Received: 17 January 2020 | Revised: 6 April 2020 | Accepted: 23 July 2020

DOI: 10.1111/exsy.12631

ORIGINAL ARTICLE

Expert Systems WILEY

Knowledge based approach to ground refuelling optimization of commercial airplanes

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Abstract

This work aims to establish a general and optimized procedure for the initial refuelling of commercial airplanes, as this loading process is strongly related to safety and energy saving issues. The on-ground refuelling is addressed as an optimization problem whose cost function involves expert knowledge about constraints and factors that influence the aircraft stability and performance. Several heterogeneous criteria (fuelling time, structural load, flow transfers, etc.) have been considered and weighted accordance to its importance in terms of stability. This allows us to adapt the strategy to any type and planned trip of the airplane. The priority is the positioning of the centre of mass of the civil aircraft within safety and manoeuvrability margins, and near the optimal position. Evolutive algorithms are applied, keeping feasible solutions by modifying genetic operators. As a case of study, the initial refuelling of a long range type commercial aircraft, the Airbus A330-200, is analysed. Simulation results have proved this methodology to be efficient and optimal. Even more, this heuristic and general approach improves the traditional solution that follows a set of pre-defined rules that are specific for each type of aircraft.

KEYWORDS

aircraft, expert system, genetic algorithm, knowledge engineering, refuelling

1 | INTRODUCTION

Airplane stability is a critical issue that must be addressed from the beginning of its design (Pamadi, 2004; Phillips, 2004). However, each year there are a number of aircraft incidents related to weight and balance issues during the on-ground operations (Čokorilo, De Luca, & Dell'Acqua, 2014). While the most common service operation on aircrafts is the filling of fuel tanks—improper fuelling procedures have caused many aircraft accidents and in-flight incidents (Čokorilo, Gvozdenović, Vasov, & Mirosavljević, 2010).

Fuel is one more component of an airplane cargo, which can entail a high percentage of its total weight; for example, in the aircraft we are dealing with in this work (A330-200E), fuel can reach up to 24% of its weight. The main challenge of fuel management is that the initial distribution of fuel depends on each type of aircraft (dimensions, number of tanks, planned trip, etc.) and it also varies during the flight. This makes it a complex problem since it depends on many variables that are interrelated and some of them even vary over time.

Fuel management in an aircraft includes three possible actions. The initial refuelling of an airplane is an operation that necessarily takes place on-ground. In addition, in military aviation, there may also be aerial refuelling systems (Li, Zhang, & Bai, 2020). Another related problem to be considered is the fuel distribution in-flight, that is, the flow of combustible between aircraft fuel tanks during the flight.

Aircraft ground handling is a critical and complex process that includes all the operations that must be performed on an aircraft when parked on a stand (Su, Han, Wu, Zhang, & Liu, 2018), including maintenance (Gharoun, Keramati, Nasiri, & Azadeh, 2019). Much importance has been given to the correct loading of the aircraft and the takeoff weight. But another influential element of optimization is filling with aviation fuels

(Vagner, Jenčová, & Szabo, 2018). In large commercial transports, it is important to direct the uplifted fuel into the appropriate tank locations to ensure that safe balance is maintained throughout the refuel process (Langton, Clark, Hewitt, & Richards, 2010). Moreover, it has also been proven that the initial refuelling influences the efficiency energy use during the entire flight, as well as the stability during the take-off.

The on-ground fuelling solutions that are currently applied are ad-hoc, for each type of aircraft and in anticipation of the routes that will be taken. The traditional refuelling procedure follows a set of hierarchical pre-defined rules that depend on the previous analysis of that specific aircraft (Langton et al., 2010). Besides, it is a discrete solution and thus it cannot fit all possible cases with the most efficient distribution. Moreover, the manual refuelling tries to find an initial fuel distribution that ensures aircraft stability but that may be quite far from the optimum. The on-ground fuel loading may be simple for small aircrafts, where the fuel system consists of a single gravity feed fuel tank with the associated fuel line connecting it to the aircraft engine. But in a modern, multi-engine passenger or cargo aircraft, the fuel system is likely to consist of multiple fuel tanks, which may be located in the wing or the fuselage (or both), and it becomes a complex issue (Langton et al., 2010).

In this work, the initial refuelling of commercial aircrafts is addressed. Our proposal aims to systematize the on-ground refuelling procedure of any airplane. That is, to develop a new general fuel loading approach adaptable to any type of aircraft, as opposed to traditional filling policies, which are specific and not optimal.

The initial fuel loading procedure is tackled as an optimization problem. The main criterion considered for the optimization is the stability of the airplane. The correct fuel loading guarantees flight safety and keeps the aircraft balance by adjusting the centre of gravity. Even more, if the initial fuel distribution is optimized, the fuel in-flight transfers can be minimized, improving the efficiency of the fuel distribution during the flight and reducing cost and energy (Long & Song, 2009). As stated by Liem, Kenway, and Martins (2014), design optimizations that maximize the performance at a single flight condition may result in unacceptable performance.

An evolutive strategy, genetic algorithms (GA), has been applied to obtain the on-ground refuelling of a long range type commercial aircraft, in particular, the A330-200 Airbus airplane (Airbus, 2020). Although no confidential data are presented, results have been validated with known real ones.

The GA cost function takes into account how the initial distribution of the fuel in the tanks affects the position of the aircraft centre of gravity (CG). Indeed, the centre of gravity positioning is one of the most important safety and stability requirements for an aircraft, both on-ground and during the flight, and it strongly depends on the on-ground fuel loading and on the consequent fuel management (Hürlimann, Kelm, Dugas, Oltmann, & Kress, 2011). Thus, it is necessary to design a fuelling procedure with the main objective of positioning the CG within a safety range and near the optimum if possible. Other various and heterogeneous criteria have also been included in the fitness function: Fuelling time, structural load, flow transfers, and so forth. Expert knowledge has been used to determine the constraints and other factors that affect the feasibility of the fuel distribution.

Simulation results show that it is possible to design a general and optimal strategy for filling aircraft fuel tank that distributes fuel more efficiently according to various criteria (safety, efficiency, etc.). This solution obtained with GA has been compared with the traditional one and validate with real data of a different aircraft.

The paper is organized as follows. A summary of related works is presented in Section 2. Section 3 describes the fuel system of the commercial aircraft. The design criteria drawn from expert knowledge are presented in Section 4. The application of GA to obtain the on-ground refuelling is developed in Section 5. Section 6 presents a real case of refuelling and compares the results with the traditional on-ground fuel filling procedure. Conclusions and future works end the paper.

2 | RELATED WORKS

Although some works on aerial refuelling have been recently published, the literature on on-ground refuelling is scarce. In Turgut and Rosen (2012), genetic algorithms are used to analyse the relationship between the fuel consumption of an aircraft and its altitude during the landing phase. An optimized trajectory of a continuous descent approach for fuel savings is designed in Ye, Wang, Tian, and Wan (2017). Wright and Grazebrook (2017) present a method for the real-time simulation of the fluid-mechanical components of the fuel storage and fuel transfer system of large civil aircrafts. It mainly models the fuel flow, and it was tested on large transport aircraft avionics, including Airbus A380.

The work by Mongeau and Bes (2003) shows the optimization of the payload distribution in an airplane using GA. However, it should be noted that, in this case, the problem is discrete since the container size is fixed. In addition, the algorithm seeks to maximize the load for each flight among all the goods to be transported. In our case, the fuel mass for a given flight is fixed, and the problem is continuous since the amount of fuel in each tank is between zero and the maximum the tank can store. In the same way, Carlson, Reiman, Overstreet, and Douglas (2017) examine several techniques to increase cargo compartment utilization and improve airlift utilization rates.

