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Two-Stage Network DEA with Undesirable Outputs: An Application in the Air Transportation in the Spain

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In this paper, two non-linear technologies are proposed based on weak disposability definitions: weak disposability with non-uniform abatement factors and new weak disposability. Both technologies are applied to Spanish airport systems and the existing technologies are modified. To remove the computational complexity of non-linear approaches, the linearization methods are proposed. Then, in order to evaluate the efficiency measure of decision making units (DMUs), a directional distance function (DDF) is applied to the linear technologies and the analysis of the results is presented.

***Keywords**: Data envelopment analysis (DEA), Efficiency, Network DEA, Undesirable outputs, Weak disposability.*

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1. Introduction

DEA, first introduced by Charnes et al. [7] is a standard tool to measuring the efficiency of peer DMUs that convert multiple inputs into multiple outputs. Many studies have been focused on the transportation systems by methodology of DEA. For instance, Barros [3], Lin and Tseng [21], Lozano [23] used DEA to ports, Hilmola [16], Martín and Reggiani [27] used DEA to railway system evaluation.

The demand for improve the air transport industry performance has increased during the recent years to develop the air transport services. On the other hand, the air transport system has a considerable economic impact by its own operation and as a contributor to other industries. This strategic industry provides welfare in terms of the availability enhancement of routes, especially for local airport communities.

Some researches applied DEA to air transportation systems such as Scheraga [35] and Greer [14] that were dealing with the airlines. Gillen and Lall [13], Pels et al. [33, 34], Martín and Roman [28, 29], Pacheco and Fernandes [30], Pacheco et al. [31], Yu [44], Yoshida and Fujimoto [43], Lin and

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Hong [20], Barros and Dieke [4, 5], Barros and Peypoch [6], Yu et al. [46], Pathomsiri [32], Lam et al. [19], Lozano and Gutiérrez [23] focused on airports evaluation. In most of these literatures, DMU is considered as a "black box" in which all inputs are consumed and all outputs are produced, neglecting the internal activities. A novel DEA model called network DEA that calculates the performance of internal processes as well as the overall efficiency. The important feature of network DEA is the existence of intermediate products that are generated by a process and consumed by another.

The network DEA models have been proposed to evaluate the performance of a wide variety of real cases. By focusing on the researches related to the air transportation system, Yu [45] proposed a network SBM model to deal with airport operations. Shao and Sun [36] proposed two models to evaluate the performance of a group of air routes in China. Zhu [47] calculate the airline efficiency using a two stage process. However, an important shortcoming of these studies is neglecting the undesirable outputs.

In many real cases, the production process may produce not only desirable products but also undesirable outputs. An important shortcoming of most of classical DEA studies is neglecting the undesirable products. Shephard [37] first developed the idea of weak disposability in which undesirable products may not be decreased alone but may be decreased with a proportional reduction of desirable outputs.

Hailu and Veeman [15] proposed a method equivalent to treating bad outputs as inputs. However, Färe and Grosskopf [10] advocate the idea of weak disposability and used uniform abetment factors of good and bad outputs. Kuosmanen [18] modified this weak disposability definition by relaxing the assumption of the uniform scaling of desirable and undesirable outputs. Since it is cost-effective to abate bad products in those DMUs where the marginal abatement costs are lowest.

Aghayi and Maleki [1] proposed a directional distance function (DDF) approach under uncertainty by considering undesirable outputs. Toloo and Hančlová [40] focused on selecting a single measure for multi-valued factors achieved using various standards in the presence of undesirable outputs. Yang et al. [42] evaluated the energy efficiency of China's provinces based on the super efficiency slacks-based measure (SBM) approach while bad outputs are produced. Song et al. [39] calculated the environmental efficiency of highway transportation system in China using the combination of window DEA and super-efficiency SBM model.

Mahdiloo et al [26] proposed a multiple objective DEA model to overcome difficulties of range adjusted measure of efficiency in the evaluation of environmental efficiency of units. Wu et al. [41] proposed an improved epsilon-based measure (EBM) approach within the DEA approach to analyze the production efficiency of a large coal company in China in which undesirable outputs are generated. Then the effect of the input and output factors on the production efficiency of the coal enterprises were analyzed at a micro level to introduce the required improvements.

Weak disposability axiom generally shows a null-joint relationship (Shephard and Färe [38]) between desirable and undesirable outputs in the production process. Good products are null-joint with bad products, if the only way to generate no bad products is by generating zero good products (Chung et al. [9]; Färe and Grosskopf [11]). Amirteimoori et al. [2] proposed a new definition of weak disposability which removes the null-joint relationship between good and bad outputs. Meanwhile, the proposed technology by Amirteimoori et al. [2] is applicable to the black box systems.

Some network studies introduced various approaches in the presence of undesirable factors. For instance, Maghbouli et al. [25] have been focused on undesirable intermediate factors. Kordrostami and Amirteimoori [17], Fukuyama and Weber [12], Chen et al. [8], Lozano et al. [24] have been involved undesirable final outputs.

Lozano et al. [24] proposed a directional distance function (DDF) approach to deal with network DEA in which the processes may produce not only final good products but also final bad products. They tested the proposed approach to 39 Spanish airports in 2008. The network structure included two processes as "aircraft movement" (AM) related to the arrival and departure of aircraft from the runway, and "aircraft loading" (AL) related to important items that an airplane must receive before take-off. According to the network structure of Spanish airports, each of the two introduced processes consumes its own inputs and produces its own outputs.

Process 1, AM, uses "total runway area", "apron capacity" and "number of boarding gates" as inputs, and produces "number of delayed flights" and "accumulated flight delays" as final bad products. Process 2, AL, uses "number of baggage belts" and "number of check-in counters" as inputs, and produces "annual passenger movements" and "cargo handled" as desirable outputs. On the other hands, aircraft traffic movement as an intermediate factor is produced by process 1 and consumed by process 2 to generate the final outputs.

