GENERATING SCENARIOS FOR AIR TRANSPORT SUSTAINABILITY

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ABSTRACT

This study addresses the issue of the aviation sustainability for the next decades. A modelling approach considering the World air transportation sector is developed by taking into account the potential contribution of air transport to fuel consumption and to environment impacts along a timeline of several decades. It is considered that to reach audacious sustainability objectives, new aeronautical technologies must be developed while air transport operations must be permanently improved through optimization. This should result in huge needs for investment in R&D from aeronautical manufacturers and for equipment by air transport operators (airlines fleets, airport infrastructures) and questions such as what, how much and when should be answered. The proposed framework allows levels of detail (air transport services, aircraft types and technologies) compatible with strategic decision making aimed at producing the supply necessary to meet the demand in air transport services while meeting sustainability objectives. Once informed this framework will allow either the test possible coherent solution scenarios through simulation or to formulate global optimization decision making problems with respect to R&D investment in civil aeronautics, air transport operators fleet renewal and airport upgrading.

Keywords: Aviation Sustainability, Energy, Environment Impacts, Systems Analysis, Modelling, Fuzzy Sets.

1. INTRODUCTION

Sustainability for humanity can be defined as meeting our own needs without compromising the ability of future generations to meet their own needs (Purvis, Mao & Robinson, 2018). Sustainability has become an essential for the aviation sector which is a direct polluter of the Earth's atmosphere through its emissions of CO_2, NOx and other particles, noise and the creation of contrails contributing to the greenhouse effect (Ackerman, 2016), (ICAO, 2019), (EASA, 2019), (EASA, 2020). Two decades ago, with the exception of the issue of aeronautical noise, reducing environmental impact was not a top priority for the aeronautical sector. In the last decade, aircraft manufacturers and airlines have faced an increasing pressure from governments, customers, employees, and investors to act assertively on environmental issues and to promote and achieve sustainable environmental goals and targets. Face to an expected global trend of sustained growth in air transport for the coming decades, sustainability appeared as a necessity as well as a genuine and enormous business opportunity for aircraft and engine manufacturers and for service providers (airports and airlines) (Boeing, 2022), (Airbus, 2022). However, during the Covid-19 pandemic air traffic fell sharply, temporarily relieving the environmental impact of this industry while airlines revenues dropped. Today fragilized airlines are struggling with a sharp increase in the price of traditional aviation fuel and the sustainability issue become momentarily less of a priority for them.

In this study it is considered that forecasting the aviation sustainability for the next decades is a goal full of pitfalls if we consider the multitude of hazards that can arise during this period. Among the many existing uncertainties, demand for air transport services will be represented using fuzzy modelling.

A modelling approach considering the World air transportation sector is developed by taking account of the potential contribution of air transport to fuel consumption and to environment impacts along a timeline of several decades. The main actors of the air transport service supply are considered globally (aircraft manufacturers, engine manufacturers, fuel producers, airlines, airports operators and air traffic management) while a new unit is introduced to allow a coherent treatment of the energy issue. It is considered that to reach audacious sustainability objectives, new aeronautical technologies must be developed while air transport operations must be permanently improved through optimization. This should result in huge needs for investment in R&D from aeronautical manufacturers and for equipment by air transport operators (airlines fleets, airport infrastructures) and questions such as *what*, *how much* and *when* should be answered.

While remaining generic at this stage of the study, the proposed framework allows levels of detail (air transport services, aircraft types and technologies) compatible with strategic decision making aimed at producing the supply necessary to meet the demand in air transport services while meeting sustainability objectives. Once informed this framework will allow either to test possible coherent solution scenarios through simulation or to formulate global optimization decision making problems with respect to R&D investment in civil aeronautics, air transport operators fleet renewal and airport upgrading.

The main part of the paper is devoted to the description of the components of the framework including the structural assumptions with respect to the air transport sector (classification of air transport services, aircraft, technologies, fuels and impacts), an energy oriented quantification of air transport activities, fuel consumption and environment impacts, the characterization in time and money of R&D investments, the formulation of quantitative objectives for environment impacts and supply-demand constraints for air transport services along the considered timeline, finally, conclusion points out the possible utilizations of the proposed framework.

2. AIR TRANSPORT COMPOSITION, SERVICES AND EMISSIONS

Let M be the number of considered classes of air transport services developed by civil aviation, such as very-short, short, medium, long range passenger/cargo air transportation.

Let N be the number of classes of air transport vehicles which may be considered. These classes can be characterized by rotary/fixed wings, single/multiple engines, piston/jet engines, narrow/medium/large body aircraft, and aircraft fuels. Today considering the multitude of existing aircraft designs to attend a given class of air transport services, it is assumed that M < N.

