Productive and Operational Efficiency of US Airports with Joint Consideration of both Desirable and Undesirable Outputs

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ABSTRACT

In the past few decades, as the aviation industry has become more competitive, airports have had to adapt their operations to become more productive. A number of studies have been conducted comparing productivity and operational efficiency of airports around the world. This study differs from previous work in that both desirable and undesirable outputs are considered. The result of the analysis is an efficiency measure that provides a comprehensive and practical basis for airport comparisons. A directional output distance function, rather than the traditional Data Envelopment Analysis (DEA), was applied to assess operational efficiency at 56 US airports from 2000 - 2003. Airports were modeled as production units with three common physical inputs; i.e., land area, number of runways, and area of runways, and three desirable outputs; i.e., passengers, number of non-delayed flights, and cargo throughput. Two undesirable outputs were also considered; i.e., number of delayed flights and time delays. For comparison purposes, a DEA model without consideration of undesirable outputs was also estimated.

As expected, when undesirable outputs were not considered, the resulting efficient airports also tended to be the most congested. These efficient but congested airports were generally either extremely busy, under slot controls, or facing regulatory constraints regarding expansion. On the other hand, if delayed flights and time delays are taken into assessment, a larger number of airports are identified as efficient because they are credited for reducing the two undesirable outputs. The results indicate that there may be a balance between quantity and quality of outputs in the achievement of efficient outcomes; i.e., airports can trade-off utilization levels for reduced flight and time delays.

INTRODUCTION

As aviation becomes more competitive, practitioners and researches have become increasingly concerned with productivity of airport investments. These days, with competition over scarce capital, airport managers often have incentives to increase productivity. They may use several key indicators, such as passenger traffic, aircraft movements, cargo throughput, and financial ratios as benchmarks to assess performance. These indicators have appeared routinely in aviation trade publications. Furthermore, there have been many academic studies of airport productivity, including case studies, conducted in recent years (*1 - 10*).

In studying airport productivity, it is necessary to develop relationships between the inputs and outputs of an airport system. In previous studies, inputs have included production factors, such as land area, number of runways, terminal area, operating expenses, and labor units. Typical outputs have been passengers, aircraft movements, and cargo throughput. Based on our own experience (*11*), and a reading of other studies (*1 - 10*), we observe that the results tend to identify busy airports as the most efficient. However, frequently, these “efficient” airports are also congested. Busy airports may be labeled as efficient because the selected set of outputs emphasizes quantity of traffic; i.e., desirable (good) outputs, and leaves out undesirable (bad) outputs.

There are always externalities inherent in airport operations, notably delay and noise, that increase, *ceteris paribus*, with airport volume. In fact, these externalities are also outputs from the production process, although undesirable (bad). In Figure 1, density of aircraft movements (number of flights per runway area) is plotted against average delay per passenger, computed for 56 major US airports during 2000 – 2003.[2] This graph shows that higher density of traffic is associated with higher average delay. According to these results, airport efficiency comes at the cost of high numbers of delays. This situation may be undesirable from the viewpoints of airports, regulators, airlines, and passengers.

This study reevaluates airport productivity and operational efficiency by taking both desirable and undesirable outputs into consideration. Based on our analysis, we are able to compare the efficiency of airports after accounting for undesirable outputs, namely delays. The rest of the paper is organized in the following sections. Next, we review literature relevant to airport productivity. This is followed by a description of our study's methodology. We then describe the data set used for the analysis, followed by a discussion of our results, before closing with the conclusions.

LITERATURE REVIEW

Before we begin to assess the operational efficiency of airports, there are two main questions that need to be answered. First, the methodology should be able to consider multiple inputs and outputs simultaneously. Second, the methodology should be able to assess efficiency when both desirable and undesirable outputs are produced.

Regarding the first question, there are generally two approaches; i.e., parametric and non-parametric. The parametric approach combines multiple inputs and outputs into one composite input and one composite output; then fits the inputs and outputs, *a priori*, with a production function, such as linear or logarithmic. As a result, for a given set of inputs, it is possible to estimate the probable output level. The major question regarding this approach is how to create the composite input and output. Generally, weights are assigned to each input and output so that they can be transformed into the same unit of measurement. Price may be a good representative weight for outputs and cost for inputs. However, weighting outputs by price may not be easily accomplished for non-market outputs, such as delays and noise. Additionally, obtaining non-subjective weights and a suitable production function may be difficult. The alternative approach is to use non-parametric methods such as Data Envelopment Analysis (DEA) that do not require assumptions regarding associated weights and functional forms. Many studies have adopted this approach.