Aircraft traffic movements as an intermediate factor is produced by process 1 to consume by process 2. On the other words, this factor is the link of two processes. The approach was tested to 39 Spanish airports in 2008 and it was applied to modeling and benchmarking of the airport operations using the weak disposability of outputs with uniform abatement factors. They proposed a directional distance network DEA approach incorporating undesirable products for benchmarking and performance assessment of Spanish airport operations. The abatement of bad products is cost-effective for those DMUs that have the lowest marginal abatement costs. It seems that the use of non-uniform abatement factors can lead to more realistic assessment.

This paper focuses on the 39 Spanish airports in 2008 evaluated in Lozano et al. [24] and utilizes the DEA framework to compare the performance of the airports. Two network DEA technologies are proposed by considering the weak disposability of outputs with non-uniform abatement factors represented by Kuosmanen [18], and new weak disposability of outputs defined by Amirteimoori et al. [2] that removes the null-joint assumption.

According to the two processes introduced for the Spanish airports system, AM and AL, two stages are established into the mathematical technologies. Since the process 1 consumes three inputs and produces one desirable output (link) and two final undesirable outputs, the weak disposability definition is considered for this process. However, the process 2 produces two final desirable outputs by consuming three inputs. Hence, this process contains simple commonplace restrictions in traditional DEA framework. Of course, it should be noted that ATM as a desirable output of process 1 is consumed by the process 2.

According to the non-linear structure of the proposed technologies, a linearization method is applied to each approach. Then the DDF measure is applied to both methods to calculate the efficiency scores and finally the results are compared. The network measures that are represented based on the proposed technologies by Lozano et al. [24], Kuosmanen [18] and Amirteimoori et al. [2] are briefly called "Lozano", "weak disposability" and "new weak disposability", respectively.

The remainder of this paper is organized as follows: In Section 2, the data and methodologies are introduced in more details. Indeed, the Lozano approach is introduced in which the weak disposability definition (with uniform abetment factors) has been used to the model as one of the axioms. Then, two proposed technologies are represented in which weak disposability (with non-uniform abetment factors) and new weak disposability definitions are used. To evaluate the efficiency of airports, the DDF approach is applied to both proposed technologies. In order to find an efficient benchmark to an inefficient airport, a projection point is provided for each approach. In Section 3, the results arising from two proposed approaches are compared with Lozano approach.

2. Methodology and Data

2.1. Methodology of DEA

Producing more outputs and consuming fewer resources is a criterion of efficiency in initial DEA approaches. But in the presence of undesirable outputs, one should design technologies with more desirable outputs, fewer undesirable outputs and fewer consumed inputs.

Many studies on undesirable outputs are based upon the concept of weak disposability axiom which says that a proportional reduction of good and bad products is feasible. Suppose there are K DMUs that each of them generates S different desirable outputs and H different undesirable outputs using N different inputs which are denoted as $v=(v_1,\dots,v_S)$, $w=(w_1,\dots,w_H)$ and $x=(x_1,\dots,x_N)$, respectively. The production possibility set is denoted by $P=\{(x,v,w)|x\ can\ produce\ (v,w)\}$ or alternatively by output set $P(x)=\{(v,w)|\ (x,v,w)\in p\}$. According to the weak disposability definition, if $(x,v,w)\in P$ and $0\le\theta\le1$ then $(x,\theta v,\theta w)\in P$. This definition implies proportional reduction of good and bad outputs while holding inputs constant. Kuosmanen [18] proposed the following output set which is imposed by weak disposability assumption:

$$P(x)=\{(v,w)|\sum_{k=1}^{K}x_n^k z^k\le x_n \qquad n=1,\dots,N \tag{1}$$

$$\sum_{k=1}^{K}\theta^k v_s^k z^k\ge v_s \qquad s=1,\dots,S \tag{2}$$

$$\sum_{k=1}^{K}\theta^k w_h^k z^k= w_h \qquad h=1,\dots,H \tag{3}$$

$$\textstyle\sum_{k=1}^{K}z^k=1 \tag{4}$$

$$z^k\ge0 \qquad k=1,\dots,K \tag{5}$$

$$0\le\theta^k\le1 \tag{6}$$

Unknown variable z is a structural or intensity variable for connecting the input and output vectors by a convex combination. Abatement factor θ^k satisfies non-uniform abatement across the firms in the constraints (2) and (3). The production technology satisfies five postulates as inclusion of observation, convexity, free disposability, weak disposability and minimum extrapolation. In addition, the null-joint assumption is satisfies as:

If $(v, w) \in P(x)$ and $w = 0$, then $v = 0$.

The null-joint assumption shows that no good output can be generated without producing bad output. So the production process should be stopped to remove the undesirable output while it is not cost-effective. In order to remove the null-joint assumption, Amirteimoori et al. [2] proposed a new weak disposability definition. According to the new weak disposability definition, outputs are new weakly disposable if $(x, v, w) \in P$ and $(\theta_s, \theta_h) \geq 0$ imply $0 \leq (x, v - \theta_s,\ w - \theta_h) \in P$ where $\theta_s = (\theta, \dots, \theta)$ and $\theta_h = (\theta, \dots, \theta)$ are s-tuple and h-tuple vectors, respectively, and $\theta \geq 0$. As a result, the production of $(v, 0)$ is possible where v is considered in the level of strictly positive and the undesirable output is considered in the level of zero. Amirteimoori et al. [2] proposed the following output set:

$$P(x) = \{(v, w) | \sum_{k=1}^{K} x_n^k z^k \leq x_n \qquad n = 1, \dots, N \tag{7}$$

$$\sum_{k=1}^{K} (v_s^k - \theta_s) z^k \geq v_s \qquad s = 1, \dots, S \tag{8}$$

$$\sum_{k=1}^{K} (w_h^k - \theta_h) z^k = w_h \qquad h = 1, \dots, H \tag{9}$$

$$v_s^k - \theta_s \geq 0 \tag{10}$$

$$w_h^k - \theta_h \geq 0 \tag{11}$$

$$\sum_{k=1}^{K} z^k = 1 \tag{12}$$

$$z^k \geq 0 \qquad k = 1, \dots, K \tag{13}$$

$$\theta_s, \theta_h \geq 0\} \tag{14}$$

where all postulates of the technology (1) to (6) are satisfied, except weak disposability definition that is replaced by new weak disposability in constraints (8) to (11). By considering $\theta_s = (\theta, \dots, \theta)$ and $\theta_s = (\theta, \dots, \theta)$ with positive components, it was assumed that a fixed reduction is applied to each desirable and undesirable output.

