of passengers within the aircraft cabin and hence the profitability of airlines [2]. Recent studies, however, have shown that the so-called shrinking aircraft seat leads to a lower comfort perspective of the passenger and seating standards that are not suited and not safe in case of emergency situations for at least 95 % of the world population [3]. By simply increasing the passenger seat dimensions, a higher level of passenger comfort can be achieved, but would in turn show a large decrease in airline revenue due to the decrease in passenger capacity. Therefore, the airline carefully weighs the passenger comfort level against the expected revenue in order to find an optimum that ensures a certain passenger loyalty towards the airline, which is shown by Atalik [4] by analyzing the influence of passenger comfort levels on the passenger's flight choice.

A possible solution to counter the trend of the shrinking aircraft seat is the design of a new aircraft cabin which ensures a minimum required level of passenger comfort and safety, while maintaining airline profitability. However, little scientific research is carried out with respect to the influence of aircraft cabin comfort enhancement from an aircraft design point of view. The design of the aircraft cabin is often led by different focus groups, in which the airline, the aircraft, the available technology, and the user are all taken into consideration [5] to arrive at an optimum cabin design. An extensive literature research carried out on this subject shows that the decisions and outcomes of these focus groups are rarely published and hence little scientific papers are available about a full aircraft cabin design from both a conceptual aircraft design point of view and an ergonomics point of view.

[1] D. Carrington, Feeling cramped? How to battle the shrinking airline seat, November 2013, http://edition.cnn.com/2013/11/07/travel/feeling-cramped-battle-airline-seat/, Accessed: 17/08/2015

1.1. THE INFLUENCE OF SEAT CHARACTERISTICS ON PASSENGER COMFORT AND CONCEPTUAL AIRCRAFT DESIGN

As shown by Konieczny [6], one of the most important cabin characteristics relating to passenger comfort is the passenger seat. The increase in human dimensions, as described in Subsection 1.1.1, and continuous innovations with respect to passenger comfort enhancement, as shown in Subsection 1.1.2, shows a growing influence on the conceptual aircraft cabin design. Eventually, this leads to changes in the overall conceptual aircraft design over the last decades, as described by Edwards [7].

1.1.1. THE RELATION BETWEEN THE AIRCRAFT SEAT AND GROWING HUMAN DIMENSIONS

The human stature growth trend over the past two hundred years, as shown by Baten and Blum [8] and Bodenhorn et al[2] and depicted in Figures 1.3a and 1.3b, indicates a fast growth of the human stature and consequently the buttock-knee length. The buttock-knee length is defined as one of the most important ergonomic parameters to be taken into account for modern cabin design, as it mainly drives the distance between the aircraft seat cushion and the back of the seat in front. The sum of the length of the seat cushion, the thickness of the backrest, and the distance between the seat cushion and the back of the seat in front is defined as the aircraft seat pitch, as visualized in Figure 1.2. In order to take the human stature growth into account for future aircraft cabin design, airlines might opt for an increase in aircraft seat pitch, thereby directly providing an increased level of passenger comfort, as shown by Kremser [9]. However, as yet mentioned, little scientific research describing the consequences of an enlarged seat pitch from a conceptual aircraft design point of view is available. The requirements that are set by the airlines for the aircraft manufacturers are therefore yet to be studied and show a knowledge gap in the current scientific conceptual aircraft design research.

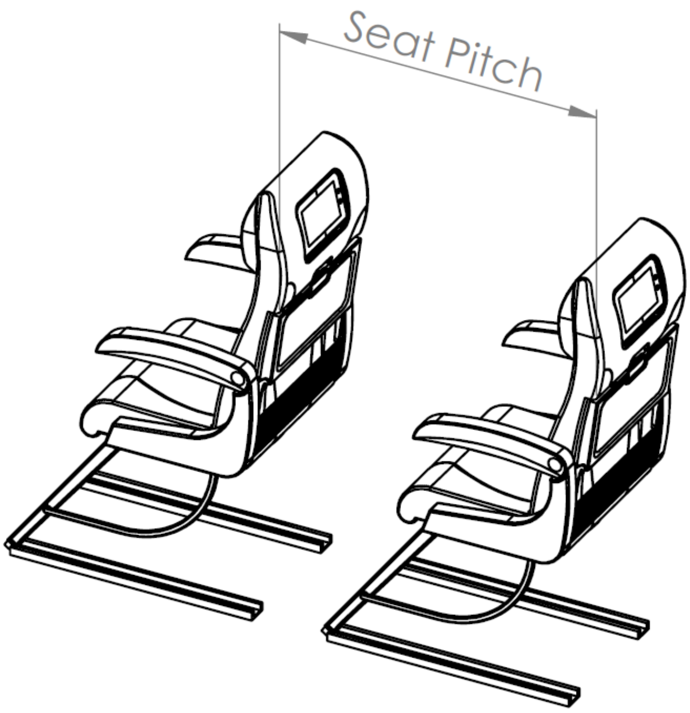
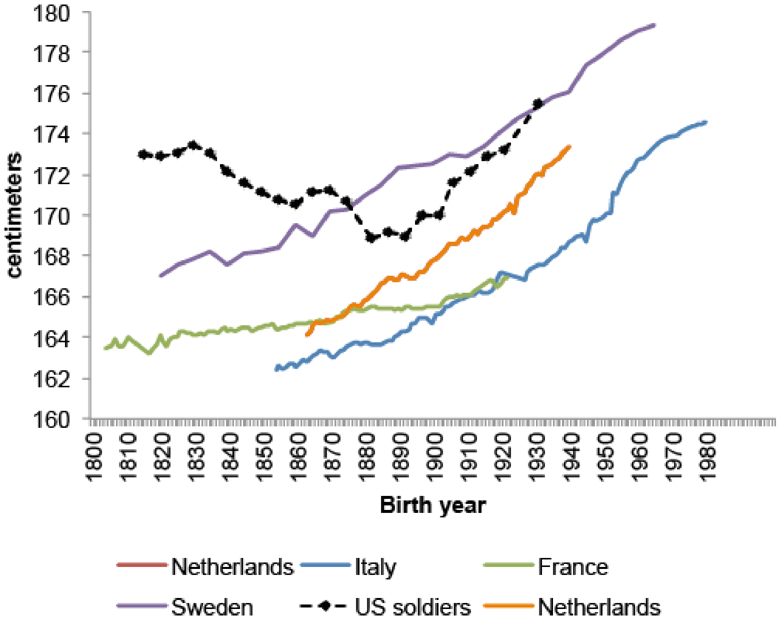


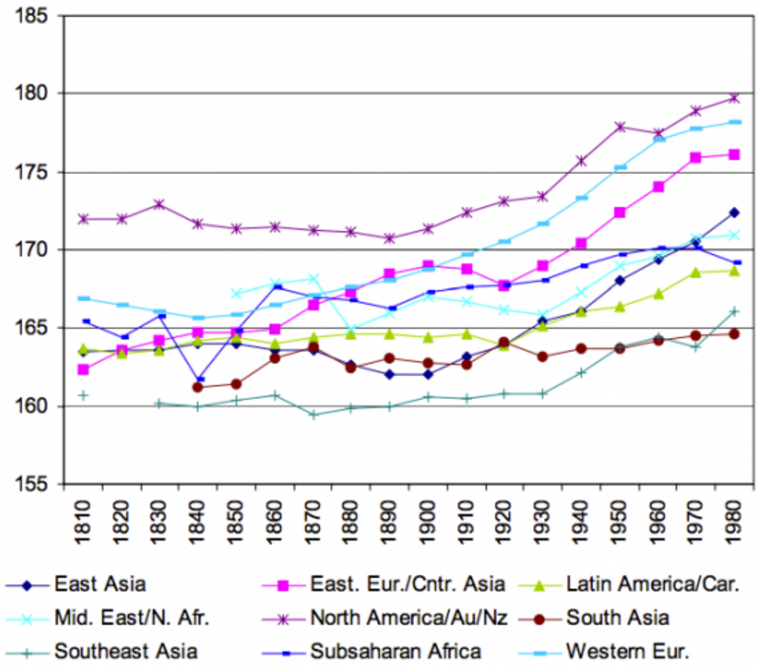
Figure 1.2: Definition of seat pitch in airline seating

Besides the growth of the human stature, an even more important trend for aircraft designers to take into account is the growth of the human circumferential dimensions, thereby influencing the aircraft seat cushion width. The growing trend of obesity among the world population, as depicted in Figures 1.4a and 1.4b, shows that a requirement for wider aircraft seats is likely to be posed in the near future by airlines in order to provide more comfort to their passengers.

[2] H. Bodenhorn, T. W. Guinnane and T. Mroz, Biased samples yield biased results: What historical heights can teach us about past living standards, Vox CEPR Policy Portal, http://www.voxeu.org/article/what-historical-heights-can-teach-us-about-past-living-standards, Accessed: 11/09/2015



(a) Mean heights of volunteer soldiers in the US and in selected countries with conscription [3]

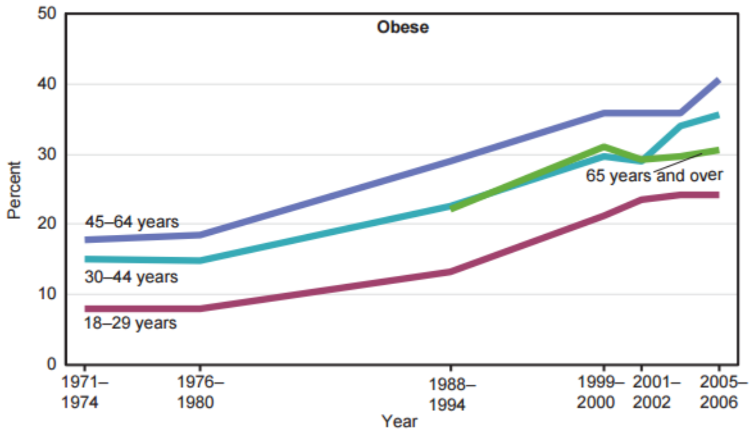


(b) Height development by world regions [8]

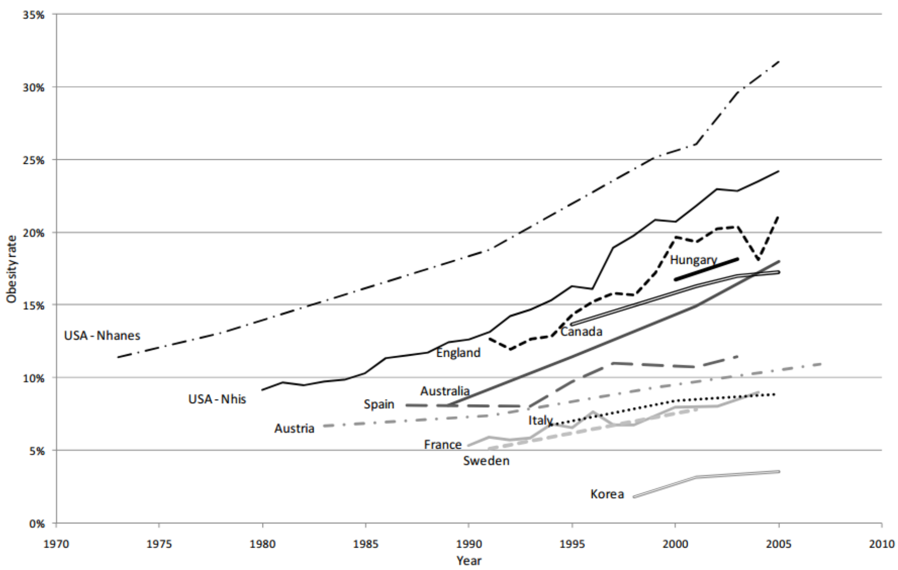
Figure 1.3: Historical growth trend of human stature

This seat width requirement could either be based on the human waist circumference, which defines the width of the seat cushion and the armrests, or on the human hip width, defining solely the seat cushion width between the armrests. Both of these dimensions show a good correlation with respect to obesity, as shown for example by Gill et al [10] and Freedman et al [11].

[3] See footnote 2



(a) U.S. human population obesity percentage by age group between 1971 and 2006 [12]



(b) Obesity rates in men aged 15-64 (age-standardized) [13]

Figure 1.4: Historical growth trend of obesity among the world population

1.1.2. The Role of Comfort Enhancement on Seat weight

At first sight the aircraft seat weight does not seem to be as connected to passenger comfort as seat width and seat pitch are. However, as a more comfortable seat is often realized through a seat weight increase, the influence of seat weight is an important parameter to take into account for an aircraft cabin comfort improvement. Examples of comfort enhancing aircraft passenger seats with a large likelihood of increased seat weight are provided by Tan [14] [15] and Kasturi [16]. A more detailed analysis of these concepts with respect to the influence on aircraft performance is considered to be beyond the scope of this thesis.

As aircraft interior design is becoming more important for aircraft manufacturers, it is necessary to show how a reduced or increased seat weight influences the preliminary design of an aircraft. Claims that are made by aircraft seat manufacturers often relate to a decrease in fuel consumption and hence a higher airline profitability. However, the detailed cost and weight estimations used in order to prove these claims are not readily accessible for the public, as shown for example by the cost estimation of Expliseat [4].

[4] Expliseat, Fuel savings calculator, http://www.expliseat.com/, Accessed: 11/08/2015

1.2. The Identification of the Aircraft Lower Deck as a Means to Improve Passenger Comfort

As previously described, the need for increased seat dimensions forces aircraft manufacturers to identify new opportunities within the aircraft cabin to provide more passenger comfort or a similar passenger capacity with increased seat dimensions. A study carried out by Airbus [17] shows that there exists a potential for airlines when use is made of the lower deck compartment of a wide-body aircraft, which can be used to enhance passenger comfort. Three potential revenue-generating possibilities of the aircraft lower deck are identified by Airbus and defined as follows:

- **Lower Deck Seating**
  A potential exists for the placement of passenger seats within the aircraft lower deck, which are accessible during all flight phases, including taxiing, take-off, and landing.

- **Lower Deck Service Facilities**
  The relocation of service facilities, such as galleys and lavatories, to the aircraft lower deck could increase the number of available passenger seats on the main deck and could lead to a large improvement in passenger comfort. Furthermore, additional service facilities for passenger comfort can be placed within the aircraft lower deck, such as showers and beds.

- **Relocation of Main Deck Components**
  Components that need to be accessible during flight, but require a medium to short response time, can be stowed above or below the passenger deck. Examples of these items are pillows, blankets, and duty-free items.

Furthermore, recent studies carried out on aircraft lower deck utilization by Blauwhoff [18], Dos Santos [19], and DLR [20] in combination with recently patented designs by Boeing [21] and Airbus [22] show that there is a reasonable chance that lower deck utilization will form part of future aircraft cabins and will be the next focus of aircraft manufacturers to provide airlines with more options in terms of cabin utilization.

1.2.1. Lower Deck Seating

The idea of implementing a lower passenger deck in an aircraft is not new: a lower deck seating (LDS) compartment has been used in the Lockheed L-1011 TriStar by PSA [23] and in the Boeing 377 Stratocruiser [24] during the 1980's. One of the main characteristics is that in these aircraft the lower deck lounges could not be occupied during taxiing, take-off and landing, leading to a non-revenue generating lower deck lounge when it is assumed that no additional fee has to be paid for the utilization of this lounge. The growing air cargo market, oil crisis, and restricting regulations caused the airlines to remove the LDS compartment and replace it with revenue generating cargo containers, resulting in the vanishing of LDS compartments nowadays. Therefore, the main requirement for the creation of an LDS compartment is that it can be occupied during all phases of the flight, eliminating the need for extra seats on the main deck.

With respect to the dimensions of the aircraft lower deck, the vertical distance between the main passenger deck and the lower deck floor is an essential element to be taken into account. The regular standing height in the aircraft lower deck equals 1.75 m, as yet estimated by Dos Santos [19] for the Airbus A340-300. It should be noted that the exact height of the Airbus A340-300 lower deck is not provided by Airbus, but the estimation of Dos Santos shows a reasonable accuracy when comparing with the scaled aircraft drawing in the Airbus A340-300 ACAPS [25]. When removing the additional cargo floor facilities, the standing height in the aircraft lower deck can be increased to 1.96 m. Again, this height can be verified by making a comparison with the observed standing height in the Lufthansa Airbus A340-600 lower deck lavatory area. Similarly, a patent laid by Schliwa et al[26] with regards to an LDS compartment assumes a lower deck standing height equal to 1.95 m, whereas Blauwhoff assumes a standing height equal to 1.98 m for the Airbus A330-300.
By assuming a standing height of 1.96 m for the aircraft lower deck compartment and by making use of the TU Delft DINED anthropometric database [5], it can be concluded that sufficient space is provided for the world 97.92 percentile population. In general it can also be concluded that an even higher percentile can be achieved when separate continents are considered, as can also be seen in Table A.1.

[5] DINED Anthropometric Database, Delft University of Technology, Faculty of Industrial Design Engineering, http://dined.io.tudelft.nl/ergonomics/, Accessed: 27/08/2015

The implementation of an LDS compartment could be of particular interest for both low cost carriers (LCC) and regular airlines that are willing to offer more passenger comfort. By implementing an LDS compartment, the airline in fact replaces a part of his revenue-generating cargo space for revenue-generating seats. This can be particularly interesting for LCC's that are willing to operate on long-haul routes due to shorter turn-around times, lower airport fees, associated cargo handling costs, and maximum utilization of the aircraft space [27] [28]. On the other hand, due to the increased space for passenger placement, there exists the possibility for regular airlines to increase the seating dimensions of the various classes and consequently improving overall passenger comfort.

1.2.2. LOWER DECK FACILITY UTILIZATION

The second possible utilization of the aircraft lower deck as suggested by Airbus [17] is to move the main passenger deck lavatories and galleys to the lower deck. This relocation of service facilities would allow for more seats on the main passenger deck and enhances main passenger deck comfort due to the removal of bad odors and a part of the noise in the aircraft cabin, caused by the presence of galleys and lavatories. Within current aviation practice the combined placement of lavatories and galleys in the lower deck is not present. Very few airlines have installed either lower deck galleys or lower deck lavatories and at present there are no airlines or aircraft manufacturers that have considered a combination of these placements. As briefly mentioned earlier, Lufthansa is one of the few airlines that has implemented a lower deck lavatory for the EC in their A340-600 [6], thereby substantially increasing the number of EC seats. It should be noted that both the Airbus A340-600 and the Boeing 777-300ER [29] are yet offering the possibility for airlines to implement these lower deck lavatories. However, any examples of lower deck facilities for the Boeing 777-300ER are not seen in current aviation practice.

With respect to the placement of lower deck galleys, several research activities have been carried out. Airbus has concluded in their Aircraft Service Logistics research [30] that a lower deck galley system would be a feasible addition to the current operating aircraft and hence could lower the effective direct operating costs (DOC). Similar results are obtained through a study carried out by Abritta et al [31], indicating an increase of 11.8 % in seating capacity and a decrease of 4.17 % in effective DOC for the Airbus A340-300. Moreover, the knowledge about the required galley lift systems is present as galley lifts are used in the Boeing 747 and Airbus A380 [31], thereby showing that all necessary conditions are yet present for the implementation of this new cabin design.

1.3. CURRENT KNOWLEDGE GAPS

Based on the background information as provided in Sections 1.1 and 1.2, the current knowledge gaps with respect to the mentioned topics can be identified.
Considering the aircraft performance analysis with respect to passenger comfort enhancement, a large knowledge gap can be filled as little research is yet carried out on this topic. The only available scientific study on this topic is carried out by Fuchte [32], who shows how the cabin dimensions can influence the overall aircraft performance by using an inside-out design approach.
With respect to the influence of the EC seat weight, performance results are usually provided for existing aircraft with replaced seats by aircraft manufacturers. Hence, little research has been carried out to measure the influence of aircraft seat weight from an aircraft conceptual design point of view. An analysis on the influence of the passenger seat weight on the aircraft performance could therefore pose new insights with respect to the aircraft conceptual design.

Furthermore, the knowledge gap related to the lower deck utilization can be filled by the implementation of such a design from a conceptual design point of view. As shown in Section 1.2, a lot of research is yet carried out in order to describe the requirements for the utilization of the aircraft lower deck from both a comfort point of view and an aircraft design perspective. However, the influence on overall aircraft performance is not known and hence an analysis within this respect could contribute to the full understanding and feasibility of the aircraft lower deck utilization. By creating a conceptual design of an aircraft with lower deck utilization, a compromise is achieved between comfort and performance and hence combines the most recent studies related to this topic.

[6]Lufthansa, Seat maps Airbus A340-600, http://www.lufthansa.com/nl/en/Seat_maps_A340-600, Accessed: 19/07/2015

1.4. THESIS GOAL AND RESEARCH QUESTIONS

Based on the provided background information and present knowledge gaps, a clear thesis goal is formulated for the aircraft passenger comfort enhancement methodology:

Arrive at an interior design concept that improves the flying experience of the passenger, while maintaining airline and manufacturer profitability

In order to arrive at this goal, a main research question is formulated and defined as:

Can the lower deck of the current conventional transport aircraft be changed to provide more satisfaction to both passenger and airline?

To support the main research question, two lower level research questions are defined and serve as a basis to answer the main research question. These two lower level research questions are defined as:

How does comfort enhancement influence the aircraft conceptual design in terms of aircraft operational performance?

What are the current problems regarding passenger comfort and which measures have to be taken in order to provide optimal passenger comfort?

1.5. THESIS OUTLINE

Based on the provided background information, the current knowledge gaps, and the research questions, a twofold research activity is carried out. First, it is shown how comfort enhancement influences the conceptual design of an aircraft. Secondly, the possibilities that exist in order to modify existing conventional aircraft cabins are shown, in order to arrive at an improved aircraft cabin from both airline and passenger perspective. In order to carry out these research activities, use is made of a conceptual aircraft design tool that is developed within the group of Flight Performance and Propulsion of the faculty of Aerospace Engineering at the Delft University of Technology, hereafter called the Initiator. A description of the Initiator and the corresponding adjustments and assumptions are described in the first part of Chapter 2, after which a set of modeled short-haul and long-haul aircraft are verified for further use in this thesis. Furthermore, Chapter 2 describes the utilization of models to make a comparison between the provided comfort levels of the modeled aircraft and describes the approach to identify the economical feasibility of the modeled aircraft.

Subsequently, a preliminary study is carried out in which is shown how comfort enhancing measures affect aircraft performance from a conceptual design perspective by making use of an inside-out approach. The methodology and obtained results of this study are provided in Chapter 3.

Furthermore, Chapters 4 and 5 describe the studies that are carried out in which two aircraft cabin conceptual designs are modeled to increase aircraft passenger comfort and maintain airline profitability. Chapter 4 describes the designed aircraft cabin by making use of an LDS compartment, whereas Chapter 5 shows the conceptual design of an aircraft cabin that makes use of lower deck service facilities. The results of the conceptual design studies as seen from a design perspective, an economical perspective, and a comfort perspective are provided in the same chapter.

A discussion about the used methodology, obtained results, and modeled aircraft is provided in Chapter 6, after which this thesis is concluded in Chapter 7 by providing a set of conclusions.

2

Design Methodology and Model Utilization

As mentioned in Chapter 1, the Initiator is used to study the effects of comfort-enhancing measures on aircraft performance as well as to model the new conceptual aircraft cabin designs. For this purpose, several modifications are made upfront to ensure the correct modeling of short-haul and long-haul aircraft, as described in Section 2.1. Secondly, the modeled aircraft to be used in this Thesis are described in Section 2.2, after which a verification is carried out and described in Section 2.3. Subsequently, detailed explanations of the cost estimation and comfort estimation methodologies are provided in Sections 2.4 and 2.5, respectively.

2.1. Initiator Adjustments and Assumptions

As the Initiator is suitable for multiple types of aircraft, several adjustments are made to ensure the correct modeling of conventional short-haul and long-haul aircraft. The most important adjustments and assumptions related to the aircraft modeling in the Initiator are described in this section, whereas it should be noted that further errors and instabilities of the Initiator are described in Chapter 6.

2.1.1. Conventional Aircraft Seat Placement Methodology

The current cabin configurator (CC) module within the Initiator, developed by Baan [33], is made suitable for both Blended-Wing-Body (BWB) aircraft and conventional aircraft by using a chair replacement algorithm (CRA) that overestimates the number of seats and subsequently exchanges these seats for service area, such as galleys and lavatories. The intention of this algorithm is to place as many chairs as possible in a BWB aircraft and replace a part of these chairs afterwards by the required galley and lavatory area. This algorithm poses an inaccuracy for conventional aircraft with respect to the cabin length,the number of placed passengers, and the fuselage length.

A modification of the existing galley and lavatory placement within the CC with respect to conventional aircraft is advised by Baan and hence a different algorithm is implemented. This algorithm is not based on chair replacement, but on the addition of required galley and lavatory area after placing the required seats. The existing CRA within the Initiator is therefore changed to the following order:

1. Placement of required galley area for FC passengers
2. Placement of required lavatory area for FC passengers
3. Placement of required seats for FC passengers
4. Placement of required galley area for BC passengers
5. Placement of required lavatory area for BC passengers
6. Placement of required seats for BC passengers
7. Placement of required seats for EC passengers

8. Placement of required galley area for EC passengers

9. Placement of required lavatory area for EC passengers

It should be noted that the galleys and lavatories for the First Class (FC) and Business Class (BC) compartments are placed in front of the seats, according to common practice in the aircraft industry. Furthermore, it should be noted that an Economy Premium Class (ECP) can be added between BC and EC as well, using the same placement algorithm as the EC compartment. The replacement of the CRA with the service area addition algorithm (SAAA) leads to a more accurate modeling of the fuselage length when compared to the original aircraft. This conclusion is drawn based on an average fuselage length difference with respect to the original aircraft of 0.18 % and 0.26 % for the SAAA and 1.68 % and 1.51 % for the CRA, for long-haul and short-haul aircraft, respectively. Besides this, the number of placed passengers is modeled better for long-haul aircraft when using the SAAA, as shown by an error difference of 0.80 % versus 1.37 %. Contradictory, for short-haul aircraft the SAAA provides a slightly larger error with respect to the number of placed passengers by showing a modeling error of 1.12 % versus a modeling error for the CRA equal to 0.72 %. It should be noted that the passenger modeling errors are based on the aircraft cabin layouts as described in Section 2.2, which serve as a baseline for the number of placed passengers. The 1.25 % difference between the two methods with respect to fuselage length is considered to outweigh the 0.40 % larger error with respect to the number of placed passengers for short-haul aircraft. This consideration is supported by the fact that the final number of placed passengers will only influence the class II operational and systems weight estimation, as the passenger corresponding payload is derived using the required amount of passengers instead of the modeled amount of passengers. The exact modeling errors per aircraft are shown in Table B.17.

It should be noted that the SAAA is based on the required amount of galley and lavatory area and therefore does not exactly displays feasible lavatories in a drawn CC output figure. However, by using the correct statistics for required galley and lavatory area, it is ensured that the required amount of lavatories and galleys will fit in the modeled aircraft. A different advantage of the SAAA becomes clear when analyzing the influence of seat pitch, width, and weight, as described in Chapter 3. The inaccuracy of the CRA as shown in Table B.17 does influence the results of these tests and therefore a more accurate method is preferred. As an example, one of the advantages of the SAAA is the enhanced control of the number of placed passengers when compared to the CRA. However, several inaccuracies remain when modeling a conventional aircraft cabin with the CC due to the absence of the following cabin items and properties which are not defined within the CC:

- **Overhead storage bins**
  Although the weight of the overhead storage bins is included within the class II furnishing weight group, it is assumed that the modeled aircraft cabins provide sufficient overhead storage by ensuring correct cabin dimensions when compared to the reference aircraft.

- **Crew rest areas**
  With respect to the modeled long-haul aircraft, the Boeing 777-300 [34], Airbus A340-300 [25] and Airbus A330-300 originally contain crew rest areas above and below the main passenger deck and hence it is not necessary to include these within the CC module for the main deck. The Boeing 767-300ER, however, utilizes a small part of the main passenger deck as a crew rest area. Therefore, a larger modeled galley area for the EC does represent the required area on the main passenger deck for the crew rest area on the Boeing 767-300ER. It is assumed that the modeled short-haul aircraft do not contain any crew rest areas.

- **Crew seats**
  Separate crew seat areas are not included within the cabin area estimation as these are usually located next to the emergency exits and therefore assumed to be located in the same area as the emergency exit aisles. The weight of the crew seats is taken into account within the class II furnishing group weight estimation.

Furthermore, it should be noted that the placement of chairs can not be done as exact as in the actual aircraft with any of the two described algorithms. The CC does not account for the tapering of the cabin and can therefore not exactly match the amount of seats that are placed in the various seating classes. This difference can also clearly be seen in Table B.17.

2.1.2. CLASS II WEIGHT ESTIMATION

The changes made to the class II weight estimation are described in this subsection, allowing for a more accurate modeling of the reference aircraft.

FURNISHING WEIGHT

The current furnishing weight method within the Initiator is based on the method of Raymer [35], defined in imperial units and dependent on the number of cabin crew, N_c, the weight of the cabin crew, W_c, and the fuselage wetted area, S_{fus}:

$$W_{furn} = 0.0577 \cdot N_c^{0.1} \cdot W_c^{0.393} \cdot S_{fus}^{0.75} \quad (2.1)$$

Using the estimation by Raymer, a largely underestimated furnishing weight is obtained, causing the need for a different furnishing weight estimation. Therefore, the furnishing weight estimation by Torenbeek [36], dependent on the aircraft zero-fuel weight, W_{ZF}, is implemented:

$$W_{furn} = 0.196 \cdot W_{ZF}^{0.91} \quad (2.2)$$

The differences between the values found with the approach of Raymer and the approach of Torenbeek are shown in Table 2.1. It can clearly be seen that the estimation as provided by Raymer largely underestimates the aircraft furnishing weight, when taking into account that the weight of an average EC seat weighs between 8 and 12 kilograms. This large underestimation is explained by the fact that Raymer combines the group weight estimation for both commercial transport aircraft and freighter aircraft, whereas Torenbeek makes a clear distinction between commercial transport aircraft and freighter aircraft. As the number of flight crew and the maximum amount of cargo weight is taken into account in Equation 2.1, it is assumed that the method of Raymer is more applicable to freighter aircraft than to commercial transport aircraft.

Table 2.1: Furnishing group weight comparison between Raymer and Torenbeek methods for modeled aircraft within the Initiator

Aircraft	Raymer Estimation		Torenbeek Estimation	
	Weight [kg]	Percentage of MTOW	Weight [kg]	Percentage of MTOW
Airbus A320-200	747	1.17 %	4572	6.18%
Airbus A321-200	894	1.11 %	5455	5.95%
Airbus A330-300	2177	1.08 %	11366	5.03%
Airbus A340-300	2144	0.91 %	12198	4.62%
Boeing 737-300	728	1.27 %	4200	6.43%
Boeing 737-800	733	1.08 %	4778	6.22%
Boeing 767-300ER	1878	1.16 %	9860	4.85%
Boeing 777-300	2800	1.11 %	15427	4.87%

FUSELAGE WEIGHT ESTIMATION

During testing of various aircraft models within the Initiator with respect to fuselage dimensions, it becomes clear that the analytical fuselage weight estimation provides peculiar results and therefore poses a large instability on the convergence loop of the Initiator. In general, it is seen that the analytical fuselage weight estimation shows a large overestimation for long-haul aircraft models when a comparison is made with empirical relations as defined by Nicolai [37], Torenbeek [36], and Howe [38]. Due to the fact that the fuselage weight estimation forms an important group weight calculation during this thesis for both the comfort enhancement testing and the conceptual cabin design, it is chosen to replace the analytical fuselage weight estimation by an empirical estimation, as defined by Nicolai [37]. The fuselage weight estimation of Nicolai depends on the fuselage length, l_{fus}, height, h_{fus}, and diameter, d_{fus}. Furthermore, the dive speed, V_D, take-off weight, W_{TO}, and maximum load factor, N_Z, are taken into account. The empirical estimation for the fuselage weight, expressed in imperial units, is defined as:

$$W_{fus} = 200 \cdot [(W_{TO} \cdot N_Z \cdot 10^5)^{0.286} \cdot \frac{l_{fus}}{10}^{0.857} \cdot \frac{d_{fus} + h_{fus}}{10} \cdot \frac{V_D}{100}^{0.338}]^{1.1} \quad (2.3)$$

AIRCRAFT CENTER OF GRAVITY AND LOADING

According to current practice in the Initiator, the aircraft is designed such that every loading sequence is considered and hence does not pose any problems during the design of the new aircraft cabin, as described in Chapters 4 and 5. Moreover, the center of gravity (CG) of the aircraft is determined by taking the CG of all aircraft components into account. To simplify these calculations, most of the group weights that are relevant to the aircraft cabin are assumed to have its CG at a similar position as the fuselage CG. It is chosen to modify the CG position of these group weights during the design of a new aircraft cabin, as described in Chapters 4 and 5. However, the CG of these weight groups is assumed to be positioned at the same location as the fuselage CG for the comfort enhancement tests as described in Chapter 3. This assumption is based on the fact that a lengthening or shortening of the fuselage does automatically include a shift in the aircraft CG, thereby highly likely providing a similar error as compared to the original modeled aircraft with respect to the CG. With respect to the aircraft seat weight variation as described in Section 3.4, which does not change the overall fuselage dimensions, a shift in the particular class II groups weights CG could occur as only the EC cabin is considered. However, as the seat weight forms a small fraction of the total furnishing weight, it is assumed that the CG remains at a similar location.

2.2. MODELED AIRCRAFT

In order to study the influence of comfort enhancing measures on aircraft performance and to serve as a baseline for cabin conceptual design, a set of narrow- and wide-body aircraft are modeled:

Wide-Body Aircraft

- Airbus A340-300
- Airbus A330-300
- Boeing 777-300
- Boeing 767-300ER

Narrow-Body Aircraft

- Airbus A320-200
- Airbus A321-200
- Boeing 737-300
- Boeing 737-800

2.2.1. AIRCRAFT LAYOUT MODELING

The baseline aircraft cabin layouts that are used to study the influence of aircraft seats on aircraft performance are shown in Figures C.1 through C.8. It should be noted that the blue areas in these figures represent the areas that are required for lavatories, while the red areas represent the areas that are occupied by galleys.

It is observed that the configurations as presented in Figures C.1 until C.8 contain various seating configurations and a varying number of seats and classes. In order to assess the influence of various comfort characteristics on the aircraft performance, it is chosen to change the characteristics with respect to the EC seat for each aircraft. This choice is motivated by using Figure 1.1, which shows that the EC cabin is mostly constraining passenger comfort. It should be noted that the effect of comfort enhancing parameters shows a larger importance for long-haul aircraft, as cabin-related comfort proves to be more important for passengers during long-haul flights. Francis et al [39] and Wensveen and Leick [40] both show that long-haul aircraft cabins are more susceptible to changes in comfort when compared to short-haul aircraft. For all modeled aircraft, the seating configuration is derived from existing airline configurations, as specified in Table 2.2.

Table 2.2: Modeled aircraft for comfort enhancement testing including airline reference

		FC		BC		EC	
Aircraft Type	Reference Airline	Pax	Seating	Pax	Seating	Pax	Seating
Airbus A320-200	Turkish Airlines [1]	-	-	12	2-2	141	3-3
Airbus A321-200	Air Canada [2]	-	-	14	2-2	169	3-3
Airbus A330-300	Turkish Airlines [3]	-	-	28	2-2-2	260	2-4-2
Airbus A340-300	Emirates Airlines [4]	12	2-2-2	42	2-3-2	213	2-4-2
Boeing 737-300	Norwegian Air [5]	-	-	-	-	148	3-3
Boeing 737-800	Japan Airlines [6]	-	-	20	3-2	145	3-3
Boeing 767-300ER	All Nippon Airways [7]	-	-	35	2-1-2	179	2-3-2
Boeing 777-300	Japan Airlines [8]	-	-	78	2-4-2	422	3-4-3

The cabin layouts as mentioned in Table 2.2 can not be exactly matched using the Initiator, due to restrictions on the CC as explained in Section 2.1. However, for all aircraft it is aimed to model the fuselage length and width as exact as possible with respect to the original aircraft in order to determine the influence of seat parameters on an inside-out cabin design approach.

2.3. INITIATOR MODEL VERIFICATION

In order to study the influence of comfort enhancement on aircraft performance and to model the new designed aircraft cabins, a verification of the Initiator results is carried out by comparison with original aircraft data. The verification of the results is carried out by making use of the modeled aircraft as described in Section 2.2. A division of the verification is made by individually assessing the aircraft group weights and sizing, as described in Subsection 2.3.1, and the engine model, as described in Subsection 2.3.2.

2.3.1. AIRCRAFT GROUP WEIGHT AND SIZING VERIFICATION

Table 2.3 shows the average modeling errors with respect to several aircraft key parameters for the short-haul and long-haul aircraft as modeled with the Initiator. It can clearly be seen from this table that the average modeling error for various key parameters is in general larger for long-haul aircraft. The small modeling errors with respect to the overall fuselage dimensions are attributed to the usage of empirical fuselage length and diameter estimations based on the aircraft cabin dimensions, as developed during the design of the CC. It is shown through the results in Table 2.3 that the empirical relations below show a better correlation with respect to long-haul aircraft when use is made of the SAAA:

$$l_{\text{fus}} = \frac{l_{\text{cab}}}{0.77} \tag{2.4}$$

$$d_{\text{fus}} = (1.045 \cdot w_{\text{cab}}) + 0.084 \tag{2.5}$$

Table 2.3: Average modeling errors for long-haul and short-haul aircraft as modeled within the Initiator

	Average Modeling Error	
Aircraft Key Parameter	Long-Haul Aircraft	Short-Haul Aircraft
Fuselage Length	0.18 %	0.26 %
Fuselage Diameter	0.81 %	1.98 %
Maximum Take-Off Weight	6.41 %	3.26 %
Typical Operational Empty Weight	5.20 %	3.84 %
Wing Reference Area	6.77 %	4.27 %

For a detailed overview of the modeling errors for each key parameter of the modeled aircraft, the reader is referred to Tables B.1 until B.16. It should be noted that the typical mission range as defined in these tables is derived from corresponding airline websites and by averaging the distances for typical routes related to the aircraft. Moreover, the specific payloads for the typical and harmonic missions are different: the payload for the harmonic mission is based on the maximum structural payload as provided by the aircraft manufacturer, whereas the payload for the typical mission is based on the number of seats.

[1] Turkish Airlines Airbus A320-200, http://www.turkishairlines.com/en-int/travel-information/turkish-airlines-passenger-cargo-airbus-boeing-all-flight-fleet, Accessed: 27/07/2015

[2] Air Canada Airbus A321-200, http://www.aircanada.com/en/about/fleet/a321-200xm.html, Accessed: 27/07/2015

[3] Turkish Airlines A330-300, http://www.turkishairlines.com/en-int/travel-information/turkish-airlines-passenger-cargo-airbus-boeing-all-flight-fleet, Accessed: 27/07/2015

[4] Emirates Airlines A340-300, http://www.emirates.com/english/flying/our_fleet/seating_chart.aspx?id=343LFJY&from=193757, Accessed: 27/07/2015

[5] Norwegian Airlines Boeing 737-300, http://www.norwegian.com/uk/about-norwegian/our-company/fleet/, Accessed: 27/07/2015

[6] Japan Airlines Boeing 737-800, https://www.jal.co.jp/en/aircraft/conf/737.html, Accessed: 27/07/2015

[7] All Nippon Airways Boeing 767-300ER, https://www.ana.co.jp/wws/japan/e/local/domestic/departure/inflight/seatmap/detail.html, Accessed: 27/07/2015

[8] Japan Airlines Boeing 777-300, https://www.jal.co.jp/en/aircraft/conf/773.html, Accessed: 27/07/2015

It should be noted that the typical mission payload ignores the fact that most airlines, with the exception of LCCs, carry additional freight to increase their revenue. This assumption is made for both the comfort enhancement tests, as described in Chapter 3, and the lower deck analyses, as described in Chapters 4 and 5. With respect to the comfort enhancement analysis, an increase in seat pitch or seat width results in an increase in fuselage dimensions and therefore additional cargo storage space. This additional space could result in an increase of typical carried freight, denying a reasonable comparison between the different cases. With respect to lower deck utilization, it is concluded that an optimal utilization of the lower deck results in a situation where no additional freight can be carried by the airline.

2.3.2. ENGINE MODEL VERIFICATION

An important parameter that has to be taken into account for the mission analysis is the specific fuel consumption (SFC). The SFC is calculated by means of an off-design engine model, which is integrated in the mission analysis module. In order to allow for the calculation of the cruise SFC, a list of input parameters is required, specifying the engine layout and related specifications. Where known from literature, input parameters are provided to the engine model. However, due to a lack of available literature about the required engines for the modeled aircraft, estimates are made for the input parameters. In order to verify these estimates, a comparison between the calculated cruise SFC and reference cruise SFC is made to determine the average modeling error in terms of the cruise SFC and hence the overall aircraft fuel burn. An average modeling error with respect to the cruise SFC of 10.68 % and 5.77 % is found for short-haul and long-haul aircraft, respectively. It should be noted that the large average error for the modeled short-haul aircraft is mainly caused by the cruise SFC error related to the Boeing 737 variants. For a more detailed overview of the calculated cruise SFC, the reader is referred to Table B.18.

2.4. AIRCRAFT ECONOMICAL FEASIBILITY ANALYSIS

To determine whether the proposed cabin solutions as described in Chapter 4 and 5 are feasible from an economical point of view, a cost-benefit analysis is carried out by using a separate cost estimation module. The feasibility study contains an analysis from a manufacturing point of view, as described in Subsection 2.4.1, and from an airline point of view, as described in Subsection 2.4.2. Furthermore, the analysis is concluded by means of various sensitivity analyses, as described in Subsection 2.4.3.

