OPTIMIZING AIR CARGO LOADING AND ITS POTENTIAL IMPACT OVER FUEL COSTS

Jury :	Thesis presented by
Supervisor :	**Frédéric SALMON**
Sabine LIMBOURG	With a view to obtaining the diploma
Readers :	of Master Degree in Business Engineering
Michael SCHYNS	specializing in Supply Chain Management
Thierry PIRONET	Academic year: 2011/2012

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Abstract

The goal of this thesis is to investigate the link between fuel savings and the shipment's distribution in airfreight by discussing data and entering some modifications to the distribution optimization software OPAL. Fuel reduction becomes more and more important for airlines as fuel prices are raising and carbon taxes are implemented. Results show that a reduction of 1% of fuel would benefit for over $500 million to the U.S. carrier sector. An automatic optimization of cargo's distribution would ensure to reach the most aft possible position of the center of gravity and lead to fuel savings. OPAL is designed to reach this optimal center of gravity quickly with the purpose to replace a labor time consuming task. But researches haven't given a clear value for the fuel saved due to an optimization of the shipment's distribution. So this thesis ends by giving a few paths that could be investigated for reaching a good estimation.

Keywords: aircraft loading; weight and balance; mixed integer programming; fuel saving; European carbon tax; fuel cost; carbon dioxide

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Chapter I. Introduction

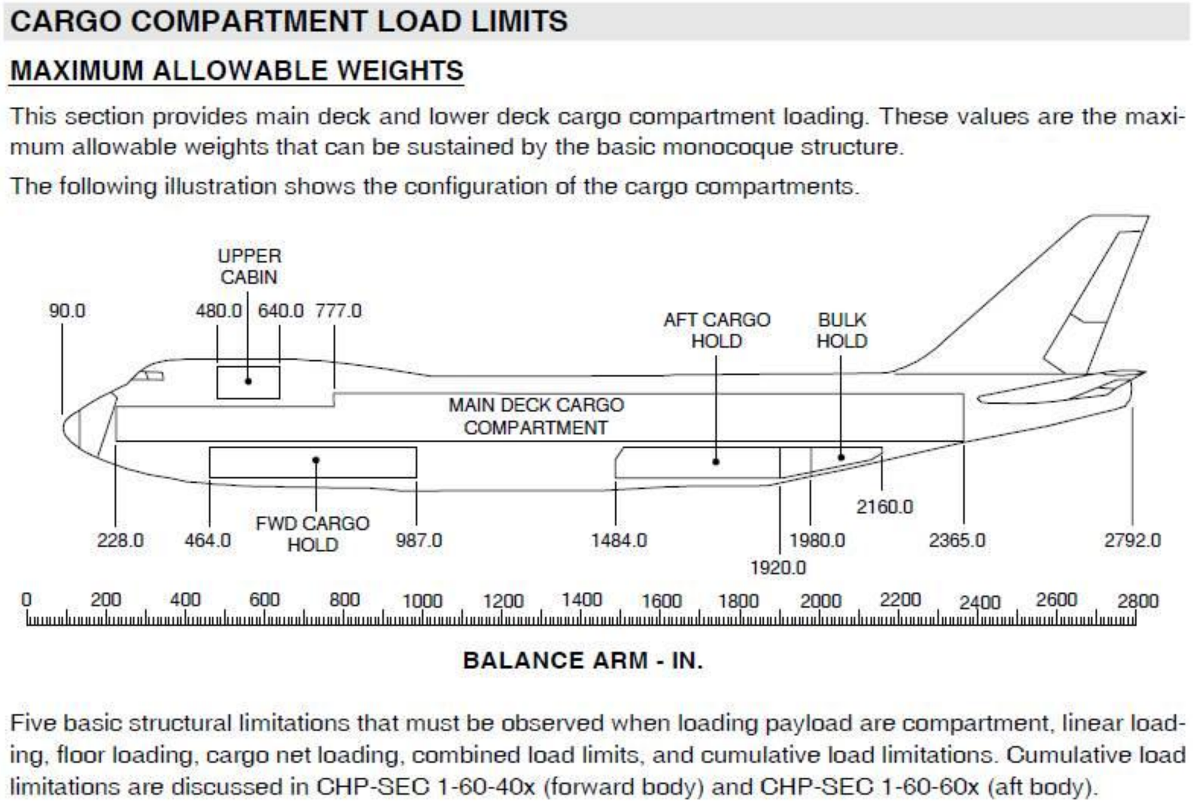
A. Presentation

With over 25 million flights a year (ICAO, 2009), the aircraft industry has to handle several issues thousands of times every day and small changes per flight can result into great changes in costs and climate impact on a larger scale. One of these issues is the weight and balance problem: on an airplane, one must ensure that the weight is properly balanced to get high performances or even to fly at all. It means that the center of gravity has to be handled carefully to keep it within specified limits to grant the plane the best performances and flight safety. From 1970 to 2005 the National Aerospace Laboratory of the Netherlands’s Air Safety database (NLR) reported 82 accidents related to weight and balance issues (van Es, 2007). The weight and balance problem occurs with every type of plane and depends on every weight relative to the flight, from the plane itself to the fuel, from the transport of people to goods and luggage, the overall balance of the aircraft will impact on its performances, its maneuverability and its fuel consumption. Among the influencing factors for the center of gravity, only passengers and freight are truly variable as the shape of the plane cannot change and even if a change of the center of gravity can be achieved with fuel transfer between tanks, the freight and passenger distribution gives a better flexibility to the center of gravity displacement.

An air carrier is loaded with a set of Unit Loading Devices (ULDs), containers or pallets where goods are bundled up, and each ULD takes standardized places into the airfreight. Data differs not only for shipments but also for planes.

Figure 1 - Different ULD types (Airlog group, 2011)

Moreover each model of airfreight has its own characteristics which need to be taken into account. They differ in their structure which gives them different capabilities impacting on structural limits, weight limits for shipments, positions of storage and so on. An airfreight is divided in compartments with various limits and the shipment is distributed into those compartments. For example the Boeing 747-400 has 4 main compartments: the Main Deck Cargo, the Forward Cargo Hold, the Aft Cargo Hold and the Bulk Hold.



CARGO COMPARTMENT LOAD LIMITS

MAXIMUM ALLOWABLE WEIGHTS

This section provides main deck and lower deck cargo compartment loading. These values are the maximum allowable weights that can be sustained by the basic monocoque structure.

The following illustration shows the configuration of the cargo compartments.

Five basic structural limitations that must be observed when loading payload are compartment, linear loading, floor loading, cargo net loading, combined load limits, and cumulative load limitations. Cumulative load limitations are discussed in CHP-SEC 1-60-40x (forward body) and CHP-SEC 1-60-60x (aft body).

Figure 2 - Cargo compartment load limits - Boeing 747-400 (Boeing; Cargolux Airlines)

Each compartment has different sizes and characteristics to be taken into account as constraints in the model. Characteristics are related to the total weight a compartment can take and also how much weight can be loaded per inch (see A*ppendix A*).

The air cargo loading problem answers the question of: How cargo should be stowed in an airplane regarding constraints.

Three types of constraints have to be applied by loadmasters (people in charge of loading the shipment):

1. Constraints relative to the weight and balance problem imply the need to balance the load to get the center of gravity in a certain feasibility envelope given by the manufacturer. Being out of this interval of feasibility is unsafe for the plane (see *II.A.2 Weight and Balance* for more details).

2. On top of the weight and balance problem, there are other constraints to take into account: an aircraft is commonly built with several cargo compartments with limited capacities but also structural limitations such as cumulative limits and maximum weight per area (see A*ppendics A* for example about compartment constraints).
3. Some products are not usual: animals, chemical products, magnetic goods and so on. All these products, named Hazards, have special rules which imply position constraints for ULDs (see *II.A.5 Hazardous goods*).

Currently the weight and balance problem of air cargo loading is handled by a trained staff called loadmasters. They are in charge of choosing the distribution of the shipment and the loading of this shipment. In most firms, the distribution process is computed semi-automatically (for example with Excel sheets) and takes about fifteen minutes. The current software for loadmasters makes the calculation but not the optimization. Therefore loadmasters still have to test some shipment's configurations and it takes some time to get a proper distribution respecting all constraints and the targeted position of the center of gravity. Limbourg *et al.* (2012) explain that an experienced loadmaster takes 15 minutes to load 40 ULDs on a Boeing 747. But the given target is not always the best one and seems to be chosen either for computation facilities or because they do not care about this issue.

This problem deserves to be looked at, not only to increase the speed of constraints and restrictions computations but also because there is another interesting point about the position of the center of gravity. The literature suggests that any modification of the center of gravity of a plane modifies its fuel consumption. A common rule is to consider that for each displacement of the center of gravity's position 5% more aft on the MAC, there is a fuel saving of 1% (Urbani, 2012). If the information is relevant it can lead to important economies for the airfreight industry as the consumption is quite huge. For example the U.S. carriers industry has an overall fuel cost of $ 46,881.4 million in 2011 for (RITA, 2012).

The airfreight traffic represents 35% of the value of world trade (Limbourg *et al.*, 2012, in reference of IATA, 2010). The forecasts from Boeing say that the world air cargo traffic in revenue tonne-kilometre (RTK[1]) could triple over the next 20 years with the best growth in Asia, followed by markets linking south to northern countries (mainly markets from South America to Europe and the United States). North American and European markets should

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[1] Revenue tonne-kilometre : measurement for airfreight traffic, it is the «utilized capacity for passengers and cargo expressed in metric tons, multiplied by the distance flown» (CEESE-ULB, 2009).

already be mature and therefore their future growths are forecasted lower than the average world traffic growth rate (Boeing, 2010).

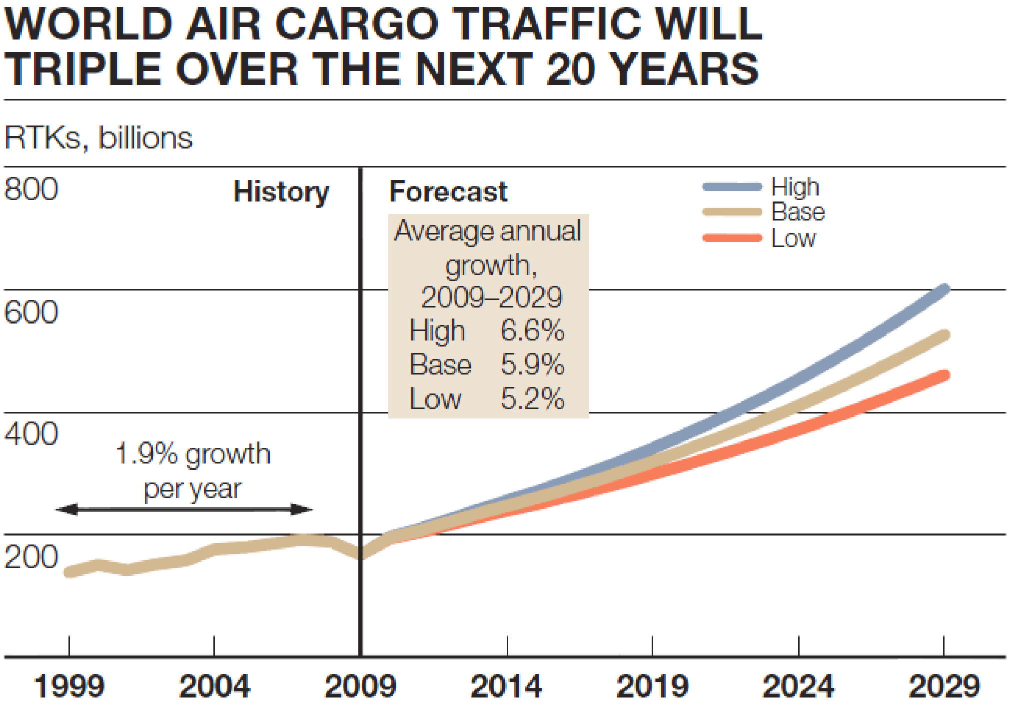


Figure 3 - Air cargo traffic forescasts (Boeing, 2010)

This project research presents and adds some constraints and modifications to the mixed integer linear program from Limbourg *et al.* (2012) called OPAL. It is designed to solve the problem of air cargo loading automatically, which should enable to put the center of gravity anywhere on the MAC in no time and therefore should permit consequent economies. The key information to reach an economic result in this project research is to determine the expected saving of fuel and the economic impact due to a change of the center of gravity.

B. Objective

The purpose of this project is to look for economies through a distribution process (air cargo loading). The literature suggests that the center of gravity can lead to important fuel consumption economies on the world scale, which is of prime importance as fossil fuel prices are rocketing and governments are implementing new taxes on pollution, like the European aviation carbon tax. Apart from profits it also helps get a greener world with less gas emissions and reduce the greenhouse effect.

Through the possibilities of Limbourg *et al.* (2012) software and the data available, this thesis tries to determine the economy resulting from a change of the center of gravity and therefore the interest for companies to use more advanced methods than the manual or semi-manual ones which is currently used for solving the weight and balance problem.

The objectives of this project are to:

1. Technically review the Limbourg *et al.* (2012) model and algorithm and implement functions and constraints to it. In order to do so, four main goals were given at the beginning of this project research:
    a. Entering the compartments total weight constraints.
    b. Entering a vertical constraint.
    c. Entering the possibility to get the most aft center of gravity.
    d. Reaching a bi-objective of minimizing the moment of inertia while minimizing the center of gravity.
2. Carry on a research to estimate how a change of the center of gravity can impact fuel economy. This research can be split into two smaller questions:
    a. What is the fuel saving induced by a change of the center of gravity of a plane?
    b. What is the economic impact of a reduction of fuel?

c. Approach

To reach these objectives, the Limbourg *et al.* (2012) model (OPAL) is compared with other models and its main strengths are highlighted. Then four given constraints and modifications are discussed and entered in the software in the methodology part of this thesis. Eventually the model is reviewed and commented on some points with possibilities of improvement.

At the same time the literature about changes in fuel consumption regarding the center of gravity is criticized by comparing documents and interviewing an expert. And some estimations are made on fuel saving and the economical profit relative to this fuel saving, not only taking into account prices but also the European carbon tax which impacts on airlines economies relative to their carbon dioxide consumption.

Chapter II. Literature

The purpose of the literature review is to present the current work of aircraft loading models and convey background information about fuel consumption on the whole and more especially the one related to the plane's center of gravity.

1. In the first part, some definitions are given in parallel with the theories used in this thesis.
2. For the second part of this chapter, the different models are presented and compared to the model from Limbourg *et al.* (2012).
3. In the third part, the model from Limbourg *et al*. (2012) is presented and commented.
4. The last part of this chapter discusses the main results and papers regarding the fuel economy resulting from a change of the plane's center of gravity.

A. Definitions and theory

1. Measurements in aviation

The measurements in aviation and in this thesis are made by taking into account the balance arm of ULDs, compartments and so on, measured in inches. The Balance Arm (B.A.) is "A true measure of distance from forward to aft, in inches, from a fixed datum. The fixed datum is selected by the airplane manufacturer. Balance Arms are used in weight and balance calculations" (Boeing; Cargolux Airlines). Usually it is a virtual point in front of the plane's nose. See the following illustration for a Boeing 747-400 (the reference plane used in this thesis):

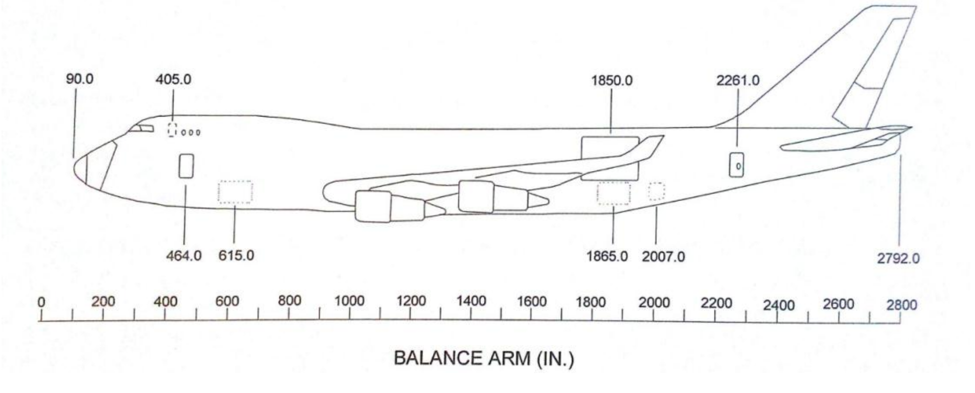


Figure 4 - Balance arm of different elements of a Boeing 747-400 (Boeing; Cargolux Airlines)

2. Weight and balance

The weight and balance issue, as said in the introduction answers the question of: How cargo should be stowed in an airplane regarding constraints. D. Anderson in Introduction to Weight and Balance (2006) splits the definition in two parts :

«Weight refers to the process of determining the total weight of the airplane for the purposes of calculating airplane performance and determining that the structural limitations of the airplane have not been exceeded. » (Anderson, 2006)

«Balance refers to the process of determining the center of gravity of the airplane and ensuring that this C.G. will not exceed the certified center of gravity limits at any time during the operation. » (Anderson, 2006)

The weight and balance issue specifies that a center of gravity must always be operated within a specified envelope often defined in percentage of the mean aerodynamic chord (MAC), see the balance envelope for a Boeing 747-40 in the appendices (A*ppendix B*). During the flight the weight of the plane decreases due to the consumption of fuel. An accurate calculation of the airplane's weight and center of gravity ensures that the certified weight and center of gravity are not exceeded. It also ensures that loading limitations are not exceeded and the structural integrity of the aircraft is preserved. Moreover the plane performance is affected by its weight and center of gravity. The more aft the center of gravity is, the less fuel the plane burns. The more forward the center of gravity is, the better the handling qualities are.