The above technology such as previous black-box DEA technologies ignores the sub-technologies and intermediate factors. But network DEA considers divisional efficiencies as well as the overall efficiency in a unified framework. In this research, 39 Spanish airports in year 2008 are

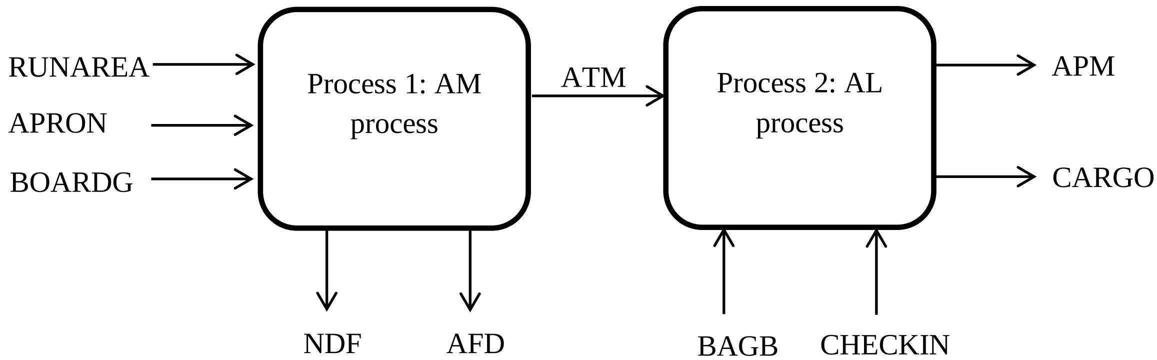

Figure 1. The network structure of Spanish airports

evaluated. Data have been represented into Lozano et al. [24]. We are facing a network structure that includes two processes as "aircraft movement" related to the arrival and departure of the aircraft, and "aircraft loading" related to the important items that an airplane must receive before take-off. According to the network structure of the Spanish airports, each of the two processes consumes its own inputs and produces its own outputs. Figure 1 illustrates the two-stage network. In the next subsection, inputs and outputs of each process are introduced in more details.

2.2. Input and output data

Process 1: In the AM process, total runway area, apron capacity and number of boarding gates are consumed as inputs. Number of delayed flights and accumulated flight delays are the final undesirable outputs of this process. It seems that the reduction of flight delays is effective on the improving public attention.

Process 2: In the AL process, number of baggage belts and number of check-in counters are inputs. Annual passenger movements and total cargo handled are outputs in this process.

Link: Aircraft traffic movements as an intermediate factor is produced by process 1 to consume by process 2 which leads to the production of final outputs. Therefore, this factor connects the processes of the system.

Table 1 is the represented table by Lozano et al. [24] to introduce the units and abbreviations of all inputs and outputs. AM process produces NDF and AFD as the undesirable outputs and ATM as the desirable output in stage 1. So the weak disposability condition is considered in stage 1 of technologies to minimize the bad products. Weak disposability postulate refers to the situations that the reduction of the NDF or AFD is applied along with the production of ATM. According to the proposed definition of weak disposability by Shephard [37], these reductions are proportional. Therefore, the reduction of the NDF and AFD may not be possible without assuming a certain cost. But according to the new weak disposability definition proposed by Amirteimoori et al. [2], a fixed reduction is applied to these outputs. Hence, in the process of reduction of the activity level, a strictly positive value of ATM can generate without the generation of the NDF and AFD. Since AL process produces no undesirable output, the second stage of the technology is designed as the original structure of DEA framework.

Table 1. Inputs and outputs (desirable and undesirable) with their abbreviations.

	variable	units	Label
Inputs	Total runway area Apron capacity Number of boarding gates Number of baggage belts Number of check-in counters	Square meters Number of stands Number of gates Number of belts Number of counters	RUNAREA APRON BOARDG BAGB CHECHIN
Intermediate product	Aircraft traffic movements	Thousand operations	ATM
Outputs (desirable)	Annual passenger movements Cargo handled	Thousand passengers Tones	APM CARGO
Outputs (undesirable)	Number of delayed flights Accumulated flight delays	Number of flights Min	NDF AFD

In the next subsection, Lozano approach is introduced and then the corresponding technologies are proposed based upon the weak disposability and new weak disposability conditions and the DDF measure is applied to evaluate the efficiency of airports.

2.3. Network DEA approach proposed by Lozano

Lozano et al. [24] proposed the following network model under variable return to scale (VRS) assumption as follows:

$$E_{Lozano} = Min\, 1 - \varphi \tag{15}$$

Stage 1

$$\sum_{k=1}^{K} \delta_k RUNAREA_k \leq RUNAREA_o \tag{16}$$

$$\sum_{k=1}^{K} \delta_k APRON_k \leq APRON_o \tag{17}$$

$$\sum_{k=1}^{K} \delta_k BOARDG_k \leq BOARDG_o \tag{18}$$

$$\theta \sum_{k=1}^{K} \delta_k NDF_k = NDF_o(1 - \varphi) \tag{19}$$

$$\theta \sum_{k=1}^{K} \delta_k AFD_k = AFD_o(1 - \varphi) \tag{20}$$

$$\sum_{k=1}^{K} \delta_k = 1 \tag{21}$$

$$0 \leq \theta \leq 1 \tag{22}$$

$$\delta_k \geq 0 \tag{23}$$

Stage 2

$$\sum_{k=1}^{K} \mu_k BAGB_k \leq BAGB_o \tag{24}$$

$$\sum_{k=1}^{K} \mu_k CHECKIN_k \leq CHECKIN_o \tag{25}$$

$$\sum_{k=1}^{K} \mu_k APM_k \geq APM_o\,(1+\varphi) \tag{26}$$

$$\sum_{k=1}^{K} \mu_k CARGO_k \geq CARGO_o\,(1+\varphi) \tag{27}$$

$$\sum_{k=1}^{K} \mu_k = 1 \tag{28}$$

$$\mu_k \geq 0 \tag{29}$$

link of two stages

$$\theta \sum_{k=1}^{K} \delta_k ATM_k \geq \sum_{k=1}^{K} \mu_k ATM_k \tag{30}$$

φ is the DDF of DMU_o along the direction vector (x_n^o, v_s^o, w_h^o) while all the inputs of both processes are non-discretionary. So the corresponding components of inputs in direction vector have been considered zero as $(0, v_s^o, w_h^o)$. Indeed, to project an inefficient airport to the efficient frontier, the undesirable outputs in stage 1 should be reduced and the outputs of stage 2 should be decreased. In order to represent the efficiency value, the distance of φ from 1 has been considered in (15).

