

Developing an Indicator System for Monitoring, Analyzing, and Assessing Airport Sustainability¹

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This paper deals with developing an indicator system for monitoring, analyzing, and assessing sustainability of airports. The sustainability implies simultaneous increasing of the overall social-economic benefits and increasing at a slower rate, stagnating, and/or diminishing of the negative impacts of these airports during the specified medium- to long-term period of time. The indicator system consists of the indicators and their measures reflecting the airport operational, economic, social, and environmental dimension of performances. These include effects-benefits and impacts-externalities of the airport operations. The effects-benefits include mainly the airport contribution to local employment, regional (local) economy, and consequently GDP (Gross Domestic Product). The impacts-externalities embrace local noise, air pollution, congestion and delays, land use (take), and waste.

The particular indicators and their measures are specified respecting interests and attitudes of particular actors involved such as users and providers of air transport services, private and public investors, governmental organizations, local community members, lobbies and pressure groups, and general public.

An application of the proposed indicator system has shown that it could be considered as an initial step in developing a "tool" for assessing the current and prospective level of the airport sustainable development.

Key words: Airport, sustainability, indicator system monitoring, analysis, assessment

1. Introduction

Commercial air transportation has become one of the fastest growing sectors of the world economy. Generally, it is expected to grow over the next two decades at an average annual rate of 5% in the passenger and 6.5% in the freight demand (Airbus, 2006; Boeing, 2007; ICAO, 1994). Such growth has created both positive and negative effects on the society and environment. Generally, the positive effects have included additional employment within and around the sector, and consequent provision of stimulus to the local (regional) and global (country and international) economy and welfare. In particular, commercial air transportation has acted as a driving force by strongly supporting globalization of the industry business and long distance tourism, and consequently contributing to the global welfare. The negative effects have included both direct and indirect negative (damageable) impacts of the system on the society and

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environment (Callum, 2000; Janic, 2007). Direct impacts have embraced aircraft noise around airports, air pollution at the local-airport-, and global- airspace- level, congestion and delays, land use (take), waste, air traffic incidents/accidents, and contamination of sources of drinking water and soil. Indirect impacts and eventual damages of the environment have involved those from producing resources for the air transport infrastructure and services, generally in terms of capital, labor, and energy, as well as those from recycling particular system's components. As expressed in the monetary terms, these damages have been called externalities (Janic, 2007).

Both positive effects and negative impacts of air transport on the society and environment interrelate with each other and are permanently in the dynamic interaction. This fact raises two questions. The first one relates to the overall strategy for managing the further system's development under rising of the public awareness on both its benefits and impacts. One of the reasonable strategies seems to be trading-off between particular effects and impacts. That means that under given circumstances, there should always be a positive net effect to society, which would imply sustainable development. The other strategy could be continuous diminishing of the negative impacts in both absolute and relative terms. The second question relates to options for achieving such development in either strategy. In general, it seems to be possible by establishing a proper balance between the sector's growth of demand driven by its own business logic on the one hand and mitigating impacts by using different technical/technological, operational, and policy measures on the other.

This paper develops an indicator system for monitoring, analysis, and assessment, of sustainable development of a given airport. This indicator system is based on the concept of an airport sustainable development, elaborated effects-benefits and impacts-costs, and specified indicators and measures for quantification of particular effects and impacts.

Therefore, the paper can be considered as a contribution to the already existing more general indicator systems for analyzing and assessing sustainability of transport systems on the one hand and specifically to those relatively scarce exclusively focusing on airports as components of the air transport system on the other. Consequently, an approach considering simultaneously effects-benefits and impacts-costs by the airport operations in the medium to long-term period of time is adopted.

In addition to this introductory section, the paper consists of four sections. Section 2 elaborates the concept including the main principles of sustainable development of an airport and particular effects-benefits and impacts-externalities. Section 3 elaborates the indicator system for monitoring, analyzing, and assessment of the airport sustainable development. The particular indicators and their measures are specified to reflect effects-benefits and impacts-externalities from the airport medium- to long-term operation under given circumstances. Section 4 contains an application of the proposed indicator system. Section 5 summaries some conclusions.

2. A Concept of Sustainable Development of an Airport

A concept of sustainable development of an airport includes us consideration as the system of interrelated components, operations, and processes, the main principles for achieving sustainable development, and elaboration of particular effects-benefits and impacts-costs from its medium- to long-term operations. The main effects-benefits embrace employment around the airports and their overall contribution to the local and national economy. The impacts-costs include the affection and cost of protective measures from airport noise, air pollution, congestion and delays, land use (take), and waste.

2.1 *An airport as the system*

An airport consists of landside and airside area. The former embraces the surface transport access systems connecting a given airport to its catchment area, and the passenger (and freight) terminal complex. The latter comprises the airspace around a given airport called the 'airport zone' (narrow airspace) and the 'airport terminal area' (wider airspace), the runway system, and the apron/gate complex (Ashford and Wright, 1992; Janic, 2000).

Given an airport, as an essential component of the air transport system is usually regarded as its infrastructure. In general, they operate as the multimodal transport nodes facilitating the air and other surface transport modes. In addition to the airport operator, airlines and the surface transport modal operators (usually road and rail) are other two large groups of transport actors involved. With exception of airport users-air passengers, the fourth and fifth group of actors can be local population in the vicinity of a given airport and the local and sometimes national authorities. In given context, the relationships between particular actors in terms of satisfying their individual interests need to be balanced. For users, the main interests are convenient and rather cheap, effective, and safe door-to-door (air) transport services. For airport itself and other transport operators these are profitable, effective, and safe operations. For local population, the main interests relate to as less as possible noise and air pollution. For the local and national authorities these are the corresponding direct and indirect contributions of a given airport to the local and national economy while simultaneously diminishing the overall impact on the society and environment.

2.2 *The main principles of airport sustainable development*

The main principles for achieving the sustainable development of a given airport imply either continuously diminishing its negative impacts or continuously widening the positive gap between the overall social effects and negative impacts in the medium- to the long-term. Both principles could be applied according to two policy strategies as follows:

Constraining the airport growth. This strategy consists of constraining further expansion of the infrastructure capacity of a given airport in order to constrain its impact mainly in terms of local noise and land use (take) and both local and global air pollution. Within in advance prescribed limits (caps). Consequently, the airport operates at the existing capacity while being able to accommodate current and eventually only slightly greater volumes of demand mainly thanks to utilizing the available capacity more efficiently and effectively. Particular constraints can be either imposed by the local and/or central authorities or be inherently present. For example, the one being inherently present could be a lack of land for expansion of the airport infrastructure and consequently the capacity for accommodating future growing demand. As well, the land can be available but its use impossible due to a high resistance from local population. In any case, constrained growth can prevent escalation of particular impacts over the prescribed caps on the one hand, but also compromise the airport's direct and indirect positive effects-benefits to the society on the other (Upham et al., 2000).

Managing the sustainable growth. This seemingly the most reasonable strategy for most airports under present circumstances consists of managing the medium- to long-term growth of a given airport in the sustainable way. This implies that, under conditions of traffic growth, the overall effects-benefits are maintained or even increased above the generally increasing, stagnating and/or decreasing overall impacts-externalities, both categories expressed in monetary terms, as shown in Figure 1.

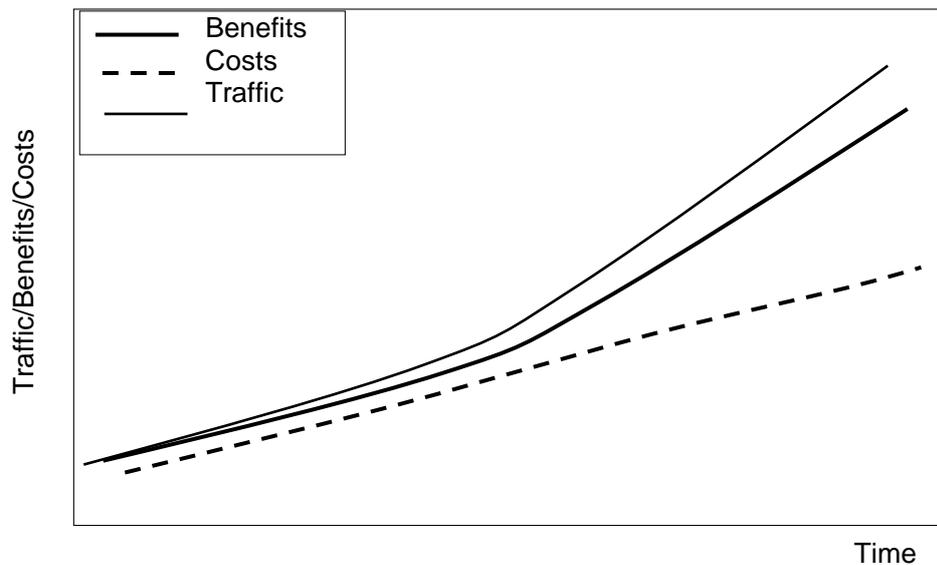


Figure 1. Simplified scheme of managing possible (desirable) unconstrained but sustainable growth of an airport

2.3 Effects - benefits

The evidence to date indicates that most airports have acted as important contributors to the local economies mainly in terms of the direct and indirect employment. The former includes staff carrying out the aviation-related activities. The latter embraces staff carrying out other businesses at the airport. In general, the larger airports employ more staff and thus provide a greater contribution to the local and national employment, GDP (Gross Domestic Product), and consequently to overall welfare. The latest embraces all direct and indirect effects for the airport itself and the local economy. In addition, all these effects are generally positively correlated to the airport size, i.e. the volume of accommodated traffic during a given period of time (usually one year) (Janic, 2007).