Let *L* be the number of different types of fuel/energy which can be potentially used with different aircraft types and technologies.

Each class of aerial vehicle *n* is devoted to a class *m* of air transport services, so that the set $\{1,\cdots,N\}$ can be partitioned in *M* subsets $S_1,\cdots,S_m,\cdots,S_M$.

A set I^n of aeronautical technologies (aircraft characterized by their propulsive systems, size and aerodynamics), is considered for each class of aerial vehicle $n \in \{1,\cdots,N\}$ with $I^n = I_E^n \oplus I_D^n \oplus I_N^n$ where I_E^n is the set of currently in operation technologies, I_D^n is the set of technologies already under development and I_N^n is the set of potentially new technologies which could be developed and implemented in the considered time horizon.

Let L_i^n be the set of fuels which are used by class *n* aircraft equipped with technology *i*. Here it is supposed that when different fuels are used, their mix is fixed since related with the adopted technology.

The timeline for the considered time horizon is composed of *K* years, starting at year 0.

It appears of interest to introduce a new unit to quantify air transport service with respect to energy consumption while the current units adopted in air transportations (tons or passengers per kilometer) are related with the revenue from customers.

Air transport service quantification:

Let us define here the special unit adopted in this study to quantify air transport service supply and demand when considering energy and environmental issues: tons per equivalent kilometer (TEK) measured in *tons* per *km*.

Consider an air service of class *m* performed by an aircraft of type *n* equipped with technology *i* with a maximum payload PL_i^{nm} and let for a corresponding standard flight LC_i^{nm} be the mean length of a cruise expressed in *km*, $ECD_i^{nm}(k)$ be the energy consumption (expressed in energy units) of the aircraft during take-off, climb to cruise level, descent from cruise level and landing, $ECR_i^{nm}(k)$ be the energy cruise consumption at cruise per flown kilometer for period *k*, the equivalent kilometer for this flight is given by:

$$EK_i^{nm}(k) = LC_i^{nm} \cdot (1 + ECD_i^{nm}(k)/ECR_i^{nm}(k)) \quad (1)$$

$P_i^n(k)$ be the total capacity in payload in tons per equivalent kilometer (*TEK*) of aerial vehicle of class *n* equipped with technology *i* for period *k* is then given by:

$$P_i^n(k) = NA_i^{nm}(k) \cdot NF_i^{nm} \cdot PL_i^{nm} \cdot EK_i^{nm}(\mathrm{k}) \quad (2)$$

where NF_i^{nm} is the maximum number of flights that an aircraft of type *n* equipped with technology *i* can perform in a year air transportation services of class *m* ·This number should be corrected to take into account network effects which can be assessed using current global operations statistics. Here $NA_i^{nm}(k)$is the number of available aircraft of type *n* equipped with technology *i* performing air transport service *m* during period *k*.

The capacity of the air transport sector in year *k*, *P*(*k*), is then given in *TEK* and is the sum for each class of aerial vehicle of the contributions of each current technology:

$$P(k) = \sum_{n=1}^{N} \sum_{i \in I^n(k)} P_i^n(k) \qquad k \in I^n(k) \subset I^n \qquad n \in \{1,\cdots,N\} \quad (3)$$

while the total *TEK* capacity of the class *n* of aerial vehicle is given by:

$$P^n(k) = \sum_{i \in I^n(k)} P_i^n(k) \quad n \in \{1,\cdots,N\} \quad (4)$$

and the total *TEK* capacity available for air transport service *m* is given by:

$$A^m(k) = \sum_{n \in S_m} P^n(k) \; m \in \{1,\cdots,M\} \quad (5)$$

Quantifying energy and environmental impacts: The environmental impact of each aeronautical technology is supposed composed of *J* different components mainly related with the type of used fuel and is relative to one *TEK*. It is assumed that continuous improvements are introduced in each aeronautical technology according to its maturity. Fuel consumption per *TEK* expressed in energy units or equivalent and environmental emissions per *TEK* expressed in tons are given respectively by:

$$EN_i^{nl}(k - k_i^n) \quad \text{for} \quad k \geq k_i^n, \quad l \in \{1, \cdots, L\}, \quad i \in I(k), \;\; n \in \{1, \cdots, N\} \tag{6}$$

$$EI_i^{nj}(k - k_i^n) \quad \text{for} \quad k \geq k_i^n, \quad j \in \{1, \cdots, J\}, \quad i \in I(k), \;\; n \in \{1, \cdots, N\} \tag{7}$$