3. MAC, %MAC, LEMAC

Those three terms denote distances and position given by manufacturers to make the calculations for the weight and balance problem. They are related to the plane's shape, therefore the aircraft model.

«MAC is the chord of a rectangular wing, which has the same area, aerodynamic force and position of the center of pressure at a given angle of attack as the given wing has. Simply stated, MAC is the width of an equivalent rectangular wing in given conditions (Aviation Glossary). » In this thesis, the length of the MAC is given in inches.

LEMAC defines the leading edge of the mean aerodynamic chord (MAC). It is the more forward limit of the MAC. In this thesis the position of LEMAC is given in inches.

The %Mac defines the position of the center of gravity of an aircraft as the percentage of the distance from the leading edge (LEMAC) of MAC to the center of gravity with respect to MAC itself. It is calculated as: $\%MAC = 100 * \frac{CG_{position} - LEMAC}{MAC}$.

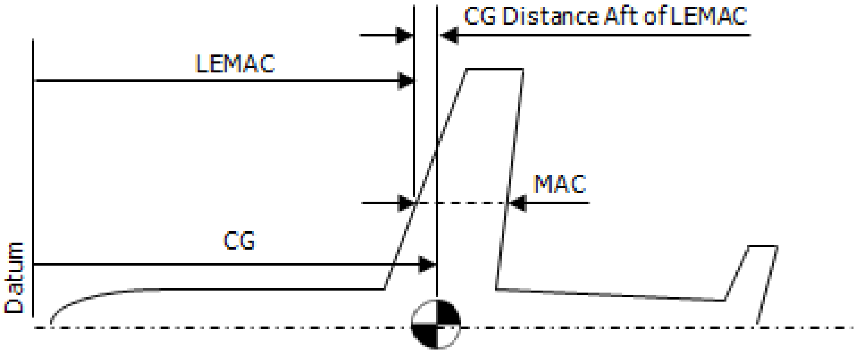


Figure 5 - LEMAC, MAC and %MAC (Monteiro, 2012)

4. Performance of flight and center of gravity

Those simple graphics from D. Anderson (Anderson, 2006) explain basically why an aft center of gravity allows better performance. It is because the plane needs a lower lift to counterbalance its weight.

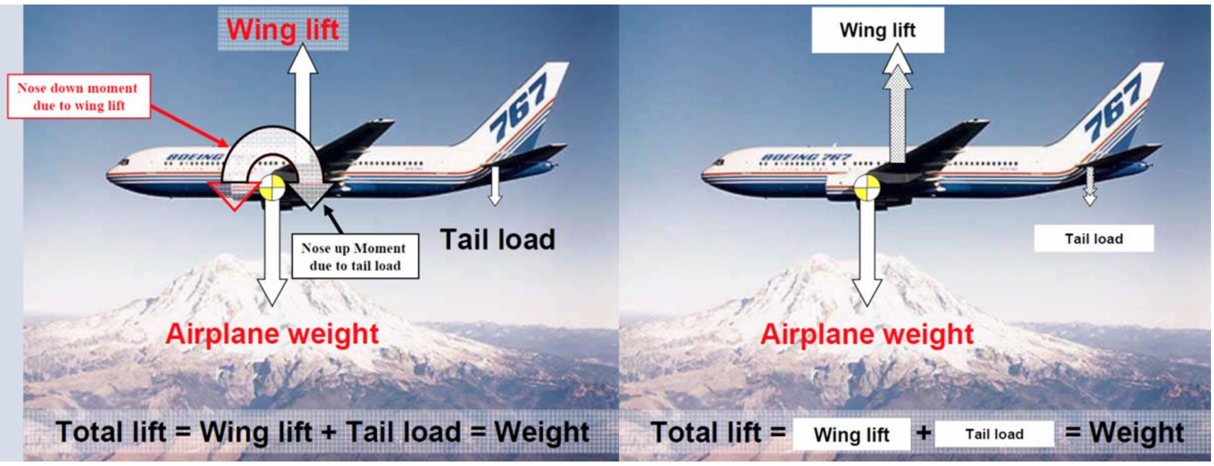


Figure 6 - Effect of the change of the center of gravity on performance (Anderson D. ,2006)

Mathematically it is explained by W.H. Cheung (Cheung, 1997): using the Anderson's fuel consumption model (Anderson J. , 1989), he reduced the equations of motion for an unaccelerated plane in a two-dimensional translational flight (see *Figure 7*) and the relation between Lift (L), Thrust (T) and Weight (W) was reduced to:

$L + T sin(\alpha) = W$

And the relation between Thrust and Drag (D) became:

$T cost(\alpha) = D$

It can be seen that raising the angle of attack (α) permits to sustain a higher weight if Lift (L) and Thrust (T) are constant but also reduces the effect of the Drag on the flight.

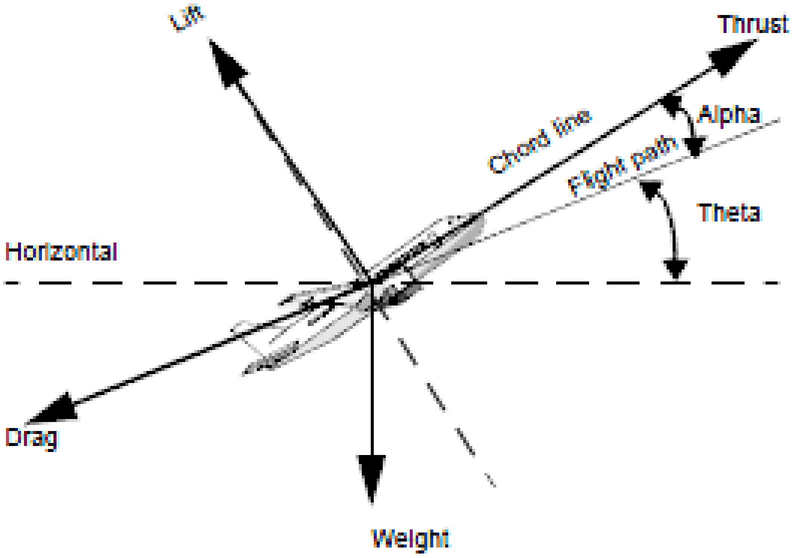


Figure 7 - Forces in action on a plane during a flight (Cheung, 1997)

5. Hazardous goods (hazmats)

Hazardous goods are defined by the U.S. Department of Transportation as materials belonging to one of the nine hazard classes. Hazard classes include solids, liquids and gases that can harm people, property or the environment (Bureau of Transportation Statistics, 2010). Due to their properties, hazmats need to be handled carefully and special regulations from the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) have been applied to air cargo. Hazmats are subjected to weight or quantity limitations but also to positioning limitations. For example radioactive material (class 7) must be separated from animals but also from any other radioactive material.

An explanatory table has been made by ICAO regarding IATA regulations concerning hazardous goods but also other goods which need to be separated from the others without being classified as hazmats, for example animals, food and undeveloped films (see A*ppendix C* for more information).

B. Different models

The problem of loading has been discussed in the literature but the emphasis was first on computer assistance and feasible plans rather than automation and optimal load planning (Mongeau & Bès, 2003). Some works were looking for heuristic solutions to optimize the location of ULDs in an aircraft like Amiouly *et al.* (1992) did with their algorithm called BALANCE:

```
Algorithm BALANCE: packing blocks so that their center of gravity lies close to the target point $p$;

1. Sort the blocks from least dense to most dense;
2. Initialize variables: $p_0 \leftarrow p, M_0 \leftarrow 0$;
3. For $j = 1, 2, \dots, n$ do:
        Place the $j$th block so that its geometric center is as far as possible from
        $p_j \leftarrow p_{j-1} - M_{j-1} / \sum_{i=j}^{n} w_i$ ,
        respecting the placement of previously-loaded blocks. Let $M_j$ be the moment
        about $p_j$ induced by the $j$th block;
```

Their work differs not only because of their heuristic approach but also because of the lack of constraints. Their algorithm only considers the distribution of the shipment in the aircraft without taking into account any structural constraints or hazard restrictions. Moreover their algorithm ensures an accuracy of $\left(\frac{1}{2}\right) l_{max}$ with l_{max} the length of the longest block to be packed when an optimal solution exists. Notwithstanding other considerations like the fact it does not take into account constraints and it is made for a one row shipment only, it does not seem usable by loadmasters because of it is not very accurate either. Indeed a block, therefore a ULD, can have a length of 96 inches. For a Boeing 747-400 the length of the MAC is 327.79 inches therefore an accuracy of $\frac{96}{2} = 48$ inches represents an interval of error of

$\frac{48}{327.79}$ =14.6% on the MAC which is not enough to solve the weight and balance problem efficiently.

Mongeau and Bès (2003) and Verstichel *et al.* (2011) made closer works to the Limbourg *et al.* (2012) model. Both proposed exact methods through integer linear programming while taking into account the structural constraints of aircrafts. But their objective differed from the reference model observed here as Mongeau and Bès (2003) focused on which ULDs should be loaded and which ULDs should be left on the ground maximizing the mass of goods transported, and Verstichel *et al.* (2011) introduced the same goal, choosing which ULDs to load, but maximizing the total cargo value and not the mass of goods loaded. Moreover their works implied fully loaded airfreights despite the fact that there are often fewer ULDs to load than the aircraft capacity (Limbourg *et al.*, 2012, basing their reflection on IATA, 2010). The work presented in this thesis left this selection phase to the airline and its commercial department which would choose the ULDs to load depending on its own interests as it is usually done. Indeed, as reported by Limbourg *et al.* (2012), the current process is in two steps: the commercial department selects the ULDs to load and then send a list to the loadmaster who will then optimize the loading. Moreover the model from Limbourg *et al.* (2012) optimizes the distribution for a set of ULDs even if they do not reach the full cargo capacity of the plane. This last difference with other models implies another way to ensure the ULDs distribution. If the model tries to minimize the center of gravity around a point and the airfreight is not fully loaded, the ULDs won't be grouped, which is required for loadmasters' ease (Limbourg *et al*, 2012). To tackle this issue the model minimizes the moment of inertia while putting range constraints for the center of gravity (see the next section *II.C Mathematical model*).

C. Mathematical model (Limbourg *et al.*, 2012)

The mathematical model from Limbourg *et al.* (2012) aims to solve the weight and balance problem by minimizing the moment of inertia and constraining the center of gravity in an interval around a goal value. Unlike models like Mongeau and Bès (2003) or Verstichel *et al.* (2011), its purpose is to solve the problem for any shipment, even if the aircraft is not fully loaded. If Limbourg *et al.* (2012) minimized the center of gravity instead of the moment of inertia, the ULDs would not be grouped in most cases and this is required by loadmasters for loading facilities. Whereas minimizing the moment of inertia is minimizing $\sum_{i=1}^{n} m_i r_i^2$, this tends to minimize in priority the distance from ULDs to a given center (see *Figure 8* and *9*).

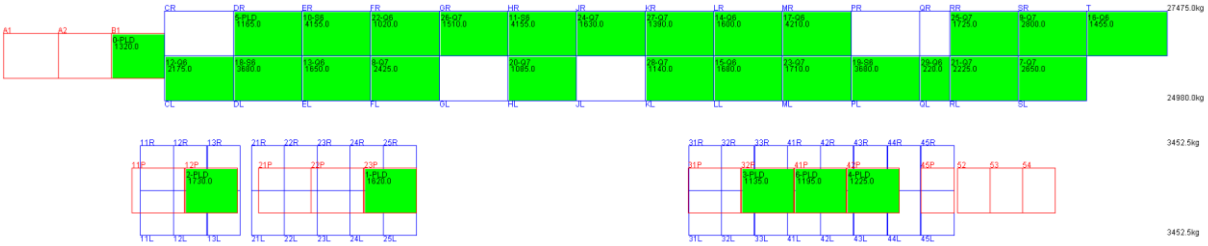


Figure 8 - Distribution obtained with OPAL while minimizing the center of gravity

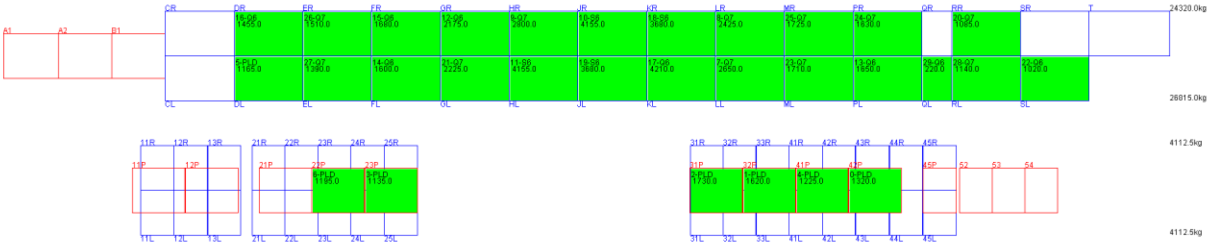


Figure 9 - Distribution obtained with OPAL while minimizing the moment of inertia

The model works with of a set $\mathbb{U}$ of i ULDs with a weight w_i to load into a compartmentalized cargo with a set $\mathbb{p}$ of predefined positions (P_j), including a set P_R of positions on the right side of the plane and a set P_L of positions on the left side. The longitudinal location of each position P_j is expressed in inches from a virtual given point called Index Datum (ID). As the model considers each ULD weight to be uniformly distributed along its length, the center of gravity for each ULD is positioned in the center of its surface and therefore the distance to be taken into account from the Datum corresponds to the central arm value a_j of each position where the ULD weight will be concentrated. W denotes the total weight of the load ($W = \sum_{i \in \mathbb{U}} w_i$) while L denotes the total length of the airfreight in inches.

1. Objective function

Minimize $\sum_{i \in \mathbb{U}} \sum_{j \in \mathbb{p}} w_i \left(a_j - ID\right)^2 x_{ij} + L^2 W y$

The first part of the objective function is the minimization of the moment of inertia, $\sum_{i=1}^{n} m_i r_i^2$, considering $a_j - ID$ the distance between the center of the ULD to the Index Datum ID.

The term L^2Wy is related to the cumulative aft constraint. It permits to minimize the number of $y = 1$; so, if possible, the result takes into account the restricted limit which is enabled when $y = 0$ (see *II.C.2 Constraints - Restricted aft body cumulative load limit (11) (12)*).

2. Constraints

- Allowable position of ULDs

x_{ij} represents the Boolean variable allocating i in j, $x_{ij} = 1$ if the ULD i is in the position j and $x_{ij} = 0$ if the ULD i is in the position j:

$$x_{ij} \in \{0; 1\} \qquad \forall i \in \mathbb{U}, \forall j \in \mathbb{p} \tag{1}$$

As seen in the introduction, there are different types of ULDs which can only go in specific positions of an aircraft, i.e. each position accepts only some ULD types:

$$x_{ij} = 0 \qquad \forall i \in \mathbb{U},\ \forall j \in \mathbb{p} | U_i \text{ does not fit in } P_j \tag{2}$$

The model has to ensure we can have only one ULD per location:

$$\sum_{i \in \mathbb{U}} x_{ij} \leq 1 \qquad \forall j \in \mathbb{p} \tag{3}$$

Some ULDs are larger than standards and take more than one position. When a ULD is loaded in such a position the underlying positions cannot be allocated to other ULDs. $\mathbb{O}_j$ denotes the set of position indices underlying position P_j:

$$x_{ij} + x_{i'j'} \leq 1 \qquad \forall i, i' \in \mathbb{U}, \forall j \in \mathbb{p}, \forall j' \in \mathbb{O}_j \tag{4}$$

The model ensures that every ULDs in the list given to the loadmaster are put in the airfreight:

$$\sum_{j \in \mathbb{p}} x_{ij} = 1 \qquad \forall i \in \mathbb{U} \tag{5}$$

- Center of gravity

As the model minimizes the moment of inertia it is unlikely it is going to reach the exact targeted center of gravity, therefore it adds an interval constraints allowing a very small deviation ε from ID:

$$-\varepsilon \le \sum_{i\in\mathbb{U}}\sum_{j\in\mathbb{p}} \frac{w_i(a_j - ID)x_{ij}}{W} \le \varepsilon \qquad (6)$$

In the methodology it is explained that minimizing the moment of inertia or allowing a small deviation relative to the Index Datum is a small unnecessary simplification but without repercussions on the result (see *III.A.5 Minimizing the moment of inertia while minimizing the center of gravity by a change of target for the moment of inertia*).