2.4 Impacts - externalities

The negative impacts from operation of a given airport usually include local noise, air pollution, congestion and delays, land use (take), and waste. In particular, air pollution can be treated both at local and global scale. In this case, each impact is considered through its primary source and the nature of impact, as an externality, and possible mitigating measures. The potential impacts of air traffic accidents and incidents at airports as those from the rather rare events are not considered.

2.4.1 Noise

The source and the nature of impact

The primary noise at airports is from the aircraft operations. In order to quantify, monitor, and control the noise level, different measures have been developed. The most recent one proposed by the EC (European Commission) measures exposure of local population around airports to daily and nightly aircraft noise as follows (EC, 2003):

$$L_{den} = 10 \log_{10} \left(\frac{1}{86400} \sum_{i,j} (N_{d/ij} + 3.16 N_{e/ij} + 10 N_{n/ij}) 10^{SEL_{ij}/10} \right) \quad (1)$$

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

where N_{dij} is the number of movements of the j -th aircraft group on the i -th flight path during the period on an average day; N_{eij} is the number of movements of the j -th aircraft group on the i -th flight path during the evening period of an average day; N_{nij} is the number of movements of the j -th aircraft group on the i -th flight path during the night period of an average day; T_n is the duration of the night period (seconds); and; SEL_{ij} is the sound exposure level from the j -th aircraft group on the i -th flight path. Similarly as at other measures, the most important characteristic of the above-mentioned measure is the dependence of the noise level on the number of aircraft operations during a given period of time.

In addition, a measure for estimating proportion of annoyed people close to a given airport has been developed. It embraces proportion of annoyed (%A) and proportion of the highly annoyed (%HA) people from population living close to a given airport. It is dependent of the indicator of daily exposure L_{den} as follows (EC 2002):

$$\% A = 8.5888 * 10^{-6} (L_{den} - 37)^3 + 1.777 * 10^{-2} (L_{den} - 37)^2 + 1.221(L_{den} - 37) \quad (2a)$$

and

$$\% HA = -9.199 * 10^{-5} (L_{den} - 42)^3 + 3.932 * 10^{-2} (L_{den} - 42)^2 + 0.2939 (L_{den} - 42) \quad (2b)$$

where particular symbols are analogous to those in the expression (1).

Noise as externality

In order to be consider noise as an airport externality, its potential and actual damage and related costs need to be estimated. This has been carried out by different techniques such as, for example, hedonic and contingent valuation method(s). The former is based on the revealed, and the latter on the stated behavior. The hedonic price method has been the most widely used for evaluation of the social cost of noise at airports, at least within the academic community (Morrell and Lu 2000; Betancor and Juan Carlos 2005). In addition to the academic-based efforts, charging for aircraft noise at airports has also been the subject of the national and international policies. One such policy contained in the European Commission's documents proposes the following equation for charging the airport noise (EC 1999):

$$c_n = c_a 10^{\frac{L_a - T_a}{10}} + c_d 10^{\frac{L_d - T_d}{10}} \quad (3)$$

where c_a , c_d is the noise charge for an arrival and a departure, respectively, which theoretically can be equal to zero (monetary units per operation); L_a , L_d is the noise level for an aircraft at the arrival and at the departure/flyover noise certificated locations, respectively (in dB(A)); and T_a , T_d is the noise threshold during an arrival and a departure, respectively, corresponding to the category of a relatively quiet aircraft (they are fixed around 13 dB below the upper threshold, corresponding to 95% of the total noise energy emitted at a given airport).

The main disadvantage of this method in the equation (3) is that the problem of choosing an appropriate technique to determine the values c_a and c_d , which has not been completely resolved. Summarizing, any charging method for the aircraft noise - from the cost of mitigation of the noise burden to its charging based on the marginal social cost - can be used depending on the local circumstances and specificity of a given airport.

Mitigating measures

Different restrictive measures have been implemented to mitigate the noise burden on local populations in the vicinity of many busy airports. In the scope of the international efforts, the 33rd ICAO Assembly taken place in the year 2001 introduced the concept of a "Balanced Approach" to the noise management and control at airports. This implies identification of the noise problems at

a given airport, analyzing, and implementation of the mitigation measures through exploration of the following elements:

- Reducing noise at sources, i.e. allowing only operations of the aircraft according to the Chapter 3 and 4 (ICAO, 1993a);
- Restricting operations of particular aircraft types, i.e. forbidding operations of particular aircraft types during the specific periods during the day;
- Using the noise abatement (operational) procedures, i.e. redistributing noise, which implies use of the preferential runways and approach/departure routes and the noise abatement approach/landing procedures; any of these procedures need to satisfy the necessary safety standards;
- Planning and managing land use, i.e. introducing the land-use zoning around a given airport aiming at minimizing the number of people affected by the aircraft noise; and
- Charging excessive noise, i.e. introducing the noise charges if the severe effects of noise exist (ICAO 1993a).

In addition, improvements in the noise performance of contemporary aircraft by investments in the innovative technologies (aircraft engines) have been substantive and permanent (ICAO, 1993a).

Last but not least, the ATC/ATM has developed several innovative operational procedures for mitigating noise around airports, some based on the existing and others on the innovative technologies. Some of the most known embrace Low Drag/Low Power (LD/LP), Continuous Descent Approach (CDA), Increased Glide Slope (IGS), Displaced Threshold (DT), and Curved Approach (CA) procedures (EC, 2005).

2.4.2 Air pollution

The nature of impact

In general, air pollution around airports includes greenhouse gases of which, in terms of the quantity and impact, the most important are Carbon Dioxide (CO₂), Nitrogen Oxides (NO_x) and water vapor (H₂O). The quantity of air pollution in an area is proportional to the volumes of air polluting activities and intensity of pollution per activity. At airports, the volume of air pollution activities closely relates to the volume of accommodated traffic usually expressed in terms of the number of passengers and aircraft movements (atm), and the weight of freight shipments (1 atm corresponds to either one arrival or one departure flight). In many cases, the number of passengers, after being expressed by their weight, and the weight of freight shipments are converted into common unit - WLU (Workload Unit) (1 WLU = 1 passenger or 100kg of freight) (Doganis, 1992).

The intensity of air pollution per an activity depends on the quantity and type of energy consumed to carry out the activity, as well as on the characteristics of applied technology. For example, at the local airport level, if it is possible to determine the average number of activities per WLU, n_a , the energy consumption per activity e_a , the quantity of air pollution per unit of consumed energy q_{ap} , and the overall volume of WLUs C_T processed during a given period of time T , the total quantity of emitted pollutants will approximately be: $Q_{ap/T} \approx n_a e_a q_{ap} C_T^\alpha$ (α as an exponent). In addition, the total quantity of air pollutants at a given airport can be determined separately for the traffic-related activities in its airside area, in its landside area, and for the overall traffic-supporting activities. In the first case, the air pollution from arriving and departing aircraft during the LTO (Landing and Take-Off) cycle is considered (Janic, 2007). In the second case, the air pollution generated by the airport ground access/leaving transport systems for both

passengers and freight is considered. Finally, the air pollution from energy consumed for the intra-airport vehicles' movements, aircraft servicing at the apron/gate complex, heating and lightening of the passenger and cargo terminal(s) and the administrative complexes, is considered.

Air pollution at a given airport can also be considered from the global perspective. This specifically relates to the airside area. There, the air pollution from the all incoming and outgoing aircraft/flights (atm) instead of only of that from the corresponding LTO cycles is considered. This implies taking into account the air pollution from maintaining a given airport in the air transport network. This pollution can be estimated as: $Q_{ap} = \sum_{k=1}^K \sum_{j=1}^M n_k(T) t_k f_k e_{kj}$, where $n_k(T)$ is

the number of atm (incoming and outgoing flights) of type (k) accommodated at a given airport during the period T; t_k is duration of the flight (k) (h) (in terms of distance and duration these can generally be the short, medium, and long-haul flights); f_k is the average unit fuel consumption of the flight (k) (ton/kg/h); e_{kj} is the emission rate of the air pollutant (j) by the flight (k) (ton of pollutant/ton of fuel/h); J is the number of relevant air pollutants (these usually are CO₂, NO_x, and H₂O) (IPCC, 1999). The above mentioned air pollution by the given airport considered at the global scale seems to be more objective particularly if the air transport system and its particular components – airlines and airports – are to be included in the schemes of charging externalities (ACI, 2008).

Air pollution as externality

Some estimates indicate that airports contribute approximately for about 5% to the total quantity of air pollutants generated by the entire air transport system, i.e. about 30 million tons per year (ACI, 2008). Since this amount certainly contributes to global warming and related climate change, charging them as externalities has been considered for including the international air transport system into the emission taxation or trading scheme(s).

