# An Application of the Multiple Criteria Decision Making (MCDM) Analysis to the Selection of a New Hub Airport

Milan Janic* and Aura Reggiani**
* OTB Research Institute
Delft University of Technology
Delft
The Netherlands
E-mail: janic@otb.tudelft.nl

**Department of Economics
University of Bologna
Bologna
Italy
E-mail: reggiani@ipazia.economia.unibo.it

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*The paper illustrates the application of three Multiple-Criteria Decision-Making (MCDM) methods to the problem of the selection of a new hub airport for a hypothetical European Union (EU) airline assumed to operate within the EU liberalised air transport market. The three MCDM methods used are SAW (Simple Additive Weighting), TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) and AHP (Analytic Hierarchy Process), and they are applied to a preselected set of alternative airports. The attributes (criteria) are defined to express the performance of particular alternatives (airports) relevant for a Decision-Maker (DM), in this case the EU airline in question.*

*In addition to illustrating the three methods, this application of three different MCDM methods is intended to lead to a preliminary judgment about their usefulness as supplementary decision-making tools for eventual practical use. The example in which seven preselected European airports are ranked according to nine performance criteria, indicates that all three methods, if applied to the same problem and using the same method for determining the importance of the different criteria, produce the same results.*

# 1. Introduction

The European air transport system consists of airports, air traffic control (i.e., aviation infrastructure) and airlines. Before market liberalisation, which took place as a gradual process between 1987 and 1997, the flight intensity between particular airports within particular European Union (EU) member states was regulated by numerous inter-state and inter-airline bilateral agreements (Button et al., 1998; Button and Stough, 2000; Button and Swan, 1991; ICAO, 1988: OECD, 1988). Consequently, most EU airlines, and particularly the national ‘flags’, had built relatively strong ‘star-shaped’ or ‘radial’ air route networks around their national hubs (usually the biggest national airports). The allowed routes and agreed flight frequencies have considerably influenced the spatial layout of the airline networks within the EU.

During the post-liberalisation period, capturing a strategic market position by using the advantages of the liberalised market has become an important policy strategy of many EU airlines (Stasinopoulos, 1992; 1993). Some of them, particularly those from the European periphery, both ‘flags’ and regional ones, have intended to strengthen their presence in the core area of Europe[1] while some airlines from the core have tried to move in the opposite direction. In both cases, setting up a new hub airport abroad, i.e., outside the domestic market (in addition to the old national one), has been considered a viable option.

This paper illustrates an application of the Multiple-Criteria Decision-Making (MCDM) approach to the problem of selecting a new hub airport for a hypothetical EU airline. Unlike traditional operations research optimisation problems, which deal with a single objective function to be optimised over a set of feasible solutions, MCDM refers to making decisions in the presence of multiple, usually conflicting and non-commensurable criteria (Zanakis et al., 1998). Three discrete MCDM methods using a given set of a countable number of alternatives and based on the inter- and intra-comparison of quantifiable attributes (criteria) of these alternatives and their implicit and explicit trading-off are chosen. These are the SAW (Simple Additive Weighting), TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) and AHP (Analytic Hierarchy Process) methods (Hwang and Yoon, 1981; Saaty, 1980; Zanakis et al., 1998). The candidate airports for establishing a new hub are the alternatives. The attributes (criteria) are defined to express and quantify the performance of particular alternatives (airports) with respect to their relevance for the Decision Maker (a hypothetical EU airline).

Both practitioners and researchers may be interested in the results of this application. Practitioners often need a simple, understandable, and easily applicable Decision Making (DM) method in order to be able to justify the decisions taken, very often, by the common rule of thumb. The airlines as the practitioners in this case may consider the proposed MCDM methods in a similar way. Researchers have generally agreed about the necessity to use these and other MCDM methods when dealing with practical multiple criteria problems. However, they have often disagreed about the concrete method to be used since, depending on the problem, the risk of different methods producing different solutions when applied to the same problem has always existed (Zanakis et al., 1998). In such a context, this paper may be

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[1] For a long time, the central parts of France and Germany, the southern part of England, the whole of Belgium and The Netherlands, and the north of Italy have been recognised as the core area, which generates about 35% of all European air traffic (IFAPA, 1988).

considered an additional contribution to clarifying the usefulness of particular MCDM methods.

Besides this introductory section, the paper consists of four sections. Section 2 provides a short overview of the problem including current policy and practice of EU airlines operating in a liberalised EU air transport market. Section 3 describes three proposed discrete MCDM methods for selecting an airport as a new (additional) airline hub. Application of the proposed methodology is presented in section 4. The last section contains some conclusions.

# 2. Overview of the problem

Liberalisation of the EU aviation market has removed the institutional barriers which have hindered the freedom and flexibility of air transport operations between particular member states. Consequently, free operations in terms of flight frequencies, fares and entrance into/exit from the market have developed with expectations to instigate competition within the industry, diminish airfares and improve the overall quality of service for both passengers and freight. In parallel, privatisation of airlines and airports has taken place as an additional (and complementary) activity with the same purpose, i.e., to improve the overall efficiency and effectiveness of the whole sector and its particular components – airlines and airports. Confronted with the new challenges and conditions, EU airlines have generally used one or a few options for keeping their existing positions and taking possession of a new strategic position in the EU aviation market as follows:

- Abandoning existing (classical) agreements with other EU airlines and re-designing bilateral and multi-lateral agreements with non-EU airlines both on the continent and abroad;
- Keeping existing and establishing new alliances with both European and non-European partners; and
- Looking for a new hub airport at a demand-attractive (i.e., strategic) location within the EU, preferably within the core area, either individually or within the scope of an alliance partnership.

## 2.1 Bilateral agreements

After liberalisation, the EU airlines have abandoned bilateral agreements between themselves, while at the same time retaining and modifying most bilateral agreements with non-EU and non-European partners. These agreements were modified mostly in terms of increased flexibility of supplying flight frequencies and setting airfares (Stainland, 1998). The existing agreements are expected to continue to be either significantly softened or even completely abandoned by the implementation of the various open-skies initiatives[2] between the EU and rest of the world.

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[2] An open skies agreement may contain all (or most) elements of the completely liberalised aviation market of the partners' countries. For example, according to the U.S. Department of Transportation, 12 European countries already have an open skies agreement with the U.S.: The Netherlands, Switzerland, Sweden, Norway, Luxembourg, Iceland, Finland, Denmark, Belgium, Austria, Czech Republic and Germany (Stainland, 1998).

## 2.2 Airline alliances

EU airlines have for a long time forged airline alliances of the types corporate merger, marketing agreement, and strong alliance involving holding stakes/equities by a merger in the partner(s) (Button et al., 1998; Oum et al, 2000; Tretheway, 1990). The number and diversity of alliances have particularly increased after the liberalisation of the EU aviation market both for EU airlines and for most important EU airports, with a dominance of those of type marketing agreement (Janic, 1997; Oum et al, 2000, Panmure, 2000; RBI, 1995/1999).

In general, the alliances have brought both advantages and disadvantages to the EU airlines. An apparent advantage has been the overall improvement of the utilisation of airline fleets, which has been achieved through complementarity of services and co-operation instead of competition, based on 'code-sharing' agreements and balanced schedules on common routes. In addition, the alliances have helped many EU airlines, particularly the 'flags', to keep a dominant position at their main hubs (Burghouwt et al., 2002). The disadvantage has seemed to be an unavoidable competition between different (global) alliances.

The users (passengers) have also experienced both advantages and disadvantages. The apparent advantages have been improved quality of service through increased flight frequencies (i.e., flight concentration on particular routes), increased diversity of destinations (markets), more reliable and efficient transfer of passengers and freight between an alliance's (i.e., code sharing) flights, and obtained benefits from FFPs (Frequent Flyer Programmes). The evident disadvantage has been the persistence of relatively high and diverse airfares throughout the EU market, primarily due to a lack of sufficient competition (Bailey et al., 1985; Button et al., 1998; IFAPA, 1988; Janic, 1997; RBI, 1995/1999).

## 2.3 A new hub airport

Several EU airlines have considered establishing a new hub airport abroad (i.e., in another member state) as a viable option in order to both strengthen their global market position within the EU, and diminish a latent risk of failure of convenient alliances. There has been evidence about such practices, which have taken place on both the national and international EU scene. For instance, on the international scene, Iberia, which operates the national hub Madrid-Barajas Airport has considered either Frankfurt-Main or Amsterdam-Schiphol Airport as its new second hub. Finnair, whose hub is Helsinki Vantaa Airport, has considered Stockholm Arlanda Airport as a potential new hub. Both SAS, which already operates three hubs (Copenhagen Kastrup, Stockholm Arlanda and Oslo Fornebu) and KLM have been looking for a new hub (Berechman and De Wit, 1996). Since Alitalia has moved its hub (and two thirds of its European routes) from Rome-Leonardo da Vinci Airport to Milan Malpensa Airport (AW, 1999) at the end of 1998, KLM has also considered this airport as potential new hub through a prospective alliance with Alitalia (AW, 2000). Recently, British Airways has tried to negotiate an alliance with KLM, but at the same time has looked at Brussels International Airport as a potential new hub abroad, particularly after the collapse of the Belgian 'flag' Sabena. BA's well-established hubs are London Heathrow Airport and, until recently, London Gatwick Airport. In addition, one of the European low-cost carriers, Virgin-Express, has been considering Paris Charles de Gaulle Airport as an additional hub. The airline's current hub is Brussels International Airport, where its market position has been strengthened after Sabena's failing in the year 2001 (http://www.airwise.com/). Another low-cost airline, Ryanair, has selected Charleroi Airport near Brussels as its fourth hub, in addition to London Stansted, Dublin, and Shannon (http://www.ryanair.com). On the national (domestic) scene, British Midland has set up a second European hub, in addition to East Midland Airport, at London Heathrow Airport, and an intercontinental hub at Manchester Airport. Lufthansa has located its second national hub at the gradually growing Munich Airport, in addition to the one at Frankfurt-Main Airport.

Bearing in mind the described real-life developments, the hub is considered in this paper broadly as an airport at which an airline has a base for its fleet. From there it may carry out either frequent 'point-to-point' or 'hub-and-spoke' operations. The latter may have a spatial but not necessarily also a temporal component in terms of 'waving' of flights (Burghouwt et al., 2002).