- Lateral balance

The lateral balance is an important point for flight security and performances. The model ensures that both sides of the plane are balanced. As with the center of gravity, the model has an interval constraint. $\overline{D}$, the threshold:

$$-\overline{D} \le \sum_{i\in\mathbb{U}} w_i\left(\sum_{j\in\mathbb{p}_R} x_{ij} - \sum_{\mathbb{p}_R} x_{ij}\right) \le \overline{D} \qquad (7)$$

- Combined load limits

Due to its structure, the different sections of the plane have particular weight limits (see *Appendix A*). O_k^D denotes the k^th^ area for the deck D, the maximum weight for area O_k^D, $\overline{O}_k^D$, is computed beforehand and o_{ijk}^D represents the proportion of w_i falling in $\{O_k^D \cap P_j\}$.

$$\sum_{i\in\mathbb{U}}\sum_{j\in\mathbb{p}|P_j\cap O_k^D\neq\emptyset} x_{ij}o_{ijk}^D \le \overline{O}_k^D \qquad \forall D \in \mathbb{D}, \forall k \in \mathbb{O}^D \qquad (8)$$

- Cumulative load limits

The cumulative load constraint defines linear limit functions over continuous parts of the aircraft. The issue is split into two parts. F_k (resp. T_k) denotes the consecutive forward (resp. aft) areas and $\overline{F}_k$ (resp. $\overline{T}_k$) the cumulative allowable weight for the section. f_{ijk} (resp. t_{ijk}) is the variable representing the proportion of w_i falling in $\{F_k \cap P_j\}$ (resp. $\{T_k \cap P_j\}$).

From the nose to the center of the plane:

$$\sum_{i\in\mathbb{U}}\sum_{j\in\mathbb{p}|P_j\cap\bigcup_{c=1}^{k}F_c\neq\emptyset}\sum_{l=1}^{k} x_{ij}f_{ijl} \le \overline{F}_k \qquad \forall k \in \mathbb{F} \qquad (9)$$

From the tail to the center of the plane:

$$\sum_{i\in\mathbb{U}}\sum_{j\in\mathbb{P}|P_j\cap\bigcup_{c=1}^{k}T_c\neq\emptyset}\sum_{l=1}^{k}x_{ij}t_{ijl}\leq\overline{T}_k \qquad \forall k\in\mathbb{T} \qquad (10)$$

These limit functions are given in the weight and balance manual (Boeing; Cargolux Airlines) ant they represent the maximum vertical weight for shipments loaded in an aircraft, which means the weight of ULDs is summed vertically for each section and cannot exceed the limit functions.

- Restricted aft body cumulative load limit

Even if the plane can take off with all other constraints respected, it is better to load the aft section under a more restrictive limit than the former cumulative load limits for the aft part (Boeing; Cargolux Airlines). Basically the constraint is similar with the new limit values $\overline{R}_k\leq\overline{T}_k$.This constraint is not mandatory for the model. Therefore it should be used only if it does not make the problem infeasible. y is a Boolean variable expressing whether or not the constraint is applied. If it is not applied $y=1$ and the constraint is enforced on true for every situation by increasing the weight limit $\overline{R}_k$ by a large unreachable value (the total weight of the shipment W):

$$y\in\{0,1\} \qquad (11)$$

$$\sum_{i\in\mathbb{U}}\sum_{j\in\mathbb{P}|P_j\cap\bigcup_{c=1}^{k}T_c\neq\emptyset}\sum_{l=1}^{k}x_{ij}t_{ijl}-Wy\leq\overline{R}_k \qquad \forall k\in\mathbb{T} \qquad (12)$$

D. OPAL

Opal is the software developed by Limbourg *et al.* (2012) to solve the weight and balance problem according to their own mathematical model. It does not differ much from the mathematical model except it locates the center of gravity as a percentage of the MAC. One of its main assets is the fact ULDs and airfreight characteristics are loaded from a possible external file. As explained, envelope and limits differ from plane to plane. The software can handle multiple aircrafts by reading their characteristics, which have previously been entered. Therefore it is adaptable to most airfreights on the condition that the characteristics have already been entered. If not, the characteristics of a plane can easily be added as following the example from the few planes already integrated in the software. For ULDs it is the same principle: the software reads the characteristics of ULDs stocked in a file and treats them. Thanks to this system, the data are not directly linked with the software and they could be loaded from an external source if needed. For example an economic department could directly give the ULDs characteristics' file to a loadmaster for loading it in the software. Another advantage is that loadmasters can still change ULDs position manually by moving ULDs on the plane. For example they can position some ULDs for which they have specific requirements and let the program optimize the distribution of the remaining ULDs. It also handles hazardous goods thanks to an addition from Kleyntssens *et al.* (2012) which incorporated the IATA dangerous goods regulation in OPAL.

Here is the view of the software as used during this thesis. *Figure 10* is the first view after having chosen the plane model (here a Being 747-400) and the ULDs to load. *Figure 11* is the result obtained after having started OPAL.

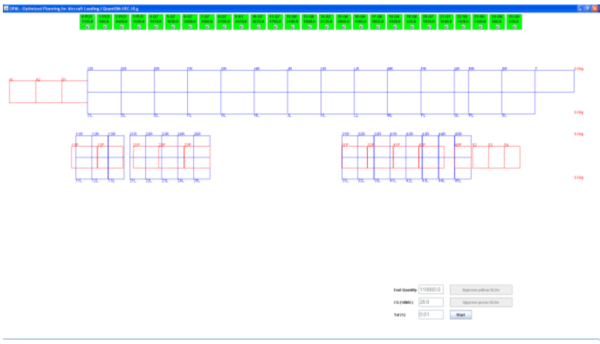


Figure 10 - Screenplay of OPAL before compilating

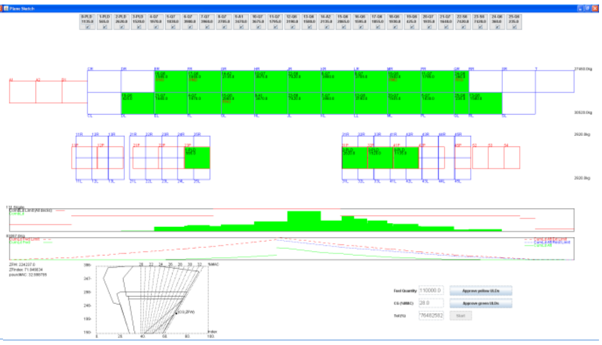


Figure 11 - Screenplay of OPAL with the result

While this thesis was done, OPAL evolved and a new version can be found on the website of QuantOM. It incorporates more constraints and options but also has a more advanced design for a better end-user experience (QuantOM, 2012).

E. Fuel consumption

The researches in the field of fuel consumption did not reach strong results for the effect of the center of gravity on fuel savings. As it is explained in this chapter, results observed in the literature cannot be taken as granted because they are not well documented.

The literature used for this thesis is silent about studies on the link between fuel consumption and a change of the center of gravity. However the majority of the papers dealing with the weight and balance problem often put into the balance a save of fuel against handling quality, it is hard to find relevant information about the current effect on fuel saving if the center of gravity is changed. And when some data are obtained, the literature never tells how such data have been reached.

In getting to grips with fuel economy (Airbus, 2004), some numbers relative to both fuel economy and increase of range due to a modification of the center of gravity are given. Here is the change of range regarding the center of gravity. The reference (aft) center of gravity is 27% for A300 and A310 and the reference center of gravity is 28% for A330 and A340.

	Range	
Aircraft Type	Aft CG (35 or 37%)	Fwd CG (20%)
A300-600	+1.7% (35%)	-0.9%
A310	+1.8% (35%)	-1.8%
A330	+0.5% (37%)	-1.3%
A340	+0.6% (37%)	-0.9%

Table 1 - Range improvement relative to a change of the center of gravity (Airbus, 2004)

If the range increases of 1% with the same amount of fuel, it is expected that for the same range, the fuel consumption should be more or less of 0.99% (1/1.01). As numbers are small, the expected fuel saving is approximately equal to the gain of range (for example, $1 - \frac{1}{1+0.017} = 0.01671583$, round to 0.017, 1.7%).

	Expected full saving*	
Aircraft Type	Aft CG (35-37%)	Fwd CG (20%)
A300-600	+1.7%	-0.9%
A310	+1.8%	-1.8%
A330	+0.5%	-1.3%
A340	+0.6%	-0.9%

Table 2 - Fuel saving estimated from Airbus' data (Table 1)

This indirect measurement of fuel saving regarding the center of gravity position gives some ideas on what could be the gain or loss regarding fuel consumption. Further reports and data are presented in other documents to permit a discussion on this topic.

In Fuel Saving: Contributing to a sustainable air transport development (ATR, 2011), ATR aircraft shared an experience about fuel saving: a trip of 300Nm (about 555.6 km) with an ATR 72-500. Cruise FL is the cruise flight level (altitude).

Flight conditions	Airline Policy	Trip fuel (kg)	Delta (kg)	Delta (%)	Trip time	Delta (min)	Cruise FL
Aft balance (34% of the MAC)	Mini time	897	-2	-0.2	1h15	0	180
	Mini fuel	821	-5	-0.6	1h20	0	230
Forward balance (17% of the MAC)	Mini time	901	2	0.2	1h15	0	180
	Mini fuel	831	5	0.6	1h20	0	230

Table 3 - ATR experiences results (ATR, 2011)

The delta is computed regarding results for the same flight with a reference center of gravity at 25%. It can be seen that the difference between the most forward and the most aft center of gravity is about 1.2% when trying to minimize the consumption.

In Introduction to Weight and Balance, D. Anderson (2006) shows the estimated fuel savings resulting from a movement of the center of gravity aft by 5% on the MAC, for Boeing aircrafts.

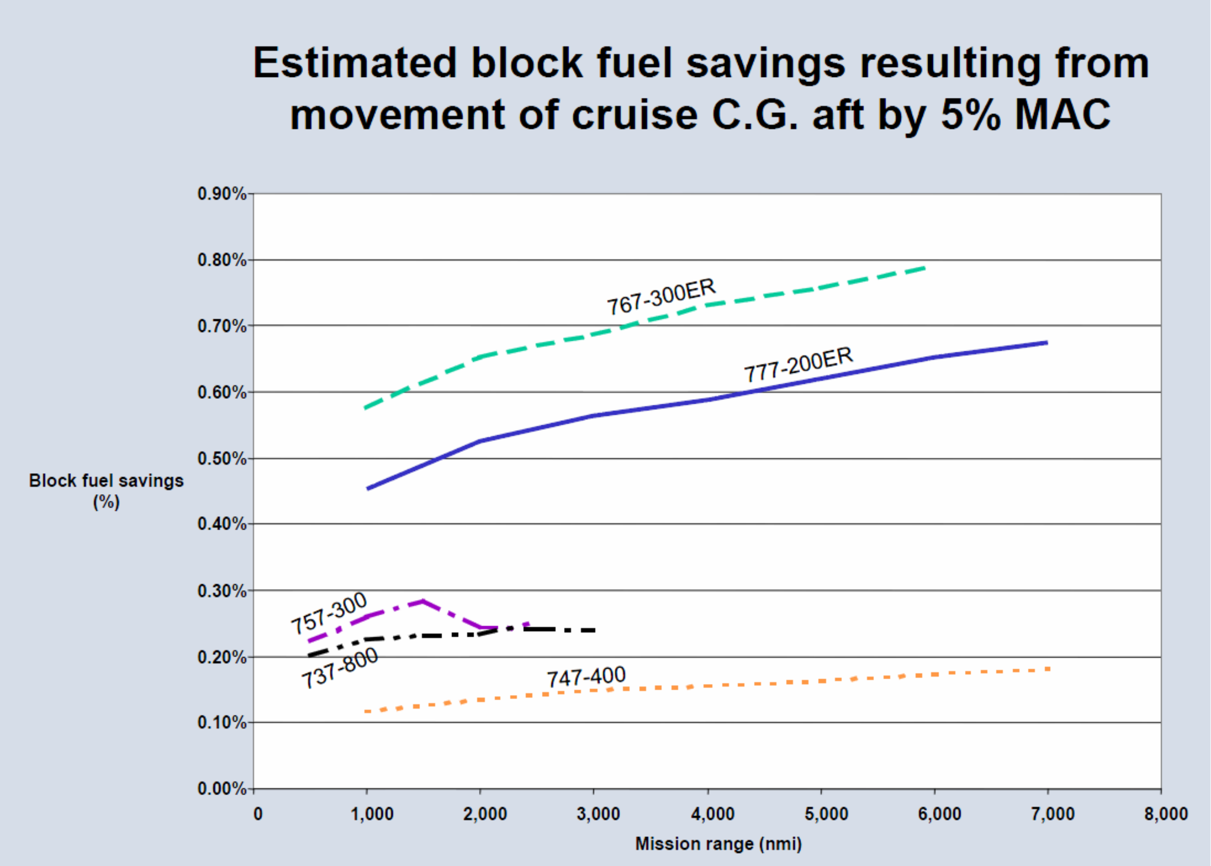
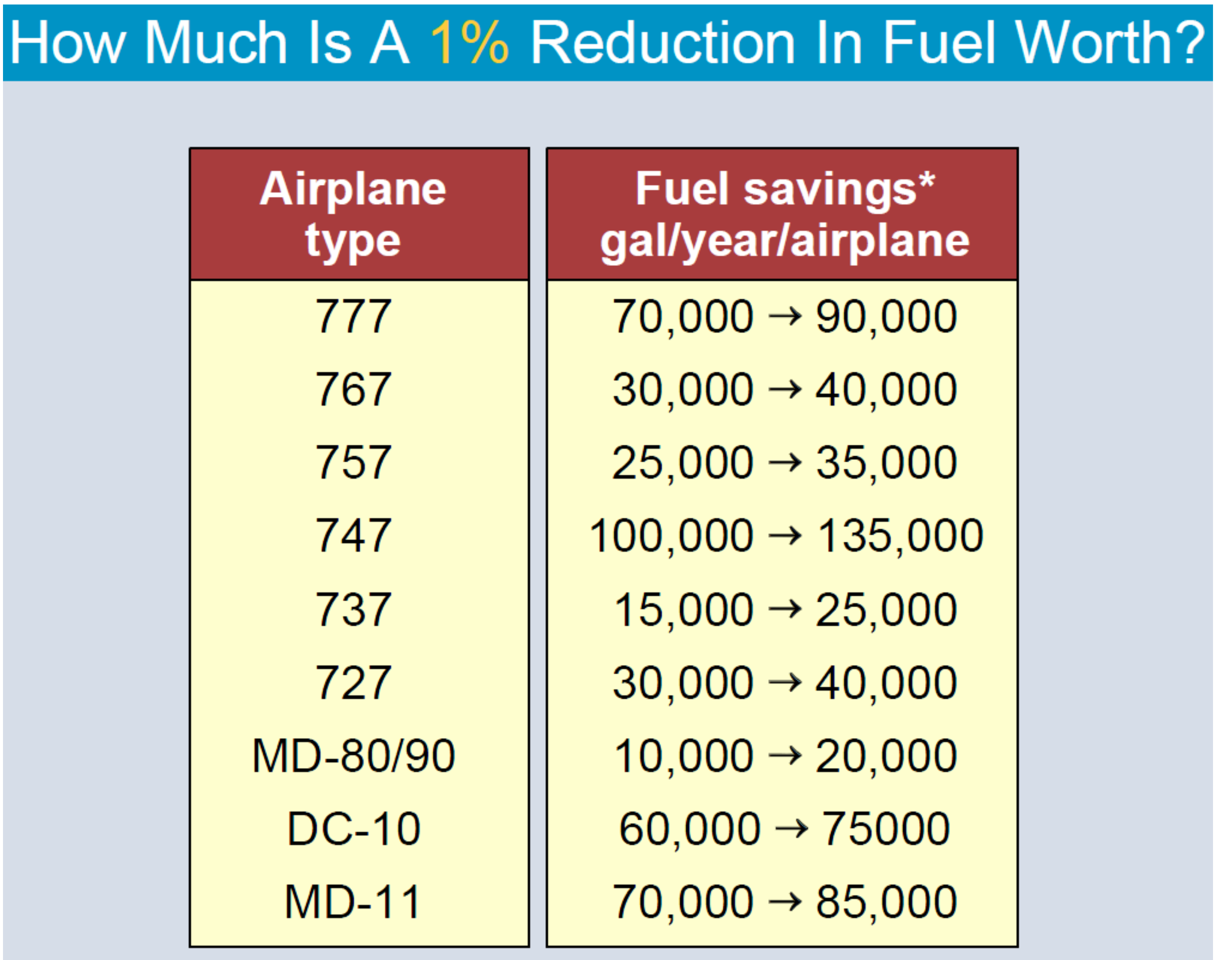


Figure 12 - Estimated fuel savings from a movement of the center of gravity (Anderson D. , 2006)

In Fuel Conservation, D. Anderson (2008) gives an estimation of the fuel savings in gallon per plane and per year (1 gallon = 3.75 liters) for typical airplane use, when each flight reduces its consumption of fuel by 1%.