Charging of each unit of the emitted air pollutants is usually called the air pollution tax whose objective is to reduce fuel consumption and consequently the related emission of air pollutants, and thus eventually slow down the climate change. The tax can be implemented by charging the consumed fuel in proportion to its air pollution content (for example for CO₂ it is 3.18 kg CO₂/kg of Jet A fuel) (ICAO, 1993b). The estimated range of the prospective tax based on the perceived contribution to global warming and related environmental damages has significantly varied, from 10\$US to 95\$US per ton of CO₂ equivalents. It seems that a given airport should be taxed on the annual basis for either global or local fuel consumption or related air pollution. However, criteria for allocating and sharing the tax between airlines and a given airport remain to be specified. It seems that such allocation should be according to the share of a given airport in the total air pollution by air transport, which will again be in proportion to the volume of traffic.

An alternative charging scheme for air pollution by airports can be emission trading. The scheme implies setting up a cap by the central authority on the quantity of air pollution. Thus, airlines and airports are issued the emission permits providing them credits on the allowable emissions within a given cap. In such case, airports and airlines, which need to pollute more, could buy credits for emissions from those, which have achieved less than the allowed pollution. Such transfer of credits is called a trade. The question remains how airports will be included in the scheme, maybe similarly as airlines, in proportion to the volumes of traffic during some past period. This scheme is expected to be in place for all EU internal flights by the year 2011 and for all flights in the year 2012 (<http://aero-defense.ihs.com/news/en>).

The air pollution tax scheme in combination with a cap on the quantity of emissions has shown unpopular at most airports considering them as a threat to their further growth (ACI, 2008). The emission trading scheme, if applied mainly to the ground-based sources, has shown to be more acceptable despite awareness of most airports that it can also indirectly affect their growth,

particularly in cases when the achieved rates of reducing emissions are shown to be lower than those of traffic growth (ACI, 2008).

Mitigating measures

Many airports have already undertaken a range of measures for mitigating air pollution, which are either under their direct or indirect control. The absolute objective is to reduce the airport-related air pollution overall. The ultimate objective is to become the “carbon-neutral” entities, both without constraining growth and imposing unnecessary air pollution charging. Some of these measures are summarized as follows (ACI, 2008):

- Preventing access of the highly polluting aircraft;
- Reduce the aircraft fuel consumption during the LTO cycles and by excluding the use of APU (Auxiliary Power Unit) while at the parking stands;
- Reduce the overall number of vehicles accessing a given airport;
- Encourage use of the low or zero emission vehicles within the airport area;
- Stimulate use of the alternative fuels;
- Reduce the energy consumption in all buildings;
- Include into the different schemes of charging externalities such as emission trading or taxation.

The above-mentioned measures seem sufficiently self-explanatory. Nevertheless, for example, the aircraft fuel efficiency has been continuously improved at an average rate of 1-2%/yr (Janic, 2008). These trends will continue at even higher rate over the next decade(s). Consequently, at most airports, more and more fuel efficient aircraft operate. The aircraft guidance during the LTO cycles is improving too in terms of both time and corresponding fuel consumption. At some airports, APUs are replaced by electric energy with allowance to aircraft to switch off their engines. Consolidating and promoting the public mainly light- and heavy-rail transport modes for the airport ground access is expected to reduce the number of vehicles (mainly individual cars) and consequently their fuel consumption and related air pollution. Operating the automated rail-based transit systems instead of the shuttle buses for connecting particular distant airport terminals can also reduce air pollution. Using other vehicles powered by the alternative fuels including Liquid Hydrogen represents also an additional positive contribution. In addition, the wind and solar energy for lighting buildings at airports are expected to considerably reduce air pollution at the local level. Inclusion of airports into different schemes of charging air pollution as an externality will stimulate and at the same time force them to maintain the current and prospective air pollution at or below the specified level under conditions of continuous traffic growth.

2.4.3 Congestion and delays

The source and nature

Congestion and delays of arriving and/or departing aircraft at/from a given airport, respectively, occur whenever the intensity of demand exceeds the available airport service rate, i.e. capacity. There may be different types of such relationships. In some cases the airport “ultimate” capacity, defined as the maximum number of aircraft/flights served during a given period of time under conditions of constant demand for service, is overall greater than the demand rate during a given period of time. But, because of the uneven spread of demand over time, the instant demand may exceed this capacity, thus causing inevitable congestion and delays of the affected aircraft/flights. As the overall demand rate approaches close to the “ultimate” capacity, the number of cases in which the instant demand rate exceeds the instant service rate

significantly increases, which rapidly increases the number of affected aircraft/flights and consequently duration of their delays. Summing up the individual delays and dividing the sum by the number of all aircraft/flights demanded service during a given (busy) period of time produces the average delay per an aircraft/flight. Generally, this delay directly depends on the intensity of demand on the one side, and indirectly on the airport "ultimate" capacity (as a reciprocal of the minimum average service time) on the other. The number of aircraft/flights served under such conditions represents the airport "practical" capacity (Janic, 2000).

Congestion and delays as externalities

In general, congestion and delays as externalities can be expressed by the cost of delays. In such context, usually, only those delays longer than 15 minutes should be counted. Their costs usually depend on the airline/aircraft operating costs and the value of passenger time. For example, the unit cost of marginal delays implying both primary and reactionary delays estimated in dependence on the aircraft size are as follows: $C_a(S) = 0.10S - 0.167$ (€/min), ($R^2 = 0.92$), where S is the number of aircraft seats ($40 < S < 450$). The average value of time for an average passenger using all categories of aircraft is estimated to be $\alpha = 39\text{€/min/pass}$ (EEC, 2005).

Mitigating measures

Congestion and delays at a given airport can be mitigated by the tactical and operational measures in the short-term and by the strategic measures in the long term. The former include matching the time pattern of particular atm to the airport capacity (slots) in the most feasible way using also the ATM (Air Traffic Management). In addition, this also implies more efficient and effective utilization of the available airport airside and landside capacity. The latter assumes physical expansion of the airport capacity by building the new airside and landside infrastructure such as new runways, aprons, and passenger terminals, respectively.

2.4.4 Land take (use)

The source and nature of impact

The air transport system takes land for settling its infrastructure – airports and ATC/ATM buildings, facilities and equipment. Airports take the most sizeable land in figures of hundreds and thousands hectares. In addition, an additional important characteristic is the intensity of use of taken land, which is usually expressed by the volume of activities performed on this land during a given period of time. These activities are usually those accommodating atm (air transport movements), air passengers, and freight shipments, i.e. WLUs during a given year (Doganis 1992).

Given the fixed size of land occupied by a given airport, the intensity of land use increases with increase in the volume of traffic. When existing infrastructure reaches saturation a new one (runway, terminal building) is added, in which case the intensity of land use temporarily falls before recovering and increasing again with increasing of traffic.

In addition, the intensity of land use can be closely related to the size and value of land. Since the higher intensity of land use increases both the airport revenues and costs, it is not always quite clear if the additional land taken for building and/or expanding a given airport should be considered as a pure externality. Finally, the intensity of land use at a given airport can also be expressed in terms of the volume of p-km (passenger kilometers) or t-km (ton-kilometers) realized per unit of land taken (ha). For such purposes, information about the structure of incoming and outgoing atm (flights) (short-, medium-, long-hail) and the number of passengers (and freight) on board should be available.

Land take (use) as externality

Considering the land taken (used) for building and/or expanding airports as an externality is generally ambiguous. The question is whether it is more socially feasible to take land for an airport or to use it for some other economical or non-economical purposes such as housing, agriculture, recreation, and the natural environment (green area with intact flora and fauna). In all these mutually exclusive cases, the land taken has a certain value, which in general can have economic, non-economic, and/or the market-based value. While assessing the social cost of such land its economic value is relevant. For example, let R_{ai} and C_{ai} be the total social revenues and costs, respectively, from operating a given airport occupying the area of land S_i ; let R_{ji} and C_{ji} be the social revenues and costs, respectively, from carrying out some other economic and/or non-economic activity (j) on the same land S_i . The value (i.e. cost) of one unit of the airport land can be determined as follows (Janic, 2007):

$$C_l = \frac{[(R_{ai} - R_{ji}) - (C_{ai} - C_{ji})]}{S_i r} \quad (4)$$

where r is the capitalization rate converting the future monetary values into the present value.

The nominator of expression (4) is often called the annual return to land. In addition, expression (4) reflects the intensity of land use in the monetary terms.

Mitigating measures

The most effective mitigating measure for the land use (take) by a given airport is its full incorporation in the regional medium- to long-term plans as well as a strict following these plans. This enables reservation of the sufficient land for the airport eventual expansion. In addition to this, the "buffer" zones free of eventual housing also need to be planned, which in turn can additionally contribute to mitigating the airport noise impact. .

2.4.5 Waste

The source and nature of impact

Waste is generated at airports in quantitative positively correlated with the airport size. .. Regarding the micro location within a given airport, waste can originate from activities of the airport terminals, offices, food outlets, aircraft cleaning area, apron/gate complex, and other smaller collecting areas. The airport waste can be broadly classified into solid and liquid waste. In addition, it can be further segregated into the non-industrial and the industrial waste. The former originates from the passenger services provided onboard the aircraft, and from consumption of the airport employees and visitors (food, newspapers, cans, paper). The latter originates from daily activities such as washing and cleaning the aircraft and other ground vehicles, the aircraft and engine maintenance, repair and testing including painting and metal work, aircraft de/anti-icing, and maintenance operations of the ground vehicles. This waste is further categorized into hazardous and non-hazardous waste. The former is managed according to the strict national and airport regulations governing collection, treatment, storage and disposal (FAA 2001).