Singh, Sharma, and Vaibhav (2016) present a simplified method to optimize the aircraft maximum take-off weight, which is considered the objective function, using genetic algorithms. It was validated against the known configuration of an aircraft. Similarly, in a study by Perez, Chung, and Behdinan (2000), adaptive genetic algorithms are used to optimize take-off weight for a medium range commercial aircraft. Chaudhry and Ahmed (2014) also apply a spread sheet based genetic algorithm approach to optimize the preliminary design of an aircraft. In this case, Breguet range equation is used as the objective function for the design evaluation. The model is applicable to commercial airlines as well as a multirole jet fighter.

A related interesting problem is reported in a study by Hubert, Guo, Mouton, and Powers (2015). Sometimes tankering involves carrying excess fuel on an aircraft (more than is required for the flight), causing an overall cost due to the additional fuel burned flying at heavier-than-required weights. This conclusion helps to strengthen the utility of our work.

The article by Marinus and Maison (2016) presents a semi-empirical model for fuel weight estimates based on mission requirements (i.e., payload and range), with the operating empty weight as parameter. The model applies to military turboprop transport aircraft, and is based on actual aircraft data. It is particularly suited for conceptual and preliminary design since it relies on the operating empty weight as sole parameter. But it also considers the dependence upon the gross weight of the specific range and the fuel flow rate along a flight at constant cruise altitude, not only on-ground.

The optimization of fuel tank structures for an aircraft wing tank, another possible approach that has been evaluated for instance in Li, Liu, and Zheng (2018), is out of the scope of this work. The general problem of aircraft ground handling at airports has also been addressed (Su et al., 2018; Tabares & Mora-Camino, 2017), as well as the aircrafts refuelling from the point of view of employees' optimization (Carotenuto, Giordani, Salvatore, & Biasini, 2019). But none of them consider on-ground refuelling for the mass estimation before the take-off when it is a crucial aspect of aircraft performance (Chati & Balakrishnan, 2018; Sun, Ellerbroek, & Hoekstra, 2018).

Therefore, to the best of our knowledge, the initial refuelling issue in relation to the aircraft stability and its optimization has not been previously analysed.

3 | FUEL SYSTEM MODEL

3.1 | External frame: The aircraft dynamics

The aircraft dynamics is a vast field that defines the physics behind the mathematical models, especially regarding stability issues, and the control and flight mechanics of these aerial vehicles. Some of the most relevant related terms and concepts are as follows.

An airplane can be considered a rigid body with six degrees of freedom (D-o-F), namely three displacements (x, y, z) and three angles (roll, pitch, yaw). The inertial, gravity, propulsion, and aerodynamic forces produce the motion of the aircraft.

The stability is associated to the relation between the aerodynamics and gravitational forces (Pamadi, 2004). The gravity is applied at the centre of gravity (CG) of the aircraft, whereas the aerodynamic force applies at the total aerodynamic centre (AC). The relation between both defines the airplane stability. This relationship is calculated as the difference between the AC and CG longitudinal components from the aircraft nose, and it is called the static margin (SM). It is made dimensionless by the Mean Aerodynamic Chord (c_w) factor.

The SM is also an indicator of the manoeuvrability of the airplane (the smaller the SM, the larger the controllability), and of the static longitudinal stability (the smaller the SM, the less the stability) (Plaza & Santos, 2014). A negative SM value indicates that the aircraft is statically unstable. The normal range of this variable in civil aviation is between 0.10 and 0.20.

The fuel distribution changes the centre of gravity position, and thus the SM factor. That is, the reason that the CG positioning is one of the most important safety and stability requirements of an aircraft, not only along the flight but also during the on-ground refuelling (Phillips, 2004).

In our model, we will use mass balance to describe the dynamics of the aircraft. The airplane CG position is calculated based, on the one hand, on the position of the centre of gravity when the airplane has no loaded fuel (Zero Fuel Weight, ZFW); and, on the other hand, on the CG of the fuel tanks (Graham & Rodríguez, 1951).

In addition, as the fuel is a fluid, in the event of large accelerations of the aircraft, the CG of each tank can be momentarily displaced.

3.2 | Internal frame: The fuel system

Along with the dynamic model of the aircraft, briefly described above, it is necessary to describe the structure of the fuel system. The main components, regarding the problem addressed in this paper, are the tanks or fuel containers. There are six fuel tanks in multi-engine commercial aircrafts, such as the one we are dealing with, the Airbus A330-200 (Airbus, 2020), as shown in Figure 1: Two inner tanks in each wing, tanks #2 and #4; two outer tanks, #1 and #5; one central tank at the bottom of the fuselage between the wings, #3; and the trim tank at the tail, #6. The inner tanks are the most important because they feed the powered motors and supply inlets. The tanks are connected by two pipes except the trim tank, which has only one connection.

The system network comprises groups of pumps and valves that feed the tanks; sensors that measure flows, levels, temperature, and so forth; and the fuel control and monitoring computer (FCMC) that is the main control system (Langton et al., 2010). The latter centralizes all logical procedures regarding fuel management, reading the status of each component (internal sensors), the status of the fuel (flows, quantities, temperature,

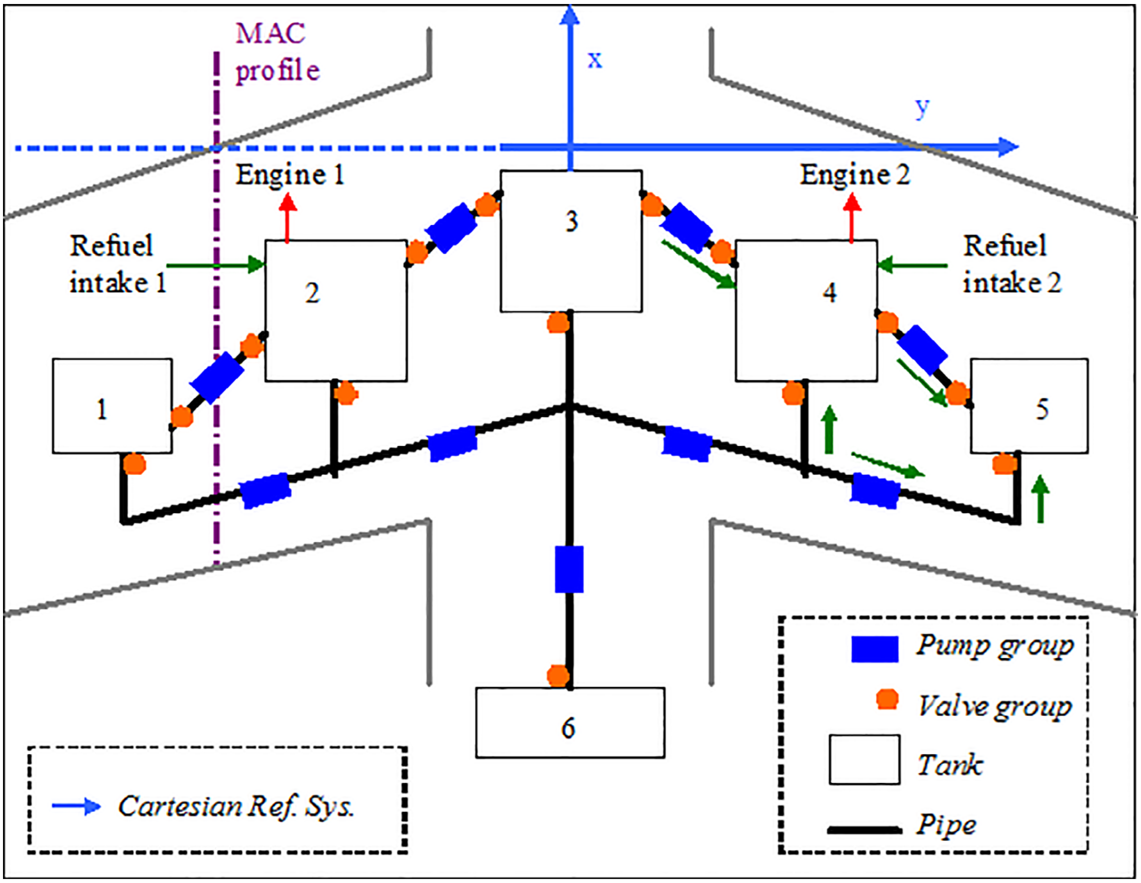

FIGURE 1 Fuel system structure

etc.), and relevant information from other on-board devices (external sensors). The solution we propose in this document for on-ground fuel filling will be implemented in the FCMC of the aircraft.

