CONSIDERING FINANCIAL AND ENVIRONMENTAL FACTORS IN AIRPORT EFFICIENCY MEASUREMENT: A NETWORK DEA ANALYSIS FOR U.S. AIRPORTS

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science

by

Jingrong Yu

December 2018

ABSTRACT

This paper applies network DEA to modelling US airport efficiency taking into account monetary expenditure and environmental impact of the undesirable taxiway delay, in order to provide airlines insights on investment potentiality and fuel cost from delay of airports. We also enhanced the model inputs by using runway configuration in addition to merely counting area and number of runways in conventional DEA application. Outputs are also improved by further transform fuel consumption to pollutants emission from the social-good perspective. Results are illustrated for 44 airports in the United States over 2011-2015.

Keywords: Airport efficiency, Network DEA, Undesirable outputs, Directional distance function, US airports

ACKNOWLEDGMENTS

I would like to thanks my advisor committee Professor Oliver Gao and Professor Samitha Samaranayake who encouraged and directed me with useful comments, remarks and engagement through the process of this thesis. I am also grateful to the all the faculty and staff at Cornell University for offering me an excellent and unforgettable study experience. Finally, I must express my very profound gratitude to my family for providing me with unfailing support and continuous encouragement throughout my years of study.

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LIST OF ABBREVIATIONS

ACI	Airports Council International
AIP	Airport Improvement Program
ASPM	Aviation System Performance Metrics
BTS	Bureau of Transportation Statistics
CO	Carbon Monoxide
CRS	Constant Returns-to-Scale
DDF	Directional Distance Function
DEA	Data Envelopment Analysis
DMU	Decision Making Units
FAA	Federal Aviation Administration
GA	General Aviation Bonds
GARB	General Obligation and Revenue Bonds
GO	General Obligation Bonds
HC	Hydrocarbon
ICAO	International Civil Aviation Organization
LTO	Landing and Take-off Cycle
NAS	National Airspace System
NDEA	Network Data Envelopment Analysis
NOx	Nitrogen Oxides
OOOI	Gate-Out, Wheels-Off, Wheels-On, and Gate-In Time
PFC	Passenger Facility Charge
PPS	Production Possibility Set
SFA	Stochastic Frontier Analysis
TFP	Total-Factor Productivity

VRS	Variable Returns-To-Scale

Abbreviations below are IATA airport codes:

ATL	Hartsfield-Jackson Atlanta International Airport
AUS	Austin-Bergstrom International Airport
BNA	Nashville International Airport
BOS	General Edward Lawrence Logan International Airport
BWI	Baltimore-Washington International Airport
CLE	Cleveland-Hopkins International Airport
CLT	Charlotte/Douglas International Airport
DAL	Dallas Love Field Airport
DCA	Ronald Reagan Washington National Airport
DEN	Denver International Airport
DFW	Dallas/Fort Worth International Airport
DTW	Detroit Metro Wayne Airport
EWR	Newark International Airport
FLL	Fort Lauderdale/ Hollywood International Airport
HNL	Honolulu International Airport
HOU	William P Hobby Airport
IAD	Washington Dulles International Airport
IAH	George Bush Intercontinental Airport
JFK	John F Kennedy International Airport
LAS	McCarran International Airport
LAX	Los Angeles International Airport

LGA	LaGuardia Airport
MCI	Kansas City International Airport
MCO	Orlando International Airport
MDW	Chicago Midway International Airport
MIA	Miami International Airport
MSP	Minneapolis-St Paul International Airport
MSY	New Orleans International Airport
OAK	Oakland International Airport
ORD	Chicago O’Hare International Airport
PDX	Portland International Airport
PHL	Philadelphia International Airport
PHX	Phoenix Sky Harbor International Airport
PIT	Pittsburgh International Airport
RDU	Raleigh-Durham International Airport
RSW	Southwest Florida International Airport
SAN	San Diego International Airport
SAT	San Antonio International Airport
SEA	Seattle-Tacoma International Airport
SFO	San Francisco International Airport
SJC	San Jose International Airport
SLC	Salt Lake City International Airport
SMF	Sacramento Metro Airport
SNA	John Wayne Airport-Orange County Airport
STL	Lambert-St Louis International Airport
TPA	Tampa International Airport

CHAPTER 1

INTRODUCTION

As an interface of airline and passengers, airport operations have been increasingly concerned. An efficient airport provides important economic catalysts that enable the local and regional economy to thrive and improve the quality of life in the region, and vice versa.

There are various of research on benchmarking airport efficiency, including data envelopment analysis (DEA), stochastic frontier analysis (SFA), total-factor productivity (TFP), etc., among which DEA is most widely used and has been proved a robust method in airport efficiency evaluation (Lampe and Hilgers, 2014). Additionally, DEA has been increasingly used in eco-efficiency topics (Emrouznejad and Yang, 2017), which is also an essential motivation for this paper.

Propose by Charnes et al. (1978), the DEA efficiency measures the relative efficiency of decision making units (DMUs) with multiple performance factors which are grouped into outputs and inputs. By defining an efficient frontier, the inefficiency of a DMU is determined by measuring its distance to that hull, indicating its potential of an efficiency increase. Based on this standard DEA, Network DEA models (NDEA) were introduced by Färe and Grosskopf in 2000, enriching traditional all-in-one DEA models by enabling the characterization of sequential or parallel processes in production. Network DEA is also proved to have more discriminatory power than single-process DEA, uncovering much more significant inefficiencies in the current operation points. However, in multiple practical situations, not all the outputs are desirable or should be maximized. Therefore, undesirable and desirable outputs should be treated differently when evaluating a production performance.

Narrowing down the DEA application to the airport, after Gillen and Lall (1997) first introduced single-stage DEA analysis of North-American airports, NDEA has become prevailing in the recent decade. In general, the corresponding NDEA model divides airport operation into two processes, related to aircraft movement and passenger/cargo movement, respectively, with two final outputs (annual passenger movement and cargo movement), one intermediate product (aircraft movements), and various of input related to airside and landside capacity. Typical work includes Yu (2010), Wanke (2013), Lozano et al. (2013), Magghbouli et al. (2014), and Chang et al. (2015); the latter three also take into account the undesirables, i.e., the number of delayed flights and accumulated delay time. Taking financial inputs and outputs into consideration, Curi (2010) examined the effects of changes in concession agreements, privatization, and network configuration on the performance of Italian airports with commercial sales as an output, and Zou (2015) investigated the possibility of substituting PFC for AIP funds as a viable option to reform airport financing.

However, little previous work has treated cost and revenues by their relationship to the two-stage network even in the study that brought up financial factors. To this end, in our proposed model, we add monetary costs as input factors according to our discussion above that the airline may want to know if an airport welcoming private stakeholders will have higher efficiency. Not simply following the asset and debt categories on the financial statement, nor dividing by aeronautical revenue or non-aeronautical revenue, we posit items by the stage they have impacts on. For example, terminal utilities fee charged to airlines is regarded as an input to the second stage, i.e. landside stage, while Passenger Facility Charge (PFC) and grant received from the government, such as the Airport Improvement Program (AIP) is an output of the second stage, because the majority of these fund are levied and allocated based on passenger enplanement (Kirk, 2009).

As for the non-financial side, the proposed model also improved undesirable output, i.e. delay, by furthering it to the fuel consumption and exhaust emissions, which is of great concern of regulators from the social good perspective. More specifically, we follow the method proposed by Simaiakis (2006), assuming that each flight taxis at a fixed throttle setting, and using fuel burn and emissions indices from ICAO Engine Emissions Databank (ICAO, 2015). In addition to tailoring the current NDEA model especially for the airlines' usage, this paper also use taxi out delay time in replace of the conventional overall delay time or number of delayed flights.

The paper continues with an introduction of airport operations, pollutants and financial performance in Chapter 2. A review of Network DEA model with it data inputs for airport efficiency measurement are presented in Chapter 3. Sequentially, Chapter 4 includes an illustrative application to the U.S. airports, followed by conclusions and directions for future research given in Chapter 5.

CHAPTER 2

AIRPORT OPERATION AND FINANCE

2.1 Airport Operation

2.1.1 Airport Components

Airport is an essential part and the interface of the air transportation system, where aircraft take off, land on, and parking; passengers check-in, on-board, deplane, claim baggage, and connect; arriving cargo are downloaded and transit and departure cargo are packed and loaded. The complexity of this system requires well-organized and highly efficient operation and management.

As shown in Figure 2.1, an airport can be divided into two parts - landside and airside. Landside includes terminal and ground transportation, where passengers switch their transportation model; while runways, taxiways and aprons constitute the airside, where aircraft performing movement and transport passengers and cargo. Sometimes the airside also includes the terminal or even approaching zone of the air traffic control system. That is to say, except for the en-route part, the entire production of air transportation are completed at airports, and the system efficiency is heavily depends on the airport efficiency.

2.1.2 Airport Delay

One major measurement of the airport efficiency is delay. Delay to aircraft is defined as the difference between the actual time it takes an aircraft to operate on an airfield (or component) and the normal time it would take the aircraft to operate without interference from other aircraft on the airfield (or component) under specific operating conditions. Delay is expressed in minutes by comparing gate-out, wheels-off, wheels-on and gate-in time (OOOI) with the flight schedule. Detailed explanation of OOOI are shown in Table 2.1. A delayed flight is then defined by flight that is delayed by 15 minutes or longer. On-time performance is a significant index of service quality of both airports and its operating airlines. In addition to the obvious efficiency and service perspective, more physically, the on-time performance of an airport is also related to fuel consumption and pollutant emissions; the former one is of great concern of airlines as the air oil being among the largest cost of their business, while the latter one plays an important role in the government and public relationship, especially in the United States where an airport is mostly a public infrastructure comparing to a profit organization.

2.1.3 Taxiing Delay

An airport delay can occur at the gate, on the ground of airfield, or in the air. Among all types of delay, taxiway delay has been long interested and prioritized, especially from the perspective of an airport, and it will be the same case of the investigation of operation efficiency. This is because comparing to other types of delay, taxiway delay are more related to the airport itself. The gate delay may be caused by aircraft mechanical issue, airline's crew/schedule planning, or weather conditions. On the other hand, the en-route delay are significantly impacted by the entire NAS system has sometimes beyond the airport's control. A detailed taxiing process and corresponded OOOI time are shown in Figure 2.2.