The quantity of waste at a given airport is usually expressed in the absolute terms as the total quantities generated over a given period of time (year), and in the relative terms as the quantity of waste per unit of the airport output (WLU) (FAA, 2001).

Waste as externality

The airport waste can be considered as an externality under conditions when it causes damage to the people's health and environment. In particular, the incidental leakage of hazardous liquid industrial waste such as aviation fuel, oil, and the vehicles' washing and cleaning liquids can contaminate the soil and drinking water, and consequently endanger health and possibly lives of people and other habitats. In these cases, the externalities are counted as the costs of repairing the

damages in the broadest sense. This usually implies cleaning up the contaminated areas and eventually strengthening the protective infrastructure and preventive measures.

Mitigating measures

The waste mitigating measures are included in the airport waste management system, which exists at almost all airports. The system usually includes identification of sources, location, type and quantity of waste generated, then the infrastructure, facilities and equipment to deal with different types and quantities of waste, and finally the efficiency and effectiveness of the waste collection, storage, recycling, and disposal.

An efficient and effective waste management system usually implies avoidance, minimization, and recycling of waste. This involves segregation of waste into the solid and liquid, hazardous, and non-hazardous components at a source, reduction of quantities of waste generated, continuous increase in reuse, recycling and reprocessing of waste materials, and permanent improvement of waste management practice. In particular, recycling implies conversion of waste into energy through the thermal treatment (processing). For example, at Frankfurt Main airport (Germany), the rate of recycled waste has increased from 50% in the year 1995 to about 85% in the year 2005. Consequently, the cost of waste management could be reduced as one of the final objectives (<http://www.fraport.com>).

The airport waste management system is usually designed and operated respecting the valid national and local legislation. This particularly refers to the requirements for storage and disposal of waste in the dedicated areas, which cannot be used for some other more profitable activities (FAA 2001).

3. An Indicator Systems for Monitoring, Analyzing, and Assessing the Airport Sustainability

3.1 Previous research

Contrary to the research carried out for the specific purposes by the international aviation organizations and consultancy, the academic research to date on developing a framework for systematic monitoring, analyzing, and assessing the sustainable development of airports is relatively scarce. This obviously creates a need for additional research as continuation of that come up about a decade and half ago when the economic and environmental issues have mainly constituted the sustainability framework (Longhurst et al., 1996). Scarcity in the given context particularly relates to development of some indicators or other tools convenient for quantification of such airport sustainable development. Nevertheless, some efforts are worthwhile to be mentioned. One of these is development of indicators for planning sustainable development of transport system (Johnston, 2008). In addition, the research has been carried out in elaborating the concept of sustainable aviation and its development (Upham et al., 2000; Upham, 2001). Then the research on developing a methodology for assessment of sustainability of air transport system consisting of airports, air traffic control, and airports was carried out (Janic, 2002). The methodology has been set up at the conceptual level with a core represented by an indicator system for quantifying performance of particular components of the air transport system. The infrastructural, technical/technological, operational, economic, environmental, social, and institutional/policy performance were considered as relevant respecting the attitudes of actors involved. This methodology consisted of about 104 indicators and their measures was soon partially applied to different components of the air transport system in order to illustrate the its potential and feasibility for eventual practical planning application (Janic, 2004, 2007). Latter on an additional research has resulted in developing the indicators of sustainable development of

civil aviation. In this research, 29 indicators derived from other transport modes and appropriately modified have been defined respecting the interests and attitudes of particular actors involved in the UK (Grimley, 2006).

This paper represents in some sense continuation of development of the above-mentioned indicator systems, but this time exclusively and deeper focusing on airports. This requires modifying the approach from more conceptual to more specific including more detailed elaboration of the effects-benefits, impacts-externalities, and ways of their quantification for the monitoring, analyzing, and assessment of the airport medium-to long-term sustainable development.

3.2 Objectives and assumptions

The main objectives in developing an indicator system is to enable relatively efficient and effective judgment on the achieved level of sustainability of a given airport, identify the most important influencing factors and contribution of particular actors involved,

In such a way, the sensitivity analysis of changing particular indicators with respect to the expected changes in the most important influencing factors according to the specified present and future scenarios of the airport development will be possible to be carried out. This will make the proposed indicator system with some although limited predictive capabilities

Consequently, the proposed indicator system is developed using the following assumptions:

The system needs to reflect preferences of particular actors, who may be involved in dealing with the airport sustainable development. Thus, the number of indicators and their measures corresponds to the number of different actors involved;

The system consists of five sub-systems corresponding to the five different dimensions of the system's performance such as operational, economic, social, environmental, and institutional;

The measures of particular indicators express quantitatively effects- benefits and impacts-costs of airport operations in either absolute or relative monetary or non-monetary terms, usually as functions of the volumes of airport output;

If a "target" value for an indicator is set up, it will be used as the reference for comparison of the current with the required development, and consequently for assessing the current level of sustainability; and

The indicators and their particular measures can be inherently dependent on each other.

3.3 The basic structure

The basic structure of the proposed indicator system for monitoring, analyzing, and assessing of the sustainable development of a given airport includes principles, criteria, and requirements for particular indicators and their scope reflecting performance of a given airport.

3.3.1 Principles, criteria, and requirements

In general, dealing with the sustainability of a given airport appears to be a rather complex task due to the following reasons:

- Multidimensionality of performance, which implies considering given airport is as a system with numerous (inherently) interdependent and diverse components, actors involved, effects-benefits and impacts-costs;

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

- Complexity of setting up the sustainability targets due to the above-mentioned interdependency;
- Complexity of assessment of the marginal and global contribution of particular policy measures and technologies on the sustainable development of a given airport.

Therefore, a reasonably acceptable indicator system and particular indicators and their measures are preferred to be developed respecting the criteria as follows (Kelly, 1998)

- Calculated by using already available or easily obtainable data;
- Easily understandable without ambiguity and exceptional overlapping;
- Measuring something important in its own right;
- Availability in a relatively short lead time;
- Comparable in terms of different geographical (national and international) scales, and actors involved;
- User-driven, i.e. useful for intended users, i.e. audience;
- Policy relevant, i.e. pertinent to policy concerns; and
- Highly aggregated, i.e. the final indices should be few in number.

Regarding the complexity of operation and development of a given airport, the various groups of actors may have their own requirements and preferences while setting up the indicator system, which are summarized as follows (ATAG 2003, 2003a; INFRAS 2000).

Users (consumers), air passengers, freight and mail shippers, constitute demand for a given airport and prefer a smooth, frequent, easily accessible, relatively cheap, punctual, reliable, safe and secure services;

The airport operator, airlines, and ATM/ATC meet the passenger and freight demand by operating the fixed infrastructure, facilities and equipment, and mobile means – the airport vehicles and aircraft. Generally, they all prefer profitability, safety and user satisfaction;

Private and public investors (banks) at local (national) level mainly finance the investments in air transport infrastructure - airports, ATM/ATC facilities and equipment, and aircraft while preferring economic and social feasibility of their investments, in the scope of a given airport;

Insurance companies deal with the financial protection of air transport system including airports and users of their services from damages. They always prefer low risk of air traffic accidents, low rate of loss of life and damage to properties caused by air transport operations including those taking place at a given airport;

Governmental authorities and policy makers are usually involved in creating and implementing policies which regulate operations of the air transport system at local (community), regional, national and international level. In some cases, they also subsidize some unprofitable air transport services in order to protect and even increase the overall social-economic welfare. In addition, they monitor and control externalities of the air transport system operations, including those at a given airport which are preferred to be as low as possible;

Community members living close to a given airport benefit and suffer from this closeness. They usually tend to maximize the potential local benefits in terms of employment and availability of the system on the one hand, and minimize the costs of impacts mainly in terms of noise, local air pollution, and land use on the other;

Lobbies and pressure groups are divided into two broad categories. The first category usually articulates interests of those people opposing any expansion of a given airport. The aerospace

manufacturers and other related businesses including a given airport operator as another category often tend to promote exclusively their commercial interests and projects and in many cases possibly postpone decisions on the system's regulation.

The general public is mainly interested in the specific aspects of air transport system whose part is also a given airport. These are cases of severe disruptions of the system's operation due to any reason, for which the public prefers objective information.

3.3.2 *The scope*

The proposed indicator system consists of twelve indicators: four for operational, two for economic, one for social, and five for the environmental performance. They can be quantified for an individual airport or for the set of close airports serving a given region (Janic 2007).

3.3.2.1 *Indicators of operational performance*

'Demand', 'capacity', 'quality of service' and 'integrated intermodal service' can be regarded as the main indicators of an airport's operational performance.