A Cartesian reference system is used to obtain the coordinates of the different elements of the aircraft, such as the position of the CG, the geometry of some tanks, and so forth (Figure 1).

4 | EXPERT KNOWLEDGE: DESIGN CRITERIA

Three types of design criteria have been considered to define the management of the refuelling, namely operational safety requirements, operation/manoeuvrability capabilities, and optimization. The expert knowledge used to define these criteria comes from one of the authors, who is a senior development engineer with more than 9 years of experience in flight simulation systems. During these years, he has gained a complete knowledge and a deep understanding about aircraft system models, based on real manufacturers' data.

1. Operational safety requirements, mainly safety procedures such as:
   a. Component structural integrity, that is, the maximum volume of each tank must not be exceeded. The system must not command a pump to inject fuel in a tank that has already reached the maximum mass.
   b. The CG must be kept within the longitudinal stability margin (SM).
   c. The CG must be placed near the aircraft symmetric vertical axis (lateral stability margin).
   d. Engines fuel supply, that is, to guarantee enough fuel for engine operations.
2. Operation/manoeuvrability.
   a. Longitudinal trimming, that is, to maintain the aircraft in a static stable condition (vertical acceleration and pitch rate must be zero). The horizontal stabilizer is deflected in a particular position that depends on the CG and, therefore, influences the aerodynamic drag and the manoeuvre capabilities.

b. Lateral trimming, similar to the longitudinal trimming but in the sideway. The vertical stabilizer, called rudder, is used to reduce the yaw rate and the lateral acceleration, for instance, in the case of asymmetric loads. The closer the CG is to the vertical axis of symmetry, the greater the manoeuvrability of the rudder.
c. Adaptability to abnormal conditions, that is, to changes in component performance or external disturbances, especially in the presence of failures in system actuators (valves, pumps), called malfunctions.

3. Optimization: Fuel distribution for minimum consumption.
   a. To place the CG as rearward as possible, where the pitch angle is smaller and the drag is reduced.
   b. Energy minimization by reducing the fuel redistribution during the flight (especially transfers between tanks that are far away from each other), and also by reducing the time the pumps are working. However, this criterion is less important than the others because the system energy consumption could be considered negligible with respect to the total energy consumption of the aircraft.

All of these criteria will be considered as the constraints of the optimization function, since they must be included in the refuelling strategy.

5 | EVOLUTIVE STRATEGY FOR ON-GROUND REFUELLING

The proposed strategy for the initial fuel loading of the aircraft is based on an evolutive strategy, genetic algorithms (Alonso & Santos, 2017; Rodríguez-Blanco, Sarabia, & de Prada, 2018). Although the optimization problem could have been solved by different methods, we have selected GA because it makes easy to incorporate expert knowledge in a natural way (Haklı, Uğuz, & Çay, 2018), even if the objective function has many cost components from heterogeneous sources, as it is the case (Zotes & Santos Peñas, 2010). Besides, GA makes possible to evaluate different combinations of the decision vector, exploring large parts of the search space to find the best solution that minimizes the cost function in a reasonable time.

Aircraft on-ground refuelling has been defined as an optimization problem that must meet requirements related to safety, manoeuvrability, and fuel consumption. Furthermore, the entire process (GA resolution and fuel distribution) must be carried out in a time that is not too long to ensure complete ground handling (Vagner et al., 2018). Once the amount of fuel mass to be loaded has been calculated, the refuelling strategy is programmed and implemented in the Fuel Control Management Computer (FCMC). The controller commands are sent to the pumps to fill each tank with the set amount of fuel.

The optimization problem formulation is as follows:

$$\text{Find}\, \boldsymbol{M} = [M_1, M_2, M_3, M_4, M_5, M_6], \tag{1}$$

$$Min\, J(\mathbf{M}) = P_1 \cdot J1 + P_2 \cdot J2 + P_3 \cdot J3 + P_4 \cdot J4 + P_5 \cdot J5, \tag{2}$$

$$s.t.C_j(\boldsymbol{M}) \leq 0, \text{for}\, j = 1, \ldots, 5, \tag{3}$$

where $\boldsymbol{M}$ is the fuel mass vector to be obtained by the GA; P_i are tuning factors that must be set by expert knowledge; J_i are the cost or objective function $J(\boldsymbol{M})$ components; and C_j are the constraints the cost function is subjected to. They are defined in the following sub-sections for this specific application.

5.1 | Cost function

The cost function and constraints are drawn from expert knowledge, taking into account all factors that can influence aircraft dynamics based on initial fuel distribution. Operational safety issues are introduced as constraints, while what can improve (or deteriorate) the performance of the aircraft is presented as costs.

The GA objective function, $J(\boldsymbol{M})$, is formed as the sum of five cost functions, J_i:

- *Cost J_1*: CG position. This component of the objective function is made up of three terms, each referring to a coordinate axis.

$$J1 = J11 + J12 + J12, \tag{4}$$

where J_{11} is the difference between the current CG coordinates and the optimal centre of gravity (CG_{obj}) in the x-axis, J_{12} in the y-axis, and J_{13} in the z-axis.

$$\begin{aligned} J11 &= \left|X_{cg\_obj} - X_{cg}\right| \\ J12 &= \left|Y_{cg\_obj} - Y_{cg}\right|. \\ J13 &= \left|Z_{cg\_obj} - Z_{cg}\right| \end{aligned} \tag{5}$$

The *x* and *y* components can be considered negligible since, on the one hand, the fuel must be symmetrically loaded regarding the longitudinal axis (*y*) and, on the other hand, as it is commonly assumed, the vertical CG component (*z*) of each fuel tank hardly changes.

The optimum CG depends on the gross weight (GW), which is known for each type of aircraft. The current CG is calculated using the mass balance equation:

$$\vec{CG} = \frac{ZFW \cdot \vec{CG}_{zfw} + \sum_{i=1}^{6}\left(\vec{CG}_{tnk\_i} \cdot M_i\right)}{ZFW + \sum_{i=1}^{6}(M_i)}, \tag{6}$$

where *ZFW* is the zero fuel weight, M_i is the fuel mass in tank *i*, and CG_{tnk_i} is the CG of tank *i*, for $i = 1, \ldots, 6$.

- *Cost* J_2: Structural load: the difference between the fuel mass of the tanks of each wing, that is, tanks 1 and 2, and tanks 4 and 5 (Figure 1). In this way, the load distribution is more homogeneous along the wings, reducing the structure effort.

$$J2 = (|M_1 - M_2| + |M_4 - M_5|)/MFtot, \tag{7}$$

where M_{Ftot} is the total fuel mass loaded.

- *Cost* J_3: Fuel transfer. The difference between the fuel mass loaded in the tanks that are supplied by the engines (tanks 2 and 4, see Figure 1) and the fuel mass that is expected to be spent by the powered motors during the flight:

$$J3 = (M_{eng}/2 - M_2 + M_{eng}/2 - M_4)/MFtot, \tag{8}$$

where M_{eng} is the expected fuel mass to be spent by engine *i* (kt), M_i is the fuel mass in tank *i*, and M_{Ftot} is the total fuel mass loaded.

This cost has a twofold goal: To improve operational safety (less risk of stopping the supply of fuel to the engines) and to decrease the energy pump consumption (less fuel amount re-distributed along the flight).

- *Cost* J_4: Fueling time. The fuel that has to be loaded in tanks that are not equipped with refuelling intakes:

$$J4 = (100M_1 + M_2 + 50M_3 + M_4 + 100M_5 + 1000M_6)/MFtot. \tag{9}$$

This cost function aims to minimize the duration of the refuelling operation.