Constraints (19) and (20) show the weak disposability condition in stage 1 by uniform abatement factor δ. Constraint (30) is the reduced form of two restrictions $\theta \sum_{k=1}^{K} \delta_k ATM_k \geq ATM_o$ and $\sum_{k=1}^{K} \mu_k ATM_k \leq ATM_o$. In the first restriction, ATM is in the role of the output of stage 1, and in the second restriction, it is in the role of the input of stage 2. The problem arising from the existence of inequality in these constraints is the identification of the different values to ATM's component in the projection point by each of two stages. On the other hands, it should be noted that the abatement of undesirable products is cost-effective for those units that have the lowest marginal abatement costs. So the use of non-uniform abatement factors can lead to more realistic efficiency assessment. Therefore, these two problems will be modified by proposing two new mathematical technologies in the next subsection.

2.4. Proposed network DEA approaches based on weak and new weak disposability

In order to consider non-uniform abatement factors to all DMUs, the following network technology is proposed based on weak disposability definition to modify the technology (1) to (6). In order to represent more accurate analyze of the results, the technologies and models are proposed using variables provided by Lozano et al. [24].

Stage 1

$$\sum_{k=1}^{K} \lambda_k RUNAREA_k \leq RUNAREA_o \quad (31)$$

$$\sum_{k=1}^{K} \lambda_k APRON_k \leq APRON_o \quad (32)$$

$$\sum_{k=1}^{K} \lambda_k BOARDG_k \leq BOARDG_o \quad (33)$$

$$\sum_{k=1}^{K} \lambda_k \theta_k ATM_k \geq ATM_o \quad (34)$$

$$\sum_{k=1}^{K} \lambda_k \theta_k NDF_k = NDF_o \quad (35)$$

$$\sum_{k=1}^{K} \lambda_k \theta_k AFD_k = AFD_o \quad (36)$$

$$0 \leq \theta_k \leq 1 \quad (37)$$

$$\lambda_k \geq 0 \quad (38)$$

Stage 2

$$\sum_{k=1}^{K} \mu_k BAGB_k \leq BAGB_o \quad (39)$$

$$\sum_{k=1}^{K} \mu_k CHECKIN_k \leq CHECKIN_o \quad (40)$$

$$\sum_{k=1}^{K} \mu_k ATM_k \leq ATM_o \quad (41)$$

$$\sum_{k=1}^{K} \mu_k APM_k \geq APM_o \quad (42)$$

$$\textstyle\sum_{k=1}^{K} \mu_k CARGO_k \geq CARGO_o \quad (43)$$

$$\mu_k \geq 0 \tag{44}$$

Unknown variables λ and μ are considered for a structural connection among DMUs in the input-output space. Constraints (34) to (36) show the weak disposability of outputs in stage 1 by abatement factor θ_k while the constraints of undesirable outputs, (35) and (36), are represented as equality constraint. ATM as the link of two stages is used once as the output of stage 1 and again as the input of stage 2 as shown in the constraints (34) and (41). The second stage has the original structure of DEA approach. Both stages of the technology have been made under constant return to scale (CRS) assumption.

The null-joint relationship between ATM as desirable output, and NDF and AFD as undesirable outputs states that the only way to achieve the zero-level NDF or AFD is to cease the production of ATM and consequently stop the production process. To eliminate the null-joint relationship, the new weak disposability axiom proposed by Amirteimoori et al. [2] is implemented and the following network technology under CRS assumption is proposed:

Stage 1

$$\sum_{k=1}^{K} \gamma_k RUNAREA_k \leq RUNAREA_o \tag{45}$$

$$\sum_{k=1}^{K} \gamma_k APRON_k \leq APRON_o \tag{46}$$

$$\sum_{k=1}^{K} \gamma_k BOARDG_k \leq BOARDG_o \tag{47}$$

$$\textstyle\sum_{k=1}^{K} \gamma_k (ATM_k - \alpha) \geq ATM_o \tag{48}$$

$$\sum_{k=1}^{K} \gamma_k (NDF_k - \alpha) = NDF_o \tag{49}$$

$$\sum_{k=1}^{K} \gamma_k (AFD_k - \alpha) = AFD_o \tag{50}$$

$$ATM_k - \alpha \geq 0 \tag{51}$$

$$NDF_k - \alpha \geq 0 \tag{52}$$

$$AFD_k - \alpha \geq 0 \tag{53}$$

$$\alpha \geq 0, \gamma_k \geq 0 \tag{54}$$

Stage 2

$$\sum_{k=1}^{K} \tau_k BAGB_k \leq BAGB_o \quad (55)$$

$$\sum_{k=1}^{K} \tau_k CHECKIN_k \leq CHECKIN_o \quad (56)$$

$$\sum_{k=1}^{K} \tau_k ATM_k \leq ATM_o \quad (57)$$

$$\sum_{k=1}^{K} \tau_k APM_k \geq APM_o \quad (58)$$

$$\sum_{k=1}^{K} \tau_k CARGO_k \geq CARGO_o \quad (59)$$

$$\tau_k \geq 0 \quad (60)$$

Since the AM process generates NDF and AFD as the undesirable outputs, the technology (7) to (14) proposed by Amirteimoori et al. [2] is used to stage 1. However, the second stage is based upon the original structure of DEA. Constraints (48) to (50) show a fixed reduction to ATM, NDF and AFD in the AM process. Like technology (4), ATM is generated as outputs by stage 1 and then consumed as inputs by stage 2 such that is visible in constraints (48) and (57).