# 3. Selecting a new hub airport by MCDM methods

### 3.1 Overview of previous research

The research dealing with the selection of a new hub facility has always been closely interrelated to the problem of development and operation of hub-and-spoke transport networks. It has been carried out in fields such as operations research, spatial planning, and economics. Usually, real-life attainments in both passenger and freight transport are followed (Aykin, 1995).

Operational researchers have mostly dealt with determining the route structure and location of one and/or a few hubs, in order to minimise the total network cost for a transport operator. In such a context, a single hub location problem has been always converted into a classical Weber's least-cost location problem. The optimal location of two or more hubs has emerged as a much more complex problem, which has usually required the development of complex algorithms based on heuristics and mathematical programming techniques (Adler and Berecham, 2001; Aykin, 1995; Daskin, 1995; Hall, 2000; O'Kelly, 1986).

The economists have mostly used regression models for studying hub-and-spoke networks and their influence on the operators' and users' welfare (Morrison and Winston, 1994). In most cases, a hub-and-spoke network has been considered a given entity in which the problem of hub location does not exist at all. It has been assumed that a hub should be located logically, at a central site in relation to other nodes of the network, and have a significant proportion of local traffic (Bailey, Graham and Kaplan, 1985). Berechman and De Wit (1996) have developed a simulation model for optimally locating a hub airport for a hypothetical West European airline. The airline profit earned by operating the network established around a preselected hub has been used as an exclusive decision-making criterion. Recently, Adler and Berechman (2001) have developed an algorithm for optimising a two-hub-and-spoke airline network operating in a deregulated market. The algorithm has maximised the airline profits under given constraints.

Evidently, most of the above studies were based on the optimisation of hub location and associated networks by using a single criterion representing the network operator's costs, revenues, or profits.

In this paper, Multiple Criteria Decision Making methods are proposed to deal with the problem of selecting a new hub airport, which makes this approach innovative compared to previous ones. To the authors' knowledge, there is no explicit evidence indicating that some airlines already use this or a similar procedure to deal with the problem of hub location. Therefore, this matter still remains within the domain of researchers. However, bearing in mind that several airlines demonstrate a high flexibility in using different operations research techniques at both tactical and strategic level (Yu, 1998), it is really to be expected that they may, as practitioners, eventually become interested in the proposed multiple criteria approach.

## 3.2 The basic structure of the chosen MCDM methods

Three discrete Multi-Criteria Decision-Making (MCDM) methods, SAW (Simple Additive Weighting), TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) and AHP (Analytic Hierarchy Process), are chosen to deal with the problem of selecting a new airline hub (Hwang and Yoon, 1981; Saaty, 1980; Winston, 1994). These methods have shown to be popular and widely used by researchers. Essentially, each one reflects a different approach to solving a given discrete MCDM problem of choosing the best among several pre-selected alternatives. All three methods require the pre-selection of a countable number of alternatives and the use of a countable number of quantifiable (conflicting and non-commensurable) performance attributes (criteria). The attributes (criteria) may indicate costs and benefits to a DM. A larger outcome always means greater preference for a benefit or less preference for a cost criterion. After inter- and intra-comparison of the alternatives with respect to a given set of performance attributes (criteria), implicit/explicit trade-offs are established and used to rank the alternatives (Zanakis et al., 1998).

The SAW method is selected as the simplest and clearest method. It is often used as a benchmark to compare the results obtained from this and other discrete MCDM methods when applied to the same problem. The TOPSIS method is selected because of its unique (specific) but also very logical way of approaching the discrete MCDM problems. However, it is computationally more complex than SAW. The AHP method is selected for its specificity, which offers a certain freedom to a DM to express his preferences for particular attributes (criteria) by using the original AHP measurement scale.

SAW and TOPSIS require the quantification of performance attributes (criteria) for particular alternatives. For these methods, the weights used to express the relative importance of attributes (criteria) can be determined either analytically or empirically by the DM himself. The final method, AHP, does not require such explicit quantification of attributes (criteria), but it needs specific hierarchical structuring of the MCDM problem. The method itself then generates the weights of the criteria by using the AHP measurement scale according to a specified procedure.

Under such circumstances, a comparison of the results from such different methods applied to the same problem appears to be very interesting and challenging from both academic and practical perspectives. In the next sub-sections, the basic structures of three MCDM methods and the procedures for assigning weight to the attributes (criteria) are described.

### *3.2.1 The SAW method*

The SAW (Simple Additive Weighting) method consists of quantifying the values of attributes (criteria) for each alternative, constructing the Decision Matrix $\boldsymbol{A}$ containing these values, deriving the normalised Decision Matrix $\boldsymbol{R}$, assigning the importance (weights) to criteria, and calculating the overall score for each alternative. Then, the alternative with the highest score is selected as the prefered (best) one. The analytical structure of the SAW method for *N* alternatives and *M* attributes (criteria) can be summarised as follows:

$$S_i = \sum_{j=1}^{M} w_j r_{ij} \quad \text{for } i = 1, 2,.., N \tag{1}$$

where

$S_i$ is the overall score of the i<sup></sup>th alternative;

$r_{ij}$ is the normalised rating of the ith alternative for the jth criterion, which is computed as $r_{ij} = x_{ij}/(\max_i x_{ij})$ for the benefit and $r_{ij} = (1/x_{ij})/\lfloor \max_i (1/x_{ij}) \rfloor$ for the cost criterion representing an element of the normalised matrix **R**;

$x_{ij}$ is an element of the Decision Matrix **A**, which represents the original value of the jth criterion of the ith alternative;

$w_j$ is the importance (weight) of the jth criterion;

N is the number of alternatives;

W is the number of criteria.

### *3.2.2 The TOPSIS method*

The TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) method, at the first stage, consists of the composition of the Decision Matrix ***A*** with the values of attributes (criteria), and the construction of the normalised Decision Matrix ***R*** based upon matrix ***A***. The elements of matrix ***R*** are computed as $r_{ij} = x_{ij}/(\sum_{i=1}^{M} x_{ij}^2)^{1/2}$, where $x_{ij}$ is the value of the *j*th criterion for the *i*th alternative, and is, as in equation (1), an element of Decision Matrix ***A***. The weighted normalised decision matrix is obtained by using the normalised decision matrix ***R*** and weights assigned to criteria as $\boldsymbol{V}[v_{ij}] = [w_j * r_{ij}]$.

At the second stage, the ideal (fictitious best) solution $A^+$ and the negative-ideal (fictitious worst) solution $A^-$, are determined, respectively, as follows:

$$A^+ = \{(\max_i v_{ij} \mid j \in J_1), (\min_i v_{ij} \mid j \in J_2) \mid i = 1,2,.., N\} = \{v_1^+, v_2^+,.., v_j^+,.., v_M^+\} \tag{2a}$$

$$A^- = \{(\min_i v_{ij} \mid j \in J_1), (\max_i v_{ij} \mid j \in J_2) \mid i = 1,2,.., N\} = \{v_1^-, v_2^-,.., v_j^-,.., v_M^-\} \tag{2b}$$

where $J_1$ is associated with the benefit and $J_2$ with the cost criteria.

Consequently, the Euclidean distance of each alternative from the overall ideal and negative-ideal solution is determined, respectively, as follows:

$$S_i^+ = \left[\sum_{j=1}^{M} (v_{ij} - v_j^*)\right]^{1/2} \quad \text{and} \quad S_i^- = \left[\sum_{j=1}^{M} (v_{ij} - v_j^-)^2\right]^{1/2} \quad \text{for } i = 1, 2,.., N \tag{3}$$

where all symbols are as above.

The relative closeness of each alternative to the ideal solution is computed as ratio $C_i^+ = S_i^- / (S_i^+ + S_i^-)$ for $i = 1,2, . ., N$. Finally, the alternative with the highest value of $C_i^+$ is selected as the preferable (best) one (Hwang and Yoon, 1981; Zanakis et al., 1998).

### *3.2.3 The AHP method*

The Analytic Hierarchy Process (AHP) method consists of three steps: decomposition of the problem, comparative judgment, and synthesis of priorities (Saaty, 1980; Winston, 1994).

*Decomposition of the problem* deals with a hierarchical schematic representation of the overall objective and the decision alternatives.

*Comparative judgment* includes the formation of the pairwise matrices and their comparison at two levels: i) the level at which all alternatives are compared with respect to each criterion, and ii) the level at which the criteria are compared with respect to the overall objective.

The following sub-steps are performed:

At level i), a pairwise comparison matrix with quadratic shape $\boldsymbol{A}_{NXN}$ is formed where $N$ corresponds to the number of alternatives. The number of matrices of type $\boldsymbol{A}$ is equivalent to the number of criteria $M$. An element of matrix $\boldsymbol{A}$, $a_{ij}$ may be assigned any value from the AHP original measurement scale containing the integers from one to nine. The particular number, usually selected by a DM, is used to express the relative importance of a particular criterion when compared across different alternatives. The following condition should always be fulfilled: $a_{ij} = 1/a_{ji}$ if $i \neq j$ and otherwise $a_{ij} = 1$.

Then, the normalised matrix $\boldsymbol{A}_{norm}$ is obtained by dividing each element of matrix $\boldsymbol{A}$ in column $i$ by the sum of all elements in the same column $i$ as follows: $r_{ij} = a_{ij} / \sum_{i=1}^{N} a_{ij}$ where $i = 1, 2,.., N$. Next, the matrix of weights, $\boldsymbol{w}$ is computed. For example, the weight for the $i^{\text{th}}$ row of the matrix $\boldsymbol{w}$, $w_i$ is determined as the average of elements in row $i$ of the matrix $\boldsymbol{A}_{norm}$ as follows: $w_i = (1/N)\sum_{j=1}^{N} r_{ij}$ for $i = 1, 2,..,N$.

A similar procedure is carried out at level ii) with the matrix of criteria $\boldsymbol{C}$, which has dimensions equivalent to the number of criteria.