2.4.1. DETAILED MANUFACTURING AND OPERATING COSTS

The proposed cabins are highly likely to influence the cost of manufacturing and hence the final list price, which subsequently influences the total operating costs (TOC) of the airline. In order to determine the influence of the proposed cabins from a manufacturing point of view, use is made of a non-recurring cost estimation of Roskam [41] and a recurring cost estimation of Beltramo [42]. The implementation of these models in the Initiator is described by Zijp [43]. Furthermore, in order to make a comparison among the modeled aircraft, the following assumptions are made:

- **Cost Estimation Approach**
  It should be noted that two different cost estimation approaches are available to calculate the associated manufacturing costs: a bottom-up approach and a top-down approach. The bottom-up approach uses existing relations based on the Beltramo method, dating from 1977, while the top-down approach is based on an initial list price in combination with a regression analysis. It is chosen to use the top-down approach to calculate the aircraft manufacturing costs, based on the fact that this approach is usually preferred during conceptual design [44].

- **Manufacturer Profitability**
  It is assumed that the profitability margin of the aircraft manufacturer remains constant for all modeled aircraft. Hence, a manufacturer profitability margin of 10 % is assumed throughout this analysis.

- **Non-Commonality Factors**
  It is assumed that the non-commonality factors among the modeled aircraft remain constant. Although it can be argued that the proposed cabins might be subject to a higher non-commonality factor due to increased manufacturing complexity, it can not be determined how the additional adaptions are influencing the non-commonality factors. As it is assumed that similar manufacturing materials are used when compared to the original Airbus A340-300, it is consequently assumed that the difference in non-commonality factors is negligible.

- **Diverse Manufacturing Factors**
  Other manufacturing factors, such as facility factors, CAD factors, and the number of tests, are kept equal among the modeled aircraft for the estimation of the aircraft list price.

Using the above mentioned assumptions and applying the methods of Roskam and Beltramo, the aircraft list price and manufacturing costs are used in order to determine the economical feasibility from a manufacturing point of view.

2.4.2. Airline Operating Costs and Revenue

For the designed aircraft to be profitable, a positive balance has to be present with respect to the TOC and revenue. First of all, the airline operating costs are calculated for a specified service life. Secondly, the airline revenue is obtained for the same service life by using a set of pre-defined yields.

Airline Operating Costs

The aircraft DOC and TOC for the modeled cabins in Chapters 4 and 5 provide a good indication for the airline operational performance in terms of associated operating costs. The DOC and indirect operating costs (IOC) of the modeled aircraft are calculated by making use of the methods of Roskam [41] and Maddalon [45] and are multiplied by a revenue inflation rate during the aircraft service life. Based on the depreciation period, service life, and discounted cash flow period, the operational costs throughout the service life are calculated. The most important input parameters for the cost estimation module, including their appropriate reference, are listed in Table D.1.

Airline Revenue Calculation

The airline revenue is determined by means of pre-defined passenger and cargo yields, as shown in Table D.1. Based on the difference between the airline revenue and operating costs, the net profit is calculated. In order to determine the net airline profit, the following assumptions are made:

- **Passenger and Cargo Yields**
  The passenger and cargo yields are kept constant among the modeled aircraft.

- **Operational Lifetime and Depreciation Period**
  The aircraft operational lifetime and depreciation period of the various aircraft components are kept constant among the modeled aircraft. Consequently, the number of flights during the aircraft operational lifetime remains constant as well.

- **Aircraft Ownership Interest Rate**
  Following the full aircraft ownership by the airline, the interest rate to be paid for the book value of the aircraft is assumed to be constant for all modeled aircraft.

- **Tax Rate**
  A constant tax rate is assumed for all modeled aircraft and is applied on the airline earnings after paying interest costs.

- **Interest Rate for Return on Investment**
  The interest rate to be paid for the earnings after taxes is assumed to be constant for all modeled aircraft. After paying the interest rate of the investment, the net airline profit is obtained.

2.4.3. Sensitivity Analyses

In order to determine the feasibility of the modeled aircraft in case of variations in uncontrollable factors, multiple sensitivity analyses are carried out. It should be noted that all assumptions as stated in Subsections 2.4.1 and 2.4.2 are valid for the analyses, unless otherwise specified.

Passenger Load Factor Sensitivity

For the typical mission profile of all modeled aircraft, a passenger load factor of 100 % is assumed. As shown in Figure 2.2, lower passenger load factors are more realistic and hence a sensitivity analysis is carried out for the typical mission profile. It should be noted that the layout and structure of the modeled aircraft remains the same, whereas only the number of passengers (and hence payload) for the typical mission is varied.

FUEL PRICE SENSITIVITY

When examining Figure 2.1, a large variation in the aviation fuel price is observed. Hence, due the expected higher OEW of the modeled aircraft and associated fuel consumption, a sensitivity analysis with respect to the fuel price is carried out in order to show the effects on the operating costs. A variation in fuel price is applied for all modeled aircraft, based on both a passenger loading factor of 80 % and 100 %. It is known upfront that a linear relationship between the airline profitability and the jet fuel price is present, based on the influence of the fuel price on the DOC. This relationship is dependent on the block fuel weight, $W_{F_{\text{Block}}}$, the block range, R_{Block}, the cost of fuel, C_F, and the fuel density, ρ_F:

$$\text{DOC}_F = \frac{W_{F_{\text{Block}}}}{R_{\text{Block}}} \cdot \frac{C_F}{\rho_F} \tag{2.6}$$

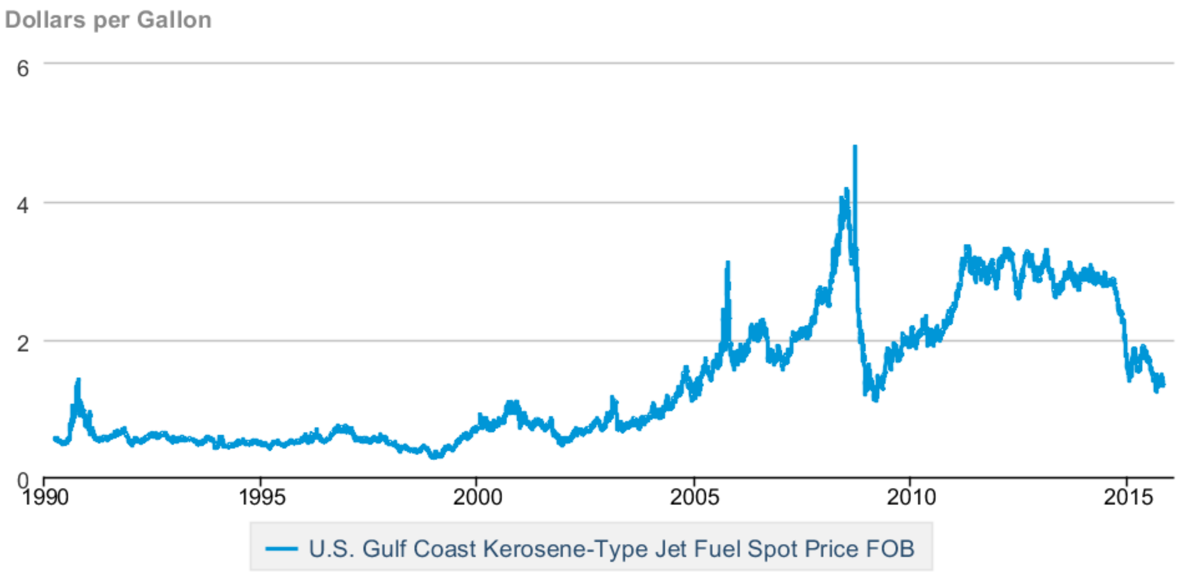


Figure 2.1: Historical jet fuel spot price trend [9]

REDUCED FREIGHT CARRYING CAPACITY

An important part of the feasibility analysis describes the comparison between the lower deck utilization for passenger placement and the lower deck utilization for cargo carriage. According to Blauwhoff [18], based on internal communication with Airbus and Zodiac Aerospace, an average cargo carrying usage of 37 percent is currently attained. This statistic correlates well with data provided by CAPA, as shown in Figure 2.2, and based on data provided by Boeing and IATA.
A critical note has to be placed with respect to the above mentioned passenger belly cargo load factors. None of the above mentioned sources describe whether the load factors include passenger luggage as well. Similarly, there exists an uncertainty whether there exists a difference between long-haul and short-haul airlines within this respect. As mentioned in Chapter 1, LCC's might choose not to carry additional cargo, which could result into a skewed figure with respect to the aircraft belly cargo load factor.

Considering the original Airbus A340-300, it is shown in Chapter 4 that at least 11 LD3 containers are required in order to provide sufficient storage space for passenger luggage. Based on Airbus A340-300 data[25], it is seen that 21 LD3 containers are left for the storage of additional cargo. Assuming a utilization of 37 percent of these containers, a total of 8 LD3 freight containers is carried on average, amounting to a volume of 33.6 m^3. It should be noted that arbitrary cargo, of varying density, can be placed, resulting in a large uncertainty with respect to the additional generated revenue.

[9] U.S. Energy Information Administration, October 2015, http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EER_EPJK_PF4_RGC_DPG&f=D, Accessed: 30/10/2015

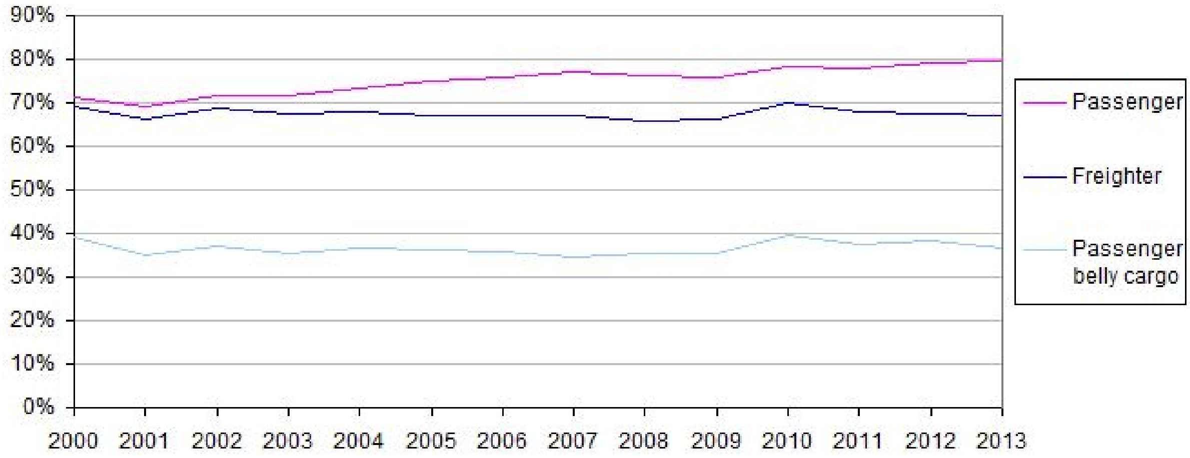


Figure 2.2: World passenger load factor, freighter load factor and passenger belly cargo load factor percentages for the years 2000 to 2013 [10]

A solution for this uncertainty is provided by the ICAO, which shows that a cargo density of 161 $\frac{kg}{m^3}$ reflects the current average packing efficiency among major airlines [46]. By using this estimation it is concluded that on average approximately 5400 kg of additional cargo is carried along with the Airbus A340-300. In turn, this weight is related to a specific airline revenue by making use of the cargo yield. In order to determine whether there exists a point where it becomes more interesting from an economical point of view for the airline to transport cargo instead of passengers in the aircraft lower deck, a sensitivity analysis is carried out showing the variation of additional cargo payload with DOC and revenue. Subsequently, the airline profits are determined as a function of additional freight carriage and hence a comparison can be made between the modeled cabins and the original Airbus A340-300.

2.5. AIRCRAFT RELATIVE COMFORT ANALYSIS

In order to determine whether the modeled aircraft are providing a higher level of passenger comfort, as required through the thesis goal in Subsection 1.4, a model is developed to describe a relative comfort level between the different aircraft. As the modeled aircraft in Chapter 3 are solely used to determine the influence of different seat dimensions on the aircraft performance, a relative comfort model is established that compares the influence of different seat dimensions on the overall level of passenger comfort. For the models as defined in Chapter 4 and 5 additional factors contributing to the overall passenger comfort are described and taken into account to provide a comparison in terms of passenger comfort.

The development of the model is split in three parts, where firstly Subsection 2.5.1 describes the definition of passenger comfort and the comfort aspects associated to the total passenger comfort perception. Secondly, Subsection 2.5.2 shows the used theories in order to assign a relative comfort score to each comfort aspect. Finally, Subsection 2.5.3 describes the developed comfort model that is used to compare the comfort levels of the modeled aircraft, based on aircraft seat and cabin parameters.

2.5.1. THE DEFINITION OF COMFORT AND RELATING FACTORS IN THE AIRCRAFT CABIN

Various definitions of comfort exist in literature, ranging from formal definitions as described in dictionaries as well as specific definitions. For a comfort analysis in this thesis, use is made of a more general expression for passenger comfort, as defined by Quehl [47]:

Passenger comfort is related to the psychological state of the passenger well-being in an optimal condition, relating to relaxation, pleasantness, satisfaction, and convenience.

[10] CAPA Center for Aviation, Air cargo: few other industries would tolerate its structural overcapacity, October 2014, http://centreforaviation.com/analysis/air-cargo-few-other-industries-would-tolerate-its-structural-overcapacity-192139, Accessed: 12/09/2015

As shown by Vink et al [48] a product, in this case an aircraft cabin, in itself can not be defined as comfortable. Hence, the modeled aircraft cabins as described in Chapters 4 and 5 cannot be directly linked to a specific state of comfort. However, comfort modeling guidelines, passenger surveys, and correlations are present in literature to allow for a relative comparison among the modeled cabins. Hence, whether or not the analyzed cabins are defined as comfortable or not, a relative comfort score can be assigned to the different cabins.

In order to assess the comfort improvement of the modeled solutions as described in Chapters 4 and 5, initial use is made of the comfort correlations as described in the works of Konieczny [6], Vink et al [48], and Richards and Jacobson [49]. A comparison between the correlation coefficients with respect to the most important passenger comfort aspects is shown in Table 2.4. It should be noted that the work of Richards and Jacobson contains rather old data, whereas the studies of Konieczny and Vink et al are based on more recent comfort data. This observation provides an explanation for the fact that certain comfort aspects are missing in the analysis of Richards and Jacobson. Furthermore, it should be noted that the data from the work of Konieczny is only a small part of his research. As this thesis only considers the impact of the aircraft cabin on the overall passenger comfort, only the hardware-related comfort correlations from the work of Konieczny is used. By focusing on the aircraft cabin as a means of enhancing passenger comfort, the pre-flight phase and post-flight phase are not considered in this comfort analysis.

Table 2.4: Comparison between correlation coefficients of specific comfort aspects on overall passenger comfort as found in the works of Konieczny [6], Vink et al [48], and Richards and Jacobson [49]

	Correlation Coefficient wrt. Overall Passenger Comfort		
Comfort Aspect	Konieczny	Vink et al	Richards and Jacobson
Legroom	-	0.718	0.54
Cabin Noise	-0.70	0.221	0.41
Cabin Climate	0.14	0.113	-
Toilet Quality	-	0.291	-
Toilet Quantity	0.13	-	-
Catering Service	-0.28	0.331	-
Movement Possibilities	0.83	-	-
Cabin Odors	-	-	0.15
Aircraft Type	-	0.11	-
Personal Space	-	0.314	-

By conducting a trade-off for the usage of the comfort correlations, it is chosen to use the statistics as stated by Vink et al. This choice is based on the fact that the correlation coefficients from the work of Vink et al independently relate to a passenger comfort level, whereas the correlation coefficients of Konieczny relate to a hierarchy in terms of passenger comfort. The latter leads to a situation that the comfort correlation coefficients can not be directly translated in a total passenger comfort level. Furthermore, the coefficients provided by Richards and Jacobson are considered to be out-of-date and do not provide sufficient information with respect to the considered comfort aspects.

2.5.2. RELEVANT COMFORT ASPECTS AND IMPACT MEASUREMENT

In order to make a relative comparison between the modeled cabins, a set of relevant comfort aspects is selected and a method is provided to calculate a relative comfort level among the modeled aircraft in Chapters 4, and 5. As the seat and cabin dimensions are mainly varied in this thesis, the relative comfort level determination is based on these parameters as well. Four associated comfort measures as found in literature are described below and ultimately merged into one relative comfort model.

SEAT PITCH AND ASSOCIATED LEGROOM

To determine a comfort level associated to a defined seat pitch, the following equation, provided by Kremser et al [9], is used and relates passenger well-being, wb, seat pitch, sp, and buttock-knee length, bkl:

$$wb = -40.86 + 2.424 \cdot sp - 0.056 \cdot bkl - 0.037 \cdot sp^2 + 0.008 \cdot sp \cdot bkl - 0.001 \cdot bkl^2 \quad (2.7)$$

It is interesting to note that a smaller buttock-knee length for a fixed seat pitch leads to a lower comfort perception of the passenger, as shown in Figure 2.3. This effect is highly likely to be caused by side effects, such as the feeling of having little personal space by passengers with larger buttock-knee lengths. This feeling could in turn lead to a higher perception of comfort when this particular passenger is subject to a seat with a larger seat pitch. A more detailed analysis of the passenger personal space is therefore provided later in this subsection, including its influence on the passenger comfort level.

The level of passenger well-being as obtained through Equation 2.7 is used as a contributing factor to the overall level of passenger comfort. From Table 2.4 it is seen that the obtained comfort level related to seat pitch has a correlation coefficient of 0.718 with respect to the overall passenger comfort level.

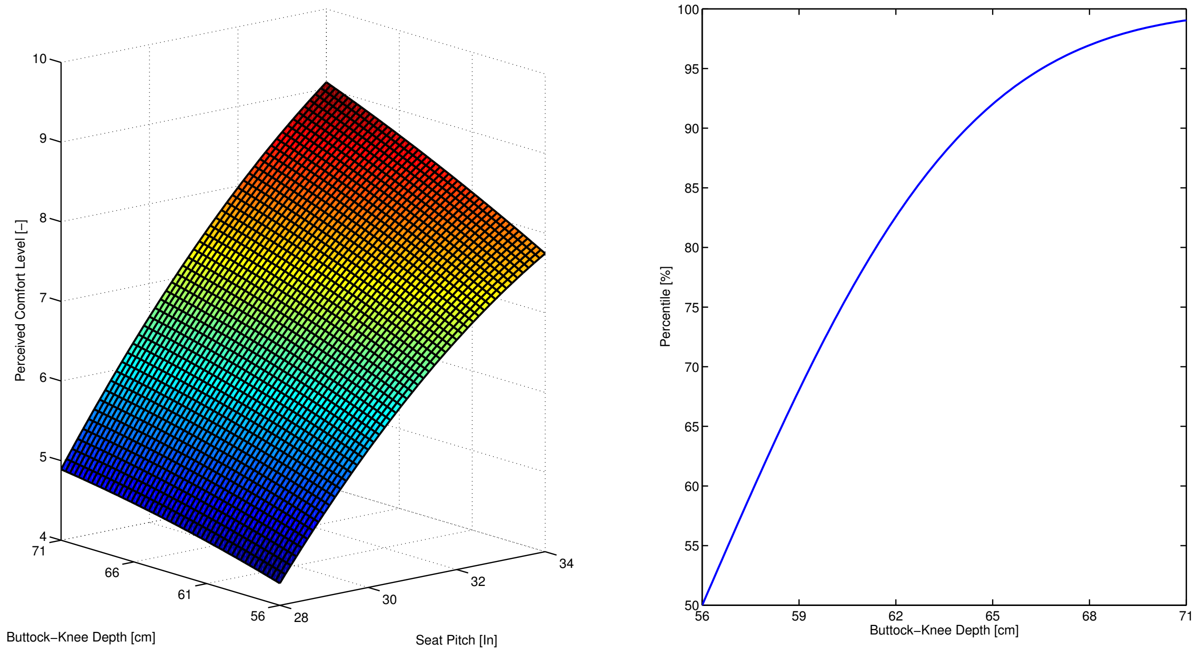


Figure 2.3: Perceived passenger comfort level and percentile as a function of buttock-knee length and seat pitch

SEAT CUSHION WIDTH

For the relation between the seat cushion width and the passenger anthropometric dimensions, no mathematical models are present in current literature. However, when examining the results as obtained by Richards and Jacobson [49], depicted in Figure 2.4, one can observe a similar trend with respect to comfort as compared to the relation found by Kremser. This similar trend is supported by a study of Tereoka [50], who stated that a strong relationship is present between the anthropometric dimensions, the dimensions of the seat, and the perceived passenger comfort level.

Based on these research activities, a comfort model is derived that relates the seated hip width and the seat cushion width to a specific passenger comfort level. Contrary to the seat pitch relation, the seat cushion width often provides insufficient space for the aircraft passenger. Hence, in case the seat cushion width does not match the actual anthropometric dimensions, a very low level of perceived comfort is achieved, based on the theory of Tereoka. The result of the constraining seat width is that a mirrored curve is obtained when compared to Figure 2.3. The final mathematical model for the determination of passenger comfort level with respect to seat cushion width is shown in Figure 2.5. It is observed from this relationship that a minimum required seat cushion width relates to a perceived comfort level that is just sufficient, being equal to values between 5.5 and 6.

With respect to the correlation between seat cushion width and the overall perceived comfort level, no coefficient is present in the work of Vink et al. However, when examining the work of Richards and Jacobson and Konieczny, it is seen that the correlation between seat cushion width and overall comfort is nearly equal to the correlation between seat pitch and overall comfort. Therefore, a correlation coefficient equal to 0.69 is assumed to be present in order to quantify the influence of the seat cushion width.

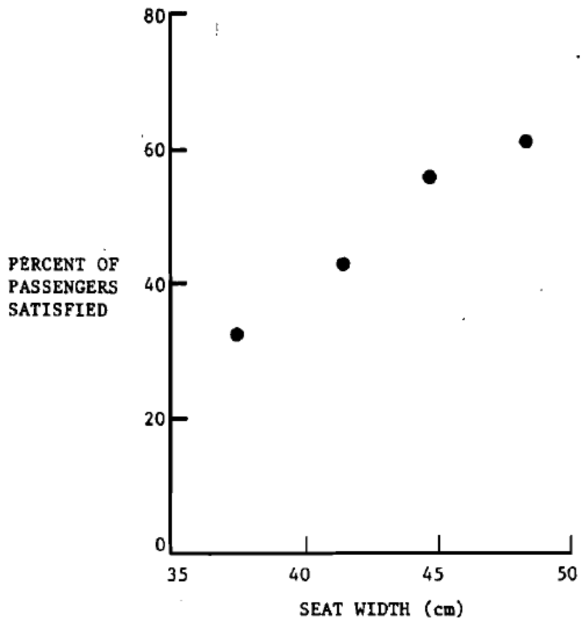


Figure 2.4: Percentage of passengers satisfied as a function of seat width [49]

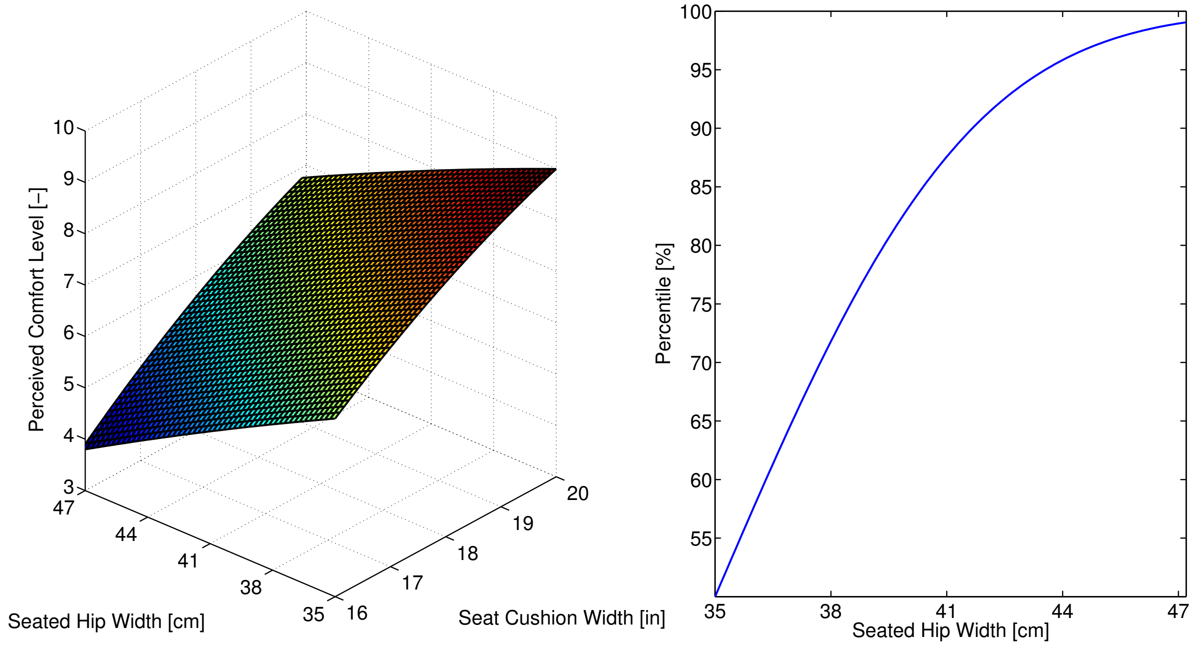


Figure 2.5: Perceived passenger comfort level and percentile as a function of seated hip width and seat cushion width

Passenger Personal Space

The perceived passenger personal space is determined by identifying the 2-dimensional personal space of the passenger, as seen from the passenger seat and depicted in Figure 2.6. The assumption is made that the passenger personal space is defined by multiplying the seat cushion width with the seat pitch minus the backrest thickness. It can be argued, based on the theory of Kremser, that a passenger with larger human dimensions is subject to a lower level of perceived comfort for a fixed amount of personal space when compared to a passenger with smaller human dimensions.

Two human dimensions are selected in order to determine the required personal space of the passenger. First of all, the buttock-knee length is taken as a measure to determine the required passenger space in longitudinal direction.

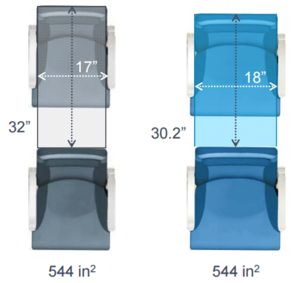


Figure 2.6: Economy class personal space calculation by Airbus [51]

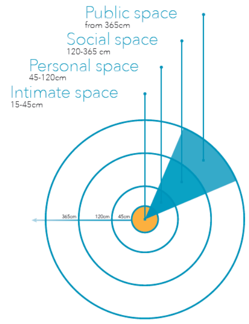


Figure 2.7: Personal space spheres as defined by Hall [52]

Secondly, the seated hip width is used in order to determine the required passenger space in lateral direction. Based on research conducted by Airbus [51], a linear relationship is identified between the perceived passenger comfort level and the passenger personal space. Hence, based on the difference between the required personal space of the passenger, defined by multiplying the buttock-knee length and seated hip width, and the provided personal space, one can define a relative comfort level. In terms of personal space, the seat cushion width has a larger influence when compared to the seat pitch. It is found by Airbus that an increase of one inch in seat cushion width relates to a similar comfort level, in terms of personal space, when increasing the seat pitch with 1.6 inch. The obtained results of Airbus are related to the social distance theory, also called proxemics theory, of Hall [5], as shown in Figure 2.7. Based on this theory, it is seen that the overall seat width determines whether the passenger intimate space is accessed and that the intimate space is rarely accessed from a longitudinal point of view. As a linear relationship is assumed by Airbus for the perceived comfort level associated to personal space, Figure 2.8 is established in order to determine the associated perceived level of comfort. In this case, the worldwide 95 passenger percentile is considered. However, it should be noted that different percentiles will result in a changed figure.

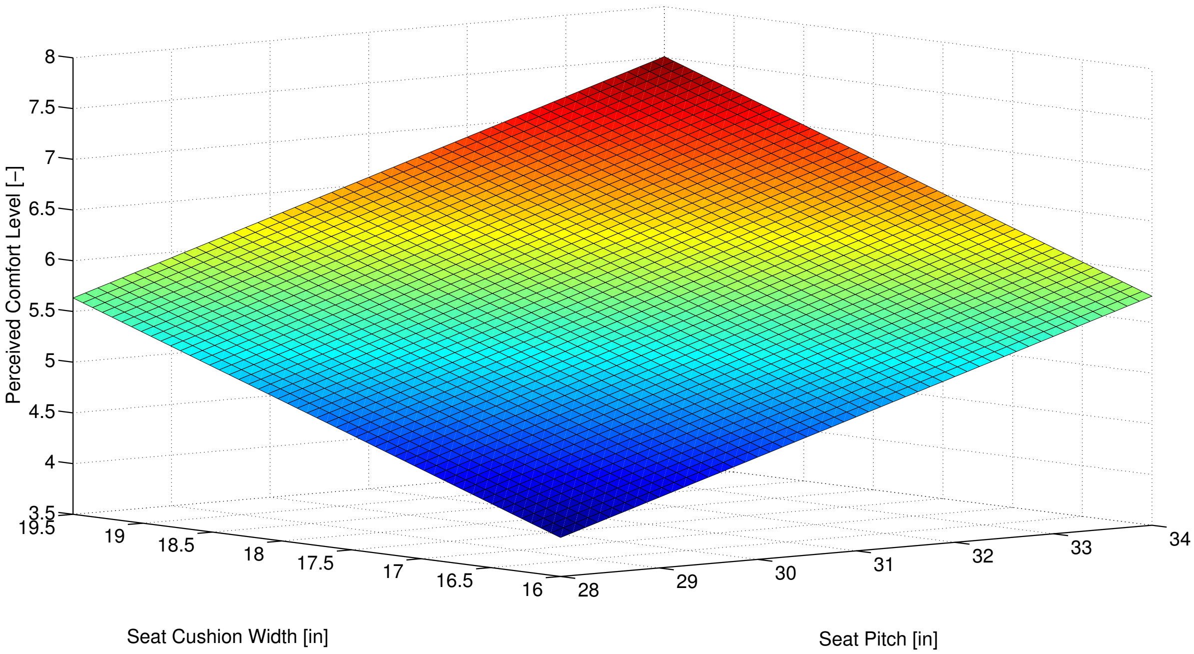


Figure 2.8: Perceived passenger comfort level as a function of seat pitch and seat cushion width relating to personal space for the worldwide 95 passenger percentile

Using the perceived comfort level as obtained through Figure 2.8, reference is made to the overall passenger comfort level by means of Table 2.4. A correlation of 0.314 exists between the passenger personal space and the overall comfort level.

AIRCRAFT CABIN WIDTH AND SEATING CONFIGURATION

According to Brauer [53], a relationship exists between a passenger preference level and the effective cabin width per seat. The latter is measured at seated eye level and is calculated by taking into account the cabin width, w_{cabin}, the number of aisles, n_{aisles}, and the number of seats abreast, n_{abreast}:

$$w_{\text{cabin}_{\text{eff}}} = \frac{w_{\text{cabin}} - n_{\text{aisle}} \cdot 0.4826}{n_{\text{abreast}}} \tag{2.8}$$

It should be noted that the constant value of 0.4826 in this equation relates to the assumed 19 inch aisle width by Brauer. Furthermore, it is seen from Equation 2.8 that the implemented seating configuration, cabin width, and number of aisles eventually depend on the seat cushion width and hence can be related to the adopted comfort model.

Based on the findings of Brauer, the passenger preference level is directly translated into a perceived comfort level and an asymptotic polynomial fit is established in order to determine the perceived comfort level as a function of the effective cabin width. The resultant curve is shown in Figure 2.9 and by using the obtained correlation coefficient of 0.11 with respect to the overall level of passenger comfort, the contribution of the seating arrangement to the overall passenger comfort level is established.

It is seen from Figure 2.9 that the exponential increase could lead to perceived comfort levels above 10. It should be noted, however, that an effective cabin width per seat at seated eye level rarely exceeds 0.51 m in the EC cabin. Nevertheless, a functionality is present in the established comfort model in order provide a maximum value of 10 when very high effective cabin widths are obtained. One could argue that a sigmoid function would ideally suit this behavior. However, a smaller correlation between the sigmoid function and the provided data points is obtained when compared to the utilized exponential function. Therefore, the exponential function as shown in Figure 2.9, in combination with the limiting functionality, is used.

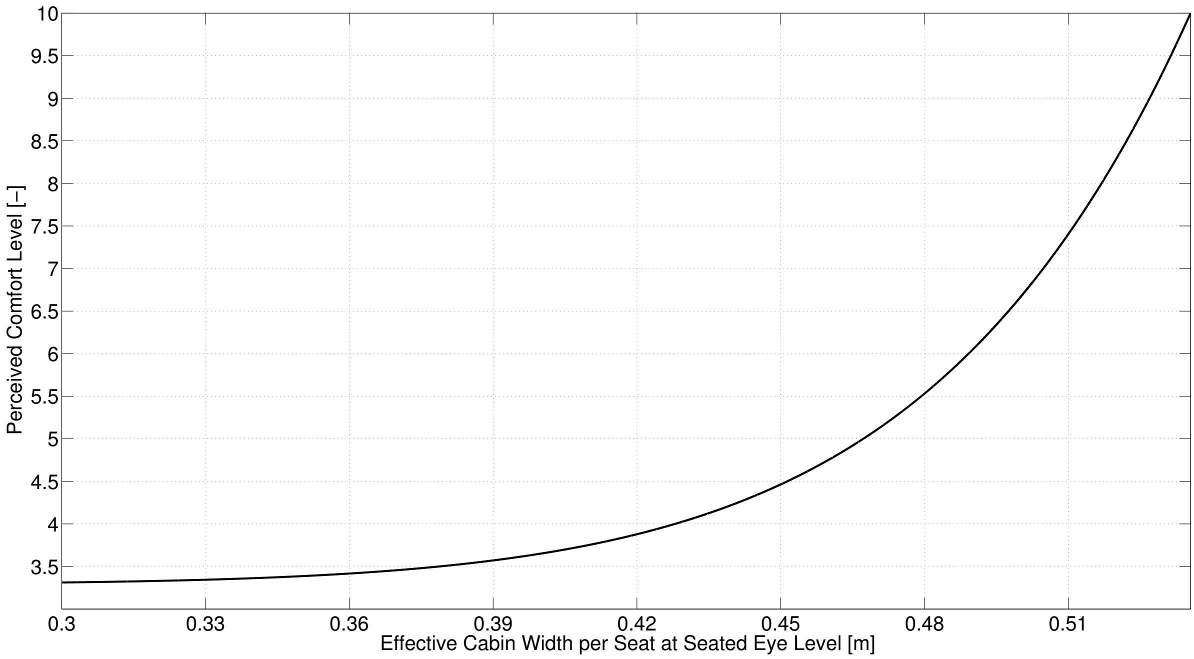


Figure 2.9: Perceived passenger comfort level versus effective cabin width at seated eye level

Table 2.5: Implemented comfort aspects for relative comfort determination

i	Related Comfort Measure	Related Comfort Theory	Correlation wrt Overall Comfort
1	Seat pitch	Kremser [9]	0.718
2	Seat cushion width	Personal Derivation	0.69
3	Personal space	Airbus [51]	0.314
4	Perceived cabin space	Brauer [53]	0.11

2.5.3. RELATIVE COMFORT MODEL BASED ON SEAT DIMENSIONS

By using the correlation coefficients as stated in Table 2.4 and the obtained comfort levels as described in Subsection 2.5.2, a relative comfort measure is established in order to compare the modeled aircraft in terms of seat and cabin dimensions. The total comfort level based on the correlation coefficients and associated comfort levels is calculated as follows:

$$wb_{\text{overall}} = \sum_{i=1}^{4} \frac{c_{\text{i}}}{\sum_{i=1}^{4} c_{\text{i}}} \cdot wb_{\text{i}} \tag{2.9}$$

The subscripts as defined in Equation 2.9 relate to the different comfort measures as described in Subsection 2.5.2 and stated in Table 2.5.

3

Aircraft Comfort Enhancement in Conceptual Cabin Design

The modeled aircraft as described in Chapter 2 are used to analyze the influence of seat pitch, width, and weight on overall aircraft performance from a conceptual aircraft design point of view. This is done by making use of an inside-out approach, which is based on the fact that the aircraft cabin is sized according to the number of passengers, the seating configurations, and the seat characteristics. The inside-out design method is chosen due to the fact that whether an outside-in approach, where the fuselage dimensions are kept fixed, or an inside-out approach is chosen, the aircraft total geometry can not be exactly matched for a large number of tests due to the convergent nature of the Initiator.
First of all, a set of metrics is defined in Section 3.1 in order to measure the aircraft performance with respect to the particular comfort enhancement. The adjustments made to the seat dimensions are described in Section 3.2, in which it is also shown how these adjustments are related to a set of optimum seat dimensions. Finally, this chapter is concluded in Sections 3.3 and 3.4 by presenting the results for the seat dimension and seat weight adjustments.

3.1. Aircraft Performance Analysis Metrics

Five overall aircraft performance parameters are analyzed after a variation in the aforementioned seat parameters. It should be noted that the performance metrics are based on a low level of granularity. Although the performance metrics will provide a global indication of the influence of the varying parameters, a higher level of detail is provided in Sections 3.3 and 3.4 where necessary. The performance parameters that are used for the analyses are specified as follows:

- **Maximum Take-Off Weight**
- **Aircraft Parasite Drag**
  The aircraft parasite drag, C_D, which primarily consists of skin friction, roughness, and pressure drag of the major aircraft components, is calculated by:

$$C_{D_\mathrm{P}} = \sum k_\mathrm{i} \cdot c_{f_\mathrm{i}} \cdot \frac{S_{\mathrm{wet}_\mathrm{i}}}{S_\mathrm{ref}} + C_{D_\mathrm{upsweep}} + C_{D_\mathrm{gap}} + C_{D_{\mathrm{nac}_\mathrm{base}}} + C_{D_\mathrm{misc}} \tag{3.1}$$

  It should be noted that Equation 3.1 takes all major aircraft components into account, ranging from the fuselage upsweep to the control surface gaps. However, by using the Initiator as a conceptual design tool, not all required parameters can be determined for the modeled aircraft, such that additional assumptions have to be made. First of all, it is assumed that the skin friction coefficient, c_f, and the form factor, k, remain constant when changing the aircraft seat parameters. Furthermore, it is assumed that the fuselage upsweep angle related drag, control surface gap related drag, and nacelle base related drag do not change throughout the above mentioned testing process. The additional parasite drag component caused by miscellaneous items is often estimated to be equal to 1.5 % of the total aircraft parasite drag.

Taking this number into account, it can be concluded that this component can be assumed to be negligible. Based on the above mentioned assumptions, the aircraft parasite drag is determined through the parasite drag area, which is specified as follows:

$$A_{\text{Parasite,Drag}} = C_{D_0} \cdot S_{\text{ref}} \tag{3.2}$$

- **Fuel Burn**
  The fuel burn of the aircraft is calculated by the Initiator for both a typical mission profile and the harmonic mission profile. The mission analysis module within the Initiator is set to a detailed level, thereby optimizing the SFC by flying at the optimum cruise altitude with the optimum cruise speed by making use of a step climb cruise with 2000 feet altitude variations. As the fuel burn of the aircraft is directly related to the equivalent CO_2 emissions, it is expected that similar trends are observed.

- **Equivalent CO_2 Emissions**
  The equivalent CO_2 emissions are calculated by using a Global Warming Potential (GWP) index, which is directly influenced by the flight altitude and aircraft fuel burn, as shown in Figure 3.1. As the CO_2 emissions are taken as a reference with respect to H_2O and NO_x emissions, it is expected that the CO_2 emissions show a similar behavior when compared with the aircraft fuel burn.

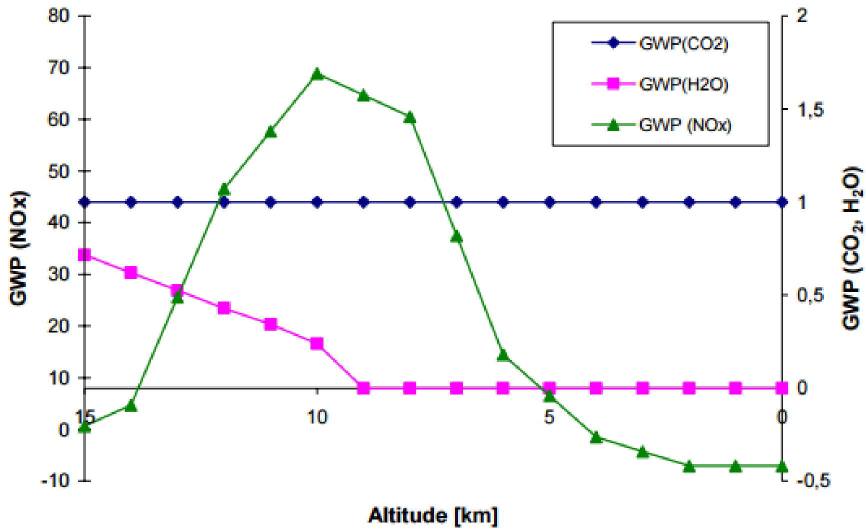


Figure 3.1: Global warming potential numbers per kilogram pollutant versus altitude [54]

Within the mission analysis module,the relations between fuel burn, W_F, and CO_2, H_2O, and NO_x are defined as:

$$\mathrm{CO_2} = 3.16 \cdot \mathrm{W_F} \tag{3.3}$$

$$\mathrm{H_2O} = 1.24 \cdot \mathrm{W_F} \cdot \mathrm{GWP_{H_2O}} \tag{3.4}$$

$$\mathrm{NO_x} = 0.014 \cdot \mathrm{W_F} \cdot \mathrm{GWP_{NO_x}} \tag{3.5}$$

From these equations it can be seen that the aircraft emissions are directly related to the fuel burn. Hence, it is assumed for the remainder of this thesis that the variation of emissions is identical to the variation of aircraft fuel burn.

- **Direct Operating Cost**
  The DOC of the modeled aircraft is calculated by making use of the cost estimation module, as described in Section 2.4. The most important input parameters for the cost estimation module, including their appropriate reference, are listed in Table D.1.