Both proposed technologies are faced with multiplying a pair of variables in the stage 1, both of them are non-linear. Since the non-linear structure of the models leads to difficulties in computations, the linearization operations are applied to the proposed technologies.

Technology (31) to (44) can be linearized defining new variables $\lambda_k = \rho_k + \pi_k$ and $\lambda_k \theta_k = \pi_k$ where $\rho_k \geq 0$ and $\pi_k \geq 0$ similar to Kuosmanen [18]. The following model is represented to evaluate the efficiency measure (using weak disposability condition) of the Spain airports in 2008 based upon the DDF measure while all constraints are linear.

$$E_{weak} = Min\, 1 - \omega \quad (61)$$

Stage 1

$$\sum_{k=1}^{K} (\rho_k + \pi_k)\, RUNAREA_k \leq RUNAREA_o \quad (62)$$

$$\sum_{k=1}^{K} (\rho_k + \pi_k)\, APRON_k \leq APRON_o \quad (63)$$

$$\sum_{k=1}^{K} (\rho_k + \pi_k)\, BOARDG_k \leq BOARDG_o \quad (64)$$

$$\sum_{k=1}^{K} \pi_k ATM_k + s^{ATM} = ATM_o \tag{65}$$

$$\sum_{k=1}^{K} \pi_k NDF_k = NDF_o - \omega d_{NDF} \tag{66}$$

$$\sum_{k=1}^{K} \pi_k AFD_k = AFD_o - \omega d_{AFD} \tag{67}$$

Stage 2

$$\sum_{k=1}^{K} \mu_k BAGB_k \leq BAGB_o \tag{68}$$

$$\sum_{k=1}^{K} \mu_k CHECKIN_k \leq CHECKIN_o \tag{69}$$

$$\sum_{k=1}^{K} \mu_k ATM_k + s^{ATM} = ATM_o \tag{70}$$

$$\sum_{k=1}^{K} \mu_k APM_k \geq APM_o + wd_{APM} \tag{71}$$

$$\sum_{k=1}^{K} \mu_k CARGO_k \geq CARGO_o + wd_{CARGO} \tag{72}$$

$$s^{ATM}\ is\ free.\ \rho_k, \pi_k, \mu_k\ and\ alld\ variables \geq 0 \tag{73}$$

In the stage 1, the inputs are weighted by the sum of unknown variables ρ_k and π_k, and others are weighted by π_k. According to the linear structure of the stage 2, all the constraints of this stage remain unchanged. d is the direction vector that is chosen by the researcher. Similar to model (15) to (30), ω is the DDF of DMU_o along the direction vector while the corresponding components of inputs have been assumed zero. E_{weak} is between 0 and 1 and if it is equal to 1, the airport is efficient.

The right hand side of the constraints (66), (67), (71) and (72) show that in order to improve the performance of an inefficient airport, APM and CARGO should be increased while NDF and AFD should be reduced. In constraints (65) and (70), s^{ATM} is a free variable that leads to increasing or decreasing in ATM. The reduced form of these two constraints can be represented as $\sum_{k=1}^{K} \pi_k ATM_k = \sum_{k=1}^{K} \mu_k ATM_k$ which leads to the adaptation of the link's component of the projection point introduced by both network stages.

Technology (45) to (60) is linearized by new variables $\gamma_k = \beta_k + \kappa_k$ and $\gamma_k \alpha = \beta_k$ where $\beta_k \geq 0$ and $\kappa_k \geq 0$. The following model is represented to assess the efficiency measure (using weak disposability condition) of the airports based upon the same DDF measure utilized in weak disposability model.

$$E_{newweak} = Min\, 1 - \delta \tag{74}$$

Stage 1

$$\sum_{k=1}^{K} (\beta_k + \kappa_k)\ RUNAREA_k \leq RUNAREA_o \tag{75}$$

$$\sum_{k=1}^{K} (\beta_k + \kappa_k)\ APRON_k \leq APRON_o \tag{76}$$

$$\sum_{k=1}^{K} (\beta_k + \kappa_k) BOARDG_k \leq BOARDG_o \tag{77}$$

$$\sum_{k=1}^{K} (\beta_k + \kappa_k) ATM_k - \sum_{k=1}^{K} \kappa_k + t^{ATM} = ATM_o \tag{78}$$

$$\sum_{k=1}^{K} (\beta_k + \kappa_k) NDF_k - \sum_{k=1}^{K} \kappa_k = NDF_o - \delta d_{NDF} \tag{79}$$

$$\sum_{k=1}^{K} (\beta_k + \kappa_k) AFD_k - \sum_{k=1}^{K} \kappa_k = AFD_o - \delta d_{AFD} \tag{80}$$

$$(\beta_k + \kappa_k)\ ATM_k \geq \kappa_k \tag{81}$$

$$(\beta_k + \kappa_k) NDF_k \geq \kappa_k \tag{82}$$

$$(\beta_k + \kappa_k)\ AFD_k \geq \kappa_k \tag{83}$$

Stage 2

$$\sum_{k=1}^{K} \tau_k BAGB_k \leq BAGB_o \tag{84}$$

$$\sum_{k=1}^{K} \tau_k CHECKIN_k \leq CHECKIN_o \tag{85}$$

$$\sum_{k=1}^{K} \tau_k ATM_k + t^{ATM} = ATM_o \tag{86}$$

$$\sum_{k=1}^{K} \tau_k APM_k \geq APM_o + \delta d_{APM} \tag{87}$$

$$\sum_{k=1}^{K} \tau_k CARGO_k \geq CARGO_o + \delta d_{CARGO} \tag{88}$$

$$t^{ATM}\ is\ free.\ \beta_k, \omega_k, \tau_k, and\ all\ d\ variables \geq 0 \tag{89}$$

Like the previous model, the stage 2 remains unchanged. d is the direction vector. δ as the DDF of DMU_o along the direction vector improves the efficiency of an inefficient airport by decreasing the undesirable outputs of stage 1, and increasing the desirable outputs of stage 2. t^{ATM} is a free variable that leads to increasing or decreasing in ATM. Clearly, the reduced form of these two constraints can be represented as $\sum_{k=1}^{K}(\beta_k + \kappa_k)ATM_k - \sum_{k=1}^{K}\kappa_k = \sum_{k=1}^{K}\tau_k ATM_k$.