At level i) the consistency of the DM's comparisons is checked by computing the matrix $\boldsymbol{B} = \boldsymbol{A}\boldsymbol{w}^{\boldsymbol{T}}$ and the value $P = (1/N)\sum_{i=1}^{N} b_i / w_i^T$ , where $b_i$ is the $i^{\text{th}}$ element of matrix $\boldsymbol{B}$ and $w_i^T$ is the $i^{\text{th}}$ element of matrix $\boldsymbol{w}^{\boldsymbol{T}}$. Then, the Consistency Index $CI$ is computed as $CI = (P - N)/(N - 1)$ and compared with the Random Index $RI$. The Random Index $RI$ for a given $N$ is provided by the AHP method.

At level ii) matrix $\boldsymbol{C}$ instead of matrix $\boldsymbol{A}$ is used to perform the above calculations.

If the condition $CI/RI \leq 0.10$ is fulfilled, the *synthesis of priorities* is carried out by computing the overall score for each alternative $S_i$ as follows (Saaty, 1980; Winston, 1994):

$$S_i = \sum_{j=1}^{M} w_j v_{ij} \text{ for } i = 1,2,.., N \tag{4}$$

where

$v_{ij}$ is the element of a priority vector of the $i^{\text{th}}$ alternative with the $j^{\text{th}}$ criterion.

Finally, the alternative with the highest overall score is selected as the prefered one.

Otherwise, if the required condition is not fulfilled, the procedure of forming the related pairwise comparison matrices should be repeated.

### *3.2.4 The importance (weight) of attributes (criteria)*

The importance (weight) of attributes (criteria) can be determined by using different procedures. Broadly there can be analytical, simulation, or empirical (heuristic) procedures.

Some of the analytical procedures which can be used with the applications of the SAW and TOPSIS methods are the right eigenvalue, the row and column geometric means, the simple raw average, and the mean transformation method, as well as the entropy method. (Hwang and Yoon, 1981; Zanakis et al., 1998). The meaning of the first four methods is relatively clear. The last, the entropy method, is often recommended as a convenient method for eliminating criteria with similar values and thus highlighting the importance of criteria with higher differences in their values. It is also recommended in cases where a DM has no reason to prefer one criterion over others (Hwang and Yoon, 1981; Zanakis et al., 1998).

Simulation can be used to determine the weights of attributes (criteria) by generating them from a given distribution, the shape of which may depend on the purpose. For example, in the case of no distribution, all weights are equalised to indicate the same importance for all criteria. Uniform distribution is used to reflect an indecisive or uninformed DM. Other distributions can be used as well, depending on the type and preferences of the DM. This procedure can be used with SAW, TOPSIS and AHP to assign weight to attributes (criteria).

The empirical (heuristic) procedure uses the judgement of the DM himself of the weights of attributes (criteria). In such a case, the assignment of weights can be based on experience (heuristic) or on specific preferences of the DM and be used to justify an *a priori* preference. This procedure can be used as imposed with both the SAW and TOPSIS methods. With the AHP method, it can be combined with the AHP’s measurement scale, which offers a flexible but consistent choice of weights for attributes (criteria).

## 3.3 The characteristics of alternatives and attributes (criteria)

### *3.3.1 Description*

A hypothetical EU airline (the DM) is assumed to consider several alternatives (airports) as potential locations of a new hub. The airline is assumed to try to evaluate their convenience by defining a set of attributes (criteria) which reflect their relevant performance. In general, these attributes (criteria) are summarised as follows:

- The strength of a candidate airport to generate air transport demand;
- The operational and economic characteristics of a candidate airport;
- The airline operating costs; and
- The environmental constraints at a candidate airport.

**The strength of a candidate airport to generate air transport demand** includes the socio-economic indicators of the airport catchment area (or the country as a whole) such as GDP (Gross Domestic Product), or combined Population and PCI (Per Capita Income). In addition, some surrogates such as attractiveness of the region (country) and/or a city (or cities) in terms of business and tourism may also be taken into account.

*Gross Domestic Product (GDP)* is shown to be the main driving force of aviation growth in many countries and regions including those served by the airport concerned. In such a context, growth of GDP is always expected to generate growth of air transport demand, and vice versa, at both macro (the country) and micro (the region and airport) scale.

Consequently, at micro-scale, airports located in the (countries) with higher GDP are always shown to be more attractive for airlines.

*Population* traditionally reflects the inherent strength of a region (or country) as a source of potential air transport demand. However, this attribute should be used carefully and selectively. For example, in regions served by one airport, it seems clear that the whole population is expected to use this single airport, but in regions or large urban agglomerations served by several airports, the population uses different airports depending on instant convenience. Therefore, an adjustment of the size of the population expected to use the candidate airport should be carried out. Under such circumstances, without taking into account competition which may already exist at the intended location for the new hub, such a modified attribute may be used to roughly indicate potential market size for the airline looking for a new hub. In addition, Per Capita Income (PCI) of a region can be used as an indicator of market strength in terms of the 'purchasing power' of the local population. In general, regions with higher PCI are always considered more lucrative air transport markets independent of the structure of activity and the type of preferred trips. In many cases, Population and PCI are considered together instead of GDP. Consequently, airports serving more densely populated regions with a higher PCI are always considered stronger generators of air transport demand, and thus more attractive for establishing a new airline business.

**The operational and economic characteristics of a candidate airport** include attributes such as the airport size, the quality of surface access, the quality of service of the airport landside and airside areas, and the cost of airport service.

*The airport size* reflects the importance of an airport at a local (regional), national, and global (international) scale. Generally, a larger airport always looks more attractive and more promising for starting a new airline business than a smaller one, since it always looks more likely to provide prospective commercially feasible demand, either through competition or co-operation with already established airlines.

*The quality of surface access* reflects the efficiency and effectiveness of passenger access to an airport by using the airport surface access systems (EC, 1998). In such a context, all airports are assumed to be accessible by individual modes such as car or taxi. However, the availability, efficiency and effectiveness of public transport such as rail and bus systems may vary significantly. Generally, airports with a greater number of more efficient (faster/cheaper) and effective (frequent/punctual/reliable) surface public transport systems are always preferred, both by passengers and by airlines (Ashford, 1988). Specifically, the number of public transport systems serving particular airports may emerge as a relevant attribute for evaluation if it significantly differs across the alternatives. For example, the quality of access is not the same at airports with and without rail connections.

*The quality of service of the airport landside area* includes the overall quality of the aviation product provided to passengers by an airport in the airport terminal. This may include the quality of service components such as queuing and waiting at different service counters, safety and security, reliability of inter-flight connections, the risk of losing or damaging baggage, and overall cleanliness. The value of this attribute (criteria) should be as high as possible and is important for evaluation particularly in cases where the airports themselves look after these quality of service elements. However, if the airlines take care of these elements or if the alternative airports offer very similar conditions, this attribute (criterion) appears to be less relevant (CAA, 2000; Bowen and Headly, 2002).

*The quality of service of the airport airside area* includes attributes such as the volume utilisation and the distribution of the airport airside capacity among the airlines operating there. Indirectly, these attributes reflect the ease with which an airline as a new entrant can get a desired number of landing and departure slots at a preferred time. Generally, at airports with a greater but less utilised capacity, establishing a desired network of routes and services is easier, and thus such a location is always considered more attractive. The distribution of capacity (i.e., the available slots) among airlines already operating at the airport in question indicates the level of market deregulation and the incumbent's (and its alliance's) relative market strength. Consequently, if slots are distributed more evenly among airlines which are not alliance partners, the airport market is considered to be more liberal-deregulated, and the incumbent's influence on the slot allocation weaker. This may make new entry much easier and consequently make the airport more attractive. In addition, the average delay per aircraft operation caused by airport reasons can be used as an attribute of the airside quality of service. The value of this attribute should preferably be as small as possible (Burghouwt et al., 2002: EUROCONTROL, 2002; Janic, 1997).

*The cost of airport service* includes passenger tax, landing fees, or both. Actually, this cost reflects the rate charged by an airport for a service, i.e., this is the charge for serving a unit of air transport demand, either passenger or aircraft. According to the business policy of many airlines, particularly those called low-cost carriers, of keeping the operational costs under strict control, the average cost of service may be an important factor when considering an airport as a new hub. In general, bigger, privatised, and more efficient airports, as well as smaller regional airports struggling to attract more air transport demand by offering cheaper services, are generally considered more attractive by most airlines (Doganis, 1992; 2001).

**The airline operating costs** consist of the total expenses incurred by an airline when operating the 'renovated' hub-and-spoke network containing the new hub.

*The airline operating costs* depend on internal and external factors. The internal factors include the size of the airline network expressed by the number of airports and routes, flight frequencies on particular routes, the types (capacity) of aircraft engaged, the airline routing strategy to incorporate a selected airport in the existing network, and the fixed costs of setting up a new hub at the preselected airport. The external factors include the prices of inputs such as, generally, labour, energy (fuel) and capital. The airline operating costs generally increase with increasing internal or external factors, and decrease with decreasing internal or external factors, and they should preferably be as low as possible for the new hub (Aykin, 1995; Janic, 2001).

**The environmental constraints** at particular airports include constraints aircraft noise, air pollution and land-take.

*The environmental constraints* may work as a 'deterring factor' when considering an airport as a candidate for a new hub in several ways. Firstly, they could significantly affect the intended volume of operations. Secondly, they may be completely unacceptable for airlines using 'old-technology' aircraft in terms of noise and air pollution burdens. And lastly, congested airports without prospective options for expansion due to land-take constraints are always considered less attractive locations for launching a prospective airline business. In general, airports with smaller numbers of less strict environmental constraints are always preferable.

Consequently, the following twelve performance attributes (criteria) can be identified as relevant for the location of a new hub:

- Population;
- Per Capita Income;
- Airport size;
- Generalised surface access cost;
- Quality of passenger service in the airport terminal;
- The airline costs of operating the ‘renovated’ air route network;
- The average cost of airport service;
- Airport capacity;
- The incumbent’s market share;
- Utilisation of airport capacity;
- The airport-induced delay;
- The environmental constraints.