- *Cost* J_5: CG displacement. The inverse of the difference between the fuel loaded in each tank and the critical mass. For each tank there is an amount of fuel, called the critical mass, that induces the maximum displacement of CG for a certain acceleration. This component of the cost function tries to minimize the displacement of CG during the take-off since the inertia of the fuel mass during this phase of strong acceleration causes the fluid to go backwards.

The CG displacement curves are specific to each type of aircraft. In the airplane, under study, we have used the ones shown in Figure 2, which have real order of magnitude. It can be seen how the trim tank (dotted black line) suffers the largest displacement.

Using these curves, we can define functions for each group of tanks depending on the filling percentage ($\mu = 100\, M_i/M_{max\_i}$). As an example, for the central tank, this cost function component is given by:

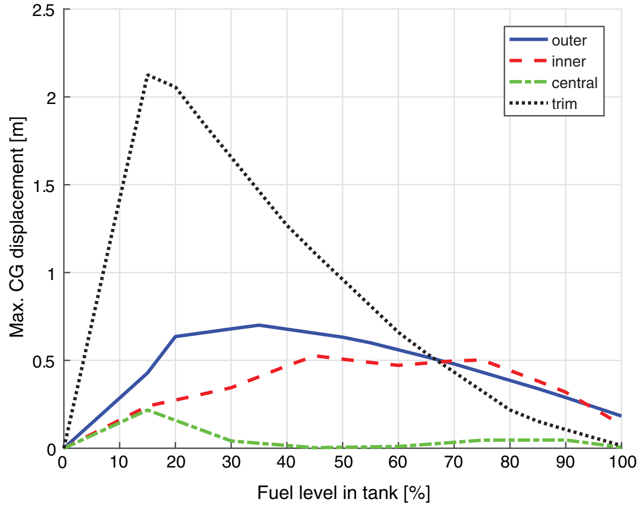

FIGURE 2 CG displacement curves

$$f_{central} = \begin{cases} 1, & si\{\mu > 10 || \mu < 20\} \\ 1 - \frac{10-\mu}{10}, & si\{\mu \leq 10\} \\ 1 + \frac{20-\mu}{80}, & si\{\mu \geq 20\} \end{cases}. \tag{10}$$

Therefore, J_5 is given by,

$$J_5 = f_{central} + 2f_{inner} + 2f_{outer} + f_{trim}. \tag{11}$$

5.2 | Constraints

To determine the optimal refuelling strategy, several restrictions must be considered.

- Constraint C_1: The amount of fuel to be loaded into each of the aircraft tanks must be equal to or less than the capacity of the fuel tank.

$$C1 = M_i - M_{max\_i} \leq 0. \tag{12}$$

- Constraint C_2: The amount of fuel mass in each tank cannot be negative.

$$C2 = -M_i \leq 0. \tag{13}$$

- Constraint C_3: The CG must not exceed the CG limits, that is, it has to be within the limits allowed for the aircraft stability.

$$\begin{aligned} C31 &= X_{CGmin}(ZFW + MFtot) - X_{CG} \leq 0 \\ C32 &= X_{CG} - X_{CGmax}(ZFW + MFtot) \leq 0 \end{aligned}. \tag{14}$$

- Constraint C_4: The amount of fuel available in the aircraft fuel tanks before the flight has to be equal to or greater than the amount of fuel required for the flight (15), where M_{Fmin} is the minimum fuel mass according to the flight plan.

$$C4 = MF\text{min} - \sum_{i=1}^{6} M_i \leq 0. \tag{15}$$

- Constraint C_5: There must be enough space in the trim tank to transfer fuel during the flight, that is, the fuel to be loaded has to be less than the capacity of this fuel tank.

$$C5 = M_6 - \eta \cdot M_{\text{max\_6}} \leq 0, \tag{16}$$

where η is the percentage of the maximum trim tank mass saved for the following flight phases.

5.3 | Configuration of the genetic algorithm

The configuration of the genetic algorithm that has been applied for the refuelling optimization of the aircraft is described in this section. The decision vector that has to be optimized is the fuel mass of the six tanks, that is,

$$\mathbf{v}_{\text{decision}} = [M_1\ M_2\ M_3\ M_4\ M_5\ M_6]. \tag{17}$$

To simplify the problem, we introduce some specific characteristics of this type of aircraft as assumptions.

- In order to ensure that the aircraft weight is not greater than allowed, the minimum necessary fuel is loaded. This is a common practice in aeronautics. Therefore, the loaded fuel mass is exactly the minimum required fuel mass.

$$M_{\text{Ftot}} = M_{Fmin}. \tag{18}$$

Taking this assumption into account that constraint C_4 is met and thus, the decision vector can be reduced. One of the mass of the tanks (M_3, for instance) can be expressed as the difference between the minimum fuel amount and the other tank masses.

$$M_3 = M_{Fmin} - M_1 - M_2 - M_4 - M_5 - M_6. \tag{19}$$

The new decision vector that defines an individual is then:

$$\mathbf{v}_{\text{individual}} = [M_1\ M_2\ M_4\ M_5\ M_6]. \tag{20}$$

- The fuel must be loaded symmetrically with respect to the longitudinal axis (y). In addition, it can also be assumed that the vertical CG component (z) of each fuel tank does not change. Then, the cost term, J_1 (4), is reduced to:

$$J_1 = J11 = \left| X_{cg\_\text{obj}} - X_{cg} \right|. \tag{21}$$

Consequently, the final formulation of the optimization problem is:

$$\text{Find}\,\boldsymbol{M}' = [M_1, M_2, M_4, M_5, M_6], \tag{22}$$

$$\begin{aligned}\text{Min}\,J(\boldsymbol{M}') = {} & P_1 \cdot J1(ZFW, MF_{\min} Mi) + P_2 \cdot J2(MF_{\min}, M_i) + \\ & P_3 \cdot J3(M_{eng}, MF_{\min}, M_i) + P_4 \cdot J4(MF_{\min}, M_i) + P_5 \cdot J5(MF_{\min}, M_i)\text{'}\end{aligned} \tag{23}$$

$$\begin{aligned}& s.t.: \\ & C1 = M_i - M_{\max\_i} \le 0, \\ & C2 = -M_i \le 0, \\ & C31 = X_{CG\min}(ZFW + MF_{\min}) - X_{CG} \le 0, \\ & C32 = X_{CG} - X_{CG\max}(ZFW + MF_{\min}) \le 0, \\ & C4 = MF_{\min} - \sum_{i=1}^{6} M_i = 0, \\ & C5 = M_6 - \eta \cdot M_{\max\_6} \le 0,\end{aligned} \tag{24}$$

where M_i corresponds to tank "*i*"; the parameters, ZFW, M_{Fmin}, and M_{eng}, are calculated for a particular flight plan; the other variables (X_{cg_obj}, X_{CGmin}, X_{CGmax}, CG_{tnk_i}, etc.) are known for a specific aircraft.

The GA configuration, summarized in Table 1, is as follows.

The number of individuals of the initial population, after trying different population sizes, was set to $N = 30$. The results of using a bigger population, more selected parents, and a larger number of iterations proved that neither the final results nor the evolution of the cost functions improve. Indeed, the amount of fuel assigned to each tank was quite similar for all the configurations that were tested.

However, as expected, the larger the population the greater the computational time. The time required for the algorithm to obtain the solution presented in Section 5.1 was 51.6519 s. When doubling the population to $N = 60$, the computational time was 72.8837 s. Keeping this number of individuals and incrementing the number of parents from Np = 8 to Np = 16, the time required was 82.2281 s. If the initial values of population and parents N = 30, Np = 8, are used, but the number of iterations is doubled, 40,000, the computational time was 102.4615 s, that is, almost twice the original one.