Demand indicates a scale of the airport operations. The number of air transport movements (atm), passengers, and the volume of freight shipments accommodated during a given period of time (hour, day, year) can be measures of this indicator. Sometimes, it is more convenient to use WLU as an aggregate measure for both passenger and freight volumes. The airport operator prefers these measures to increase over time (Doganis 1992)).

Capacity reflects the airport's capability to accommodate a certain volume of demand under given conditions. Two measures can be used: the airside capacity in terms of the maximum number of atm, and the landside capacity in terms of the maximum number of WLUs accommodated over a given period of time (hour, day, year). They both can be expressed as the "ultimate" or "practical" capacity. The former implies conditions of constant demand for service. The latter implies conditions of imposing an average delay on each unit of demand. Both are preferred to be as high as possible and to increase in line with growing demand.

Quality of service reflects the relationship between the airport demand and capacity. Generally, the average delay per atm or WLU, which occurs whenever the demand exceeds the capacity, can be used as a measure preferred to be as low as possible and to decrease with increasing of demand, such as the number of atm and/or WLU. Figure 2 shows the real-life development of relationship between demand and capacity for atm at large congested European London Heathrow airport

As can be seen, the average delay per atm has increased exponentially with growing demand. The intensity of accommodated demand at which the average delay is guaranteed to each aircraft/flight has represented the airport "practical" or "declared" capacity. the "practical" capacity of the system of two parallel runways operated in the 'segregated' mode (i.e. one exclusively for arrivals and another exclusively for departures) has declared to be 78 atm/h (i.e. 39 atm/h per runway), thus guaranteeing an average delay per any atm during the period of 10 busy hours of the day of about 18 minutes (ACL, 2007). The above-mentioned development has proved exactness of the theory of airport runway "practical" capacity by indicating the very similar if not identical type of the delay-demand-capacity relationship (de Neufville and Odoni, 2005);

Integrated intermodal service is an indicator, which may be relevant for those airports connected to the surface regional, national, and international transport networks. Generally, these airports have opportunity to improve utilization of their capacity by substitution of some the short-haul flights by adequate surface, usually conventional and/or High-Speed-Rail, services on the one

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

hand, and by using such freed slots for more profitable long-haul air services. For example, three European hubs – Frankfurt Main, Paris CDG and Amsterdam Schiphol airport - are connected to the Trans-European High-Speed-Rail Network. The above mentioned air/rail substitution has already taken place there (EC 1998; HA 1999; INFRAS 2000). If the above-mentioned substitutions were carried out without filling in the freed slots by the long-haul flights, congestion and delays, associated local and global air pollution, and noise would eventually be diminished. Under such circumstances, this indicator could also be considered as an environmental indicator and a measure of this indicator could be the ratio between the number of substituted flights and the total number of viably substitutable flights carried out over a given period of time (year). In such case, this ratio is preferred to be as high as possible and to increase with increasing of the number of substitutable flights.

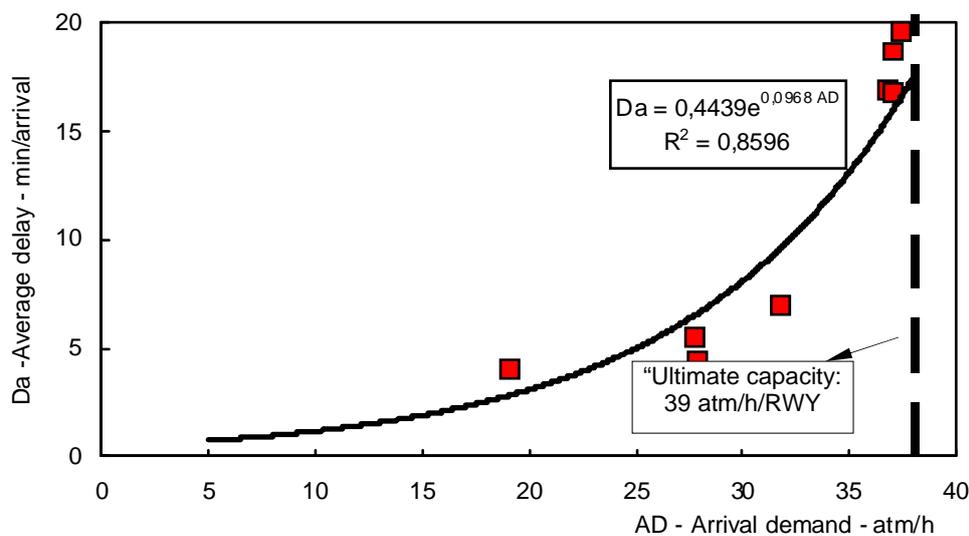


Figure 2. Relationships between demand, capacity, and the average aircraft/flight delay at London Heathrow airport developed over time (2000-2007) (UK) (Compiled from: ACL, 2007)

3.3.2.2 Indicators of economic performance

A given airport as a business enterprise also looks after its economic performance, for which 'profitability' and 'labor productivity' can be the most convenient indicators:

Profitability usually reflects the airport's financial-business success. It is usually measured by the operating profits, i.e. difference between the operating revenues and the operating costs per unit of the airport's output – WLU (Doganis 1992). This measure is preferred to be as high as possible and to increase with increasing of the airport's output. Figure 3 shows an example of profitability of Amsterdam Schiphol airport (The Netherlands).

As can be seen, the airport's profitability in terms of €/WLU (Euro per Work Load Unit) related to the total annual volumes of WLUs accommodated at the airport has increased during the observed period at decreasing rate, thus indicating the long-term airport's sustainability, but with diminishing annual marginal contribution.

Labor productivity reflects the efficiency of labor use at a given airport. The output in terms of the number of WLU (or ATM) per employee carried out over a given period of time (year) is usually used as a measure (Doganis 1992; Hooper and Hensher 1997). It should be mentioned that only the airport's direct employment is taken into account. This measure is preferred to be as high as possible and to increase with increasing of the number of employees. Figure 4 shows an example

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

for Amsterdam Schiphol airport (The Netherlands). As can be seen, during the observed period, this productivity has generally increased with increasing of the number of WLU at a decreasing rate, which becomes zero after the annual number of WLU has exceeded 45 million. Such development indicates how sustainability with respect to this indicator could stagnate or completely vanish with the airport growth.

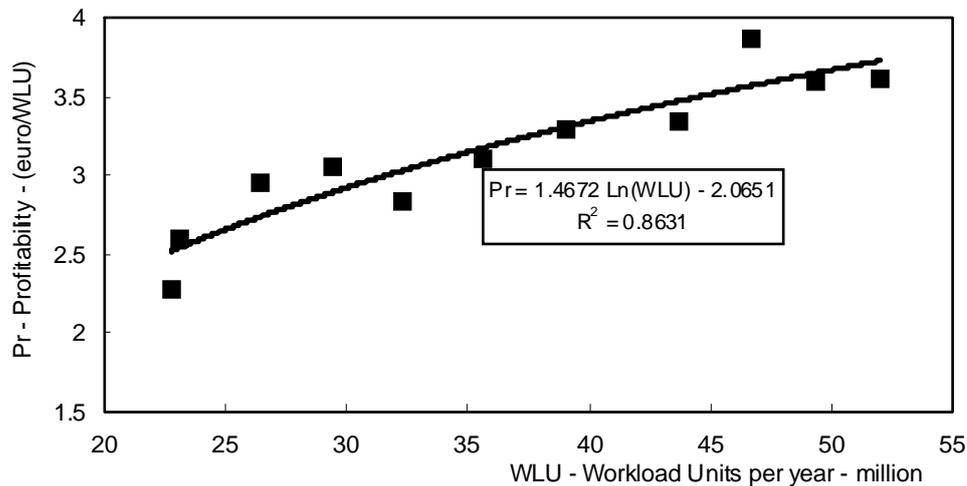


Figure 3. Profitability vs the traffic volume of Amsterdam Schiphol airport for the period 1990-2000 (Compiled from: Schiphol Airport 2004)

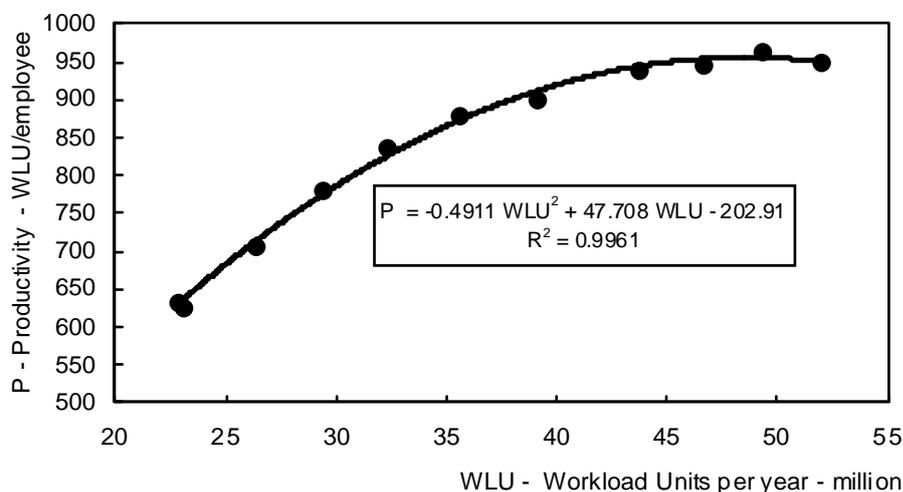


Figure 4. Labor productivity vs the traffic volume at Amsterdam Schiphol airport for the period 1990-2000 (Compiled from Schiphol Airport 2004)

3.3.2.3 Indicators of social performance

The indicator of social performance is considered as both direct and indirect employment by a given airport. This indicator can be represented by the causal relationship between the total number of employees at and around a given airport and the annual volume of airport traffic. Some examples of such relationship for both direct and indirect employment across selected European airports are regressed as follows (ACI Europe 1998; Janic, 2007):

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

Direct employment:

$$E_d(N) = 1.4702N - 4.209; R^2 = 0.901; N = 22 \quad (5a)$$

Total employment:

$$E_t(N) = 0.577N^{1.493}; R^2 = 0.930; N = 22 \quad (5b)$$

where Q is the annual number of passengers handled at a given airport (million).