Furthermore, it should be noted that all graphs in this chapter are normalized, leading to a more comprehensive overview of the test data without experiencing any disturbances due to modeling errors. Hence, a value of 1 on the z-axis corresponds to the value that is related to the original aircraft with the reference seating configuration as shown in Section 2.2. Furthermore, a linear interpolation with a high density of interpolated data points is created in order to generate a smooth curve between the modeled data points. A small level of inaccuracy could therefore be present between the data points as shown in these figures.

3.2. SEAT DIMENSION ADJUSTMENT

In order to quantify the influence of the seat dimensions in conceptual aircraft design, a sensitivity analysis is carried out showing the influence of the aircraft seat dimensions on the defined performance metrics. Both lateral, in terms of seat pitch, and longitudinal, in terms of seat width, adjustments are made to the aircraft seat, as described in Subsections 3.2.1 and 3.2.2. Furthermore, the ideal seat dimensions from an ergonomic point of view are described in Subsection 3.2.3.

3.2.1. SEAT PITCH ADJUSTMENT

A seat pitch adjustment is carried out in order to determine its effect on aircraft performance. It should be noted that only the seat pitch of the EC is varied, based on the need for passenger comfort improvement in the EC cabin especially, as mentioned in Section 2.2. By taking into account both short-haul and long-haul aircraft, recent literature shows that the seat pitch for EC varies between 28 inch and 34 inch [1] [2] among different airlines. Hence, it is chosen to vary the EC seat pitch within the Initiator accordingly in order to assess its influence on aircraft performance. While increasing the EC seat pitch, the fuselage length of the various aircraft increases as shown in Tables 3.1 and 3.2. The results of the seat pitch adjustment are described in Section 3.3.

Table 3.1: Modeled Airbus aircraft fuselage length variation with change in EC seat pitch

EC Pitch	Airbus A340-300		Airbus A330-300		Airbus A321-200		Airbus A320-200	
	l_{fus} [m]	Difference	l_{fus} [m]	Difference	l_{fus} [m]	Difference	l_{fus} [m]	Difference
28"	61.10	3.90 %	60.50	4.68 %	42.07	5.56 %	35.56	5.76 %
29"	61.93	2.60 %	61.49	3.12 %	42.90	3.69 %	36.28	3.85 %
30"	62.75	1.31 %	62.48	1.56 %	43.72	1.85 %	37.01	1.92 %
31"	63.58	0.00 %	63.47	0.00 %	44.55	0.00 %	37.74	0.00 %
32"	64.41	1.31 %	64.46	1.56 %	45.37	1.85 %	38.46	1.92 %
33"	65.23	2.60 %	65.45	3.12 %	46.19	3.69 %	39.19	3.85 %
34"	66.06	3.90 %	66.44	4.68 %	47.02	5.56 %	39.91	5.76 %

Table 3.2: Modeled Boeing aircraft fuselage length variation with change in EC seat pitch

EC Pitch	Boeing 777-300		Boeing 767-300ER		Boeing 737-300		Boeing 737-800	
	l_{fus} [m]	Difference	l_{fus} [m]	Difference	l_{fus} [m]	Difference	l_{fus} [m]	Difference
28"	69.80	5.24 %	52.59	4.15 %	31.17	6.79 %	37.35	5.74 %
29"	71.08	3.49 %	53.35	2.77 %	31.92	4.55 %	38.11	3.82 %
30"	72.37	1.74 %	54.11	1.39 %	32.68	2.27 %	38.87	1.90 %
31"	73.66	0.00 %	54.87	0.00 %	33.44	0.00 %	39.62	0.00 %
32"	74.94	1.74 %	55.63	1.39 %	34.20	2.27 %	40.38	1.90 %
33"	76.23	3.49 %	56.39	2.77 %	34.96	4.55 %	41.14	3.82 %
34"	77.52	5.24 %	57.14	4.15 %	35.71	6.79 %	41.90	5.74 %

[1] Seatguru, Short-haul Economy Class Comparison Chart, http://www.seatguru.com/charts/shorthaul_economy.php, Accessed 27/07/2015

[2] Seatguru, Long-haul Economy Class Comparison Chart, http://www.seatguru.com/charts/longhaul_economy.php, Accessed 27/07/2015

3.2.2. SEAT WIDTH ADJUSTMENT

In order to determine the effect of the EC seat width on aircraft performance, a variation between 16 inch and 19.5 inch with incremental steps of 0.5 inch is applied. As the EC seat width determines the width of the aircraft cabin within the Initiator, it is highly likely that the aircraft MTOW and parasite drag are directly influenced, due to an increase in fuselage weight and zero-lift drag. It should be noted that a wider fuselage does not automatically lead to a shorter fuselage,as it is assumed that the required service area length remains constant. This assumption is based on the fact that a single parameter evaluation is carried out by changing the EC seat width and that the combined influence of fuselage lengthening and widening is shown in Section 3.3.

3.2.3. IDEAL AIRCRAFT SEAT DIMENSIONS

As a practical example for the results in this chapter, an estimation is made for the dimensioning of the ideal aircraft seat. First of all, it should be stressed that there does not exist such a thing as an ideal aircraft seat. This statement is supported by the fact that each person has its own preference in terms of sitting posture, its own perception of a minimum level of achieved sitting comfort, and a variability in its dimensions. However, one could provide specific seat dimensions in order to ensure that a large part of the world population can be accommodated in a specific aircraft seat. In order to do so, use is made of various anthropometric databases and studies that are related to this topic.

Based on the recommendations of the study conducted by Quigley et al [3], the optimal aircraft seat dimensions for the 95 percentile and 99 percentile of the world population can be determined in terms of seat pitch and seat cushion width. Although the ideal seat pitch is not mentioned by Quigley et al, a reasonable estimate can be made using the provided data. As mentioned in Chapter 1, the aircraft seat pitch is composed of the seat back thickness, the seat cushion length, and the distance between the seat cushion and the seat in front. Furthermore, the seat cushion length is related to the buttock-popliteal length, whereas the distance between the seat cushion and the seat in front is related to the human body depth or thigh depth.

To determine the optimal seat cushion length, a worldwide 99 percentile buttock-popliteal length can not be explicitly used due to the fact that a too large seat cushion length could result in a slumping movement for smaller passengers, leading to potential back injuries and pressure on the back of the knee. In accordance with the report of Quigley et al, the worldwide minimum buttock-popliteal length is assumed for the dimensioning of the ideal aircraft seat. This assumption leads to a world 95 percentile seat cushion length equal to 393 mm and a world 99 percentile seat cushion length equal to 379 mm. It should be noted that no statistical data for the worldwide buttock-popliteal length is present in DINED. However, the data provided by Quigley et al is yet validated in their study and is shown to exhibit a good correlation with data from PeopleSize 2000 [55] and Adultdata [56].
Nevertheless, it should be noted that the implementation of a variable seat cushion length could alleviate the above mentioned problem with respect to the dimension of the ideal seat cushion length. As an active seat cushion length variation is rarely seen in commercial transport aircraft, the minimum seat cushion lengths as described above apply.

Secondly, the distance between the seat cushion and the seat in front is determined using either the human whole body depth or the thigh depth at knee height. By assuming the whole body depth to be the leading dimension in this case, the optimal seat ensures that standing upright between the seats is possible. Similar to the buttock-popliteal length, no worldwide data for the whole body depth is present in DINED, leading to the use of data as provided by Quigley et al. Use is made of the maximum body depth dimensions in order to ensure sufficient space for seat access and egress. Consequently, the 95 percentile worldwide whole body depth equals 405 mm, whereas a value of 438 mm is obtained for the worldwide 99 percentile population. Finally, due to the lack of reliable data sources, an estimation is made for the seat back thickness, being equal to 38 mm [3].

[3] Independent Traveller: The shrinking airline seat, http://www.independenttraveler.com/travel-tips/travelers-ed/the-shrinking-airline-seat, Accessed: 18/08/2015

With respect to the seat width, two measures can be leading for the optimum seat design. The hip width determines the required seat cushion width, whereas the shoulder (bi-deltoid) width determines the width of the seat including the armrests. Little attention to the seat cushion width is paid in the report of Quigley et al, leading to the utilization of DINED for the human hip and shoulder width dimensions. Considering the hip width, dimensions equal to 436 mm and 472 mm are obtained for the worldwide 95 percentile and 99 percentile population, respectively. Alternatively, the shoulder width dimensions equal 496 mm and 532 mm for the corresponding worldwide population percentiles. As the seat cushion width is the varying parameter throughout this chapter, a check is made whether the width of the optimum seat cushion including the armrest widths provides sufficient space with respect to the shoulder width dimensions. Throughout this chapter, an armrest width equal to 50 mm is used, showing that the mentioned seat cushion widths allow for sufficient width at shoulder level as well. It should be noted that the cushion width within this respect is measured at the seat pan, whereas the total seat width including armrests is measured at the top of the armrests. A verification is carried out for these seat cushion width dimensions using the work of Hiemstra-van Mastrigt [57]. Using DINED 2004 data for a Dutch population aged between 20 and 60 years, Hiemstra-van Mastrigt identifies a seat pan cushion width of 480 mm to be suitable for 99.7 percent of the tested population whereas a seat pan cushion width of 473 mm suits 99.5 percent of the tested population.

Summarizing the above mentioned parameters, the optimal seat dimensions suitable for the worldwide 95 percentile of passengers are defined by a seat width and seat pitch equal to 436 mm (17.17 inch) and 836 mm (32.91 inch), respectively. For the worldwide 99 percentile, these values amount to 472 mm (18.58 inch) and 855 mm (33.66 inch). In order to show the influence of these seat dimensions on the performance metrics as defined in Section 3.1, indication markers are present in the resulting figures in Section 3.3.

3.3. Seat Dimension Adjustment Results

The results of the seat dimension adjustments are shown in Subsections 3.3.1 through 3.3.4. Within these subsections, the resulting figures contain indicators to show the effect of a seat dimension adjustment corresponding to the ideal aircraft seat dimensions as defined in Subsection 3.2.3. The black indicator shows the reference point, always positioned at a seat pitch of 31 inch, a seat width of 17.5 inch, and a z-position equal to 1. Furthermore, the red markers correspond to the ideal seat dimensions for the 95 percentile of the world population, whereas the blue markers correspond to the ideal seat dimensions for the 99 percentile of the world population.

3.3.1. MTOW

Figures 3.2 and 3.3 show the variation of the MTOW for the modeled short-haul and long-haul aircraft respectively.

It can be seen that the MTOW of the modeled short-haul aircraft shows an almost linear increase when enlarging the EC seat pitch, whereas for long-haul aircraft more discrepancies can be seen, which can be amounted to the convergent nature of the Initiator. It is also observed that the influence of the seat width causes the largest variations in MTOW. For the Boeing 777-300, the aircraft having the largest fuselage diameter, the influence of larger seat widths with respect to the original configuration is seen to be the largest. For both long-haul and short-haul aircraft, the MTOW varies between 96 % and 105 % of $MTOW_{ref}$, with the Boeing 777-300 showing an absolute peak with a variation up to 108 % of $MTOW_{ref}$. Of course, the driving factor behind the increase in MTOW is the fuselage weight, which is shown versus seat pitch and seat width in Figures 3.4 and 3.5.

A comparison is made between the results shown in Figures 3.4 and 3.5 and the research carried out by Fuchte [32], as shown in Figures 3.6a and 3.6b. Although Fuchte considers multiple cabin cross-sections, it is seen that Fuchte only modeled an exact Airbus A320-200 and implemented various changes to this model, such as the widening of the fuselage, expressed in the number of aisles and seats abreast, and a stretch of the fuselage, expressed in single class passenger capacity. No direct comparison can be made between these figures, but a similar relationship between fuselage weight and aircraft length can be seen in both Figure 3.4 and Figure 3.6b. By translating the single class passenger capacity to fuselage length, for which a relation can be found in Figure 3.6a, and translating the seat pitch in Figure 3.4 to fuselage length, the slope of the regular single aisle configuration graph in Figure 3.6b with the modeled Airbus A320 graph in Figure 3.4 can be compared, as shown in Figure 3.7.

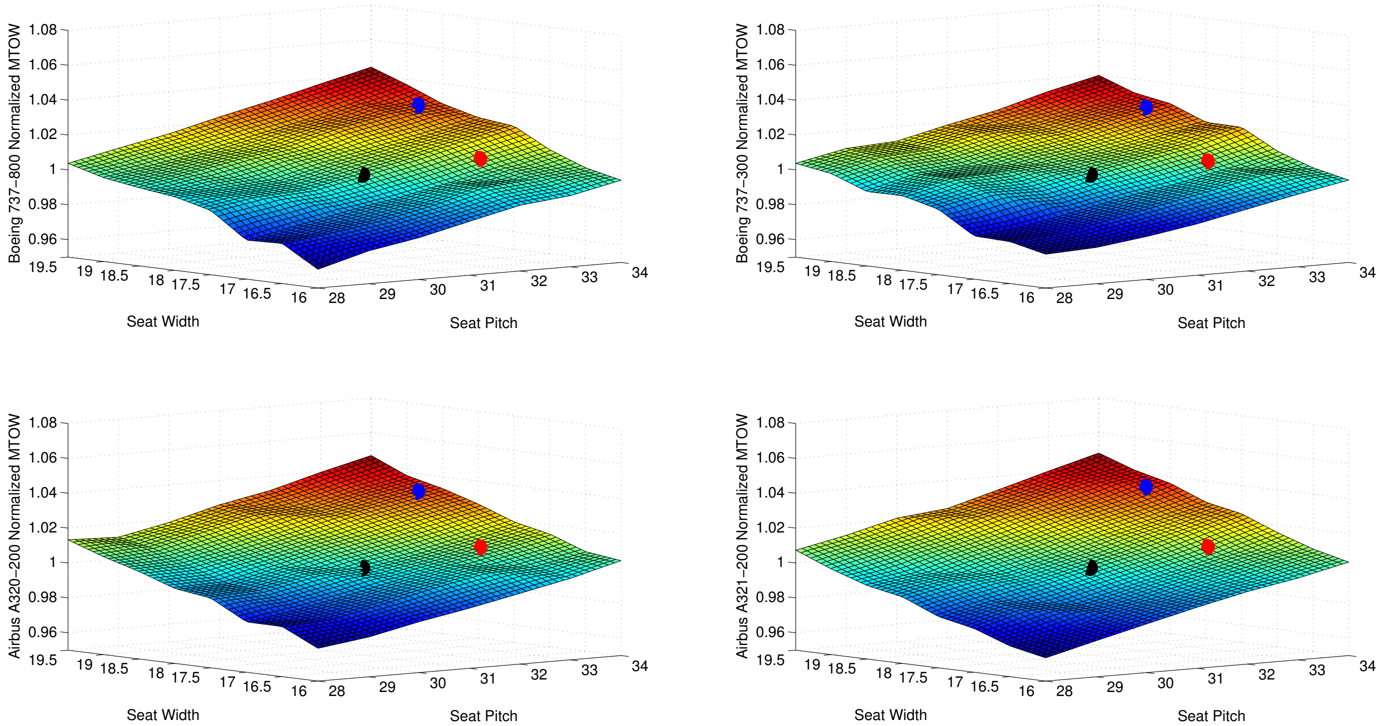


Figure 3.2: Variation of MTOW with EC seat dimensions for short-haul aircraft

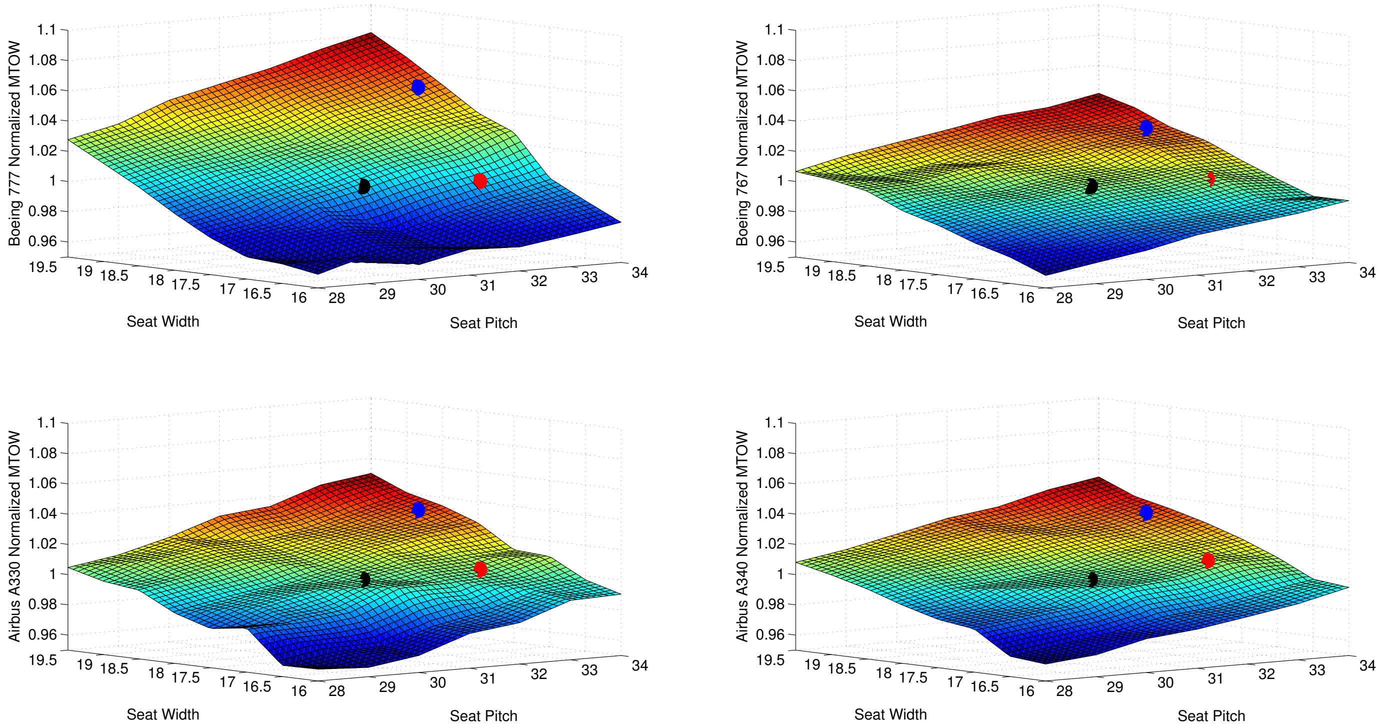


Figure 3.3: Variation of MTOW with EC seat dimensions for long-haul aircraft

From this figure, it is concluded that the fuselage weight estimation of Fuchte shows a nearly similar trend when compared with the modeled A320-200 fuselage weight variation. The empirical fuselage weight estimation as designed by Nicolai and implemented in the Initiator is therefore immediately verified when compared with the finite element model of Fuchte.

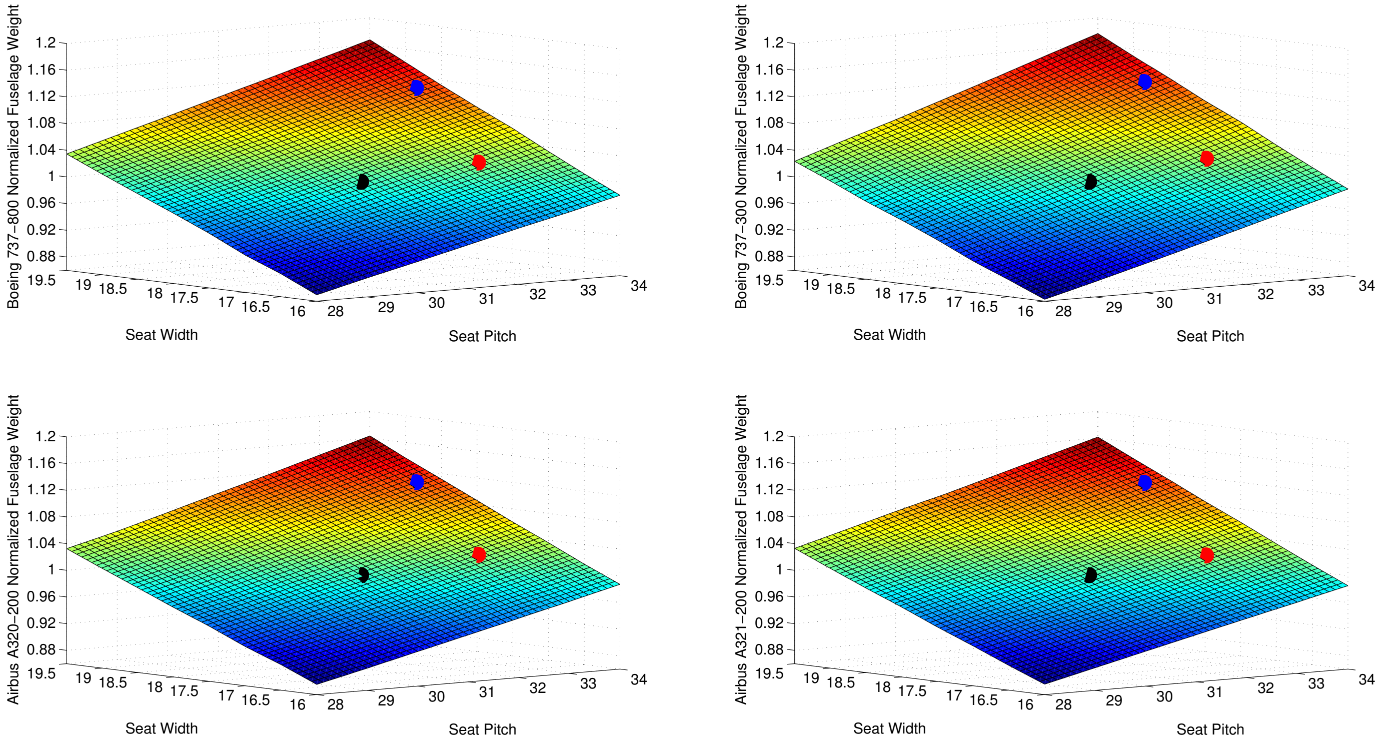


Figure 3.4: Variation of fuselage weight with EC seat dimensions for short-haul aircraft

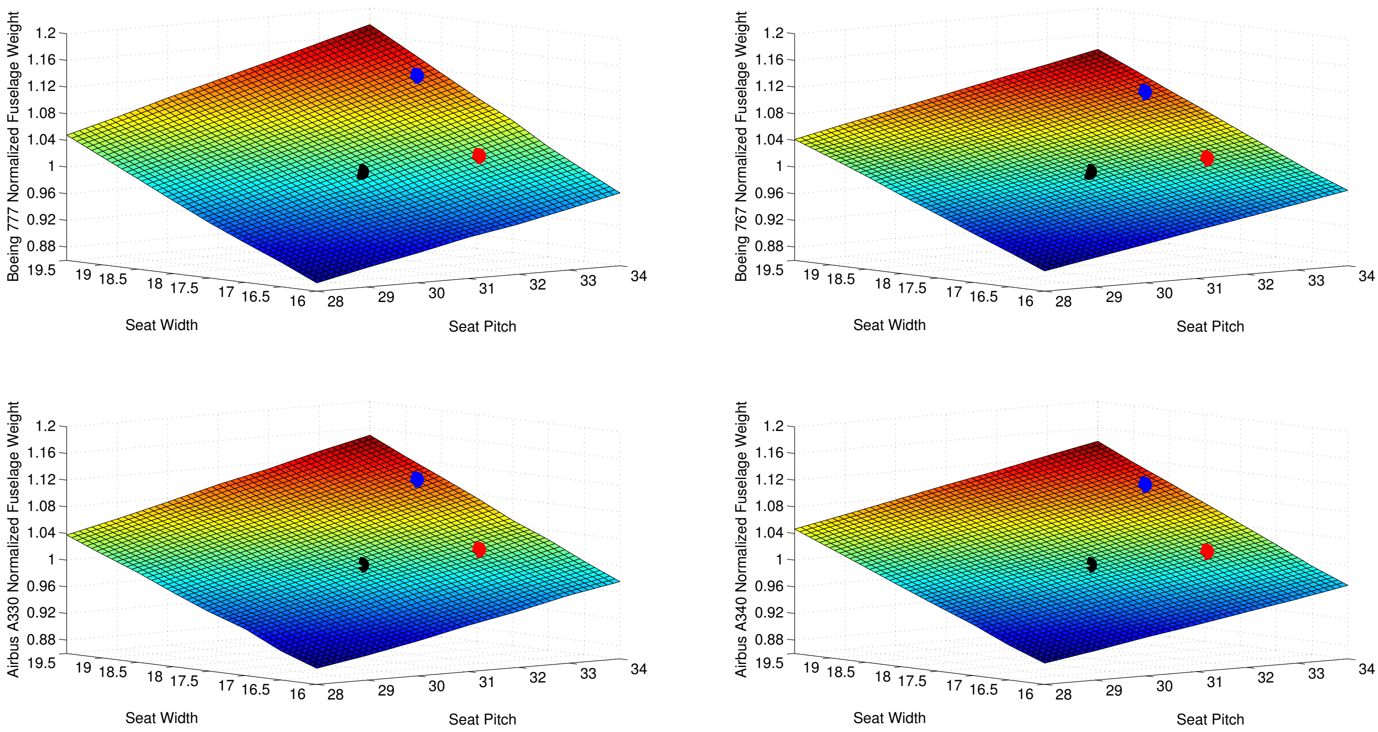
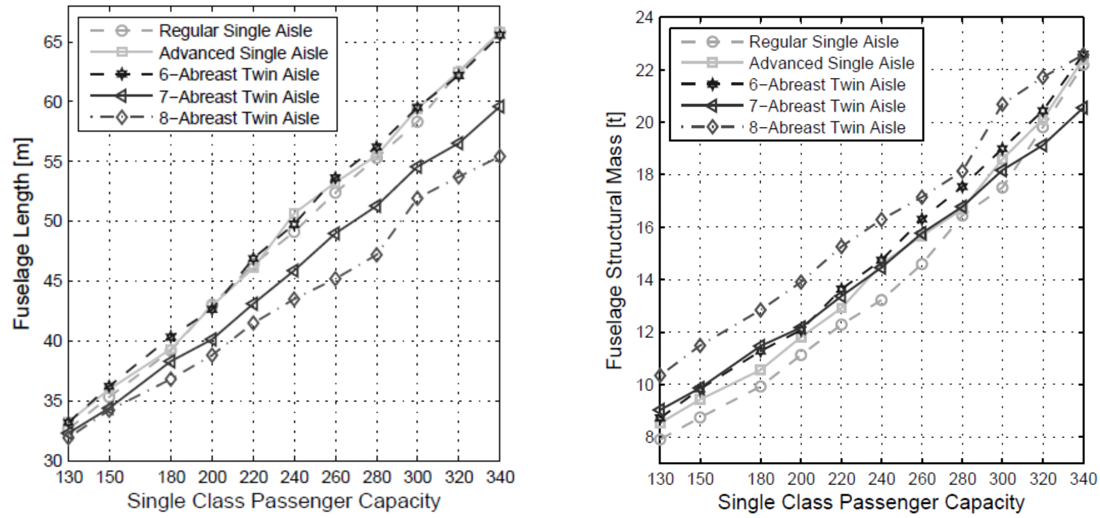


Figure 3.5: Variation of fuselage weight with EC seat dimensions for long-haul aircraft

3.3.2. AIRCRAFT PARASITE DRAG

The aircraft parasite drag variation, as expressed through the parasite drag area, is shown in Figures 3.8 and 3.9. It is seen that a similar trend is present when comparing these figures with the MTOW variations as shown in Figures 3.2 and 3.3.



(a) Variation of aircraft fuselage length with single class passenger capacity

(b) Variation of aircraft fuselage structural mass with single class passenger capacity

Figure 3.6: Influence of single class passenger capacity on fuselage weight and length [32]

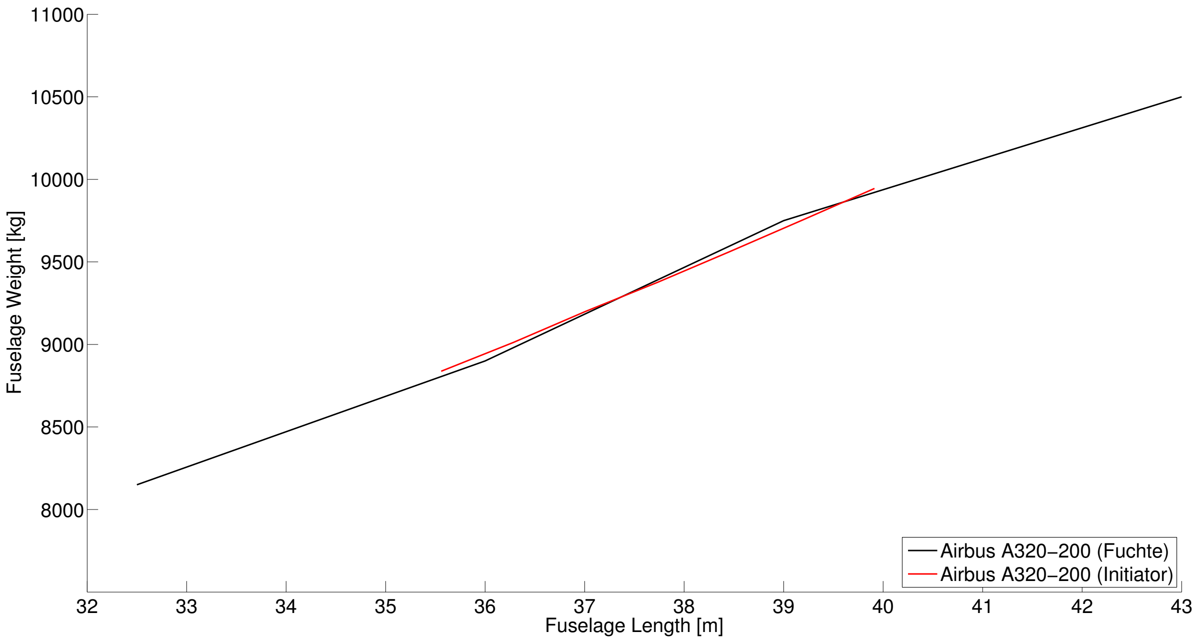


Figure 3.7: Variation of aircraft fuselage weight with aircraft fuselage length for both the model by Fuchte and the model by the Initiator

This similar variation is based on the fact that the wing loading diagram is barely affected by a change in seat, and hence fuselage, dimensions. As the fuselage dimensions are varied linearly and the tail is mainly determined through user input parameters, the wing area mainly determines the variation in the parasite drag area. For nearly every modeled aircraft, the constraining factor with respect to the aircraft wing loading is related to the landing distance. As the landing distance, which determines the stall speed in landing configuration, V_{SL}, is a given top level requirement and the maximum lift coefficient, $C_{L_{\text{Max,Landing}}}$, and flight altitude are estimated user input parameters, the wing loading is furthermore only influenced by the MTOW and the maximum landing weight (MLW). The relationship between these parameters is defined as:

$$\frac{W}{S} = 0.5 \cdot \rho \cdot V_{SL}^2 \cdot C_{L_{\text{Max,Landing}}} \cdot \frac{MTOW}{MLW} \tag{3.6}$$

Other wing loading constraints, relating to the stall speed, maximum cruise lift coefficient related to buffet, and maximum wing span are not shifting either due to the stagnant behavior of the related parameters. Furthermore, an important assumption that is made during this analysis is that the aircraft wing always provides sufficient storage space for the maximum required mission fuel. Hence, the wing loading constraint relating to the fuel tank volume is removed from the Initiator during this analysis, such that no complete redesign of the wing occurs during the convergence runs. This assumption is supported by the fact that a similar variation between the required fuel weight, as described in Subsection 3.3.3, and the wing dimensions can be observed when changing the EC seat dimensions.

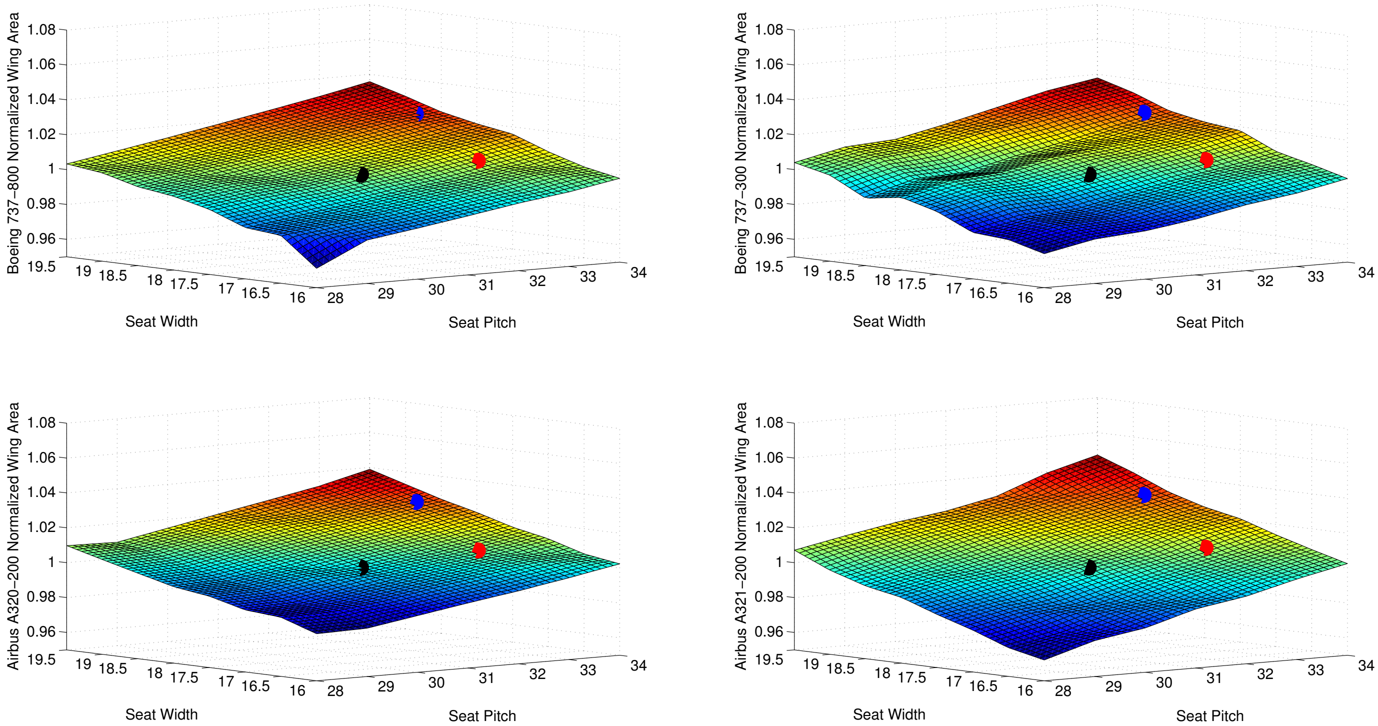


Figure 3.8: Variation of parasite drag area with EC seat dimensions for short-haul aircraft

3.3.3. FUEL BURN

The aircraft fuel burn related to the harmonic mission is shown in Figures 3.10 and 3.11. Although a similar trend can be observed when compared with the aircraft MTOW, it is seen that these figures show larger local variations. When looking at the global trend of these figures, it is concluded that the harmonic mission fuel burn varies similarly to the MTOW in terms of the maximum increase and decrease with respect to the reference point. However, when looking at the typical mission fuel burns as shown in Figures 3.12 and 3.13, a different variation can be observed. It is seen that the fuselage dimensions have less influence on the typical mission fuel burn when compared to the harmonic mission fuel burn and that the slope of the curve for the typical mission fuel burn is less steep as compared to the harmonic mission fuel burn.

The large amount of local variations with respect to the calculated fuel burn can be caused by several reasons. First of all, a detailed mission analysis is carried out, thereby taking step climbs during cruise into account and hence changing cruise altitude continuously. Simultaneously, an off-design engine module calculates the SFC according to the mission profile and a retrim of the drag polar is carried out. Depending on the retrim interval, the mission analysis detail, and the step climb interval, the stability of the mission analysis module is determined. As a high level of detail is set for the analyses of the modeled aircraft, a high level of instability is observed in Figures 3.10 through 3.13.