Although the algorithm is not required to work in real time, it has been designed to be run before the refuelling operation, so it is desirable that it does not take too much time. Thus, those GA configuration parameters were set to the values in Table 1, trying to find a compromise between execution time and solution convergence.

A random initialization of the initial population produces non-feasible solutions. Therefore, sequential filling of the tanks, distributing the total fuel mass in cascade, was tried. Each tank was loaded with a random fuel quantity within a range (up to 10% of the maximum tank capacity). With this option, the solution was feasible but random perturbations make the resultant CG to be laterally outside the vertical asymmetric plane. For this reason, this last strategy was modified and a random quantity was added to both sides of the aircraft, that is, adding the same amount of fuel in both inner tanks and in both outer tanks. This way, the constraints are fulfilled.

The number of parents was eventually fixed to Np = 8. They were selected using the roulette method. Three types of crossover operator were applied, namely asymmetric, simulated binary, and binary with constraints. After some tests, the first one was chosen (asymmetric) because it is the simplest one and the others do not significantly improve the solution. At each generation, the parents are replaced by the resultant children.

Uniform and semi-random mutation operators were applied to a random number of individuals (adding up to 20% of the maximum tank mass). As an alternative, semi-random mutation was also applied to a random number of individuals of symmetric tanks (if exists). This last option was selected because it gave better results.

The maximum number of generations was set to 20,000. This value provides a good convergence in an acceptable computational time.

TABLE 1 GA configuration parameters

Initial population (N)	30
Number of parents (np)	8
Selection method	Roulette
Crossover operator	Asymmetric (P_c < 0.8)
Mutation operator	Semi-random (P_m < 0.2)
Recombination method	Direct substitution of children by parents
Stop method	N° of generations <20,000

5.4 | Tuning the objective function weights

As introduced at the beginning of this section, each term of the objective function is weighted by a tuning factor, P_i. This is a multi-objective problem since the optimal value of any of the five costs of the objective function influences the other values. For example, cost J_3 reaches its minimum when the mass of fuel in the inner tanks is equal to M_{eng}. However, the cost function, J_2, reaches its minimum when the amount of fuel in the inner and outer tanks is the same. That is, there are several possible solutions and weights are used to find a good solution based on experience.

Nevertheless, it is necessary to come up with a viable and safe compromise solution. That is why the weights must be adjusted by experts who know their effects on the final solution. Adjusting the weights of the cost function is not an easy task. A brief analysis will demonstrate this statement.

The gain P_1 weights the objective function term J_1 (CG positioning); if it is set to a very large value compared to the other weights, the solution will converge to a fuel mass distribution with an aircraft CG near the optimum, but the other cost functions will increase a lot. For example, let the initial vector of weights be P = [100 1 1 1 1]. In Figure 3 (right), it is possible to see how the CG of the best individual (blue line) is very close to the optimum (dotted green line), being the difference around 30 cm. But according to Figure 3 (left), the cost of the other objective function terms is quite high, especially structure load (green line), CG displacement (magenta line), and refuelling time (blue line).

Giving larger values to P_3 (in-flight transfers) and to P_4 (refuelling time), such as P = [1 1,100,100 1], the solution does not converge to the optimum CG (Figure 4, right), which is the most important requirement. In Figure 4 (left), we can see that the cost of the CG optimization (green line) is high.

If all the weights have the same value, the GA randomly minimizes the cost functions, but the solution does not converge. Figure 5 shows the results of giving the same value to all weights, P = [1 1 1 1 1]. The variability of the best solution increases at each iteration, without a clear trend, opposite to previous cases. That is why there are so many jumps in all the costs associated with the fuel distribution.

A very different distribution of weights would not be feasible because not all criteria are equally relevant. Besides, small variations of the weights are not significant since the randomness of the GA makes the variations not noticeable. For example, Figure 6 shows the cost functions (left) and the CG evolution (right) when there is little difference between the weights.

Therefore, cost functions need to be adjusted based on this expert knowledge and experience. The most important objective is to keep the CG position within a stable range, first, because this is the main objective of the refuelling algorithm; second, since there are several tanks, there are several possible distributions of the fuel between the tanks that allow the aircraft to reach the same CG position. That is, if the CG is very close to the optimum, different weights can be selected for the rest of the costs depending on other considerations.

The second criterion in order of importance is to reduce transfers during the flight; that is, the inner tanks must be loaded with the mass of fuel that the engines are expected to consume during that particular flight. This is also important since, in the event of a total failure of the fuel transfer system, the engines would continue to be powered.

Therefore, costs, J_1 and J_3, are the most important ones because they improve the aircraft efficiency and safety; so, their corresponding weights, P_1 and P_3, should be larger than the others. On the other hand, the cost function, J_2, has less relevance because forces due to fuel mass are almost negligible with respect to other forces that cause structure loads; so, the weight P_2 can be smaller than the others. The weight

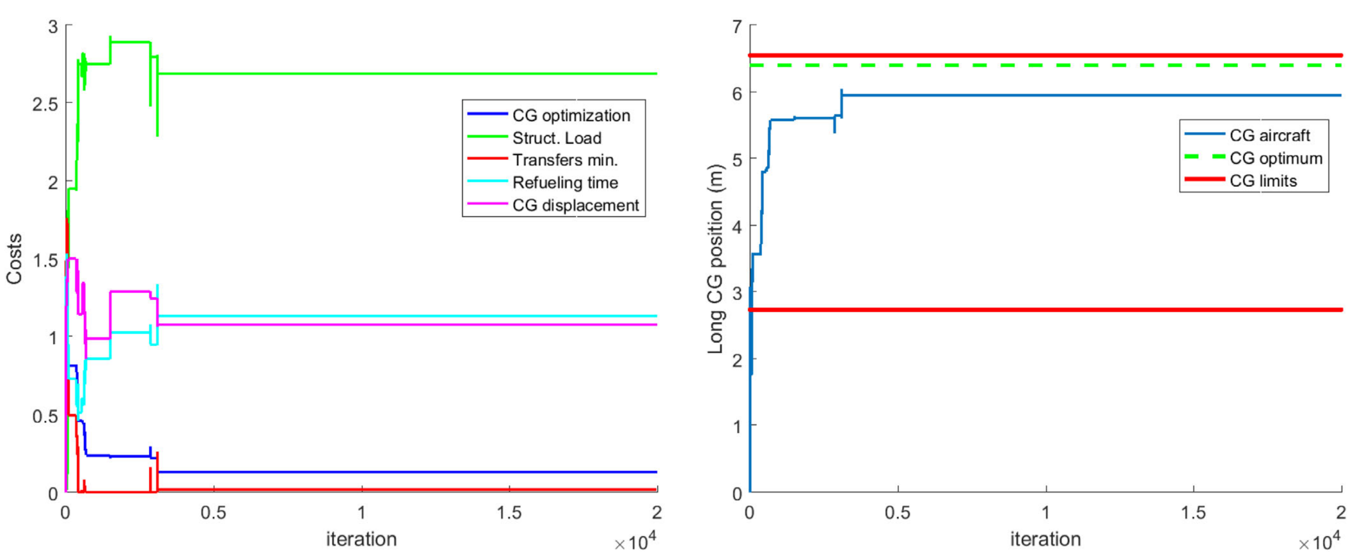

FIGURE 3 Cost functions (left); CG evolution (right). P = [100 1 1 1 1]

