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Modeling fair air traffic assignment in the vicinity of airports

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ABSTRACT

Aircraft noise is recognized as a serious environmental concern and creates significant political problems. This paper presents a new mathematical model to deal with the aircraft noise in the vicinity of airports. The problem to be solved is defined as an assignment of aircraft operations over the routes in order to minimize the total annoyance to citizens at the same time as respecting a fairness scheme. A social-welfare perspective on the noise distribution problem is taken, in contrast to more traditional acoustics-based approaches.

Starting from the so-called α-fairness Social Welfare Function (SWF) used for maximization problems, we have defined a new α-fairness function for minimization problems. We show that this function has similar properties to the maximization α-fairness SWF. Analytic results (optimal air traffic assignment, bounds for the Price of Fairness) are provided for the basic case i.e. when routes do not intersect. For more complex cases, when routes cross each others, we show, using a case study (the Brussels Airports case), that modern solvers are able to solve the problem to optimality for realistic scenarios.

The model can be used as a decision support tool for a Central Decision Maker (CDM) to allocate flight operations (take-off and landing) over the routes and establish policies in the vicinity of the airport. The paper also provides insights into understanding the relationship between efficiency and fairness.

1. Introduction

Air transport generates social and economic benefits (taxes, employment, city attractiveness…). Unfortunately, it also generates negative environmental externalities among which noise pollution is one of the most cited. This pollution can create social and political problems (Janic, 1999; Schipper et al., 2001). In addition to being uncomfortable on a daily basis, these externalities can increase the risk of serious health damage in the long run (Morrell et al., 1997; Stansfeld and Matheson, 2003; Eriksson et al., 2007).

An important part of the literature[1] is dedicated to the measurement of the noise (defined as an undesired sound) and its resulting annoyance.

Worldwide, the two most widely used cumulative sound energy measures are L_{dn} and L_{den}, which give extra weight to noise which occurs during the evening and the night. These measures are used in much research and by many airports to develop noise disturbance plans, as advocated by Mestre et al. (2011) for the Federal Aviation Administration (FAA). Other cumulative sound energy measures exist and are discussed in the literature; for a complete review see Simpson and Hays (1973),More (2011), Bennett and Pearsons (1981). Based on those measures, authors have proposed a wide variety of annoyance functions such as the “dose-response

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[1] Bassarab et al. (2009) catalog 628 social surveys of residents’ reaction to environmental noise (from 1943 to 2008).

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relationship" (Schultz, 1978; Miedema and Oudshoorn, 2001; Fidell, 2003).

As outlined by Girvin (2009), mitigation strategies can be of four different types. First, reduction at the source by developing quieter airplanes (motor and aerodynamics). Secondly, land-use planning and airport vicinity management. This consists of noise barrier construction, soundproofing of residences and aircraft-compatible path preservation (by expropriation or a building ban). Since this strategy does not deal directly with the source of the negative externality, it does not reduce total aircraft noise. But it can reduce the effects on the impacted population. A third strategy is operating restrictions. This mainly consists of controlling the airport's activity level by imposing a restrictive measure. Those can be either direct restrictions (cumulative noise level limit, prohibition of overflight of aircraft whose noise exceeds a threshold, total number of movements quota or imposition of a curfew) or indirect restrictions through noise taxes or charges.

The last strategy is the noise-abatement operating procedure. As mentioned by Zaporozhets and Tokarev (1998), there are three different types of procedures: (1) take-off and landing approach flight procedures, (2) flight route optimization in the airport's vicinity and (3) optimal distribution of the aircraft over the routes and runways. The two first refer to the optimal control problem (also called optimal aircraft trajectories problem). Gardi et al. (2016) offer a broad view of the problem (formulation and resolution) with a focus on multi-objective optimization. The optimization criterion can be an average sound energy measure (Xue and Atkins, 2006; Khardi and Abdallah, 2012), or a global cost which embeds the fuel price, the delay cost and the noise cost (Nejjari et al., 2005; Visser, 2005). Prats et al. (2010) present a methodology to design optimal aircraft trajectories in which the fairness scheme follows the Rawls principle i.e the objective function is a minimax function. This has been implemented at Girona Airport (Prats et al., 2011b,a). The last procedure refers to the optimal air traffic assignment, which consists of allocating the aircraft operations (take-off and landing) over the predefined routes in order to minimize the objective function, generally an annoyance function (see Section 2.1).