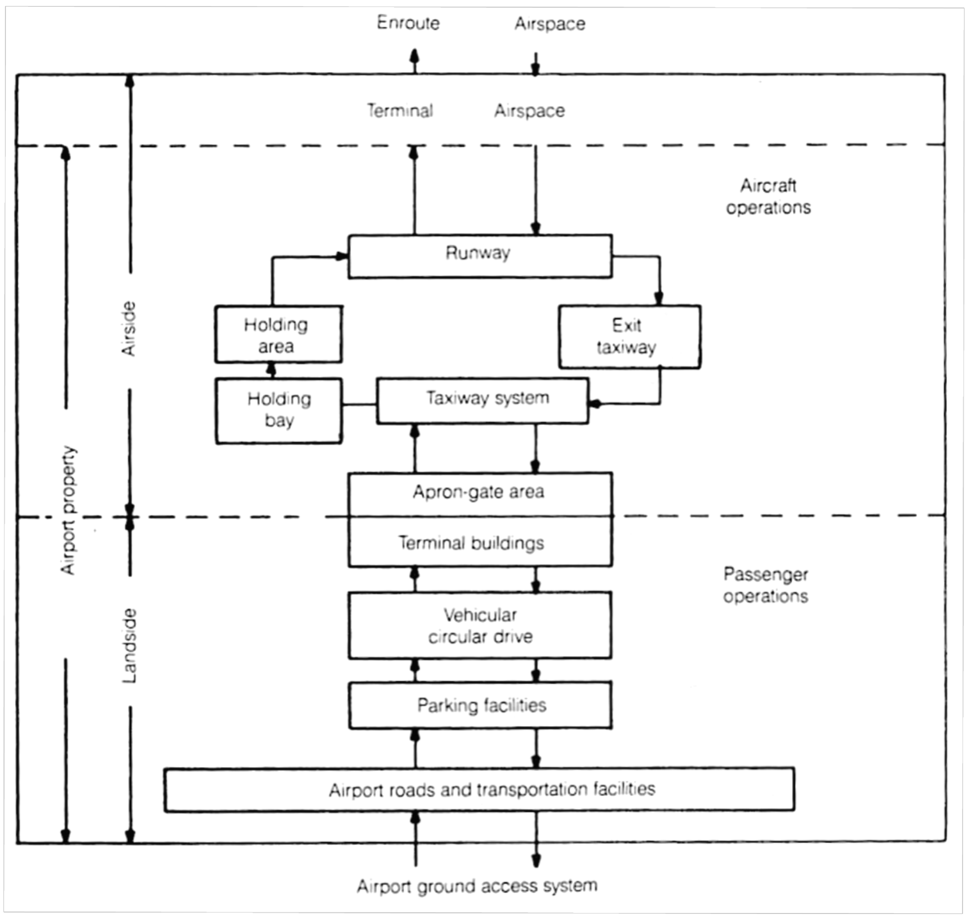

Figure 2.1. Airport Components

Aircraft taxiing on the surface not only have negative impact on airports' and airlines' on-time performance, but also contribute significantly to the fuel burn and emissions at airports. The quantities of fuel burned, as well as different pollutants such as CO, NOx, HC, and Particulate Matter, are proportional to the taxi times of aircraft, as well as other factors such as the throttle settings, number of engines that are powered, and pilot and airline decisions regarding engine shutdowns during delays.

In the United States, airport surface congestion at major airports is responsible for increased taxi-out times, fuel burn and emissions. Similar trends have been noted in Europe, where it is estimated that aircraft spend 10-30% of their flight time taxiing, and that a short/medium range A320 expends as much as 5-10% of its fuel on the ground (Cros and C. Frings, 2008). Domestic flights in the United States emit about 6 million metric tons of CO_2, 45,000 tons of CO, 8,000 tons of NO_x, and 4,000 tons of HC taxiing out for takeoff; almost half of these emissions are at the 20 most congested airports in the country (Simaiakis and Balakrishnan, 2011).

Table 2.1 OOOI Time

Time	Action	Condition
Gate Out	Aircraft leaves gate or parking position.	Parking brake is released.
Wheels Off	Aircraft takes off.	Air/ground sensor on landing gear set to “airborne” state.
Wheels On	Aircraft touches down.	Air/ground sensor on landing gear set to “ground” state.
Gate In	Aircraft arrives at gate or parking position.	Parking brake is applied.

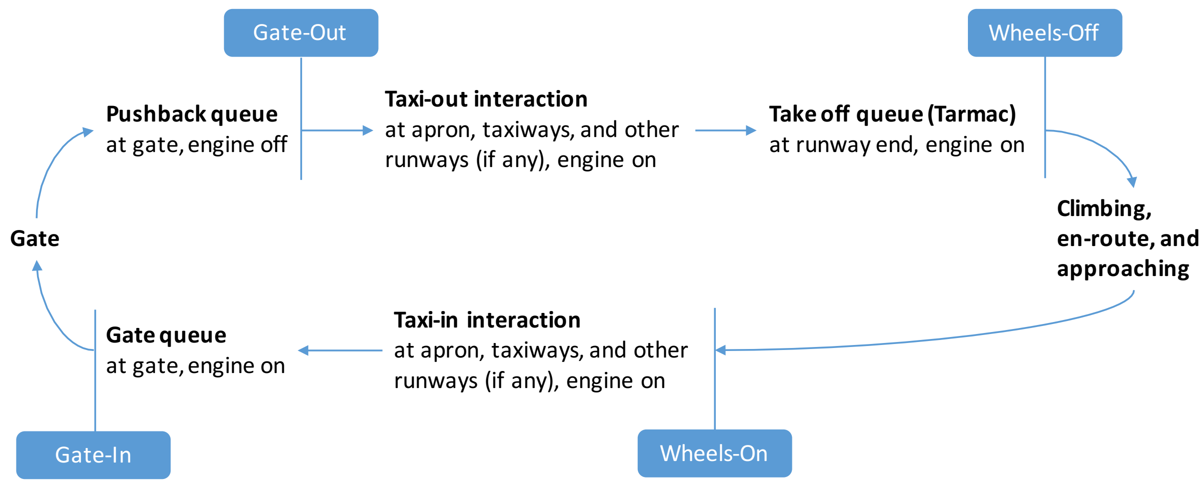

Figure 2.2. Taxiing Procedure

2.2 Airport Finance

2.2.1 Financing Sources

Although nearly all U.S. airports are owned by state or local governments, airports are required by the federal government to be as self-sustaining as possible and receive little or no taxpayer support. This means that airports must operate like businesses – funding their operations from their revenue and thoughtfully and diligently planning to fund for major improvement projects – which can often be very expensive. For example, building new runways at Chicago O'Hare Airport will cost $6.6 billion. The airport, capital markets, the airlines, and their passengers provide funds to help pay for these long-term projects.

Sources of capital for airport development include:

a) Governmental or international organization loans and grants

b) Commercial loans from financial institutions: including 1) long-term bonds, such as general obligation and revenue bonds (GARBs), General Aviation Bonds (GA), and General Obligation Bonds (GO), as well as PFC bond; 2) loans and interim financing; and 3) special facility bonds

c) Equity or debt (typically, bonds) from commercial capital market : including private investors, banks investment houses, or fund pools

d) The extension of credit from contractors and suppliers.

e) Existing airports may have retained earnings building in a capital development account.

2.2.2 Revenue

2.2.2.1 Aeronautical revenue

Airline rents, usage fees, and charges are the primary sources of the aeronautical, or airside, revenue. Each airline pays the airport for the use and maintenance of its facilities. Although varies among the specific Use and Lease Agreements between the airport and its operating airlines, regulated tariffs, or a combination thereof, the compensation the airline pays to the airport for use and maintenance of its facilities usually includes:

a) Terminal rents: Based on the number of space airlines use inside the terminal.

b) Landing fees: A per plane charge, usually based on the weight of the aircraft.

c) Other charges: Specific fees for extra airport services (e.g. use of jet bridge).

An airline does not have to have a signed contract to use an airport. However, an airline with a contract, typically called a signatory airline, enjoys special benefits such as lower rates. At some airports, these contracts give an airline a voice in the management and long-term planning of the airport.

The largest proportion of aeronautical income is generated from charges that apply directly to passengers (i.e. passenger service charges, security and transfer charges). These passenger-based revenues represent 63% of total aeronautical income, with the 37% balance being charged that apply directly to aircraft operators (landing, parking, boarding bridges, lighting, and airport-related navigational aid charges). However, from the airlines' side, airport costs continue to be a minor expense for airlines when one includes PFCs in the equation - landing fees, terminal rents, and PFCs accounted for just 6% of airline operating expenses in 2012.

It is important to highlight the shift away from aircraft to passenger-based charging, i.e. PFC in the case of the U.S. Passenger-related charges do not become part of the airlines' costs in terms of their balance sheets, they are pass-through items, so the actual operating cost of carriers is reduced by shifting charges to passengers. By applying this charging scheme, airports share the risk of decreasing traffic with the carriers as revenues are dependent on the actual number of passengers departing from the airport and less on the number of aircraft movements or aircraft size.

2.2.2.2 Non-aeronautical revenue

As noted, airports finance their own operating and development costs. Airports have diversified their sources of revenue; they not only relying on the traditional aeronautical revenues made up of airport charges, but also continue to look beyond being an infrastructure provider to more profitable commercial enterprises, in order to increase a variety of other revenues including retail, parking, real estate, and other commercial activities. According to the 2016 ACI Economics Report, global non-aeronautical revenues (including non-operating revenues) reached $58 billions representing 40% of total income as an average for world airports. In Asia, non-aeronautical income can be as high as 51%.

Non-aeronautical revenues critically determine the financial viability of an airport, as these revenue sources tend to generate higher profit margins in comparison with aeronautical activities, and also provides a cushion during adverse economic times, such as financial crises and epidemics such as the recent Ebola and Zika outbreaks with more diversification of income streams. Thus, airports are heavily reliant on the non-aeronautical side of the business as a driver of revenue growth.

These non-aeronautical revenue sources include:

a) Concessions: Rents paid by gift shops, restaurants, and newsstands, and, if agreed to in the concession contract, a percentage of the profits.

b) Parking and Airport Access: Fees for all airport-owned parking lots and in some cases, off-airport concessions bringing travelers to and from the airport.

c) Rental Car: Revenue from rental car operations within or outside a terminal.

d) Land rent: Excess airport land may be rented for golf courses, office buildings, hotels, farming or other uses.

e) Advertising: Ads placed on airport interior and exterior walls, billboards, and buses generating income.

Globally, the income generated from commercial revenues shows that retail and car parking took the largest parts, 28.3%, and 22.3% respectively, although the retail percentage is only 9.2% but with a high of over 55% of car parking in North America.

2.2.3 Costs

An airport seeking to expand its facilities, or a governmental entity facilities, or a governmental entity seeking to build a new airport, must seeking to build a new airport and raise sufficient capital to finance raise sufficient capital to finance such infrastructure development such infrastructure development from public or private sources, or a from public or private sources, or a combination of both.

Capital costs consist of the consist of the component costs (e.g., labor, materials and equipment) of construction of the airport and its construction of the airport and its component parts.

CHAPTER 3

METHODOLOGY AND DATA

3.1 Data Envelopment Analysis (DEA)

3.1.1 Single-Stage DEA

DEA was first proposed by Charnes, Cooper, and Rhodes (1978), and has been widely recognized as an effective technique for measuring the relative efficiency of a set of decision making units (DMUs) that apply multiple inputs to produce multiple outputs. From the perspective of different factors targeted to improve, a DEA model can be categorized as input-oriented and output-oriented.

Also, both constant returns-to-scale (CRS) and variable returns-to-scale (VRS) are used in DEA, where VRS DEA efficiency measurement evaluate "pure technical efficiency" that indicates how appropriately the input combination is designed for a certain target level of output mix in an output-oriented case, and output combination for input mix in an input-oriented case. VRS also does not evaluate "scale efficiency" which is associated with the deviation of return to scale of CRS. VRS is adopted in this paper since given the limited competition among the airports it cannot be expected that they operate at the most productive scale size (Banker, 1984).