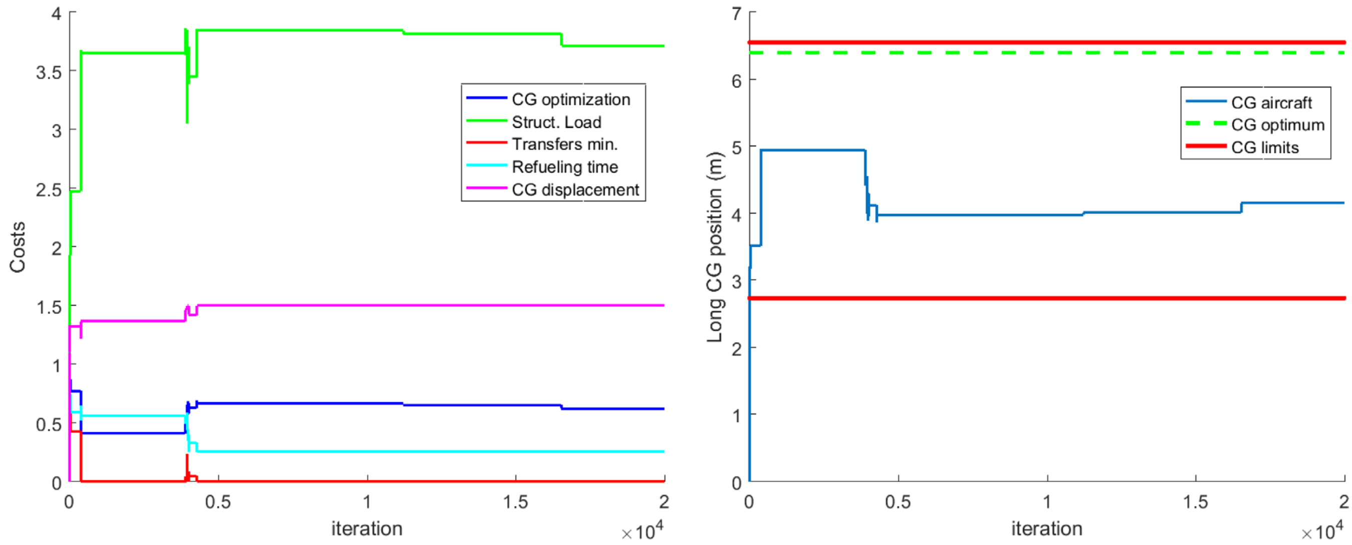

FIGURE 4 Cost functions (left); CG evolution (right). P = [1 1,100,100 1]

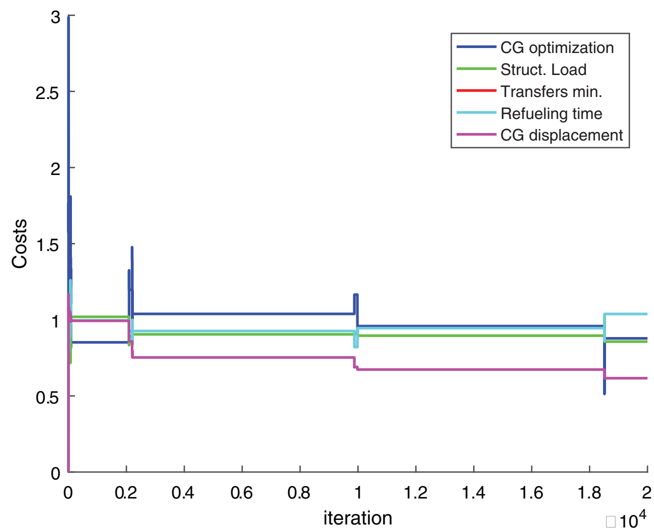

FIGURE 5 Cost functions, P = [1 1 1 1 1]

associated to the cost function J_4 is set to a small value since, for this particular plane, the fuel management system transfers the fuel between tanks quickly enough with respect to the handling time.

Considering all these criteria, the cost weight vector is tuned as follows.

$$P=\begin{bmatrix}\text{CG position optimization}\\ \text{Stuctural load}\\ \text{Fuel transfers min.}\\ \text{Refueling time}\\ \text{CG displacement}\end{bmatrix}=\begin{bmatrix}100\\70\\90\\60\\80\end{bmatrix}.$$

6 | A CASE STUDY

The GA based on-ground refuelling algorithm has been applied to a real case. Let us suppose that the initial solution is far away from the optimum one and, not only that, but it is unfeasible. For example, let the initial fuel mass vector of the six tanks be as follow:

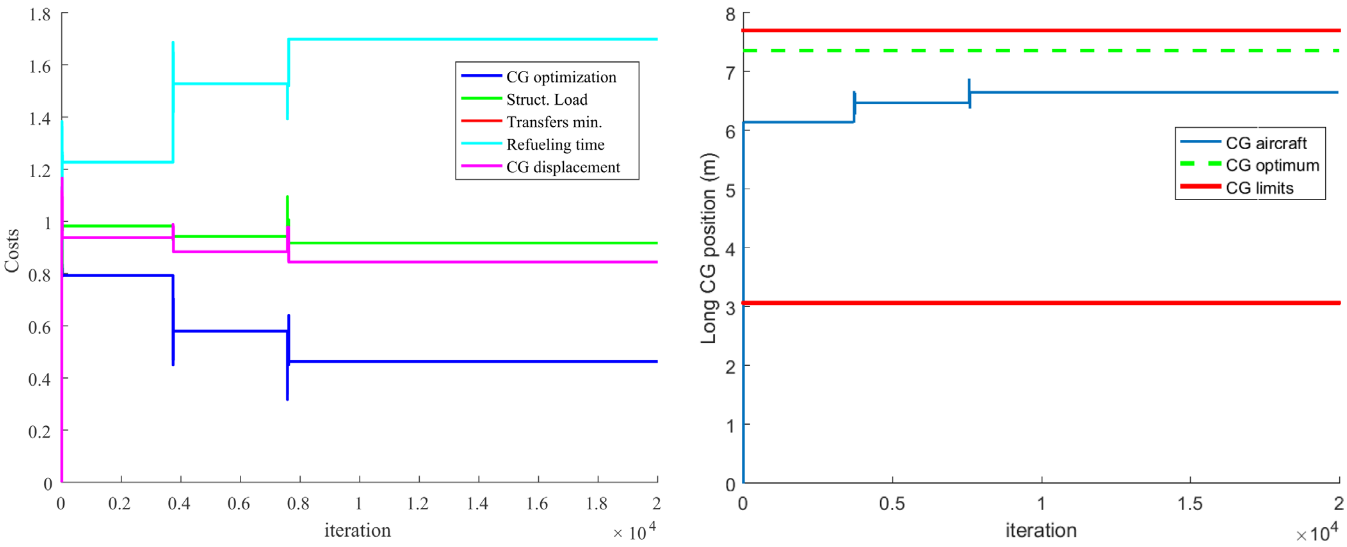

FIGURE 6 Cost functions (left); CG evolution (right). P = [95 75 85 65 75]

$$v_{\text{individual}}\big|_{\text{init}}[2865, 0, 0, 2865, 40000].$$

Considering that the aircraft will be refuelled with 75,000 kg, with a payload of 10,000 kg and the ZFW-CG at 0.4 m behind the reference point, the initial decision vector is then given by:

$$v_{\text{decision}}\big|_{\text{init}} = \begin{bmatrix} 2865 \\ 0 \\ 75000-2865-2865-40000 \\ 0 \\ 2865 \\ 40000 \end{bmatrix} = \begin{bmatrix} 2865 \\ 0 \\ 29270 \\ 0 \\ 2865 \\ 40000 \end{bmatrix}$$

That is, initially the inner tanks are empty, the outer tanks are at their maximum capacity, the central one is near its maximum level, and the trim tank overflows its capacity. This initial solution is non-suitable: The constraint C_1 is unfulfilled and the CG position is outside the stability margin, located behind the limit (around 7 m respect to the origin).

Figure 7 (left) shows the evolution of the costs for the best individual. The GA generates suitable solutions very quickly, and it also reduces the costs, especially the ones with higher weights (as CG positioning, dark blue line). Besides, when an acceptable solution is found (at iteration 200, approximately), it is difficult to further improve the best individual.

Regarding the evolution of the fitness of the population, during the first iterations, it is zero because the individuals are not feasible. Then, there is a jump when you get the first viable individual. From here, the GA tries to improve the solution using the crossover and mutation operators.