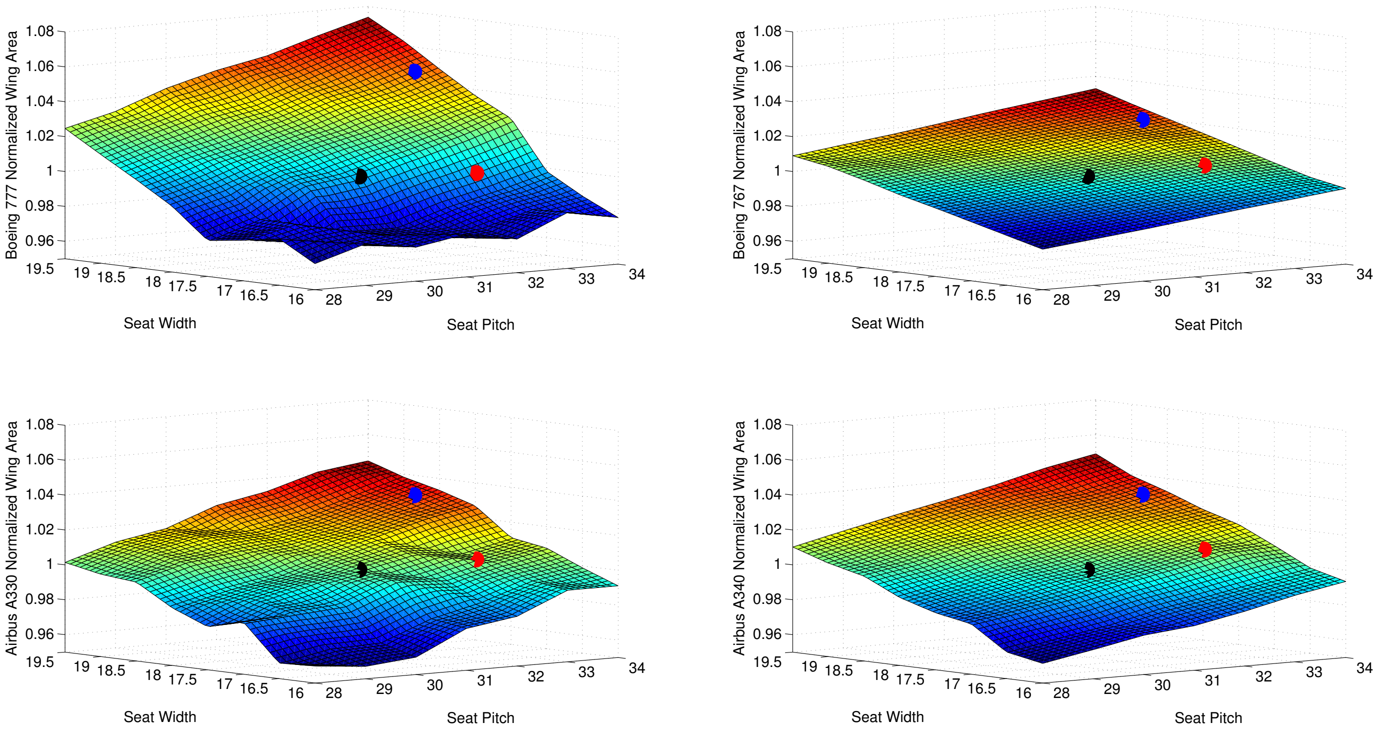


Figure 3.9: Variation of parasite drag area with EC seat dimensions for long-haul aircraft

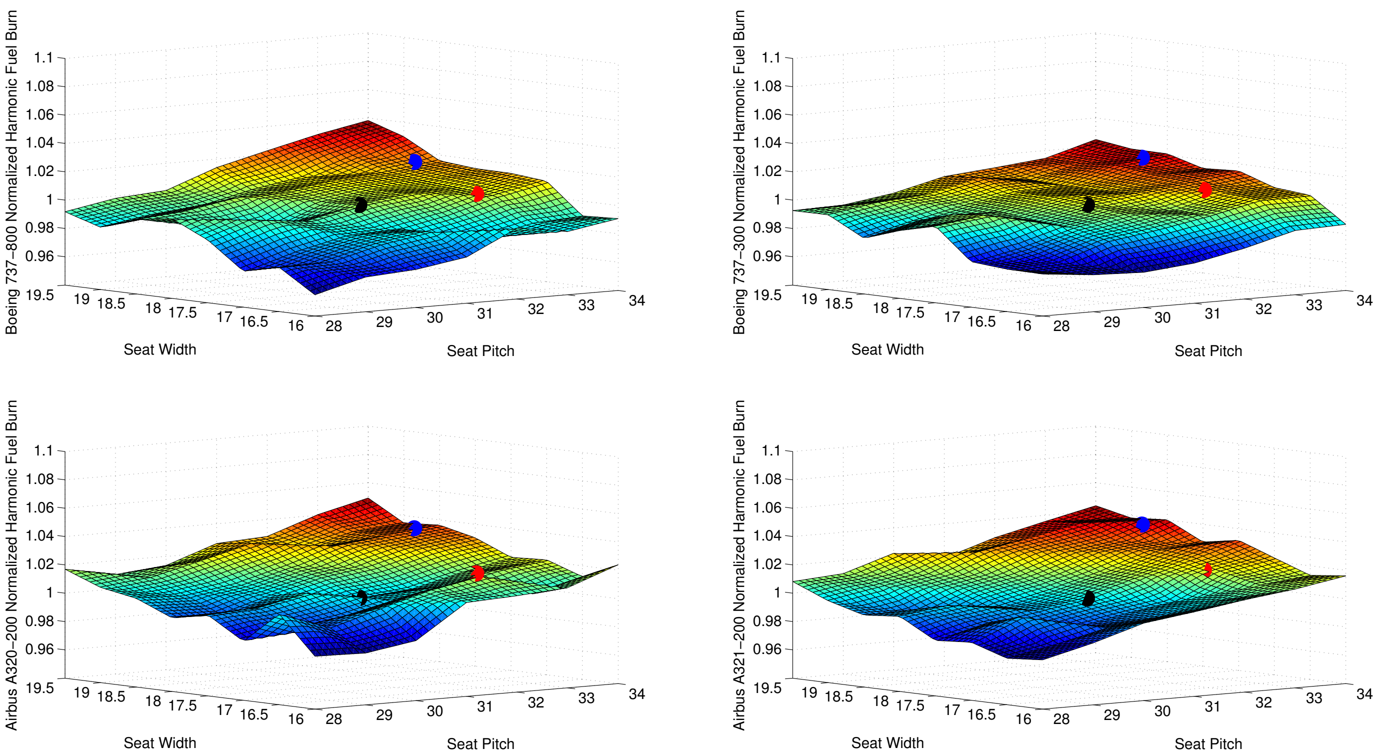


Figure 3.10: Variation of Harmonic Wf with EC seat dimensions for short-haul aircraft

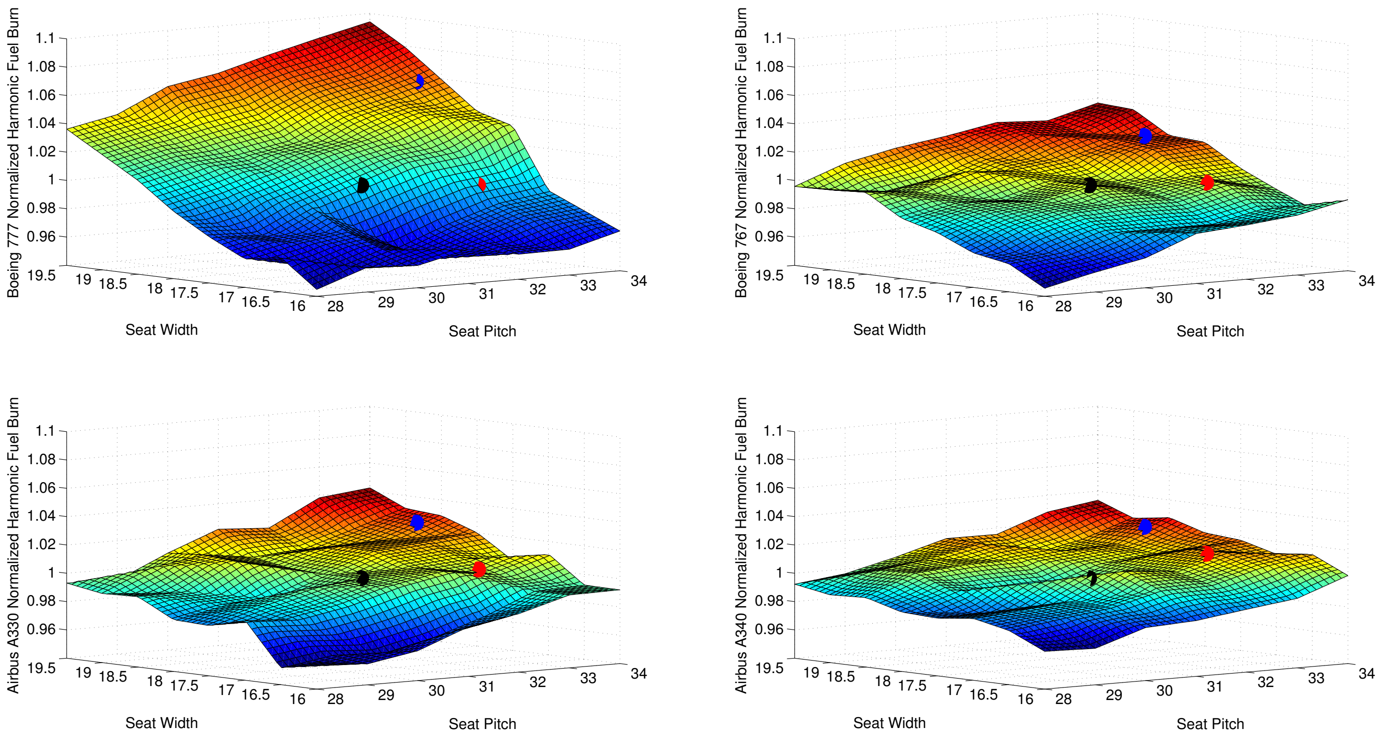


Figure 3.11: Variation of Harmonic Wf with EC seat dimensions for long-haul aircraft

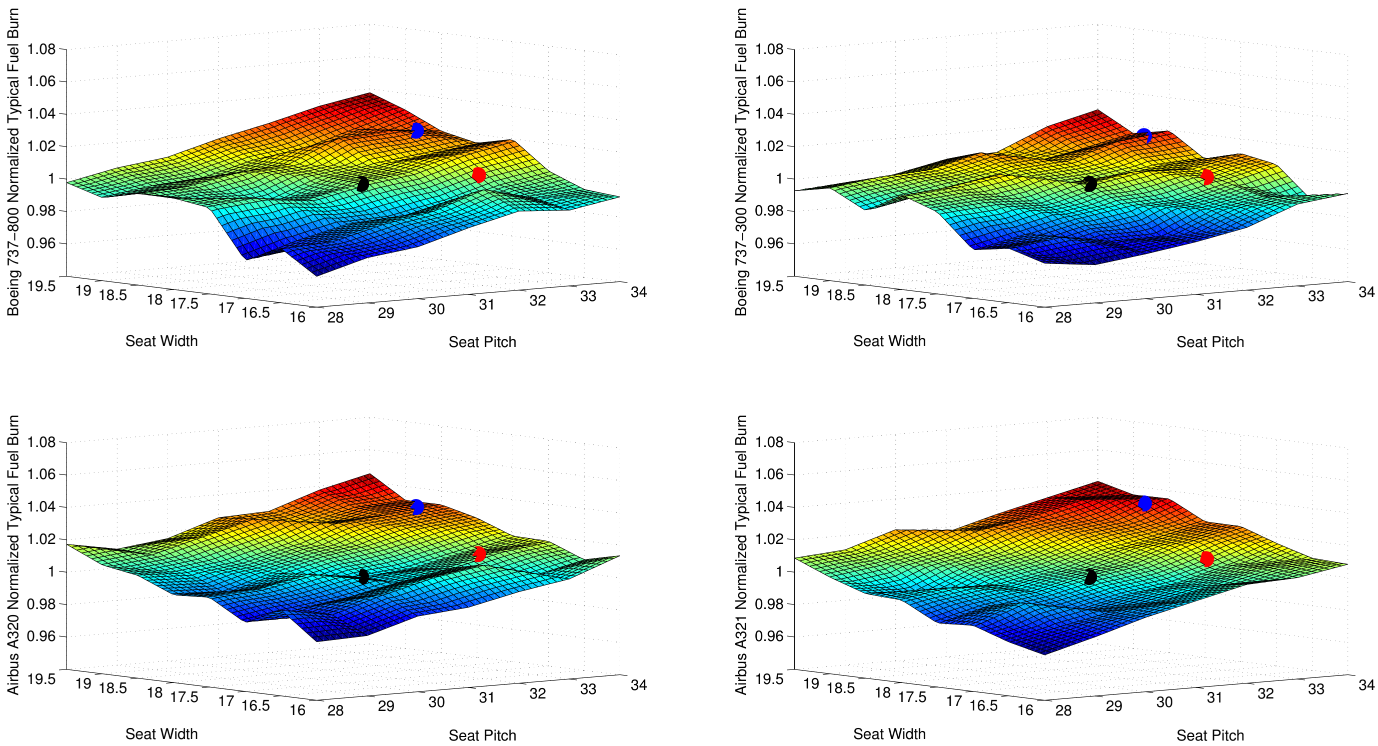


Figure 3.12: Variation of Typical Wf with EC seat dimensions for short-haul aircraft

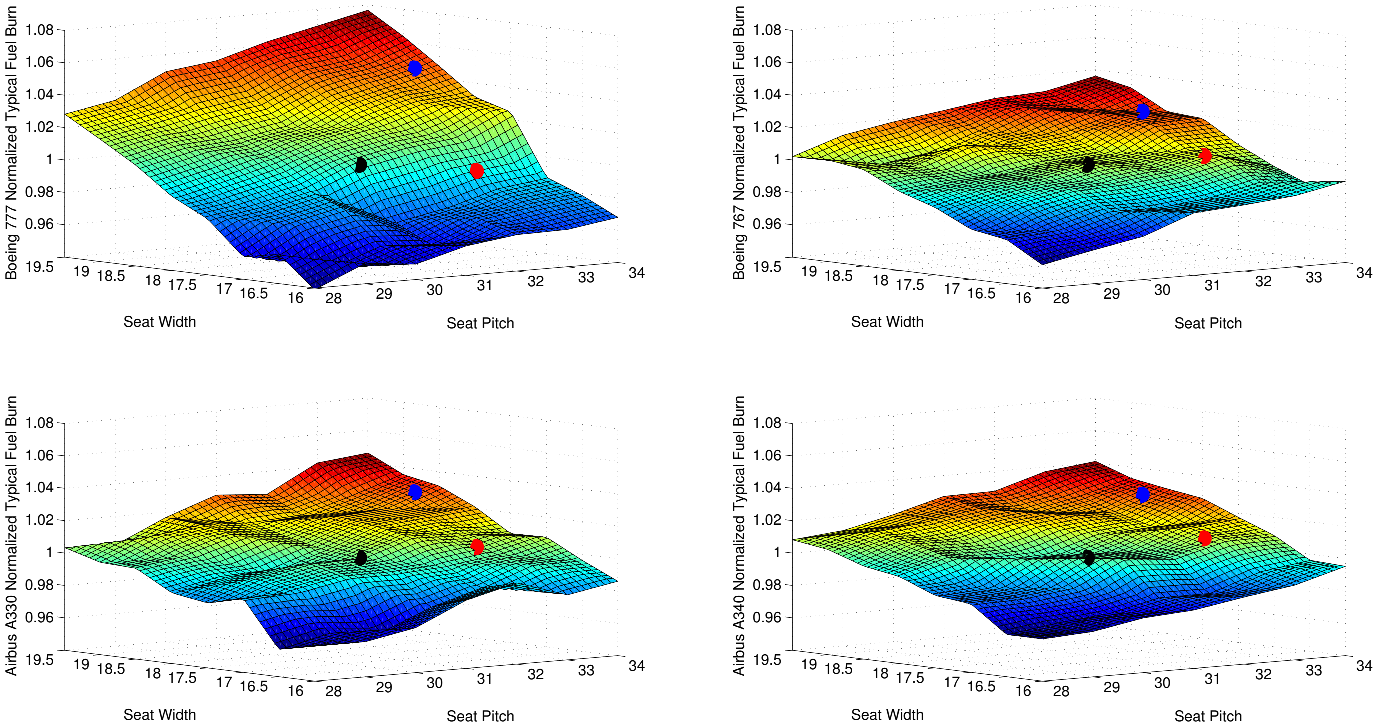


Figure 3.13: Variation of Typical Wf with EC seat dimensions for long-haul aircraft

3.3.4. OPERATING COST

The influence of EC seat dimensions on the DOC of the aircraft is shown in Figures 3.14 and 3.15. It is clear from first sight that the aircraft DOC is influenced more by the increased MTOW when compared to the variation of harmonic fuel burn. This behavior is mainly caused by the production cost analysis of the aircraft, which shows a large part price increase when enlarging the fuselage dimensions. Following the higher part prices, the maintenance costs and costs of depreciation show a large increase as well. The influence of the fuselage dimensions is seen to be the highest for the DOC of the short-haul aircraft, which is caused by the smaller contribution of the fuel costs when compared to long-haul aircraft.

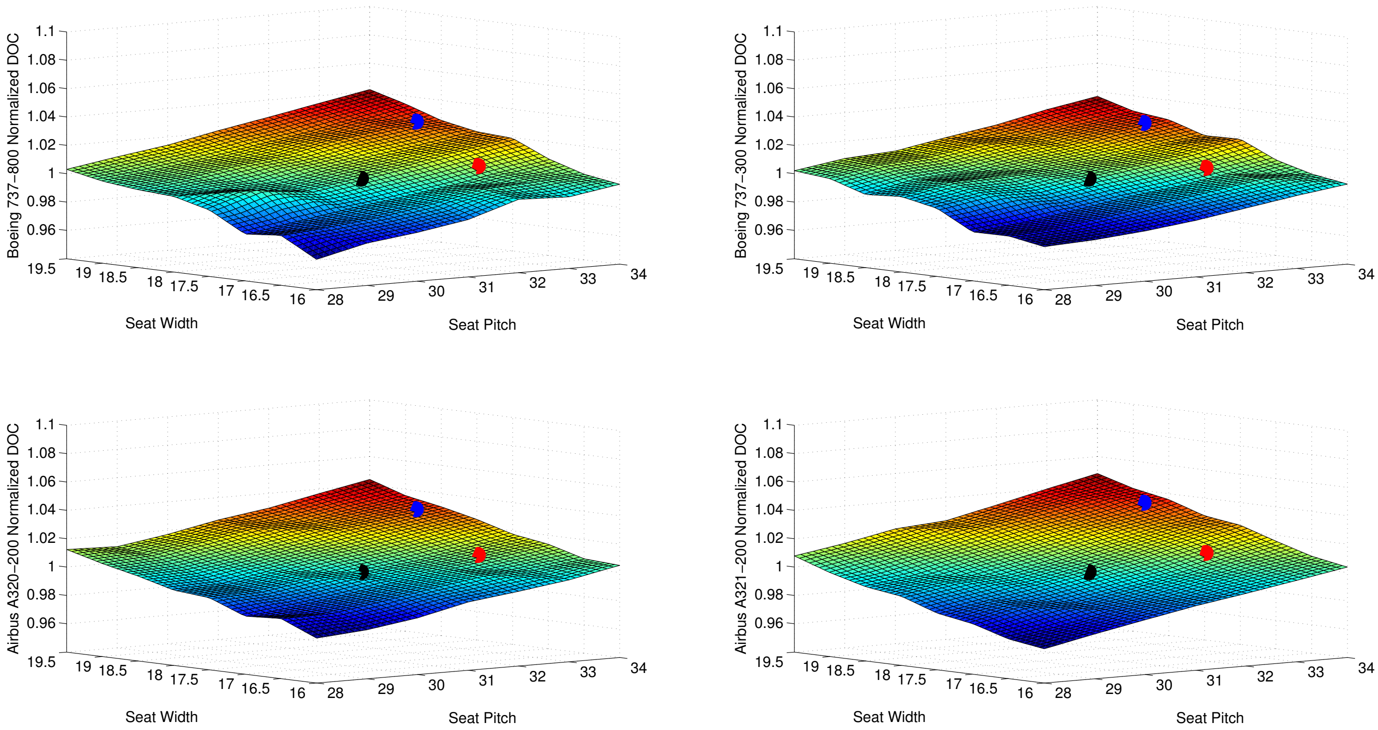


Figure 3.14: Variation of DOC with EC seat dimensions for short-haul aircraft

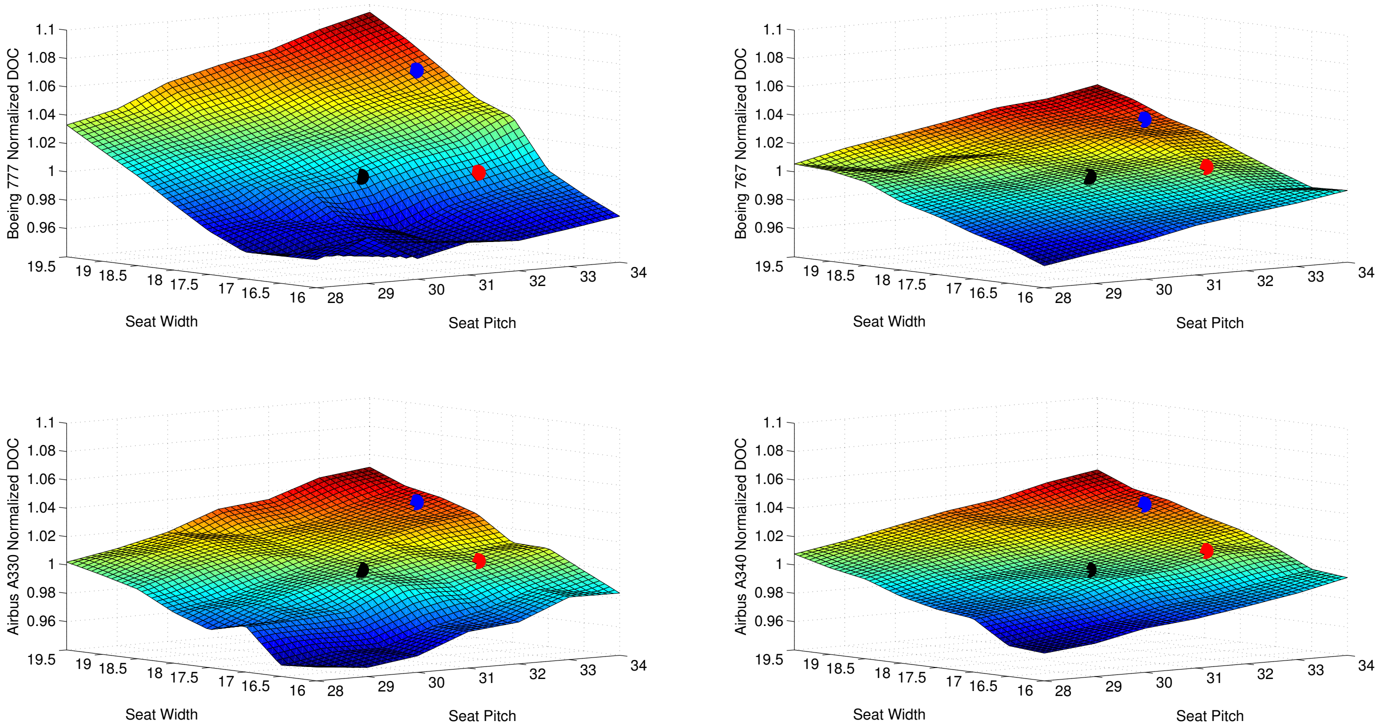


Figure 3.15: Variation of DOC with EC seat dimensions for long-haul aircraft

3.4. SEAT WEIGHT ADJUSTMENT

The influence of the seat weight on the defined aircraft performance parameters is analyzed by means of a variation in the class II weight estimation. The furnishing mass of the aircraft is calculated using the method of Torenbeek, as shown in Equation 2.2.

As the seat weight is not particularly mentioned in Equation 2.2 and a large variation exists among aircraft seat weights, the influence of the EC seat weight is assessed by adding or subtracting different weights from the calculated furnishing mass. As the amount of EC seats in the modeled aircraft are calculated by the CC, it is chosen to vary the difference in EC seat weight from -5 kg per seat to +5 kg per seat by multiplying the seat weight difference with the number of EC passengers. Assuming that modern EC seats weigh approximately 11 kg, an increase of nearly 50 % and a decrease of nearly 50 % in seat weight is therefore taken into account in this analysis.

Subsections 3.4.1, 3.4.2, 3.4.3, and 3.4.4 describe the influence of the EC seat weight on aircraft MTOW, parasite drag, fuel burn, and DOC, respectively.

3.4.1. Maximum Take-Off Weight

The EC seat weight has a direct influence on the MTOW of the modeled aircraft due to the increase of the above mentioned furnishing weight. The influence of the EC seat weight on MTOW is shown in Figure 3.16, from which it becomes clear that the EC seat weight is almost linearly correlated with the aircraft MTOW for both short-haul and long-haul aircraft. The effect of aircraft seat weight is more pronounced for the modeled short-haul aircraft, showing a steeper curve relating MTOW and EC seat weight. It is seen in general that a maximum MTOW decrease of 2 percent and a maximum increase of 2 percent is attained when the seat weight is halved or doubled, respectively.

3.4.2. Aircraft Parasite Drag

A nearly similar trend with respect to the parasite drag area is observed when comparing with the aircraft MTOW, caused by a non-variable wing loading constraint, as yet explained in Subsection 3.3.2. As the fuselage dimensions do not vary in this case, the aircraft wing is the only large contributor to the parasite drag area. A peculiar result is obtained for the Boeing 777-300 when decreasing the typical seat weight with 5 kg. It can clearly be seen that this data point is not in line with the general trend for the Boeing 777-300 and should be attributed to an early design convergence. Moreover, this explanation is also valid for the obtained results for the Airbus A330-300 when increasing the seat weight with 1 kg and 3 kg.

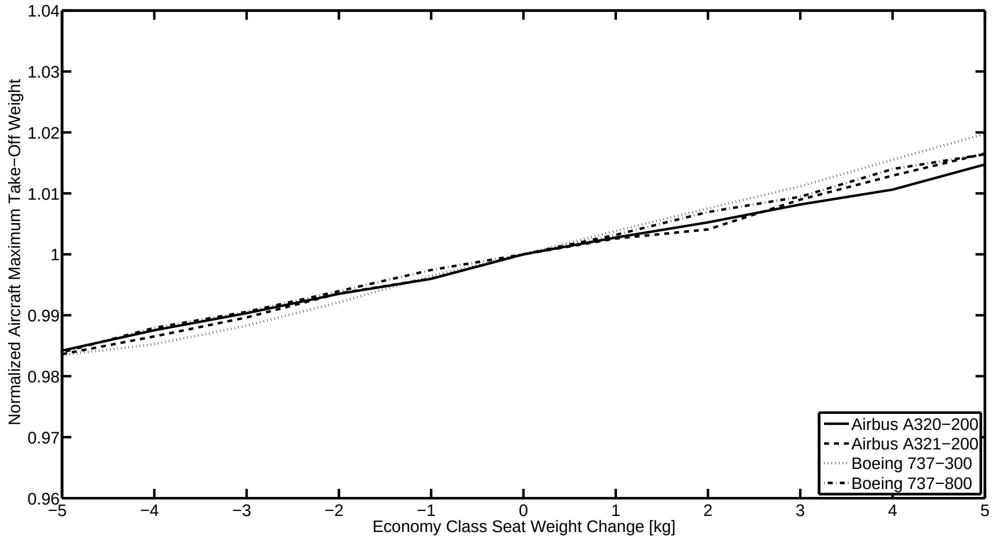
3.4.3. Fuel Burn

The influence of the EC seat weight on the aircraft fuel burn for the harmonic mission and the typical mission is shown in Figures 3.18 and 3.19. The influence of the aircraft seat weight on fuel burn is an often mentioned performance parameter by aircraft seat manufacturers. French aircraft seat manufacturer Expliseat claims for example that their new lightweight seat, weighing approximately 4 kilograms less when compared to a regular EC seat, leads to a 3-5% fuel burn reduction [4]. When comparing this figure with the results from the modeled aircraft, it is seen that a 2% and 1% fuel weight reduction is a more realistic figure for the aircraft harmonic mission and typical mission, respectively. Of course, this result is obtained by making use of an inside-out approach, whereas the result of Expliseat is likely to occur when making use of an outside-in approach.

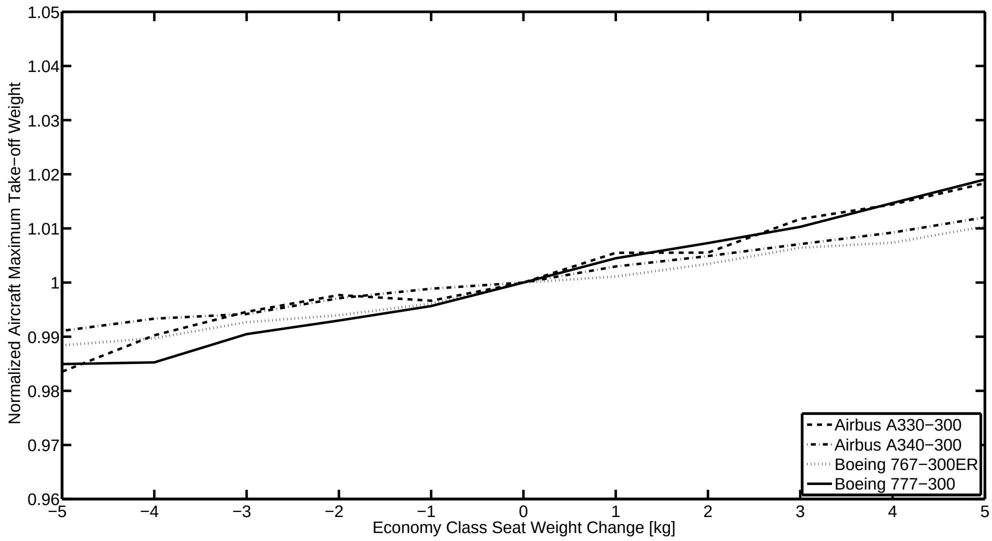
3.4.4. Operating Cost

The change in DOC due to a variation in EC seat weight is shown in Figure 3.20. The value of implementing lighter EC seats becomes clear from these figures, showing that both short-haul and long-haul aircraft can achieve a cost saving of approximately 0.5 % per kilogram seat weight reduction for the harmonic mission. Furthermore, it is noted that a more steady graph is obtained for the short-haul aircraft when compared to the long haul aircraft. This fact is attributed to the higher dependency of the aircraft fuel burn with respect to long-haul aircraft, thereby showing more instabilities in the graph.

[4] ESI Group, Expliseat uses ESI's Virtual Seat Solution to develop the world's lightest aircraft seat, https://www.esi-group.com/company/press/news-releases/, Accessed: 11/08/2015

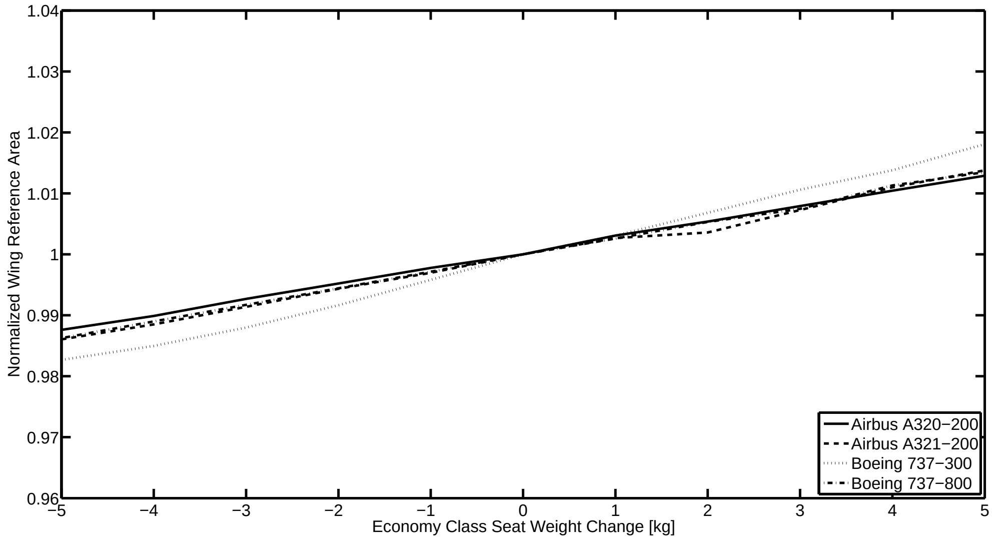


(a) Short-Haul Aircraft

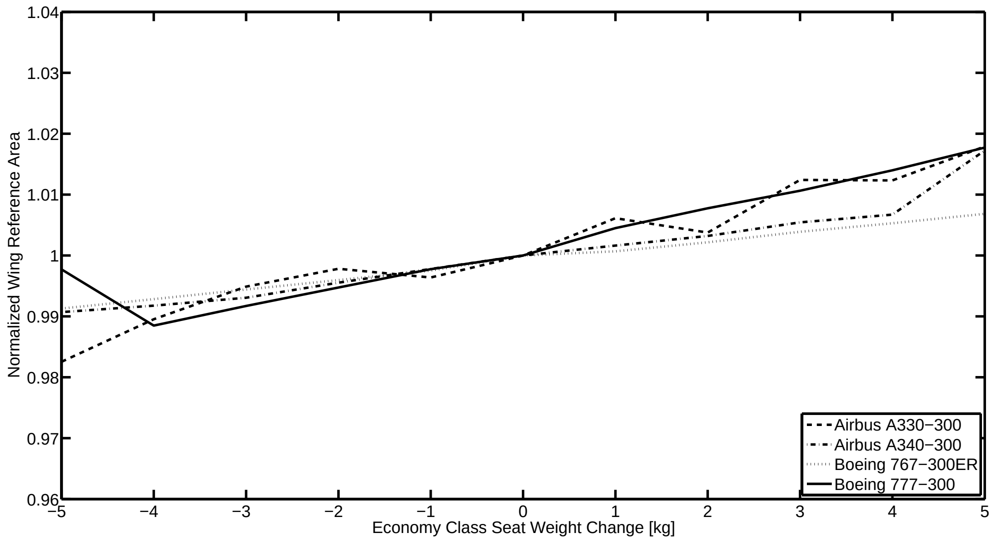


(b) Long-Haul Aircraft

Figure 3.16: Variation of normalized aircraft MTOW with EC seat weight

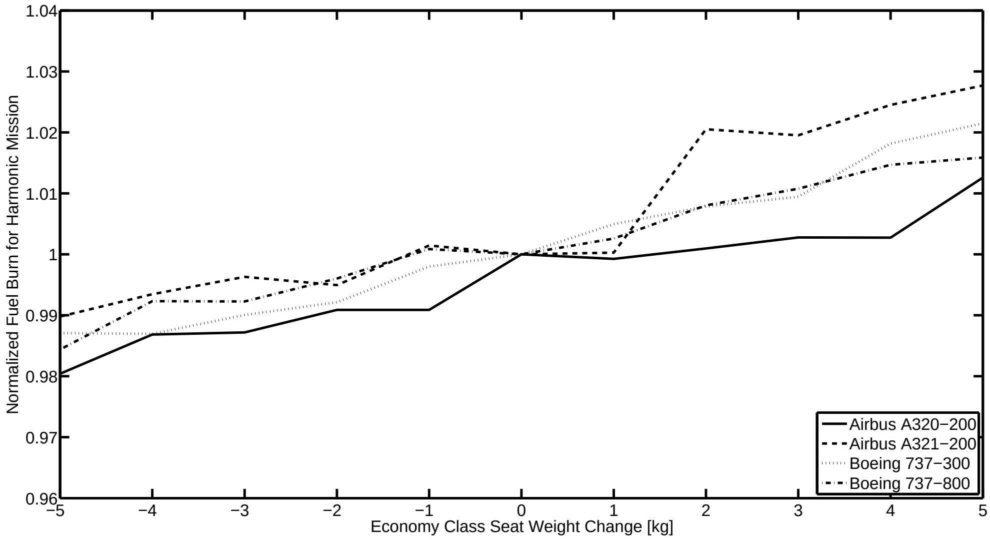


(a) Short-Haul Aircraft

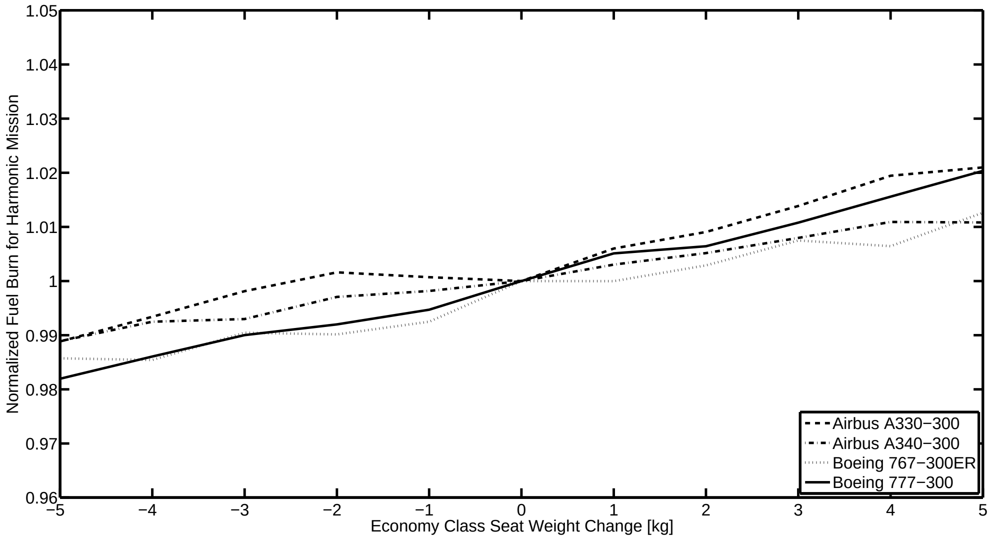


(b) Long-Haul Aircraft

Figure 3.17: Variation of aircraft parasite drag area with EC seat weight

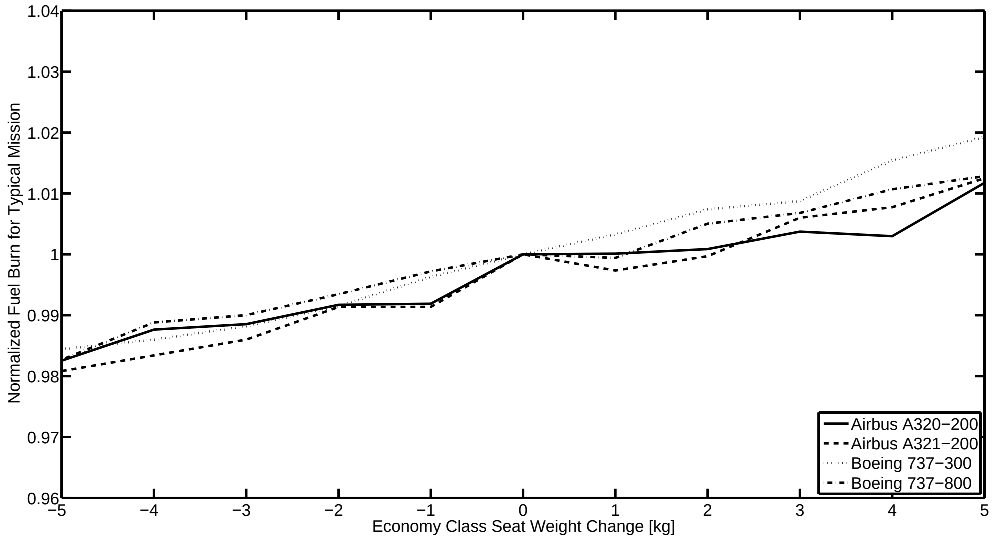


(a) Short-Haul Aircraft

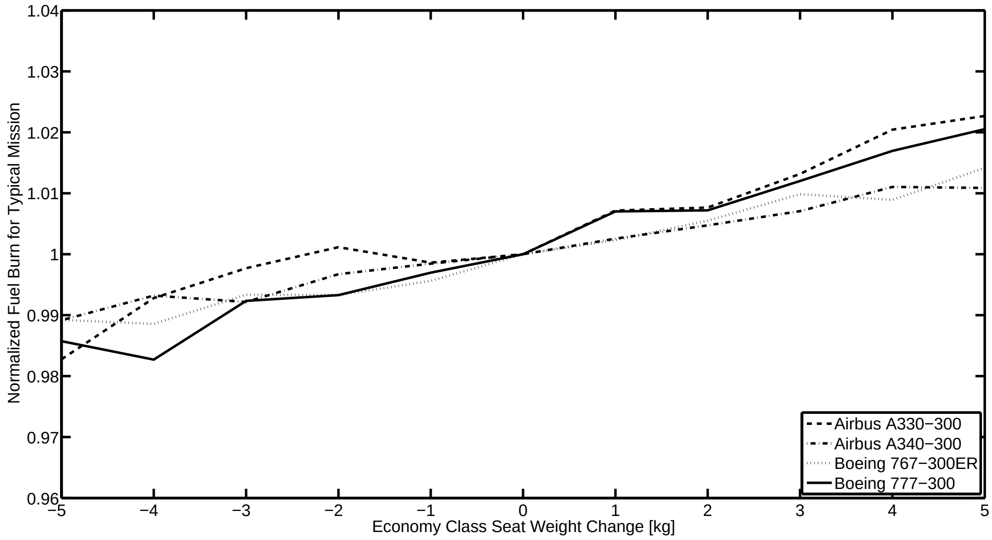


(b) Long-Haul Aircraft

Figure 3.18: Harmonic fuel burn per passenger per kilometer versus EC seat weight

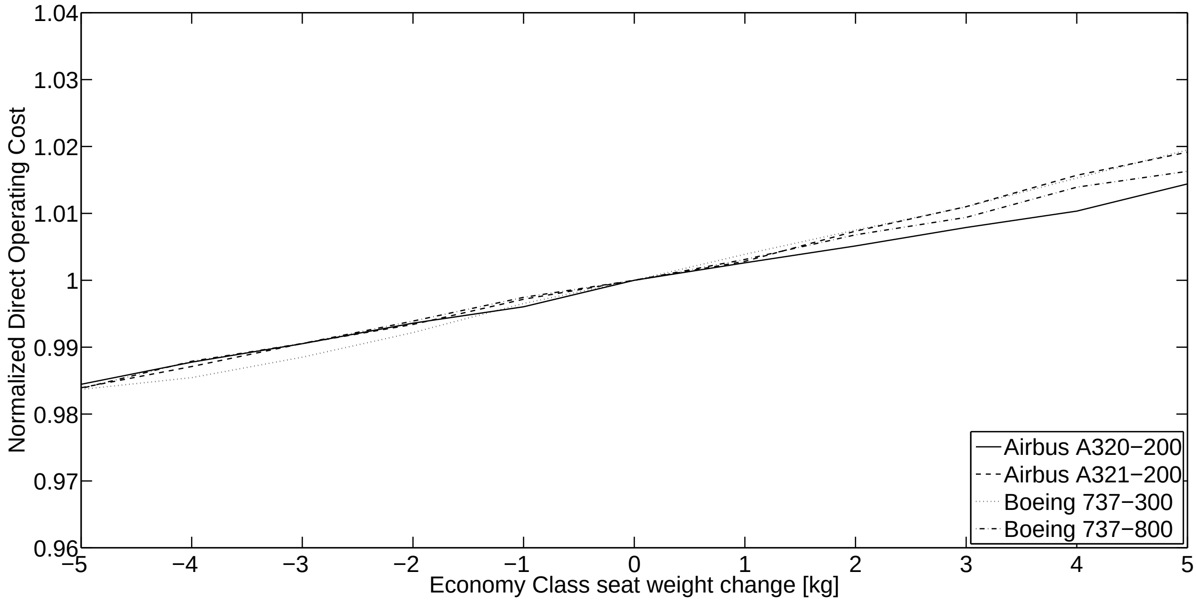


(a) Short-Haul Aircraft

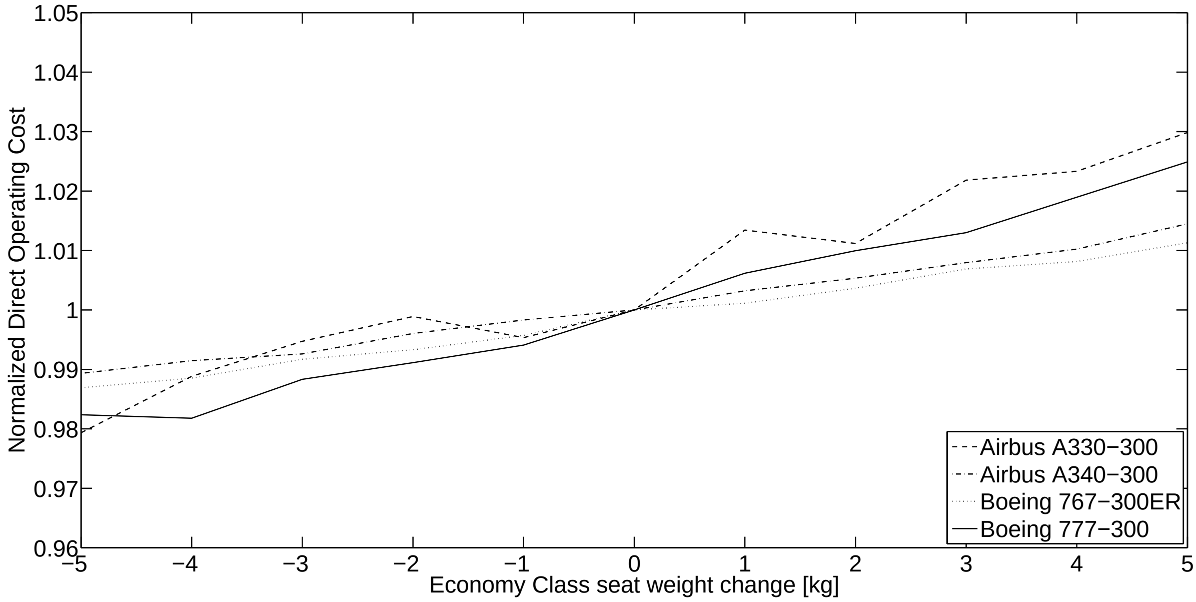


(b) Long-Haul Aircraft

Figure 3.19: Typical mission fuel burn per passenger per kilometer versus EC seat weight



(a) Short-Haul Aircraft



(b) Long-Haul Aircraft

Figure 3.20: Direct operating costs versus EC seat weight

4

Lower Deck Seating

According to Airbus [17] a future aircraft cabin utilization enhancement can be realized by incorporating an LDS compartment in a long-haul wide-body aircraft. First of all, the dimensional constraints for an LDS compartment are described in Section 4.1, after which the associated regulatory restrictions are described in Section 4.2. Subsequently, additional safety requirements and comfort requirements are described in Sections 4.3 and 4.4, respectively. Following the specification of constraints, regulatory restrictions, and additional requirements, a set of proposed cabin layouts is shown in Section 4.5. Finally, the implementation of the LDS compartment in the Initiator and the obtained results are stated in Sections 4.6 and 4.7, respectively.

4.1. LDS Interior Dimension Constraints

The modeled Airbus A340-300 as described in Chapter 2 is used within the Initiator to model the LDS compartment, for which several design constraints are taken into account and described in the separate subsections of this section. It should be noted that the Airbus A340-300 is selected as a reference aircraft for the implementation of an LDS compartment due to the fact that most references in literature related to lower deck utilization are based on either an Airbus A340-300 or an Airbus A330-300. By using the Airbus A340-300 as a reference aircraft for the implementation of the lower deck utilization, a comparison between previously found results can be made.