However, all of the previous non-parametric studies measuring airport productivity, with one exception (*12*), have ignored undesirable outputs. A potential consequence of this omission is that the results show a strong association between efficiency and congestion. It may be that after the inclusion of undesirable outputs, that the busy airports are no more efficient than airports with lower utilization and a lower number of flight delays.

In fact, traditional DEA techniques may not be fully applicable where there is joint production of desirable and undesirable outputs (*13 – 16*). The reason lies in its mathematical mechanism for determining whether an airport is on the efficient frontier. In general, DEA

[2] Note, for the purposes of this study, we use delay data from the National Aviation System (NAS). These data include delays due to a large variety of conditions, including heavy traffic volume and air traffic control, but exclude other delays, such as those due to extreme weather. For future research, we also intend to use delay data from the Bureau of Transportation Statistics (BTS). The BTS data cover a wider variety of delay causes, but also have drawbacks, in that the data are collected for a more limited number of airports and require self-reported information from airlines.

models would typically seek to maximize the expansion of both desirable and undesirable outputs, rather than expand only the desirable outputs and contract the undesirable outputs. In reality, an airport manager never wishes to expand both number of passengers and delays simultaneously. To account for joint production characteristics, we resort to the directional output distance function, described below. To the best of our knowledge, this approach has been applied to airport productivity problems only once (*12*). In that study, the author considered aircraft noise (valued in New Taiwan dollars) as the lone undesirable output.

DIRECTIONAL OUTPUT DISTANCE FUNCTION

Let $y \in R_M^+$ denote a vector of desirable outputs, $b \in R_J^+$ denote a vector of undesirable outputs, and $x \in R_N^+$ denote a vector of inputs. In our context, we examine production of K airports with (x^k, y^k, b^k). We define the production possibility set as the set of desirable and undesirable outputs that can be produced from a given level of inputs which is represented by:

$$P(x) = \{(y,b) : x \text{ can produce } (y,b)\} \tag{1}$$

We assume the following fairly general conditions:

- Null-jointness: If $(y,b) \in P(x)$, and $b = 0$, then $y = 0$. In other words, if an output vector (y,b) is feasible and there are no undesirable outputs produced, then under the null jointness assumption, only zero desirable outputs can be produced. Equivalently, if some positive amount of the desirable outputs is produced, then undesirable outputs must also be produced.
- Weak disposability between desirable and undesirable outputs: If $(y,b) \in P(x)$ and $0 \le \theta \le 1$, then $(\theta y, \theta b) \in P(x)$. This assumption implies that if undesirables are to be decreased, then the desirable outputs must also be decreased, holding inputs, x, constant. In other words, both desirable and undesirable outputs may be proportionally contracted, but undesirable outputs cannot, in general, be freely disposed. This assumption models the idea that there is a cost to 'cleaning up' undesirable outputs.
- Strong disposability of desirable outputs and of inputs: If $(y,b) \in P(x)$, then for $y' \le y, (y',b) \in P(x)$, and for $x' \ge x, (y',b) \in P(x) \subseteq P(x')$. Strong disposability of desirable outputs implies that it is possible to freely dispose of desirable outputs and still remain in $P(x)$. Strong disposability of inputs implies that an increase in any one input does not reduce the size of $P(x)$.
- $P(x)$ is convex and compact and the condition of no free lunch is satisfied. This implies: $P(0) = (0,0)$.

Based on the above assumptions, we can construct the production technology for an individual airport, represented by the following output set:

$$P(x^k) = \{(y,b): \tag{2}$$

$$\sum_{k \in K} \lambda_k y_{km} \geq y_{km}, m = 1,..........., M,$$

$$\sum_{k \in K} \lambda_k b_{kj} = b_{kj}, j = 1,............, J,$$

$$\sum_{k \in K} \lambda_k x_{kn} \leq x_{kn}, n = 1,.............., N,$$

$$\lambda_k \geq 0, k = 1,.........., K\}$$

In Figure 2, we construct $P(x)$ from four hypothetic airports; i.e., A, B, C, and D. These airports are assumed to use the same amount of inputs, x, but produce different amounts of desirable output, y, and undesirable output, b. Since we will make use of linear programming methods to estimate efficiency, $P(x)$ is drawn as piecewise linear. The production possibility set, $P(x)$, is bounded by 0ABCD.