How Much Is A 1% Reduction In Fuel Worth?

Airplane type	Fuel savings* gal/year/airplane
777	70,000 → 90,000
767	30,000 → 40,000
757	25,000 → 35,000
747	100,000 → 135,000
737	15,000 → 25,000
727	30,000 → 40,000
MD-80/90	10,000 → 20,000
DC-10	60,000 → 75000
MD-11	70,000 → 85,000

Figure 13 - Fuel savings in gallons per year per plane model for a fuel consumption reduction of 1% (Anderson D. , 2008)

In both its presentations, Introduction to Weight and Balance and Fuel Conservation, D. Anderson didn’t give clues about how he got these results.

To sum up, the literature teaches us that calculating the fuel saving resulting from a move of the center of gravity is a nearly non-discussed topic where it is hard to get reliable information and no formula has been given by manufacturers. As pointed out by W.H. Cheung (1997) it could be because the information required to determine fuel consumption is usually considered proprietary by most aircraft production companies and cannot be obtained from them. The most interesting point highlighted is the fact there are quite important differences between aircrafts for fuel saving regarding a change of the center of gravity. So economies through a change of the center of gravity highly depend on the type of aircraft.

Chapter III. Methodology

This project research has two goals; the first one is to incorporate and modify constraints for the software developed by Limbourg *et al.* (2012). The second one is to determine what the cost saving impact of this software could be for air cargo companies.

In the first part of the methodology, the focus is on the implementations of and modifications to the Limbourg *et al.* (2012) model and software. In the second part, the literature about fuel economies is reviewed and criticized to get an overall idea on the subject and determine which data are reliable because sources are not clear enough to take the information for granted.

A. Program development

Limbourg *et al.* (2012) are working on an integer linear programming model for the aircraft load planning model (see *II.C Mathematical model*). They developed OPAL software, using the CPLEX integer linear programming solver to reach the solution of their model. This project research implements compartments total weight constraints, tests the possibility of a vertical constraint, allows the software to reach the most aft result and redefines the objective function to minimize the center of gravity while minimizing the moment of inertia.

1. Framework

The software is based on the mixed programming model from Limbourg *et al.* (2012). It is developed on the Eclipse platform in JAVA for data manipulations and it uses the professional optimization library IBM ILOG CPLEX to run the optimization model. It also uses a library for graphics in 2d, the jlibeps library, but within the content of this project the graphical aspect of the software has not been altered.

2. Compartments total weight constraints

As seen in the introduction (see *I.A Presentation* and *Appendix A*), an airfreight is divided in compartments with various limits. The combined load limits: $\sum_{i\in\mathbb{U}}\sum_{j\in\mathbb{p}|P_j\cap O_k^D\neq\emptyset} x_{ij}o_{ijk}^D \leq \overline{O}_k^D$, $\forall D \in \mathbb{D}, \forall k \in \mathbb{O}^D$ (see *II.C.2 Constraints – Combined load limits (8)*), specifies that the maximum weight for area O_k^D, $\overline{O}_k^D$, so a compartment, is computed beforehand. The problem is split into two constraints in the software, one for the constraint of floor loading given in kg/inch, and the other is implemented by this thesis, the total maximal weight of the compartment. If $\overline{F}_k^D$ is the maximum weight regarding floor loading for area O_k^D and $\overline{C}_k^D$ is the maximum weight defined by the airfreight's manual for area O_k^D, then we should always have the relation $\overline{C}_k^D \leq \overline{F}_k^D$. It is verified for the 747-400 used as default plane to make the software.

The implementation of this constraint has been made on the same model as the combined load limits algorithm already in the software by adding new plane characteristics and new data to the aircraft. In the software compartment data are presented as follow: the first data specifies the deck, the following first and second numbers represent the position of the compartment and the last number is the total weight limit of the compartment.

```
Main;228;525;11450
Main;525;1000;36627
Main;1000;1480;63140
Main;1480;2218;56907
Main;2218;2365;2041
Lower;464;987;27669
Lower;1484;1980;26081
Lower;1980.00;2040.00;1905
Lower;2040.00;2100.00;1469
Lower;2100.00;2160.00;1034
```

The algorithm adding the compartment constraints is based on four loops. It checks all positions each ULD can take in all compartments on every deck. Similarly to the combined load limits, a constraint is added to the solver CPLEX for each compartment:

$$\sum_{i \in \mathbb{U}} \sum_{j \in \mathbb{P} | P_j \cap C_k^D \neq \emptyset} x_{ij} c_{ijk}^D \leq \overline{C}_k^D \qquad \forall D \in \mathbb{D}, \forall k \in \mathbb{O}^D,$$

C_k^D denotes the kth compartment for the deck D, $\overline{C}_k^D$ the maximum weight for this compartment is given by the aircraft manual and c_{ijk}^D represents the proportion of w_i falling in $\{C_k^D \cap P_j\}$. The algorithm takes into account each ULD which can be put in a compartment thanks to the four loops. Compartments are checked one after the other and once a couple ULD / position is identified to be into that compartment the algorithm adds a line to the solver. The algorithm is designed to handle ULDs which are on two compartments (for example when a ULD is larger than a single position at the beginning or the end of the compartment, or a position is defined as a joint between two compartments). In that case, the algorithm verifies the part of the ULD which is effectively in the compartment to take only into account the portion of w_i falling in $\{C_k^D \cap P_j\}$.

```
System.out.println("Compartment Constraint Starting");
//Loop for decks
for (int deck=1;deck<3;deck++)
{
    //Loop for compartments
    for (int c=0;c<nbCompartment[deck];c++)
    {
        float CompAFT,CompFWT,CompLIM;
        boolean atLeastOne=false;
        CompAFT=compartment[deck][c].getBA_aft();
        CompFWT=compartment[deck][c].getBA_fwt();
        CompLIM=compartment[deck][c].getKgLimit();
        IloLinearNumExpr comp=cplex.linearNumExpr();
        //Check every ULD possible with a loop
        for (i=0;i<NombreULDtoLoad;i++)
        {
            itp=uldtoLoad[i].getPosition2List().iterator();
            int j=0; //allow to give the position of the ULD in the PositionList.
            //Check every feasible position for the ULD with a loop
            while (itp.hasNext())
            {
                        int pos= itp.next();
                        boolean inArea;
                        inArea=false;
                        //For every position the algorithm checks if it is in the compartment
                        //1. Check if it is the good deck
                        if ((deck==1) && (p[pos].getDeck().compareTo("Main Deck")==0))
```

```
{
    inArea=true;
}
    else if ((deck==2) && (p[pos].getDeck().compareTo("Lower
    Deck")==0))
{
    inArea=true;
}
//2. Check if the position is totally in the compartment
if (inArea)
{
    //Position of the ULD between AFT and FWD
        if (p[pos].getBA_aft()<= CompAFT+0.000001 &&
        p[pos].getBA_fwd() >= CompFWT-0.000001)
    {
        comp.addTerm(uldtoLoad[i].getWeight(), x[i][j]);
        atLeastOne=true;
    }
    //Position of the ULD at the crossroads of "FWT"
        else if (p[pos].getBA_aft()>= CompFWT-0.000001 &&
        p[pos].getBA_fwd() <= CompFWT+0.000001)
    {
        comp.addTerm(uldtoLoad[i].getWeight()/
                (p[pos].getBA_aft()-p[pos].getBA_fwd())*
                (p[pos].getBA_aft()-CompFWT), x[i][j]);
    }
    //Position of the ULD at the crossroads of "AFT"
        else if (p[pos].getBA_aft()>= CompAFT-0.000001 &&
            p[pos].getBA_fwd() <= CompAFT+0.000001)
    {
    comp.addTerm(uldtoLoad[i].getWeight()/
            (p[pos].getBA_aft()-p[pos].getBA_fwd())*
            (CompAFT-p[pos].getBA_fwd()), x[i][j]);
```

```
                        }
                    }
                    j++;
                    }
            }
            if (atLeastOne=true)
            {
                    lpmatrix.addRow(cplex.le(comp,CompLIM,"Compartment "+c+" -deck-
                    "+deck));
            }
    }
}
System.out.println("Compartment Constraint Ending");
```

3. Vertical constraint

OPAL already handles the lateral imbalance of the center of gravity, forcing it to stay in a given interval. The vertical constraint has not been explained in the weight and balance manual (Boeing; Cargolux Airlines) therefore after some discussions with S. Limbourg, the decision was made to enforce a vertical equilibrium for the shipment around the wings' height. Sadly the wings' height is not clearly given. Therefore it could only be estimated graphically as a position between the upper and lower deck (see F*igure 14*).

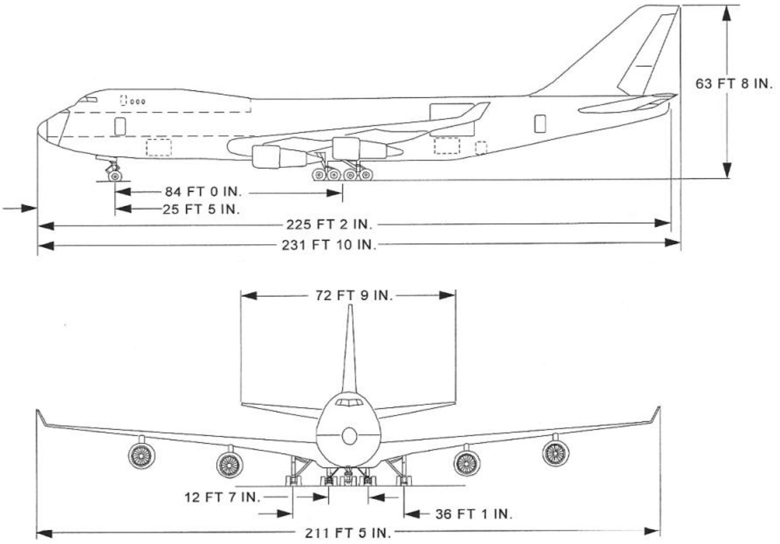


Figure 14 - Aircraft dimensions - Boeing 747-400 (Boeing; Cargolux Airlines)

As no relations have been founded between fuel consumption and the vertical position of the center of gravity, the initial goal for this constraint has been changed ant the new objective is to enforce a distribution on the lower deck. The logic behind this goal is that the vertical position of the center of gravity should influence the roll oscillations (see *Figure 15*). Indeed a lower center of gravity position should make the airfreight more stable. It is a supposition based on ship stability and it has not been studied because it was not the purpose of this study.

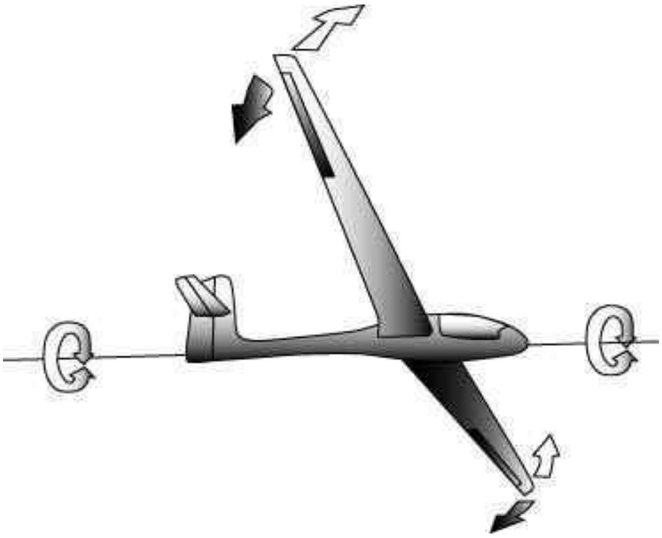


Figure 15 - Roll oscillations (Bories)

A key element for this constraint is the average center of gravity for upper and lower shipments: it cannot be computed because it varies a lot depending on ULDs. Therefore instead of computing a solution thanks to centers of gravity position, the model has been built to enforce a certain percentage of weight on the lower deck. As the goal is to enforce ULDs on the lower deck, the model enforces a percentage of the total weight to be on the lower part.

```
//Vertical constraint
IloLinearNumExpr cHigh = cplex.linearNumExpr();
double limHigh = 0.05; //% of weight on the lower deck
for ( i=0;i<NombreULDtoLoad;i++)
    {
        itp=uldtoLoad[i].getPosition2List().iterator();
        np=0;
        while (itp.hasNext())
         {
             int k= itp.next();
```

```
                if (p[k].getDeck().compareTo("Lower Deck")==0)
                  {
                   cHigh.addTerm((uldtoLoad[i].getWeight()/TotalCargoWeight), x[i][np]);
                   }
                np++;
                }
           System.out.println("cHigh : "+cHigh);
           }
//cHigh >= limHigh
lpmatrix.addRow(cplex.ge(cHigh,limHigh));
```

This model could be changed to have a maximization of the percentage of ULDs by changing the objective constraint and the constant percentage limHigh to a variable the same way the center of gravity was pushed the most aft (see the next section *III.A.4 The most aft center of gravity*). But as it is discussed in a next chapter (see *IV.A Software integration*), the interest for entering this variable is doubtful and it was not entered in the software.

4. The most aft center of gravity

One of the objectives of this thesis is to highlight the relation between the center of gravity and fuel consumption. This small modification of OPAL's code permits to reach the most aft feasible solution. It permits to maximize fuel saving but also to see the degree of improvement available from a given position of the center of gravity to the most fuel efficient one. It has been done by modifying the initially constrained target position. The modification targets the most forward position on the envelope of feasibility, 33% of the MAC for a Boeing 747-400 (see *Appendix B*), and minimizes the interval of error between the result and the target by incorporating it in the objective function minimized by the solver.

Initial software:

```
float constante=(this.getMomentConstant()*(this.getOperatingEmptyIndex()+
                    IndexPassengers+this.getPayloadFuelIndex()-this.getDatumConstant())
                    /ZFW+this.getIndexDatumBA()-this.getLEMAC())*100
                    /this.getMAC()-pourcMACtoReach;
```

```
IloNumVar epsilon = cplex.numVar(0,MACtol,"epsilon");
System.out.println("MACtol: "+MACtol);
obj.setConstant(constante);
System.out.println("Constante: "+constante);
obj.addTerm(-1, epsilon);
lpmatrix.addRow(cplex.le(obj,0,"ObjectifPlus"));

obj.addTerm(2, epsilon);
lpmatrix.addRow(cplex.ge(obj,0,"objectifMoins"));

obj.setConstant(constante);
obj.addTerm(-1, epsilon);
lpmatrix.addRow(cplex.le(obj,0,"ObjectifPlus"));

System.out.println("obj: "+obj);
cplex.addMinimize(inertie);
System.out.println("inertie: "+inertie);
```

Modifications to get the most aft solution:

```
//Maximum %MAC on a Boeing 747-400. It is taken as target.
float maxMAC=33;
float constante=(this.getMomentConstant()*(this.getOperatingEmptyIndex()
                    +IndexPassengers+this.getPayloadFuelIndex()
                    -this.getDatumConstant())/ZFW+this.getIndexDatumBA()
                    -this.getLEMAC())*100/this.getMAC()-maxMAC;

//An interval error of 0 to 5 %MAC is taken because the more the solution is constrained, the less time it takes to compute.
IloNumVar epsilon = cplex.numVar(0,5,"epsilon");
obj.setConstant(constante);
obj.addTerm(2, epsilon);
lpmatrix.addRow(cplex.ge(obj,-0.01,"objectifMoins"));
//The next line was already put in the program as en "option" by Limbourg et al.
```

```
//It enforces the minimum epsilon, so the closest solution from the target.
inertie.addTerm(getLength()*getLength()*TotalCargoWeight, epsilon);
cplex.addMinimize(inertie);
```

5. Minimizing the moment of inertia while minimizing the center of gravity by a change of target for the moment of inertia.