In order to reduce this negative externality for the airport's neighboring populations, The International Civil Aviation Organization (ICAO), in its guidelines (ICAO, 2008), strongly recommends a balanced approach which consists of applying a coherent combination of the different strategies. For a quantitative study on the implementation of the strategy at different airports see Ganic et al. (2015) and Netjasov (2012).

In this paper, we focus on the optimal assignment of the aircraft operations on the routes in order to minimize the total annoyance. We propose to study the problem from a social-welfare perspective, in contrast to the more traditional acoustics-based approaches. Our main contribution is to add the notion of fairness to this problem i.e. the optimal assignment follows a fairness scheme. The fairness scheme is controlled by a single parameter. Moreover, we show that the proposed model can improve the decision process of a Central Decision Maker (CDM) in evaluating the efficiency-fairness trade-off of different allocations.

The next section presents an overview of the theoretical background on social welfare function and fairness in optimization, as well as the relevant literature on the air traffic assignment problem. Section 3 introduces an abstract mathematical representation of the problem and provides analytic results (optimal solution, bounds for the Price of Fairness). In Section 4 we apply our method to the case of Brussels Airport. Finally, Section 5 discusses our results and presents possible extensions of the proposed method.

2. Theoretical background and literature review

2.1. Optimal air traffic assignment

Frair (1984) proposes a mathematical model in order to minimize community annoyance. It includes population distribution in the vicinity of the airport and several technical constraints such as airport capacity and flight demand. The variables of the model are the number of arrivals (or departures) per type of aircraft on (predefined) trajectories during a certain period (e.g. during the day or the night). Annoyance is measured through a dose–response function. It results in a non-linear mathematical problem (NLP), solved by the use of a successive linear approximation optimization algorithm (large instances can be solved). The authors achieve a reduction of between 20% and 40% in the number of people highly annoyed.

Heblij and Wijnen (2008) describe the extension of a Decision Support System (DSS), named HARMOS, with a runway allocation optimization module. This extension allows the user of the DSS to give weight to different objectives functions (for noise, third-party risk and delay) and to obtain the optimal runway allocation relative to weight and population distribution. Hence the optimization module is a multi-objective mixed-integer linear program (MILP). Data for noise and for risk are precomputed respectively by the Integrated Noise Model (INM) and by a third-party risk model developed by the UK National Air Traffic Services. The authors present a case study made on Amsterdam Airport Schipol. After the optimization process, a reduction of almost 30% was obtained both in the number of highly annoyed people and in the risk.

Zachary et al. (2010) present a multi-impact optimization model to reduce aviation noise and CO_2 emissions over a 24 h period. The model is very complete as it makes it possible to "select between available aircraft trajectories, schedules (day, evening, night), operational procedures (e.g. time profiles of turbine power levels at takeoff and climb, flap settings in takeoffs and approaches, altitude variation, …) and fleet composition". Different impact factors (i.e. measure of annoyance) are proposed for the noise. The noise data are preprocessed in the Integrated Noise Model (INM 7.0). Hence for each aircraft type, for each trajectory, for each operational procedure and for each spatial point, a measure of noise (in dB) is given. In order to solve the problem, linearization is applied to the objective function, resulting in an integer programming optimization problem. It is shown that solving the problem can lead to significant improvements. Finally, Ho-Huu et al. (2018) present a new multi-objective optimization formulation for the design