This figure illustrates how the assumptions are used in the construct. The origin is included in $P(x)$ because of the null-jointness assumption. The assumption of weak disposability implies that for any point on, or inside, $P(x)$, a proportional contraction in both (y,b) is feasible. The vertical line segment, CD, occurs because of strong disposability between desirable outputs. The negative slope portion, BC, is possible because traffic may be blocked due to a long queue of delayed flights, hence reducing throughput. Note that if we ignore undesirable outputs, $P(x)$ will be the area bounded by 0GBCD.

Next we are interested in estimating the level of inefficiency for all airports. In other words, we would like to know how far each airport is from the efficient frontier. For example, suppose we were to check how far Airport E is away from the frontier along the diagonal line, EJ, or in the direction of vector $g = (g_y, -g_b)$. This measurement is justified on the premise that we seek to maximize the expansion of desirable outputs and the contraction of undesirable outputs simultaneously. The directional output distance function is then formulated as follows:

$$\vec{D}_0(x, y, b; g_y, -g_b) = \max\{\beta : (y + \beta g_y, b - \beta g_b) \in P(x)\} \tag{3}$$

To assess the level of inefficiency for an individual airport, we then solve the following linear programming problem:

$$\begin{aligned}
&\max \beta \\
&s.t. \\
&\sum_{k \in K} \lambda_k y_{km} \geq y_{km} + \beta g_y, m = 1,..........., M, \\
&\sum_{k \in K} \lambda_k b_{kj} = b_{kj} - \beta g_b, j = 1,............, J, \\
&\sum_{k \in K} \lambda_k x_{kn} \leq x_{kn}, n = 1,.............., N, \\
&\lambda_k \geq 0, k = 1,.........., K\}
\end{aligned} \tag{4}$$

The directional output distance function, $\vec{D}_0(x, y, b; g_y, -g_b)$, or an optimal β, takes the minimum value of zero when it is not possible to expand the desirable outputs and contract undesirable outputs. This means that the airport is efficiently producing at the maximum possible desirable outputs. A higher value of β indicates a higher level of inefficiency. Selection of the directional vector $g = (g_y, -g_b)$ is rather flexible. For example, using $g = (0, b)$ means that we measure the level of inefficiency along the horizontal line EI, projected to the frontier at H. Meanwhile, using $g = (y, 0)$ yields the projection to the frontier at K. Using $g = (1, -1)$ gives the same weight to both inputs and outputs. In this study, we use $g = (y, -b)$ which means that the projected direction depends on an individual airport's desirable and undesirable outputs.

The terms $y_{km} + \beta g_y$ and $b_{kj} - \beta g_b$ in (4) give the projection of desirable and undesirable outputs onto the frontier. For an efficient airport with $\beta = 0$, the terms are simply (y_{km}, b_{kj}) or the current level of outputs. For inefficient airports, these terms represent the maximum possible production outputs or highest potential outputs that an airport could have produced. The results may provide benchmarks for airports to improve operational efficiency. However, as is shown below, the selection of an appropriate set of outputs is crucial to the reasonableness of the benchmark.

DATA

We are interested in assessing operational efficiency of major US airports. Due to readily available data, some samples are taken from our previous airport productivity study (*11*). Additional data are also collected in order to increase the sample size. In total, there are 56 airports in our dataset, a relatively high number compared to most previous studies (*1 – 10, 12*). For each airport, the methodology requires data on inputs and outputs. Selection of inputs and outputs for the analysis largely depends on the focus of the management and on the availability of such data. The ideal is to have a common but comprehensive set of inputs and outputs across all airports so that airport efficiency can be fairly compared.

In this study, three common physical inputs are considered; i.e., land area, number of runways, and runway area. Runway area is included to reflect the effect of design configuration, such as length, width, and separation, on productivity. On the output side, it is assumed that an airport manager aims at producing three desirable outputs; i.e., passengers, non-delayed flights and, cargo throughput. By nature of airport operations, there are also at least two undesirable outputs produced, notably delayed flights and time delays.