In the optimization model, Limbourg *et al.* (2012) minimized the moment of inertia regarding the Index Datum and treated it as the requested center of gravity: «ID is the index datum value representing the requested CG» (Limbourg *et al.*, 2012, p. 3). It is a misunderstanding because the Index Datum is a given axis serving as reference to compute the center of gravity (see *II.A.1 Measurements in aviation*) but not the center of gravity itself. It is logical because the aim is to choose the best center of gravity possible therefore it has to move in the airplane because of changes in the ULDs distribution. Indeed the moment of inertia I is a measure of an object's resistance to any change in its state of rotation. It is calculated regarding an axis O as $I_o = \sum_{i=1}^{n} m_i r_i^2$, where there are n components of mass m_i situated at distance r_i from the axis O. It is minimal when O coincides with the components' center of gravity. Therefore when Limbourg *et al.* (2012) minimized the moment of inertia around an axis, ID, they made the ULDs distribution around ID and not the requested center of gravity. It is also the case in the software but the interval constraint for the center of gravity $-\varepsilon \leq \sum_{i\in\mathbb{U}} \sum_{j\in\mathbb{P}} \frac{w_i(a_j-ID)x_{ij}}{W} \leq \varepsilon$ is redefined for reaching a given MAC and therefore it enforces a good solution. Correcting this small simplification permits to reach better results when the interval of error (ε) is lowered. The new algorithm looks for the center of gravity, *positionCgCargo*, which is needed by the shipment to get a given MAC, *pourcMACtoReach*, and then it minimizes the moment of inertia regarding this point and not the Index Datum.

Initially, without looking at constraints, the minimization of the moment of inertia on the Index Datum tended to move the shipment's center of gravity position closer to the Index Datum position. However the center of gravity of the plane without shipment is a static position elsewhere. Therefore the combination of both centers of gravity cannot target the given MAC (eventually the given MAC is reached thanks to constraints). The initial software adds up the variation of inertia implied by each ULD regarding the Index Datum to the objective function.

The variation of inertia for each ULD in all its feasible positions is coded as:

```
objvals2[i][np]= uldtoLoad[i].getWeight()*(p[k].getArmPosition()-this.getIndexDatumBA())
                                          *(p[k].getArmPosition()-this.getIndexDatumBA());
```

Then the variation of inertia for each ULD is added up into the objective function:

```
inertie.addTerm(objvals2[i][j], x[i][j]);
```

The moment of inertia is computed as $I_o = \sum_{i=1}^{n} m_i r_i^2$. The variation of inertia represents $m_i r_i^2$ while the objective function is the addition of them $\sum_{i=1}^{n} m_i r_i^2$. Minimizing the objective function is selecting the couples of ULD / position which minimize the moment of inertia regarding the Index Datum while respecting other constraints. With this way of doing the center of the shipment should be near the Index Datum if the interval constraint for the center of gravity would not been applied.

In this thesis the algorithm is changed to minimize the objective function by selecting the couples of ULD / position which are close to position needed to get a given mac, *pourcMACtoReach*, and not the Index Datum. To achieve this goal the algorithm calculates the variation of MAC needed by the entire shipment to move the overall center of gravity (plane + fuel + passengers + shipment) to the position needed to get a given MAC. Even if the center of gravity of the aircraft is not given, the problem is tackled by computing the MAC variation induced by the shipment to get the given MAC. Once the MAC variation is known, the position needed by each ULD for this variation can be computed by asking each couple of ULD / position to target this variation.

The first thing to do is to determining the components of the %MAC computation. The %MAC is constrained by a very small deviation ε (see *II.C.2 Constraints – Center of gravity*), it allows the algorithm to approach the given %MAC, *pourcMACtoReach*, with an interval of error. It is computed with mainly two components, a constant value giving the %MAC calculated as if all the weights of the plane (shipment included) were centered on the axis of reference the Index Datum and the second component is the total variation of %MAC induced by the shipment and also taking the Index Datum as referential axis.

A constant value which represents the %MAC without shipment, ZFW includes the total cargo weight:

```
float constante=        (this.getMomentConstant()*(this.getOperatingEmptyIndex()+
                        IndexPassengers+this.getPayloadFuelIndex()-
                        this.getDatumConstant())/ZFW+this.getIndexDatumBA()-
                        this.getLEMAC())*100/this.getMAC()-pourcMACtoReach;
```

The variation of %MAC for each ULD in all its feasible positions taking axis the Index Datum as reference: $\Delta\%MAC_{i,j} = 100 * \frac{w_i(a_j-ID)x_{ij}}{ZFW*MAC}$

```
objvals[i][np]=         100*uldtoLoad[i].getWeight()*(p[k].getArmPosition()-
                        this.getIndexDatumBA())/(ZFW*this.getMAC());
```

The variation of %MAC for each ULD is added up into the constraint:

```
obj.addTerm(objvals[i][j], x[i][j]);
```

While the constant is set once in the constraint:

```
obj.setConstant(constante);
```

To sum up, the %MAC to reach equals the %MAC of the plane centered on the Index Datum plus the variation $\Delta\%MAC_{i,j}$ induced by each ULD loaded. $needMAC$ denotes the targeted %MAC, $datumMAC$ the %MAC of the plane centered on ID and $cargoMAC$ the variation of %MAC induced by the total shipment.

$$needMAC = datumMAC + cargoMAC$$

$$cargoMAC = \sum_{i\in\mathbb{U}}\sum_{j\in\mathbb{p}}\Delta\%MAC_{i,j} = \sum_{i\in\mathbb{U}}\sum_{j\in\mathbb{p}} 100 * \frac{w_i(a_j-ID)x_{ij}}{ZFW*MAC}$$

$needMAC$ is given as it is equal to *pourcMACtoReach* and $datumMAC$ is equal to the constant value. Therefore $cargoMAC$ is known and equals $needMAC - datumMAC$. This value is used to compute the center position for the distribution of ULDs. To reach $cargoMAC$, the moment of inertia is minimized regarding the position an average ULD would take to get this $cargoMAC$ on its own. Indeed if the distribution around this position is equal, the sum of the variations $\Delta\%MAC_{i,j}$ for each ULD would be $cargoMAC$. The problem to get the target position is that each ULD is unique.Therefore a simple simplification has been done: considering the mean weight for ULDs as: $W = \frac{\sum_{i=1}^{n} w_i}{n}$ for n ULDs, the position can be computed after some manipulations as $positionCgCargo = \frac{cargoMAC*ZFW*MAC}{100*W} + ID$. Indeed minimizing the center of inertia on that point tends to group closer ULDs to this position and to take it as center of gravity for the whole shipment due to the fact the minimum moment of inertia is when its axis coincide with the center of gravity of its components (see). But more importantly for the software, it means each ULD tends to get the $cargoMAC$ by itself. Due to the distribution, some ULDs get a higher or lower $\Delta\%MAC_{i,j}$. The average result tends to the $cargoMAC$.

In the software all these computations are made with this code:

```
float needMAC=pourcMACtoReach;
/*datumMAC is the %MAC calculated by the constant in which the pourcMACtoReach is
substracted.*/
float datumMAC=     (this.getMomentConstant()*(this.getOperatingEmptyIndex()+
                    IndexPassengers+this.getPayloadFuelIndex()-
                    this.getDatumConstant())/ZFW+this.getIndexDatumBA()-
                    this.getLEMAC())*100/this.getMAC();
float cargoMAC=needMAC-datumMAC;
/*positionCgCargo is the position of the center of gravity for the whole shipment which
induces cargoMAC.*/

float positionCgCargo=      ((cargoMAC*ZFW*this.getMAC())/
                            (100*(TotalCargoWeight)/NombreULDtoLoad))+this.getIndex
                            DatumBA();
```

And the variation of %MAC for each ULD in all its feasible positions takes in this project research $positionCgCargo$ as referential axis:

```
objvals2[i][np]=    uldtoLoad[i].getWeight()*(p[k].getArmPosition()-
                    positionCgCargo)*(p[k].getArmPosition()-positionCgCargo);
```

B. Fuel

As seen previously (see *II.E Fuel consumption*), the literature is not really accurate about fuel consumption correlated with a change of the center of gravity. As it is said in the next chapter (see the next section *III.B.1 No formula*), no formula has been found in the literature joining the fuel consumption or the need of energy of a plane with its center of gravity. Instead there are numbers and graphics given without any satisfactory explanation and in this part the aim is to understand why there are no formulae and if the numbers and graphics found in the literature can be used to determine the fuel economies related to changes of the center of gravity. To answer these questions, the main sources for this part are:

1. The thesis from Cheung (1997) where he explains the Consumption Model from Collins (1982).
2. A tool for Loadmasters at Cargolux: they use an Excel loading sheet where the fuel saving resulting from a movement of the center of gravity for a Boeing 747-400 is calculated.
3. An interview with the TNT performance manager at Liege Airport, Jean-Marc Urbani.

1. No formula

At the beginning of this thesis, the belief was that it could be possible to cross the Limbourg *et al.* (2012) software with a fuel consumption model or formula, allowing the direct computing of the benefice from a good optimization. After reviewing the literature it turned out to be impossible with the knowledge shared by aircraft manufacturers. Indeed the Fuel Consumption Model (Collins, 1982, explained by Cheung, 1997, p. 18-24) does not incorporate the center of gravity as parameter. Moreover, «the information required to determine these coefficients are usually considered proprietary by most aircraft production companies and cannot be obtained from them. Instead, flight testing and wind tunnel testing are used as sources of information» (Cheung, 1997, p. 10). Therefore the consumption model is impractical for this project research.

2. Observation of Cargolux loadmaster Excel sheets

Cargolux uses Excel to compute its load sheets. It is presented as a multiple sheets file where the loadmaster has to specify the ULDs positions and characteristics, the fuel and other information needed to handle the weight and balance problem. Once the needed data are entered, Excel computes the %MAC, the take-off weight, the landing weight and verifies if everything is correct. Moreover Cargolux added an estimation of the fuel saved thanks to the center of gravity's position, taking as reference a center of gravity at 28% of the MAC.

For a Boeing 747-400 with $CG_{target} = 28$, the referential center of gravity, $CG_{original}$ represents the center of gravity computed by Cargolux, the percentage of fuel saving related to the longitudinal position of the center of gravity is given by:

$$\frac{\left(CG_{target} * (0.17007867 - (0.002476898 * CG_{target}))\right) - \left(CG_{original} * (0.17007867 - (0.002476898 * CG_{original}))\right)}{100}$$

The next graphic represents this formula without the division by 100. The axis y represents the percentage of fuel saving multiplied by 100 (i.e.: 0.1 is 0.001% of fuel saving) and the axis x represents the position %MAC of the center of gravity.

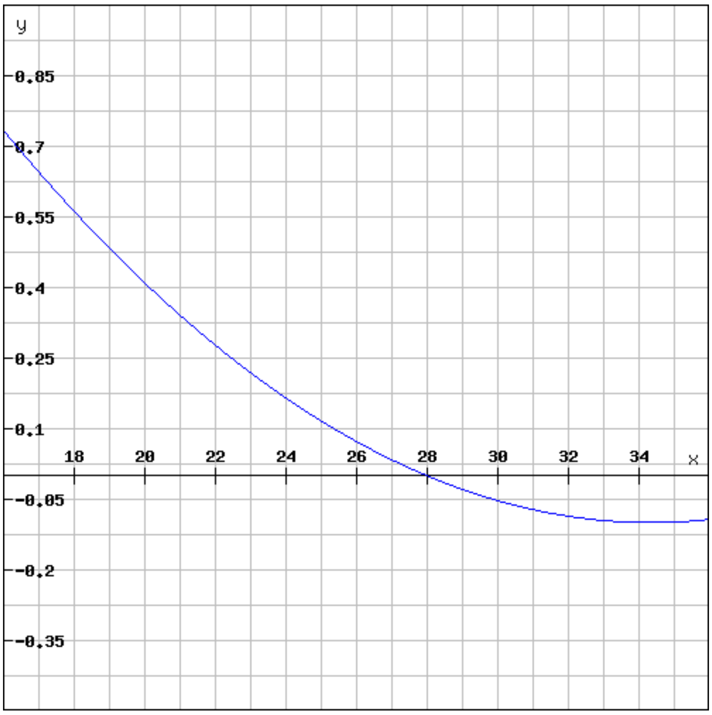


Figure 16 - Fuel saving function relative to the center of gravity's position – Cargolux (axis y : fuel saving in 1/10000 ; axis x : %MAC position of the center of gravity)

The result from Cargolux is a lot more pessimistic than what the literature lets expect. The details of the formula are not explicit and furthermore after questioning the person who shared this Excel sheet, it seems no one knows how it was computed and they do not even use it. This result has also been discussed with S. Limbourg, M. Schyns and J-M. Urbani, and none of them gave it strong credits.

3. Interview with a performance manager at TNT Bierset

As the two later sources did not help a lot for this project research, a last attempt was made by interviewing a professional, mister J-M. Urbani, who is responsible for performance at TNT Liège Bierset. He pointed out a few points:

The gain or loss related to a change of the center of gravity is mainly due to the change of the drag related to this center of gravity (see *Figure 12* and *17*) and he confirmed implicitly that the graphics from Introduction to Weight and Balance (D. Anderson, 2006) were right as he showed the same graphics from his data shared by Boeing.

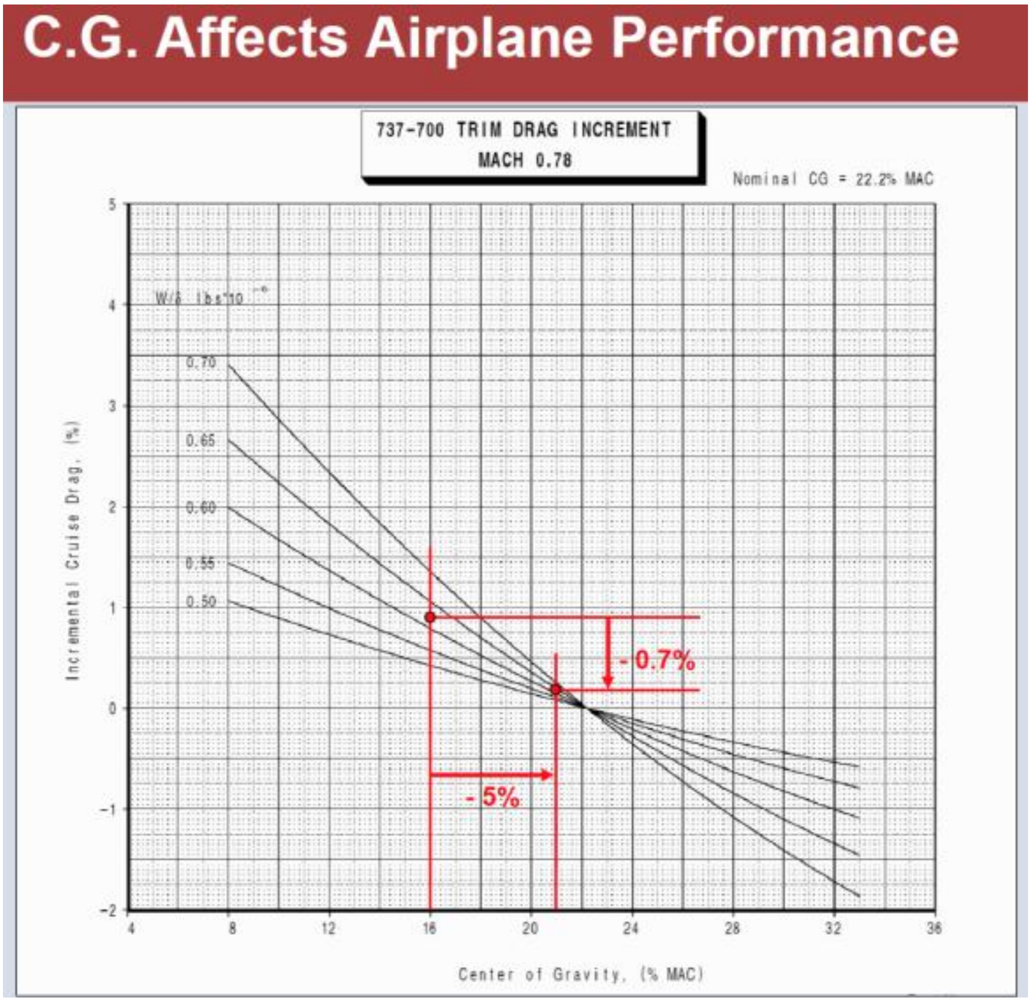


Figure 17 - Drag induced by the position of the center of gravity (Anderson D. , 2006)

Sadly the link between drag and fuel saving has not been explained and mister Urbani did not know how those graphs were computed or the functions behind them.