where k_i^n= 0 if $i \in I_E^n$ and is the year of introduction in operations of the new aeronautical technology $i \in I_D^n \oplus I_N^n$. The $EN_i^{nl}(k - k_i^n)$ and $EI_i^{nj}(k - k_i^n)$ are supposed to be known decreasing functions of the time. The reference cruise consumption for aircraft type *n* equipped with technology *i* during year *k* is given by:

$$ECR_i^{nm}(k) = \sum_{l \in L_i^n} EN_i^{nl}(k - k_i^n) \tag{8}$$

Accordingly, the operations costs associated to a produced *TEK* (no scale economics are considered in the present model) obeys to decreasing functions of time tending to a limit value and representing improved procedures through learning:

$$C_i^n(k - k_i^n) \quad \text{for} \quad k \geq k_i^n, \quad j \in \{1, \cdots, J\}, \quad i \in I^n(k) \tag{9}$$

This expected decreasing functions $E_i^{nj}$and C_i^n are the result of improved operations conditions through experimental knowledge and training. The contribution of aeronautical technology *i* to the consumption of fuel *l* and environmental impact *j* for class *n* aerial vehicle at period *k* are respectively given in year *k* by:

$$f_i^{nl}(k) = EN_i^{nl}(k - k_i^n) \cdot P_i^n(k) \quad l \in \{1, \cdots, L\}, \quad i \in I^n(k) \tag{10}$$

$$e_i^{nj}(k) = EI_i^{nj}(k - k_i^n) \cdot P_i^n(k) \quad j \in \{1, \cdots, J\}, \quad i \in I^n(k) \tag{11}$$

and the contribution of air transport service *m* to consumption of fuel *l* and environmental impact *j* at period *k* are given respectively by:

$$\varphi^{ml}(k) = \sum_{n \in S_m} \sum_{i \in I^n(k)} EN_i^{nl}(k - k_i^n) \cdot P_i^n(k) \quad l \in \{1, \cdots, L\}, \;\; m \in \{1, \cdots, M\} \tag{12}$$

$$\xi^{mj}(k) = \sum_{n \in S_m} \sum_{i \in I^n(k)} EI_i^{nj}(k - k_i^n) \cdot P_i^n(k) \quad j \in \{1, \cdots, J\}, \;\; m \in \{1, \cdots, M\} \tag{13}$$

When some selective fuel restrictions are applied to particular air transport services or globally to the whole sector, constraints such as the following must be considered:

$$\varphi^{ml}(k) \leq \varphi_{max}^{ml}(k) \quad \text{for some} \quad l \in \{1, \cdots, L\} \text{ and some } \; m \in \{1, \cdots, M\} \tag{14}$$

$$\sum_{m \in \{1, \cdots, M\}} \varphi^{ml}(k) \leq \Phi_{max}^l(k) \quad \text{for some} \quad m \in \{1, \cdots, M\} \tag{15}$$

where $\varphi_{max}^{ml}(k)$ is an upper limit of fuel type *l* to air transport service m and $\Phi_{max}^l(k)$ is the amount of available fuel of type *l* for the whole air transport service sector.

3. INVESTMENTS AND SUSTAINABILITY OBJECTIVES

A common development model is adopted for each technology under development (I_D^n) or to be developed (I_N^n): a minimum level of investment $IN_i^{n\,min}$expressed in the base year 0 is necessary to develop the new technology and a minimum development delay $T_i^{n\,min}$must be considered.

Let z_i^n be the year in which development of technology *i* has been launched (z_i^n is negative for $i \in I_D^n$) for class *n* aerial vehicle, then the following conditions must be considered:

1) $k_i^n = 0$ for $i \in I_E^n$ and $k_i^n \geq z_i^n + T_i^{n\,min}$ for $i \in I_D^n \oplus I_N^n$ (16)

2) $\sum_{k=z_i^n}^{k_i^n} \frac{IN_i^n(k)}{(1+\rho)^k} \geq IN_i^{n\,min}$ $i \in I_D^n \oplus I_N^n$ with $IN_i^n(k) = 0$ $k \geq k_i$ for $i \in I^n(k)$ (17)

where ρ is a discount rate which can be changed accordingly with different scenarios.

If technology (*i*, *n*) with $u \in I_N^n$, depends of the availability of technology (*u*, *m*) with $m \neq n, u \in I_D^m \oplus I_N^m$, it will be necessary to introduce antecedence restrictions such as:

$$z_i^n \geq k_u^m \tag{18}$$

Observe that this type of constraints allows to take into account situations where a technological improvement is profitable to different types of aerial vehicles or air transport services.