Generally, some of the above attributes (criteria) may be dependent on each other. For example, the attribute “airport size” depends on the attributes “population” and “PCI”. This is particularly the case for airports with a large proportion of terminating traffic. In addition, the attribute “airport size” may also depend on the airport location within the airline and air transport route network, in which case the transit/transfer traffic generated by the airline itself may have a significant proportion in the total airport traffic. The attribute “generalised surface access cost”, which reflects the availability, efficiency and effectiveness of the airport surface access modes may depend on “airport size”. The attribute “airport capacity” mainly correlates with the attribute “airport size”, and the “average cost of airport service” may also depend on the attribute “airport size” (and vice versa). The attribute “airport-induced delay” may depend on the attributes “airport size” and “airport capacity”, etc. However, such overall interdependence between particular attributes (criteria) does not exclude their consideration by the DM both individually and independently. This may be an argument in favour of the application of the proposed MCDM methods. Also, such an approach forces the DM to be selective and flexible in selecting particular attributes (criteria) and assigning values to them.

### *3.3.2 Quantification of attributes (criteria)*

Attributes (criteria) of airport performance can be quantified by using different methods. For example, some of them such as “Per Capita Income” and “airport size” can simply be extracted from relevant databases. “Population” can also be extracted from an appropriate database, but in most cases it needs additional modification with respect to the allocation to particular airports. Attributes such as “airport capacity” and “environmental constraints” can be obtained from the airport and air traffic control operators. The values of other attributes (criteria) such as “generalised surface access cost”, “reliability of passenger and baggage handling”, “airline operating cost of the ‘renovated’ air route network”, “average cost of airport service”, “incumbent’s market share”, “utilisation of airport capacity” and “airport induced delays” can again be compiled from relevant databases.

- *Generalised surface access cost* comprises both passengers’ out-of-pocket costs for travel and the cost of their time spent within surface access systems. The ‘time of being within the system’ includes ‘defer’ time, which depends on the departure frequency, and ‘invehicle' time, which depends on the average running speed and the distance between an airport and its catchment area. The value of passenger time may depend on the type of travel (business, leisure) and the characteristics of the passengers (sex, age, etc) (Janic, 2001). In general, this cost can be estimated with equation A1 (Appendix)

- *Quality of service in an airport terminal* can be measured by the average passenger delay while getting the basic service within the terminal (Janic, 2001). Another measure may be the reliability of service, which can be expressed by the proportion of miss-connecting flights or miss-handled/damaged baggage during a given period (month, year). The values of this attribute can be obtained from the airport, airlines, and dedicated consumers' reports (Bowen and Headly, 2002).
- *The airline operating cost of operating the 'renovated' hub-and-spoke network* can be estimated for a given network configuration (size, structure: two hubs) and traffic scenario determined by the flight frequencies on particular routes, aircraft types (size), and the average cost per unit of airline output (passenger-kilometre). These costs can be quantified with equation A2 (Appendix).
- *The average cost of airport service* can, in most cases, be obtained by using convenient modelling techniques. In such a context, regression analysis is frequently used to estimate the relationship between this cost (dependent variable) and the volume of airport output (independent variable).
- *The incumbent's market share* can be estimated, for a given airport, by dividing the total number of the incumbent's incoming and outgoing flights by the total number of incoming and outgoing flights carried out by all airlines during a given period of time (hour, day, month, year). This should include usage of aircrafts of comparable seat capacity.
- *Utilisation of airport capacity* can be expressed as the ratio between the actual number of aircraft movements and the airport capacity[3].
- *The airport- induced delay* can be obtained from the airport and air traffic control reports. However, sometimes it is very difficult to extract the portion of this kind of delay from the available aggregate figures.

# 4. Application of the proposed MCDM methods

The application of the three proposed MCDM methods is carried out under the assumption that a hypothetical EU airline already operates a network with one hub located, in the example, at Rome-Leonardo da Vinci Airport (Italy). Evidently, such a geographical position, at the European periphery relative to its core area, makes the airline's intentions to look for a new, additional hub sensible. The following seven alternatives (airports) are preselected as potential locations: Brussels - $A_1$, Paris (Charles de Gaulle-CDG) – $A_2$, Frankfurt Main – $A_3$, Düsseldorf – $A_4$, Amsterdam Schiphol – $A_5$, London Heathrow – $A_6$, and Milan Malpensa – $A_7$. Six of the above airports are located within and the seventh one on the edge of the core area. These are shown to be, generally, the most attractive airports with potentially lucrative markets both for European continental and intercontinental traffic. However, these are also

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[3] The airport capacity is usually defined as the maximum number of aircraft movements accommodated at an airport during a given period of time (one hour) under given conditions (Janic, 2001).

the most congested European airports where the incumbents and their alliance partners (with exception of Brussels International Airport after the collapse of Sabena) still keep the majority of slots. In general, some evidence indicates that bilateral agreements relating to intercontinental services are the main reasons why the incumbents are still strongly attached to these airports as their national hubs (Burghouwt et al., 2002). Under such circumstances, setting up a new hub at some of these airports may be very difficult or even impossible. Therefore, the presented numerical example intends to illustrate how the procedure of multiple criteria evaluation of these seven airports can be carried out, and to test the convenience and consistency of the proposed methods for prospective academic and eventual practical use.

### 4.1 The SAW and TOPSIS methods

#### *4.1.1 Description of inputs*

In order to apply the SAW and TOPSIS methods, the values of relevant attributes are sorted out for each of seven preselected alternative airports and given as criteria in Table 1, which represents the Decision Matrix (Hwang and Yoon, 1981).

**Table 1. Decision Matrix for a given example: seven alternative airports with nine attributes (criteria)**

| Alternative/Airport | Attributes (Criteria) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **POP** | **PCI** | **AS** | **GAC** | **TAC** | **AAC** | **AC** | **MS** | **UC** |
| Sign | + | + | + | - | - | - | + | - | - |
| | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | $X_9$ |
| $A_1$-Brussels | 1.1 | 15423 | 18.5 | 13.28 | 1.56 | 5.16 | 70 | 66 | 77 |
| $A_2$-Paris (CDG) | $6.3^*$ | 16468 | 38.6 | 21.73 | 1.61 | 2.71 | 84 | 63 | 74 |
| $A_3$-Frankfurt | 3.6 | 18308 | 42.7 | 8.12 | 1.62 | 2.16 | 72 | 61 | 84 |
| $A_4$-Dusseldorf | 3.0 | 18200 | 15.8 | 9.30 | 2.18 | 6.62 | 34 | 33 | 79 |
| $A_5$-Amsterdam | 1.1 | 15111 | 34.4 | 8.32 | 1.65 | 2.84 | 90 | 66 | 68 |
| $A_6$-London (H) | $4.2^*$ | 13293 | 60.7 | 21.64 | 1.68 | 1.76 | 78 | 39 | 93 |
| $A_7$-Milan (M) | 4.3 | 15589 | 13.6 | 14.47 | 2.25 | 7.37 | 32 | 64 | 59 |

| | |
|---|---|
| POP | Population of airport catchment area (million); *: the modified values according to the share of the airport traffic in the total air traffic of the region |
| PCI | Per Capita Income (ECU/inhabitant) |
| AS | Airport size (million of passengers per year (1998)) |
| GAC | Minimum generalised access cost (€/passenger) |
| TAC | Total airline cost of operating two-hub and spoke network (million €) |
| AAC | The average airport cost per service (€/WLU) |
| AC | Airport capacity (aircraft/hour) |
| MS | Market share of the incumbent at given airport (%) |
| UC | Utilisation of airport capacity during peaks (%); € - EURO |

The first two attributes $X_1$ and $X_2$ are “Population” and “Per Capita Income”, respectively (EC, 1997/1999). The attribute “Population” for the airports Paris (CDG) and London (H) is determined by allocating the total population of a region to the airport proportionally to its share in the total airport traffic of the region. The third attribute $X_3$, the “airport size”, is expressed by the total number of passengers accommodated at a particular airport in 1998

(RBI, 1995/1999). The fourth attribute $X_4$ is the minimum "generalised surface access cost" calculated by using the generalised cost function (equation A1 in the Appendix) and data on travel distance, departure frequencies, charges per passenger by the airport surface public systems, and the average value of passenger time (Lufthansa, 1998).

The attribute "quality of service in an airport terminal" is not taken into account since its values are assumed to be the very similar at the selected candidate airports.

The "airline operating costs" are adopted as the fifth attribute $X_5$ in Table 1. These costs are calculated for the conditions when one hub is always kept fixed while another one is alternatively chosen from a given set of alternatives. The calculation is carried out by using equation A2 is the Appendix. In each case, the airline network is assumed to consist of 20 nodes representing the most famous EU airports, among which two are the hubs and rest spokes. The spokes are assigned to each hub according to the minimum (great circle) distance. Then, the traffic scenario in terms of the volume of passenger inter-airport O/D flows and flight frequencies serving them is set up. The data from 1995 relating to 380 main intra-European inter-city one-way passenger flows, flight frequencies, aircraft capacity (size) and the average load factor are sorted out to quantify this scenario (ICAO, 1997). The average airline cost per passenger kilometre is estimated by the cost function given in Table 2. The fixed cost of setting up a new hub is assumed to be the same for each alternative airport, so it is not included in the values of attribute $X_5$. The potential intercontinental traffic at particular airports is not taken into account either, since the airline is assumed to first start its business within the EU.

The values of the attribute "cost of airport service" are estimated depending on the annual volume of services accommodated at a given preselected airport. This is carried out in two steps. Firstly, the regression model is calibrated by using the appropriate cross-sectional data for 30 European airports. This model is given in Table 2. Secondly, the average airport cost per service is computed by inserting the annual volume of services accommodated at each candidate airport into the regression model. The values for this attribute $X_6$ are given in Table 1.

The "airport capacity" is given in Table 1 as attribute $X_7$ (EUROCONTROL, 1998).

The "incumbent's market share", attribute $X_8$ in Table 1, is determined as the ratio between the number of the incumbent's weekly flights and the number of weekly flights carried out by all other airlines at a given airport (ABC, 1998). The "average utilisation of the airport capacity" is compiled from various sources and given in Table 1 as attribute $X_9$ (EUROCONTROL, 1998; RBI, 1995/1999; Urbatzka and Wilken, 1997).

The attributes "airport-induced delay" and "environmental constraints" are not taken into account due to a lack of precise data in the former and a similarity of impacts in the latter case.