In the case of measuring the efficiency of airport k with other airports, an input-oriented DEA aims at minimizing the airport resources that are used (X_{ik}) to generate airport operation, such as the use of runway, gates, and fund, without sacrifice its current level of production (Y_{jk}), of which the indexes may include aircraft movements, passenger and cargo traffic, and financial revenue.

Figure 3.1. Standard DEA

3.1.2 Network DEA

DEA was originally developed to measure the efficiency of a DMU as a whole unit, without considering its internal structure. In other words, the system is treated as a black box, within which inputs are supplied to produce outputs, with there generally being a positive correlation between the two. However, there are empirical studies indicate that in some cases, an overall system may be efficient, even while all component processes are not (Cron and Sobol 1983, Wang et al, 1997, Kao and Hwang, 2008). Therefore, the traditional DEA discussed in 3.1.1 may not explicitly identify key sub-processes engaged within an airport, and a Network DEA (NDEA) model is required to produce correct results when measuring airport efficiency.

The first work on network DEA was carried out by Charnes et al. (1986), which examined army recruitment, and where the system was divided into two processes, awareness creation and contract establishment, and each process was treated as a DMU to measure its efficiency. Following first proposed by Fare and Grosskopf in 2000, most network DEA papers deal with series-of-processes systems, although parallel-processes and general networks of processes have also been studied. Many theoretical developments and practical applications on NDEA has been reported, widely span transportation (Yu, 2010, Zhu, 2011), banking (Fukuyama, 2011), utilities (Tone and Tsutsui, 2010) and sports (Moreno and Lozano, 2013), among others.

In the context of an airport, among all the productions coming out from airport operation, aircraft movement is actually not the ultimate output. Consider an airport with regular aircraft landing-on and taking-off but has no passenger or cargo in those movement: On the one hand, the airport does have income from the landing fees, gate, and jet rent, and ground maintenance fees; however, on the other hand, it’s transporting passenger and cargo that generates the positive income of operating an airport – an airport with no passengers should be treated as insufficient taking into account the resource it consumed, regardless of the busyness of handling aircraft movement.

In order to fully consider revenue and cost throughout the entire airport system, we model a given airport k using a two-stage NDEA. Following the actual airport operation flow discussed in Chapter 2, an airport can be divided into two part, airside and land side, which naturally becomes the two stage of the proposed model. The two-stage network structure implies that airports do not generate passengers and cargoes directly from using labor, materials, and capital inputs; rather, aircraft movements mediate between uthe se of these inputs and passenger/cargo flows. This network idea follows the previous airport efficiency studies using network DEA (Lozano et al., 2013, Wanke, 2013), with different terms, "aircraft movement" and "aircraft loading"", respectively. However, using the conventional terms of "airside" and "landside" as used in airport planning topics more precisely describes the features in each stage, especially when taking financing stages into consideration. The aircraft movement becomes the intermediate product (Z_k), meaning that it's internally generated from the inputs prior to it and consumed by the outputs after it. Note that the NDEA model allows multiple intermediate products although only one in our case.

The division of process also makes possible arranging inputs and outputs into the specific stage where it occurs or starts to impact. For example, landing fees, a large portion of airside revenue, is the output of the first stage and has no impact on the landside, as it's charged by the number of flights landed based on a given rate contracted between airport and airlines. Also, there are investments in upgrade terminal interior or expanding parking area that not occurred until the second stage and should not be treated as inputs into airside. More generally, each input supplied from outside into a process can be used directly only by the process itself and processes after it; each output can be either the final production of the system prior to it or the intermediate products to be used by its following processes. The flow chart of NDEA is illustrated in Figure 3.2.

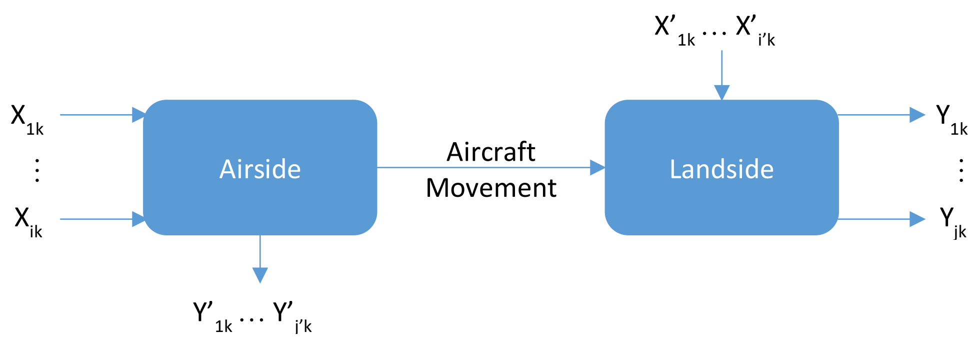

Figure 3.2. Network DEA

3.1.3 Network DEA with Undesirable Outputs

In the NDEA model discussed in 3.1.2, decreases in outputs are not allowed and only inputs are allowed to decrease; similarly, increases in inputs are not allowed and only outputs are allowed to increase. However, in multiple practical situations, not all the outputs are desirable or should be maximized with the inputs being their only limit. That is to say, undesirable and desirable outputs should be treated differently when evaluating a production performance.

When undesirable outputs are ignored, DEA models tend to label as efficient those airports with a higher activity level, although some of which may be over-saturated and causing excessive pollution, noise and inconveniences to passengers. When such saturated airports are considered as efficient then all airports are projected using them as benchmarks which means that the targets thus computed would also suffer from those drawbacks. Thus, in the area of airport efficiency, taking into account the undesirable effects, e.g. delays and fuel consumption, of airport operations, not only increases the realism of the analysis but also contributes to a fairer performance assessment. Figure 3.3 shows the flow chart with undesirables which are denoted by U_{bk}.

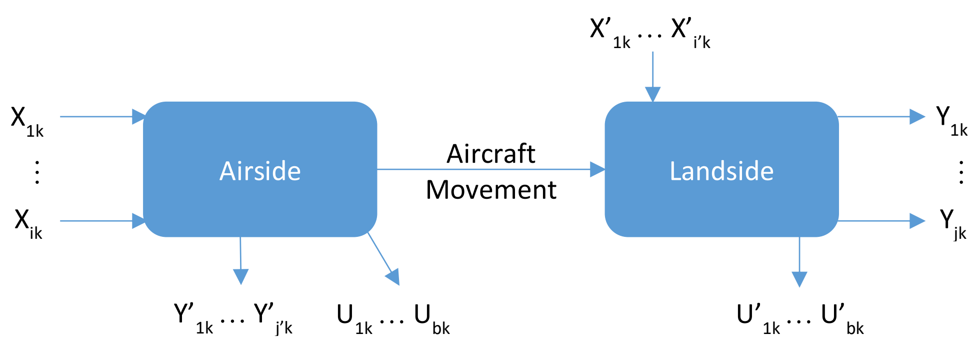

Figure 3.3. Network DEA with undesirable outputs

The Directional Distance Function (DDF) is a common approach when undesirable outputs are present. DDF measures the distance from a certain operation point (e.g. DMU 0) to the weakly efficient subset of the network PPS along a given direction vector $\boldsymbol{g} = (g_i^x, g_j^y, g_b^u)$ (Chung et al, 1997). It is the largest step size that can be given along that direction from that operation point without abandoning the network production possibility set (PPS).

Following the work of Lozano (2013), the direction vector $\boldsymbol{g}$ used in the airport efficiency becomes $\boldsymbol{g}' = (0, g_j^y, g_b^u)$ as all the inputs are non-discretionary and the corresponding components of the direction vector should be zero. Also, following Fare et al.(1989) and numerous other DEA studies that deal with undesirable outputs the desirable and undesirable outputs have been considered jointly weakly disposable, i.e. it is assumed that the undesirable outputs can always be decreased in the same proportion in which desirable outputs are decreased. Therefore, the direction vector further become a proportional directional distance vector $\boldsymbol{g}'' = (0, y_{0k}, u_{0b})$ after taking into account components corresponding to the final and the undesirable outputs.

Hence, the step size β is bounded only by the desirable and undesirable outputs potential improvements, and the computed optimal step size β^* can be interpreted as the percentage that all output variables can be simultaneously improved, where improvement means a reduction in the case of undesirable outputs and an increase in the case of desirable outputs.

3.2 Data Inputs of Airport NDEA

3.2.1 Taxiing Delay

Taxiing delay is defined by the difference between actual taxiing time and unimpeded taxiing time. The actual taxiing time is the time elapsed between the gate-off time and wheels-off time for departure flights, and the time between the wheels-on time and gate-in time for arrival flights. The unimpeded taxiing time is the taxiing time in non-congested conditions at airports, which is related to the physical configuration of the airport, including but not limited to the distance from the terminal to the runway or the assigned gate location of contracted airlines.

Although actual taxiing time varies by flight, the unimpeded taxiing time is the same for all flights for the same airport. That is to say, the unimpeded time is an averaged time among each airport. From the dataset of ASPM (Aviation System Performance Metrics), we can obtain airport-annual-averaged taxi-out time and taxi-out delay data. Hence, the unimpeded taxi-out time of departure flights for each airport can be calculated by subtracting average taxi-out delay from average taxi-out time.

ASPM dataset does not provide average taxi-in time. However, we still have the taxi-in time by flight from the Bureau of Transportation Statistics (BTS) On-time Performance data bank; they are then aggregated by each airport to get an airport average. Note that aggregating from each flight is less preferable than adopting ASPM airport average, and the reason is that in the BTS On-time Performance, not all the flights are provide taxiing time, and they are eliminated when averaging. From ASPM we can also obtain the annual average taxi-in delay data by each airport. Therefore, identical to departure, the unimpeded taxi-in time of arrival flight for each airport can be calculated by subtracting average taxi-in delay from average taxi-in time.

With unimpeded time at hand, the simulated taxiing delay for each flight can be calculated by subtracting unimpeded taxiing time from actual taxiing time, for taxi-in and taxi-out respectively, and the total taxiing delay is the sum of both direction. This result of taxiing delay for each flight will be used for calculating fuel and air pollutants the extended taxiing time.

The amount of delayed flights of each airport is also calculated using ASPM dataset by sum the multiplication between (1 − % of On-time Airport Departure) to number of departure flights and (1 − % of On-time Gate Arrival) to number of arrival flight. Note that ASPM also provides % of On-time Gate Departure data while it should not be used for calculating delayed departure flight in this model, since the Airport Departure is the wheels-off time which includes the taxi-out time while the Gate Departure does not.

3.2.2 Environmental Outputs

One of the contributions of this paper is to take into account two environmental factors, fuel consumption, and air pollutants emission from excessive taxiing time. Both factors are undesirable outputs from the first stage, coming along the desirable first-stage output aircraft movement.

Both environmental factors are related to the engine that is turned on while taxiing, which is further related to the aircraft type. While BTS On-Time Performance dataset is used as an alternative of ASPM when calculating the average taxiing delay time for each airport with its flight-specific details including tail number, it may not be the best source when aircraft information is needed. This is because the BTS On-Time Performance dataset only includes flights of U.S. certified air carriers that account for at least one percent of domestic scheduled passenger revenues, where domestic meaning both origin and destination airports are located within the boundaries of the United States and its territories. However, flights with foreign carriers or international origin or destinations bring over 25% of total passengers and 15% of total flights nationwide; numbers can be higher for major hub airports.