Expression (5) indicates that the number of directly employed staff at an European airport is about fourteen hundred employees per million passengers, which is about 40% higher than the commonly used ratio of about ten hundreds per million. In addition, the total number of employees increases more than proportionally with increasing of the volume of airport traffic.

3.3.2.4 Indicators of environmental performance

'Energy efficiency', 'noise', 'air pollution', 'land use efficiency' and 'waste efficiency' are defined as indicators of the airport's environmental performance. These indicators, which appear relevant while undertaking the mitigating measures, relate to impacts of the airport on the health of local people and environment.

Energy efficiency relates to the total energy consumed by a given airport over a given period of time (year). This energy, obtained from different sources, is used for lighting and heating. A measure for this indicator is the energy consumed per unit of airport output - WLU - over a given period of time (year). This measure is preferred to be as low as possible and to decrease with increasing of the volume of airport output.

Noise efficiency relates to the noise energy generated by air transport movements (atm) over a given period of time. Some of the measures for this indicator are the area expressed in square kilometers exposed to the equivalent long-term noise level L_{eq} (in decibels - dB(A)), population, and the number of household exposed to the above-mentioned long-term noise. This indicator is preferred to be as low as possible and to diminish with increasing of the number of atms. Table 1 gives an example of reducing noise, the exposed area, related population, and the number of exposed households around London Heathrow airport (UK).

Table 1. An estimation of the area, population, and number of households within the noise contours L_{den} at London Heathrow airport

Contour level dB(A)	Area (km ²)	Population (thousands)	Household (thousands)
>55	302.3	782.9	344.9
>60	114.3	260.5	109.8
>65	47.7	74.5	29.9
>70	20.8	16.6	6.5
>75	7.5	1.7	0.7

Source: CAA 2004; Janic, 2007

Air pollution efficiency relates to the total air pollution generated by operations of a given airport. The amount of all or only of the specific air pollutants can be taken into account. In addition to that of atm, air pollution from the airport surface access (road) traffic, and that from the airport handling operations needs to be taken into account (EPA 1999). Generally, the amount of air pollutants per polluting event - LTO cycle - can be used as the standard measure recommended by ICAO (International Civil Aviation Organization) (ICAO 1993b). The non-LTO cycle related pollution could be allocated to each of them. This measure is preferred to be as low as possible

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

and to decrease with increasing of the number of LTO cycles over a given period of time (year). In addition, the total air pollution generated by all incoming and outgoing aircraft/flights connecting given airport to the rest of air transport network during a given period of time (one year) can be used as a measure of this indicator.

Land use efficiency relates to utilization of land acquired for building and operating a given airport – both the airside and landside area. Once the infrastructure has been constructed, the intensity of use of acquired land becomes dependent on the volume of demand. However, this intensity is always limited by the capacity of infrastructure. In such context, a convenient measure for this indicator is the volume of WLUs accommodated during a given period of time (year) per unit of the acquired land. This measure is preferred to be as high as possible and to increase with increasing of the area of land occupied by the airport. Figure 5 shows an example of the land use efficiency at Amsterdam Schiphol airport (The Netherlands) during the period before and after building a new (sixth) runway in the year 2002.

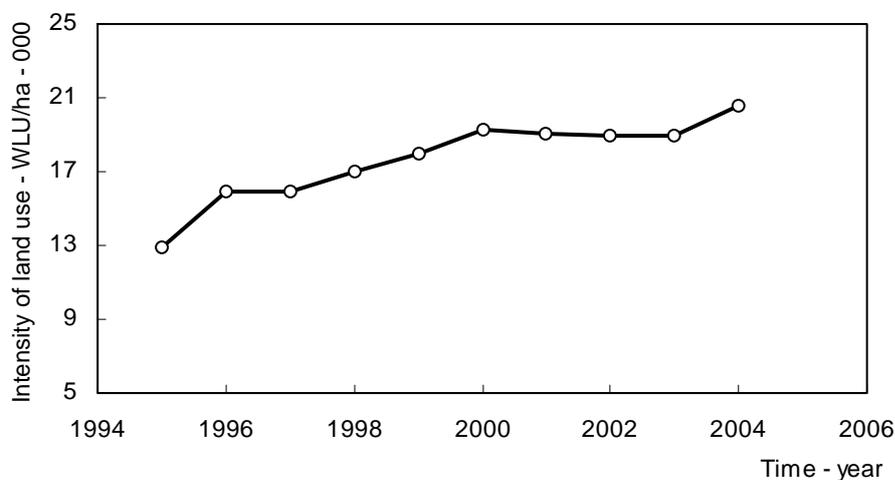


Figure 5. Efficiency of land use over time at Amsterdam Schiphol airport (Compiled from Schiphol Airport 2004; Janic, 2007)

As can be seen, the intensity of land use rose due to increase in the air traffic volumes before the year 2001 (the year of crisis caused by September 11 terrorist attack on the US). Over the next three years it stagnated due to a combination of factors such as stagnation of traffic growth and opening of the new runway (2002). The latter actually increased the area of land used by the airport. Later on, the intensity of land use recovered again thanks to recovering and continuation of the air traffic growth.

Waste efficiency relates to waste generated by operations of a given airport, excluding the airline-generated waste (BA 2001). A convenient measure for this indicator van is the amount of waste generated per unit of the airport's output (passenger/and/or WLU). This measure is preferred to be as low as possible and to decrease with increasing of the airport's output over a given period of time (year). Figure 6 shows two examples of the waste efficiency at Frankfurt Main airport (Germany) and three London airports - Heathrow, Stansted, and Gatwick (UK).

As can be seen, this average amount has decreased at Frankfurt Main airport and increased at London airports with increasing of the annual number of passengers, thus indicating their sustainable and unsustainable development, respectively, with respect to this indicator.

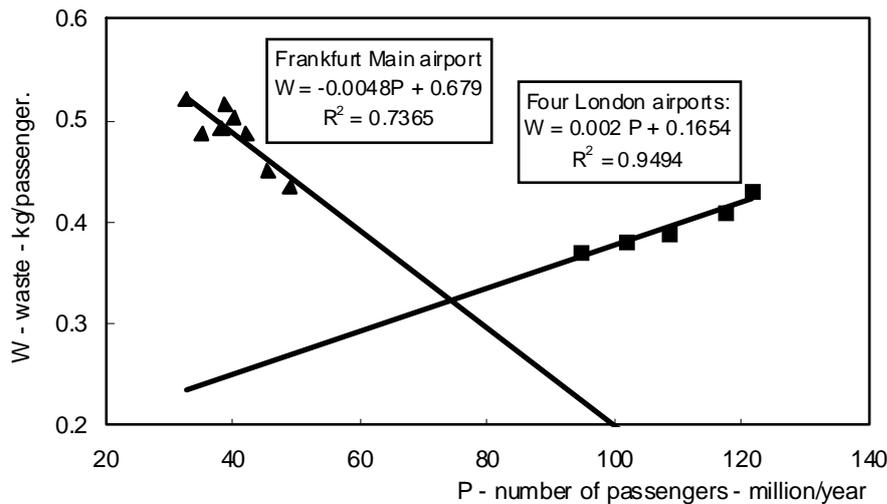


Figure 6. The waste efficiency at European airports (Compiled from: Fraport 2001; BAA 2004; Janic, 2007)

4. An Application of the Indicator System

The above-mentioned indicator system has been applied to indicate eventual existence of trade-off between particular effects-benefits and impacts-costs across different airports. A such, this trading-off could be of relevance for policy makers and the airport authorities while deciding on the current and prospective developments of these airports. The application is illustrated by two examples. The first example represents an analysis of the prospective relationship between the airport operational capacity (an indicator of the operational performance), and the noise and/or air pollution cap (quota) set up to constrain the environmental and social impact (the indicators of environmental performance). For such a purpose, in addition to the above-mentioned concepts of the “ultimate” and “practical” capacity, the concept of “environmental” capacity is defined as the maximum number of atms, passengers, and/or freight (i.e. WLUs) accommodated at a given airport during a given period of time under conditions of constant demand for service and the specified environmental cap(s) (quota(s)).

The second example describes some principles of trading-off between the total social benefits and costs while intending to develop and operate given airport in the sustainable way.