The fact that the CG positioning is prioritized (close to the optimal) can be seen in Figure 7 (right), even if it does not reach the optimal value due to the influence of the other cost functions. The CG was initially outside the limits, but the GA quickly finds a solution where the CG is within the stability margin.

6.1 | Results discussion: Comparison with the traditional refuelling

In the aeronautical sector, the typical refuelling operation on a civil aircraft is performed using a sequence of pre-established hierarchical rules. That is, some tanks are loaded up to a predefined amount of fuel mass, then others are filled, and so on until the total mass of fuel is fully charged in the tanks.

In a study by Langton et al. (2010), an example of a refuelling process for the A340-600 aircraft is presented. That aircraft has a large number of tanks, specifically four feed tanks (one per engine), two outboard feed tanks (one in each wing), a centre tank located between the wings and below the cabin, and a trim tank located within the horizontal stabilizer. The set of rules that are applied to refuel this aircraft are as follows. The

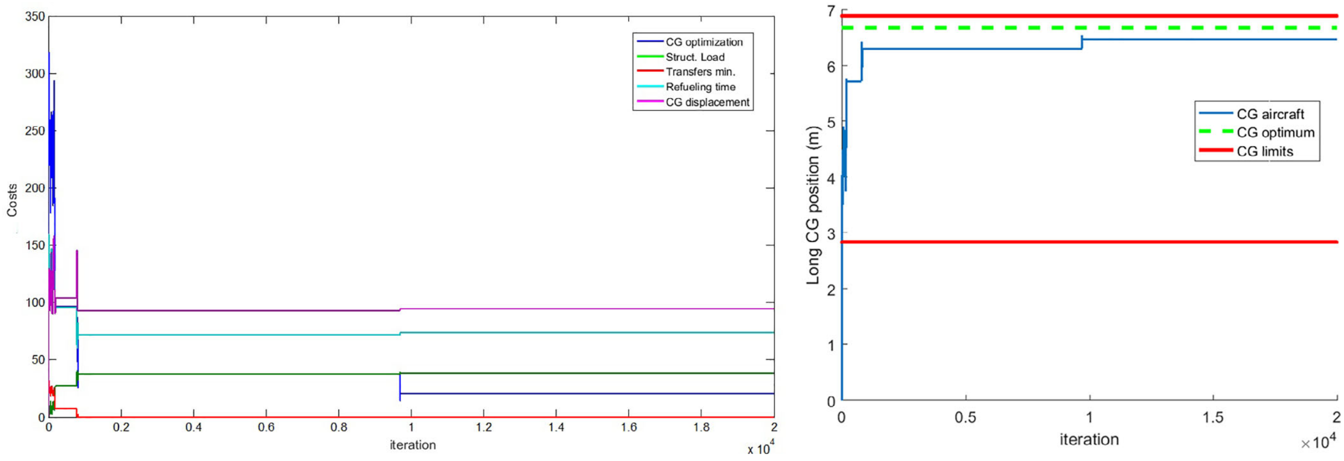

FIGURE 7 Cost functions evolution (left); CG positioning optimization (right)

feed tanks are first filled to three tones, each making the total fuel upload 12 tons. Outboard wing tanks are then filled to about 95% of capacity before the feed tank fill process is restarted. When the total fuel on board reaches about 86 tons, the centre tank and trim tanks begin filling. Moreover, at this point, the outer feed tanks (which are about five tons smaller than the inner feed tanks) stop filling. At 110 tons, the outer feed tanks stop filling and the centre tank and trim tanks continue filling. At 144 tons on total fuel load, all tanks begin the final topping-up to a maximum of 171.5 tons based on a fuel density of 0.88 kg per litre.

This manual refuelling procedure is going to be compared with the proposed automatic and optimal refuelling. The initial conditions are: 65,000 kg total fuel mass, 10,000 kg payload, and ZFW-GG at 0.4 m behind the reference point. It is assumed that 80% of the total fuel mass will be spent by the engines during the flight. Taking as starting point, the traditional distribution of the 65,000 kg of fuel mass, the initial decision vector is:

$$v_{\text{decision}}|_{\text{init}} = [2865, 28435, 0, 28435, 2865, 2400]$$

According to this initial fuel distribution, both outer tanks are filled at their maximum capacity, the inner tanks are loaded close to the maximum (i.e., 56,870 Kg = 2 × 28,425 kg), the central tank is empty and the trim tank has the remaining fuel; the CG position is 5.7735 m behind the reference point.

The cost vector is:

$$C_{\text{init}} = \begin{bmatrix} \text{CG position optimization} \\ \text{Stuctural load} \\ \text{Fuel transfers min.} \\ \text{Refueling time} \\ \text{CG displacement} \end{bmatrix} = \begin{bmatrix} 158.91 \\ 38.55 \\ 0 \\ 46.61 \\ 109.09 \end{bmatrix}$$

Now, we apply the heuristic GA refuelling strategy. The cost function evolution is represented in Figure 8 (left). We can observe how the cost associated to the CG positioning (blue line) shows a rapid convergence as in the previous scenario.

The minimization of fuel transfers is barely seen in Figure 8 (left) because its cost is always zero. The reason is that the best member at each iteration has loaded more than 80% of the total mass of fuel into the inner tanks. In other words, the algorithm has prioritized solutions in which at least this amount of fuel is kept inside the inner tanks and, therefore, the transfer of fuel is not necessary.

In Figure 8 (right), it is possible to see how the final solution for the CG positioning is quite acceptable, with the CG near the optimum, at 7.25 m from the reference.

Minimization of CG displacement during take-off is also relevant. In fact, during the first few iterations, the algorithm finds a solution that improves the CG position at the expense of increasing the CG displacement. However, GA evolves towards a better solution with a slight increase in cost J_1 (CG position) but significantly decrease in cost J_5 (CG displacement).

It is also possible to see in the previous figures that there are not many jumps in the evolution of the best solution. That is, it is difficult to greatly improve the classic solution, which was viable from the beginning. This was to be expected as the expert knowledge used to load the tanks is the same as that included in the heuristic evolutionary algorithm. This shows that the objective function we have defined is adequate. Finally, it is worth noting that the convergence of the algorithm to the solution is good.

The final solution found by the GA is:

$$v_{\text{decision}}|_{\text{final}} = [2852, 25681, 3519, 25681, 2852, 4414]$$

Compared to the classical solution, part of the fuel mass is drawn from the outer and inner tanks (51,362 kg), but more than 80% of the total fuel mass is kept in the inner tanks (where the fuel that is going to be used during the flight is stored). This fuel has been transferred to the central and trim tanks. That is, almost all the fuel that will be consumed by the engines is in the inner tanks, which means that the GA has been able to make the intelligent decision to withdraw all the amount of fuel that is left to be consumed by the engines.

In addition, some of the fuel that is removed is used to fill a large part of the trim tank, so that the CG moves back. But it is also used, along with some fuel mass from the outer tanks, to transfer fuel to the centre tank with two goals: First, to improve as far as possible the weight distribution on the wings (improving structural load) and, on the other hand, to globally improve the displacement of the CG during the take-off.

This new distribution places the CG behind, closer to the optimal position (6.4467 m behind the reference point), since the CG target position is 7.25 m, and the classical solution placed it 5.7735 m behind.

The cost vector is now:

$$C_{\text{final}} = \begin{bmatrix} \text{CG position optimization} \\ \text{Stuctural load} \\ \text{Fuel transfers min.} \\ \text{Refueling time} \\ \text{CG displacement} \end{bmatrix} = \begin{bmatrix} 91.5784 \\ 34.4197 \\ 0.3973 \\ 82.9021 \\ 94.34 \end{bmatrix}$$

In other words, the GA solution is similar to the classical one but slightly better in terms of positioning the CG, being feasible and staying within the safety margins.