4.1.1. LDS Luggage Constraint

It is assumed that the luggage volumes and weights as stated in Table 4.1 apply, which are based on the average checked luggage dimensions and weights provided by Delta Air Lines [1], Air France [2], British Airways [3], Virgin Atlantic [4], and Qantas Airways [5]. The total luggage space required for the main deck passengers in the modeled Airbus A340-300 is found to be equal to 50.10 m^3, when making use of Table 4.1 and the number of placed FC, BC, and EC passengers resulting from the CC. However, if the maximum certified number of passengers for the Airbus A340-300 is taken into account, amounting to 440 [58], a total cargo volume of 65.60 m^3 is required. This volume is based on a single-class layout with 440 EC passengers and is dependent on the airline policy with respect to luggage restrictions and cabin layout. It should furthermore be noted that an additional 5 % margin is taken into account with respect to the luggage dimensions in order to account for oversized luggage and packing efficiency.

[1] Delta Air Lines, Checked Bags and Optional Service Fees, http://www.delta.com/content/www/en_US/traveling-with-us/baggage/before-your-trip/checked.html, Accessed: 19/07/2015

[2] Air France, Checked Baggage, http://www.airfrance.us/US/en/common/guidevoyageur/pratique/bagage-soute-airfrance.htm, Accessed: 19/07/2015

[3] British Airways, Checked Baggage, https://www.aa.com/pubcontent/jbax/includes/main.jsp?category=baggage&locale=en_GB&airlineCode=ba&file=bagchk.html, Accessed: 19/07/2015

[4] Virgin Atlantic, Check in Baggage, http://www.virgin-atlantic.com/gb/en/travel-information/baggage/check-in-baggage.html, Accessed: 19/07/2015

[5] Qantas Airways, Baggage Allowance, http://www.qantas.com.au/travel/airlines/checked-baggage/global/en, Accessed: 19/07/2015

According to data provided by Airbus [25], the total cargo hold, consisting of a bulk, forward, and aft compartment, provides space for 32 LD3 containers and a bulk volume of 19.7 m^3. Using data of Morell [27], Air Canada[6], and Swiss World Cargo[7] , it is known that the usable volume of an LD3 container equals 4.2 m^3. As the aft cargo hold of the Airbus A340-300 provides space for 14 LD3 containers, amounting to a total usable volume of 58.8 m^3, it is observed that for the maximum certified number of passengers, the complete forward cargo deck can still be used for the placement of passenger seats. It is assumed that the bulk cargo hold can be used for passenger luggage storage as well.

Table 4.1: Average checked luggage volumes for FC, BC, and EC passengers

Passenger Type	Max. Luggage [pcs]	Max. Luggage Volume [m^3/pc]	Max. Luggage Weight [kg/pc]
First Class	3	0.142	32
Business Class	2	0.142	32
Economy Class	1	0.142	23

4.1.2. LDS SERVICE AREA CONSTRAINT

For the LDS compartment, a similar service area requirement is present when compared to the main passenger deck. Hence, the service area requirements in Table 4.2 are used to calculate whether the aircraft lower deck provides sufficient space for the placement of service facilities. A critical note with respect to the service area constraint is that use is made of a galley and lavatory area requirement instead of a volume requirement. This assumption might lead to a slight underestimation of the required service area for the LDS compartment, due to the fact that the LDS compartment provides a lower cabin height when compared to the main deck.

Table 4.2: Service area requirements for modeled Airbus A340-300

Type	Economy Class	Business Class	First Class
Lavatory Utilization [$\frac{pax}{lav}$]	46	21	14
Galley area [$\frac{m^2}{pax}$]	0.07	0.28	0.41
Lavatory area [$\frac{m^2}{lav}$]	1	1	1

4.1.3. LDS STAIRCASE CONSTRAINT

To access the LDS compartment, two staircases are installed in the LDS compartment, leading up to the main deck. The placement of two staircases in the LDS compartment is determined according to FAA regulations, as explained in Section 4.2. Based on the provided cabin layout and corresponding seat dimensions of the Airbus A340-600 by Lufthansa [8], it is known that the interior staircase dimensions equal 0.94 m by 2.31 m, spanning a floor area of 2.1714 m^2. Based on the cabin planform provided by Lufthansa, it is concluded that the two staircases lead to a reduction of 12 EC seats. The area requirement for the staircases is added to the area requirement for service facilities, thereby effectively defining the floor area that is left for the placement of passengers within the lower deck. It should be noted that the staircase dimensions are verified by comparing with the requirements for the lower deck stairs as set by Blauwhoff [18], as shown in Table 4.3 and Figure 4.1.

[6] Air Canada, Unit Load Devices (ULDs), https://www.aircanada.com/cargo/en/shipping/ulds.html, Accessed: 05/08/2015
[7] Swiss World Cargo, LD-3 Container, http://www.swissworldcargo.com/web/EN/about_swiss/profile/fleetulds/ulds/Pages/nf-uld-co-ld3.aspx, Accessed: 05/08/2015
[8] Lufthansa, Seat maps Airbus A340-600, http://www.lufthansa.com/nl/en/Seat_maps_A340-600, Accessed: 19/07/2015

Table 4.3: Recommended staircase dimensions for lower deck access and egress as derived by Blauwhoff [18]

		Minimum [cm]	Maximum [cm]	Best [cm]
A	Step Width	24	30	28-30
B	Riser Height	13	20	17-18
C	Width (rail to rail)			
	One-Way Stairs	56	-	56
	Two-Way Stairs	122	-	122

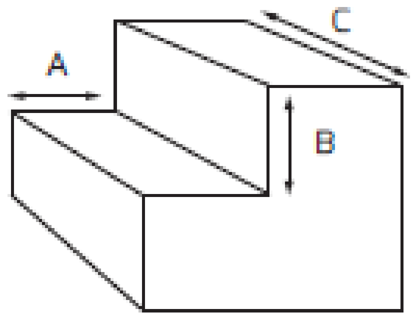


Figure 4.1: Lower deck staircase dimension parameters corresponding to Table 4.3

4.1.4. FORWARD CARGO DECK DIMENSIONS

The Airbus A340-300 forward cargo deck length specified by Airbus [25] equals 15.03 m. Furthermore, the forward and aft cargo deck width of the Airbus A340-300 is provided by Jane's [9], being equal to 3.175 m. An estimate of the LDS compartment floor width, w_{LDS}, is made by calculating the cabin sagitta:

$$w_{\text{LDS}} = \sqrt{2 \cdot (h_{\text{LDS}} + x_{\text{m-c}}) \cdot r_{\text{fus}} - (h_{\text{LDS}} + x_{\text{m-c}})^2} \tag{4.1}$$

When implementing the known fuselage dimensions and the LDS compartment height, a floor width equal to 2.59 m is obtained. Multiplying this value with the forward cargo deck length leads to an LDS compartment floor area equal to 38.99 m^2. By assuming that the lower deck height equals 1.96m, the usable forward cargo deck volume equals 76.03 m^3.

4.1.5. MATHEMATICAL LDS CONSTRAINT EXPRESSIONS

The above mentioned constraints can be mathematically expressed by making use of two equations relating to the luggage constraint and area constraints:

$$pax_{\text{FC}} \cdot LQ_{\text{FC}} \cdot 1.05 \cdot LV + pax_{\text{BC}} \cdot LQ_{\text{BC}} \cdot 1.05 \cdot LV + (pax_{\text{EC}_{\text{main}}} + pax_{\text{EC}_{\text{LDS}}}) \cdot LQ_{\text{EC}} \cdot 1.05 \cdot LV \leq 78.5 \tag{4.2}$$

$$pax_{\text{EC}_{\text{LDS}}} \cdot A_{\text{GEC}} + \frac{pax_{\text{EC}_{\text{LDS}}}}{LU_{\text{EC}}} + 4.3428 + \frac{pax_{\text{EC}_{\text{LDS}}}}{n_{\text{abreast}_{\text{LDS}}}} \cdot (w_{\text{cab}_{LDS}} \cdot sp_{\text{EC}}) \leq 38.99 \tag{4.3}$$

It is chosen to make use of these mathematical expressions as airlines make use of varying luggage policies, service area placements, and passenger seating specifications. Hence, by creating these constraints, a uniform model is created and can be applied to every airline policy. From Equations 4.2 and 4.3 it becomes clear that the only unknown variable upfront of the LDS modeling is the number of passengers in the LDS compartment. In this case, Equations 4.2 and 4.3 show the relation for an LDS layout in full EC configuration. Different classes can be implemented in the LDS compartment as well, leading to a change in subscripts accordingly.

[9] IHS Jane's: Defense & Security Intelligence & Analysis, Jane's Aircraft Upgrades: Airbus A340, https://janes.ihs.com/CustomPages/Janes/DisplayPage.aspx?DocType=Reference&ItemId=+++1539118&Pubabbrev=JAU_, Accessed: 02/10/2015

4.2. REGULATORY RESTRICTIONS

Additional restrictions are posed on the LDS compartment when compared to the regular aircraft cabin with respect to FAA regulations, as stated in FAR Sec. 25 [59]. The most important regulations relating to the LDS compartment are described in Subsections 4.2.1 through 4.2.4. Considering the implementation of additional safety measures with respect to the aircraft structural integrity, the reader is referred to Section 4.3.

4.2.1. MAXIMUM NUMBER OF AIRCRAFT PASSENGERS

Depending on the number of emergency exits in the Airbus A340-300, the maximum number of passengers for which the aircraft is certified is determined. As mentioned in Subsection 4.1.1, the Airbus A340-300 type certificate shows that a maximum number of 440 passengers can be placed within the aircraft. This maximum number is based on FAR Sec. 25.807, which shows the required number and type of emergency exits for a corresponding aircraft passenger capacity. For aircraft having a capacity of more than 179 passengers, Table 4.4 shows the required type of emergency exits and the amount of passengers for which this exit is certified for.

Table 4.4: Minimum required type of emergency exit and corresponding passenger allocation for aircraft with a seating capacity of more than 179 seats

Emergency exit type	Maximum allowed increase in passenger placement
Type A	110
Type I	45
Type II	40
Type III	35

4.2.2. EMERGENCY EVACUATION REGULATIONS

One of the most important regulations with regards to the LDS compartment is based on the evacuation of the aircraft in case of an emergency, as stated in FAR Sec. 25.803. Each aircraft having a capacity of more than 44 passengers should be able to evacuate all of its passengers within 90 seconds by using half of the available exits. By adding an LDS compartment to the aircraft, which is accessible by two staircases, the evacuation time is assumed to be increased due to the slower movement of passengers on these stairs towards the emergency exit. It should be noted that the usage of two staircases in the LDS compartment is based on FAR Sec. 25.819, which relates to existing lower deck service compartments and states that at least two emergency evacuation routes are required at each end of a lower deck compartment.

The testing of a certified evacuation process requires a full scale test with an Airbus A340-300 with an LDS compartment. However, this test is beyond the scope of this thesis and an alternative method is used to assess the emergency evacuation process. The current evacuation possibilities of the Airbus A340-300 are illustrated in Figure 4.2 and show that only four emergency locations are present in the aircraft, thereby confirming the validity of the cabin top view as shown in Figure C.4.
The evacuation process of an Airbus A340-300 with an LDS compartment has been evaluated by Dos Santos by means of a computer aided simulation [19] and shows that no additional emergency exits are required in order to comply with FAR Sec. 25.803. This conclusion is based on the fact that the lower deck passengers make use of the emergency exits of the FC and BC compartments, which results from the implementation of an LDS compartment in the forward cargo hold.

Some critical notes are placed upon the research done by Dos Santos. First of all, it is seen that the evacuation process for the Airbus A340-300 with an LDS compartment is modeled for one specific seating configuration, amounting to a total number of passengers being equal to 300. Taking into account the evacuation time of the original Airbus A340-300, equaling 78.8 seconds (+- 3.8 seconds), and of the Airbus A340-300 with LDS compartment, equaling 81.1 seconds (+- 3.6 seconds), it is concluded that the placement of an LDS compartment does not pose any problems with respect to FAR Sec. 25.803 for this specific seating configuration. The question remains whether these results can be extrapolated for a larger amount of passengers and which number of passenger seats represents the maximum number of passenger seats complying with FAR Sec. 25.803.

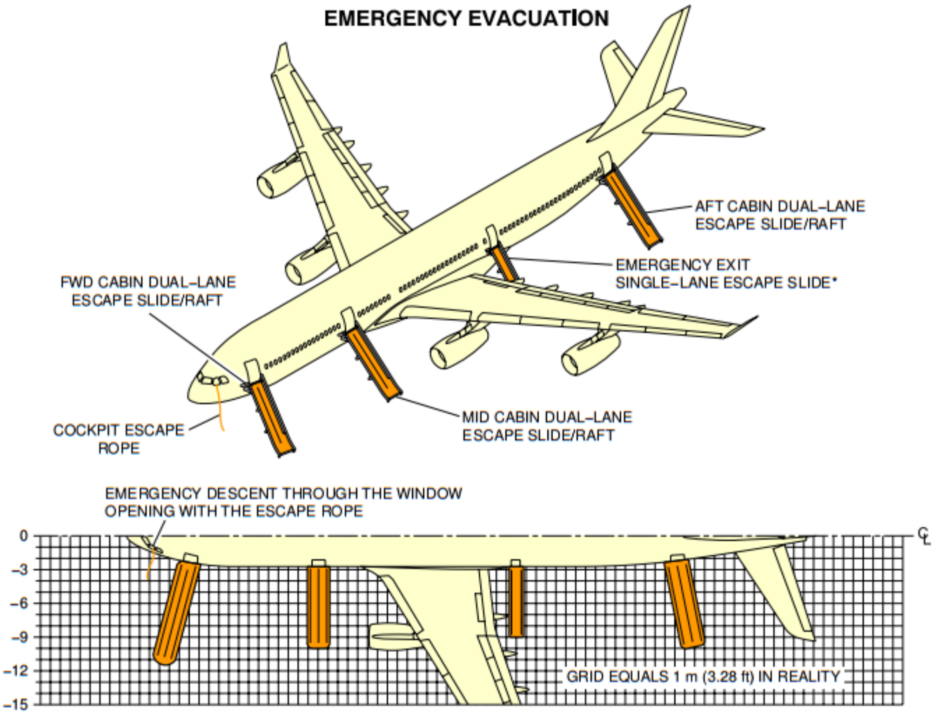


Figure 4.2: Current emergency evacuation procedure of the Airbus A340-300 [25]

Secondly, Dos Santos assumes that in both of the simulations passengers automatically choose the nearest emergency exit available in the aircraft. For the lower deck compartment, the nearest emergency exits are located on the main passenger deck. To ensure that the LDS compartment passengers are using the closest emergency exit in case of an emergency evacuation, information has to be provided by crew members and through instruction leaflets. A study conducted by Galea et al [60] shows that only 22 % of the passengers is aware of the number, location, and size of the emergency exits in the aircraft that they are flying with. Therefore, Galea shows that a better emergency exit performance in terms of evacuation time can be achieved by providing appropriate configuration information and exit capacity information to the passenger. The provision of additional information to the passenger leads to the requirement of additional crew instructions and training for the Airbus A340LDS, as similarly confirmed by Muir [61] for double-deck aircraft that are using the upper-deck as a passenger compartment.

4.2.3. WATERLINE RESTRICTIONS

Even if the emergency evacuation of an LDS compartment is shown to be executed within a sufficient time frame, airlines might opt for additional emergency exits in the lower deck to provide additional passenger safety. A lower deck exit is shown by PSA in the Lockheed TriStar [10] and by Ilyushin in the IL-86. However, strict regulations are posed with respect to the aircraft waterline during ditching. Both Airbus and Boeing have incorporated a ditching switch in their aircraft, forcing all valves and exits to be closed during ditching. Hence, if an airline is willing to incorporate additional emergency exits, it should be kept in mind that these can not be used at controlled landings on water and are only useful in case of land-based emergency landings. Furthermore, FAR Sec. 25.807 states that with respect to ditching, each aircraft having a capacity of more than 10 seats should have at least one emergency exit of Type III above the waterline for each side of the fuselage for every 35 seats present. For compliance to this regulation, the four Type A exits present on the main passenger deck could serve as emergency exits present above the waterline.

[10] Lockheed-Martin Corporation, The layout of the lower lounge, from a Lockheed promotional brochure via Jon Proctor, http://www.psa-history.org/sites/default/files/aircraft/l10-loungelayout.jpg, Accessed: 02/10/2015

4.2.4. GENERAL LOWER DECK SAFETY MEASURES

Besides the regulations as stated above, additional measures are required to ensure a similar level of passenger safety as compared to the main deck. Based on FAR Sec. 25.819, the following requirements are posed upon a lower deck compartment in order to ensure the minimum required passenger safety level:

- A two-way voice communication system is required between the main deck and the lower deck.
- An aural emergency alarm system has to be present in the lower deck, such that the crew on the main can be informed in case of emergency.
- Similar to the main deck, a means has to be present to indicate that the passenger seat belts have to be fastened. This condition is obvious for an LDS compartment, but shows its importance for the LDGL compartment, as described in Chapter 5, in order to inform passengers to return to their main deck seats.
- Similar to the main deck, a public address system is required in the LDS compartment.

With respect to the height of the LDS compartment, attention should be paid to FAR Sec. 25.785, which describes the regulations with respect to passenger seats, berths, safety belts, and harnesses. An important regulation stated in this section is the prohibition to install any object within a specified headstrike zone, as measured from the cushion reference point (CRP), if it is not shown that the installed object will not pose any threat to passenger safety during normal operation. As the height of the LDS compartment is significantly lower than the height of the main passenger deck, attention has to be paid with respect to the installment of any overhead devices. A visualization of the headstrike zone as mentioned in FAR Sec. 25.785 [62] is shown in Figure 4.3.

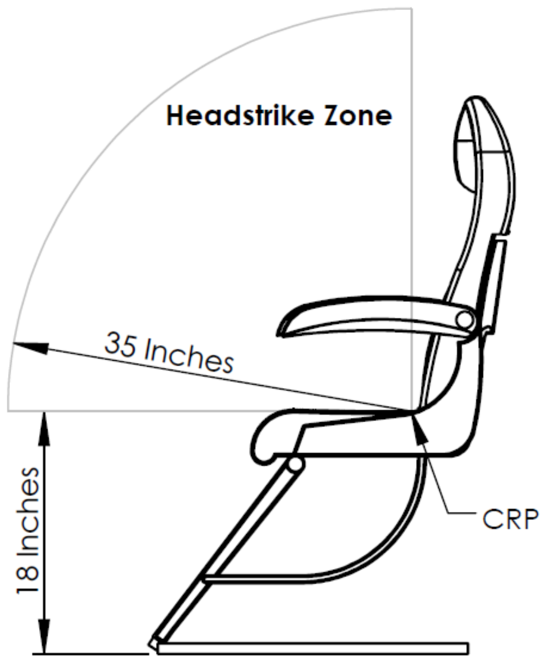


Figure 4.3: Visualized headstrike zone as indicated by FAR Sec. 25.785

4.3. LDS SAFETY REQUIREMENTS AND STRUCTURAL REINFORCEMENTS

According to the recent DLR report on LDS with respect to crash simulation [20], reinforcements in both the original cargo floor and lower deck compartment structure are required in order to make the lower aircraft deck suitable as a passenger compartment. Two major reinforcements to the aircraft structure are required for the implementation of an LDS compartment. First of all, a reinforcement of the structure below the original cargo floor is required to resist belly crash landing loads.

Secondly, a reinforcement of the lower deck in itself is required in order to carry the weight of the main passenger deck in case of a crash landing, thereby ensuring sufficient escape possibilities for the LDS compartment passengers. The requirements as set by DLR are derived by means of a KRASH model analysis, which in general shows a good correlation with actual crash landing impact load analyses [63]. Both structural improvements are described in Subsections 4.3.1 and 4.3.2 and are mainly required for compliance with FAA regulations with respect to belly crash landings. As the conceptual design phase is still regarded, several assumptions are made in order to estimate the weight penalty due to the required structural reinforcements:

- The material used for the structural members is AL2024-T3, which is a commonly used material for aerospace structures and yet present for the modeling of various fuselage components within the Initiator.
- A structural safety factor of 1.5 is applied to the modeled structural members, similar to the safety factor of every other common fuselage component and prescribed in FAR Sec. 25.303.
- As the aircraft conceptual design phase is considered, only static loads are used for a simplified structural analysis of the LDS compartment. This assumption leads to the fact that the additional structural members are sized according to the highest load that is expected to occur. Following this assumption, an overestimation of the weights of the structural members is likely to occur.
- Only two failure modes relating to the additional support struts are assumed to possibly occur during a belly crash landing. These failure modes are defined as buckling failure and static deflection of the modeled support struts.
- Contrary to the fuselage shell, the modeled support struts are sized without taking any cyclic loading into account. This assumption is based on the fact that a continuous load is present on the sized support struts throughout the complete mission profile and hence is not dependent on flight phase.

It should be noted that the lowering of the aircraft cargo floor can be established, as shown through the patents laid by Airbus [22] and Boeing [21]. Examples of the Airbus A330 and A340 family cross sections can be found in Figures E.1a and E.1b, both showing that a small adjustment will have to be made in order to lower the cargo technical floor. This adjustment is specified as the relocation of the aircraft hydraulic lines, which are located below the structural cargo floor. Due to the lack of detailed aircraft structural information and the present example of lower deck utilization in the Airbus A340 by Lufthansa, the assumption is made that the relocation of these hydraulic lines is feasible.

4.3.1. IMPROVED LOWER DECK COMPARTMENT

In order to enhance the survival chances of the passengers in the LDS compartment, it should be ensured that the escape routes from the lower deck compartment are not obstructed and kept as large as possible. To prevent the main passenger deck from deforming and hence minimizing the escape route for the LDS compartment passengers, vertical struts are required in the middle of the LDS compartment aisle, carrying the load of the main deck [20]. A graphical representation of this set-up is shown in Figure 4.4, in which the additional strut between the lower deck and the main deck is displayed.

For the estimation of the increase in structural weight due to the vertical support struts, the following assumptions are made:

- The maximum allowable vertical deflection of the main deck passenger floor equals 0.025 m, based on the DLR crash simulation report[20] in which it is shown that this deflection ensures sufficient escape possibilities for LDS compartment passengers.
- The load of the main passenger deck is assumed to act as a point load on each vertical strut and hence an undetermined static load problem exists. It is assumed that due to this assumption, no deflection of the main passenger deck floor occurs between the vertical struts. Hence, a critical load case is defined, where the lower deck side struts are not taken into account for the carriage of the loads.
- The cross section of the vertical strut is assumed to be circular shaped. The circular cross section does not only contribute positively towards axial loading resistance, but also to the aesthetics of the cabin interior.

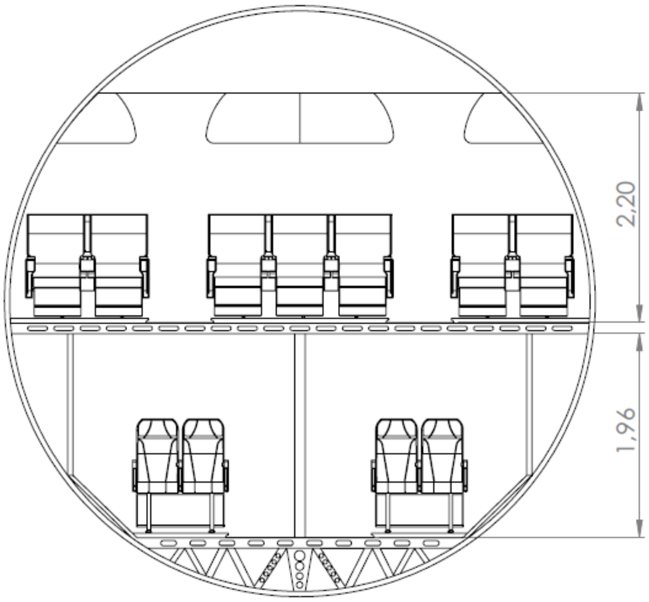


Figure 4.4: LDS compartment cross section drawing, including lower deck structural reinforcements

- The total load acting on the main deck floor is scaled with respect to the lower deck compartment length in order to calculate the load on the main deck above the LDS compartment. It is assumed that the part of the main passenger deck that is not present above the LDS compartment is only supported by the side struts in the lower deck, which are yet present in the aircraft and shown in Figures 4.4, E.1a, and E.1b.
- The vertical support struts are assumed to be placed every 2 meters in order to provide sufficient passenger space and visibility within the LDS compartment. When a regular aircraft frame spacing of 0.5 m [64] is considered, an additional structural element in longitudinal direction has to be present. This additional structural element is integrated in the main deck floor in order to connect the aircraft frames and transfer the loads towards the vertical support struts.

The load acting on the total main deck floor, including the main deck weight itself, is calculated and scaled according to the length of the main cabin deck that is present above the LDS compartment. Hence, the total load that is assumed to act on the support struts, P_{struts}, is defined as:

$$P_{\text{struts}} = (W_{\text{pax}_{\text{main}}} + W_{\text{furn}_{\text{main}}} + W_{\text{attendants}_{\text{main}}} + W_{\text{floor}}) \cdot g \cdot \frac{l_{\text{cab}}}{l_{\text{LDS}}} \tag{4.4}$$

Using the assumption that a vertical support strut is placed every 2 meters within the lower deck compartment, the total number of required struts equals 7 for the corresponding lower deck compartment dimensions. Furthermore, taking into account the prescribed structural safety factor, n, and a maximum load factor, j, of 16g [20] [65], the total load per strut is calculated by:

$$P_{\text{strut}} = \frac{P_{\text{struts}} \cdot n \cdot j}{n_{\text{struts}}} \tag{4.5}$$

As yet mentioned, two failure modes are assumed while analyzing this statically undetermined problem, relating to a maximum vertical deflection of the strut and buckling of the strut. For these failure modes, the following equations are used:

$$\delta = \frac{P \cdot l}{E \cdot A} \tag{4.6}$$

$$P_{\text{crit}} = \frac{\pi^2 \cdot E \cdot I}{l^2} \tag{4.7}$$

By assuming a maximal deflection of 0.025 m [20], a strut length, l, equal to 1.96 m, a material Young's modulus, E, of 73.1 GPa, and a point load equal to P_{strut} as defined in Equation 4.5, the required cross sectional area, A, of a single strut is calculated. As the cross sectional area of the strut is assumed to be a hollow cylinder, two unknown variables are present. These unknown variables are related to the cylinder outer radius and the cylinder thickness.

Using Equation 4.7, the required area moment of inertia, I, for the vertical strut is calculated. Similar to the use of Equation 4.6, the assumed strut height, strut load, and material Young's modulus are used. Furthermore, the largest required cross sectional area determines the critical load case for the vertical strut. It is shown for the vertical support strut that the buckling load case is critical and hence the vertical strut is sized accordingly. By multiplying the cross sectional area with the length of the vertical strut, the volume of the strut is obtained and hence the total weight of one vertical strut by using a density of 2780 kg/m^3. Multiplying this weight with the total number of struts provides the total weight of the required vertical support struts.

4.3.2. IMPROVED LOWER DECK FLOOR FLOOR STRUCTURE

In order to increase the safety of the passengers in the lower deck compartment, an energy absorbing structure below the original cargo floor is required to withstand the impact on the fuselage in case of a belly crash landing. The energy absorbing structure required for the lower deck passenger floor consists of diagonal lower deck floor struts, placed below the lower deck passenger floor, as described by Boeing [21]. Hence, in order to model the improved lower deck floor structure within the Initiator, it is assumed that the lower deck floor in itself does not need any structural reinforcement and that a weight penalty is added for the diagonal struts that are present below the lower deck floor.

A similar approach as mentioned in Subsection 4.3.1 is required for the computation of the weight of the improved lower deck structure. It is assumed that the total load acting on the vertical support strut is transferred to the lower passenger deck and hence is taken into account for the load calculation of the lower deck floor structure. The total load acting on the lower deck diagonal floor struts is therefore defined as:

$$P_{\text{lower}} = (P_{\text{strut}} \cdot n_{\text{struts}}) + (W_{\text{pax,LDS}} + W_{\text{att,LDS}} + W_{\text{struts}} + (W_{\text{cargofloor}} \cdot \frac{l_{\text{cab}}}{l_{\text{LDS}}} + W_{\text{furn,LDS}})) \cdot g \cdot n \cdot j \tag{4.8}$$

A graphical representation of the loads acting on the lower deck floor structure is shown in Figure 4.5. In this figure, it can be seen that the load originating from the vertical support strut is acting on the floor as a point load. However, the other load components as described in Equation 4.8 are acting as a distributed load on the lower deck floor. By using similar equations as described in Subsection 4.3.1, the weight penalty for the improved lower deck floor structure is calculated. Of course, it should be noted that the lower deck support struts are placed at an angle with respect to the lower deck floor and hence is taken into account as well. In order to simplify the calculation of the weight penalty for the the lower deck floor structure, it is assumed that an angle of 45 degrees is present between the structural members and the lower deck floor. Furthermore, a frame spacing of 0.5 m is applied for the lower deck structure, which leads to 30 individual frames that carry the combined load as shown in Equation 4.8. Moreover, by using the sagitta equation as defined in Equation 4.1, the maximum distance between the lower deck floor and the fuselage skin is determined. By making use of 12 individual structural members below the lower deck floor, the weight penalty due to the lower deck structural reinforcement is obtained.

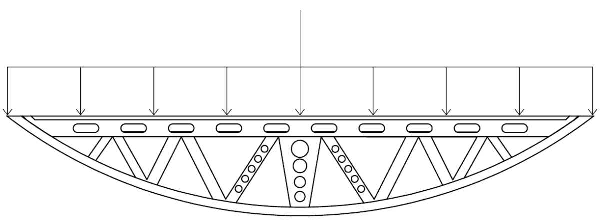


Figure 4.5: Distributed load and point load acting on LDS floor reinforcement structure

4.3.3. ADDITIONAL LDS COMPARTMENT SAFETY MEASURES

Besides the additional reinforcements in the LDS compartment, two additional internal LDS compartment changes are made in order to ensure maximum passenger safety. First, it is recommended to move the LDS seats as far outwards as possible in order to enhance the passenger escape route as well as to minimize the vertical accelerations placed on the LDS seats. By using this requirement, a doubled aisle width as compared to the main passenger deck is used within the LDS compartment. It should be noted that the doubling of the aisle width contributes positively towards boarding times and passenger comfort as well.

Secondly, a recommendation is made by DLR to attach the overhead bins to the LDS floor rather than the ceiling. Independent of the DLR study, Blauwhoff provides a similar recommendation regarding the placement of the luggage bins, based on the fact that the side-wall clearance is sufficient in case of a 2-2 LDS seating configuration. Contrary to the findings of Blauwhoff, no additional overhead luggage bin can be provided for the aisle seat passenger as the vertical accelerations on the bins in case of an emergency landing would impose a large safety risk for the LDS passengers. It should also be noted that FAR Sec. 25.787 regulates the usage of stowage compartments in commercial transport aircraft, stating that the compartments will have to prevent the contents from shifting and becoming a hazard. By using the DLR test results and the recommendation of placing the overhead storage bins on the floor, compliance is shown with respect to FAR Sec. 25.787.

4.4. LDS COMFORT REQUIREMENTS

When designing and analyzing the LDS compartment from a comfort perspective several comfort requirements will have to be taken into account. The most important comfort requirements are described in Subsections 4.4.1 and 4.4.2.

4.4.1. WINDOW REQUIREMENT

A design aspect that should be taken into account with respect to the LDS compartment is the placement of windows. Usually, no windows are present in the cargo hold and this has also not been the case for the lower lounge of the Lockheed TriStar. The much older Boeing Stratocruiser, however, contained windows in the lower lounge. As passengers are expected to be in the LDS compartment during the entire journey, the absence of any windows could impose the experience of claustrophobia. Whereas this effect is not particularly studied for aircraft, similar examples can be found for office rooms in which no windows are present, as shown by Rachman and Taylor [66] and Aries et al [67]. With respect to the passenger condition from a medical point of view, the presence of windows exhibits a positive influence. It is shown by Money et al [68] that the absence of windows could pose a mismatch between the movement perception of the individual and the actual movement of the vehicle. This mismatch could in turn lead to motion sickness, characterized by vomiting, nausea, and sweating. According to Turner et al [69], 16.2 percent of the passengers reports illness during a flight, ranging from nausea to vomiting. The placement of windows therefore proves to be extremely important and should therefore not be ignored during the design of the LDS compartment.

Furthermore, it should be noted that there exists a high possibility of passengers choosing the window seat when booking flight tickets. Although very little academic evidence exists for this seating preference, many newspaper articles and internet research shows that this is indeed the case. Providing the opportunity of window seats in the LDS compartment could therefore strengthen the market potential of an LDS compartment.

Following from the above, the necessity for passenger windows in the LDS compartment is taken into account and modeled as such in the Initiator. It is shown by Blauwhoff [18] that the placement of windows in the LDS compartment is feasible, but that if an original Airbus A330-300 is used, the windows offer less viewing possibilities. As conceptual design is regarded in this thesis, it is assumed that the placement of lower deck windows would not pose any problems as seen from a manufacturing point of view.

4.4.2. PASSENGERS WITH REDUCED MOBILITY

One of the main obstacles in the design of the LDS compartment is the suitability for passengers with reduced mobility. As can readily be seen by the design of the LDS compartment, the presence of staircases leading to the LDS compartment could impose a severe obstacle for passengers with reduced mobility.

One of the solutions is the installment of a lift to transport passengers from the main deck to the LDS compartment, as reportedly being used by the DC-10 for access to the lower deck galley [70]. However, this solution can be ignored due to the fact that FAR Sec. 25.819 states that the use of the evacuation routes may not only be dependent on any powered device. Combining this constraint with the waterline regulations as stated in Subsection 4.2.3, it becomes clear that the best solution is found in placing passengers with reduced mobility on the main deck.

4.5. Proposed LDS Cabin Layouts

Based on the constraints as described in Section 4.1 it is concluded that a limited number of cabin layouts is achievable for the LDS compartment. Based on the additional safety requirements, as described in Section 4.3, the vertical struts pose a large restriction within this respect. Hence, either a 2-2, a 2-1, or a 1-1 seating configuration is considered for the LDS compartment. Several of the proposed layouts as described by Blauwhoff [18], such as the 2-3 and 0-3-0 seating configurations, are therefore ignored.

4.5.1. 2-2 Seating Configuration

The proposed 2-2 seating configuration can be used as a high density layout in the LDS compartment, allowing the placement of 48 additional passengers if a similar seat pitch is assumed as compared to the main deck EC cabin of the reference Airbus A340-300. Of course, for every layout it should be considered that the net increase in the total number of passengers is 12 passengers less due to the fact that multiple staircases are installed. Furthermore, it should be noted that by using this high density layout, no changes can be made with respect to the aircraft seat width dimensions as used for the reference Airbus A340-300. Due to the requirement of the doubled aisle width, the placement of luggage bins next to the seats is not possible. A solution to this problem is suggested by Blauwhoff and yields the implementation of a luggage storage compartment. Similar to Table 4.1, an average value for the allowed EC hand luggage volume is obtained. By multiplying the number of lower deck passengers with the average hand luggage volume and an additional factor of 15 % for oversized luggage, the required volume for this compartment is obtained. By using the LDS compartment height, the floor area that is required for the storage of passenger hand luggage in the lower deck is obtained.

Nevertheless, an Airbus A340-300 with LDS compartment using a regular 2-2 seating configuration does not imply any comfort enhancement for the passenger, as only a capacity increase is obtained without any comfort enhancements. Hence, the above mentioned case could be a good example for an LCC who is willing to fit as many passengers in its aircraft without providing enhanced comfort. However, as the goal of this thesis is to provide a new aircraft cabin design with enhanced passenger comfort, a second LDS layout possibility is added to the design methodology where an EC seat pitch increment is applied, based on the findings on the minimum required seat dimensions in Chapter 3. This case allows for the design of an aircraft cabin in which the world 99 percentile passenger is given the minimum required legroom. Up to a maximum seat pitch of 33.8 inch, the airline is able to suit 11 rows of seats in the LDS compartment. Hence, the net increase in passengers would therefore amount to 44. Contrary, when using a seat pitch being equal to 28 inch, one additional seat row can be installed in the lower deck, allowing for a total of 52 LDS compartment passengers. However, this configuration is highly likely to be unfeasible due to the fact that a seat pitch of 28 inch is rarely used on long-haul aircraft and is only seen at LCCs for short-haul flights.

When comparing the regular 2-2 seating configuration with 48 passengers with the proposed 2-2 seating configuration by Blauwhoff, it can be seen that Blauwhoff assumes that 2 additional seats are placed in the LDS compartment. This difference can be amounted to several factors, including the service area constraint as set in Subsection 4.1.5 and the modeled staircase dimensions as described in Subsection 4.1.3. The eventual 2-2 high density layout, containing 12 seat rows, and 2-2 comfort layout, containing 11 seat rows, are shown in Figure 4.6.

4.5.2. 2-1 Seating Configuration

An asymmetric 2-1 seating configuration allows the airline to offer a part of the LDS compartment passengers a wider seat cushion. It should be noted that the seats of the double row in the LDS compartment can not be widened due to the vertical middle strut constraint, as described in Section 4.3. Using the 2-1 seating configuration, an additional comfort class can be created, allowing a wider passenger seat for 12 LDS compartment passengers when a 31 inch seat pitch is assumed.

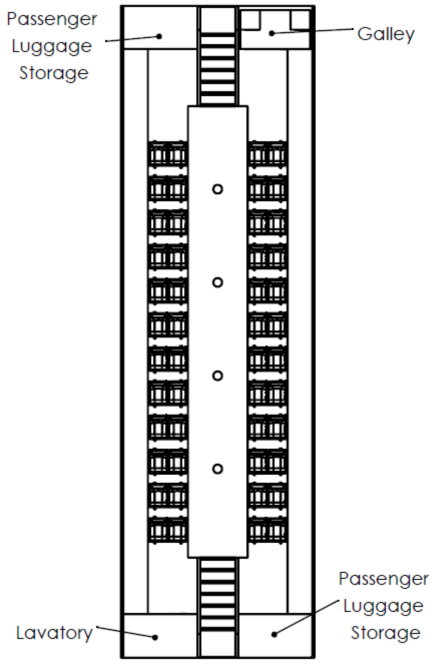


Figure 4.6: LDS compartment 2-2 high density (left) and 2-2 comfort (right) layout

By using this seat pitch, 36 additional passengers can be placed in the LDS compartment, yielding a net increase of 24 passengers. An asymmetric 2-1 seating configuration is not seen in literature with respect to the LDS compartment and usually only occurs in business jet cabins or cabins of regional aircraft. The 2-1 asymmetric LDS layout is shown in Figure 4.7 for clarity. It has to be stressed that a herringbone configuration could be implemented for the single seat rows, allowing for even more passenger space and comfort.

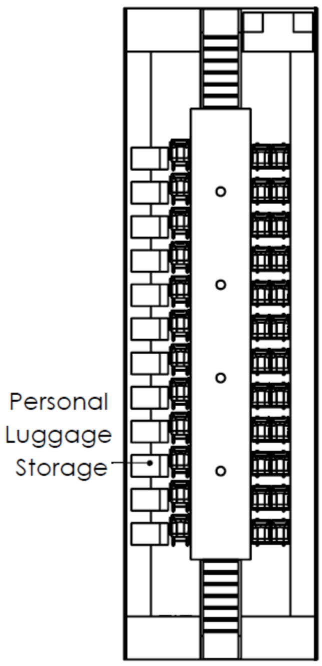


Figure 4.7: LDS compartment 2-1 asymmetric layout

4.5.3. 1-1 SEATING CONFIGURATION

By using a 1-1 seating configuration, the airline is able to create an additional premium EC class in the LDS compartment, allowing for a wider seat cushion for all LDS compartment passengers. The large downside is that the net passenger increase is limited to 12 when assuming a similar seat pitch as compared to the main deck. This small net passenger increase leaves the question whether a 1-1 seating configuration can be considered as economically feasible and which additional premium will have to be paid by the LDS compartment passenger in order to provide a sufficient level of airline profitability. A visual representation of the 1-1 seating layout is shown in Figure 4.8. Contrary to this figure, it should be noted that a herringbone set-up would ideally support the 1-1 configuration, allowing for more passenger legroom and personal storage space. Finally, an overview of the cross sections of the utilized layouts is shown in Figure 4.9.