The evolution of the production potential of each technology, $i \in I^n(k)$, for each class of aerial vehicle, $n \in \{1, \cdots, N\}$, follows the equations:

$$P_i^n(k) = P_i^n(0) \qquad if\ k \leq k_i^n \tag{19}$$

$$P_i^n(k) = P_i^n(k-1) - R_i^n(k) + N_i^n(k) \quad if\ k > k_i^n \tag{20}$$

where $P_i^n(0)$ is the initial contribution of technology i to $R_i^n(k)$ is the *TEK* capacity of technology (i, n) removed from operation of class n during period k and $N_i^n(k)$ is the capacity of technology (i, n) put into operation during year k. The mean number of aircraft involved in these operations is:

$$RA_i^n(k) = R_i^n(k) / (NF_i^{nm} \cdot PL_i^{nm} \cdot EK_i^{nm}) \tag{21}$$

and

$$NA_i^n(k) = R_i^n(k) / (NF_i^{nm} \cdot PL_i^{nm} \cdot EK_i^{nm}) \tag{22}$$

To the fleet restructuration decisions are associated unit costs CR_i^n and CN_i^n. Unit costs CR_i^n represent the residual value of aircraft which are removed from operation. It is assumed here that CN_i^n includes not only the acquisition cost of new aircraft to perform their reference air transport service but also the costs supported by airports to allow the operation of new aircraft of type n equipped with technology i.

Over period [0, K], the total investment costs which is the sum of R&D investments and aircraft fleets renewal and airport upgrading costs, is expressed in the base year 0 by:

$$C_{Tot} = \sum_{n \in \{1, \cdots, N\}} \left(\begin{array}{c} \displaystyle\sum_{k=0}^{K} \sum_{i \in I^n(k)} \frac{IN_i(k)}{(1+\rho)^k} + \\ \displaystyle\sum_{k=1}^{K} \sum_{i \in I^n(k)} \left(\begin{pmatrix} C_i^n(k-k_i) \\ +CR_i^n \cdot RA_i^n(k) \\ +CN_i^n \cdot NA_i^n(k) \end{pmatrix} / ((1+\rho)^k) \right) \end{array} \right) \tag{23}$$

Here the operational revenues and costs of air carriers and airports are not considered. While this complex issue is related with the future economic conjuncture, it can be observed that historically global profit/loss margins remain small with respect to the global revenues and costs of the air transport sector.

Funds for investment are always limited and this has consequences on the choice of the technologies to be developed, on the timing of this development and on the renewal of aircraft fleets and airports up gradings. These upper limits are not clear in the sector of air transportation since they may be subject to decisions resulting from more global politics. When globally considering investments in R&D in the aeronautical sector devoted to air transportation, it appears possible to relate these levels to some percentage of the total GDP of industrialized countries, while fleet and airport investments can be related with the total flow cash of the air transportation operators (air carriers and airports).

With respect to the sustainability issue, different types of constraints can be considered:

a) When flow constraints about the environmental impacts at the end of the considered time horizon are considered, they are written such as:

$$\sum_{n=1}^{N} \sum_{i \in I^n(K)} EI_i^{nj}(K - k_i^n) \cdot P_i^n(K) \leq F_{max}^j \qquad j \in \{1, \cdots, J\} \tag{24}$$

where F_{max}^j $j \in \{1, \cdots, J\}$ are target upper values for each flow of them, this type of objective having been considered in different aviation forums.

b) When the objective is to limit the global pollution levels resulting from the repeated effect of the air transportation sector on the environment, the following equations can be considered:

$$L^j(k) = \left(1 - \sigma^j\right) \cdot L^j(k-1) \sum_{n \in \{1, \cdots, N\}} \sum_{i \in I^n(K)} \pi_i^{nj}(k) \qquad k \in \{1, \cdots, K\}, j \in \{1, \cdots, J\} \tag{25}$$

where $L^j(0)$ is the initial level of pollution of type j and σ^j is a natural weathering rate for component j. Then, for example, the final pollution level constraints are written as:

$$L^j(K) \leq L_{max}^j \quad j \in \{1, \cdots, J\} \tag{26}$$

where L_{max}^j, $j \in \{1, \cdots, J\}$, are the target upper value for the level of each type of environmental impact. This measure of performance is difficult to be assessed considering the limited availability of reliable models and the complexity in discriminating from other sources of pollution.

c) When the objectives with respect to environmental impacts are categorized by class of air transportation services, final flow level restrictions can be written such as:

$$\sum_{n\in S_m}\sum_{i\in I^n(K)} EI_i^{nj}(K-k_i^n)\cdot P_i^n(K) \le F_{max}^{jm}$$
$$j\in\{1,\cdots,J\},\ \ m\in\{1,\cdots,M\} \qquad (27)$$

where L_{max}^{jm} , $j\in\{1,\cdots,J\}$, are the target upper values for the level of each type of environmental impact produced by air transport service m, $m\in\{1,\cdots,M\}$.