Attributes $X_1$ *(POP)*, $X_2$ *(PCI)*, $X_3$ *(AS)*, and $X_7$ *(AC)* are considered by the airline (the DM) as benefit attributes; the others as cost attributes. If the given values of attributes are considered as their boundary values, they become decision-making criteria. In Table 1 the benefit criteria are marked by a '+' sign and the others by a '-' sign.

**Table 2. The models used to determine the airline and airport unit cost per service in a given example**

The airline unit cost **c**

$$\mathbf{c} = \underset{(3.266)}{6.206} \quad \underset{(4.339)}{(N\lambda)^{-0.397}} \quad \underset{(4.733)}{L^{-0.344}}$$

$R^2_{adj} = 0.896$; $F = 77.477$; $DW = 1.692$; $N = 21$

Where **c** is expressed by €/passenger-kilometre; N is the seat capacity of an aircraft; $\lambda$ is the load factor; L is the route length (the adopted average values are: $N = 146$ and $\lambda = 0.65$). The values in parentheses below particular coefficients are t –statistics, which illustrate the relative importance of particular coefficients for the regression model (Compiled from Janic, 1997).

The cost of airport service **C**

$$\mathbf{C} = 72.366\, W^{-0.882}$$

$R^2 = 0.561$; $N = 30$

Where **C** is expressed by €/WLU; W is the annual volume of Workload Units (WLU) accommodated at an airport; 1 WLU is the equivalent of one passenger or 100 kg of freight (Doganis, 1992; 2001) (Compiled from ACI, 1997; RBI, 1995/1999).

For the sensitivity analysis, three scenarios are used for assigning importance (weight) to attributes.

Scenario a) assumes that equal weights are assigned to attributes, which implies their equal importance to the DM.

Scenario b) uses the weights generated from the uniform distribution [0,1] by simulation. A set of random numbers equivalent to the number of attributes (criteria) is generated and then the weights are calculated by normalisation, i.e., by dividing each simulated value by the sum of all generated values in order to arrive at a total sum of the weights equal to one. This scenario may reflect the preferences of an indecisive DM, as the authors or a hypothetical EU airline may be at this stage of the DM process.

In scenario c) the SAW and TOPSIS methods use the entropy method given in Appendix A3. AHP uses its own weighting procedure to assign weights to attributes.

### *4.1.2 Analysis of the results*

As mentioned above, Table 1 represents the Decision Matrix $\boldsymbol{A}[a_{ij}]$, which enables the application of the SAW and TOPSIS methods as follows.

*STEP1* Calculation of the normalised decision matrix ***R**[$r_{ij}$]* given below, based upon the Decision Matrix ***A**[$a_{ij}$]* in Table 1:

SAW – R**[$r_{ij}$]**

| **Alt./Crit.** | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
|---|---|---|---|---|---|---|---|---|---|
| $A_1$ | 0.175 | 0.842 | 0.305 | 0.611 | 1.000 | 0.341 | 0.778 | 0.500 | 0.766 |
| $A_2$ | 1.000 | 0.899 | 0.636 | 0.374 | 0.969 | 0.649 | 0.933 | 0.524 | 0.797 |
| $A_3$ | 0.571 | 1.000 | 0.703 | 1.000 | 0.963 | 0.815 | 0.800 | 0.541 | 0.702 |
| $A_4$ | 0.476 | 1.000 | 0.255 | 0.873 | 0.716 | 0.266 | 0.378 | 1.000 | 0.747 |
| $A_5$ | 0.175 | 0.825 | 0.567 | 0.976 | 0.945 | 0.620 | 1.000 | 0.500 | 0.868 |
| $A_6$ | 0.667 | 0.726 | 1.000 | 0.375 | 0.929 | 1.000 | 0.867 | 0.846 | 0.634 |
| $A_7$ | 0.683 | 0.851 | 0.224 | 0.561 | 0.693 | 0.239 | 0.356 | 0.516 | 1.000 |

TOPSIS – R**[$r_{ij}$]**

| **Alt./Crit.** | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
|---|---|---|---|---|---|---|---|---|---|
| $A_1$ | 0.110 | 0.361 | 0.195 | 0.338 | 0.325 | 0.424 | 0.382 | 0.434 | 0.385 |
| $A_2$ | 0.624 | 0.385 | 0.408 | 0.552 | 0.336 | 0.223 | 0.459 | 0.414 | 0.37 |
| $A_3$ | 0.356 | 0.428 | 0.451 | 0.206 | 0.338 | 0.178 | 0.393 | 0.401 | 0.42 |
| $A_4$ | 0.297 | 0.427 | 0.167 | 0.236 | 0.454 | 0.544 | 0.186 | 0217 | 0.395 |
| $A_5$ | 0.109 | 0.353 | 0.363 | 0.211 | 0.344 | 0.223 | 0.492 | 0.434 | 0.34 |
| $A_6$ | 0.416 | 0.311 | 0.641 | 0.55 | 0.35 | 0.145 | 0.426 | 0.257 | 0.425 |
| $A_7$ | 0.426 | 0.365 | 0.144 | 0.368 | 0.469 | 0.606 | 0.175 | 0.421 | 0.295 |

*STEP 2* Determination of the relative importance of particular criteria for the SAW and TOPSIS methods given below in Table 3 according to scenarios a), b) and c):

**Table 3. The weights of criteria for the SAW and TOPSIS methods**

| **Weight- w** | **Attributes (criteria)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
| Scenario a) | 0.111 | 0.111 | 0.111 | 0.111 | 0.111 | 0.111 | 0.111 | 0.111 | 0.111 |
| Scenario b) | 0.066 | 0.148 | 0.131 | 0.087 | 0.110 | 0.108 | 0.089 | 0.115 | 0.148 |
| Scenario c) | 0.238 | 0.010 | 0.212 | 0.129 | 0.020 | 0.225 | 0.099 | 0.050 | 0.017 |

As can be seen, in scenario a), the weights are equal, in scenario b) they are generated by the uniform distribution [0,1], and in scenario c) they are calculated using the entropy method. The third group of values indicates that “Population” and “average cost per airport service” are the most important, and “Per Capita Income”, “incumbent’s market share” and “utilisation of airport capacity” the least important criteria. This is caused by the nature of the entropy method itself, which tends to assign the greatest importance to the criteria with the greatest difference in their values.

*STEP 3* Calculation of the weighted decision matrix ***V**[$v_{ij}$]*:

SAW- V**[$v_{ij}$]**

For scenarios a), b) and c), the calculation of the normalised weighted matrix ***V*** is straightforward and the row values corresponding to the particular alternatives are summed up by using equation (1). Thus, the overall score for each alternative $S_i$ is obtained.

TOPSIS - V[$v_{ij}$], $v^+$ ***and*** $v^-$

*Scenario a)*

The normalised weighted matrix ***V*** is calculated by using the normalised matrix ***R***$[r_{ij}]$ and the corresponding weights of criteria for scenario a). It is given below.

| **Alt./Crit.** | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
|---|---|---|---|---|---|---|---|---|---|
| | + | + | + | – | – | – | + | – | – |
| $A_1$ | 0.012 | 0.040 | 0.022 | 0.038 | 0.036 | 0.047 | 0.042 | 0.048 | 0.043 |
| $A_2$ | 0.069 | 0.043 | 0.045 | 0.061 | 0.037 | 0.025 | 0.051 | 0.046 | 0.041 |
| $A_3$ | 0.040 | 0.048 | 0.050 | 0.023 | 0.038 | 0.020 | 0.044 | 0.045 | 0.047 |
| $A_4$ | 0.033 | 0.047 | 0.019 | 0.026 | 0.050 | 0.060 | 0.021 | 0.024 | 0.044 |
| $A_5$ | 0.012 | 0.039 | 0.040 | 0.023 | 0.038 | 0.025 | 0.055 | 0.048 | 0.038 |
| $A_6$ | 0.046 | 0.035 | 0.071 | 0.061 | 0.039 | 0.016 | 0.047 | 0.029 | 0.047 |
| $A_7$ | 0.046 | 0.041 | 0.016 | 0.041 | 0.052 | 0.067 | 0.019 | 0.047 | 0.033 |

The ideal and negative ideal solutions $v^+$ and $v^-$ are sorted out from the matrix ***V*** by using equation (2) as follows:

| **Ids/Criteria** | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
|---|---|---|---|---|---|---|---|---|---|
| $v^+$ | 0.069 | 0.048 | 0.071 | 0.023 | 0.036 | 0.016 | 0.055 | 0.024 | 0.033 |
| $v^-$ | 0.012 | 0.035 | 0.016 | 0.061 | 0.052 | 0.067 | 0.019 | 0.048 | 0.047 |

Then, the Euclidean distance of each alternative to the ideal and negative ideal solution $S_i^*$ and $S_i^-$, respectively, and its closeness to the ideal solution $C_i^*$ is calculated by using equation (3).

*Scenario b)*

The normalised weighted matrix ***V*** is calculated as in scenario a) by using the corresponding weights of criteria for scenario b). It is given below.

| **Alt./Crit.** | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
|---|---|---|---|---|---|---|---|---|---|
| | + | + | + | – | – | – | + | – | – |
| $A_1$ | 0.0073 | 0.0531 | 0.0255 | 0.0291 | 0.0358 | 0.0458 | 0.0340 | 0.0499 | 0.0570 |
| $A_2$ | 0.0412 | 0.0566 | 0.0534 | 0.0449 | 0.0370 | 0.0241 | 0.0409 | 0.0476 | 0.0548 |
| $A_3$ | 0.0235 | 0.0629 | 0.0591 | 0.0177 | 0.0372 | 0.0192 | 0.035 | 0.0461 | 0.0622 |
| $A_4$ | 0.0196 | 0.0628 | 0.0219 | 0.0203 | 0.0499 | 0.0588 | 0.0166 | 0.0250 | 0.0581 |
| $A_5$ | 0.0072 | 0.0519 | 0.0476 | 0.0181 | 0.0378 | 0.0241 | 0.0438 | 0.0499 | 0.0503 |
| $A_6$ | 0.0275 | 0.0457 | 0.0840 | 0.0473 | 0.0385 | 0.0157 | 0.0379 | 0.0296 | 0.0629 |
| $A_7$ | 0.0281 | 0.0537 | 0.0189 | 0.0316 | 0.0516 | 0.0654 | 0.0156 | 0.0484 | 0.0437 |

The ideal and negative ideal solutions $v^+$ and $v^-$ are sorted out from the matrix ***V*** by using equation (2) as follows:

| **Ids/Criteria** | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
|---|---|---|---|---|---|---|---|---|---|
| v+ | 0.0412 | 0.0629 | 0.0591 | 0.0177 | 0.0370 | 0.0157 | 0.0438 | 0.0250 | 0.0437 |
| v - | 0.0072 | 0.0457 | 0.0189 | 0.0473 | 0.0516 | 0.0654 | 0.0156 | 0.0499 | 0.0629 |

Then, the Euclidean distance of each alternative to the ideal and negative ideal solution $S_i^*$ and $S_i^-$, respectively, and its closeness to the ideal solution $C_i^*$ is calculated by using equation (3).