Secondly he affirmed that anywhere in the MAC, the change in handling of the plane does not change significantly. Therefore the center of gravity should always be the most aft possible, respecting the constraints.

The last important point relative to the center of gravity discussed during this interview was the fact flights are calculated taking into account a standard center of gravity which is situated at 20% of the MAC, at TNT, for a Boeing 747-400. It means that even if the real center of gravity is more aft, the flight is calculated for a center of gravity more forward and therefore the plane takes more fuel and the Cruise FL (flight level) differs from the optimal one regarding the real center of gravity. All these miscalculations lead to less fuel saving than what could effectively be done.

C. Carbon dioxide emission

Another interest for this thesis is linking the fuel saving with the carbon dioxide emission saving (CO_2). Carbon dioxide emission is a worldwide pollution problem and lots of states have signed agreements to reduce their CO_2 emissions. Europe is taking it seriously as it has fixed a goal of -20% of emissions by 2020 (European commission). To fulfill these goals the legislation has become more and more aggressive towards pollution and the transport industry has not been exempted from taxes. Economically there are two things to take into account for airline companies regarding carbon dioxide: The emission of CO_2 per consumption of fuel and the price of CO_2 emission taxes according to the law.

1. Emission of CO_2 per consumption of fuel

The emission of CO_2 depends on the fuel used in the airplane. Most commercial airplanes use fuel based on kerosene. According to ICAO Carbon emissions Calculator (ICAO, 2010), one ton of aviation fuel produces 3.157 tons of CO_2. Which seems correct as aviation fuel is based on kerosene and according to Wikipedia, Kerozen is a mixture of hydrocarbons containing alkanes (C_nH_{2n+2}) with chemical formulas going from $C_{10}H_{22}$ to $C_{14}H_{30}$. On average:

$$C_{12}H_{26} + \frac{37}{2}O_2 \rightarrow 12CO_2 + 13H_2O$$

1 mole of kerosene ($C_{12}H_{26}$) = 12*12+26*1 = 170g

1 mole of carbon dioxide (CO_2) = 12+2*16 = 44g ➔ 12 moles = 12*44 = 528g

Therefore 1 ton of kerosene produces on average: 528/170 = 3.11 tons of carbon dioxide. Depending on the fuel used, the law fixes an emission factor which will be used to calculate CO_2emissions (see the next section *III.C.2 European carbon tax*).

2. European carbon tax

In Europe the European carbon tax was implemented on 01/01/2012. According to directive 2008/101/EC of the European parliament and of the council of 19 November 2008 (European parliament, 2008), it is applied for every flight with departure or arrival in Europe. The legislation enforces companies to buy European emission allowances to cover their carbon emissions relative to their activities in Europe. Carbon dioxide emissions are computed thanks to the fuel consumption of companies multiplied by a standard emission factor. European Emission factors are:

Aviation fuel type	Emission factor (tCO2/t fuel)
Aviation gasoline (AvGas)	3.10
Jet gasoline (Jet B)	3.10
Jet kerosene (Jet A1 or Jet A)	3.15

Tableau 4 - Emission factors (European comission, 2009, p. 42)

The price for a ton of CO_2 is defined on European and international markets. In Europe the European Trading System (EU ETS) sells emission allowances each year on the primary market. Companies can afterwards sell and buy European Emission Allowances among themselves on the secondary market, similarly like shares on stock markets (EEX, 2012). If a airline does not comply with its obligations towards the European Carbon Tax it will risk a penalty of €100 per ton of carbon dioxide emitted and not paid. For 31/07/2012, the price for European Emission allowances was €6.64 per ton of CO_2 (EEX, 2012).

Airfreight companies can ask for free allowances to cover a part of their carbon emissions. These free allowances for 2012 are calculated on the basis of the tonne-kilometre (tkm[2]) these companies complied 2 years before, so for 2012 it is based on 2010's tkm. The amount of free European Emission Allowances an airline can get for 2012 is obtained by multiplying their referential tkm (2010) by 0.000679695907431681 (it will be multiplied by 0.000642186914222035 from 01/01/2013 until 31/12/2020 (European commission, 2011)).

---

[2] Tonne-kilometre : measurement for airfreight traffic, it multiplies the shipment's weight in ton per the traveled kilometers

For example an American airline which would have done 2,000,000 tkm worldwide in 2010, among which 1,000,000 tkm related to flights with departure or arrival in Europe, would be entitled to $1{,}000{,}000 * 0.000679696 = 679.696$ European Emission Allowances in 2012, if it requested it, so 679.696 free tons of carbon dioxide. If in 2012 it had 1,000 tons of carbon emissions relative to Europe then the airline would have to buy $1{,}000 - 679.696 = 320.304$ allowances to respect the law, or receive a fine of 100 euros per ton of carbon dioxide emitted.

Chapter IV. Results

Like the other chapters, results are split in two parts: the results to be exposed are the ones for software modifications and implementations; the second results are relative to fuel savings.

A. Software integration

Out of the four initial constraints to implement, the compartments load limits permit to respect all the compartment constraints explained in the weight and balance manual (Boeing; Cargolux Airlines). It is quite important because it affects the safety of the flight and therefore the one of the passengers and the environment. Moreover it seems this constraint is more restrictive than the one which was already implemented for combined load limits (see *II.C.2 Constraints – Combined load limits (8)*), at least for the Boeing 747-400.

The vertical limit constraint has been designed but not implemented because without knowing where the initial vertical position of the center of gravity without shipment is and also where it should be with the shipment, it is impossible to determine a good solution. Looking at aircraft dimensions (*Figure 14*), if the center of gravity has to be positioned at the same height as the wings, it seems any solution should be right because the lowest part of the upper deck is already at the wing level. And if the center of gravity position should lie between the upper and lower decks, the minimization of the moment of inertia would ensure a distribution of ULDs on both decks (because they would try to be as close as possible to the referential axe without taking account on which deck they are). The vertical limit constraint is very restrictive due to the fact that the lower deck cannot take as many ULDs as the upper deck (because of available positions and constraints). Therefore the vertical limit constraint should not be put too high. So the interest of the constraint is very doubtful and besides it rises the computation time. The percentage could also not be given but maximized as when the software tries to reach the most aft center of gravity but it adds significant computation time, still with a doubtful result. Eventually this constraint does not seem required for the weight and balance problem or fuel saving. Therefore it was not entered in the software because it could lead to false infeasible solutions if the percentage asked was too high or longest computation if the percentage asked was maximized as variable.

The possibility to put the center of gravity the most aft possible has been easily entered as seen in the methodology (see *III.A.4 The most aft center of gravity*). For security reason, i.e.

to make it impossible for the center of gravity to get out of the feasibility envelope (see A*ppendix B*), the software asks to approach the maximum %MAC minus 0.01. The results obtained were each time optimal but the computation time increased significantly compared with to the initial computation time while targeting a %MAC and not maximizing it. But it is still a lot faster than manually as the slowest computation time took less than 10 seconds (see results for real samples in the next section *IV.B Fuel saving*).

The goal of re-positioning the referential axis is to correct a non-consequent model's simplification, considering equations about the objective (see *II.C.1 Objective function*) and the center of gravity constraint (see *II.C.2 Constraints – Center of gravity (6)*). To correct the model one has to simply replace $ID$with the targeted center of gravity. But the software, OPAL, goes further as it does not aim a center of gravity but a %MAC. The relation between %MAC and center of gravity is known: the %MAC is the position of the center of gravity relative to its position on the MAC (see *II.A.3 MAC, %MAC, LEMAC*). Therefore aiming one is aiming the other. Initially the first thought while correcting this simplification in the software was that it would not only minimize the moment of inertia but also the center of gravity as the minimal moment of inertia is centered on the center of gravity's position. So it would reach the bi-objective of minimizing the moment of inertia while minimizing the center of gravity. But results show that even if it gets better results with a larger interval of error ε, the interval of error is still needed. It ensures good results and it permits to restrain variables which run the algorithm a lot faster than without. The reason of this inefficiency certainly lies in the fact that ULDs are large and storage positions are limited. Furthermore other constraints also impact on the ULDs distribution. To sum up the reasons: ULDs cannot take the best positions to minimize the center of inertia. Therefore each time a ULD does not take the perfect position, it creates an error which, reported for each ULD, should lead to this inefficiency. The reason has not been analyzed as it does not impact really on the software because it still needs the center of gravity constraint to reduce the time of compilation. For example, with $\varepsilon = 10\%$ the software compiled an unsatisfying solution in more than 15 minutes where the same computer computes the best solution with $\varepsilon = 1\%$ in less than 20 seconds. Tests without constraints have been aborted after more than 30 minutes of compilation on the same sample. Therefore this modification, while correcting core model does not change the final result.

B. Fuel saving

One important point is to know if an optimization of the center of gravity regarding fuel savings can be made: Four real samples of shipments were entered in the OPAL software to know if a more aft center of gravity could be reached. And here are the results:

Sample	**A**	**B**	**C**	**D**
#ULDs	26	30	42	23
Weight	63,810 kg	59,360 kg	103,975 kg	60,418 kg
Targeted %MAC	28	28	28	28
%MAC Loadmasters	27.4	27.3	28,1	26.1
Percent deviation	2.143%	2.500%	0.357%	6.786%
%MAC OPAL	27.991	27.999	27.997	27.99
Percent deviation	0.032%	0.004%	0.011%	0.036%
Computation time	0.11 s	0.42 s	0.60 s	0.35 s
%MAC maximal	32.998	32.25	32.992	32.55
Computation time	0.11 s	9.27 s	0.48 s	5.48 s

Table 5 - OPAL results for real samples

Loadmasters are targeting a %MAC of 28 and as seen in the results the deviation between the target and the %MAC reached is better with OPAL than the one reached by loadmasters. It is calculated in less than 10 seconds for the longest case. Regarding fuel savings the most important point to highlight is the fact loadmasters are targeting (and quite well) a %MAC of 28 while they could reach a better fuel efficiency %MAC of 32.7 on average. This is 4.7% more aft on the MAC than the initial target. According to the literature, the fuel saving relative to this improvement for a Boeing 747-400 should be between 0.10 and 0.20% (F*igure 12*).

As seen in the literature and the methodology, it is hard to determine a proper impact for fuel saving related to the center of gravity of a plane. However the profit obtained thanks to a given diminution of fuel consumption can be estimated for planes but also for airlines.

To give a clear idea on how a gain of 1% is important for airfreight, here are the gains a fuel reduction of 1% would benefit to the U.S. carrier industry. Data are from the U.S. Department of Transportation (RITA, 2012).

		Consumption (million gallons)	Cost (million dollars)	Cost per Gallon (dollars)
2011	January	1,405.8	3,665.8	2.61
2011	February	1,276.9	3,519.4	2.76
2011	March	1,515.5	4,231.6	2.79
2011	April	1,477.3	4,394.7	2.97
2011	May	1,504.9	4,562.6	3.03
2011	June	1,554.1	4,543.6	2.92
2011	July	1,621.3	4,758.1	2.93
2011	August	1,568.2	4,587.1	2.93
2011	September	1,422.5	4,186.3	2.94
2011	October	1,442	4,070.2	2.82
2011	November	1,372.5	3,912.9	2.85
2011	December	1,433.7	4,055.8	2.83
2011 Total		17,594.7	50,488.1	2.87

Table 6 - RITA's statistics for airline fuel cost and consumption -U.S. carriers in 2011 (RITA, 2012)

Therefore a difference of 1% in fuel consumption would lead to:

	Consumption (million gallons)	Cost (million dollars)	Cost per Gallon (dollars)
2011 Total	17,594.7		2.87
-0.01	17,418.75	49,983.22	
Difference	175.95	504.88	

Table 7 - Impact on U.S. carriers economy of a 1% fuel reduction in 2011

The CO_2 consumption is computed thanks to the ratio given by the ICAO Carbon emissions calculator (ICAO, 2010): 3.157. Knowing that 1 gallon equals 3.103kg, we can calculate the CO_2 consumption as follow:

	Consumption (million gallons)	CO2 consumption (million tons)
2011 Total	17,594.70	172.36
-0.01	17,418.75	170.64
Difference	175.95	1.72

Table 8 - Carbon dioxide consumption of U.S. carriers in 2011, with and without the 1% fuel reduction

To sum up, a fuel saving of 1% would yield an economy of over $500 million and 1.7 million tons of CO_2 for US cargo airlines. But there are more, here is an estimation of the economy relative to the European carbon tax:

At least 14% of the U.S. carriers' traffic goes to Europe (RITA, 2012), therefore at least 14% of the traffic should be subjected to the European carbon tax. Due to lack of data, a simple assumption is made to estimate CO_2emission: the CO_2 emission should be very correlated to the traffic portion of an area. Therefore the CO_2emission related to U.S. carriers in Europe is taken as 14% of all the U.S. carriers' CO_2emission. For 31/07/2012, the price for European Emission allowances was €6.64 per ton of CO_2 (EEX, 2012).

	CO2 consumption (million tons)	CO2 relative to Europe (14%) (million tons)	Cost for the European Carbon Tax (million euro)
2011 Total	172.36	24.13	160.23
-0.01	170.64	23.89	158.62
Difference	1.72	0.24	1.60

Table 9 - Cost for the European carbon tax for U.S. carriers in 2011, with and without the 1% fuel reduction

It means that if in 2012 U.S. carriers made the same numbers as in 2011 they would have to pay for the European carbon tax at least 14% of 1.7 million tons of CO_2 on top of what they would have to pay if they did not reduce their consumption by 1%. The free allowances remain equal with or without fuel savings as they depend on the tkm from 2010. Therefore an economy of 1.7 million tons of CO_2, so 0.241 tons for Europe (14%), would lead to a profit of over €1.6 million.

Chapter V. Discussion

Like the other chapters, the discussion is split in two parts: the first one emphasizes is on OPAL and what could still be improved; the second one discusses fuel saving and the theoretical benefits an airline would gain from an automatic procedure like OPAL.

A. OPAL

OPAL gives fast and accurate results for a given number of ULDs. It could easily be implemented in a supply chain by making ULDs data compatible between the airline resource planning (an ERP) and OPAL.

Among these thesis objectives the vertical constraint has not been entered and should not be studied further if new data about relations between stability, safety or fuel saving relative to the vertical position of the center of gravity is not found. Currently the addition of this constraint is too restrictive or too time consuming and no results are expected regarding data. Its utility is very doubtful.

On the other hand the objective of minimizing the moment of inertia and the center of gravity could be interesting to get rid of the interval of error constraint but the solution given in this thesis, i.e. targeting the center of gravity wanted to minimize the moment of inertia, did not give the expected results. Another approach could have been made by asking the minimization of the interval of error ε thanks to the same process as the one for putting the center of gravity the most aft possible (see *III.A.4 The most aft center of gravity*). In any case, both proposed approaches can minimize the center of gravity but only after having minimized the moment of inertia so the result should not fulfill the bi-objective.

The software can still be improved on other points: during tests, one lack in the software became quite annoying, i.e. the fact it does not pint out why the solution is infeasible. To tackle this problem a solution could be to load the maximum number of ULDs possible, therefore if the software cannot load every ULD it would load the maximum and hopefully the remaining ULDs should give a clear indication on why they cannot be loaded. An attempt has been made to reach this result (see A*ppendix D*) but the computation time became too high and the result was not fully reliable. But other paths can be investigated: regarding the small computation time of the software, the possibility to make two optimizations should be studied, like one calculating the maximum number of ULDs which can be put in the airfreight followed by another solver minimizing the moment of inertia for this number of ULDs.

Another improvement for a professional use would be to make a report listing all ULDs, constraints and results for the optimal solution reached. It would give a lot of information to loadmasters in case they would like to change some positions or take other things into account for the flight.

Eventually if the data about fuel saving could be taken for granted, OPAL could estimate the fuel saving related to the optimization of the center of gravity which could allow loadmasters to make their changes knowing the impact on costs.