The BTS T-100 data bank is a better option to calculate the movement of each aircraft type. T-100 data for domestic and international segments includes both U.S. and foreign air carriers flights at least one point of service is in the United States or one of its territories. Note that flights with both origin and destination in a foreign country, i.e. only make a connection in the U.S., are not included. The proportion of movements of each aircraft type are then calculated for each airport.

For each engine type, fuel flow (kg) per second of taking-off can be obtained from the ICAO Aircraft Engine Emissions Databank, which contains information on exhaust emissions of production aircraft engines, According to the Landing and Take-Off cycle (LTO) reference by ICAO, an engine is at 100% thrust during the take-off period, and it's generally assumed that each flight taxis at 7% of take-off thrust. Therefore, the fuel consumption per second of taxiing can be calculated by multiplying fuel consumption per second of taking-off by 7%.

Three emission indices namely CO, NO_x, and HC are considered in this paper. For each index, the same ICAO Engine Performance and Emissions Data Bank provides the amount of emission (g) per kg of fuel burnt at take-off period. Therefore, the air pollutants emitted per second of taxiing can be calculated by multiplying emission per kg of fuel burnt at take-off, fuel burnt per second of taking-off, and the 7% thrust of taxiing. An example of fuel consumption and air pollutant emissions for engine mode CFM International CFM56-7B-18 turbofan, which belongs to engine family CFM56, a typical engine equipped on Boeing 737, are shown in Table 3.1. Note that only take-off row are used to obtain data while taxiing, and row with * are calculated data.

Table 3.1 Fuel burn and emissions for engine CFM56-7B-18 turbofan

Mode	Fuel Flow, kg/s	HC, g/kg fuel	CO, g/kg fuel	NO_x, g/kg fuel
Take-off	0.842	0.03	0.17	14.81
Climb out	0.702	0.03	0.28	13
Approach	0.256	0.08	5.54	7.78
Idle	0.092	4.51	46.64	3.65
Taxiing *	0.05894	0.001768	0.01002	0.872901

Each aircraft type in the T-100 has been reviewed manually for its typical engine type and number of engines, and then matched to the calculated Engine and Emission databank. If an aircraft type has multiple engine types in use, its fuel and emission are averaged among all. Finally, fuel and emissions in each airport are both added up, weighted by the percentages of operations of each engine type. Figure 3.4.1 – Figure 3.4.3 provide an illustrative flow chart of calculating delay and environmental factors.

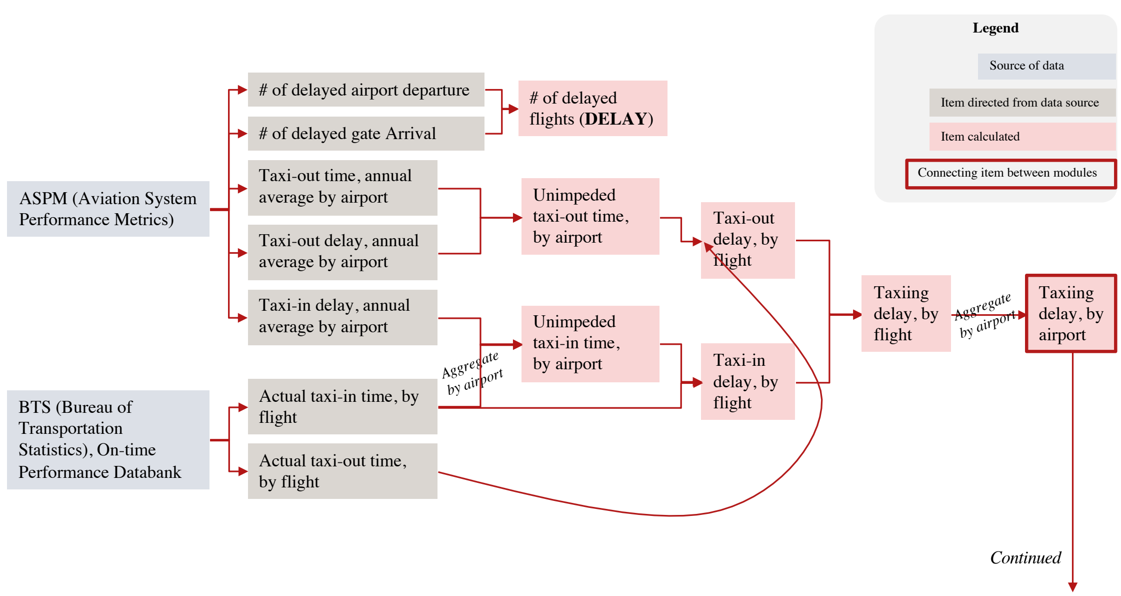

Figure 3.4.1 Data calculation module of delay

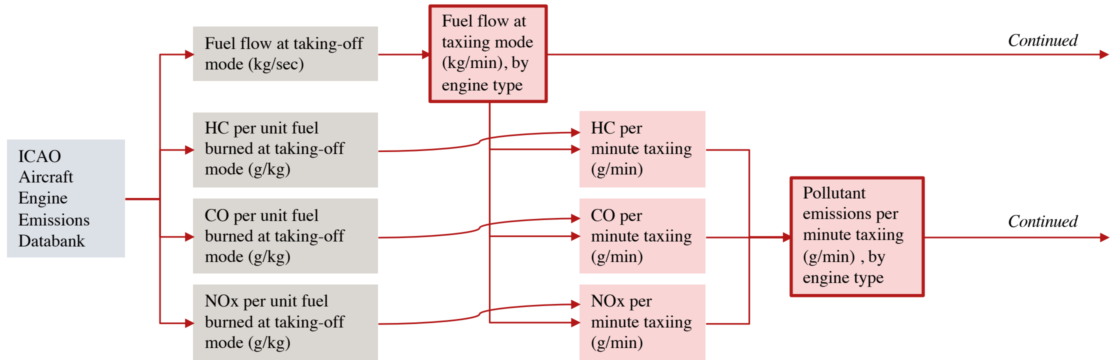

Figure 3.4.2 Data calculation module of environmental factors by engine type

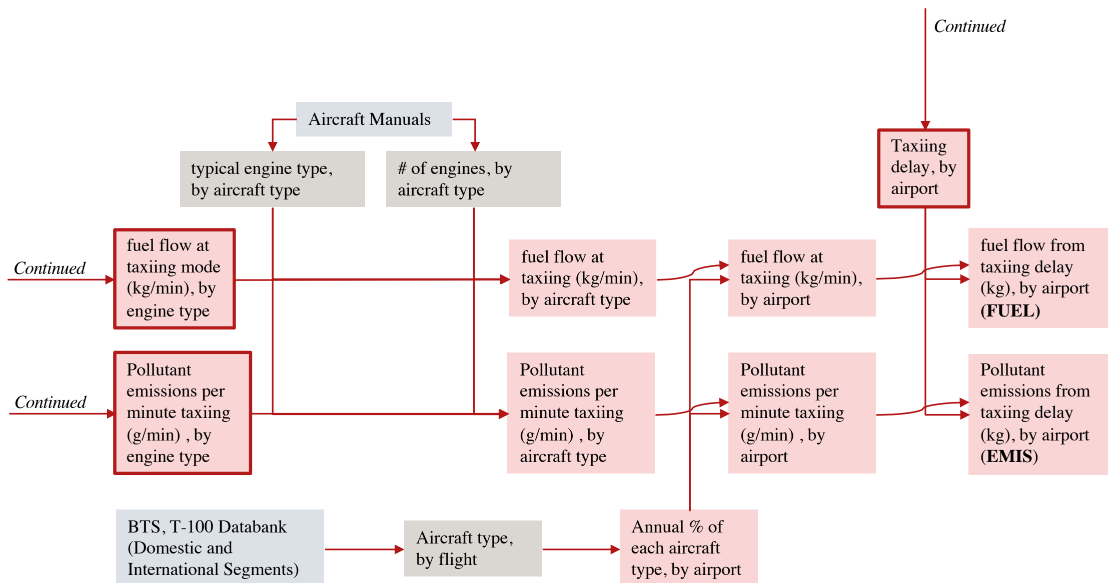

Figure 3.4.3 Data calculation module of environmental factors by airport

3.2.3 Financial Inputs and Outputs

These financial data are obtained from The Operating and Financial Summary, FAA Form 5100-127, which includes revenues, expenses, and other financial information of reporting airport, with a manual review of Comprehensive Annual

Financial Reports (CAFR) of each airport. A list of financial item reported in FAA Form 5100-127 is shown in Table 3.2.

Although widely used in previous airport NDEA studies to place items to each operation stages, the method of categorize financial items by aeronautical and non-aeronautical mentioned in Chapter 2.2 is actually designed to identify airport management performance of operating as a business entity beyond a public infrastructure, and should not be directly related to airside and landside stages. Therefore, in this paper, financial factors are decomposed from Form 5100-127 and rearranged into airside and landside separately.

Airside-related cost, i.e. inputs at the first stage, are identified as airfield capital expenditures (Item 10.1). However, follow the idea of the NDEA, the overall cost, i.e. labor (Item 6.1) and material cost (Item 6.2, 6.3), are also included because they started to have an impact on the overall system at the first stage. Similarly, external financing funds (Item 11.1-11.3) come in at the first stage as well. Airside revenue streams, i.e. final desirable outputs of the first stage, can include both passenger-related items, such as passenger airlines landing fees (Item 1.1), terminal area apron charges/tie-downs (Item 1.3), and non-passenger items, such as landing fees from cargo (Item 2.1), landing fees from general aviation and military (Item 2.2), FBO and contract revenue (Item 2.3), cargo and hanger rentals (Item 2.4), and fuel sales or fuel flowage fees (Item 2.5).

Regarding the landside, the stage-only inputs, or the cost of operation landside, include terminal capital expenditures (Item 10.2) and parking and ground transportation expenditures (Item 10.3, 10.4); while the revenue can come from terminal facility fees from passenger airlines (Item 1.2), terminal concessions such as F&B (Item 4.2), retail (Item 4.3), and service facilities (Item 4.4), and off-terminal facilities such as car rental (Item 4.5), parking/ ground transportation (Item 4.6), and affiliated or contracted hotels (Item 4.7). It's also notable that the amount of grant received from AIP, federal or local government (Item 8.3), along with passenger facility charges (PFC, Item 8.4) are also recorded as an output from the landside, in that PFC and the formula part of AIP funds, which accounts for 70–76% in total AIP funds (Kirk, 2009), are levied and allocated based on passenger enplanement.