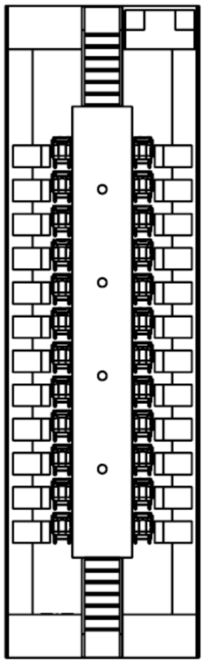


Figure 4.8: LDS compartment 1-1 seating layout

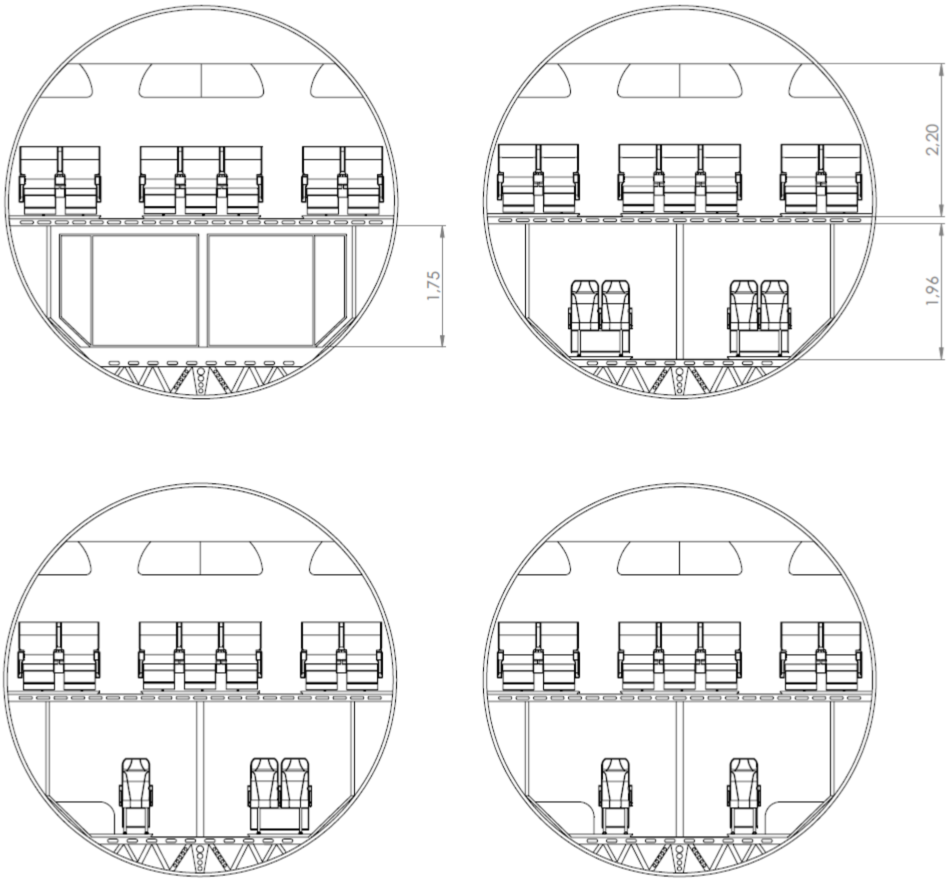


Figure 4.9: Overview of utilized LDS compartment layouts

4.6. MODELED LDS

To analyze the effect of an LDS compartment on aircraft performance, a baseline model is created in the Initiator for the Airbus A340-300 and called Airbus A340-300LDS. To model the LDS compartment correctly, the following changes are made:

- **Fuselage Structural Weight**
  The structural improvements as described in Subsections 4.3.1 and 4.3.2 are implemented in the fuselage weight estimation module. The weight estimation of these structural improvements is added to the modeled fuselage weight. The structural improvements are based on the maximum number of passengers that are able to fit in the Airbus A340-300. This means that 440 passengers are considered, of which 52 are placed in the LDS compartment.

- **Cargo Bay Margin**
  To provide more passenger space and a larger aisle height in the LDS compartment, the cargo bay height margin is increased from 0.15 m to 0.35 m, leading to an LDS compartment aisle height of 1.96 m. The overall fuselage dimensions are not affected by this change and simply lead to the lowering of the structural cargo floor by the Initiator.

- **Additional Cabin Attendant**
  Two additional cabin attendants are assumed to be required for the LDS compartment, influencing the class II weight estimation and the cost estimation.

- **Additional Lower Deck Furnishing**
  The furnishing weight of the LDS compartment is added to the total furnishing weight, thereby ensuring that the main deck floor does not experience this additional furnishing weight. The additional furnishing weight consists of the additional passenger chairs and luggage bins plus the additional service facility weights, such as the lavatories, galleys, and stairs.

A scaling factor of 1:7 is used with respect to the main deck to estimate the additional weight, based on the number of passengers in the LDS compartment.

- **Smaller Front Cargo Compartment Door**
The need for a large cargo door in the front compartment is vanished when no containers are placed in the front cargo compartment, leading to a lower structural weight penalty for the installment of freight doors. Instead, a regular door with comparable dimensions of a type A passenger door is modeled as lower deck door. This door, only present on one side of the cabin, is assumed to be sufficient for the loading of the lower deck galley. In order to calculate the weight decrease due to the smaller cargo door, use is made of the empirical cargo door weight estimation as defined by Howe [71]:

$$W_{\text{CargoDoor}} = 10 \cdot (1{+}0.75 \cdot w_{\text{CargoFloor}}) \cdot S_{\text{CargoDoor}} \tag{4.9}$$

The surface area of the cargo door,$S_{\text{CargoDoor}}$, is derived from the dimensions of the unit load device in combination with a safety margin of 10 %.

- **Additional Lower Deck Windows**
Using the theory of Howe, an approximation is made for the weight penalty due to the lower deck windows. It should be noted that the placement of multiple windows in vertical direction could show different behavior when compared with the estimation of Howe. The empirical relationship for the window weight provides an estimated weight penalty for the usage of these lower deck windows:

$$W_{\text{Windows}} = 90 \cdot S_{\text{Windows}} \cdot \Delta P \tag{4.10}$$

The aircraft differential pressure, ΔP, is obtained by subtracting the cabin pressure level from the cruise altitude pressure level and multiplied with the default safety factor. When using a safety factor of 1.5 and a typical cabin altitude of 1900 m, the weight penalty due to the additional windows amounts to 262 kg.

- **Class II Group Weight & Passenger Center of Gravity**
As described in Chapter 2, the assumption for the CG in case of an LDS compartment is not longer valid for the furnishing weight group, operational items group, and cargo weight group, which in total represent approximately 7 % of the aircraft MTOW. Based on the LDS dimensions as described in Section 4.1 it is assumed that the CG of the LDS compartment is positioned at approximately 30 % of the fuselage length. Subsequently, by using the fact that the mentioned group weights are related to each other with a ratio of 1:7 and using the obtained fuselage CG position of the modeled original aircraft, it is shown that the CG of the aforementioned group weights are shifted 1.77 m towards the nose of the aircraft. Using the shift in CG position, the CG of the passengers is scaled accordingly.

As described in Section 4.5, various layouts for the LDS compartment are assessed using the Initiator. The following main LDS configurations are assessed, after which additional analyses are made with respect to the mentioned LDS compartment layouts:

1. **Inside-Out LDS Configuration**
The first LDS configuration to be assessed is an LDS configuration from an inside-out design point of view. Using this design, the influence of the LDS compartment on the required wing area, CG location, and other components is assessed.

2. **Outside-In LDS Configuration**
Secondly, the maximum structural payload is lowered in order to obtain an identical aircraft geometry as compared to the original Airbus A340-300. By using a similar geometry with a changed payload-range diagram, a so-called retrofit of the original Airbus A340-300 is obtained.

Once both the inside-out configuration and outside-in configuration are modeled with the Initiator, a variation of the LDS compartment is carried out according to the proposed layouts in Section 4.5. These proposed layouts do not affect the harmonic top level requirements (TLR), but will change the secondary mission TLR's with respect to the number of placed passengers and associated payload. The following LDS compartment layouts are modeled, including the described changes to the main deck:

1. **High Density Layout**
   The high density LDS compartment layout comprises of a 2-2 seating configuration with similar seat properties as the main deck EC passengers as compared to the reference Airbus A340-300 layout. As described in Section 4.5, this layout yields a net increase of 36 passengers, making a total of 306 passengers in the modeled aircraft.

2. **2-2 Seating Comfort Layout**
   A more comfortable 2-2 seating configuration is used in the LDS compartment, yielding a seat pitch equal to 33.66 inch. As it is shown in Chapter 3 that this seat pitch allows for sufficient space for the 99 percentile of the world population, a more comfortable passenger cabin is designed. However, in order to provide every EC passenger this similar level of legroom, it is chosen to adjust the main deck EC seat properties accordingly as well. The result of this changed layout yields an aircraft passenger capacity being equal to 286 passengers.

3. **Asymmetric Seating Configuration**
   Although the CC is not able to design and visually display an asymmetric seating configuration, a modification to the CC can simulate the number of placed passengers in an asymmetric cabin. By using the proposed 2-1 seating configuration as described in Section 4.5, a net increase of 24 passengers is established, leading to a passenger capacity equal to 294.

4. **1-1 Seating Configuration**
   As described in Section 4.5, a 1-1 seating configuration yields a net passenger increase of 12 passengers. Although the seats are modeled in the CC using a regular pattern, it should be noted that a herringbone configuration yields the optimum configuration.

4.7. RESULTS

The obtained results for the Airbus A340-300LDS are described in this section. First of all, the results with respect to the baseline model are described in Subsection 4.7.1. Secondly, the results relating to the various LDS layouts are described in Subsection 4.7.2, after which a feasibility analysis from an economical point of view is described in Subsection 4.7.3. Finally, a comfort analysis is provided in Subsection 4.7.4.

4.7.1. BASELINE LDS CONFIGURATIONS

By modeling the aircraft models as described in Section 4.6 the aircraft performance can be compared among the baseline models, as shown in Table 4.5. It is seen that the modeling of an LDS compartment from an outside-in design point of view leads to an MTOW increase of 7.91 % with respect to the original aircraft and a wing reference area increase of a similar order of magnitude. When comparing the harmonic fuel burn, one can see that an even higher increase is attained, amounting to 9.72 %. Moreover, the implemented fuselage reinforcements lead to a weight increase of 2410 kg, yielding a 7.21 % increase with respect to the original fuselage.

In order to create the retrofit LDS compartment in the Airbus A340-300, a lowered maximum structural payload weight is attained, equal to 45560 kg. Hence, it is concluded that a decrease of 12.38 % of the maximum structural payload weight is sufficient to compensate for the implementation of an LDS compartment. Interesting to note is that due to the larger OEW of the retrofit aircraft, a higher harmonic fuel burn is attained when compared to the original Airbus A340-300. This increase, amounting to 1.52 % for the harmonic mission, is assumed to occur as well for the typical mission. The results of the typical missions are described in Subsection 4.7.2. An important note that has to be made with respect to the outside-in aircraft modeling is that a post-process linearization of the results is applied in order to match the aircraft weight components as compared with the original Airbus A340-300. This linearization is based on the aircraft MTOW difference, amounting to 0.015 %. By linearizing the other components as shown in Table 4.5, an accurate comparison is made between the original Airbus A340-300 and the Airbus A340-300LDS. The corresponding wing reference area shows a slight discrepancy with respect to the original Airbus A340-300, which is caused by the fact that the final wing loading is determined by making use of a design convergence as well. Using this design convergence, a tolerance of maximum 1 % is accepted with respect to the actual wing loading. Hence, a difference in wing reference area equal to 0.8 % results from this design convergence method.

Table 4.5: Initiator results for varying LDS configurations

	A340-300	A340-300LDS Inside-Out	A340-300LDS Outside-In
Max. Struct. Payload [kg]	52,00 t	52,00 t	45,56 t
MTOW [kg]	264,1 t	285,0 t	264,1 t
OEW [kg]	118,9 t	130,8 t	123,8 t
W_{fus} [kg]	33,42 t	35,83 t	35,02 t
S_{ref} [m^2]	348.8	375.5	351.6
Harmonic Fuel Burn [kg]	93,24 t	102,3 t	94,66 t

The shift of the CG of the various group weights, as described in Section 4.6, has a major impact on the final aircraft design, as shown in Figure 4.10. Moreover, the lowering of the maximum structural payload of the A340-300LDS for an outside-in approach leads to a change in the payload-range diagram, as illustrated in Figure 4.11.

4.7.2. LDS LAYOUT PERFORMANCE

In order to determine the performance of the Airbus A340-300LDS with different LDS layouts, the secondary mission requirements in the Initiator are varied, thereby changing the total number of passengers and the associated payload. For the original Airbus A340-300, the secondary mission is specified using the 270 modeled passengers and layout as shown in Figure C.4. Furthermore, the range for the secondary mission is set equal for all layouts and amounts to 9500 km.

Table 4.6: Initiator results for varying LDS Layouts

	A340-300	High Density 2-2	Comfort 2-2	Asymmetric 2-1	1-1 Seating
Passengers Placed [-]	270	306	286	294	282
Payload Weight [kg]	28350	32130	30030	30870	29610
Mission Fuel Burn [kg/pax/km]	0.0313	0.0292	0.0309	0.0302	0.0313
Mission DOC [US$/pax/km]	0.0593	0.0534	0.0570	0.0555	0.0578
Mission TOC [US$/pax/km]	0.0718	0.0657	0.0696	0.0680	0.0705

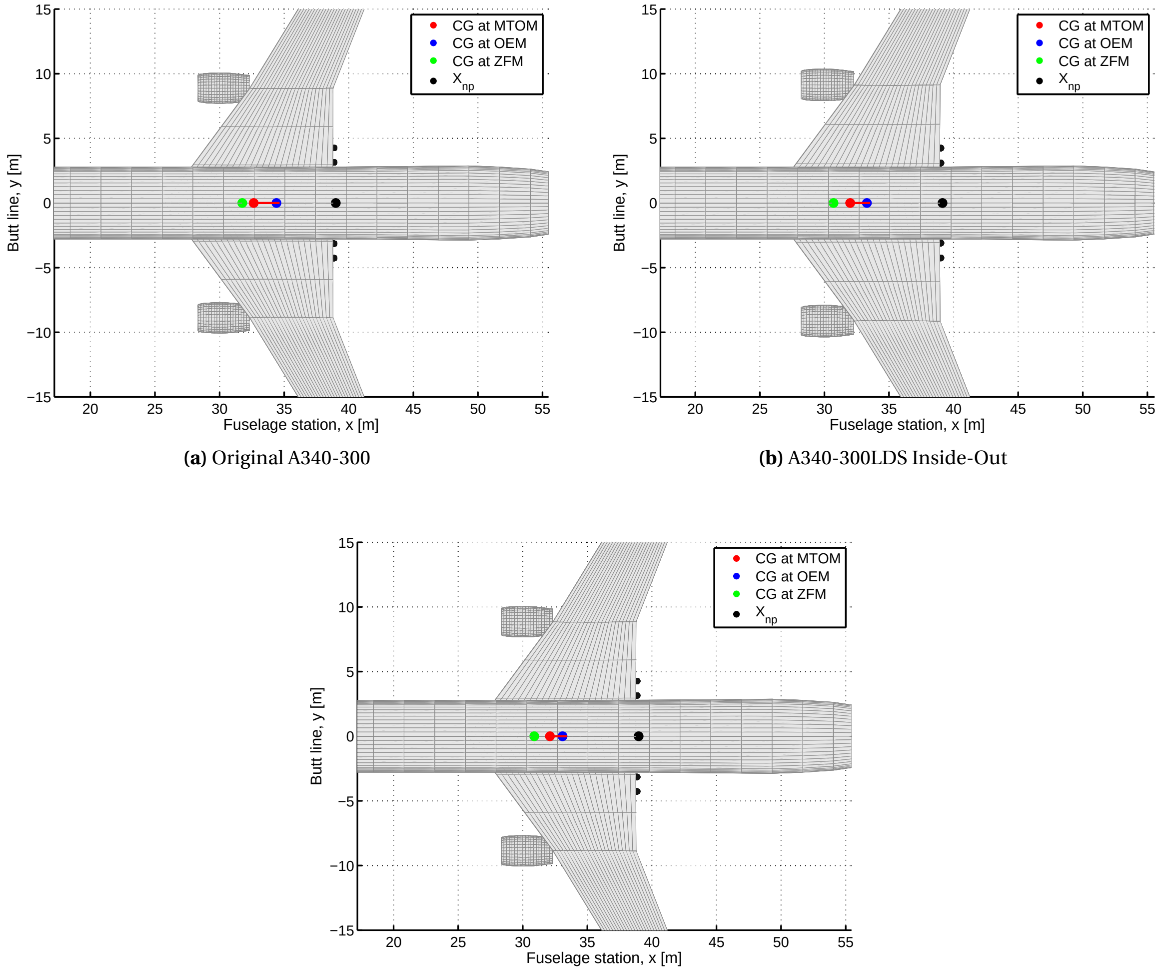
From Table 4.6 it is observed that the higher OEW of the Airbus A340-300LDS leads to a higher fuel consumption with respect to the secondary mission. This statement is supported by the fact that a downward trend can be observed in the typical mission fuel burn per passenger when increasing the number of passengers. However, when comparing the original Airbus A340-300 with 270 placed passengers to the Airbus A340-300LDS with 282 passengers, a relatively higher fuel burn per passenger is seen.

4.7.3. ECONOMICAL FEASIBILITY ANALYSIS

Based on the methods as described in Section 2.4, the feasibility of the designed aircraft cabins from an economical point of view can be determined. The economical feasibility analysis is carried out by analyzing the associated costs with respect to manufacturing and airline operation and by analyzing the profitability of the various LDS layouts.

MANUFACTURING ASSOCIATED COSTS

The aircraft list price is calculated by means of a top-down approach and a comparison between the Airbus A340-300 and the Airbus A340-300LDS in terms of manufacturing costs can therefore be made. As shown in Table 4.7, the Airbus A340-300LDS list price shows a 1.84 % increase with respect to the original Airbus A340-300. This increase is mainly caused by the larger structural weight of the fuselage, as mentioned in Subsection 4.7.1.

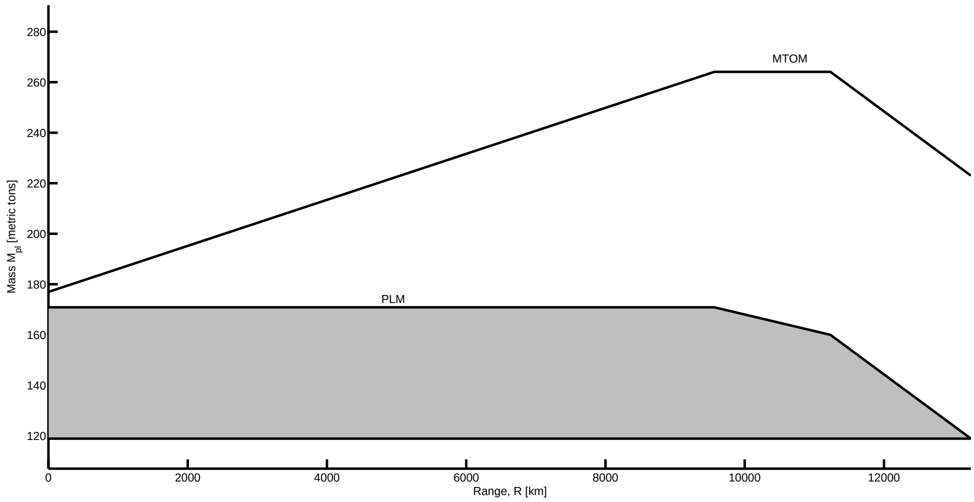


(a) Original A340-300

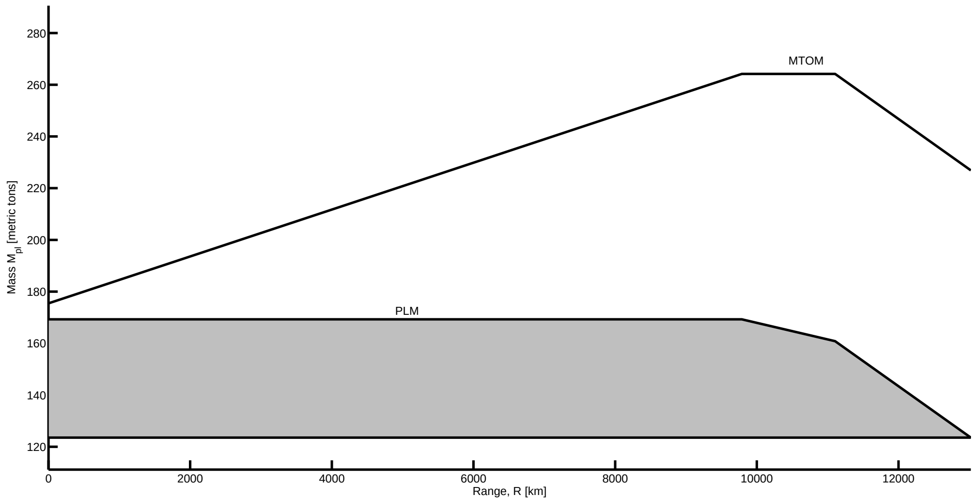
(b) A340-300LDS Inside-Out

(c) A340-300LDS Outside-In

Figure 4.10: CG locations for modeled Airbus A340-300 aircraft



(a) Original A340-300



(b) A340-300LDS Outside-In

Figure 4.11: Payload-range diagrams for modeled Airbus A340-300 aircraft

Table 4.7: Comparison of resulting aircraft list price for various Airbus A340-300 configurations

	Aircraft List Price [US$]
Airbus A340-300	189,78 Million
Airbus A340-300LDS	193,28 Million

Table 4.8: Operating profitability for the various LDS layouts corresponding to an operational life of 20 years

	Original	High-Density 2-2	Asymmetric 2-1	2-2 Seating	1-1 Seating
Operating Profit at 80% LF [US$/pax/flight]	9.94	28.41	20.32	14.20	8.73
Operating Profit at 100% LF [US$/pax/flight]	88.35	97.74	92.72	89.13	85.38

The associated maintenance costs, expressed as a part of the DOC, automatically increases due to the higher list price. It is seen for the Airbus A340-300LDS that the DOC related to maintenance equals 7.88 US$/nm, yielding an increase of 0.8 % with respect to the original aircraft. Furthermore, the higher aircraft list price relates to a higher cost of depreciation and hence a higher tax payment due to the higher book value of the aircraft.

Airline Operating Costs and Profitability

As shown in Table 4.6, the DOC of the various LDS layouts is higher when compared to the original Airbus A340-300. It should be noted that the DOC as shown in this table is related to a continuous 100 % passenger load factor. As mentioned in Section 2.4, this load factor is practically seen unfeasible and hence a passenger load factor sensitivity is shown as well. A more detailed breakdown of the DOC and IOC of the various LDS layouts is shown in Table F.2 for both a 80 % and 100 % passenger load factor. Furthermore, the operational profit, expressed in average profit per passenger per flight, for the various LDS layouts is provided in Table 4.8.

Reduced Freight Carrying Capacity

Due to the fact that the original Airbus A340-300 is able to carry additional freight in order to generate additional revenue, an analysis is carried out showing the effect of additional cargo carriage on the operational costs and revenue. Figure 4.12 shows how the costs and revenues vary with additional carried cargo weight for the original Airbus A340-300. The colored lines provide the equivalent values for the various LDS layouts. The average profit per passenger per flight is shown in Figure 4.13, from which it can be seen that the 282 and 306 passenger LDS variant can not be compared to the original Airbus A340-300 due to the fact that the profitability of these aircraft can not be achieved with the original Airbus A340-300. The 282 variant shows an average profit of 8.73 US$ per passenger per flight, whereas the 306 variant results in a value of 28.41 US$ per passenger per flight.

Based on Figure 4.13, it is concluded that a 282 passenger variant of the Airbus A340-300LDS is not a feasible option when similar yields are applied. Furthermore, it is concluded that a higher freight carriage with respect to the current average is required by the original Airbus A340-300 in order to achieve similar profitability levels as the 286 and 294 passenger variants. The high-density 306 passenger LDS variant, however, is seen to outperform the original Airbus A340-300, whereby it is shown that only a continuous higher passenger loading factor of the original Airbus A340-300 could result in similar profitability levels.

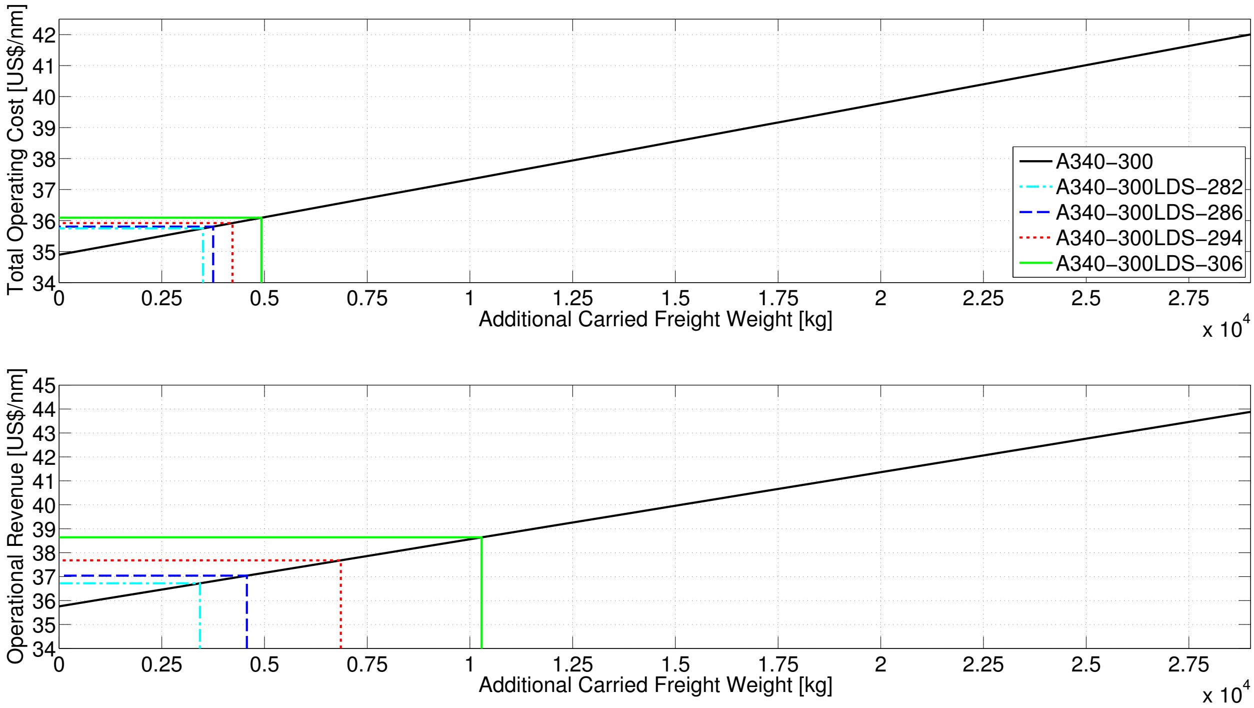


Figure 4.12: Airline TOC and revenue versus additional carried freight, based on a continuous passenger loading factor of 80 %

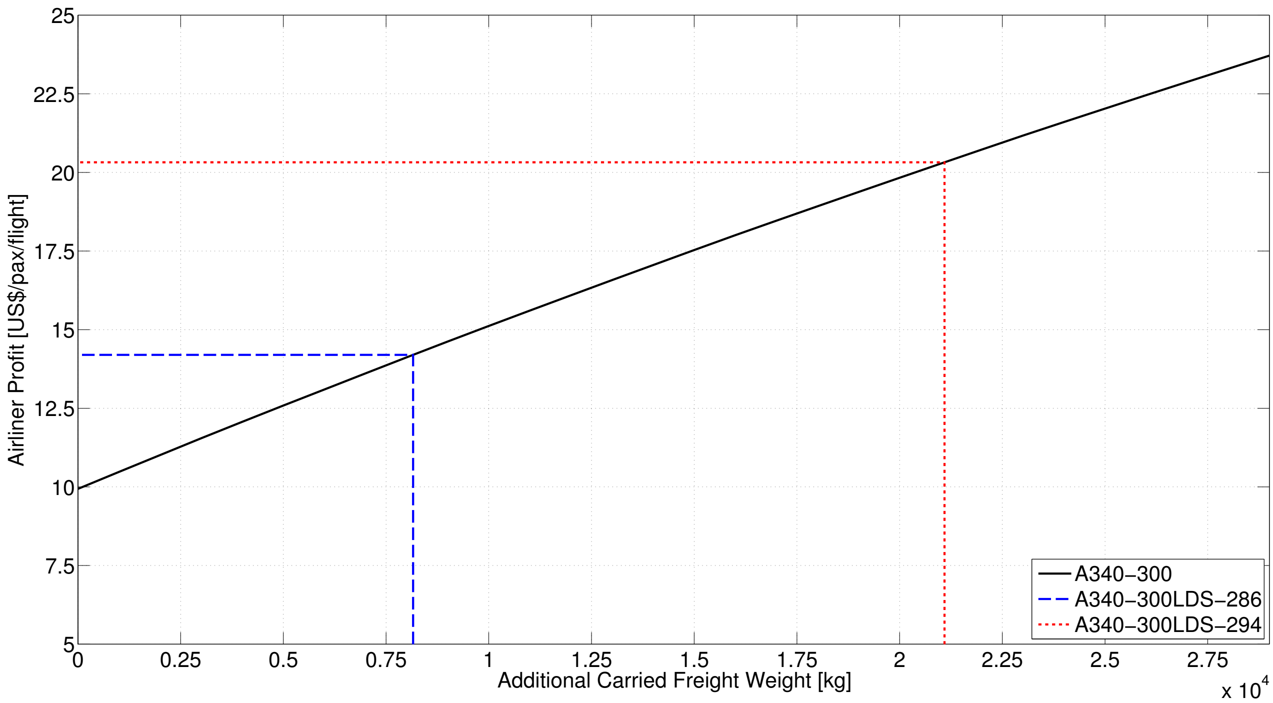


Figure 4.13: Airline profit versus additional carried freight, based on a continuous passenger loading factor of 80 %

FUEL PRICE SENSITIVITY

For both a continuous 80 % and 100 % passenger load factor, the fuel price sensitivity of the various LDS layouts is determined. It should be noted that a comparison is made between these layouts and the original Airbus A340-300 without additional freight carriage.

This comparison is shown in Figure 4.14, from which it can be observed that a larger profit difference between the various modeled aircraft is present when increasing the fuel price. Hence, it can be concluded that the aircraft equipped with an LDS compartment show less sensitivity with respect to the jet fuel price and would therefore provide a more sustainable solution when compared to the original Airbus A340-300.

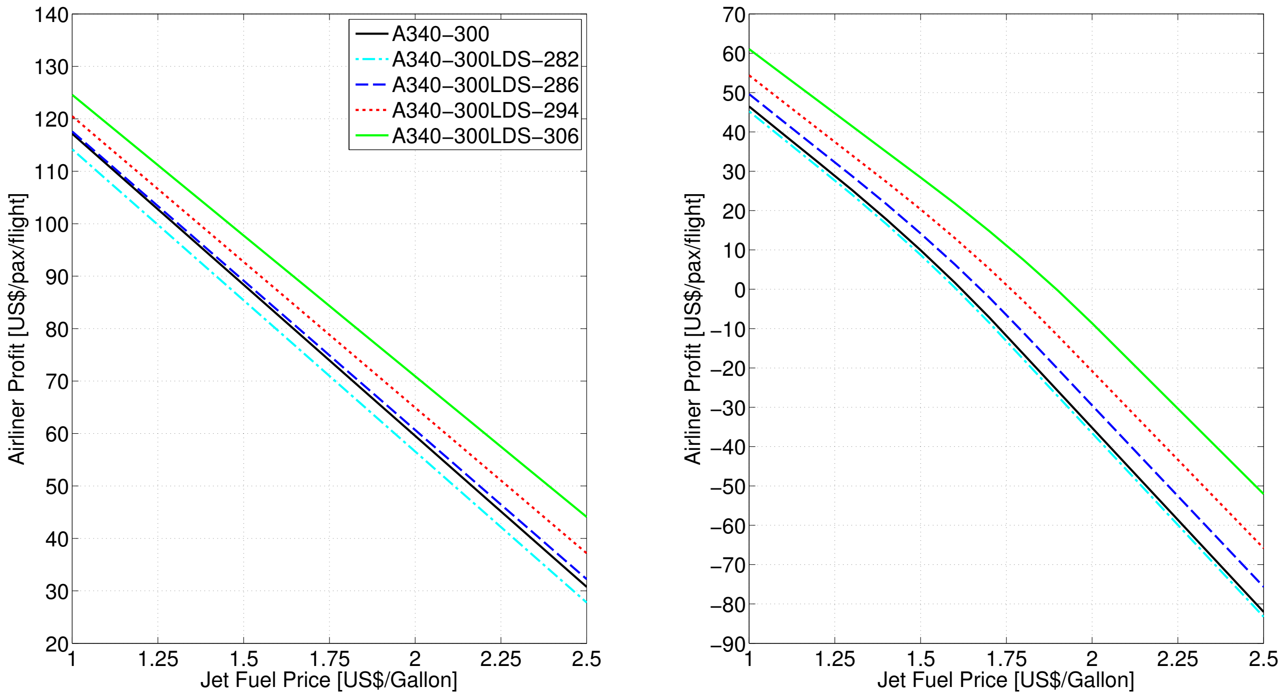


Figure 4.14: Fuel price sensitivity for the various modeled LDS layouts. The left figure displays a hypothetical 100 % passenger load factor, whereas the right figure displays the more realistic 80 % passenger load factor.

4.7.4. COMFORT ANALYSIS

Using the comfort model as described in Chapter 2 and available scientific literature, a conclusion can be drawn with respect to the LDS compartment from an ergonomics point of view. Moreover, the most influential comfort aspects related to the LDS compartment are mentioned in this subsection as well.

COMFORT MODEL APPLICATION

Using the comfort model as described in Chapter 2, it is shown in Table 4.9 that the LDS compartment does not show a large difference with respect to the main passenger deck in terms of passenger comfort related to the seat and cabin dimensions. It is seen from this table that the highest average level of passenger comfort is achieved by using the comfort 2-2 layout. With respect to the reference layout, the comfort 2-2 layout offers a perceived passenger comfort level increase of 12.21 % for the main deck and a 11.75 % increase for the lower deck when assuming a worldwide 95 percentile passenger. When assuming a worldwide 99 percentile passenger, these values change to 13.61 % and 12.86 %, respectively. Although it is seen that the 1-1 seating provides a large improvement of passenger comfort in the LDS compartment, it is also concluded that by leaving the main passenger deck configuration the same, a lower average level of passenger comfort is achieved. Therefore, it is concluded that the 2-2 comfort layout provides the best overall passenger comfort perspective for the EC cabin.

WIDENED LOWER DECK PASSENGER AISLE

As mentioned in Section 4.3, the aisle width of the LDS compartment is doubled in order to provide sufficient space for the passengers in case of an emergency evacuation. However, the widened aisle does not only contribute positively towards the passenger safety, but also to the passenger comfort perception in the LDS compartment. This influence is yet established by means of the comfort model as described above. Contrary, the height of the LDS compartment could negatively influence the psychological state of mind of the passengers occupying this compartment.

Table 4.9: Relative comfort scores for the various modeled Airbus A340-300LDS configurations, based on a worldwide 95 percentile and worldwide 99 percentile passenger population

Airbus A340-300 Configuration	Deck	Relative Perceived Comfort Level	
		Worldwide 95 percentile	Worldwide 99 percentile
Original	Upper	6.248	5.878
High Density 2-2	Upper	6.248	5.878
	Lower	6.193	5.772
Comfort 2-2	Upper	7.011	6.678
	Lower	6.982	6.634
Asymetric 2-1	Upper	6.248	5.878
	Lower Double	6.231	5.799
	Lower Single	7.079	6.733
1-1 Seating	Upper	6.248	5.878
	Lower	7.159	6.851

Claustrophobia in combination with aviaphobia, also known as fear of flying, could pose a severe mental health issue for the aircraft passengers. The regular cabin height of the Airbus A340-300 equals 2.40 m [25] and when compared to the LDS compartment, a reduction of 18 % is observed. This reduction causes the LDS compartment to be smaller in terms of cabin height when compared to typical short-haul aircraft, such as the Airbus A320-200 (2.22 m) and the Boeing 737-300 (2.20 m). With respect to cabin height, the lower deck compartment can therefore be compared with typical business jets, such as the Dassault Falcon 900 (1.90 m), the Bombardier Global Express (1.93 m), and the Bombardier Challenger 850 (1.85 m).

LOWER DECK ACCESSIBILITY

As discussed in Section 4.4.2, it is shown that passengers with reduced mobility could experience a lower level of comfort due to the LDS compartment. This reduced level of comfort is caused by the fact that they can only select seats on the main passenger deck. Nevertheless, by providing a larger personal space on the main deck through the comfort layout, this negative effect can be countered.

Furthermore, it has to be noted that the storage of carry-on luggage could provide a negative impact on the passenger comfort perception. As mentioned in Section 4.5, only the single seat rows do provide adequate space for the storage of carry-on luggage. The storage of carry-on luggage in an LDS storage compartment forces the passenger to get out of the seat and walk towards the compartment in order to obtain the luggage. The negative effect of this feature, however, can not be measured. Nevertheless, it is known from literature that the correlation between the available luggage storage volume and the overall passenger comfort level equals 0.44 and shows a strong influence within this respect [72].

5

Lower Deck Galley and Lavatory

Besides the LDS configuration, the aircraft lower deck compartment can be used for the placement of galleys and lavatories of the main deck. This placement would allow for more seats on the main passenger deck and enhances passenger comfort due to the removal of bad odors and a part of the noise in the aircraft cabin, caused by the presence of galleys and lavatories.

Similar to the previous chapter, the interior constraints and regulatory restrictions are described in Sections 5.1 and 5.2. Furthermore, the proposed cabin layouts are described and shown in Section 5.3. Finally, the implementation and obtained results are shown in Sections 5.4 and 5.5, respectively.

5.1. Aircraft Interior Constraints

In order to verify whether the above mentioned concept is feasible with respect to the required area in the lower deck and main passenger deck, similar interior constraints to the ones discussed in Chapter 4 are defined. First of all, the luggage constraint is described in Subsection 5.1.1. Secondly, the service area constraints are discussed in Subsection 5.1.2.

5.1.1. Passenger Luggage constraint

A similar passenger luggage constraint is associated with this concept when compared to the LDS configuration, as described in Subsection 4.1.1. As shown in this subsection, the required luggage volume for the maximum certified number of passengers equals 65.60 m^3. Using the bulk cargo hold for passenger luggage storage as well, it is concluded that a maximum of 11 LD3 containers is required for the total passenger luggage storage. It should be noted that the constraint for the required luggage volume, V_{Luggage}, is simplified when compared to the constraint for the LDS configuration:

$$V_{\text{Luggage}} = pax_{\text{FC}} \cdot LQ_{\text{FC}} \cdot 1.05 \cdot LV + pax_{\text{BC}} \cdot LQ_{\text{BC}} \cdot 1.05 \cdot LV + pax_{\text{EC}} \cdot LQ_{\text{EC}} \cdot 1.05 \cdot LV \tag{5.1}$$

5.1.2. Service Area constraint

Similar to the Airbus A340-300LDS, a service area constraint is present which relates the required service area to the total number of placed passengers. Contrary to the LDS configuration, the required service area should fit within the lower deck compartment when taking into account the lavatories and service areas that remain on the main deck. In Subsection 4.1.4 it is shown that the floor width of the forward and aft cargo deck equals 2.59 m when a lower deck height of 1.96 m is assumed. By assuming a lower deck height of 1.75 m, the cargo floor width increases to 3.175 m, as yet obtained through Jane's [1]. When assuming that a similar height of 1.96 m is required for the lower deck lavatories and galleys, one can establish a relationship between the number of placed LD3 containers, the required service area, and the total cargo deck length.

[1] IHS Jane's: Defense & Security Intelligence & Analysis, Jane's Aircraft Upgrades: Airbus A340, https://janes.ihs.com/CustomPages/Janes/DisplayPage.aspx?DocType=Reference&ItemId=+++1539118&Pubabbrev=JAU_, Accessed: 02/10/2015

The cargo floor length occupied by the LD3 containers containing passenger luggage is determined by:

$$l_{\text{CargoFloor}_{\text{Luggage}}} = \left\lceil \frac{\left\lceil \frac{V_{\text{Luggage}} - V_{\text{Bulk}}}{V_{\text{LD3}}} \right\rceil}{2} \right\rceil \cdot 1.5 \tag{5.2}$$

As mentioned, the assumption is made that the bulk cargo hold volume is taken into account for passenger luggage placement as well. Furthermore, the constant of 1.5 in Equation 5.2 is based on the exterior dimensions of an LD3 container and an additional safety margin based on the packing efficiency of the containers in the cargo hold.

The required cargo floor length occupied by the service area is calculated by making use of the service area requirements as stated in Table 4.2. The number of downstairs lavatories is calculated by taking into account that a specified number of lavatories, N_{Lav}, can be kept on the main passenger deck:

$$A_{\text{L,lower}} = \frac{pax_{\text{FC}}}{LU_{\text{FC}}} + \frac{pax_{\text{BC}}}{LU_{\text{BC}}} + \frac{pax_{\text{EC}}}{LU_{\text{EC}}} - N_{\text{Lav}_{\text{Main}}} \tag{5.3}$$

As it assumed that the floor area of a single lavatory equals 1 m^2, Equation 5.3 directly provides the required lower deck area to be reserved for lavatories. Similarly, the required lower deck galley area, A_{G}, is calculated by:

$$A_{\text{G,lower}} = pax_{\text{FC}} \cdot A_{\text{G}_{\text{FC}}} + pax_{\text{BC}} \cdot A_{\text{G}_{\text{BC}}} + pax_{\text{EC}} \cdot A_{\text{G}_{\text{EC}}} + N_{\text{Lifts}} \cdot 0.8 \tag{5.4}$$

It should be noted that the area required for the galley lift systems is included in this equation. It is assumed that a dual galley lift system, as described by Abritta et al [31], is used in order to bring the galley carts from the lower deck to the main passenger deck. As the dimensions of the galley lift system are unknown, the lift system dimensions are based on the average dimensions of an aircraft trolley [2] [3], resulting in the aircraft dual galley lift dimensions being equal to 1 m by 0.8 m, spanning 0.8 m^2. Moreover, by taking into account a full service area compartment in the aircraft lower deck, it is ensured that all galley trolleys can be stored in the lower deck. This storage capacity in the lower deck relieves the storage capacity on the main deck, providing additional space for the placement of passenger seats.