*Scenario c)*
The normalised weighted matrix *V* given below is calculated as in scenarios a) and b) by using the weights of criteria for scenario c) determined by the entropy method:

| **Alt./Crit.** | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
|---|---|---|---|---|---|---|---|---|---|
| | + | + | + | - | - | - | + | - | - |
| $A_1$ | 0.0260 | 0.0036 | 0.0410 | 0.0440 | 0.0070 | 0.0950 | 0.0380 | 0.0220 | 0.0070 |
| $A_2$ | 0.1490 | 0.0039 | 0.0860 | 0.0710 | 0.0070 | 0.0500 | 0.0450 | 0.0210 | 0.006 |
| $A_3$ | 0.0850 | 0.0043 | 0.0960 | 0.0270 | 0.0070 | 0.0400 | 0.0390 | 0.0200 | 0.0070 |
| $A_4$ | 0.0710 | 0.0043 | 0.0350 | 0.0300 | 0.0091 | 0.1220 | 0.0180 | 0.0110 | 0.0070 |
| $A_5$ | 0.0260 | 0.0045 | 0.0770 | 0.0270 | 0.0070 | 0.0500 | 0.0490 | 0.0220 | 0.0060 |
| $A_6$ | 0.0990 | 0.00310 | 0.1360 | 0.0710 | 0.0070 | 0.0330 | 0.0420 | 0.0130 | 0.0070 |
| $A_7$ | 0.1014 | 0.0037 | 0.0305 | 0.0475 | 0.0094 | 0.1364 | 0.0173 | 0.0211 | 0.0050 |

The ideal and negative ideal solutions $\boldsymbol{v}^+$ and $\boldsymbol{v}^-$ are sorted out from the matrix ***V*** by using expression (2) as follows:

| **Ids/Criteria** | **$X_1$** | **$X_2$** | **$X_3$** | **$X_4$** | **$X_5$** | **$X_6$** | **$X_7$** | **$X_8$** | **$X_9$** |
|---|---|---|---|---|---|---|---|---|---|
| $v^+$ | 0.1490 | 0.0043 | 0.1360 | 0.0270 | 0.0070 | 0.0330 | 0.0490 | 0.0110 | 0.0050 |
| $v^-$ | 0.026 | 0.0031 | 0.0305 | 0.0710 | 0.0094 | 0.1364 | 0.0173 | 0.0220 | 0.0070 |

As in scenarios a) and b), the Euclidean distance of each alternative to the ideal and negative ideal solution $S_i^*$ and $S_i^-$, respectively, and its closeness to the ideal solution $C_i^*$ is calculated by using equation (3).

*STEP 4* Selection of the best alternative obtained by SAW and TOPSIS in scenarios a), b) and c) is given in Table 4.

**Table 4. The SAW and TOPSIS ranking of alternatives in a given example**

| **Alternative** | **The MCDM method** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **SAW** | | | | | | **TOPSIS** | | | | | |
| **Overall score** | **Si** | | | **Rank** | | | **Ci*** | | | **Rank** | | |
| **Scenario** | **a)** | **b)** | **c)** | **a)** | **b)** | **c)** | **a)** | **b)** | **c)** | **a)** | **b)** | **c)** |
| $A_1$ – Brussels | 0.590 | 0.615 | 0.405 | 7 | 6 | 7 | 0.330 | 0.666 | 0.245 | 5 | 6 | 7 |
| $A_2$ – Paris (CDG) | 0.783 | 0.752 | 0.728 | 2 | 3 | 3 | 0.616 | 0.675 | 0.700 | 2 | 2 | 2 |
| *$A_3$ – Frankfurt* | *0.788* | *0.794* | 0.745 | *1* | *1* | 2 | *0.643* | *0.689* | 0.645 | *1* | *1* | 3 |
| $A_4$ – Düsseldorf | 0.634 | 0.654 | 0.464 | 5 | 5 | 5 | 0.195 | 0.380 | 0.286 | 7 | 5 | 6 |
| $A_5$ – Amsterdam (S) | 0.719 | 0.737 | 0.593 | 4 | 4 | 4 | 0.537 | 0.530 | 0.516 | 3 | 4 | 4 |
| *$A_6$ – London (H)* | 0.782 | 0.792 | *0.809* | 3 | 2 | *1* | 0.486 | 0.649 | *0.714* | 4 | 3 | *1* |
| $A_7$ – Milan (M) | 0.569 | 0.589 | 0.437 | 6 | 7 | 6 | 0.324 | 0.230 | 0.330 | 6 | 7 | 5 |

As can be seen, both methods produce the same results for a given scenario for assigning the weights to criteria. The results are also the same for scenarios a) and b), in which both methods rank Frankfurt Main Airport as the best alternative. In addition, both methods again produce the same results in scenario c), where they rank London Heathrow Airport as the best alternative. In addition, while ranking other alternatives, the SAW method produces more similar ranks across different scenarios than the TOPSIS method, which may indicate its lesser sensitivity to the changes in methods for assigning weights to criteria. Apart from its simplicity, this may be the reason why this method is frequently used as a benchmarking method.

### 4.2 The AHP method

#### *4.2.1 Description of inputs*

*Decomposition of the problem* in the scope of AHP is carried out in the form of a diagrammatic representation of the problem of the selection of a new hub shown in Figure 1.

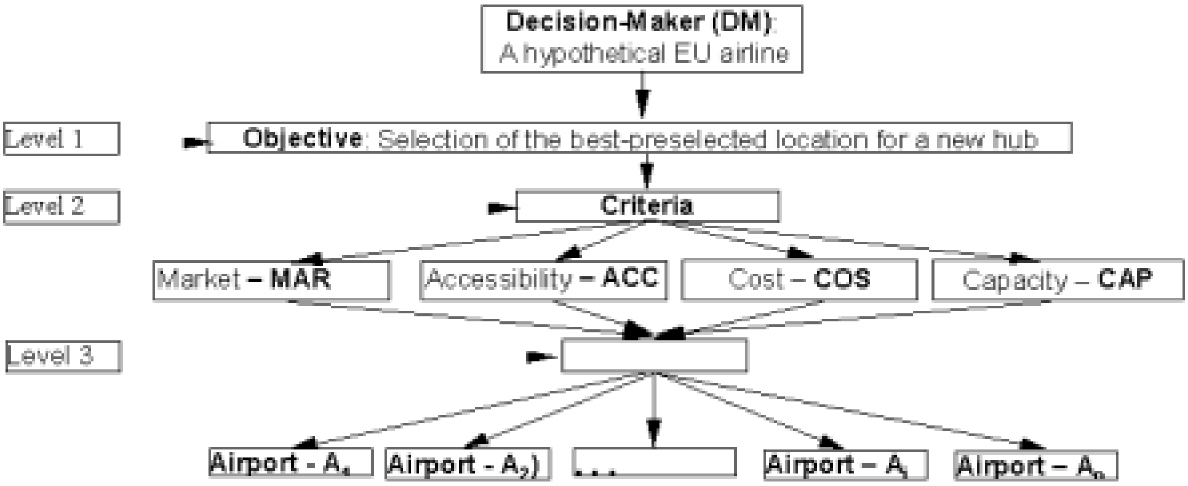

*Figure 1. The AHP method: hierarchical structuring of the MCDM problem for a given example*

As can be seen, there are three levels. At the first level, the overall objective is established. At the second level, the attributes (criteria) are set up. At the last level, the alternatives to be evaluated (airports) are set up. The number of criteria is reduced from nine for SAW and TOPSIS to four. Thus, the criterion "Market" (MAR) includes the sub-criteria "population", "Per Capita Income" and "airport size". The criterion "Accessibility" (ACC) includes the sub-criterion "generalised surface access cost". The criterion "Cost" (COS) embraces sub-criteria such as "total airline operating costs" and "average airport cost of service". Finally, the criterion "Capacity" (CAP) takes into account sub-criteria such as "airport capacity", "incumbent's market share" and "utilisation of airport capacity". The alternatives (i.e., candidate airports) $A_i$, $i = 1,2, .,7$ are put at the lowest level in Figure 1.

The *comparative judgment* includes a pairwise comparison of the alternatives and criteria at two levels as discussed in section 3.2.3.