Clearly, the equality form of the link constraint implies that an identical value be determined to the ATM's component in the projection point. In the next subsection, the projection points of inefficient airports are introduced for both models.

2.5. Projection point of an inefficient DMU

By the optimal solution of the weak disposability models, the projection point of an inefficient airport is computed as follows:

$$NDF_o^* = \sum_{k=1}^{K} \pi_k^* NDF_k$$

$$AFD_o^* = \sum_{k=1}^{K} \pi_k^* AFD_k$$

$$ATM_o^* = ATM_o - s^{ATM*} = \sum_{k=1}^{K} \pi_k^* ATM_k = \sum_{k=1}^{K} \mu_k^* ATM_k$$

$$APM_o^* = \sum_{k=1}^{K} \mu_k^* APM_k$$

$$CARGO_o^* = \sum_{k=1}^{K} \mu_k^* CARGO_k$$

Similarly, the following projection point is represented to an inefficient airport by new weak disposability model:

$$NDF_o^{*\prime} = \sum_{k=1}^{K}(\beta_k^* + \kappa_k^*)NDF_k - \sum_{k=1}^{K}\kappa_k^*$$

$$AFD_o^{*\prime} = \sum_{k=1}^{K}(\beta_k^* + \kappa_k^*)AFD_k - \sum_{k=1}^{K}\kappa_k^*$$

$$ATM_o^{*\prime} = ATM_o - t^{ATM*} = \sum_{k=1}^{K}(\beta_k^* + \kappa_k^*)ATM_k - \sum_{k=1}^{K}\kappa_k^* = \sum_{k=1}^{K}\tau_k^* ATM_k$$

$$APM_o^{*\prime} = \sum_{k=1}^{K} \tau_k^* APM_k$$

$$CARGO_o^{*\prime} = \sum_{k=1}^{K} \tau_k^* CARGO_k$$

The structure of the two constraints related to ATM factor in each model implies that there is only one choice to improving ATM in the projection point. Theorem 2.1 proves that the efficiency measure of an airport achieved by weak disposability model is not less than the efficiency measure of it calculated by new weak disposability model.

Theorem 2.1: $E_{newweak}^* \leq E_{weak}^*$.

Proof. Let the general form of the proposed weak and new weak disposability models, (61) to (73) and (74) to (89), is considered as follows:

$$\begin{aligned} & E_{weak} = Min\, 1 - \omega \\ & \text{Stage 1} \\ & \lambda X \leq x_o \\ & \lambda\theta Z + s_z = z_o \\ & \lambda\theta W = w_o - \omega d_W \\ & \text{Stage 2} \\ & \mu M \leq m_o \\ & \mu Z + s_z = z_o \\ & \mu Y \geq y_o + \omega d_Y \\ & 0 \leq \theta \leq 1 \\ & s_z\ is\ free, \lambda, \mu \geq 0 \end{aligned} \tag{90}$$

$$E_{newweak} = Min\, 1 - \delta$$

Stage 1

$$\gamma X \leq x_o$$

$$\gamma(Z-\alpha)+t_z=z_o$$

$$\gamma(W-\alpha)=w_o-\delta d_W$$

$$Z-\alpha\geq 0$$

$$W-\alpha\geq 0 \tag{91}$$

Stage 2

$$\tau M\leq m_o$$

$$\tau Z+t_z=z_o$$

$$\tau Y\geq y_o+\omega d_Y$$

$$t_z\ is\ free, \gamma,\tau,\alpha\geq 0$$

where the vectors of input and undesirable output in the first stage are denoted as the $X=(x_1,\dots,x_N)$ and $W=(w_1,\dots,w_H)$, respectively. While the vectors of inputs and desirable outputs of the second stage are denoted as $M=(m_1,\dots,m_P)$ and $Y=(y_1,\dots,y_L)$, respectively. The intermediate factor is denoted by the vector $Z=(z_1,\dots,z_Q)$.

The assumed direction is $(0,y_o,w_o)$. Similarly, it can be proved to other represented directions. Consider the set of restrictions (90) in the optimality form and the set of restrictions (91) in the feasibility form as follows:

Stage 1

$$\lambda^*X+s_x^*=x_o \tag{92}$$

$$\lambda^*\theta^*Z+s_z^*=z_o \tag{93}$$

$$\lambda^*\theta^*W=w_o(1-\omega^*) \tag{94}$$

Stage 2

$$\mu^*M+s_m^*=m_o \tag{95}$$

$$\mu^*Z+s_z^*=z_o \tag{96}$$

$$\mu^*Y-s_y^*=y_o(1+\omega^*) \tag{97}$$

Stage 1

$$\gamma X + t_x = x_o \tag{98}$$

$$\gamma(Z-\alpha) + t_z = z_o \tag{99}$$

$$\gamma\,(W-\alpha) = w_o(1-\delta) \tag{100}$$

$$Z-\alpha \geq 0 \tag{101}$$

$$W-\alpha \geq 0 \tag{102}$$

Stage 2

$$\tau M + t_m = m_o \tag{103}$$

$$\tau Z + t_z = z_o \tag{104}$$

$$\tau Y - t_y = y_o(1+\delta) \tag{105}$$

The restriction (93) is represented as $\lambda^*\theta^*Z - \lambda^* + \lambda^* + s_z^* = z_o$. We have:

$$\lambda^*(\theta^*Z-1) + \lambda^* + s_z^* = z_o \rightarrow \lambda^*(Z-\frac{1}{\theta^*}) + \frac{\lambda^*}{\theta^*} + \frac{s_z^*}{\theta^*} = \frac{z_o}{\theta^*}$$

$$\rightarrow \lambda^*\left(Z-\frac{1}{\theta^*}\right) + \left(\frac{\lambda^*}{\theta^*} + \frac{s_z^*}{\theta^*} - \frac{z_o}{\theta^*} + z_o\right) = z_o$$

Suppose that $\gamma = \lambda^*$, $\alpha = \frac{1}{\theta^*}$ and $t_z = \frac{\lambda^*}{\theta^*} + \frac{s_z^*}{\theta^*} - \frac{z_o}{\theta^*} + z_o$. This structure is corresponds to the restriction (99).