Table 3.2 Item Reported in FAA Form 5100-127

1.0 Passenger Airline Aeronautical Revenue	
1.1 Passenger airline landing fees	**3.0 Total Aeronautical Revenue**
1.2 Terminal arrival fees, rents, and utilities	
1.3 Terminal area apron charges/tie-downs	**4.0 Non-Aeronautical Revenue**
1.4 Federal Inspection Fees	4.1 Land and non-terminal facility leases and revenues
1.5 Other passenger aeronautical fees	4.2 Terminal- food and beverage
1.6 Total	4.3 Terminal- retail stores and duty free
	4.4 Terminal -services and other
2.0 Non--Passenger Aeronautical Revenue	4.5 Rental cars -excludes customer facility charges
2.1 Landing fees from cargo	4.6 Parking and ground transportation
2.2 Landing fees from GA and military	4.7 Hotel
2.3 FBO revenue; contract or sponsor operated	4.8 Other
2.4 Cargo and hangar rentals	4.9 Total
2.5 Aviation fuel tax retained for airport use	
2.6 Fuel sales net profit/loss or fuel flowage fees	**5.0 Total Operating Revenue**
2.7 Security reimbursement from Federal Government	
2.8 Other non--passenger aeronautical revenue	**6.0 Operating Expenses**
2.9 Total	6.1 Personnel compensation and benefits

6.2 Communications and utilities	**11.0 Indebtedness at End of Year**
6.3 Supplies and materials	11.1 Long Term Bonds (GA, GARB, PFC, etc.)
6.4 Contractual services	11.2 Loans and interim financing
6.5 Insurance claims and settlements	11.3 Special facility bonds
6.6 Other	11.4 Total Debt at End of Year
6.7 Subtotal	
6.8 Depreciation	**12.0 Externally Restricted Assets**
6.9 Total Operating Expenses	12.1 Externally Restricted Debt Reserves
	12.2 Other Externally Restricted Assets
7.0 Operating Income (Loss)	12.3 Total
8.0 Non-Operating Revenue (Expenses) and Capital	**13.0 Unrestricted Cash and Investments**
8.1 Interest Income, restricted and non-restricted	
8.2 Interest expense (use minus sign)	**14.0 Reporting Year Proceeds**
8.3 Grant receipts	14.1 Bond proceeds
8.4 Passenger Facility Charges	14.2 Proceeds from sale of property
8.5 Capital Contributions (for withdraw use minus sign)	
8.6 Special items (loss)	15.0 Debt Service
8.7 Other	15.1 Debt service, excluding coverage
8.8 Total Non-Operating Revenue (Expenses)	15.2 Debt service, net of PFCs and Offsets
9.0 Net Assets	**16.0 Operating Statistics (* optional for airports having fewer than 25,000 enplanements in the preceding calendar year).**
9.1 Change in net assets	
9.2 Net assets (deficit) at beginning of year	
9.3 Net assets (deficit) at end of year	* 16.1 Enplanements
	* 16.2 Landed weights in pounds
10.0 Capital Expenditures and Construction in Progress	* 16.3 Signatory landing fee rate per 1,000 lbs.
	* 16.4 Annual aircraft operations
10.1 Airfield	16.5 Passenger Airline CPE (line 1.6/16.1)
10.2 Terminal	* 16.6 Full time equivalent employees at end of year
10.3 Parking	16.7 Security and law enforcement costs
10.4 Roadways, rail, and transit	16.8 ARFF costs
10.5 Other	16.9 Repairs and maintenance
10.6 Total	16.10 Marketing/Advertising/Promotions

3.2.4 Other Variables

Airside uses runway area and number of gates to produce aircraft operations, which are obtained from Airport Master Plan Update of each airport, which is required by FAA to including Existing Conditions update, providing an inventory of pertinent data for use in subsequent plan elements. We also manually review the airport terminal maps for some details.

As for the airport operational data used in the intermediate product and landside outputs, the aircraft movement and passenger enplanement data can be extracted from FAA Form 5100-127, and cargo handling data from BTS T-100 data bank.

3.3 Model Formulation

Finally, combining all the factors discussed in this session into the NDEA method discussed in Chapter 3.2, a flow chart of airport efficiency measurement model using NDEA with undesirables is illustrated in Figure 3.5.

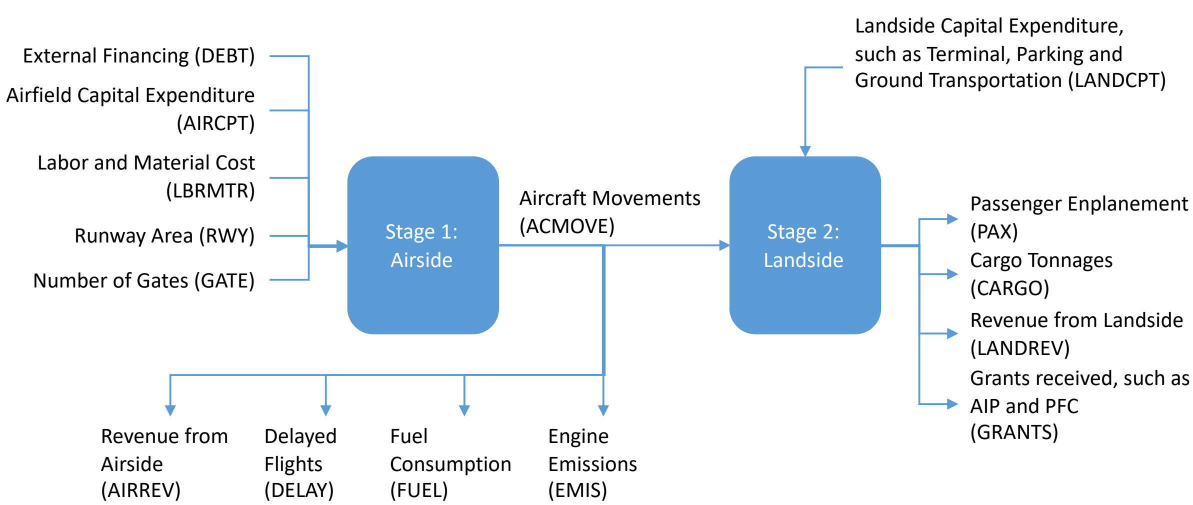

Figure 3.5. Two-Stage Airport NDEA Model with Undesirables

Following the flow chart, the first-stage production airside take airfield capital expenditure, labor and material cost, runway area, and the number of gates as inputs, and generates revenue airside revenue as a desirable output and delayed flight and fuel consumption and its derivative pollutant emissions as undesirable outputs. The first stage also produces aircraft movement as the intermediate factor that also serves as an input of the second stage. The second stage, landside, uses aircraft movement and landside capital expenditure to produces passenger and cargo flows, taking total passenger enplanement and total cargo handled (freight and mail) as its outputs, and also generate landside revenue and has an impact on the grants and PFC received.

The proposed model can be formulated as function (1) – (20).

Constraints (2) – (7) and (9) – (13) impose the input reductions and desirable outputs increases respectively, corresponding to both stages. For each input, left-hand side of the constraint (2) – (7) compute the sum, for all the processes that consume that input, of the target input of the operation points of these processes. The corresponding right-hand size relates the target total input consumption to the current input consumption thus bounding from below the maximum step size β that can be achieved along the direction given by vector $\boldsymbol{g} = (0, y_{0k}, u_{0b})$ as discussed in Chapter 3.1.3. The explanation is symmetric for constraint (9) – (13) with corresponding outputs.

$$
\begin{aligned}
&Max \;\; \beta && (1)\\
&s.t \;\; \sum_k \lambda_k^{S1} \cdot RWY_k \le RWY_0 && (2)\\
&\sum_k \lambda_k^{S1} \cdot GATE_k \le GATE_0 && (3)\\
&\sum_k \lambda_k^{S1} \cdot AIRCPT_k \le AIRCPT_0 && (4)\\
&\sum_k \lambda_k^{S1} \cdot LBRMTR_k \le LBRMTR_0 && (5)\\
&\sum_k \lambda_k^{S1} \cdot DEBT_k \le DEBT_0 && (6)\\
&\sum_k \lambda_k^{S2} \cdot LANDCPT_k \le LANDCPT_0 && (7)\\
&\theta_{S1} \cdot \sum_k \lambda_k^{S1} \cdot ACMOVE_k - \sum_k \lambda_k^{S2} \cdot ACMOVE_k \ge 0 && (8)\\
&\theta_{S1} \cdot \sum_k \lambda_k^{S1} \cdot AIRREV_k \ge AIRREV_0 \cdot (1+\beta) && (9)\\
&\sum_k \lambda_k^{S2} \cdot PAX_k \ge PAX_0 \cdot (1+\beta) && (10)\\
&\sum_k \lambda_k^{S2} \cdot CARGO_k \ge CARGO_0 \cdot (1+\beta) && (11)\\
&\sum_k \lambda_k^{S2} \cdot LANDREV_k \ge LANDREV_0 \cdot (1+\beta) && (12)\\
&\sum_k \lambda_k^{S2} \cdot GRANTS_k \ge GRANTS_0 \cdot (1+\beta) && (13)\\
&\theta_{S1} \cdot \sum_k \lambda_k^{S1} \cdot DELAY_k = DELAY_0 \cdot (1-\beta) && (14)\\
&\theta_{S1} \cdot \sum_k \lambda_k^{S1} \cdot FUEL_k = FUEL_0 \cdot (1-\beta) && (15)\\
&\theta_{S1} \cdot \sum_k \lambda_k^{S1} \cdot EMIS_k = EMIS_0 \cdot (1-\beta) && (16)\\
&\sum_k \lambda_k^{S1} = 1 && (17)\\
&\sum_k \lambda_k^{S2} = 1 && (18)\\
&0 \le \theta_{S1} \le 1 && (19)\\
&\lambda_k^{S1} \ge 0, \;\; \lambda_k^{S2} \ge 0, \;\; \beta \; free && (20)
\end{aligned}
$$

Constraints (8) is the global balance constraints imposing that the amount of intermediate product produced in the system is sufficient to satisfy the amount of that term in the constraint represents the sum of the target production of that intermediate product by the processes that produce it while the second terms compute the sum of the target consumption of that intermediate product by the processes that consume it.

Constraint (14) – (16) impose the possible reduction that can be obtained, as before, to bound the maximum step size along direction vector $\boldsymbol{g} = (0, y_{0k}, u_{0b})$ for each undesirable output. An important difference with the previous constraints is that, due to the weak disposability of undesirable outputs assumption, these constraints are equalities.

Convexity constraints (17) – (18) imposed the VRS of both stages, and objective (1) related to the output-oriented type of DEA is used. Also, variable θ is required for the VRS stage that generate undesirable outputs, which relates to constraints corresponding to Stage 1, (8) – (9) and (14) – (16). The efficiency score e is then calculated by $(1 - \beta)$ / $(1 + \beta)$, the closer score e to 1 the more efficient an airport, airport with $e = 1$ are identified as operating at full efficiency.

CHAPTER 4

CASE STUDY: 44 U.S. AIRPORTS, 2011-2015

4.1 Data Sources and Results

Samples of case study come from Airport Council International top 50 airport in North American. Input and output values for each airport in 2015 are listed in Table 4.5 and Table 4.6 respectively as an example of five years.

Inputs and outputs should meet isotonicity according to Charnes et al. (1985), i.e., increasing inputs should lead to higher outputs. To test whether this is the case in our data, we conduct correlation analysis between inputs and outputs. The correlation coefficients in 2015 are reported as an example in Table 4.1. Overall, it is observed that the data meet the isotonicity condition.