Depending on the main deck class division and airline policy, multiple separate lavatory and galley areas can be defined in the lower deck. In this case, two separate lower level lavatory and galley areas are created, of which one is only accessible for the FC and BC cabin passengers. By using this separation, the airline can offer additional service to their FC and BC passengers. However, the number of internal staircases are dependent on the number of areas, as shown in Section 5.2. It should be noted that a minimum of one staircase per lower deck lavatory area is required from a regulatory point of view. By summing up the required staircase area and the required service areas as described in Equations 5.3 and 5.4, the total required service floor area to be placed in the lower deck is obtained. Due to the smaller cargo floor width, the required cargo floor length is calculated by:

$$l_{\text{CargoFloor}_{\text{Service}}} = \frac{A_{\text{G,lower}} + A_{\text{L,lower}} + N_{\text{Stairs}} \cdot A_{\text{Stairs}}}{w_{\text{cab}}} \tag{5.5}$$

The cargo floor length that is left and can possibly be used for the placement of additional LD3 containers or additional service area compartments, such as modular crew rests, is calculated by:

$$l_{\text{CargoFloor}_{\text{Remaining}}} = l_{\text{CargoFloor}_{\text{fwd}}} + l_{\text{CargoFloor}_{\text{aft}}} - l_{\text{CargoFloor}_{\text{Luggage}}} - l_{\text{CargoFloor}_{\text{Service}}} \tag{5.6}$$

Furthermore, the number of LD3 containers that can still be placed in the remaining cargo hold space can be obtained:

$$N_{\text{LD3}_{\text{Additional}}} = 2 \cdot \frac{l_{\text{CargoFloor}_{\text{Remaining}}}}{1.5} \tag{5.7}$$

[2] SkyArt, Atlas Full Size Aircraft Meal Trolley, http://www.skyart.com/service-trolleys/atlas-full-size-aircraft-meal-trolley, Accessed: 20/07/2015

[3] Promolding BV, Full Polymer Catering Trolley Technical Datasheet, http://promolding.nl/contentdownloads/Tigris_techical_datasheet_091123.pdf, Accessed: 20/07/2015

Besides the service area constraints that are posed on the lower deck, a service area requirement is placed on the main deck as well. This requirement is based on the required area for the placement of staircases and galley transport lifts, the minimum amount of main deck lavatories, and the space required to maneuver the galley carts out of the galley lifts. The latter is assumed to be equal to the area required for the galley lift. Furthermore, an additional margin of 10% is taken into account with respect to the main cabin service area in order to account for additional service items, such as the storage of emergency equipment and crew-related attributes. This service area constraint is expressed as:

$$A_{\text{Service}_{\text{MainDeck}}} = 1.1 \cdot (N_{\text{Stairs}} \cdot A_{\text{Stairs}} + N_{\text{Lav}_{\text{Main}}} + 2 \cdot N_{\text{Lifts}} \cdot A_{\text{Lifts}}) \tag{5.8}$$

Based on the required main deck service area, the required main deck cabin length for service area placement and the number of additional passenger seats is calculated, based on the desired seating configuration. An important design consideration with respect to the CC is that a minimum service area length of 2.31 m has to be attained to ensure the placement of the staircases. This design consideration is taken into account due to the fact that the SAAA, as described in Chapter 2, determines the required area without regards to the actual placement of the service elements.

5.2. REGULATORY RESTRICTIONS

With respect to the design of lower deck lavatories and galleys, less regulatory constraints have to be taken into account when compared to the LDS compartment design. This is mainly caused by the fact that the occupation of the lower deck service compartments is assumed to be restricted during taxiing, take-off, and landing, as described in Subsection 5.2.1. Besides this regulation, it is common practice in commercial transport aircraft industry to prohibit the utilization of lavatories and galleys during taxiing, take-off, and landing.

5.2.1. ACCESS TO LOWER LEVEL COMPARTMENTS

Current aircraft regulations allow the presence of passengers in the lower deck lavatory compartment by means of FAR Sec. 25.819. By abiding to these regulations, it is not allowed for passengers to be present in the lower deck lavatory during taxiing, take-off and landing. It is assumed that for the lower deck galley and lavatory concept no additional structural improvements are made in order to certify the presence of passengers in the lower deck during cruise. Moreover, according to FAR Sec. 25.819 (f), additional seats have to be present in the lower deck lavatory and lower deck galley, matching the certified number of occupants within these areas. Furthermore, similar safety measures within these compartments have to be present as compared to the passenger cabin. Hence, a requirement for sufficient oxygen masks, fire-fighting equipment, and a two-way communication system between the lower deck and the main passenger deck is present. These additional measures are described in more detail in Subsection 4.2.4.

Special conditions for lower deck lavatories are set by EASA regarding the Airbus A330 and A340 by means of an appendix to Type Certificate Data Sheet (TCDS) A.004 [73]. It should be noted that this TCDS is based on a specific lower deck lavatory set-up and that for a different lower deck set-up, new tests have to be conducted. The most important measures that are noted on the TCDS is that the occupation of the lower deck lavatories is not permitted during taxiing, take-off, and landing. Contrary to the LDS compartment, a single evacuation route from the lower deck to the main passenger deck is permitted, unless it is shown that a single evacuation route does not provide the necessary safety in case of emergency situations. The latter regulatory statement therefore justifies the placement of a single staircase for each lower deck service compartment, as described in Subsection 5.1.2.

5.2.2. GALLEY LIFT SYSTEM

Based on FAR Sec. 25.819 (g), the requirements for the galley lift system are specified. These specifications are related to lift control switches, emergency stop buttons, and other operational constraints. It is assumed that the currently used aircraft galley lift systems are certified with respect to this FAR section. This assumption is based on the fact that galley lift systems operating in the Boeing 747, for example, are certified and are in accordance with the above mentioned standards [74].

5.3. Proposed Aircraft Layouts

Depending on airline policies and seating configurations, the main passenger deck layout can be determined. As a comparison is made with the reference Airbus A340-300, a similar seating configuration for the BC and FC is assumed. Furthermore, two separate lavatory and galley areas are assumed. One area is combined for the BC and FC cabin, whereas the other is reserved for the EC cabin. By using these assumptions, 12 FC passengers are placed in a 2-2-2 configuration and 42 BC passengers are placed in a 2-3-2 configuration. The configuration of the EC cabin is subsequently varied in order to obtain various cabin layouts.

5.3.1. Regular EC Cabin Extension

By using similar EC passenger seat dimensions as defined for the reference Airbus A340-300, an extension of the current EC cabin is obtained. By assuming two dual galley lifts for the EC cabin and one dual galley lift for the combined BC/FC cabin and by taking into account two separate lavatory and galley areas, the required service area on the main deck is determined and equal to 13.36 m^2. It should be noted that a single lavatory is kept on the main deck for the FC and BC passengers and that two lavatories are kept on the main deck for the EC passengers. The modeled aircraft cabin is shown in Figure 5.1, from which can be seen that the EC cabin extension leads to four additional EC passenger rows and increases the seating capacity to 302 passengers. Hence, an increase of 32 passengers is achieved, compared to the reference Airbus A340-300.

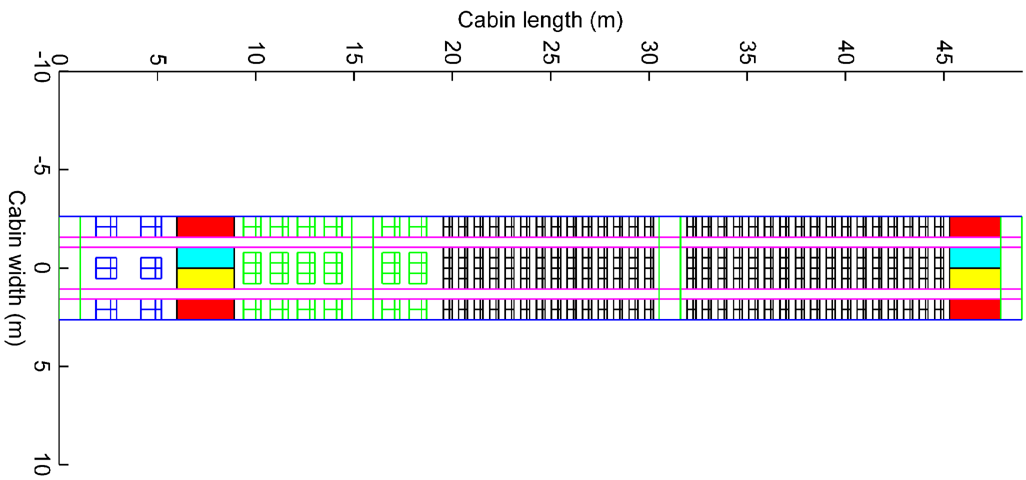


Figure 5.1: Airbus A340-300LDGL aircraft cabin model with extended EC cabin layout. The red, blue, and yellow areas represent galleys, lavatories, and staircases, respectively.

5.3.2. EC Cabin with Enhanced Comfort

The additional space that is available by moving the main deck service area to the lower deck compartment can be used to provide more comfort to the EC passengers as well. Like the comfortable 2-2 seating configuration as described in Section 4.5, an increased seat pitch is provided to the EC passengers. By increasing the seat pitch to 33.66, the airline is able to suit the worldwide 99 percentile population in terms of required seat pitch. By increasing the seat pitch to this length, the operating airline is be able to fit 278 passengers in the aircraft. Using the constraints as described in Section 5.1, the available space for additional LD3 containers to be placed in the lower hold can subsequently be calculated and used in order to generate additional airline revenue.

5.4. MODELED LOWER DECK GALLEY AND LAVATORY

Using data from the studies of Airbus [30] and Abritta [31], a model of the Airbus A340-300 with lower deck lavatories and lower deck galleys is created. In order to model the Airbus A340-300 with lower deck lavatories and lower deck galleys, the following requirements are posed upon the design in the Initiator:

- **Crew members**
  One additional crew member is required during operation of the aircraft. As it is common practice for airlines to ensure the safety of passengers near the lavatories, it is assumed that one additional crew member is required. It should be noted that the additional crew member is not required from a regulatory point of view. However, it is reportedly common practice at Lufthansa to have an additional crew member on board when utilizing the lower deck lavatories.

- **Additional Operational Items**
  Considering the increase in passengers on the main deck and the possibility of passengers being in the lower deck during cruise phase, additional operational items are required. Additional oxygen masks, fire fighting equipment and other safety equipment are modeled in the Initiator to account for the lower deck area, according to the regulatory restrictions as described in Subsection 5.2.1. Furthermore, when using the lower deck galley and lavatory configuration, it is assumed that other operational items, such as the water toilet chemicals, food and beverage supplies, and the required potable water on board still vary with the number of main deck passengers, as defined by Torenbeek.

- **Galley Lift System**
  Based on data provided by Abritta [31], an additional weight penalty is added in terms of furnishing weight in the class II weight estimation. This weight penalty is dependent on the number of galley lift systems that is used in the aircraft, for which it should be noted that each dual galley lift system leads to an additional weight penalty of 380 kg.

- **Staircase Weight**
  To provide access to the lavatories, multiple staircases are placed within the cabin. It is assumed that the weight of a single staircase equals 100 kg. The additional staircase weight is added to the class II furnishing weight of the modeled A340-300, next to the added galley lift system weight.

- **Additional Emergency Seats**
  As mentioned in Subsection 5.2.1, additional emergency seats have to be placed in the lower deck compartment. Depending on certification procedures and the number of lower deck lavatories, the number of additional required passenger seats is determined. It is assumed that the number of additional passenger seats is equal to the number of lower deck lavatories added by two additional seats per lower lavatory compartment in order to provide seating space for waiting passengers. This means that each lower deck lavatory compartment is assumed to be certified for a number of passengers that is equal to the number of lavatories plus two.

- **Additional Windows**
  Based on the additional number of passengers with respect to the original Airbus A340-300, additional cabin windows are modeled on the main passenger deck. It should be noted that no additional windows are modeled in the lower deck compartments in order to minimize the weight penalty on the aircraft fuselage weight estimation. The weight penalty due to the placement of additional main deck windows is calculated by means of Equation 4.10.

5.5. RESULTS

Similar to the Airbus A340-300LDS, both an inside-out and an outside-in approach are used in order to model the lower galley and lavatory placement. The results of these baseline models, denoted by Airbus A340-300LDGL, are described in Subsection 5.5.1. Secondly, the results of the various layouts are shown in Subsection 5.5.2. A feasibility analysis from an economical point of view is provided subsequently in Subsection 5.5.3. Finally, an analysis from a passenger comfort perspective is provided in Subsection 5.5.4.

5.5.1. Baseline LDGL Configurations

In order to create an outside-in designed Airbus A340-300LDGL, an inside-out configuration is determined first to show the influence of the additional measures on the aircraft design. Afterwards, an outside-in design relates to an Airbus A340-300LDGL with similar geometrical dimensions and weight components as compared to the original Airbus A340-300. It can be seen from Table 5.1 that the maximum structural payload is lowered by 6.27 % in order to obtain a similar geometry and similar weight components. Furthermore, similar to the LDS configuration as discussed in Subsection 4.7.1, a linearization is applied on the results of the outside-in model, based on a MTOW difference of 0.02 %.

Table 5.1: Initiator results for varying LDGL configurations

	A340-300	A340-300LDGL Inside-Out	A340-300LDGL Outside-In
Max. Struct. Payload [kg]	52000	52000	48740
MTOW [kg]	264107	272802	264107
OEW [kg]	118863	124731	122696
W_{Fus} [kg]	33424	34317	34317
S_{ref} [m^2]	348.80	360.46	350.99
Harmonic Fuel Burn [kg]	93244	96070	92680

5.5.2. LDGL Layout Performance

The results for the various modeled LDGL layouts are shown in Table 5.2, from which it can be concluded that both the high-density layout and the comfort layout exhibit a lower fuel burn for the typical mission profile when related to the number of passengers. However, a 2.90 % and 1.23 % increase in TOC can be observed for the 302 passenger and 278 passenger variants, respectively. An economical feasibility analysis, as provided in Subsection 5.5.3, is therefore required in order to assess whether the higher operating costs are justified against the potential airline revenue.

Table 5.2: Initiator results for varying LDGL Layouts

	A340-300	High Density 2-4-2	Comfort 2-4-2
Passengers Placed [-]	270	302	278
Payload Weight [kg]	28350	32130	29190
Mission Fuel Burn [kg/pax/km]	0.0313	0.0286	0.0308
Mission DOC [US$/pax/km]	0.0593	0.0537	0.0582
Mission TOC [US$/pax/km]	0.0718	0.0660	0.0705

5.5.3. Economical Feasibility Analysis

Similar to Subsection 4.7.3, the feasibility of the designed LDGL aircraft cabins from an economical point of view is determined. Therefore, this subsection describes the costs associated to manufacturing, the airline operating costs and profitability, the influence of the reduced freight carriage capacity, and the sensitivity towards the fuel price.

Manufacturing Associated Costs

Similar to the Airbus A340-300LDS, a comparison is made with the original aircraft list price and associated maintenance costs. As can be seen in Table 5.3, the A340-300LDGL list price shows a 0.69 % increase with respect to the original Airbus A340-300. Furthermore, it is seen for the Airbus A340-300LDGL that the DOC related to maintenance equals 7.89 US$ per nautical mile, yielding an increase of 1.02 % with respect to the original aircraft.

Airline Operating Costs and Profitability

As shown in Table 5.2, the DOC of the various LDGL layouts is higher when compared to the original Airbus A340-300. The DOC as shown in this table is related to a continuous 100 % passenger load factor and is therefore also compared to a continuous 80 % passenger load factor.

Table 5.3: Comparison of resulting aircraft list price for various Airbus A340-300 configurations

	Aircraft List Price [US$]
Airbus A340-300	189,783,408
Airbus A340-300LDGL	191,085,633

Table 5.4: Operating profitability for the various LDGL layouts corresponding to an operational life of 20 years

	Original	High-Density 2-4-2	Comfort 2-4-2
Operating Profit at 80% LF [US$/pax/flight]	9.94	28.29	12.72
Operating Profit at 100% LF [US$/pax/flight]	88.35	98.22	89.25

A breakdown of the DOC and IOC of the various LDGL layouts is shown in Table F.1 for both a 80 % and 100 % passenger load factor. Furthermore, the operational profits for the various LDGL layouts, expressed in average profit per passenger per flight, are provided in Table 5.4.

REDUCED FREIGHT CARRYING CAPACITY

Due to the fact that the original Airbus A340-300 is able to carry additional freight in order to generate additional revenue, an analysis is carried out showing the effect of additional cargo carriage on the operational costs and revenue. Figure 4.12 shows how the costs and revenues vary with additional carried cargo weight for the original Airbus A340-300. The colored lines provide the equivalent values for the various LDGL layouts. The average profit per passenger per flight is shown in Figure 4.13, from which it can be seen that the 302 passenger LDGL variant can not be compared to the original Airbus A340-300 due to its high profitability. Hence, the original Airbus A340-300 can only reach a similar level of profitability if the continuous passenger load factor is increased.

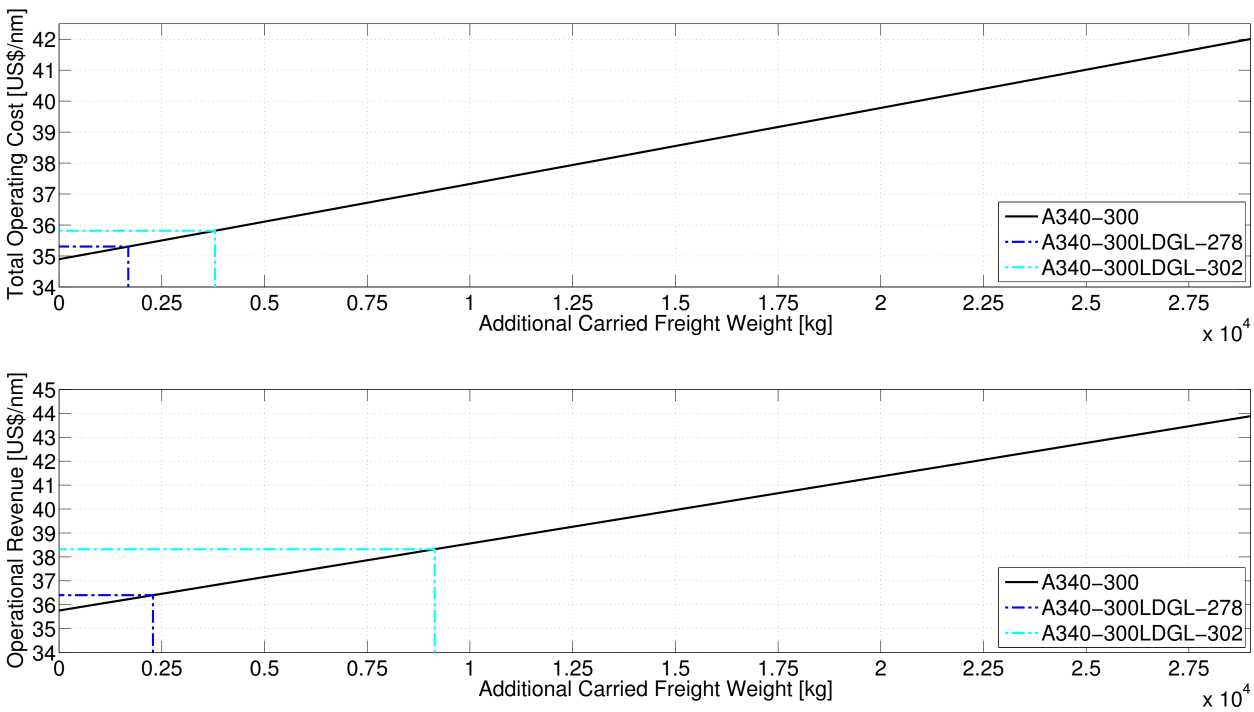


Figure 5.2: Airline TOC and revenue versus additional carried freight, based on a continuous passenger loading factor of 80 %

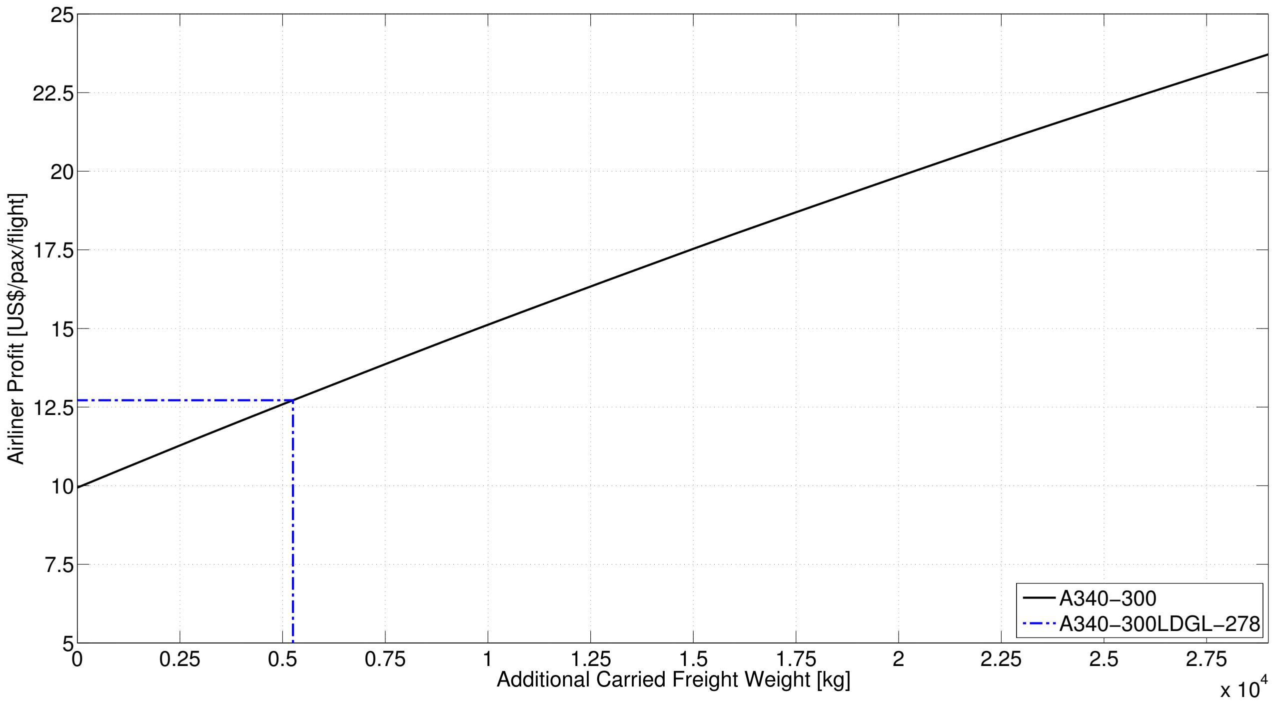


Figure 5.3: Airline profit versus additional carried freight, based on a continuous passenger loading factor of 80 %

FUEL PRICE SENSITIVITY

For both a continuous 80 % and 100 % passenger load factor, the fuel price sensitivity of the various LDGL layouts is determined and shown in Figure 5.4. It should be noted that a comparison is made between the LDS layouts and the original Airbus A340-300 without additional freight carriage. From Figure 5.4 it is observed that a larger profit difference between the various modeled aircraft is present when the fuel price is increased. This similar sensitivity is also observed when compared with the LDS configurations as described in Subsection 4.7.3.

5.5.4. COMFORT ANALYSIS

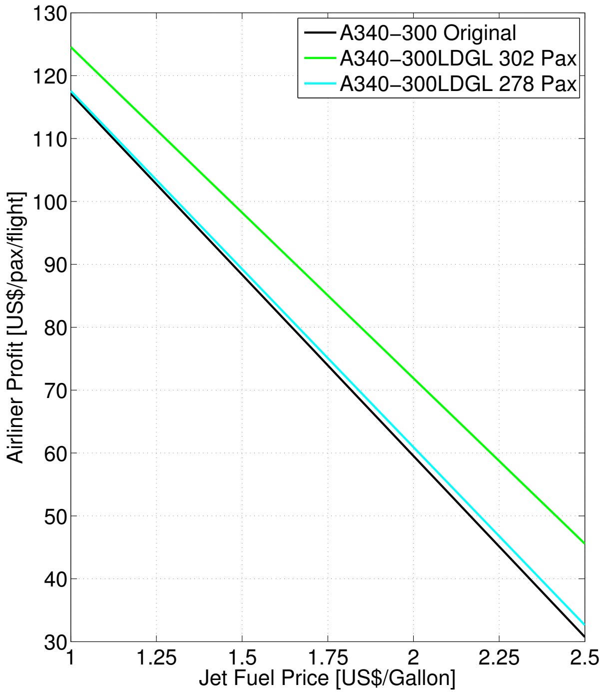
This subsection describes the results of the lower deck galley and lavatory layout in terms of passenger comfort. First of all, the results from the comfort model are described. Subsequently, other influential comfort parameters are discussed in order to provide information about the most important comfort aspects related to this configuration.

COMFORT MODEL APPLICATION

Using the comfort model as described in Chapter 2, it is shown in Table 5.5 that the LDGL configurations do not show any difference with respect to the reference layout in terms of passenger comfort related to the seat and cabin dimensions. Due to the fact that the total number of passengers and the passenger density ratio is not incorporated in the comfort model, it is seen that a similar level of comfort is achieved. However, it is concluded from Table 5.5 that a higher average level of passenger comfort is achieved by using the comfort 2-2 layout. With respect to the reference layout, the comfort 2-2 layout offers a perceived passenger comfort level increase of 12.21 % when assuming a worldwide 95 percentile passenger. When assuming a worldwide 99 percentile passenger, however, the perceived comfort level is increased with 13.61 %.

CABIN NOISE

Due to the placement of the galleys and lavatories in the lower deck, a significant improvement in the cabin noise can be achieved. As shown in Table 2.4 a large correlation exists between the cabin noise and the overall passenger comfort level. Besides these correlations, other studies have been carried out in order to assess the effect of aircraft cabin noise on the passenger comfort perception.



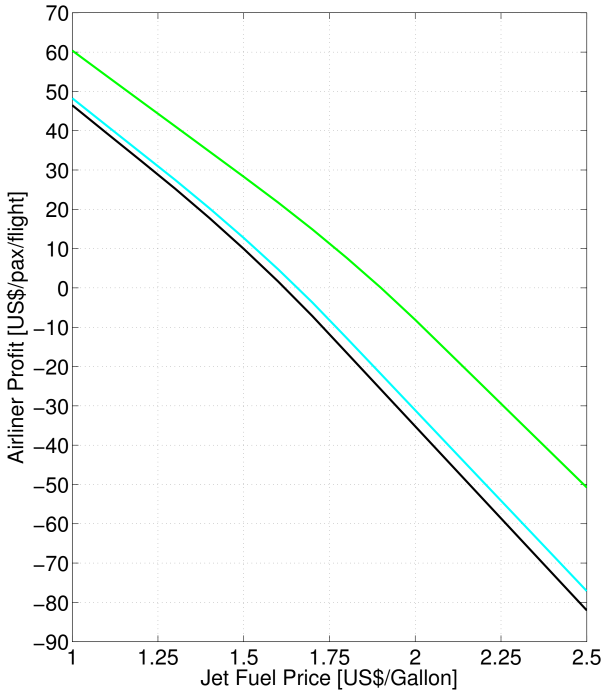


Figure 5.4: Fuel price sensitivity for the various modeled LDGL layouts. The left figure displays a hypothetical 100 % passenger load factor, whereas the right figure displays the more realistic 80 % passenger load factor.

Table 5.5: Relative comfort scores for the various modeled Airbus A340-300LDGL configurations, based on a worldwide 95 percentile and worldwide 99 percentile passenger population

Airbus A340-300 Configuration	Relative Perceived Comfort Level	
	Worldwide 95 percentile	Worldwide 99 percentile
Original	6.248	5.878
High Density 2-4-2	6.248	5.878
Comfort 2-4-2	7.011	6.678

First of all, Ahmadpour [75] relates the aircraft noise with respect to the passenger peace of mind and shows that next to the seat characteristics and the cabin temperature, aircraft noise is the most influential parameter with respect to the passenger peace of mind, thereby showing more influence than air quality, activity possibilities, and passenger service. This theory is supported by the work of Pennig et al [76], showing that the passenger comfort experience is highly dependent on the equivalent sound pressure level. Secondly, not only for passengers on the main deck, but also for the cabin crew, a significant improvement with respect to health can be achieved if the main passenger deck flight attendants are considered. Mellert et al [77] have shown that that the cabin noise level does dramatically impact the cabin crew level of annoyance, overall satisfaction, perception of vibration and movement, and the occurrence of negative health symptoms. Especially the latter influence on the cabin crew can be reduced by the placement of lower lobe galleys and lavatories, as Mellert et al have shown that a noisy cabin could lead to an increase of 57 % in neck muscle pain and an increase of 43 % in swollen feet. Although the exact influence of lower deck galleys and lavatories can not be assessed in this thesis, it is shown by the above information that the relocation of these service facilities does provide a positive influence on the passenger comfort level.

CABIN ODORS

Considering the concept of placing the main deck lavatories and galleys in the aircraft lower deck, a significant improvement is obtained in terms of cabin odor reduction. Richards and Jacobson have defined the correlation between cabin odours and passenger comfort to be very small, but more recent studies have shown that the impact of smell can severely influence the passenger comfort perception.

Van Egmond [78] and Kuijt-Evers [79] both show that smell is influencing the passenger comfort experience in a negative sense. By minimizing the bad odours in the aircraft cabin, a substantial passenger comfort perception increase can be obtained.
Furthermore, Vink et al [72] derived a discomfort pyramid, as shown in Figure 5.5, using the work of Bubb and Estermann [80], in which it is shown that smell overrules nearly all other aspects relating to discomfort. Similar to cabin noise, the reduction in cabin odors due to the relocation of the galleys and lavatories can not be determined. However, it can be concluded that this relocation does have a significant influence on the passenger comfort perception and could therefore positively influence the relative comfort score, as shown in Table 5.5.

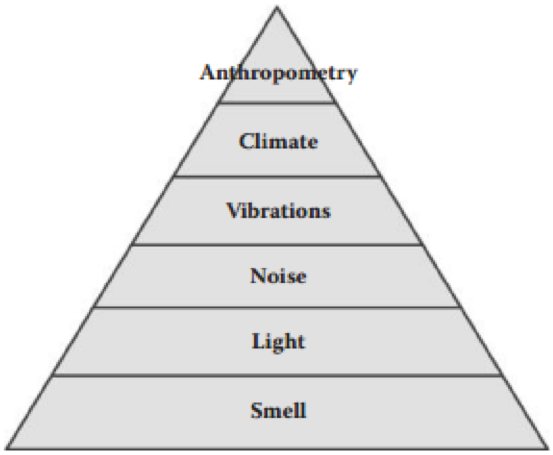


Figure 5.5: Discomfort pyramid as defined by Vink and Brauer [72] after the work of Bubb and Estermann [80]

AIRCRAFT CABIN RELATIVE HUMIDITY

A final comfort aspect that is mainly influenced by the relocation of the galleys and lavatories is the relative humidity in the cabin. The accepted humidity level related to an appropriate level of passenger comfort is defined by de Ree et al [81] and equals 20 %. By moving the galleys and lavatories to the lower deck, a decrease in overall cabin relative humidity is achieved. However, it should be noted that a low humidity could pose temporary health issues, such as dry eyes and sore throats, to passengers that are susceptible for this. Besides this, an 8 hour flight could lead to a passenger water loss of 100 ml. Therefore, the provision of sufficient hydration to the body should counter any long-term or short-term health issues within this respect. Another disadvantage of a dry passenger cabin is that the perception of odor intensity levels is higher and by moving galleys and lavatories to the lower deck, the odor intensity of other odor causing sources within the aircraft cabin is strengthened. When taking a closer look at the correlation between comfort and cabin humidity, Rankin et al [82] concluded that air humidity shows a lower correlation with perceived passenger comfort (0.47) as compared to lavatory odors (0.471), available lavatories (0.477), cabin quietness (0.482), cabin air odor (0.514), and cabin appearance (0.521). Using these correlation coefficients, it is concluded that the benefits of placing lavatories and galleys in the lower deck will outperform the effect of a lower humidity in the passenger cabin with respect to passenger comfort.

6

Discussion and Recommendations for Further Research

This chapter describes the uncertainties and possible improvements with respect to the performed analyses as described in Chapters 3 through 5. First of all, Section 6.1 discusses the uncertainties involved with using the Initiator as a conceptual design tool and the cost estimation module for the economical analysis. Secondly, a reflection on the used comfort model is shown in Section 6.2, after which the results of the different lower deck utilizations are discussed in Section 6.3.

6.1. Initiator Model Discussion

This section describes the inaccuracies that are involved with the usage of the Initiator as a conceptual design tool. First, the general utilization of the Initiator is discussed in Subsection 6.1.1. After this, the cost estimation module of the Initiator is discussed in Subsection 6.1.2.

6.1.1. Initiator Inaccuracies

With respect to Initiator usage, several inaccuracies and uncertainties can be noted. First of all, it should be noted that the convergent nature of the Initiator does not allow for a fixed aircraft geometry. Hence, the modeling of the baseline aircraft, as described in Chapter 2, can not be performed with geometrical constraints and definitions. This poses an inaccuracy with respect to the outside-in modeling of the A340-300LDS and A340-300LDGL. By lowering the maximum structural payload of these models, a similar geometry for the wing, fuselage and tail is obtained. However, the dimensioning of the engine and other components can not be controlled, thereby posing a small inaccuracy. Nevertheless, the inaccuracy with respect to the engine diameter, for example, is just below 0.1 % and can therefore not be seen as a major contributor to the results in terms of aircraft weight.

Secondly, it has to be noted that the calculation of the aircraft neutral point is not done accurately by the Initiator. Due to this inaccuracy, a wrong estimation of the aircraft static margin is made, leading to errors in terms of longitudinal stability. Moreover, no accurate loading diagram can be established for the modeled aircraft and hence only a description can possibly be given about the expected changes with respect to the loading diagram. However, one of the advantages of the Initiator is that the aircraft is designed for all possible loading sequences. Therefore, it is expected that an overestimation of the static margin ensures that the aircraft with lower deck utilization does not pose any problems with respect to the loading sequence of the original aircraft.

A third discussion point that has to be noted is that a large overestimation of the aircraft maximum lift coefficient is observed when examining the output files of the Initiator. This large overestimation is mainly caused by the extrapolation of the found lift coefficients by AVL. However, the overestimation of the maximum lift coefficient does not influence the aircraft runway performance in the Initiator, as the high lift devices module is not yet implemented. User input settings for the landing and take-off lift coefficients are therefore used to determine the runway performance of the aircraft.

However, the drawn aircraft V-n diagram is influenced by the overestimation of the maximum lift coefficient and can therefore not be used as a reasonable output from the Initiator.

Finally, the modeling of the aircraft wing within the Initiator could provide peculiar results with respect to the actual wing planform. Although the modeled wing area shows a good correlation with respect to the reference aircraft, as can be seen in Tables B.1 through B.16, the actual dimensions such as the leading edge (LE) sweep angle can show large discrepancies. In fact, the LE sweep angle is determined by means of a historical trendline as defined by Raymer [35], which relates the user-defined Mach number to the LE sweep angle. Subsequently, other wing parameters, such as the taper ratio, are related to this sweep angle by making use of similar methods. However, an investigation with respect to these parameters shows that a large variation exists among commercial transport aircraft and that the methods as used by the Initiator provide an underestimation of the LE sweep angle and the wing taper ratio.

6.1.2. Cost Estimation Module Discussion

The method for the calculation of the IOC, as defined by Madallon, is developed in 1980 and might therefore not accurately describe the current costs associated to airport landing rights, aircraft insurance, and required on-board food and beverages. However, as no recent models are present in scientific literature for a detailed calculation of the aircraft IOC, the calculated values for the IOC are used in order to make a relative comparison between the original Airbus A340-300 and the Airbus A340-300LDS. Moreover, the cost estimation module only allows the user to calculate the operating costs based on full aircraft ownership by the airline. Based on the fact that many airlines currently adopt an aircraft leasing policy, a small overestimation of the operating costs is expected when calculating for this case. Following these remarks, it is recommended that a newer cost estimation model is applied, which analyzes the effect of aircraft leasing and allows for the calculation of more recent cost information.

A second critical note that has to be placed upon the cost estimation module is that several fixed airline costs are not taken into account when up-scaling any aircraft. It is reasonable to assume that an aircraft with a larger amount of passengers would require different airport gates and support facilities. However, these fixed costs are only related to passenger handling and landing rights in the cost estimation module. Therefore, it is recommended to implement a method to estimate these fixed cost parameters in order to make a more accurate estimation of the airline operating costs.

6.2. Applied Comfort Model

First, Subsection 6.2.1 describes the utilized comfort model and the limitations related to its usage. Secondly, the comfort enhancement testing is described in Subsection 6.2.2, relating to the results as obtained in Chapter 3.

6.2.1. Comfort Model Utilization

First of all, it should be noted that the utilization of the developed comfort model is purely based on a combination of existing scientific research. A recommendation for further research would therefore include an experimental set-up, in which both seat properties and cabin dimensions can be varied. By varying these parameters, the influence on passenger comfort levels can be measured and evaluated. Moreover, the mutual influence of these parameters can be assessed as well.

Secondly, it is seen that the developed comfort model only uses seat and cabin parameters in order to determine a level of passenger comfort. Although these parameters are measurable and usable for a comfort model, it is recommended to include more comfort aspects in the model. Possible measurable comfort aspects, related to aircraft design, could include the cabin pressure altitude, the ventilation of the aircraft cabin, the personal luggage storage volume, and the number of personnel on board. Other comfort aspects, such as cabin noise and cabin odors, can be measured and should be scaled to a specific reference. Once a measurement of these variables is performed, a model relating to these variables can be created and implemented in the developed comfort model by using the comfort correlations as stated in Chapter 2.

6.2.2. Comfort Enhancement Testing

The comfort enhancement testing as described in Chapter 3 is based on an empirical fuselage weight estimation method as described by Nicolai. Although an analytical fuselage weight estimation method is present within the Initiator, it is chosen not to use this estimation. This choice is based on the fact that during the comfort enhancement testing it is concluded that the fuselage weight estimation could provide inaccurate results. This inaccuracy is mainly posed by the wrong estimation of the available cargo volume and the placement of different cargo containers. At the moment of writing, a new fuselage weight estimation is under development, which takes this inaccuracy into account. Although the empirical estimation of Nicolai is proven in Chapter 3 to be accurate, a second test using an analytical fuselage weight estimation is recommended in order to obtain a more detailed aircraft design.

Furthermore, it should be noted that the comfort enhancement testing is based on very small differences between several aircraft models, thereby forcing the Initiator to provide a high level of accuracy. As can clearly be seen in several figures in Chapter 3, a large number of data points are created that are not in compliance with the overall trends. This is highly likely being caused by the user settings for the design convergence accuracy, which leads to an aircraft design that is based on a convergence that is reached either too soon or too late. A recommended method to resolve these instabilities is found by setting the design convergence to a very high level of accuracy and by filtering the most extreme deviating data points. However, this in turn leads to long convergence loops and a time-consuming process.

6.3. Lower Deck Utilization Cabin Models

With respect to the lower deck compartment modeling as described in Chapters 4 and 5, several inaccuracies are observed. First of all, it should be stressed that the outside-in design approach using the Initiator yields an approximation of a retrofit aircraft in terms of aircraft component weights, top level requirements, and geometry estimation. Consequently, a small uncertainty is posed upon the designed aircraft, leading to a linearization of the results with respect to the component weight groups. Furthermore, by lowering the maximum structural payload, one can assume that a slight change with respect to the aircraft stability could occur. This effect is assumed to be negligible in this paper, due to the fact that the original Airbus A340-300 is designed to contain bodies of mass in the forward cargo hold as well. However, the movement of passengers in the aircraft lower deck could provide instabilities with respect to aircraft trim and consequently fuel burn. Therefore, a more detailed analysis in terms of aircraft longitudinal and lateral stability is required and recommended for further research.

Secondly, a more detailed structural analysis is recommended for the structural reinforcement in the lower deck. Due to the assumptions of static and maximum loads on the structural members, a large possibility exist of an overestimation with respect to the weight of these structural members. Furthermore, a detailed analysis has to be carried out in order to estimate the effect of a longitudinal, load-transferring, member on the aircraft structural weight. An approach to this problem would yield the implementation of an optimizing routine, which automatically leads to a minimization of the weight of the structural members. By carrying out a detailed structural analysis, in combination with an analytical fuselage weight estimation, a higher level of granularity and hence weight estimation is achieved.

Finally, as mentioned in Chapter 4, a full scale test with respect to the emergency evacuation of the LDS compartment is required in order to establish a guideline for the maximum allowed number of passengers in the aircraft lower deck. Alternatively, a large variation of lower deck layouts has to be tested using dedicated software in order to establish a similar guideline.

7

Conclusions

The conclusions from this thesis are drawn with respect to the influence of comfort enhancing measures on aircraft conceptual design and with respect to the utilization of the lower deck in wide-body aircraft. These subjects are described in Sections 7.1 and 7.2, respectively.

7.1. The Influence of Comfort Enhancement on Aircraft Conceptual Design

With respect to the seating dimensions in aircraft conceptual design, it is concluded that a change in the current aircraft seat dimensions is required. Following from this change in conceptual design, it can be concluded that wider and shorter fuselages would suit the needs from an ergonomic perspective. Moreover, it is concluded that a conceptual aircraft design related to the current human dimensions would not impose a large penalty with respect to any of the analyzed aircraft performance metrics. This conclusion is supported by the fact that a seating configuration based on the worldwide 95 percentile passenger, yielding a larger reference seat cushion width and a smaller reference seat pitch, shows an average increase of 0.32 % with respect to the aircraft MTOW. This increase in MTOW relates to an increase of 0.44 % in harmonic mission fuel burn and related emissions, as well as a 0.31 % increase in harmonic mission DOC. It should be noted that the effect of changing the aircraft design based on a worldwide 95 percentile is larger for short-haul aircraft due to a larger change in the aircraft fineness ratio.

However, the conceptual design of aircraft relating to a higher worldwide percentile does show larger penalties with respect to component weights and associated aircraft performance. It is concluded that a design for the worldwide 99 percentile passenger requires both an increase in seat width and seat pitch in order to comply to the required anthropometric dimensions. The design for the worldwide 99 percentile passenger relates to an increase of 6.23 % in seat cushion width and 8.47 % in seat pitch with respect to a reference seat cushion width of 17.5 inch and reference seat pitch of 31 inch. These increased seat dimensions result in an average MTOW increase of 3.25 % among short-haul and long-haul aircraft. Moreover, this increase in MTOW relates to an average increase of 3.90 % with respect to the harmonic mission fuel burn and 4.17 % with respect to the harmonic mission DOC. Contrary to the design for a worldwide 95 percentile passenger population, it is shown that the design for a worldwide 99 percentile passenger population yields a larger influence with respect to long-haul aircraft.