Now, the restriction (94) is considered. We have:

$$\lambda^*\theta^*W - \lambda^* + \lambda^* = w_o(1-\omega^*) \rightarrow \lambda^*(\theta^*W-1) + \lambda^* = w_o(1-\omega^*)$$

$$\xrightarrow{\div\theta^*}\ \lambda^*\left(W-\frac{1}{\theta^*}\right) + \frac{\lambda^*}{\theta^*} = \frac{w_o}{\theta^*}(1-\omega^*)$$

$$\lambda^*\left(W-\frac{1}{\theta^*}\right) + \frac{\lambda^*}{\theta^*} + w_o = \frac{w_o}{\theta^*} - \frac{w_o\omega^*}{\theta^*} + w_o$$

$$\lambda^*\left(W-\frac{1}{\theta^*}\right)+\frac{\lambda^*}{\theta^*}+w_o-\frac{w_o}{\theta^*}=w_o(1-\frac{\omega^*}{\theta^*})$$

Suppose that $\gamma=\lambda^*$, $\frac{\lambda^*}{\theta^*}+w_o-\frac{w_o}{\theta^*}=0$ and $\delta=\frac{\omega^*}{\theta^*}$. Similarly, it can be applied to the other restrictions. So the optimal solution of the weak disposability model is a feasible solution of new weak disposability model. Now, we have:

$$E^*_{newweak}\leq E_{newweak}=1-\delta=1-\omega^*=E^*_{weak}$$

Hence, $E^*_{newweak}\leq E^*_{weak}$.■

In the next section, the efficiency measures by three methods, Lozano, weak disposability and new weak disposability, are calculated and the results are compared.

3. Results and Discussion

We deal with data on a different scale. Hence all data have been normalized to have value between 0 and 1. Tables 2 and 3 present the calculated efficiency values by three approaches. The 2nd column of Table 2 shows the evaluation results of Lozano approach; however they are provided as the distance from 1. The used direction by Lozano et al. [24] is $(0,y_o,w_o)$.

In the 3nd to 6nd columns of Table 2, and 2nd to 5nd columns of Table 3, the efficiency values of the proposed models, weak disposability and new weak disposability, have been represented, respectively. Four different directions are used to both proposed approaches while the directions are the multiples of the data under evaluation.

The comparison between the results of three network approaches in direction $(0,y_o,w_o)$ shows that eight airports are efficient using Lozano approach while weak disposability and new weak disposability models introduces six same efficient airports. All efficient airports introduced by weak disposability and new weak disposability models are efficient by Lozano model. But Albacete and Madrid Barajas airports are inefficient by both proposed models while Lozano approach introduced them efficient.

The average of efficiency values calculated by Lozano model in direction $(0,y_o,w_o)$ is 0.634, but weak disposability and new weak disposability models represented it 0.452 and 0.345, respectively. Valladolid airport has the worst performance by Lozano approach; however weak disposability and new weak disposability approaches introduce Salamanca airport.

The 4nd column of Table 2 and 3nd column of Table 3 show the efficiency value of weak disposability and new weak disposability models by considering the direction $(0,3y_o,3w_o)$. The average of efficiency values calculated by weak disposability model is 0.817 while it is 0.789 by new weak disposability model. The 5nd column of Table 2 and 4nd column of Table 3 show the efficiency value of weak disposability and new weak disposability models by considering the direction $(0,7y_o,7w_o)$.

Table 2. The efficiency measures calculated by model (6)

	E^*_{Lozano}	E^*_{weak}			
DMU	$(0, y_o, w_o)$	$(0, y_o, w_o)$	$(0, 3y_o, 3w_o)$	$(0, 7y_o, 7w_o)$	$(0, 10y_o, 10w_o)$
A Coruña	0.352	0.2596	0.7532	0.8942	0.9260
Albacete	1.000	0.0071	0.6690	0.8582	0.9007
Alicante	0.986	0.9626	0.9875	0.9947	0.9963
Almeria	0.214	0.0920	0.6973	0.8703	0.9092
Asturias	0.374	0.3010	0.7670	0.9001	0.9301
Badajoz	0.803	0.0722	0.6907	0.8675	0.9072
Barcelona	1.000	1.0000	1.0000	1.0000	1.0000
Bilbao	0.919	0.2221	0.7407	0.8889	0.9222
Cordoba	1.000	1.0000	1.0000	1.0000	1.0000
El Hierro	0.919	0.3597	0.7866	0.9085	0.9360
Fuerteventura	0.435	0.3359	0.7786	0.9051	0.9336
Girona-Costa Brava	1.000	1.0000	1.0000	1.0000	1.0000
Gran Canar	0.829	0.8194	0.9398	0.9742	0.9819
Granada-Jaen	0.471	0.3501	0.7834	0.9072	0.9350
Ibiza	0.777	0.7741	0.9247	0.9677	0.9774
Jerez	0.327	0.2373	0.7458	0.8910	0.9237
La Gomera	0.736	0.0514	0.6838	0.8645	0.9051
La Palma	0.671	0.5183	0.8394	0.9312	0.9518
Lanzarote	0.591	0.5370	0.8457	0.9339	0.9537
Leon	0.201	0.0069	0.6690	0.8581	0.9007
Madrid Barajas	1.000	0.8225	0.9408	0.9746	0.9822
Malaga	0.940	0.9308	0.9769	0.9901	0.9931
Melilla	0.719	0.1835	0.7278	0.8834	0.9184
Murcia	0.478	0.4015	0.8005	0.9145	0.9402
Palma de Mallorca	1.000	1.0000	1.0000	1.0000	1.0000
Pamplona	0.550	0.0856	0.6952	0.8694	0.9086
Reus	0.485	0.3703	0.7901	0.9100	0.9370
Salamanca	0.090	0.0037	0.6679	0.8577	0.9004
San Sebastian	0.160	0.0663	0.6888	0.8666	0.9066
Santander	0.256	0.1226	0.7075	0.8747	0.9123
Santiago	0.293	0.2067	0.7356	0.8867	0.9207
Saragossa	1.000	1.0000	1.0000	1.0000	1.0000
Seville	0.642	0.4542	0.8181	0.9220	0.9454
Tenerife North	0.738	0.6491	0.8830	0.9499	0.9649
Tenerife South	0.766	0.6625	0.8875	0.9518	0.9662
Valencia	0.596	0.4973	0.8324	0.9282	0.9497
Valladolid	0.138	0.0576	0.6859	0.8654	0.9058
Vigo	0.269	0.1959	0.7320	0.8851	0.9196
Vitoria	1.000	1.0000	1.0000	1.0000	1.0000