B. Benefits through fuel saving

Results confirm that companies would gain substantial benefits from even a small fuel saving. The percentage of fuel saving which can be achieved through a change of the center of gravity of planes exists but is unclear. The result for real situations shows a small benefit but it is partly because of the plane model, a Boeing 747-400. Indeed the targeted %MAC is quite high regarding the fact that the maximum position for the center of gravity in a Boeing 747-400 is at 33% on the MAC. Two main reasons can stand out: To compute the possible fuel saving of an airfreight company relative to a change of the center of gravity, one needs to know the currently targeted %MAC per plane and the estimated gain of fuel per change of the center of gravity per plane. The currently targeted %MAC has not been looked for in this thesis but companies should know it and a survey would have to be done to estimate the targeted %MAC per plane model. The estimated gain of fuel per change of the center of gravity has not been put into a function or taken into account in fuel consumption models therefore the estimations given by companies do not cover all the field of possibilities and the lack of explanation about these data does not allow to ensure such a fuel saving per specific flight. This is explained by the fact manufacturers do not share all their information but also because of the complexity of such computations. Indeed fuel consumption is hard to calculate beforehand because there are a lot of variables impacting on it: wind speed, air pressure, safety fuel, weight, distance … and of course the center of gravity position. Nevertheless the overall data available confirm the fact that fuel saving can be achieved through a change of the center of gravity of a plane thanks to a better loading of ULDs. The range of this saving depends on the type of plane but the 5% aft 1% less fuel rule (see *I.A Presentation*) does not seem realistic as Boeing and Airbus data tend to get an average of 1% less fuel for a position 10% more aft (+/- 0.7% fuel saved per 10% for Boeing and +/- 1.4% fuel saved per 10% for Airbus, regarding the data (see *II.E Fuel consumption*).

Lots of points are unclear about how the fuel saving is estimated. Firstly, do they take into account the fact the fuel saved is not to be carried anymore? It could lead to another possible gain or to more free space for shipment (which does not seem needed in most cases as most aircrafts are not fully loaded).

Another point which should be studied is the fact flight calculations like the cruise FL and speed are made regarding a standard center of gravity, at least for TNT (see *III.B.3 Interview with a performance manager at TNT Bierset*). It means even if the center of gravity is more efficiently positioned the calculations for the flight would not change. Therefore the flight would not be the most efficient regarding its center of gravity position. When D. Anderson (2006), Boeing and others (see *II.E Fuel consumption*) estimate a reduction of fuel consumption related to a change of the center of gravity, do they take the change of flight characteristics into account and do they make new calculations for flights ?

D. Anderson (2006) linked the fuel saving to the modification of the drag induced by a change of the angle of attack resulting from a move of the center of gravity. This information, if relevant, leads to two reflections : Fristly the relation between drag and the angle of attack is known as $Tcost(\alpha) = D$ for an unaccelerated plane (see *II.A.4 Performance of flight and center of gravity*). So the direct relation between fuel saving and a change of the center of gravity could be studied by looking for the relation between angle of attack and center of gravity and also between drag and fuel saving. Secondly D. Anderson (2006) implies that the estimation for fuel savings is made regarding the relation between drag and center of gravity. This is full of hidden meanings because if the estimations are only based on the drag, they should not take into account the reduction of weight due to the need of less fuel but also the miscalculations due to the use of a standard center of gravity for flight computations. Therefore more fuel could be saved thanks to a movement of the center of gravity and maybe the unproven rule of 5% more aft 1% less fuel rule would be more realistic than expected previously.

Coming back to the result about the four real cases studied in this thesis and taking into account the estimated fuel saving from Boeing: The small theoretical benefice which would be obtained by putting the center of gravity the most aft possible is due to the fact the airlines already put the center of gravity very aft on the MAC. Indeed on Boeings 747-400 the available center of gravity is from 13 to 33% on the MAC, therefore the initial positioning is quite good because it could only be improved by 5% in the best cases. And for a Boeing 747-400, an improvement of 5% would only lead to a fuel saving between 0.12% and 0.18%. Therefore on a Boeing 747-400 it seems really hard to get good fuel saving results through a change of the center of gravity. But it would not be the same with other planes like a Boeing 777-200 where an improvement of 5% on the MAC would lead to a fuel saving between 0.45% and 0.65%. Another thing to take into consideration is the initial positioning: 28% of the MAC for the samples is already really high but are other airlines doing like them? As it has been said earlier survey should be made to answer this question. But at least the case of eWBS (enhanced Weight and Balance System) could be discussed without taking it for granted because it comes from its presentation and not from verified data and also it is from 2007 and things could have changed since then. eWBS is an enterprise selling an automatic procedure, working mainly with Chinese airlines. In its presentation, basing its data on one of its customers (EVA AIR), eWBS announces it helped going from an average center of gravity at 21.48 %MAC to an average center of gravity at 22.84 %MAC for MD-11 (aircraft type) which has an available center of gravity from 13 to 33% on the MAC (eWBS). Even if this data is uncertified it lets presume that other airlines are not putting the center of gravity at its best position regarding fuel efficiency.

What was unexpected during all this project is the poorness of the data. There are not a lot of measurements and a lot of them are sold by companies but they do not even cover the entire field of aviation. Some basic information like the price of carbon dioxide quotas or the average consumption of a plane is hard to find or quite incomplete. For example the European air cargo consumption shown in the Fuel and transport report for the European commission in 2008 uses data from 2002 gathered by IATA and ICAO, which does not permit to make efficient estimations of the current situation for Europe. Is this lack of information or difficulty to find it due to the secrecy from manufacturers and airfreight companies or is it due to the complexity of the task?

Another point to highlight is the lack of studies around this thesis subject. As it has been written before in this project research, most papers about the weight and balance issue say that a change of the center of gravity influences the fuel consumption but no studies dedicated to this topic were encountered during the search for material for this thesis. But there are rooms for improvements and maybe fast and quite easy ones: as seen before airlines can get good results to position the center of gravity of their airfreights, at least with automatic procedures like OPAL. Therefore even if the economical profit using automatic procedures like OPAL is not great, which seems to be the case in the four real examples studied here (see *IV.B Fuel saving*), there are still benefits not only for the position of the center of gravity and the fuel saving induced by it but also for the staff as it drastically reduces their time to make those computations. Moreover the staff should need less training time than what is currently requested. Even if this last point cannot be affirmed it seems logical and similar results are advanced by eWBS in their presentation, going from 40 hours of training for classical loadmasters from its customer EVA air to less than 5 hours with their program (eWBS). Again eWBS' data cannot be taken for granted and it does not reflect the reduction of staff training which would be achieved with any other automatic procedures like OPAL.

Eventually the use of such automatic procedures could give more control to the commercial department of airlines. Indeed on top of giving the list of ULDs to load, an automatic procedure like OPAL could permit to compute the ULDs distribution in the commercial department before giving it to loadmasters who would only have to load the plane without making any calculations. The benefit from this system would be that all calculations are done at the same place and at the same time. Less trained staff and less time would be needed, which would permit to make other tasks more efficiently or to reallocate a part of the staff to new valorizing tasks.

Chapter VI. Conclusion

The conclusion part sums up the different elements of this thesis. For a better understanding of the methodology, results and discussions, it incorporates a section dedicated to the software reviewed and modified during this research project, OPAL; it incorporates a second section for the fuel saving and the financial impact related to a change of the center of gravity of a plane and the use of OPAL.

A. OPAL

The airfreight traffic is growing as emerging countries are becoming richer. The environmental aspect of business impacts more and more on profits due to international agreements for overall pollution reduction and the implementation of new taxes in favor of green energies. A reduction of costs thanks to fuel saving and reduction of carbon dioxide emission can be achieved through better shipment distribution. The use of automatic procedures like OPAL permits to reach the most aft center of gravity possible per flight and therefore the highest cost reductions for airlines.

The compartment total weight constraint has been entered in OPAL and is working well. It ensures that the software does not go out of the plane's limits.

The vertical constraint has been coded but due to the lack of information concerning the position the center of gravity should vertically take, it has not been entered in the software. Moreover some information lets think that it is not a needed constraint for safety flights.

The possibility to get the most aft result has been entered in OPAL and it is working well. It permits to reach the most aft center of gravity possible per flight and therefore it leads to the largest profits possible through shipment's distribution.

With the goal to reach the bi-objective of minimizing the moment of inertia while minimizing the center of gravity, a small simplification by Limbourg *et al.* (2012) has been corrected and permits a better methodology for reaching the optimal result. But it does not fulfill the bi-objective as the targeted center of gravity still needs to be constrained. On the other hand, relaxing this constraint implies an important increase of the computation time.

To conclude on OPAL, the software does what it is asked to do without having experienced mistakes. The latest version of the software is more user friendly and takes more parameters into consideration (QuantOM, 2012). Some improvements could be made but the core part of OPAL is working and therefore the majority of improvement possibilities are related to the end-user's experience or the ease of use. The improvements which could be made to OPAL are related to the end-user and not to OPAL itself.

For a better end-user experience some tools could also be added like the creation of a final report when giving results. Another thing which could improve the end-user experience is the possibility to maximize the number of ULDs to load from a list. It could help commercial departments to make ULD lists per plane but it could also help to identify why a list of ULDs is infeasible by looking at which ULDs were not taken in the optimal distribution solution.

For the ease of use, a ULDs creator could facilitate the utilization of OPAL in airlines, even if the final goal for airlines using software like OPAL should be to integrate it in the airline system with common ULDs files between departments and IT tools. On the same idea, another tool which could help airlines to adopt such software is a plane configurator which could permit an easier integration of other plane models.

B. Fuel saving

The fuel saving induced by a change of the center of gravity of a plane exists. It depends on plane models with high differences between them. Notwithstanding the existence of this property, the fuel saving is unclear and cannot be measured with the information discussed in this thesis. The estimations encountered give an average fuel saving of 1% for a position 10% more aft. But as said in the discussion part of this thesis, there are no explanations behind these estimations; therefore the subject needs further studies to confirm such fuel savings.

The economic impact of a reduction of fuel does not only take into the cost of fuel account but also the taxes relative to the carbon dioxide emission. In this thesis a reduction of 1% of fuel has been calculated for the case of U.S. carriers. It led to a profit of over $500 million for fuel saving and €1.6 million related to the European carbon tax (only 14% of U.S. carriers goes to Europe).

Sadly the percentage of fuel saving cannot be estimated and 1% was taken for measurements. To measure this fuel reduction two things are needed. As said previously the impact of a change of the center of gravity is needed, but also the current position of the center of gravity used for shipments. Indeed airlines don’t put the center of gravity at the same position. Therefore without this information related to the current center of gravity position the possibility of improvement cannot be estimated. A means to get this information would be by doing a survey among all airlines, asking them where they put the center of gravity for their planes.

To conclude on fuel saving, it can potentially lead to important profits for airfreight industries but it depends on the impact of the center of gravity on fuel consumption and on the current center of gravity position of aircrafts. With the data gathered in this project research, the economic impact from a change of the center of gravity and the use of OPAL cannot be calculated.

This thesis proposes a few paths that could be further investigated to highlight the relations between the center of gravity, the fuel consumption and their ensuing impact on the airlines costs. For example, one could wonder:

- What the exact relation between the center of gravity and fuel saving is. This could be answered by studying the relation between the center of gravity and the angle of attack together with the one between the drag and the fuel saving.

- What the fuel saving induced by the fuel saving itself could be. Indeed with fuel reductions the plane has less fuel therefore it weighs less and should save more fuel due to this loss of weight.

- What fuel saving could be reached by better flight calculations taking the real position of the center of gravity into account and not a standardized one.

No doubt such studies could be of global interest as this thesis has started to show there are huge economies to be made if the projections from the theoretical estimations of the current literature used in this thesis could be refined by studying the paths given in this project research.

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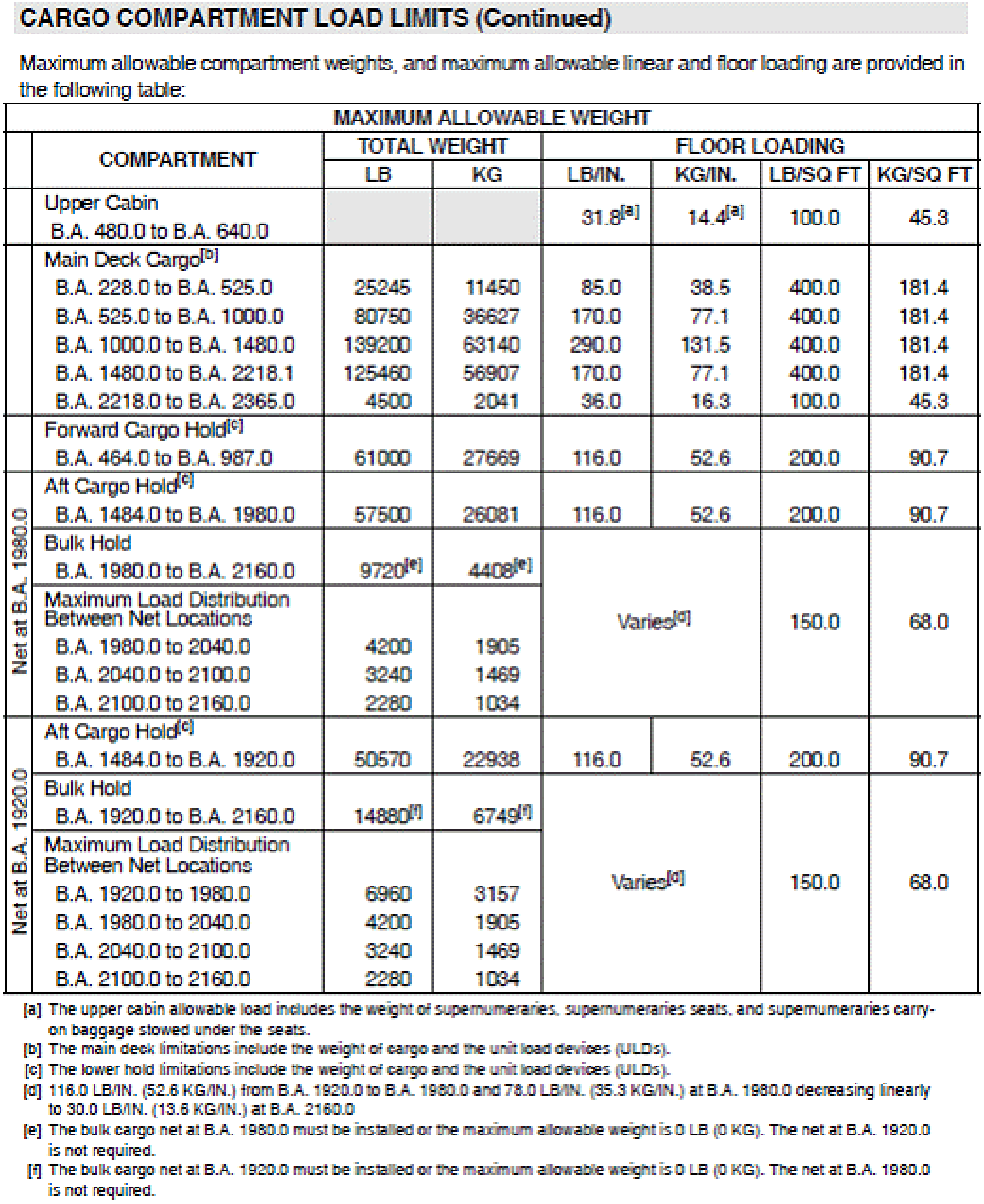
Table of Appendices

Appendix A – Cargo compartment load limits



CARGO COMPARTMENT LOAD LIMITS (Continued)

Maximum allowable compartment weights, and maximum allowable linear and floor loading are provided in the following table:

		MAXIMUM ALLOWABLE WEIGHT					
	COMPARTMENT	TOTAL WEIGHT		FLOOR LOADING			
		LB	KG	LB/IN.	KG/IN.	LB/SQ FT	KG/SQ FT
	Upper Cabin B.A. 480.0 to B.A. 640.0			31.8[a]	14.4[a]	100.0	45.3
	Main Deck Cargo[b]						
	B.A. 228.0 to B.A. 525.0	25245	11450	85.0	38.5	400.0	181.4
	B.A. 525.0 to B.A. 1000.0	80750	36627	170.0	77.1	400.0	181.4
	B.A. 1000.0 to B.A. 1480.0	139200	63140	290.0	131.5	400.0	181.4
	B.A. 1480.0 to B.A. 2218.1	125460	56907	170.0	77.1	400.0	181.4
	B.A. 2218.0 to B.A. 2365.0	4500	2041	36.0	16.3	100.0	45.3
	Forward Cargo Hold[c] B.A. 464.0 to B.A. 987.0	61000	27669	116.0	52.6	200.0	90.7
Net at B.A. 1980.0	Aft Cargo Hold[c] B.A. 1484.0 to B.A. 1980.0	57500	26081	116.0	52.6	200.0	90.7
	Bulk Hold B.A. 1980.0 to B.A. 2160.0	9720[e]	4408[e]	Varies[d]		150.0	68.0
	Maximum Load Distribution Between Net Locations						
	B.A. 1980.0 to 2040.0	4200	1905				
	B.A. 2040.0 to 2100.0	3240	1469				
	B.A. 2100.0 to 2160.0	2280	1034				
Net at B.A. 1920.0	Aft Cargo Hold[c] B.A. 1484.0 to B.A. 1920.0	50570	22938	116.0	52.6	200.0	90.7
	Bulk Hold B.A. 1920.0 to B.A. 2160.0	14880[f]	6749[f]	Varies[d]		150.0	68.0
	Maximum Load Distribution Between Net Locations						
	B.A. 1920.0 to 1980.0	6960	3157				
	B.A. 1980.0 to 2040.0	4200	1905				
	B.A. 2040.0 to 2100.0	3240	1469				
	B.A. 2100.0 to 2160.0	2280	1034				

[a] The upper cabin allowable load includes the weight of supernumeraries, supernumeraries seats, and supernumeraries carry-on baggage stowed under the seats.