A panel data of the 56 airport for the years 2000 – 2003 was analyzed. Data on inputs are mainly from the Airport Master Record database (*20*). Since these data are updated on a regular basis, we checked to see if there were major changes in inputs at any of the airports during the period of analysis. After verification with airport websites, airport managers, and reports, it was found out that there were few changes. For example, runway 15R/33L at George Bush Intercontinental (IAH) was expanded and extended to 10,000' x 150' in 2002. Detroit Metropolitan Wayne County (DTW) opened its 6th runway on December 11, 2001. The data for these inputs have been edited accordingly. For example, for the Detroit Metropolitan Wayne County Airport, we concluded that it had 5 and 6 runways in 2001 and 2002, respectively.

The airports in our sample are all well-established and have served their respective markets for a number of years. This knowledge helps to relieve concerns about possible efficiency drops during the early years of airport operation due to initial lumpy investments. As noted, only at a few airports was there construction of new runways and/or runway extensions during the period of data collection.

Data on number of passengers, aircraft movements (aggregation of delayed and non-delayed flights), and cargo throughput are available in annual statistics reports published by the Airports Council International (*17 – 19*). Number of delayed flights and total time delays can be queried from an on-line Federal Aviation Administration (FAA) database (*21*). Table 1 shows the list of airports along with International Civil Aviation Organization (ICAO) airport codes, as well as corresponding outputs for the airports in 2003. The data are ordered by number of annual passengers. Descriptive statistics for our panel data are shown in Table 2. Number of non-delayed flights is simply the difference between aircraft movements and number of delayed flights. Non-zero minimum undesirable outputs indicate that all airports experienced some delays. Large standard deviations indicate that airports are different in both scale and scope of operations.

RESULTS AND DISCUSSION

For each year, the directional distance output function in (4) is solved 56 times; i.e., one time for each airport. In order to see the effect of the inclusion of undesirable outputs on operational efficiency scores, we also solve a DEA model that ignores undesirable outputs. In such case, number of aircraft movements, regardless of delay status, are considered as desirable outputs. The resulting scores are shown in Table 3. An efficient airport must yield a score of zero, implying that increases in desirable outputs or decreases in undesirable outputs and inputs from current levels, are not necessary to be on the efficient frontier. In Table 3, the efficient airports are emphasized with bold typeface.

When delayed flights and time delays are ignored, the results are typical of those reported in past studies (*1 – 11*), such that operational efficiency is associated with busy airports. As is evident from the 2003 data, six efficient airports are also very busy. For examples, Hartsfield-Jackson Atlanta (ATL) and Memphis (MEM), respectively, are the busiest airports in the world in terms of number of passenger and cargo throughput. On the contrary, when undesirable outputs are also considered, the results show a greater number of efficient airports, including less-congested airports. In 2003, 28 airports are identified as efficient when undesirable outputs are considered. The additional 22 airports received credit due to their relatively low numbers of delayed flights and total time delays.

The results indicate that there may be a balance between quantity and quality of outputs in the achievement of efficient outcomes; i.e., airports can trade-off utilization levels for reduced flight and time delays. For certain stakeholders, this option may be an optimal strategy. Passengers and shippers receive service with fewer flight delays. The FAA, as the regulator, has less concern about congestion and safety. Meanwhile, airport managers are able to balance traffic volume with customer satisfaction. By all accounts, the inclusion of undesirable outputs in the analysis appears to provide a fairer assessment of airport efficiency.

Based on our analysis, we computed maximum possible production outputs for the two cases; i.e., with and without consideration of undesirable outputs, as shown in Table 4. For each case, we also computed the percentage increase from current levels of outputs. For example, without considering delayed flights and time delays, Albuquerque International (ABQ) had the potential to produce 54,411,318 passengers rather than 6,051,879 that was actually produced in 2003, a 799% increase in passengers. However, if ABQ were to produce this high output, it is likely that delayed flights and time delays would be very high. However, after consideration of delayed flights and time delays, the maximum possible output at ABQ is just 6,935,011 passengers, or a 14.6% percent increase over the current level. In general, ignoring undesirable outputs may yield unrealistic maximum possible production outputs. After consideration of undesirable outputs, based on our DEA results, it is suggested that the 56 airports in our dataset have the potential to increase passengers, aircraft movements and cargo throughput by 23.03%, 20.19%, and 34.54%, respectively. If the undesirable outputs are not considered, the increases are 133.50%, 90.98% and 363.68%, respectively. The numbers are shown at the end of Table 4.