4.1 Operational capacity versus noise cap (quota)

The airport “environmental” capacity with respect to noise can be defined as the maximum number of atms, which can be accommodated during a given period of time under conditions of constant demand for service generating the total sound energy within the prescribed limit, i.e. the noise cap (quota). The cap (quota) can be set up differently for arrivals and departures. Thus, for those arrivals and those departures carried out during time T , the ‘average energy sound level’, or the ‘equivalent continuous noise’ index $L_{a/eq/T}$ and $L_{d/eq/T}$, respectively, can be used.

The Leq index is designed to accumulate all the aircraft sound energy for the multiple noise events, either arrivals or departures realized during a given period of rime (one hour, 8 hours, or 24 hours). For example, in the UK, the concept of Leq is applied to 16-hours period over daytime (ACL, 2007; Ashford and Wright, 1992; DETR, 2000). The cumulative sound energy contained in Leq is assumed to be uniformly distributed over the time period T , and at the most airports, it is

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

different for the day and night period³. Analogously, $L_{a/*}/T$ and $L_{d/*}/T$ represent a noise in dB(A) generated by an individual noise event, i.e. by an arriving and departing aircraft of type (*), respectively, during time T (ECAC, 1997). This noise is usually estimated at the noise reference locations, which may be either the aircraft noise certification points or some other preselected locations in the vicinity of a given airport (ICAO, 1993b).

As the noise quotas $L_{a/eq/T}$ and $L_{d/eq/T}$ are set up according to the maximum level of tolerance of the affected population, the airport environmental capacity in terms of noise can be determined as $C_{a/T} = T \circ 10^{L_{a/eq/T}/10}$ for arrivals and $C_{d/T} = T \circ 10^{L_{d/eq/T}/10}$ for departures. The period T is expressed in seconds. Similarly, the sound energy of an individual noise event - arrival and/or departure - can be expressed as $N_{i/a} = 10^{L_{a/k/T}/10}$ and $N_{i/d} = 10^{L_{d/k/T}/10}$, respectively. By dividing the airport noise capacity by the average sound energy per individual event, the number of aircraft movements satisfying the prescribed noise quota during time T can be estimated as: $C_{e/n} = C_{a/T}/N_{i/a-d}$. Figure 7 shows an example of the potential relationships.

As can be seen, for the given noise quota, the airport capacity in terms of the number of operations increases with reducing the average noise per individual event - arrival and/or departure. In addition, by increasing of the available noise quota, the airport capacity increases given the average noise per individual event. The average noise per an individual event depends on the structure of aircraft fleet using the airport as well as on classiness of the aircraft paths to the noise measurement points. Generally, the average noise per event will be higher in line with increasing of the proportion of heavy and Category 2 noisier aircraft in the arrival/departure mix and if the noise measurement points are closer to the aircraft path (ICAO, 1993b).

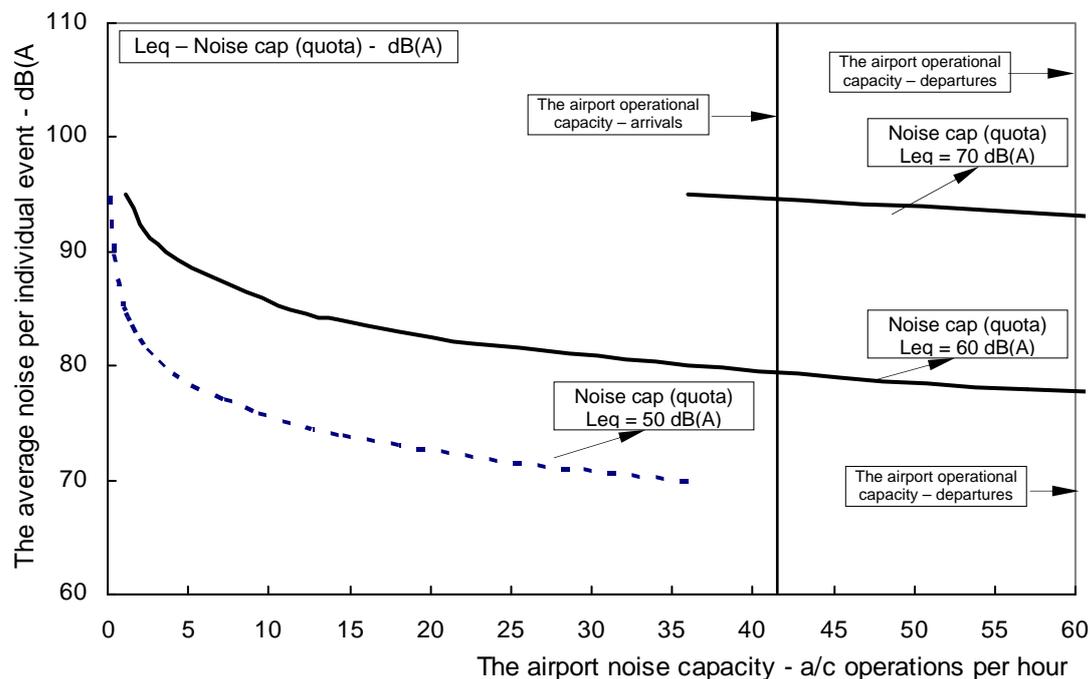


Figure 7. Relationship between the airport operational capacity, noise cap (quota) and the average noise per an atm t (Compiled from Janic, 2008)

³ At airports imposed a night flight ban, the noise quota is set up to zero during the ban period. During the day, it is above zero such for example: 57 dB(A) at London Heathrow, 85 dB(A) at Birmingham, and 73 dB(A) at Frankfurt airport (DETR, 1999).

The noise cap (quota) may also act as a real constraint to the airport capacity under specific circumstances such as for example imposition of the severe night limitations or complete night-flight ban. Figure 7 (dotted line) shows that in such cases, if the noise quota is set up at the level of minimal exposure (for example 50 dB(A)), only a few if any aircraft movements will be allowed (Ashford and Wright, 1992). Contrary, as an average noise per event is set up to 80 dB(A), the number of landings in the scope of a given noise quota of 60 dB(A) will be about 40 ops/h. Generally, relaxing the noise constraints generally enables increasing of the number of runway operations at a given airport up to the full operational capacity.

4.2 Operational capacity versus air pollution cap (quota)

The airport environmental capacity with respect to a given air pollution cap (quota) can be expressed by the maximum number of atms and/or WLUs served during a given period of time under conditions of constant demand for service whose total air pollution remains within the cap. This implies that if this cap during time T is $Q_{m/T}$, and if the total air pollution increases proportionally to increase in the volume of traffic, the capacity achieved within the prescribed cap can be estimated as: $C_{e/ap} \approx Q_{m/T} n_a e_a q_{ap}$, where: n_a is the average number of air pollution activities per unit of traffic (atms, WLUs); q_{ap} is the average energy consumption per activity; and e_a is the air pollution per unit of the consumed energy. In addition, this capacity can be considered in a more complex. For example, particular activities, energy consumption, and related air pollution can be separately analyzed (quantified) for the airport airside and landside area. In the airside area, this capacity can be expressed by the 'number of atms/ T ' or by the 'number of LTO cycles/ T '. In the landside area, this capacity can again be expressed by the 'volume of WLU/ T '.

4.3 General relationship between effects-benefits and impacts-externalities

Growth of a given airport usually brings increasing benefits to the airport operator, local community, and the overall society. Their size and structure, mainly expressed in terms of local employment and consequent direct contribution to GDP, and by revenues gained from visitors to the region, are usually proportional to the volume of accommodated airport demand under given conditions. This demand, satisfied by the airport operational capacity, may be faced with some acceptable congestion and delays. The particular environmental constraints such as the above-mentioned for noise and/or air pollution may affect (constrain) the airport operational capacity, which, under given level of demand, may increase congestion and delays. If taken place for a longer time, these caps may constrain the overall volumes of accommodated demand, and consequently affect the airport medium- to long-term growth and expected effects-benefits. In addition, charging particular externalities in the form of taxes may increase airfares and consequently deter some passengers and airlines from using given airport, which in turn, again may affect its growth. The cap on using land for expansion of the airport airside and landside infrastructure directly affects the airport operational capacity, congestion and delays, and consequently the airport medium- to long-term growth, i.e. the related overall effects-benefits. Therefore, trading off between particular effects and related impacts-benefits by using different policy instruments (tools) needs to be carefully carried out respecting rather strong inherent mutual interrelations between them all. In some sense, the above-mentioned indicator system could be used for such a purpose when both total and/or partial effects-benefits and impacts-externalities are expressed in the monetary terms. In such case, ratio $r = R/C$ can be used, where R is the total social benefits and C is the total social cost either from the already realized or

⁴ In this case, air pollution in the airport airside area is mainly generated during the aircraft LTO cycles and the aircraft ground servicing vehicles, and other facilities and equipment (Gosling, 1999; EPA, 1999; ICAO, 1993b; Liang and Chin, 1998; EC, 2005)

perceived (forecasted) operations of a given airport during a specified period of time (one or few years). Under such conditions, if $r > 1$, the airport will develop in the sustainable way; if $r = 1$, the airport development will be "neutral" or "zero" sustainable; and if $r < 1$, the airport development will be unsustainable. This ratio could be also used in evaluation of feasibility of investments in the airport (and overall) transport infrastructure.