Since seven alternative airports are evaluated with respect to four criteria, four pairwise comparison matrices of dimension 7x7 are designed, which contain the judgments on each alternative with respect to each criterion. In addition, a fifth pairwise comparison matrix is designed, which contains the judgments on each criterion with respect to the overall objective. The AHP original scale is used to determine the values of these matrices, which are the authors' choices. The importance (weight) of particular criteria, the Consistency Index (CI), the Random Index (RI) and the check of the consistency of the evaluation are calculated as mentioned in Section 3.2.3 (Saaty, 1980; Winston, 1994). The two-level evaluation is given below:

*Level i) - Pairwise comparison of seven alternative airports with respect to four criteria:*
**Market (MAR)**

| | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | **Priority - $v_{i1}$** |
|---|---|---|---|---|---|---|---|---|
| $A_1$ | 1 | 1/7 | 1/3 | 1/3 | 1 | 1/7 | ½ | 0.038 |
| $A_2$ | 7 | 1 | 5 | 5 | 5 | 3 | 5 | 0.381 |
| $A_3$ | 3 | 1/5 | 1 | 2 | 2 | 1/5 | 3 | 0.109 |
| $A_4$ | 3 | 1/5 | 1/2 | 1 | 3 | 1/5 | 1 | 0.085 |
| $A_5$ | 1 | 1/5 | 1/2 | 1/3 | 1 | 1/5 | 2 | 0.058 |
| $A_6$ | 7 | 1/3 | 5 | 5 | 5 | 1 | 5 | 0.282 |
| $A_7$ | 1 | 1/5 | 1/3 | 1 | 1/5 | 1/5 | 1 | 0.047 |

CI/RI = 0.088/1.32 = 0.067

For example, in the above matrix, the element $a_{15} = 1$ indicates that the criterion "market" is equally important at Brussels-International and Amsterdam Schiphol Airport, i.e., these two markets are considered approximately equivalent for the DM. The element $a_{21} = 7$ indicates that the criterion "market" is about seven times as important at Paris Charles de Gaulle as at Brussels International Airport. The value $a_{35} = 2$ indicates that Frankfurt Main Airport as a "market" is considered about twice as important as Amsterdam Schiphol Airport. Similar explanation relates to other candidate airports and criteria whose Decision matrices are given below:

**Accessibility (ACC)**

| i) | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | **Priority - $v_{i2}$** |
|---|---|---|---|---|---|---|---|---|
| $A_1$ | 1 | 3 | 1/3 | 1/5 | 1/3 | 3 | 2 | 0.087 |
| $A_2$ | 1/3 | 1 | 1/5 | 1/5 | 1/5 | 1/2 | 1/3 | 0.039 |
| $A_3$ | 3 | 5 | 1 | 2 | 2 | 5 | 3 | 0.284 |
| $A_4$ | 5 | 5 | 1/2 | 1 | ½ | 5 | 3 | 0.207 |
| $A_5$ | 5 | 5 | 1/2 | 2 | 1 | 5 | 3 | 0.248 |
| $A_6$ | 1/3 | 2 | 1/5 | 1/5 | 1/5 | 1 | 1/3 | 0.046 |
| $A_7$ | ½ | 3 | 1/3 | 1/3 | 1/3 | 3 | 1 | 0.089 |

CI/RI = 0.089/1.32 = 0.068

**Cost (COS)**

| i) | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | **Priority - $v_{i3}$** |
|---|---|---|---|---|---|---|---|---|
| $A_1$ | 1 | 1/6 | 1/7 | 5 | 1/7 | 1/9 | 7 | 0.065 |
| $A_2$ | 6 | 1 | 1/3 | 7 | 3 | 1/3 | 7 | 0.161 |
| $A_3$ | 7 | 3 | 1 | 7 | 5 | 1/2 | 8 | 0.259 |
| $A_4$ | 1/5 | 1/7 | 1/7 | 1 | 1/8 | 1/6 | 3 | 0.034 |
| $A_5$ | 7 | 1/3 | 1/5 | 8 | 1 | 1/5 | 9 | 0.132 |
| $A_6$ | 9 | 3 | 2 | 6 | 5 | 1 | 7 | 0.327 |
| $A_7$ | 1/7 | 1/7 | 1/8 | 1/3 | 1/9 | 1/7 | 1 | 0.022 |

CI/RI = 0.093/1.32 = 0.070

**Capacity (CAP)**

| i) | **$A_1$** | **$A_2$** | **$A_3$** | **$A_4$** | **$A_5$** | **$A_6$** | **$A_7$** | **Priority - $v_{i4}$** | |
|---|---|---|---|---|---|---|---|---|---|
| **$A_1$** | 1 | ½ | 2 | 2 | 1/3 | 5 | 1/5 | 0.095 | |
| **$A_2$** | 2 | 1 | 3 | 2 | 1/3 | 5 | 4 | 0.125 | |
| **$A_3$** | ½ | 1/3 | 1 | 2 | 1/5 | 5 | 1/7 | 0.072 | |
| **$A_4$** | ½ | 1/2 | 1/2 | 1 | 1/3 | 5 | 5 | 0.067 | |
| **$A_5$** | 3 | 3 | 5 | 3 | 1 | 5 | 1/3 | 0.214 | |
| **$A_6$** | 1/5 | 1/5 | 1/5 | 1/5 | 1/6 | 1 | 1/9 | 0.025 | |
| **$A_7$** | 5 | 4 | 7 | 6 | 3 | 9 | 1 | 0.402 | CI/RI = 0.075/1.32 = 0.057 |

*Level ii) Pairwise comparison of four criteria with respect to the overall objective*
The matrix of the criteria comparison is composed as follows:

| | **MAR** | **ACC** | **COS** | **CAP** | **Priority - $w_j$** | |
|---|---|---|---|---|---|---|
| **MAR** | 1 | 4 | 1/2 | 2 | 0.275 | |
| **ACC** | 1/4 | 1 | 1/4 | ¼ | 0.076 | |
| **COS** | 2 | 4 | 1 | 4 | 0.473 | |
| **CAP** | ½ | 4 | 1/4 | 1 | 0.176 | CI/RI = 0.074/0.90 = 0.082 |

As can be seen, the criterion “market” is considered to be about four times as important as the criterion “airport access” and twice as important as the criterion “capacity”. The criterion “cost” is considered to be about three times as important as the criterion “market” and approximately four times as important as the criterion “access”. The criterion “cost” is considered to be about twice as important as the criterion “capacity”. Finally, the criterion “capacity” is assumed to be about four times as important as the criterion “access”. Consequently, it can be seen that the proposed weighting by using the AHP scale may look like the judgement made by a so-called ‘low-cost carrier’.

The vectors of priorities for particular alternatives with respect to particular criteria $v_{ij}$ $(i = 1\text{-}7;\ j = 1\text{-}4)$, and the weights of particular criteria $w_j$ $(j = 1\text{-}4)$ for scenarios a), b), and c) are synthesised and given as follows:

| i) | **$A_1$** | **$A_2$** | **$A_3$** | **$A_4$** | **$A_5$** | **$A_6$** | **$A_7$** | **Priority - weights – $w_j$** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| j) | | | | | | | | **Scenario a)** | **Scenario b)** | **Scenario c)** |
| **MAR** | 0.038 | 0.381 | 0.109 | 0.085 | 0.058 | 0.282 | 0.047 | 0.250 | 0.220 | 0.275 |
| **ACC** | 0.087 | 0.039 | 0.284 | 0.207 | 0.248 | 0.046 | 0.089 | 0.250 | 0.226 | 0.076 |
| **COS** | 0.065 | 0.161 | 0.259 | 0.034 | 0.132 | 0.327 | 0.022 | 0.250 | 0.280 | 0.473 |
| **CAP** | 0.095 | 0.125 | 0.072 | 0.067 | 0.214 | 0.025 | 0.402 | 0.250 | 0.274 | 0.176 |

### *4.2.2 Analysis of the results*

The *synthesis of priorities* is carried out by calculating the overall score $S_i$ for each alternative (airport) by using the last two synthetic matrices and equation (4) in Section 3.2.3. The ranking of alternatives is shown in Table 5.

**Table 5. The AHP ranking of alternatives in a given example**

| Alternative - Airport | Scenario a) | | Scenario b) | | Scenario c) | |
|---|---|---|---|---|---|---|
| | Score - Si | Rank | Score - Si | Rank | Score - Si | Rank |
| A1 – Brussels | 0.071 | 7 | 0.072 | 7 | 0.065 | 7 |
| A2 - Paris (CDG) | 0.177 | 2 | 0.172 | 2 | 0.206 | 2 |
| *A3 – Frankfurt* | *0.181* | *1* | *0.180* | *1* | 0.187 | 3 |
| A4 – Dusseldorf | 0.098 | 6 | 0.093 | 6 | 0.067 | 6 |
| A5 – Amsterdam (S) | 0.163 | 4 | 0.164 | 4 | 0.135 | 4 |
| *A6 – London (H)* | 0.170 | 3 | 0.171 | 3 | *0.240* | *1* |
| A7 - Milan (M) | 0.140 | 5 | 0.147 | 5 | 0.101 | 5 |

As Table 5 shows, AHP, like SAW and TOPSIS, produces different results when it uses different methods for assigning weights to criteria. This illustrates the sensitivity of the method to such changes. However, for the corresponding scenarios, the same best alternative is chosen as by of using the SAW and TOPSIS methods. It is Frankfurt Main Airport in scenarios a) and b), and London Heathrow Airport in scenario c). The results may illustrate an inherent consistency between this and the other two methods, SAW and TOPSIS.

### 4.3 Comparison of the results from different studies

The outcomes from different studies relating to the problem of the selection of a new hub airport for a hypothetical European airline are summarised in Table 6.

**Table 6. Comparison of the results from different studies**

| Alternative - Airport | Methodology | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Single criterion | | | | Multi-criteria1) | | | | | | | | |
| | Minimum cost[1] | Maximum profits[2] | | | SAW | | | TOPSIS | | | AHP | | |
| | | | | | Scenario | | | | | | | | |
| | | BR | PT1 | PT2 | a | b | c | a | b | c | a | b | c |
| $A_1$- Brussels | 1 | 4 | 4 | 4 | 7 | 6 | 7 | 5 | 6 | 7 | 7 | 7 | 7 |
| $A_2$ - Paris (CDG) | 2 | 5 | 5 | 5 | 2 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 2 |
| *$A_3$ - Frankfurt (M)* | 3 | - | - | - | *1* | *1* | 2 | *1* | *1* | 3 | *1* | *1* | 3 |
| $A_4$ – Düsseldorf | 6 | 3 | 2 | 1 | 5 | 5 | 5 | 7 | 5 | 5 | 6 | 6 | 6 |
| $A_5$ - Amsterdam (S) | 4 | *1* | *1* | *1* | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 4 |
| *$A_6$ - London (H)* | 5 | - | - | - | 3 | 2 | *1* | 4 | 3 | *1* | 3 | 2 | *1* |
| $A_7$ - Milan (M) | 7 | - | - | - | 6 | 7 | 6 | 6 | 7 | 6 | 5 | 5 | 5 |

[1] The author's calculations

[2] Berechman and de Wit (1996): Simulation runs: (BR - Base Run; PT1 – Policy Test 1; PT2 - Policy Test 2)

As can be seen, the outputs are different when different single or multiple criteria methods are applied. The results from various single criterion methods are different depending on the objective function used for evaluation. The selected multi-criteria methods produce the same results if the same procedure for assigning weights to criteria is used. For example, according to scenario a), in which equal weights are assigned to criteria, and scenario b), in which the weights are generated from the uniform distribution [0,1] by simulation, all three methods rank the same alternative as the prefered one: Frankfurt Main Airport ($A_3$). In scenario c), where the entropy method is used to assign the weights to the criteria, all three methods again rank the same alternative as the prefered one, however, this is a different alternative than in scenarios a) and b): London Heathrow Airport ($A_6$). For each scenario the three methods give the same results, despite the different number of criteria for the SAW and TOPSIS methods on the one hand, and the AHP method on the other hand. This indicates the consistency and integrity of the selected methods for this kind of application. It also indicates that the methods for assigning weights to criteria and not the MCDM method are of crucial importance for the results, which points out the importance of choosing a proper method.