CONCLUSIONS

Given the competitive forces in all aspects of the aviation industry, airports have had to adapt their operations to increase efficiency. As a result, airport managers have become increasingly enthusiastic about enhancing their airport's productivity. A number of studies have been conducted comparing productivity and operational efficiency of airports around the world during the past decade. This study differs from most of the previous work in that both desirable and undesirable outputs are considered. The result of the analysis is an efficiency measure that provides a comprehensive and practical basis for airport comparisons. For this study, we adopted the directional output distance function, rather than traditional Data Envelopment Analysis, due to its ability to incorporate undesirable factors. The model was applied to assess operational efficiency at 56 US airports from 2000 - 2003. Airports were modeled as production units with three common physical inputs; i.e., land area, number of runways, and area of runways. Given these inputs, it was assumed that an airport manager's aim was to produce three desirable outputs; i.e., passengers, number of non-delayed flights, and cargo throughput. However, given the nature of airport operations, two undesirable outputs are also produced; i.e., number of delayed flights and time delays. For comparison purposes, we also estimated a DEA model without consideration of undesirable outputs.

As expected, when undesirable outputs are not considered, the resulting efficient airports tend to also be the most congested. These efficient but congested airports are generally either extremely busy, under slot controls, or facing regulatory constraints regarding expansion. From a benchmarking perspective, it is questionable whether inefficient airports should try to emulate their efficient counterparts. On the other hand, if delayed flights and time delays are taken into assessment, a larger number of airports are identified as efficient because they are credited for reducing the two undesirable outputs. The results seem to be encouraging such that airports do not necessarily have to be busy and/or congested to be regarded as efficient. Airports need only to serve a sufficiently high traffic volume while maintaining a good quality of service by keeping delays as low as possible. In our opinion, the model results, after the inclusion of undesirable outputs, are reasonable and practical. Moreover, the estimated maximum possible production outputs are also reasonable. The results indicate potential increases of traffic from current levels at around 23%, 20% and 35% for passengers, aircraft movements and cargo throughput, respectively, as compared to 133%, 91%, and 364% when undesirable outputs are ignored. The lower maximum throughput with the model that considers undesirable outputs represents the tradeoff that an airport has to bear in exchange for higher quality of service.

There are a number of potential extensions to this paper that could be conducted in future research. As we showed, different sets of production factors and outputs can lead to very different results. A reasonable question is how to choose a set of input/output factors that yields robust results, yet is meaningful for management purpose. Although this study has included a number of reasonable inputs and outputs, other potentially useful factors have been excluded. For example, on the input side, factors that could be added include the number of available airport gates and a measure of passenger terminal space. On the output side, a measure of noise pollution could be included as an undesirable output. In addition, the measurement of delays could be expanded to encompass a wider number of delay causes.