6.2 | Validation with real data

Comparisons of this automated and optimized on-ground refuelling strategy with other real cases would be highly desirable but, due to the confidentiality to which the aeronautical companies are subjected, it is not easy to obtain real data to validate the optimization with new examples.

In fact, the on-ground refuelling process is typically manually done, and it changes for each type of aircraft and also depends on the planned flight. Typically, the classical on-ground refuelling scheme is programmed into on-board computers and/or is only accessible to operators who

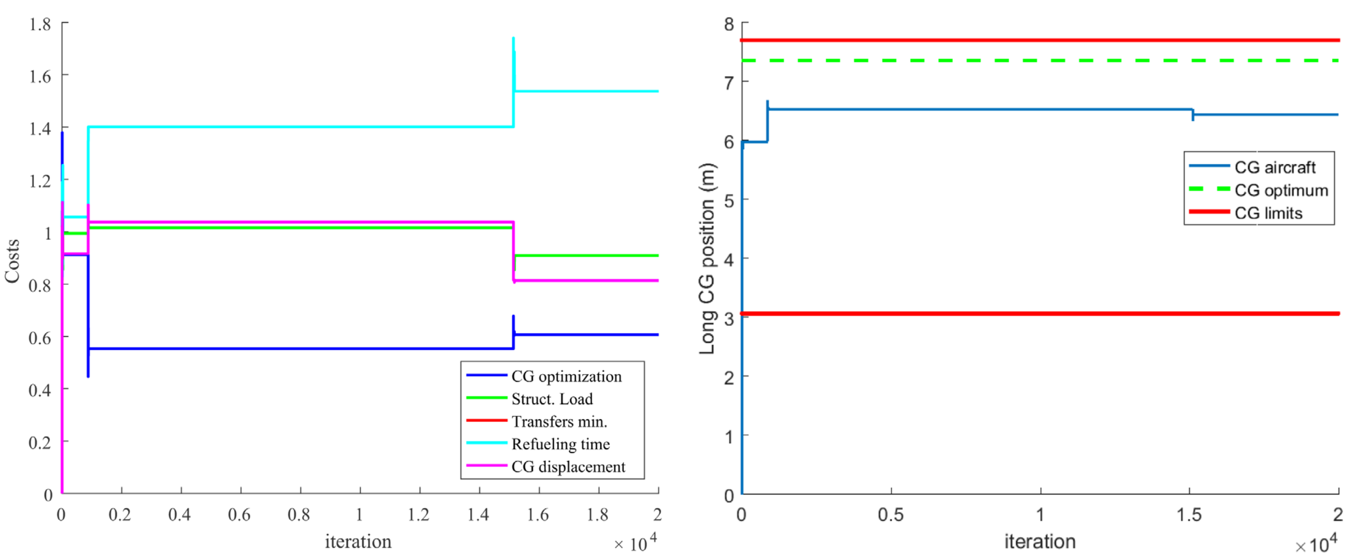

FIGURE 8 Cost functions evolution (left); CG positioning optimization (right)

have to follow it. For each aircraft, a specific refuelling strategy is developed based on the technical and operational specifications of the aircraft, and can be considered confidential and protected information.

While this is true, in a recent article by Yusuf, Bello, Gimba, and Usman (2019), some data on the initial refuelling for an aircraft, relatively similar to ours, are reported. So, we have applied our optimized refuelling algorithm and compared the results.

The initial data of this aircraft, which has seven fuel tanks, are as follows: Left and right feed tanks: 23,000 kg × 2; left and right mid tanks: 14,000 kg × 2; left and right outer tanks: 4,000 kg ×2; Trim tank: 0 kg. That means a total of 82,000 kg of fuel.

Taking that initial fuel amount as starting point, and applying the optimized on-ground refuelling algorithm, results are: left and right central tank: 5,835 kg; left and right inner tanks: 32,901 kg × 2; left and right outer tanks: 2,767 kg × 2; trim tank: 4,828 kg.

The differences between the distribution of the reference paper and our solution are mainly due to:

- It is not the same aircraft. This aircraft has seven tanks, three in each wing and none in the centre, while ours has six tanks, two in each wing and one in the centre; they both have a tank in the tail.
- The second difference is that we cannot be sure that the fuel has been loaded following a classic distribution, since no reference is made to any particular aircraft in the cited paper.

If we assume that the mid and feed tanks, from the paper of Yusuf et al. (2019), are equivalent to our inner tanks, and that the load of our central tank would be distributed in the mid tanks, then:

- The sum of mid and feed fuel load, that is, 37,000 kg × 2, is equivalent to the sum of the fuel load of our inner tanks and half of the central tank (35,819 kg × 2). That is, the magnitudes are very similar, but with slightly lower load in ours.
- Comparing Yusuf's outer tanks (4,000 kg ×2) with ours (2,767 kg ×2), the order of magnitude is similar but with a certain decrease in load in our case.
- Comparing trim tank loads, 0 kg versus 4,828 kg, the reason of the difference is due to the fact that our algorithm distributes the fuel to obtain a more optimal CG; in fact, in the work of Yusuf et al. (2019) is possible to see how, at the beginning of the simulation, the fuel is moved to the trim tank, thus following the same trend.

Therefore, it can be said that, although the comparison is not completely fair since the aircrafts are not the same, the magnitudes of the amount of fuel in the tanks are similar, and the differences come precisely from the improvement that the algorithm introduces when weighting the objective refuelling function.

In any case, the approach proposed in this work, a constrained weighted objective fuel distribution, can be applied to any aircraft without loss of generality. Each component of the cost function can be derived from the parameters of the particular aircraft, and each cost component is prioritized using weights, and, therefore, can be adjusted for a specific aircraft refuelling procedure.

7 | CONCLUSION AND FUTURE WORK

In this paper, we have addressed the problem of on-ground refuelling in commercial aircraft. This has allowed us to propose a new approach based on evolutionary algorithms that improve the traditional refuelling solution. The procedure is more general and optimal.

An objective function has been designed for the heuristic optimization algorithm based on expert knowledge, taking into account the actual design criteria of civil aircraft to maintain margins of stability and safety. Using the position of the centre of gravity as the main criterion, but at the same time including other objectives, a strategy is developed that fills the fuel tanks of the airplane keeping them within the desired margins. Due to the strong restrictions of this problem, genetic operators have been modified to obtain feasible solutions.

These requirements have been weighted to prioritize some of the criteria, and have been adjusted after a qualitative and quantitative analysis of the problem. This approach works with heterogeneous variables and, in addition to maximizing safety and stability criteria, it takes into account aircraft structure load, the displacement of the centre of gravity, and in-flight fuel transfers, which are minimized.

This approach has a clear advantage over the traditional refuelling strategy, which follows a set of predefined rules. The latter cannot be improved by adding new considerations or new criteria, or changing the importance of any of them. Furthermore, for the design of a new airplane, it is necessary to analyse and define a new hierarchy of rules for its on-ground refuelling. However, using the GA, the initial loading strategy can be easily obtained simply by changing some of the aircraft parameters and the weights of the cost functions.

The GA solution meets the requirements and limitations imposed. In fact, the results are very encouraging: It obtains a CG position very close to the optimal one, minimizing fuel transfers and ensuring sufficient supply of engines. This shows the usefulness of this evolutionary approach to tackle this problem.

As future work, self-learning methods could be included to adjust the weights of the objective function. Furthermore, the definition of the objective function and the adjustment of the cost weights have been made according to expert knowledge and based on experience. It would be interesting to adjust these weights using historical flight data.

On the other hand, this problem is common to other vehicles where fuel distribution influences stability, such as ships (Chou, Chou, Hsu, & Lu, 2017), where this approach can be extended.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article. Some technical characteristics that have been also used can be found in (Airbus, 2020).

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How to cite this article: Plaza E, Santos M. Knowledge based approach to ground refuelling optimization of commercial airplanes. *Expert Systems*. 2021;38:e12631. https://doi.org/10.1111/exsy.12631