[b] The main deck limitations include the weight of cargo and the unit load devices (ULDs).

[c] The lower hold limitations include the weight of cargo and the unit load devices (ULDs).

[d] 116.0 LB/IN. (52.6 KG/IN.) from B.A. 1920.0 to B.A. 1980.0 and 78.0 LB/IN. (35.3 KG/IN.) at B.A. 1980.0 decreasing linearly to 30.0 LB/IN. (13.6 KG/IN.) at B.A. 2160.0

[e] The bulk cargo net at B.A. 1980.0 must be installed or the maximum allowable weight is 0 LB (0 KG). The net at B.A. 1920.0 is not required.

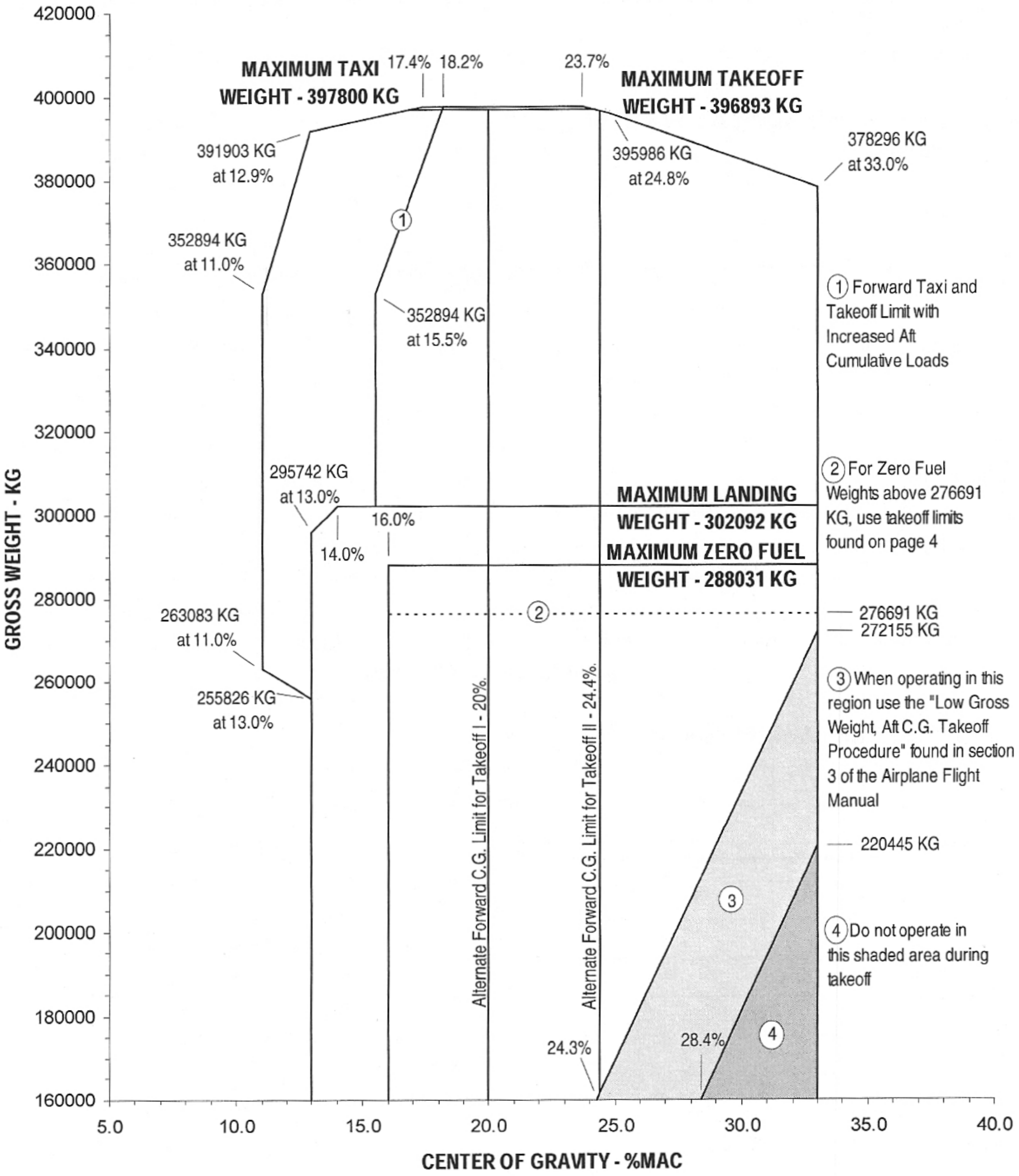
[f] The bulk cargo net at B.A. 1920.0 must be installed or the maximum allowable weight is 0 LB (0 KG). The net at B.A. 1980.0 is not required.

Appendix B – Feasibility envelope

CERTIFIED WEIGHT AND CENTER OF GRAVITY LIMITS (Continued)

C.G. LIMITS - MTW 397800 KG, MLW 302092 KG, MZFW 288031 KG

The following diagram represents the certified Center of Gravity Limits in Metric units:



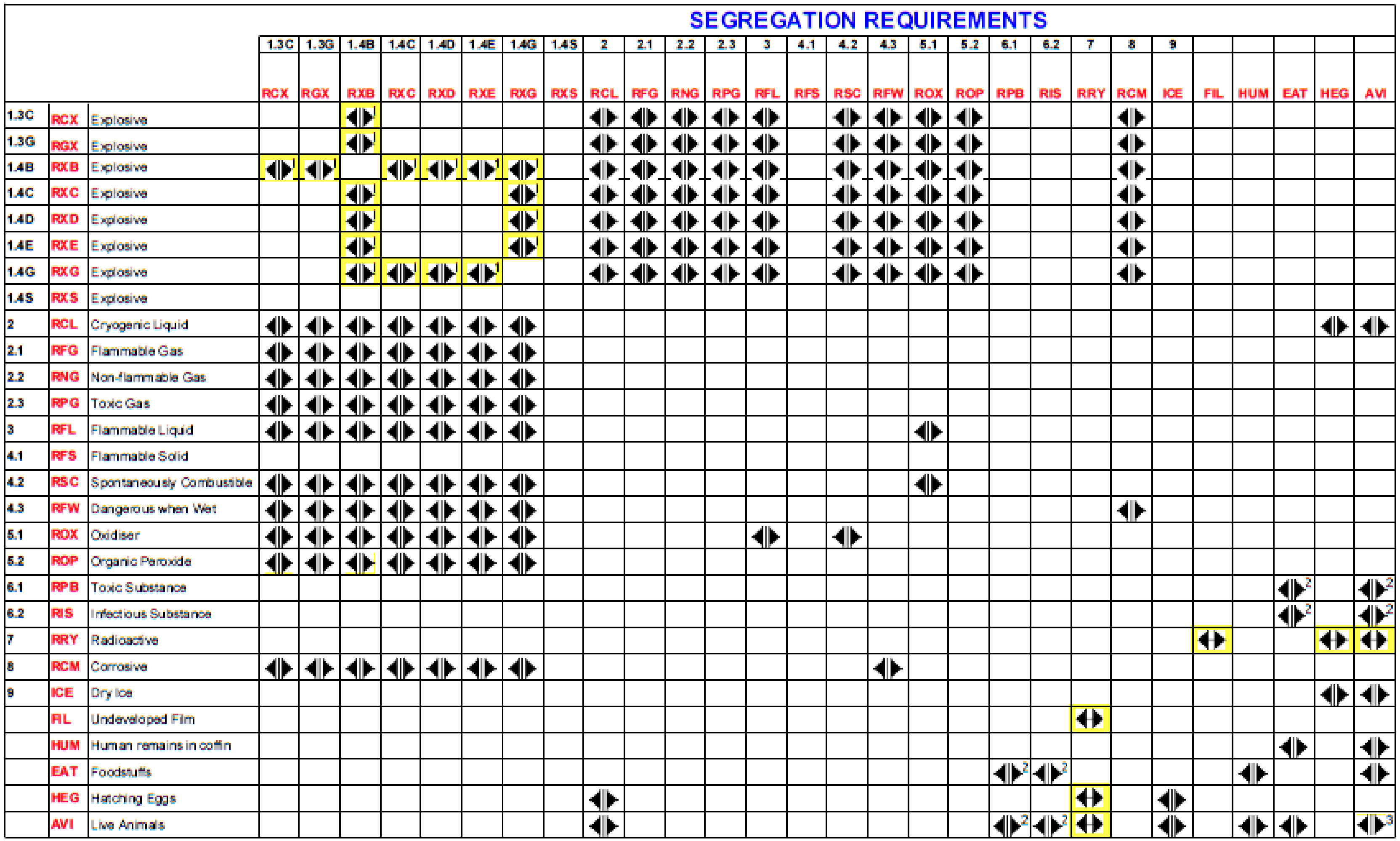
① Forward Taxi and Takeoff Limit with Increased Aft Cumulative Loads

② For Zero Fuel Weights above 276691 KG, use takeoff limits found on page 4

③ When operating in this region use the "Low Gross Weight, Aft C.G. Takeoff Procedure" found in section 3 of the Airplane Flight Manual

④ Do not operate in this shaded area during takeoff

Appendix C – Hazmats table



SEGREGATION REQUIREMENTS

			1.3C	1.3G	1.4B	1.4C	1.4D	1.4E	1.4G	1.4S	2	2.1	2.2	2.3	3	4.1	4.2	4.3	5.1	5.2	6.1	6.2	7	8	9					
			RCX	RGX	RXB	RXC	RXD	RXE	RXG	RXS	RCL	RFG	RNG	RPG	RFL	RFS	RSC	RFW	ROX	ROP	RPB	RIS	RRY	RCM	ICE	FIL	HUM	EAT	HEG	AVI
1.3C	RCX	Explosive			🟨◀▶[1]						◀▶	◀▶	◀▶	◀▶	◀▶		◀▶	◀▶	◀▶	◀▶				◀▶						
1.3G	RGX	Explosive			🟨◀▶[1]						◀▶	◀▶	◀▶	◀▶	◀▶		◀▶	◀▶	◀▶	◀▶				◀▶						
1.4B	RXB	Explosive	🟨◀▶[1]	🟨◀▶[1]		🟨◀▶[1]	🟨◀▶[1]	🟨◀▶[1]	🟨◀▶[1]		◀▶	◀▶	◀▶	◀▶	◀▶		◀▶	◀▶	◀▶	◀▶				◀▶						
1.4C	RXC	Explosive			🟨◀▶[1]				🟨◀▶[1]		◀▶	◀▶	◀▶	◀▶	◀▶		◀▶	◀▶	◀▶	◀▶				◀▶						
1.4D	RXD	Explosive			🟨◀▶[1]				🟨◀▶[1]		◀▶	◀▶	◀▶	◀▶	◀▶		◀▶	◀▶	◀▶	◀▶				◀▶						
1.4E	RXE	Explosive			🟨◀▶[1]				🟨◀▶[1]		◀▶	◀▶	◀▶	◀▶	◀▶		◀▶	◀▶	◀▶	◀▶				◀▶						
1.4G	RXG	Explosive			🟨◀▶[1]	🟨◀▶[1]	🟨◀▶[1]	🟨◀▶[1]			◀▶	◀▶	◀▶	◀▶	◀▶		◀▶	◀▶	◀▶	◀▶				◀▶						
1.4S	RXS	Explosive																												
2	RCL	Cryogenic Liquid	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶																				◀▶	◀▶
2.1	RFG	Flammable Gas	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶																					
2.2	RNG	Non-flammable Gas	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶																					
2.3	RPG	Toxic Gas	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶																					
3	RFL	Flammable Liquid	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶										◀▶											
4.1	RFS	Flammable Solid																												
4.2	RSC	Spontaneously Combustible	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶										◀▶											
4.3	RFW	Dangerous when Wet	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶															◀▶						
5.1	ROX	Oxidiser	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶						◀▶		◀▶													
5.2	ROP	Organic Peroxide	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶																					
6.1	RPB	Toxic Substance																										◀▶[2]		◀▶[2]
6.2	RIS	Infectious Substance																										◀▶[2]		◀▶[2]
7	RRY	Radioactive																								🟨◀▶			🟨◀▶	🟨◀▶
8	RCM	Corrosive	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶	◀▶									◀▶												
9	ICE	Dry Ice																											◀▶	◀▶
	FIL	Undeveloped Film																					🟨◀▶							
	HUM	Human remains in coffin																										◀▶		◀▶
	EAT	Foodstuffs																			◀▶[2]	◀▶[2]					◀▶			◀▶
	HEG	Hatching Eggs									◀▶												🟨◀▶		◀▶					
	AVI	Live Animals									◀▶										◀▶[2]	◀▶[2]	🟨◀▶		◀▶		◀▶	◀▶		◀▶[3]

This table must be read and used in conjunction with the IATA Dangerous Goods Regulations

🟨◀▶ Minimum separation distance as specified by IATA Regulations

◀▶ Shall not be loaded in close proximity of one another

🟨◀▶[1] Refer to IATA Dangerous Goods Regulations 9.3.2.2

◀▶[2] Must not be stowed in the same compartment, unless loaded in ULD's not adjacent to one another or in closed ULD's

◀▶[3] This segregation requirement applies only to laboratory animals and to animals which are natural enemies

Appendix D – Maximum loading

To maximize the loading of ULDs, the idea tried during this thesis was to put a negative weight on each couple of ULD / position in the objective function. Therefore, if the weight is high enough, the minimization of the objective function should lead to a maximum of ULDs possible as taking the maximum number of negative weight. Sadly the computation time became too high and the result was not fully reliable.

The initial objective function as build in the software:

```
for( i = 0; i < NombreULDtoLoad; i++)
    {
          for(int j = 0; j < x[i].length; j++)
            {
                obj.addTerm(objvals[i][j], x[i][j]);
                inertie.addTerm(objvals2[i][j], x[i][j]);
                }
           }
```

The modification adding the negative weight:

```
/*Weighting each ULD / position possibilities with a big negative number:
the function will be at its minimum when the maximum of ULDs are loaded
for( i = 0; i < NombreULDtoLoad; i++)
    {
          for(int j = 0; j < x[i].length; j++)
           {
               obj.addTerm(objvals[i][j], x[i][j]);
               inertie.addTerm(objvals2[i][j]/1000000, x[i][j]);
               inertie.addTerm(-getLength()*getLength()*TotalCargoWeight, x[i][j]);
               }
          }
```

Abstract

The goal of this thesis is to investigate the link between fuel savings and the shipment's distribution in airfreight by discussing data and entering some modifications to the distribution optimization software OPAL. Fuel reduction becomes more and more important for airlines as fuel prices are raising and carbon taxes are implemented. Results show that a reduction of 1% of fuel would benefit for over $500 million to the U.S. carrier sector. An automatic optimization of cargo's distribution would ensure to reach the most aft possible position of the center of gravity and lead to fuel savings. OPAL is designed to reach this optimal center of gravity quickly with the purpose to replace a labor time consuming task. But researches haven't given a clear value for the fuel saved due to an optimization of the shipment's distribution. So this thesis ends by giving a few paths that could be investigated for reaching a good estimation.

Keywords: aircraft loading; weight and balance; mixed integer programming; fuel saving; European carbon tax; fuel cost; carbon dioxide