Table 3. The efficiency measures calculated by model (7)

	$E^*_{newweak}$			
DMU	$(0, y_o, w_o)$	$(0, 3y_o, 3w_o)$	$(0, 7y_o, 7w_o)$	$(0, 10y_o, 10w_o)$
A Coruña	0.0148	0.6716	0.8593	0.9015
Albacete	0.0002	0.6667	0.8572	0.9000
Alicante	0.9626	0.9875	0.9947	0.9963
Almeria	0.0081	0.6694	0.8583	0.9008
Asturias	0.0169	0.6723	0.8596	0.9017
Badajoz	0.0057	0.6686	0.8580	0.9006
Barcelona	1.0000	1.0000	1.0000	1.0000
Bilbao	0.0150	0.6717	0.8593	0.9015
Cordoba	1.0000	1.0000	1.0000	1.0000
El Hierro	0.0485	0.6828	0.8641	0.9048
Fuerteventura	0.2309	0.7436	0.8901	0.9231
Girona-Costa Brava	1.0000	1.0000	1.0000	1.0000
Gran Canar	0.8194	0.9398	0.9742	0.9819
Granada-Jaen	0.0310	0.9770	0.8616	0.9031
Ibiza	0.5628	0.8543	0.9375	0.9563
Jerez	0.0147	0.6716	0.8592	0.9015
La Gomera	0.0081	0.6673	0.8574	0.9002
La Palma	0.0371	0.6790	0.8624	0.9037
Lanzarote	0.5370	0.8457	0.9339	0.9537
Leon	0.0003	0.6668	0.8572	0.9000
Madrid Barajas	0.8225	0.9408	0.9746	0.9822
Malaga	0.9098	0.9699	0.9871	0.9910
Melilla	0.0148	0.6716	0.8593	0.9015
Murcia	0.3175	0.7725	0.9025	0.9318
Palma de Mallorca	1.0000	1.0000	1.0000	1.0000
Pamplona	0.0063	0.6688	0.8580	0.9006
Reus	0.0903	0.6968	0.8700	0.9090
Salamanca	0.0001	0.6667	0.8572	0.9000
San Sebastian	0.0054	0.6685	0.8579	0.9005
Santander	0.0103	0.6701	0.8586	0.9010
Santiago	0.0123	0.6708	0.8589	0.9012
Saragossa	1.0000	1.0000	1.0000	1.0000
Seville	0.2877	0.7626	0.8982	0.9288
Tenerife North	0.4869	0.8290	0.9267	0.9487
Tenerife South	0.6625	0.8875	0.9518	0.9662
Valencia	0.4973	0.8324	0.9282	0.9497
Valladolid	0.0051	0.6684	0.8579	0.9005
Vigo	0.0115	0.6705	0.8588	0.9012
Vitoria	1.0000	1.0000	1.0000	1.0000

The average of efficiency values provided by weak disposability model is 0.922 while it is 0.906 by new weak disposability model. The 6nd column of Table 2 and 5nd column of Table 3 shows the efficiency value of weak disposability and new weak disposability models by assumption of the direction $(0, 10y_o, 10w_o)$. The average of efficiency values represented by weak disposability model is 0.945 while it is 0.934 by new weak disposability model.

Salamanca airport has the worst efficiency value and six same airports, Barcelona, Cordoba, Girona-Costa Brava, Palma de Mallorca, Saragossa and Vitoria, are efficient using both proposed models in all supposed directions. All same efficient airports by weak disposability and new weak disposability models are efficient by Lozano approach. For example, Barcelona is an efficient airport by all three models.

Cleary, by increasing the multiple of the data under evaluation in direction vector, the least amount of efficiency and average of efficiencies are increased. On the other hands, the efficiency values calculated by new weak disposability model are less than the efficiency values calculated by weak disposability as proved in Theorem 2.1. It seems that the power of discrimination of new weak disposability approach is more than weak disposability and Lozano approaches. However, new weak disposability model has been eliminates the null-joint condition, but the other two models do not. The models are solved by GAMS software on a 2.6 GHz Intel Core i5-3230M CPU with 4 GB of RAM.

4. Conclusion

Some DEA researches treat undesirable products to assess the performance measure of units under assumption of weak disposability. This assumption focuses on the proportional reduction of good and bad outputs which leads to the reduction of the activity level. Kuosmanen [18] represented the definition of weak disposability by using the non-uniform abatement factors in definition of production technology. The null-join assumption was satisfied to the proposed technology. Hence, Amirteimoori et al. [2] proposed a new weak disposability definition which removes the null-joint relationship, and then represented a new production technology. These technologies had a black-box structure. Recently, Lozano et al. [24] proposed a directional distance network DEA model to evaluate 39 Spanish airports in 2008 based on the weak disposability definition with uniform abatement factors.

In the current paper, two novel directional distance network models were proposed by using the proposed technology based on the weak disposability and new weak disposability definitions. In the first technology, the non-uniform abatement factor was applied. In order to remove the null-joint relationship, the second technology was proposed based on the new weak disposability definition. The performance measures of the both proposed approaches were calculated in four different directions, and the results are compared with Lozano approach which was only represented in one direction. Eight airports were introduced efficient by Lozano while weak and new weak disposability models introduced six airports in all directions. All calculated efficiency measures by new weak disposability approach are not more than the efficiency measures achieved by weak disposability measures; hence it seems that the power of discrimination of the new weak disposability approaches is more than the weak disposability and Lozano approaches.

The current paper focused on a network production process incorporating final undesirable outputs. As a suggestion, further researches are necessary to be focused on network DEA by considering intermediate undesirable outputs.

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