4. GLOBAL AIR TRANSPORTATION MARKET

Here, after introducing a fuzzy representation of demand along the whole time horizon, supply-demand constraints are considered for the air transport sector represented by its main services. The demand for each class of air transportation service, expressed in *TEK*, is supposed to evolve according to a possible trend to which are added uncertainties resulting from the economic and environmental dynamic situations. Although it is impossible for the demand for air transportation to get reliable estimations not only on the long run but also in the short to medium run, different scenarios can be generated. Here for each class of air transport service four close trend scenarios are considered to generate a fuzzy representation (Capitanul, Mora-Camino & Krykhtine, 2016), (Chang & Wang, 1999) of air transportation demand along the planning horizon:

$$D_{min}^m(k) \le D_-^m(k) \le D_+^m(k) \le D_{max}^m(k)$$
$$k\in\{1,\cdots,K\}, m\in\{1,\cdots,M\} \qquad (28)$$

In the case in which yearly rates are considered, these demand levels can be written for $k\in\{1,\cdots,K\}, m\in\{1,\cdots,M\}$ as:

$$D_{min}^m(k) = (1+\alpha_k^m)\cdot D_{min}^m(k-1) \ \text{ with } D_{min}^m(0) = D^m(0) \quad (29)$$

$$D_-^m(k) = (1+\beta_k^m)\cdot D_-^m(k-1) \ \text{ with } D_-^m(0) = D^m(0) \quad (30)$$

$$D_+^m(k) = (1+\gamma_k^m)\cdot D_+^m(k-1) \ \text{ with } D_+^m(0) = D^m(0) \quad (31)$$

$$D_{max}^m(k) = (1+\delta_k^m)\cdot D_{max}^m(k-1) \ \text{ with } D_{max}^m(0) = D^m(0) \quad (32)$$

where $D^m(0)$ is the current level of demand for *TPK* with class n aerial vehicle at the beginning of the considered time horizon. Here we have:

$$\alpha_k^m \le \beta_k^m \le \gamma_k^m \le \delta_k^m \ \text{ for } k\in\{1,\cdots,K\},$$
$$m\in\{1,\cdots,M\} \qquad (33)$$

Supply constraints

Now, adopting a fuzzy notation for each air transport demand, the capacity constraints can be written so that each class of demand m is approximatively covered:

$$\textstyle\sum_{n\in S_m} P^n(k) \ge \widetilde{D}^m(k) \qquad \text{for } k\in\{1,\cdots,K\},$$
$$m\in\{1,\cdots,M\} \qquad (34)$$

The above inequalities cover for air transportation service m for period k the four differentiated situations:

$$D_{min}^m(k) \le \textstyle\sum_{n\in S_m} P^n(k) < D_{mi-}^m(k) \qquad (35)$$

In that case it is accepted that the offered capacity may be slightly smaller than demand.

$$D_{-in}^m(k) \le \textstyle\sum_{n\in S_m} P^n(k) < D_+^m(k) \qquad (36)$$

In that case it is considered that the offered capacity will meet demand.

$$D_+^m(k) \le \textstyle\sum_{n\in S_m} P^n(k) < D_{max}^m(k) \qquad (37)$$

In that case it is considered that the offered capacity may be slightly larger than demand.

$$D_{max}^m(k) \le \textstyle\sum_{n\in S_m} P^n(k) \qquad (38)$$

In that case it is considered that the offered capacity will be larger than demand.

5. CONCLUSION

In this paper a generic framework has been proposed to give support to strategic analysis and decision making with respect to the future of air transportation as a whole when considering the energy and sustainability issues. This model may be improved in many ways, for example by considering that demand for air transport services is not completely exogen and depends of its performance, by taking into account networks effects when considering the production of air transport operators, by including energy consumption of ground vehicles at airports and other air terminals. The information of such a model is a complex task involving many sources of technological, operational and economic knowledge while many uncertainties with respect to, for example, the effectiveness of prospective technologies, should be considered. Once informed this model and once chosen the different constraints levels along the considered time horizon, the feasibility of different global strategies can be assessed while a series of mixed integer optimization problems can be formulated and solved to approach the definition of an efficient sustainable future of air transportation.

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