5. Conclusions

This paper has elaborated the methodology for monitoring, analyzing, and assessment of the sustainable development of an airport. This methodology has consisted of the concept of sustainable development and the indicator system for quantifying outcome from such development. The concept has included identifying and analyzing particular effects-benefits and impacts-externalities created by operation of a given airport. The indicator system consisted of indicators and their measures has reflected the airport infrastructural/technological, operational, economic, environmental, social, and institutional performance. Quantification of some of these indicators and measures has indicated that airports, with exemption of congestion and delays as well as waste in some specific cases, have developed in the rather sustainable way, i.e. overall they have increased effects-benefits and simultaneously diminished some impacts-externalities in both absolute and relative terms over time.

In some cases, trading-off between particular effects-benefits and impacts-externalities has indicated their high mutual dependability. For example, some strict targets on impacts of noise, air pollution, and available land for the infrastructure expansion might ultimately constrain the volume of airport operations in the short- (daily) but also in the medium- to long-term, thus consequently affecting the overall airport effects-benefits. Therefore, policies on the airport sustainable development should consider its medium- to long-term development using the proposed methodology at least at an initial stage in developing a "tool" for monitoring, analyzing, and assessing the overall effects-benefits and impacts-externalities. The outcome should enable particular actors involved such as the airport operator, local and national authorities and communities, airlines, and users - air passengers and freight shippers to judge about the level of airport (un)sustainable development as well as perceive more precisely their role and contribution to it.

A prospective future research could be focused to completing and improving the proposed indicator system for monitoring, analyzing, and assessing the sustainable development of airports. This implies developing indicators and their measures for the infrastructural and technical/technological dimension of the airport performance. In addition, the framework for providing regular data and supportive information on the influencing factors on particular indicators and measures, thus enabling assessment their both quantitative and qualitative influence. This could be followed by more detailed analyzing and establishing the relationships between indicators and measures from different dimensions of airport performance. As well, research on possibilities of standardization of particular indicators, measures, and influencing factors could be undertaken in order to enable them to be applied to fair and consistent comparison of the achieved level of sustainable development at the specified different airports.

References

- ACI Europe (1998). *Creating Employment and Prosperity in Europe, A Study of the Social and Economic Impacts of Airports*. Airport Council International Europe, Brussels, Belgium.
- ACI (2008). *Airports - Actions on Climate Change*. Airport Council International, Montreal, Canada.

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

ACL (2007). *Peak Periods at Heathrow Airport*. Report Submitted to CAA, Attachment 1, Airport Co-ordination Ltd, London, UK

AIRBUS (2006). *Airbus Global Market Forecas*. Airbus Industrie, Toulouse, France.

Ashford, N. and Wright, P.H. (1992). *Airport Engineering*. A Wiley-Interscience Publication, John Wiley & Sons, Inc., New York, USA.

ATAG (2003). *Aviation & the Environment*. Air Transport Action Group, Geneva, Switzerland.

ATAG (2003a). *Industry as a Partner for Sustainable Development*. Air Transport Action Group, Geneva, Switzerland.

BA (2004). *Social and Environmental Report*, British Airways, London, UK

BAA (2001). *Waste Management*. British Airport Authority, London, UK

Betancor, O. and Carlos Martin, J. (2005). Social Noise Cost at Madrid Barajas Airport. 8th NECTAR Conference, June 2-4, Las Palmas, Grand Canaria, Spain.

Boeing (2007). *Current Market Outlook 2007: How Will You Travel Through Life?* Boeing Commercial Airplanes: Market Analysis, Seattle, WA, USA.

CAA (2004). *Noise Mapping – Aircraft Traffic Noise Research Study on Aircraft Noise Mapping at Heathrow Airport Conducted on behalf of Defra*. ERCD Report 0306, Civil Aviation Authority, London, UK

Caves, R.E. and Gosling, G.D. (1999). *Strategic Airport Planning*. Pergamon, Elsevier Science, Amsterdam.

DETR (1999). *Noise from Arriving Aircraft: Final Report of the ANMAC Technical Working Group*. Department of the Environment, Transport and Regions, London, UK.

DETR (2000). *The Future of Aviation*. The Government's Consultation Document on Air Transport Policy, Department of the Environment, Transport and the Regions, London, UK.

De Neufville, R. and Odoni, A. (2005). *Airport Systems Planning, Design, and Management*. McGraw Hill Book Company, New York, USA.

Doganis, R. (1992). *The Airport Business*. Routledge, London, UK.

EC (1998). *Interaction between High-Speed Rail and air Passenger Transport*. Final report on the Action COST 318, EUR 18165, European Commission, Luxembourg.

EC (1999). *Air Transport and the Environment: Towards Meeting the Challenges of Sustainable Development*. European Commission, The Economic and social Committee and the Committee of the Regions, The European Parliament, (COM), Brussels, Belgium.

EC (2003). Guidelines on the revised Interim Computation Methods for Industrial Noise Aircraft Noise, Road Traffic Noise, Railway Noise, and Related Emission Data, Annex. *The Official Journal of the European Union*, pp. 50-64, Brussels, Belgium.

EC (2005). *Optimum Procedures and Techniques for the Improvement of Approach and Landing – OPTIMA*. Deliverable D1.2, Sixth Framework Programme, European Commission, Brussels, Belgium.

ECAC (1997). *Report on Standard Method of Computing Noise Contours Around Civil Airports*. European Civil Conference, ECAC. CEAC Doc. 29, Sec Ed., Neuilly-sur-Seine Cedex, France.

EEC (2005). *Standard Inputs for EUROCONTROL Cost-Benefit Analysis*. EUROCONTROL, Brussels, Belgium

Janic

Developing an Indicator System for Monitoring, Analyzing,
and Assessing Airport Sustainability

EPA (1999). *Evaluation of Air Pollution Emissions from Subsonic Commercial Jet Aircraft*. EPA-420R-99-013, ICF Consulting Group, Environmental Protection Agency, Washington, D.C., USA.

FAA (2001). *Management of Airport Industrial Waste*. Federal Aviation Administration, U.S. Department of Transport, Report No. 150/5320-15, Washington DC, USA.

FAA (2005). *FAA Aerospace Forecasts: Fiscal Years 2006-2017*. U.S. Department of Transportation, Federal Aviation Administration, Office of Policy & Plans, Washington DC, USA.

Fraport (2001). *Frankfurt Airport: Environment – Noise Reduction*. Fraport AG, Frankfurt, Germany.

Grimley, P.M. (2006). *Indicators of Sustainable Development in Civil Aviation*. PhD Thesis, Loughborough University of Technology, Loughborough, UK.

ICAO (1993a). *Aircraft Noise*. Environmental Protection, Annex 16, Vol. 1, International Civil aviation Organisation, Montreal, Canada.

ICAO (1993b). *Aircraft Engine Emissions*. Environmental Protection, Annex 16, Vol. 2, International Civil aviation Organisation, Montreal, Canada.

IPCC (1999). *Aviation and the Global Atmosphere*. Intergovernmental Panel of Climate Change, Cambridge University Press, Cambridge, UK.

HA (1999). *Environmental Impact of Air Transport in Comparison with Railways and Transport by Rail in the European Union*. Intermediate Report, Hera - Amalthea, S.L., Madrid, Spain.

INFRAS (2005). *Sustainable Aviation*. Study carried out for Air Transport Research Group - ATAG, Zurich, Switzerland.

Janic, M. (2002). Methodology for Assessing Sustainability of Air Transport System. *Journal of Air Transportation*, Vol. 7, No. 2, pp. 115-162.

Janic, M. (2004). An Application of the Methodology for Assessment of the Sustainability of Air Transport System. *Journal of Air Transportation*, Vol. 9, pp. 40-82.

Janic, M. (2007). *The Sustainability of Air Transportation: A Quantitative Analysis and Assessment*. Ashgate Ltd Limited, Aldershot, UK.

Janic, M. (2008). The Potential of Liquid Hydrogen for the Future “Carbon-Neutral” Air Transport System. *Transportation Research D* (forthcoming).

Johnston, R. (2008). Indicators for Sustainable Transport Planning. *Transportation Research Record (TRR)*, No. 2067, pp. 146-154.

Longhurst, J., Gibbs, D.C., Raper, D.W. and Conlan D.E. (1996). Towards Sustainable Airport Development. *The Environmentalist*, Vol. 16, No. 3, pp. 197-202.

Morrell, P. and Lu, C.H-Y. (2000). Aircraft Noise Social Cost and Charge Mechanisms – A Case Study of Amsterdam Airport Schiphol. *Transportation Research D*, Vol. 5, pp. 305-320.

Schiphol Airport (2004). *Annual Statistical Review 1990-2004*. ZG Schiphol, The Netherlands.

Smith, M. J. T., (1989). *Aircraft Noise*. Cambridge University Press, Cambridge, USA.

Upham, P., Maughan, J., Raper, D. and Thomas C. (2000). *Towards Sustainable Aviation*. EARTHSCAN, UK.

Upham, P. (2001). Environmental Capacity of Aviation: Theoretical Issues and Basic Research Directions. *Journal of Environmental Planning and Management*, Vol. 44, No. 5, pp. 721-734.