Table 4.1 Input-Output Correlation, 2015

	ACMOVE	DELAY	FUEL	EMISSION	AIRREV	PAX	CARGO	LANDREV	GRANTS
AIRCPT	0.474	0.561	0.017	0.031	0.644	0.472	0.420	0.416	0.617
LBRMTR	0.750	0.818	0.382	0.501	0.907	0.789	0.826	0.949	0.796
DEBT	0.691	0.675	0.215	0.266	0.398	0.701	0.677	0.810	0.670
RWY	0.692	0.648	0.165	0.234	0.441	0.679	0.488	0.674	0.594
GATE	0.893	0.866	0.311	0.372	0.542	0.873	0.599	0.760	0.830
LANDCPT	0.621	0.608	0.478	0.497	0.473	0.646	0.562	0.601	0.631

Table 4.2 shows the efficiency score for each airport over 2011-2015. An illustrative map for this result is shown in Figure 4.1; note that alternative airports (i.e. airports in the same city or serving the same area) are intentionally aligned up for comparison. The overall results show a generally stable result over the five-year period, which partially proves the solidity of the model given the fact that airport developments and operations is practically a long-term and gradually process: the amount of fully efficient airport range from 11 to 17 out of 44, and the average efficiency score of each year varies over 0.82 to 0.87, with an overall total of 0.84. Besides, there are 11 airports operated at full efficiency over the five-year period, namely ATL, JFK, LAX, MIA, OAK, ORD, RSW, SMF, SNA, DTW, and FLL.

Table 4.2. The efficiency of 44 U.S. Airport, 2011-2015

Airport	2011	2012	2013	2014	2015	Average	Airport	2011	2012	2013	2014	2015	Average
ATL	1.000	1.000	1.000	1.000	1.000	1.000	**MDW**	0.866	0.853	0.874	0.963	0.927	0.897
AUS	1.000	0.849	0.782	0.781	0.789	0.840	**MIA**	1.000	1.000	1.000	1.000	1.000	1.000
BNA	0.666	0.632	0.695	0.684	0.802	0.696	**MSP**	0.678	0.672	0.664	0.718	0.744	0.695
BOS	0.540	0.689	0.548	0.748	0.815	0.668	**MSY**	0.970	0.839	0.796	0.824	0.855	0.857
BWI	0.847	0.771	0.734	0.811	0.832	0.799	**OAK**	1.000	1.000	1.000	1.000	1.000	1.000
CLE	1.000	0.466	0.476	0.631	0.737	0.662	**ORD**	1.000	1.000	1.000	1.000	1.000	1.000
CLT	0.670	0.629	0.638	0.659	0.667	0.652	**PDX**	0.680	0.667	0.688	0.691	0.703	0.686
DCA	0.671	0.572	0.898	0.676	0.668	0.697	**PHL**	0.617	0.548	0.491	0.616	0.607	0.576
DEN	0.985	0.772	0.779	0.880	0.798	0.843	**PHX**	0.974	0.804	1.000	0.955	0.828	0.912
DFW	0.839	0.816	0.796	0.813	0.820	0.817	**PIT**	0.564	0.635	0.678	0.590	0.721	0.637
DTW	1.000	1.000	1.000	0.991	1.000	0.998	**RDU**	0.645	0.622	0.630	0.650	0.681	0.645
EWR	0.723	0.684	1.000	0.817	0.744	0.794	**RSW**	1.000	1.000	1.000	1.000	1.000	1.000
FLL	1.000	1.000	0.976	1.000	1.000	0.995	**SAN**	0.861	0.844	0.834	0.829	0.855	0.845
HNL	1.000	0.974	1.000	0.960	0.969	0.981	**SAT**	1.000	0.971	0.816	1.000	1.000	0.958
IAD	0.870	0.942	0.836	0.979	1.000	0.926	**SEA**	0.874	0.873	0.883	0.877	0.855	0.872
IAH	0.674	0.665	0.649	0.714	0.891	0.719	**SFO**	0.783	0.887	0.808	0.795	0.877	0.830
JFK	1.000	1.000	1.000	1.000	1.000	1.000	**SJC**	0.932	0.893	1.000	0.763	1.000	0.918
LAS	0.827	0.811	0.959	1.000	1.000	0.920	**SLC**	0.773	0.680	1.000	1.000	0.800	0.851

LAX	1.000	1.000	1.000	1.000	1.000	1.000	**SMF**	1.000	1.000	1.000	1.000	1.000	1.000
LGA	0.574	0.582	0.682	0.690	0.619	0.629	**SNA**	1.000	1.000	1.000	1.000	1.000	1.000
MCI	1.000	0.803	0.672	0.733	0.880	0.818	**STL**	0.677	0.627	0.635	0.648	0.792	0.676
MCO	1.000	0.914	0.864	0.870	0.984	0.926	**TPA**	0.890	0.953	0.908	0.921	0.953	0.925
							Average	**0.856**	**0.817**	**0.834**	**0.847**	**0.868**	**0.844**

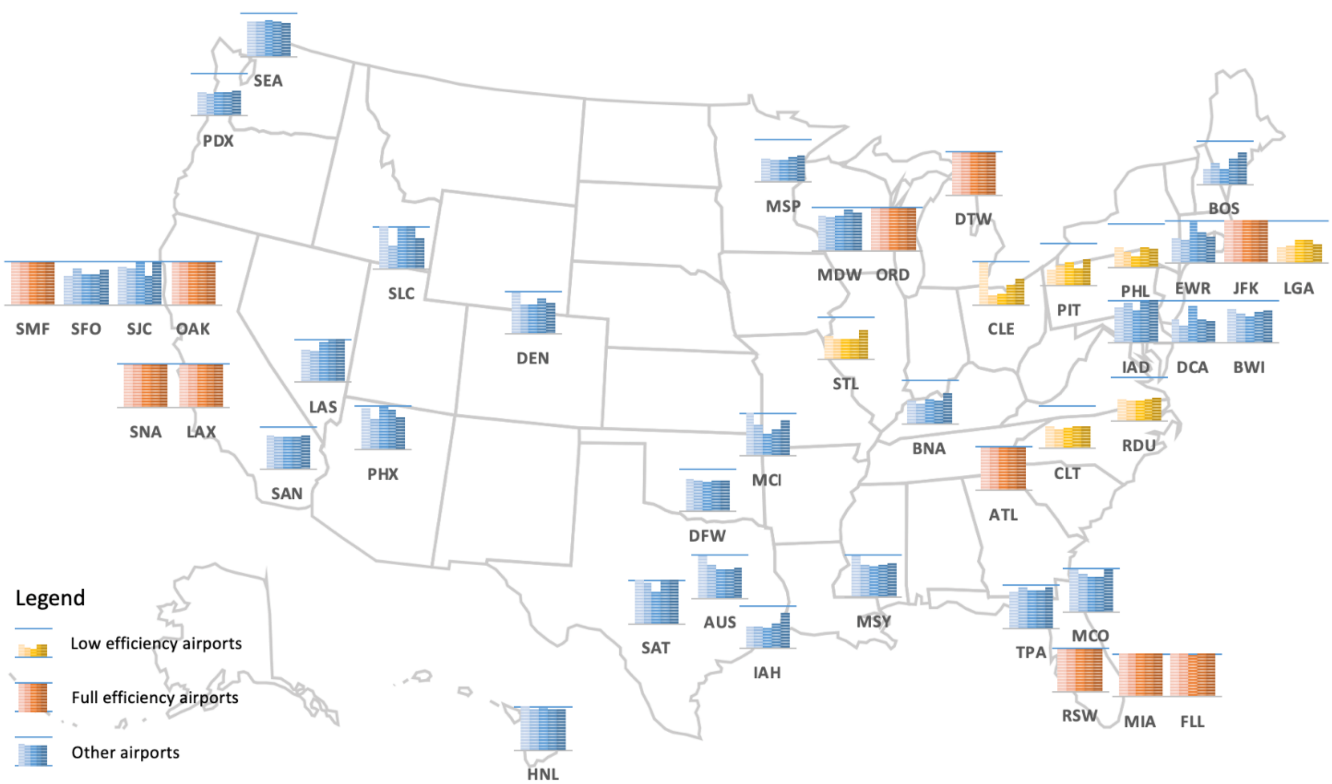

Figure 4.1 Efficiency of 44 U.S. Airport, 2011-2015

4.2 Results Analysis

4.2.1 High Efficiency for Complementary Airport Pairs

Most of the full-efficiency airports are located in the same area with highly competitive airport cluster, and some of them are alternative or complementary airport to each other. Examples are LAX and SNA in Los Angeles metropolitan, MIA and FLL in south Florida area, and OAK and SMF in the Bay area; ORD and MDW can also be included with MDW operating in almost full efficiency.

Following the logic of our proposed model, this can be explained by the unified or cooperated management of each area, since the collaboration between alternative airports to maintain a stability of the neighbor air traffic system is prioritized as a public transportation infrastructure. This collaboration, especially between large hub airport and small local airport, will bring in fewer congestions and therefore less delay by separating short-term and long-term flight or different take-off and approaching direction. In addition, although facing fiercer competitors, locating in an airport cluster also means more passenger and cargo throughput which can also raise the efficiency score.

One concern for the collaborated airport cluster is that, if take en-route delay taken into account, the score may fall back because of the congestion of the air route or approaching area.

4.2.2 High Efficiency for Large Hub Airports

In addition to the complementary airport pairs being both efficient, it is also noticeable that some commonly regarded as insufficient airports Examples are LAX, JFK and DTW. However, based on the proposed model, this result is actually reasonable. Consider the financial factors, on the one hand, large hub airports are more attractive to concessionaires and therefore generating more landside non-aeronautical revenue. On the other hand, large hub airport are commonly managed by specified airport authority rather than the government, which brings in more efficient and various funds utilization. Therefore, a large hub airport are more self-sustaining, which comply with the model which is to find an optimized balanced point between input and output. In addition, large airports handles more long-term especially international flights, which are more tend to use larger long-haul aircraft. This makes airports to transporting more passengers without proportionally increase the ground congestion and its negative impact.

A concern of these large airports labeled at efficient is that the service quality is not included in the model while it may impact on especially the landside efficiency and the lower reputation which leads to a decrease of passenger enplanement.

4.2.3 Low Efficiency for Medium-Size Airports

The result also shows that airports “in-between” has the worst efficiency performance; some examples are CLE, PIT, and PHL, where PHL has the almost lowest efficiency score throughout the five years and shows a decreasing trend.

This type of airports normally serves a medium-large metropolitan, which may, on the one hand, cause taxi delay and environmental undesirable outputs, on the other hand, has less flexibility and regulated by the authorities bounded by serving as a public infrastructure. They are also receiving a decent amount of funding being an airport located in the capital or economic center of a state. However, their traffic level is not enough to make the most use of their financial investment and the current airfield inventory. Another reason would be the competitors near-by. Indeed, these airports are concentrated in the north-eastern area, however, looking at prior mentioned smaller airports located in busy airport group area but still able to obtain high efficiency, this exterior factor should not be an excuse of the insufficient of airport internal operation performance.

The low efficiency may also come from the large investments in expansions with sometimes decades before they start to generating profit. This caused by the default of airport being a complicated and continuous construction project. Comparing to large airports that are focused on improving current inventory utilization, and small airport with limited funding sources, medium airports are most likely invest on expansion and renovation with its generally sufficient budget and managerial/financial flexibilities. Depreciation methods can be used in further studies in order to eliminate the bias of one-time large investment with long payback period.

4.2.4 Comparison with Models without Environmental or Financial Factors

In order to illustrate the result of the model, two other models are run: both of them have the same structure of the proposed airport efficiency NDEA model but removed the environmental factors and financial factors respectively. Figure 4.2 and Figure 4.3 provide the efficiency score of a given airport in three different models. Note that airports are ordered by efficiency score in our proposed model, and colors are tinted correspondingly. Detailed numbers for each airport are shown in Table 4.4.