Furthermore, it is concluded that the influence of the seat cushion width, and hence the overall fuselage width, appears to be larger with respect to the aircraft conceptual design and associated performance metrics. It is shown by means of a multi-parameter analysis that a 15 % increase in seat pitch leads to an average increase of 3.97 % in MTOW and consequently an average increase of 4.08 % in DOC for both short-haul and long-haul aircraft. However, a similar increase in seat width yields an average increase of 4.15 % in MTOW and an average increase of 4.23 % in DOC for short-haul and long-haul aircraft.

Finally, it is concluded that the influence of the EC seat weight is substantial during aircraft conceptual design. It is shown that a seat weight reduction of 1 kg yields a reduction of 0.5 % in airline DOC. Moreover, when reducing the weight of current EC seats with 50 %, it is shown that a conceptual aircraft design exhibits an average decrease of 1.55 % in terms of MTOW. This decrease in turn leads to an average reduction of 1.31 % in parasite drag, as well as a fuel burn saving of 1.62 %.

7.2. FEASIBILITY OF AIRCRAFT LOWER DECK UTILIZATION

Based on available literature and the implementation of structural requirements, safety requirements, and comfort requirements in the Airbus A340-300, it can be concluded that both a lower deck seating configuration and a lower deck galley and lavatory configuration show to be a feasible alternative when compared to the carriage of additional freight.

For the lower deck seating configuration, through lowering of the lower deck structural floor, a passenger cabin is designed that is suitable for the worldwide 97.92 percentile population in terms of human stature. Furthermore, it is shown that due to the dimensional and safety constraints, a small range of lower deck layouts is achievable, yielding a maximum of four seats abreast. Based on a reference three-class layout with 267 passengers, it is shown that extending the EC cabin with the aircraft lower deck yields a maximum passenger increase of 14.6 % when using similar seat characteristics.

In terms of aircraft performance, it is concluded that by lowering the maximum structural payload to 45560 kg, yielding a decrease of 12.4 %, a lower deck passenger compartment can be installed in an existing Airbus A340-300. The lowered structural payload is mainly based on required structural improvements in order to comply with current regulatory restrictions and constraints. The implemented structural improvements are sized for the maximum certified number of passengers and the maximum achievable load factors, thereby allowing for different cabin layouts as presented in this paper.

From an economical perspective, it is shown that by increasing the number of passengers by 14.6 % with respect to the reference layout, a triple increase in airline profitability is achieved. However, by extending the EC cabin with the lower deck and incorporating a seat pitch of 33.8 inch throughout the EC cabin, a 12 % higher level of passenger comfort can be achieved for the worldwide 95 percentile passenger when compared to the reference layout. Utilizing this comfortable layout, the total number of seats in the aircraft is increased to 286, thereby showing a profitability level that is comparable to the Airbus A340-300 carrying an additional cargo weight of 9245 kg. As it is also shown that the average additional carried cargo weight equals 5400 kg, it is concluded that by implementing an LDS compartment, an enhanced level of passenger comfort and airline profitability is achieved without compromising manufacturer profitability.

For the lower galley and lavatory configuration, it is concluded that similar performance results are obtained when compared to the LDS configuration. By retrofitting the Airbus A340-300, a list price increase of just 0.69 % is seen. Furthermore, the lowering of the maximum structural payload to 48740 kg allows for 32 additional passengers when compared to the reference layout. Alternatively, an increased level of passenger comfort is achieved when increasing the seat pitch to 33.8 inch, which still results in 8 additional passengers. From an economical point of view, it is shown that the comfort layout with increased seat pitch compares similar to the original Airbus A340-300 when taking the average freight carriage into account. However, when the carriage of additional freight is not considered, a profitability increase of 28 % is seen when considering a typical 80 % passenger load factor.

Therefore, as the main conclusion of this thesis, it is shown that the implementation of lower deck utilization can result in a significant increase in airline and passenger satisfaction. Hence, a positive answer is provided to the research question in this thesis. When examining the historical growth trend in passenger load factors and the declining historical trend in freight load factors and associated yields, it can be concluded that a utilized lower deck compartment, once approved by the aviation authorities, is certainly an opportunity for airlines to add in current aviation industry.

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A

DINED Human Dimensions

Table A.1: Obtained human stature dimensions for various origins from DINED [1]

Origin (Mixed)	Mean [mm]	Standard Deviation [mm]	1960 mm percentile [%]
International	1650	152	97.92
North American	1720	98	99.29
Latin American (Indians)	1550	89	99.99
Netherlands	1743	106	97.97
Central Europe	1685	65	99.99
Eastern Europe	1690	82	99.95
South East Europe	1675	80	99.98
France	1700	97	99.63
North Africa	1650	79	99.99
West Africa	1600	94	99.99
South-East Africa	1625	79	99.99
Middle-East	1660	72	99.99
Northern India	1605	86	99.99
Southern India	1560	86	99.99
Southern China	1590	81	99.99
South-East Asia	1580	75	99.99
Australia (European)	1720	84	99.79
Japan	1655	84	99.99

[1] DINED Anthropometric Database, Delft University of Technology, Faculty of Industrial Design Engineering, http://dined.io.tudelft.nl/ergonomics/, Accessed: 27/08/2015

B

Modeled Aircraft Performance

Table B.1: Modeled Airbus A320-200 baseline configuration top level requirements

	Primary Mission	Secondary Mission
Cruise Mach [-]	0.78	0.78
Range [km]	4000	3000
Take-Off Distance [m]	2300	2300
Landing Distance [m]	1600	1600
Maximum Payload [kg]	19500	16065
Cruise Altitude [m]	11278	11278

Table B.2: Modeled Airbus A320-200 baseline configuration key parameters

Aircraft Key Parameter	**Original Aircraft**	**Modeled Aircraft**	**Difference**
Fuselage Length [m]	37.57	37.74	0.53 %
Fuselage Width [m]	4.14	4.02	2.90 %
Cabin Length [m]	27.50	29.06	5.67 %
Cabin Width [m]	3.70	3.77	1.89 %
Number of Passengers [-]	153	156	1.96 %
Maximum Take Off Weight [kg]	78000	74006	5.12 %
Operational Empty Weight [kg]	42220	38659	8.43 %
Maximum Landing Weight [kg]	66000	62977	4.58 %
Maximum Ramp Weight [kg]	78400	75508	3.69 %
Wing Span [m]	34.10	32.82	3.75 %
Wing Reference Area [m^2]	122.6	114.73	6.42 %
Wing Loading []	6241	6332	1.46 %
Ferry Range [km]	7870	7489	4.48 %
Harmonic Range [km]	4167	3993	4.18 %

Table B.3: Modeled Airbus A321-200 baseline configuration top level requirements

	Primary Mission	Secondary Mission
Cruise Mach [-]	0.78	0.78
Range [km]	4300	3250
Take-Off Distance [m]	2500	2500
Landing Distance [m]	1750	1750
Maximum Payload [kg]	24000	19215
Cruise Altitude [m]	11278	11278

Table B.4: Modeled Airbus A321-200 baseline configuration key parameters

Aircraft Key Parameter	**Original Aircraft**	**Modeled Aircraft**	**Difference**
Fuselage Length [m]	44.51	44.55	0.09 %
Fuselage Width [m]	4.14	4.02	2.90 %
Cabin Length [m]	34.44	34.30	0.41 %
Cabin Width [m]	3.70	3.77	1.89 %
Number of Passengers [-]	183	184	0.55 %
Maximum Take Off Weight [kg]	93500	91682	1.94 %
Operational Empty Weight [kg]	48139	46622	3.15 %
Maximum Landing Weight [kg]	77800	76698	1.42 %
Maximum Ramp Weight [kg]	93900	93543	0.38 %
Wing Span [m]	34.10	34.71	1.79 %
Wing Reference Area [m^2]	122.6	128.33	4.67 %
Wing Loading []	7482	7013	6.27 %
Ferry Range [km]	7500	7118	5.09 %
Harmonic Range [km]	4200	4285	2.02 %

Table B.5: Modeled Airbus A330-300 baseline configuration top level requirements

	Primary Mission	Secondary Mission
Cruise Mach [-]	0.82	0.82
Range [km]	7000	8000
Take-Off Distance [m]	2900	2900
Landing Distance [m]	1646	1646
Maximum Payload [kg]	45000	26775
Cruise Altitude [m]	11887	11887

Table B.6: Modeled Airbus A330-300 baseline configuration key parameters

Aircraft Key Parameter	**Original Aircraft**	**Modeled Aircraft**	**Difference**
Fuselage Length [m]	63.70	63.47	0.36 %
Fuselage Width [m]	5.64	5.58	1.06 %
Cabin Length [m]	50.35	48.87	2.94 %
Cabin Width [m]	5.28	5.26	0.38 %
Number of Passengers [-]	288	286	0.69 %
Maximum Take Off Weight [kg]	242000	226146	6.55 %
Operational Empty Weight [kg]	126000	113177	10.18 %
Maximum Landing Weight [kg]	187000	173173	7.39 %
Maximum Ramp Weight [kg]	242900	230738	5.01 %
Wing Span [m]	60.30	58.09	3.67 %
Wing Reference Area [m^2]	363.1	335.42	7.62 %
Wing Loading []	6538	6618	1.22 %
Ferry Range [km]	12000	12471	3.93 %
Harmonic Range [km]	7000	7005	0.07 %

Table B.7: Modeled Airbus A340-300 baseline configuration top level requirements

	Primary Mission	Secondary Mission
Cruise Mach [-]	0.82	0.82
Range [km]	10000	9500
Take-Off Distance [m]	3100	3100
Landing Distance [m]	2100	2100
Maximum Payload [kg]	52000	28350
Cruise Altitude	11000	11000

Table B.8: Modeled Airbus A340-300 baseline configuration key parameters

Aircraft Key Parameter	**Original Aircraft**	**Modeled Aircraft**	**Difference**
Fuselage Length [m]	63.60	63.58	0.03 %
Fuselage Width [m]	5.64	5.58	1.06 %
Cabin Length [m]	50.37	48.96	2.80 %
Cabin Width [m]	5.28	5.26	0.38 %
Number of Passengers [-]	267	270	1.12 %
Maximum Take Off Weight [kg]	276500	264107	4.48 %
Operational Empty Weight [kg]	130200	118863	8.71 %
Maximum Landing Weight [kg]	192000	189893	1.10 %
Maximum Ramp Weight [kg]	277400	269469	2.86 %
Wing Span [m]	60.30	59.21	1.81 %
Wing Reference Area [m^2]	363.1	348.80	3.94 %
Wing Loading []	7470	7433	0.50 %
Ferry Range [km]	15500	13248	14.53 %
Harmonic Range [km]	9500	9564	0.67 %

Table B.9: Modeled Boeing 737-300 baseline configuration top level requirements

	Primary Mission	Secondary Mission
Cruise Mach [-]	0.74	0.74
Range [km]	3240	2500
Take-Off Distance [m]	2400	2400
Landing Distance [m]	1650	1650
Maximum Payload [kg]	20000	15540
Cruise Altitude [m]	11278	11278

Table B.10: Modeled Boeing 737-300 baseline configuration key parameters

Aircraft Key Parameter	**Original Aircraft**	**Modeled Aircraft**	**Difference**
Fuselage Length [m]	33.40	33.44	0.12 %
Fuselage Width [m]	3.76	3.80	1.06 %
Cabin Length [m]	24.18	25.75	6.49 %
Cabin Width [m]	3.54	3.56	0.56 %
Number of Passengers [-]	148	150	1.35 %
Maximum Take Off Weight [kg]	63276	65299	3.20 %
Operational Empty Weight [kg]	32700	32975	0.84 %
Maximum Landing Weight [kg]	52889	57372	8.48 %
Maximum Ramp Weight [kg]	63503	66625	4.92 %
Wing Span [m]	28.88	30.6	5.96 %
Wing Reference Area [m^2]	105.4	102.23	3.01 %
Wing Loading []	5889	6270	6.47 %
Ferry Range [km]	6667	7390	10.84 %
Harmonic Range [km]	3519	3218	8.55 %

Table B.11: Modeled Boeing 737-800 baseline configuration top level requirements

	Primary Mission	Secondary Mission
Cruise Mach [-]	0.785	0.785
Range [km]	3710	2500
Take-Off Distance [m]	2300	2300
Landing Distance [m]	1600	1600
Maximum Payload [kg]	21100	17325
Cruise Altitude	11278	11278

Table B.12: Modeled Boeing 737-800 baseline configuration key parameters

Aircraft Key Parameter	**Original Aircraft**	**Modeled Aircraft**	**Difference**
Fuselage Length [m]	39.47	39.62	0.38 %
Fuselage Width [m]	3.76	3.80	1.06 %
Cabin Length [m]	29.97	30.51	1.80 %
Cabin Width [m]	3.54	3.56	0.56 %
Number of Passengers [-]	165	166	0.61 %
Maximum Take Off Weight [kg]	79016	76839	2.76 %
Operational Empty Weight [kg]	41145	39944	2.92 %
Maximum Landing Weight [kg]	66361	66125	0.36 %
Maximum Ramp Weight [kg]	79333	78399	1.18 %
Wing Span [m]	34.32	33.85	1.37 %
Wing Reference Area [m^2]	125.0	121.28	2.98 %
Wing Loading []	6201	6220	0.31 %
Ferry Range [km]	9260	7829	15.45 %
Harmonic Range [km]	3797	3698	2.61 %

Table B.13: Modeled Boeing 767-300ER baseline configuration top level requirements

	Primary Mission	Secondary Mission
Cruise Mach [-]	0.80	0.80
Range [km]	7400	8500
Take-Off Distance [m]	2900	2900
Landing Distance [m]	1646	1646
Maximum Payload [kg]	44000	22470
Cruise Altitude	11887	11887

Table B.14: Modeled Boeing 767-300ER baseline configuration key parameters

Aircraft Key Parameter	**Original Aircraft**	**Modeled Aircraft**	**Difference**
Fuselage Length [m]	54.90	54.87	0.05 %
Fuselage Width [m]	5.03	5.03	0 %
Cabin Length [m]	42.86	42.25	1.42 %
Cabin Width [m]	4.72	4.73	0.21 %
Number of Passengers [-]	214	211	1.40 %
Maximum Take Off Weight [kg]	186880	203398	8.84 %
Operational Empty Weight [kg]	90010	91320	1.46 %
Maximum Landing Weight [kg]	145150	150068	3.39 %
Maximum Ramp Weight [kg]	187334	207527	10.78 %
Wing Span [m]	47.60	49.63	4.26 %
Wing Reference Area [m^2]	283.3	308.22	8.80 %
Wing Loading []	6471	6478	0.11 %
Ferry Range [km]	13797	12977	5.94 %
Harmonic Range [km]	7686	7337	4.54 %

Table B.15: Modeled Boeing 777-300 baseline configuration top level requirements

	Primary Mission	Secondary Mission
Cruise Mach [-]	6500	7000
Range [km]	0.84	0.84
Take-Off Distance [m]	3840	3840
Landing Distance [m]	2200	2200
Maximum Payload [kg]	60000	52500
Cruise Altitude	11000	11000

Table B.16: Modeled Boeing 777-300 baseline configuration key parameters

Aircraft Key Parameter	**Original Aircraft**	**Modeled Aircraft**	**Difference**
Fuselage Length [m]	73.86	73.66	0.27 %
Fuselage Width [m]	6.20	6.27	1.13 %
Cabin Length [m]	51.85	56.72	9.39 %
Cabin Width [m]	5.87	5.92	0.85 %
Number of Passengers [-]	500	500	0 %
Maximum Take Off Weight [kg]	299370	316648	5.77 %
Operational Empty Weight [kg]	160500	161197	0.43 %
Maximum Landing Weight [kg]	237680	242866	2.18 %
Maximum Ramp Weight [kg]	300280	323077	7.59 %
Wing Span [m]	60.90	62.95	3.37 %
Wing Reference Area [m^2]	427.8	456.49	6.71 %
Wing Loading []	6865	6809	0.82 %
Ferry Range [km]	15460	12614	18.41 %
Harmonic Range [km]	6667	6584	1.24 %

Table B.17: Differences between long-range aircraft with respect to cabin and fuselage dimensions using different modeling techniques within the Initiator

Aircraft	Fuselage Length [m] Chair Exchange	Area Addition	Original	Pax Placed Chair Exchange	Area Addition	Original
Airbus A320-200	38.26	37.74	37.57	154	156	153
Airbus A321-200	45.70	44.55	44.51	186	184	183
Airbus A330-300	62.35	63.47	63.70	284	286	288
Airbus A340-300	63.67	63.58	63.60	272	270	267
Boeing 737-300	33.45	33.44	33.40	148	150	148
Boeing 737-800	40.02	39.62	39.47	164	166	165
Boeing 767-300ER	56.12	54.87	54.90	217	211	214
Boeing 777-300	75.53	73.66	73.86	504	500	500

Table B.18: Comparison between Initiator engine model cruise SFC and reference cruise SFC

Aircraft Model	Model SFC_{Cruise}	Reference Engine Type	Reference Engine SFC_{Cruise}	Reference Engine Type	Reference Engine SFC_{Cruise}	Modeling Error
Airbus A320-200	0.5472	CFM56-5B4 [83]	0.55	V2500-A1 [84]	0.581	3.16 %
Airbus A321-200	0.5472	CFM56-5B1 [83]	0.6	V2533-A5 [84]	0.574	6.73 %
Airbus A330-300	0.5140	CF6-80E1A2 [83]	0.56	Trent 772 [84]	0.565	8.62 %
Airbus A340-300	0.5169	CFM56-5C2 [84]	0.545	-	-	5.16 %
Boeing 737-300	0.5306	CFM56-3C1 [84]	0.667	-	-	20.45 %
Boeing 737-800	0.5494	CFM56-7B2 [1]	0.627	-	-	12.38 %
Boeing 767-300ER	0.5595	CF6-80C2B2 [83]	0.58	RB211-524H [84]	0.57	2.69 %
Boeing 777-300	0.5146	GE90-85B [84]	0.545	Trent 892 [84]	0.557	6.60 %

[1] N. Meier, Civil Turbojet / Turbodan Specifications, http://www.jet-engine.net/civtfspec.html, Accessed: 02/09/2015

C

Modeled Aircraft Cabin Layouts

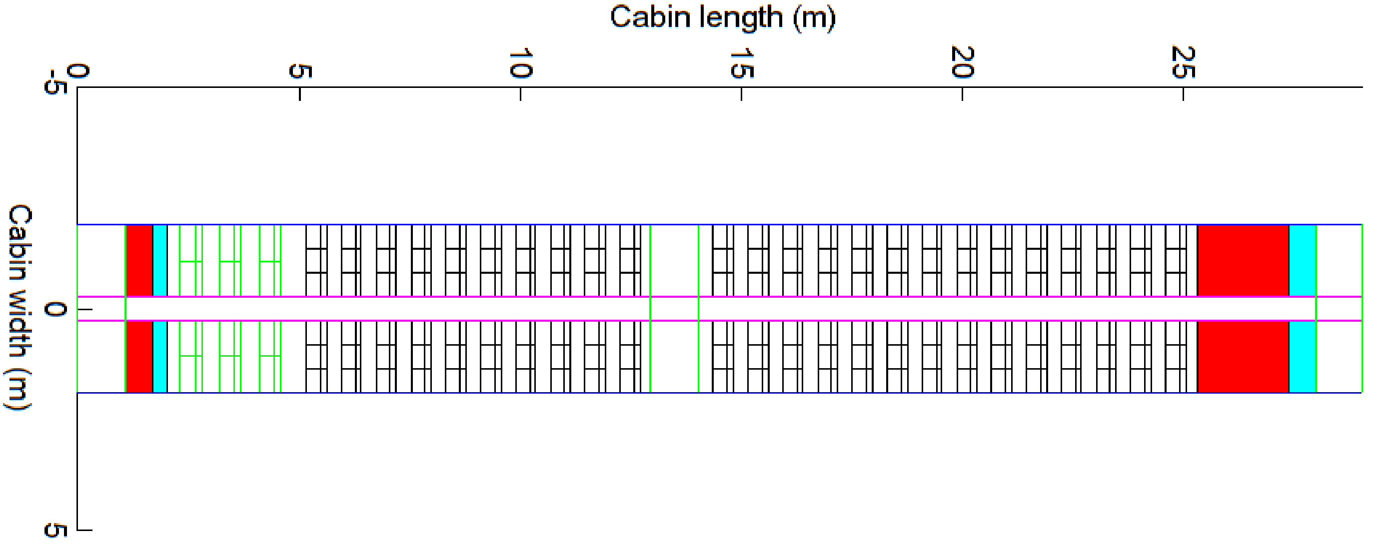


Figure C.1: Airbus A320-200 aircraft cabin model as used within the Initiator, based on the Turkish Airlines Airbus A320-200 layout [1]

[1] Turkish Airlines Airbus A320-200, http://www.turkishairlines.com/en-int/travel-information/turkish-airlines-passenger-cargo-airbus-boeing-all-flight-fleet, Accessed: 27/07/2015

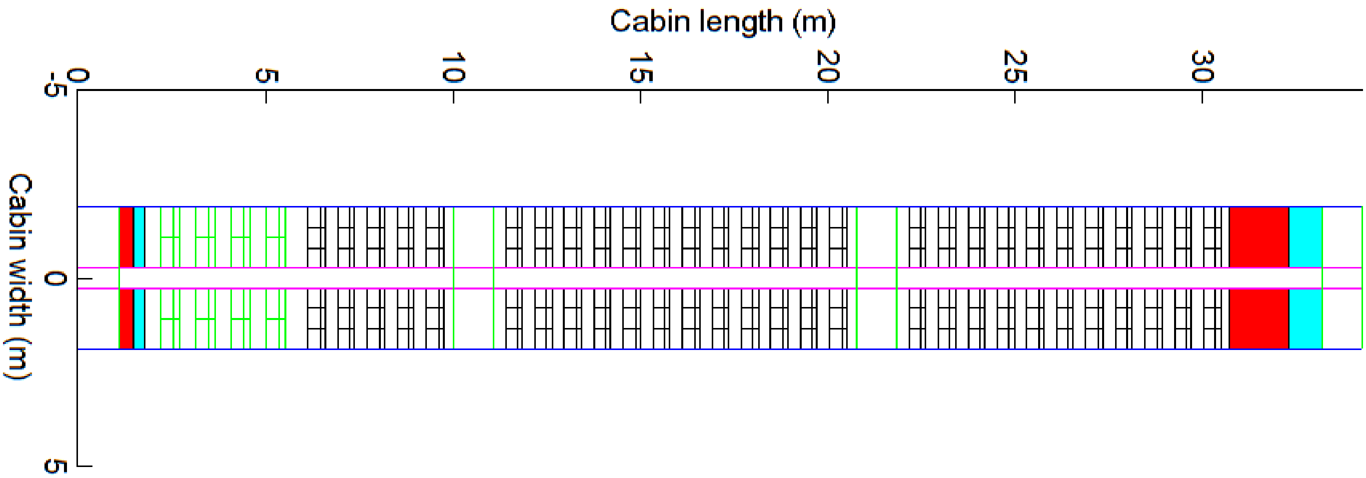


Figure C.2: Airbus A321-200 aircraft cabin model as used within the Initiator, based on the Air Canada Airbus A321-200 layout [2]

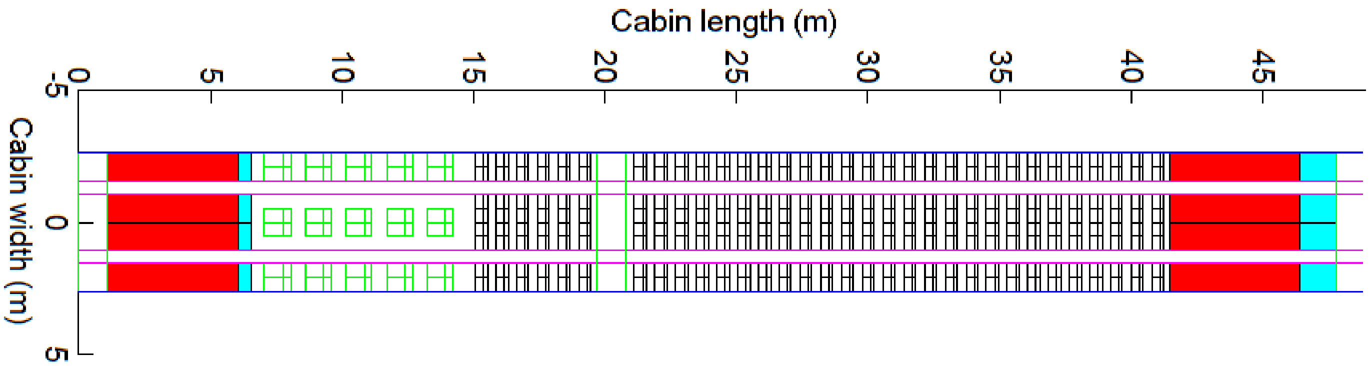


Figure C.3: Airbus A330-300 aircraft cabin model as used within the Initiator, based on the Turkish Airlines Airbus A330-300 layout [3]

[2] Air Canada Airbus A321-200, http://www.aircanada.com/en/about/fleet/a321-200xm.html, Accessed: 27/07/2015

[3] Turkish Airlines A330-300, http://www.turkishairlines.com/en-int/travel-information/turkish-airlines-passenger-cargo-airbus-boeing-all-flight-fleet, Accessed: 27/07/2015

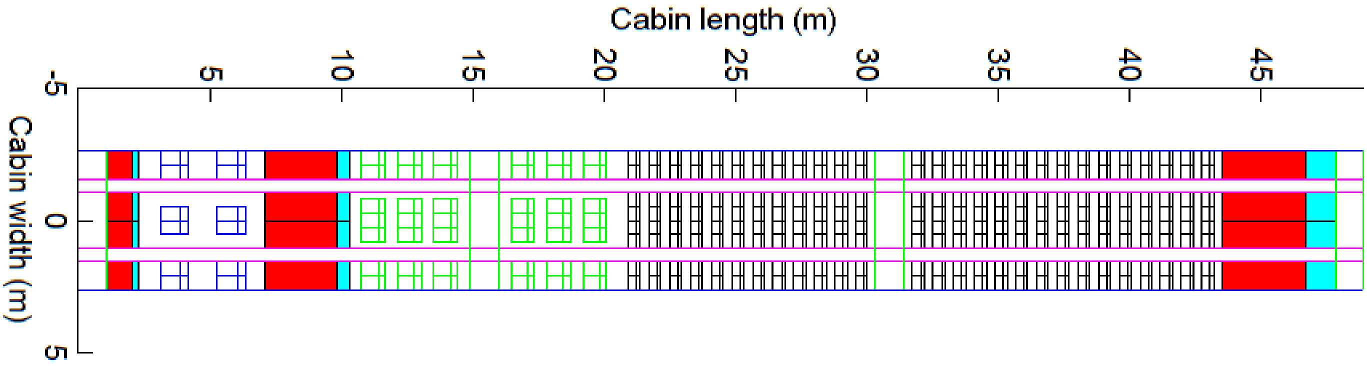


Figure C.4: Airbus A340-300 aircraft cabin model as used within the Initiator, based on the Emirates Airlines Airbus A340-300 layout [4]

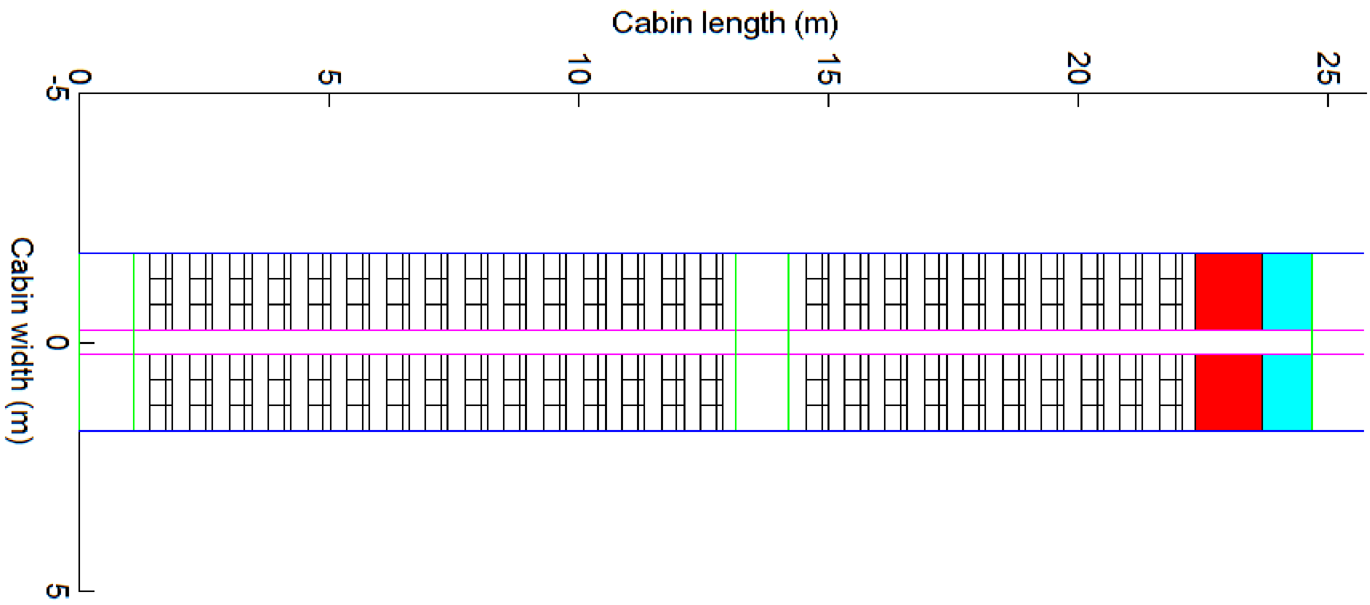


Figure C.5: Boeing 737-300 aircraft cabin model as used within the Initiator, based on the Norwegian Air Boeing 737-300 layout [5]

[4]Emirates Airlines A340-300, http://www.emirates.com/english/flying/our_fleet/seating_chart.aspx?id=343LFJY&from=193757, Accessed: 27/07/2015

[5]Norwegian Airlines Boeing 737-300, http://www.norwegian.com/uk/about-norwegian/our-company/fleet/, Accessed: 27/07/2015

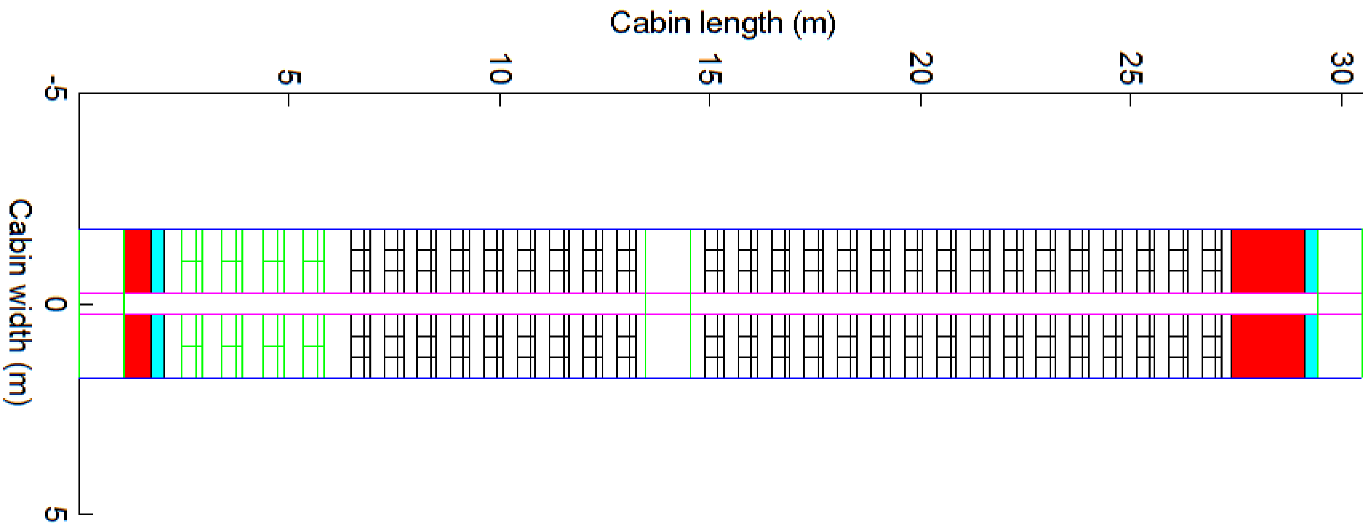


Figure C.6: Boeing 737-800 aircraft cabin model as used within the Initiator, based on the Japan Airlines Boeing 737-800 layout [6]

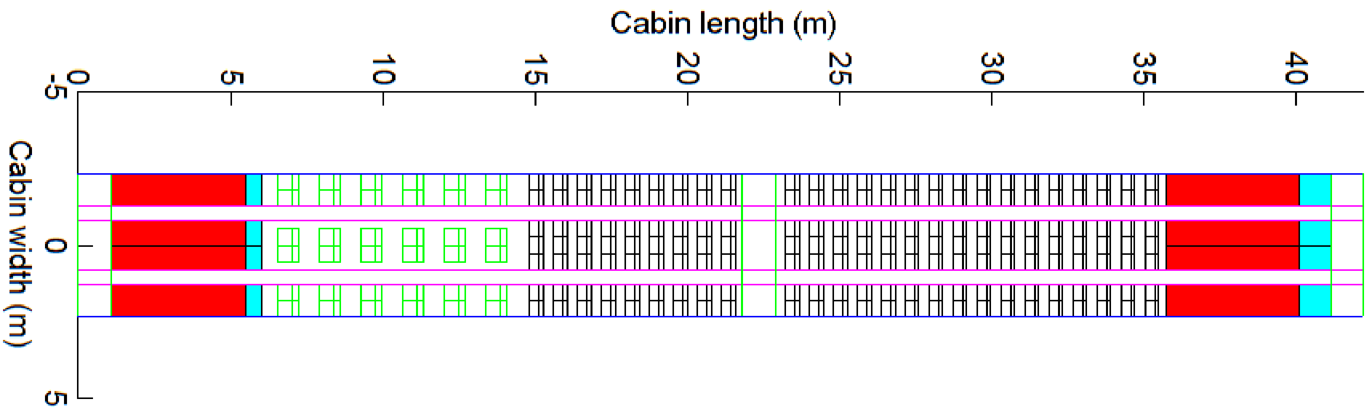


Figure C.7: Boeing 767-300ER aircraft cabin model as used within the Initiator, based on the All Nippon Airways Boeing 767-300ER layout [7]

[6]Japan Airlines Boeing 737-800, https://www.jal.co.jp/en/aircraft/conf/737.html, Accessed: 27/07/2015

[7]All Nippon Airways Boeing 767-300ER, https://www.ana.co.jp/wws/japan/e/local/domestic/departure/inflight/seatmap/detail.html?c=b6s, Accessed: 27/07/2015

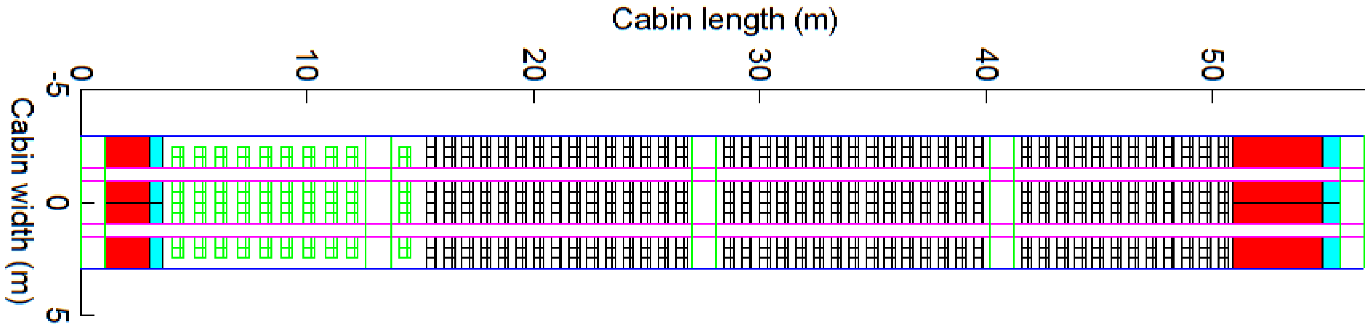


Figure C.8: Boeing 777-300 aircraft cabin model as used within the Initiator, based on the Japan Airlines Boeing 777-300 layout [8]

[8]Japan Airlines Boeing 777-300, https://www.jal.co.jp/en/aircraft/conf/773.html, Accessed: 27/07/2015

D

Cost Estimation Input Parameters

Table D.1: Cost estimation module input parameters

Cost Estimation Constant	Short-Haul Aircraft	Long-Haul Aircraft
Salary Captain [US$ / year] [1]	124000	124000
Salary Co-Pilot [US$ / year] [2]	90000	90000
Salary Flight Engineer [US$ / year]	85000	85000
Fuel Price [US$ / US gal] [3]	1.65	1.65
Aircraft Service Years [-]	20	20
Yield Factor First Class Passengers [ct/pax/nm]	0.35	0.35
Yield Factor Economy Class Passengers [ct/pax/nm]	0.1	0.1
Aircraft List Price Year [-]	2014	2014
Cost Estimation Fiscal Year [-]	2015	2015
International Flight [-]	No	Yes
Aircraft Depreciation Period [yrs]	8	14

[1] International Business Machines Corporation, Captain/Pilot in Command (Large Jet) Salaries, http://www1.salary.com/Captain-Pilot-in-Command-Large-Jet-Salary.html, Accessed: 10/08/2015

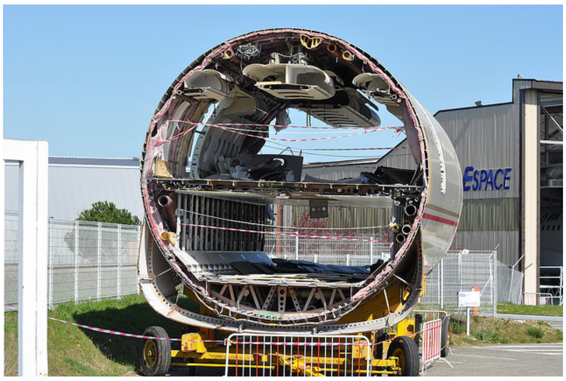
[2] International Business Machines Corporation, Co-Pilot (Large Jet) Salaries, http://www1.salary.com/Co-Pilot-Large-Jet-Salary.html, Accessed: 10/08/2015

[3] International Air Transport Association, Fuel Price Analysis, http://www.iata.org/publications/economics/fuel-monitor/pages/price-analysis.aspx, Accessed: 10/08/2015

E

Airbus A330/A340 Cross Section Views

(a) Airbus A330 cross-sectional view [18]



(b) Airbus A340-600 cross-sectional view

Figure E.1: Airbus A330/A340 cross-sectional views

F

DETAILED DOC AND TOC BREAKDOWN

Table F.1: DOC and IOC breakdown for various modeled LDGL layouts, expressed in US$/nm

		Original		High-Density 2-4-2		Comfort 2-4-2	
DOC		80% LF	100% LF	80% LF	100% LF	80% LF	100% LF
	Flight	12.16	12.33	12.32	12.52	12.26	12.44
	Maintenance	7.81	7.81	7.89	7.89	7.89	7.89
	Depreciation	6.87	6.87	6.96	6.96	6.96	6.96
	Landing and Navigation	0.89	0.89	0.89	0.89	0.89	0.89
	Registry Taxes	0.26	0.26	0.26	0.27	0.26	0.26
	Financing	1.47	1.48	1.49	1.50	1.49	1.50
IOC							
	System	0.09	0.09	0.10	0.10	0.10	0.10
	Local	0.20	0.20	0.20	0.20	0.20	0.20
	Aircraft Contract	0.01	0.01	0.01	0.01	0.01	0.01
	Cabin Attendants	0.70	0.70	0.87	0.87	0.70	0.70
	Food	0.48	0.60	0.52	0.65	0.49	0.61
	Passenger Handling	0.70	0.88	0.78	0.98	0.72	0.90
	Cargo Handling	0	0	0	0	0	0
	Other	2.00	2.50	2.23	2.79	2.06	2.57
	Freight Comission and Advertising	0	0	0	0	0	0
	General Administration	1.26	1.27	1.27	1.28	1.27	1.28

Table F.2: DOC and IOC breakdown for various modeled LDS layouts, expressed in US$/nm

		Original		High-Density 2-2		Asymmetric 2-1		2-2 Seating		1-1 Seating	
DOC		80% LF	100% LF	80% LF	100% LF	80% LF	100% LF	80% LF	100% LF	80% LF	100% LF
	Flight	12.16	12.33	12.59	12.81	12.56	12.77	12.54	12.74	12.53	12.72
	Maintenance	7.81	7.81	7.88	7.88	7.88	7.88	7.88	7.88	7.88	7.88
	Depreciation	6.87	6.87	6.90	6.90	6.90	6.90	6.90	6.90	6.90	6.90
	Landing and Navigation	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89	0.89
	Registry Taxes	0.26	0.26	0.26	0.27	0.26	0.27	0.26	0.27	0.26	0.27
	Financing	1.47	1.48	1.50	1.51	1.50	1.51	1.49	1.50	1.49	1.50
IOC											
	System	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
	Local	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
	Aircraft Contract	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Cabin Attendants	0.70	0.70	0.87	0.87	0.87	0.87	0.87	0.87	0.87	0.87
	Food	0.48	0.60	0.52	0.66	0.51	0.64	0.50	0.63	0.49	0.62
	Passenger Handling	0.70	0.88	0.79	0.99	0.76	0.95	0.74	0.93	0.73	0.91
	Cargo Handling	0	0	0	0	0	0	0	0	0	0
	Other	2.00	2.50	2.26	2.83	2.17	2.72	2.11	2.64	2.08	2.61
	Freight Comission and Advertising	0	0	0	0	0	0	0	0	0	0
	General Administration	1.26	1.27	1.29	1.30	1.28	1.29	1.28	1.29	1.28	1.29