The prefered airport in scenarios a) and b) is Frankfurt Main Airport. This airport appears to be the most attractive choice due to a relatively high potential strength in generating air transport demand, modest generalised airport access cost, modest total airline costs, relatively low airport cost per service, relatively high airport capacity, and a reasonably high level of utilisation of this capacity.

The prefered airport in scenario c) is London Heathrow Airport. It appears as the most attractive due to its specificity in comparison to the other airports, which is highlighted by the use of the entropy method for assigning weights to criteria. This specificity is visible through the size of the potential market and the size of airport itself, reasonable airline costs for incorporating the airport into its ‘renovated’ hub-and spoke network, relatively low cost of airport service, and a relatively modest incumbent’s domination. The disadvantages in terms of higher generalised access cost and a relatively high utilisation of the airport capacity are shown to be less relevant.

# 5. Conclusion

The paper has illustrated the application of three discrete Multi-Criteria Decision-Making (MCDM) methods to the problem of the selection of a new hub airport for a hypothetical EU airline, an opportunity which has particularly emerged after the liberalisation of the EU aviation market. The proposed MCDM methods were SAW (Simple Additive Weighting), TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution), and the AHP (Analytic Hierarchy Process).

In the presented example, seven European airports were preselected as alternatives with nine relevant performance attributes (criteria). For each alternative the attributes were quantified and then used as evaluation criteria.

The results have indicated the following. Firstly, the three chosen MCDM methods have produced the same results under conditions where the same procedure for assigning weights to criteria was used. When the same MCDM method used weights for criteria obtained from different procedures then depending on the procedure, either the same or different results emerged. This implies that the weights of the criteria and not the MCDM method, should be considered more carefully when dealing with this and similar MCDM problems.

Consequently, due to this inherent sensitivity, which actually represents their disadvantage, the chosen discrete MCDM methods could not be recommended for final decisions, but only for learning more about a problem and reaching some decisions. Under such circumstances, *a posteriori* robustness analysis will always be necessary to consolidate the final decision.

The numerical example has shown that a preferable new hub airport for a hypothetical EU airline is a big airport with a strong local market, modest generalised cost of airport access, modest cost of airport service, modest airline cost of incorporating the airport in its hub-and-spoke network, a reasonably modest incumbent's market dominance, respectable airport capacity, and a reasonable level of utilisation of this capacity.

Because of the limited value of the results obtained by particular MCDM methods due to both their similarities and their differences, future research should be directed towards additional testing of the feasibility and stability of the solutions obtained by the three proposed MCDM methods. This would imply using different sets of alternatives (airports) with the same or different sets of performance attributes (criteria), and also, in the scope of the sensitivity analysis, checking the effects of other methods for assigning weights to the criteria.

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# Appendix

### A1. The generalised cost of airport surface access

Generally, the generalised cost of airport surface access per passenger can be expressed as:

$$c_g = p(d) + \alpha T(d) \qquad \text{(A1)}$$

where

| | |
|---|---|
| $p\,(d)$ | is the fare paid by a passenger for travelling to/from an airport by one of the available surface public airport access systems (€/km); |
| $d$ | is the average travel distance between an airport and its catchment area; |
| $\alpha$ | is the average value of passenger time while being within a given airport surface access system; this value may be dependent on type of passengers (leisure, business) and type of journeys (domestic, international) (€/unit of time/passenger); |
| $T\,(d)$ | is the perceived travel time along distance $d$ between an airport and its catchment area ($T(d) = s + d/v(d)$, where $s$ is a 'slack' or 'defer' time dependent on the departure frequency of a given access system, and $v(d)$ is the system's average speed along distance $d$). |

## A2. Operating cost of the airline two-hub and spoke network

The total operating cost of an airline's two-hub-and-spoke network for the case when the $k^{\text{th}}$ alternative airport is considered as the new (second) hub is estimated as follows (O'Kelly, 1986; Aykin, 1995).

$$C_T(k) = \left[ \begin{array}{l} \sum_{i=1}^{P-1} \sum_{j=1}^{P-1} Q_{ij} \left( c_{i\,h1} l_{i\,h1} + c_{h1\,j} l_{h1\,j} \right)\Big|_{i \neq j;\, ij \in P; k \in K} + \sum_{i=1}^{P+Q} \sum_{j=1}^{P+Q} Q_{ij} \left( c_{i\,h1} l_{i\,h1} + c_{h1\,hk} l_{h1\,hk} + c_{hk\,j} l_{hk\,j} \right)\Big|_{i \in P;\, j \in Q;\, k \in K} + \\ \sum_{i=1}^{Q-1} \sum_{j=1}^{Q-1} Q_{ij} \left( c_{ihk} l_{i\,hk} + c_{hkj} l_{hk\,j} \right)\Big|_{i \neq j;\, ij \in Q;\, k \in K} + C_k \end{array} \right] \quad \text{(A2)}$$

where

| | |
|---|---|
| $P$ | is the number of spokes assigned to existing hub $h_1$; |
| $Q$ | is the number of spokes assigned to the new hub $h_k$ $(k = 1,2,\ldots K)$; |
| $K$ | is the number of preselected alternative airports for a new hub $(K \in P+Q)$; |
| $Q_{ij}$ | is the passenger flow between spokes $i$ and $j$; |
| $c_{ih1}$, $c_{h1j}$ | is the average cost per unit of passenger flow when connecting the spokes $i$ and $j$ with existing hub $h_1$; |
| $c_{h1\,hk}$ | is the average unit cost of passenger flow when connecting existing hub $h_i$ to the new one $h_k$; |
| $c_{ihk}$, $c_{hkj}$ | is the average cost per unit of passenger flow when connecting spokes $i$ and $j$ to the new hub $h_k$; |
| $l_{ih1}$, $l_{h1j}$ | is the length of a route connecting existing hub $h_1$ to the spokes $i$ and $j$, respectively; |
| $l_{h1\,hk}$ | is the length of a route connecting existing hub $h_1$ to the new hub $h_k$; |
| $l_{ihk}$, $l_{hkj}$ | is the length of a route connecting the new hub $h_k$ to the spokes $i$ and $j$, respectively; |
| $C_k$ | is the fixed cost for the location of the new hub at a preselected airport$k$ $(k \in K)$. |

The cost function (A2) is modified according to specific conditions under which the location of the existing hub is fixed and the location of the new (additional) hub is alternatively chosen from a given set of alternatives. This function consists of four parts. The first part represents the costs of connecting the existing hub to the associated spokes. The second part represents the costs of connecting the spokes assigned to the different hubs. The third part represents the costs of connecting the new hub to the assigned spokes. The last part represents the fixed airline costs needed to set up the new hub.

The first part of (A2) is not directly dependent on location of the new hub while the other three parts are. For each location $k$ $(k \in K)$, each part of (A2) is computed for a given strict routing policy, O/D given passenger flows matrix, the airline unit cost per passenger-kilometre, and the route length.

### A3. The entropy method

The entropy idea has played an important role and has been a concept within physics and social sciences. In particular, entropy has widely been used in information theory as a measure of uncertainty of a discrete probability density function as follows (Hwang and Yoon, 1981; Straja, 2000):

$$S(p_1, p_2, \ldots, p_n) = -k \sum_{i=1}^{n} p_i \ln(p_i) \qquad \text{(A31)}$$

where

$p_i$ is a probability of the $i^{th}$ outcome;
$k$ is a constant.

Under the conditions of the highest uncertainty, when all probabilities are equal, the entropy function $S(p_1, \ldots, p_i)$ will reach its maximum.

Since for a set of alternatives and attributes (criteria) the Decision Matrix contains a certain amount of information, the entropy concept can analogously be used to assess the contrasts between the values of attributes (criteria) for particular alternatives. According to the entropy idea, for example, if the values of particular criteria are very similar or even the same for given alternatives, their entropy will be higher, and thus the weight assigned to such a criterion smaller. This is likely when a criterion should be dropped because of a lack of relevance. However, if the values of a criterion vary more for particular alternatives, their corresponding entropy will be smaller and the weight assigned to such a criterion higher.

Let a set of alternatives $A_i$ $(i = 1,2,3, \ldots, N)$ be evaluated according to $X_j$ criteria $(j = 1,2,3, \ldots, M)$. Let $X_{ij}$ be the outcome of the $i^{th}$ alternative with respect to the $j^{th}$ criterion and an element of the Decision Matrix **A**. Let $p_{ij}$ be determined as follows (Hwang and Yoon, 1981; Straja, 2000):

$$p_{ij} = \frac{X_{ij}}{\sum_{i=1}^{N} X_{ij}}, \text{ for } \quad j \in M \qquad \text{(A32)}$$

The entropy of attribute (criterion) $j$, $E_j$ for $N$ alternatives can be expressed as follows:

$$E_j = -1/\ln(N) \sum_{i=1}^{N} p_{ij} \ln(p_{ij}) \quad \text{for } j \in M \qquad \text{(A33)}$$

where the term $[-1/\ln(N)]$ provides the condition $0 \leq E_j \leq 1$ to be fulfilled.

If a Decision Maker (DM) does not have a reason to prefer one criterion over others, the weight of criteria $X_j$, $w_j$ can be determined as follows (Hwang and Yoon, 1981):

$$w_j = (1 - E_j) / \sum_{j=1}^{M} (1 - E_j) \qquad \text{(A34)}$$