Figure 4.2 provides an interesting fact that although the score of each airport varies among models, the three models are presenting a similar ranking. This from an aspect supports the solidity of the NDEA model measuring airport efficiency, regardless of the specific factors chosen. Moreover, it’s observable that the rankings for efficiency scores in all three models comply with the common impression of popularity of airports, which directly related to the size of airports, such as runway area, aircraft movement or passenger enplanement, and this is generally stable for a given airport over a short time window which is 5 years in our case.

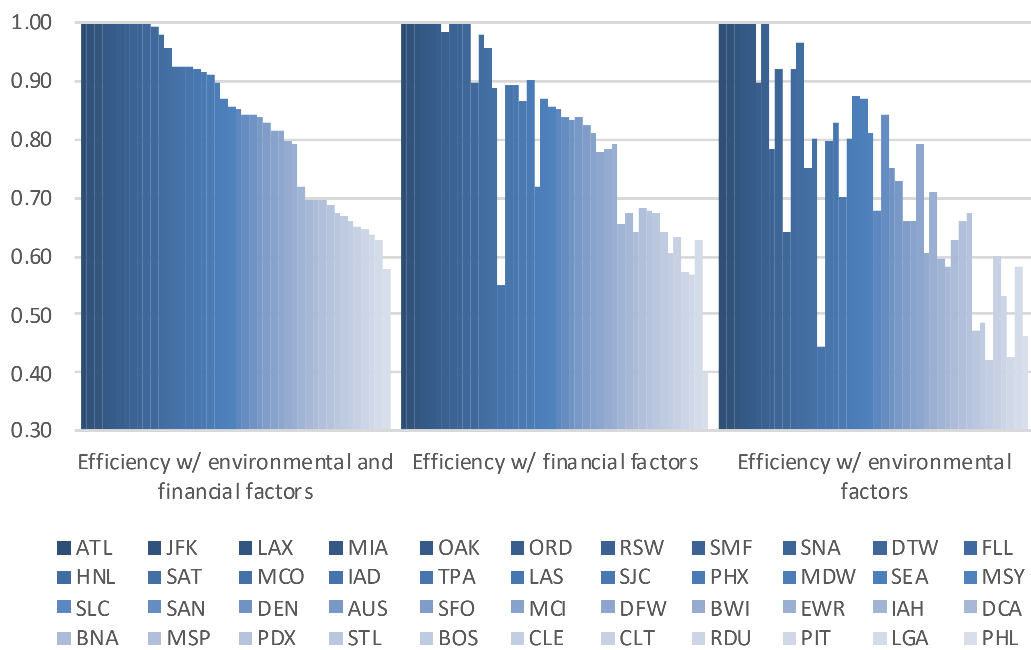

Figure 4.2. Score rankings of models with or without environmental or financial factors

However, by reading the colored area for three models in Figure 4.2, one can find the proposed model with both environmental and financial factors are showing less variation and higher average. This fact become more apparent in Figure 4.3, where the proposed model significantly raised the score especially for airports that do not perform well with the absence of finance and environmental factors.

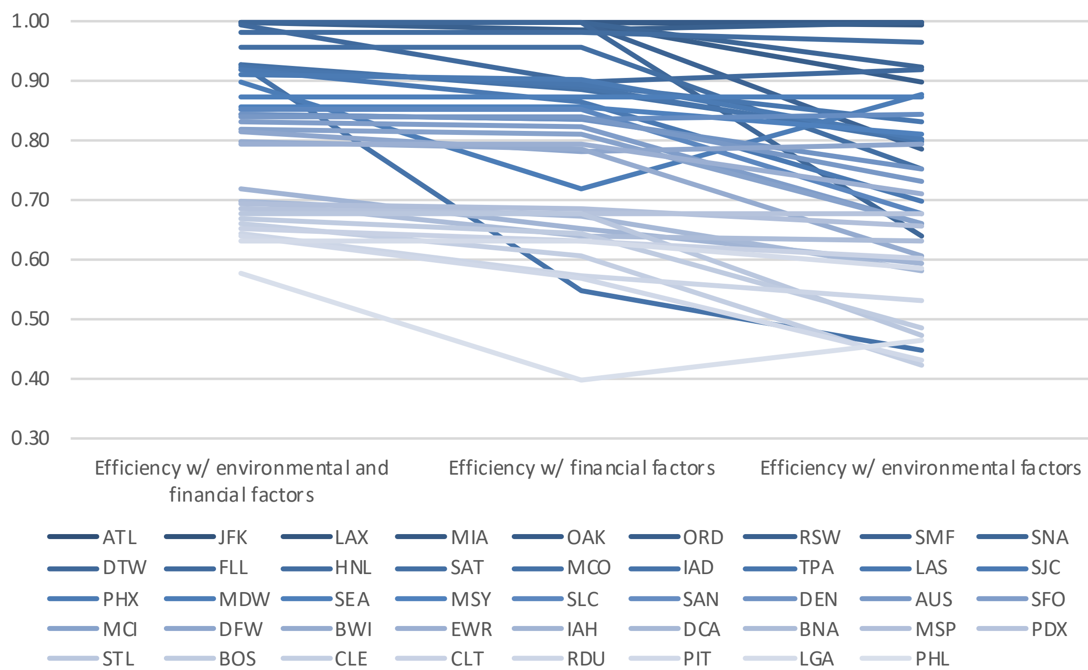

Figure 4.3. Comparison with efficiency not considering environmental or financial factors

This fact supports the idea of development the NDEA model adding in environmental and financial factors in order to balance the large traffic throughput of the large airport by considering their meanwhile large consumption of airport resources and negative impact on the neighbor community. Without environmental and financial factors, because the physical configuration is not frequently changed, a large airport with more traffic always outscore smaller ones. However, as an environmental and financial factor more versatile among years, although the busyness level of operation keeps unchanged, higher costs to maintain and operate within the large physical configuration are shown. Therefore, we can observe that the input and output of financial factors and adding undesirable environmental outputs give small airports chances and improve the fairness of the overall measurement system.

Another important findings from the result is that, the removal of financial factors results in more significant difference of score ranking to the proposed model, comparing to the removal of environmental factors, which can be intuitively observed from the more fluctuated edge for model with only financial factors includes in Figure 4.2, and the more concentrated lines in Figure 4.3. Statistically, removing the environmental factors results in a 4% change while the number is 13.4% if removing financial factors. This fact provide an important insight of the NDEA model which are supposed to be a black box within each process, only calculating the relative efficiency with the sample set not the impact of specific factors. Looking from the scope of individual airport, PIT, RDU, MDW, PHL and IAD have a score over 10% lower if environmental factors are removed; the score of STL, DTW, PIT, CLE, and IAD are lowered by 30% or more if financial factors are removed. Table 4.3.1 and Table 4.3.2 provide the percentage of change of efficiency score for each airport with environmental and financial factors removed in the model.

Table 4.3.1 Score change % w/o environmental factors

Airport	Change % if remove environmental factors	Airport	Change % if remove environmental factors
IAD	-40.715	**SAN**	-0.841
PHL	-30.774	**DEN**	-0.839
MDW	-19.852	**SFO**	-0.753

Table 4.3.2 Score change % w/o financial factors

Airport	Change % if remove financial factors	Airport	Change % if remove financial factors
IAD	-87.483	**EWR**	-10.733
CLE	-39.474	**BNA**	-10.298
PIT	-36.706	**ORD**	-10.275

RDU	-11.324	**MCI**	-0.689
PIT	-10.764	**LAX**	0.000
FLL	-9.619	**HNL**	0.000
IAH	-9.063	**ATL**	0.000
CLE	-8.583	**JFK**	0.000
BNA	-7.878	**MIA**	0.000
SJC	-5.734	**OAK**	0.000
DFW	-4.358	**ORD**	0.000
MCO	-4.166	**SMF**	0.000
BOS	-3.934	**SNA**	0.000
TPA	-3.596	**DTW**	0.000
DCA	-3.232	**AUS**	0.000
CLT	-3.120	**EWR**	0.000
LAS	-2.896	**LGA**	0.000
BWI	-1.666	**STL**	0.000
MSP	-1.596	**MSY**	0.000
RSW	-1.523	**SLC**	0.000
PDX	-1.148	**SEA**	0.000
PHX	-0.983	**SAT**	0.000
		Average	**-3.995**

DTW	-35.883	**LAS**	-9.979
STL	-29.902	**FLL**	-8.332
BOS	-28.511	**CLT**	-8.209
PHL	-27.893	**SNA**	-7.795
SJC	-25.177	**LGA**	-7.138
BWI	-24.504	**MSY**	-5.455
SMF	-21.615	**MSP**	-5.446
SAT	-21.555	**DFW**	-3.110
SFO	-20.588	**MDW**	-2.948
SLC	-20.532	**HNL**	-1.625
RDU	-19.691	**PDX**	-1.522
MCI	-19.629	**MIA**	-0.149
IAH	-19.045	**RSW**	0.000
DCA	-16.935	**SEA**	0.000
TPA	-14.363	**ATL**	0.000
MCO	-13.790	**JFK**	0.000
AUS	-13.032	**LAX**	0.000
PHX	-12.233	**OAK**	0.000
DEN	-11.027	**SAN**	0.000
		Average	**-13.407**

4.3 Results Implication

In addition to providing the efficiency ranking of airports, the study also reveals several directions for airports with different sizes to improve their efficiency.

For small airports, with delay and the environmental issues are not usually the main problem, becoming more self-sustained or financially independent may be a good direction to raise the efficiency score, comparing to investing into expansion or renovation that requires a large one-time cost with long payback period. Another option worth to consider for small airports is to collaborate with large airports serving the same area or in the same airport cluster, by separating short-term and long-term flight or different take-off and approaching direction.

For large airports, on the other hand, it is advised to prioritize the optimization of ground operation to raise the efficiency score. The reason is that, large airports are already established a mature and stable system to financing the airport and generating revenues to support the daily operation as well as long-term expansion plan. However, the taxiing delay on the ground and the negative environmental impacts coming along can be a major reason of being labeled with low efficiency. In addition to improving the ground operation process, for large airports it is also advised to welcome aircraft type with larger capacity so that they may generate larger passenger and cargo throughput without proportionally increase the congestion and environmental impacts.

For medium-size airports, which shown to be most vulnerable group to the proposed efficiency measuring system, it may be beneficial if the airports can combine advantages of both large and small airport and make effort to overcome the disadvantages. That is to say, on the one hand, a medium-size airport should pertain its unsaturated ground capacity and attract more passengers. With the increase of passenger traffic, investing in the operation that generate sustainable income besides receiving grants, such as shopping, parking and hotel, is another option to improve the efficiency without a large cost. On the other hand, these medium-size airports should prudently, if not possible to completely halt, investments in physical expansion.

In addition to the strategic insights, we also found some directions for further study, based on this case study result. Firstly, one may adopt appraisal and depreciation methods for investment into the airside to improve the fairness of the ranking system especially for airports that made a large investment within or shortly before the studies period. Also, runway configuration can be taken into consideration with current runway area input, because with the same area of runway, a crossing runway system may have less capacity than parallel runway systems and cost more maintenance and ground operation sources.

Table 4.4 Comparison with efficiency not considering environmental or financial factors

Airport	Avg Efficiency, w/ environmental and financial factors	Avg efficiency, w/ financial factors	Avg efficiency, w/ environmental factors	Airport	Avg Efficiency, w/ environmental and financial factors	Avg efficiency, w/ financial factors	Avg efficiency, w/ environmental factors
ATL	1.00	1.00	1.00	**SLC**	0.85	0.85	0.68
JFK	1.00	1.00	1.00	**SAN**	0.84	0.84	0.84
LAX	1.00	1.00	1.00	**DEN**	0.84	0.84	0.75
MIA	1.00	1.00	1.00	**AUS**	0.84	0.84	0.73
OAK	1.00	1.00	1.00	**SFO**	0.83	0.82	0.66
ORD	1.00	1.00	0.90	**MCI**	0.82	0.81	0.66
RSW	1.00	0.98	1.00	**DFW**	0.82	0.78	0.79
SMF	1.00	1.00	0.78	**BWI**	0.80	0.79	0.61
SNA	1.00	1.00	0.92	**EWR**	0.79	0.79	0.71
DTW	1.00	1.00	0.64	**IAH**	0.72	0.65	0.59
FLL	1.00	0.90	0.92	**DCA**	0.70	0.67	0.58
HNL	0.98	0.98	0.96	**BNA**	0.70	0.64	0.63
SAT	0.96	0.96	0.75	**MSP**	0.70	0.68	0.66
MCO	0.93	0.89	0.80	**PDX**	0.69	0.68	0.68
IAD	0.93	0.55	0.45	**STL**	0.68	0.68	0.47
TPA	0.92	0.89	0.80	**BOS**	0.67	0.64	0.49
LAS	0.92	0.89	0.83	**CLE**	0.66	0.61	0.42
SJC	0.92	0.87	0.70	**CLT**	0.65	0.63	0.60

PHX	0.91	0.90	0.80	**RDU**	0.65	0.57	0.53
MDW	0.90	0.72	0.88	**PIT**	0.64	0.57	0.43
SEA	0.87	0.87	0.87	**LGA**	0.63	0.63	0.58
MSY	0.86	0.86	0.81	**PHL**	0.58	0.40	0.46
				Average	**0.84**	**0.81**	**0.74**

Table 4.5. Inputs of 44 U.S. Airport, 2015

Airport	AIRCPT	LBRMTR	DEBT	RWY	GATE	LANDCPT
ATL	57509000	570777737	2978917000	7408350	209	155934000
AUS	6967446	154911545	538361072	3187500	25	46643545
BNA	24310789	147408571	148094233	5210400	44	5216946
BOS	24101020	650836172	1845820000	5998800	102	189940870
BWI	107381000	261212889	646275000	3500300	68	72529000
CLE	2116016	157437159	782369999	3746100	50	23775902
CLT	20724000	222631408	737782000	5276850	97	102940000
DCA	27878694	363331434	1073306368	2605950	44	5701762
DEN	36293915	836053860	4071742061	12200000	95	211476528
DFW	38084340	863755265	6232745000	13850500	165	432391524
DTW	71089212	389259366	2085712116	9682150	129	4160309
EWR	16173976	1060990202	0	4158900	121	31716768
FLL	92240810	247323515	1526375000	2550000	63	164274033
HNL	53413849	259109807	1420816570	6639600	70	30598709
IAD	10936274	559581447	3706953632	6435150	139	31926043
IAH	22419627	468574228	1894947834	7560450	123	13976580
JFK	215709773	1398470873	1435938953	8498000	128	55147290
LAS	44523380	608047337	4287115000	6569400	92	8003574
LAX	30171864	1417810296	4157083000	7129100	128	636380037
LGA	149468793	500853983	0	2100600	119	96488230
MCI	14036505	155681657	274777255	4470300	42	3300398
MCO	-471858	484585369	1010470000	7651950	129	68547485
MDW	22431648	257874441	1585418850	3773790	43	8897734
MIA	31574373	943515019	6082900000	6746850	131	26655720
MSP	8680177	377237204	1304180000	6080900	131	131060822
MSY	18535899	90070798	978158698	2565750	35	30618655
OAK	28606868	189865150	224886495	3328650	30	24891994
ORD	199579323	1310829253	7840664039	9891500	185	190699944
PDX	19917049	241136131	673384192	4023750	48	35828062

PHL	26680280	476965137	1361515000	5550150	124	60687729
PHX	18106087	463791713	1499660000	4438350	116	60476468
PIT	7224215	174548415	233716849	6706700	69	10170203
RDU	2515913	132020064	642015000	2982000	45	7928939
RSW	7229881	123288859	300597640	1800000	29	8605313
SAN	11980326	249716607	1356489291	1880000	55	29557161
SAT	24835368	123216964	488880000	3102950	24	26487066
SEA	75595000	520661094	2518431343	4474050	87	75733000
SFO	45486143	983315495	4536390000	7910200	115	208930413
SJC	772430	167535161	1375052000	3300000	33	2152160
SLC	28406048	166150575	0	5173500	83	6435639
SMF	7119	185461134	1041278088	2580450	32	4938806
SNA	546538	141590217	202535651	1071675	22	14164373
STL	9880094	178497127	726010000	6045450	60	22019729
TPA	10878052	246884889	1219658527	3945150	59	58374908

Table 4.6 Outputs of 44 U.S. Airport, 2015

Airport	ACMOVE	DELAY, 10^3	FUEL,kg	EMIS,kg	AIRREV, 10^6	PAX, 10^6	CARGO, 10^6	LANDREV, 10^6	GRANTS, 10^6
ATL	864694	161.18	1319.03	34.82	40.47	49.06	1640.53	336.38	214.16
AUS	117555	26.96	1032.88	25.47	29.73	5.79	199.94	84.55	30.8
BNA	130288	27.76	744.75	16.73	15.05	5.6	104.09	91.83	32.99
BOS	343754	80.21	1301.74	38.74	128.05	16.07	639.88	346.47	121.76
BWI	215132	48.69	1183.55	29.39	61.93	11.41	253.52	116.53	77.43
CLE	102134	20.61	637.27	14.86	33.23	3.99	167.09	91.06	19.6
CLT	502811	122.36	1033.83	26.88	25.12	22.19	283.21	138.96	81.2
DCA	285156	61.33	599.55	12.49	56.29	11.5	6.18	212.82	59.42
DEN	522731	119.55	1132.46	29.17	147.38	27.02	598.82	414.84	106.63
DFW	659852	152.5	1034.33	25.71	111.27	32.46	1756.78	474.91	142.58
DTW	368061	65.54	404.4	9.92	77.43	16.44	447.85	224.02	65.17
EWR	395501	115.68	1289.24	39.92	298	18.79	1619.92	374.67	97.74
FLL	222652	45.4	629.11	17.93	38.01	13.21	220.27	139.69	121.88
HNL	170824	24.8	764.87	26.03	46.21	9.71	1327.22	105.21	46.82
IAD	229308	67.56	926.05	29.31	53.51	10.71	607.52	312.69	77.52
IAH	478795	118.23	677.16	17.44	92.53	20.96	1052.78	231.58	97.88
JFK	427315	123.36	720.92	23.86	426.36	28.31	2826.7	519.94	161.58
LAS	338828	72.96	1036.45	26.13	60.38	21.88	239.31	379.46	113.93
LAX	613794	148.69	1460.77	44.77	289.85	36.11	4492.64	571.45	168.82
LGA	353172	122.81	1132.84	23.94	167.98	14.24	16.4	176.66	83.69

MCI	111685	18.93	887.02	21.83	21.66	5.14	212.93	91.64	20.5
MCO	290780	57.8	1091.2	30.84	41.31	18.83	423.04	313.01	73.18
MDW	187685	49.82	338.68	7.69	47.18	11.12	54.68	103.66	50.97
MIA	369795	84.35	824.71	25.56	111.08	21.38	4381.58	597.04	79.8
MSP	372514	73.5	617.52	15.44	76.91	18.27	495.04	200.72	82.17
MSY	103691	18.54	981.25	22.34	13.63	5.34	110.49	58.11	31.57
OAK	118270	27.09	774.52	21.24	45.87	5.37	1190.48	92.37	41.59
ORD	850501	228.44	960.5	25.02	255.51	38.4	3702.18	541.04	222.04
PDX	181262	28.74	982.92	32.22	43.14	8.06	481.43	152.43	32.18
PHL	383325	103.45	933.84	27.02	75.68	15.31	961.16	260.66	63.07
PHX	390864	76.08	1111.21	27.95	53.03	21.49	657.88	261.1	105.74
PIT	114338	25.16	838.14	22.61	21.7	4.05	176.06	89.6	27.68
RDU	120534	31.08	709.34	16.18	13.47	4.81	178.05	86.19	21.57
RSW	67643	12.5	671.51	18.19	15.37	4.16	33.88	65.32	16.59
SAN	175430	31.81	1032.53	27.22	28.69	9.71	324.38	139.81	38.52
SAT	91866	21.26	931.32	22.11	12.4	4.21	281.81	57.37	36.01
SEA	373636	67	837.35	25.85	96.75	21.11	895.17	318.76	103.16
SFO	396880	100.06	1063	31.43	184.78	24.02	1198.52	538.24	93.2
SJC	94556	20.91	913.53	22.88	14.17	4.77	112.54	96.33	19.36
SLC	236679	40.2	388.48	9.87	26.69	10.83	405.28	86.56	56.12
SMF	94791	15.01	980.98	25.72	23.81	4.63	140.45	127.88	30.44
SNA	84536	18.72	706.26	16.24	17.9	4.79	45.2	99.08	28.17
STL	163527	33.26	1281.15	35.03	65.81	6.25	167.14	70.08	47.47
TPA	158625	28.64	725.97	19.44	19.18	9.26	220.54	174.1	62.7

CHAPTER 5

CONCLUSION

This study investigates the efficiency performance of 44 U.S. airports throughout the period of 2011-2015 with the consideration of their attention toward sustainable development principles, financially, environmentally, and service-related. It considers both profit-targeting and social-welfare nature, since the balance of these two are of great importance in managing an airport - making profit for its own expansion and minimizing the fuel consumption and pollutants emissions while generating traffic.

A model framework based on a network DEA structure with financial and environmental constraints is developed. This approach makes it possible to have a comprehensive and unique consideration of current sustainability situation of airports as a crucial part of air transportation system. The model reflects more realistically airport production in several aspects: 1) decomposing airport production into airside and landside stages; 2) reassigned financial factors, both aeronautical and non-aeronautical, to two operation stages accordingly, and further separating the factors to investment and revenues; and 3) take fuel consumption and hazardous emissions into consideration, as an alternative of delayed time or fights in previous studies. Using the model, the productive efficiency score is computed for 44 airports in the U.S. and compared vertically over the five years.

This study raises the possibility of carrying out several other studies in the future. Financial factors in this study are approximated from the Report-127 in the FAA database, therefore, more accurate information on varies of funds and investment can be used to reduce potential bias arising from the approximation. Additionally, dataset that exact match between aircraft tail number and equipped engine can significantly improve the accuracy of environmental factors, which is available for only U.S. registered aircraft currently. Future studies can also concentrate on exploring alternative network structures and input/output variable choice in order to determine airports' productivity.

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