REFERENCES

1. Gillen D., Lall A., Developing Measures of Airport Productivity and Performance: an Application of Data Envelopment Analysis, Transportation Research Part E, Volume 33, Number 4, December 1997, pp. 261 – 273.
2. Bazargan M., Vasigh B., Size versus Efficiency: a Case Study of US Commercial Airports, Journal of Air Transport Management, Volume 9, Issue 3, May 2003, pp. 187 – 193.
3. Sarkis J., An Analysis of the Operational Efficiency of Major Airports in the United States, Journal of Operations Management, Volume 18, Issue 3, April 2000, pp. 335 – 351.
4. Sarkis J., Talluri S., Performance Based Clustering for Benchmarking of US Airports, Transportation Research Part A, Volume 38, Issue 5, June 2004, pp. 329 -346.
5. Martin J. C., Roman C., An Application of DEA to Measure the Efficiency of Spanish Airports Prior to Privatization, Journal of Air Transport Management, Volume 7, Issue 3, May 2001, pp. 149 – 157.
6. Pacheco R.R., Fernandes E., Managing Efficiency of Brazilian Airports, Transportation Research Part A, Volume 37, Issue 8, October 2003, pp. 667 – 680.
7. Fernandes E., Pacheco R.R., Efficient Use of Airport Capacity, Transportation Research Part A, Volume 36, Issue 3, March 2002, pp. 225 – 238.
8. Pels E., Nijkamp P., Rietveld P., Inefficiencies and Scale Economies of European Airport Operations, Transportation Research Part E, Volume 39, Issue 5, September 2003, pp. 341 – 361.
9. Oum, T H; Yu, C., Measuring Airports' Operating Efficiency - A Summary of the 2003 ATRS Global Airport Benchmarking Report, Transportation Research Part E: Logistics and Transportation Review, Vol. 40, No. 6, Nov. 2004, pp. 515-532.
10. Adler N., Berechman J., Measuring Airport Quality from the Airlines’ Viewpoint: an Application of Data Envelopment Analysis, Transport Policy, Volume 8, Issue 3, Jul 2001, pp. 171 – 181.
11. Pathomsiri S., Haghani A., Dresner M., Windle R. J., Measurement and Determination of Airport Productivity in Competitive Markets, *Transportation Research Board 85th Annual Meeting Compendium of Papers (CD-ROM)*, Washington DC, January 2006.
12. Ming-Miin Yu, Measuring Physical Efficiency of Domestic Airports in Taiwan with Undesirable Outputs and Environmental Factors, Journal of Air Transport Management 10, 2004, pp. 295 – 303.

13. Seiford L.M., Zhu J., Modeling Undesirable Factors in Efficiency Evaluation, European Journal of Operational Research 142, 2002, pp. 16 – 20.

14. Färe R., Grosskopf S., Modeling Undesirable Factors in Efficiency Evaluation: Comment, European Journal of Operational Research 157, 2004, 242 - 245.

15. Seiford L.M., Zhu J., A Response to Comments on Modeling Undesirable Factors in Efficiency Evaluation, European Journal of Operational Research 161, 2005, pp. 579 – 581.

16 Färe R., Grosskopf S., New Directions: Efficiency and Productivity, Kluwer Academic Publishers, 2004.

17. Airports Council International, Worldwide Airport Traffic Report – 2001, July 2002.

18. Airports Council International, Worldwide Airport Traffic Report – 2002, June 2003.

19. Airports Council International, Worldwide Airport Traffic Report – 2003, June 2004.

20. Federal Aviation Administration, Airport Data (5010), http://www.faa.gov/arp/safety/5010/index.cfm?nav=safedata, Accessed March 1, 2004.

21. Federal Aviation Administration, Operational Network (OPSNET), http://www.apo.data.faa.gov/faaopsnetall.htm, Accessed on August 29, 2005.

TABLE 1 List of 56 Major US Airports under Consideration and their Outputs in 2003

	Airport Name	Airport Code	Total Passengers	Aircraft Movements	Cargo (ton)	Delayed Flights	Total Time Delays (min)
1	Hartsfield-Jackson Atlanta International	ATL	79,086,792	911,723	798,501	37,520	1,543,038
2	O'Hare International	ORD	69,508,672	928,691	1,510,746	69,185	3,840,760
3	Los Angeles International, CA	LAX	54,982,838	622,378	1,833,300	2,200	97,004
4	Dallas/Fort Worth International, TX	DFW	53,253,607	765,296	667,574	9,423	354,234
5	Denver International, CO	DEN	37,505,138	499,794	325,350	1,325	44,066
6	Phoenix Sky Harbor International, AZ	PHX	37,412,165	541,771	288,350	11,800	298,077
7	McCarran International, NV	LAS	36,285,932	501,029	82,153	6,697	255,334
8	George Bush Intercontinental, TX	IAH	34,154,574	474,913	381,926	15,989	478,604
9	Minneapolis/St. Paul International, MN	MSP	33,201,860	510,382	315,987	7,333	266,731
10	Detroit Metropolitan Wayne County, MI	DTW	32,664,620	491,073	220,246	4,842	154,092
11	John F. Kennedy International, NY	JFK	31,732,371	280,302	1,626,722	6,085	190,827
12	Miami International, FL	MIA	29,595,618	417,423	1,637,278	4,864	125,557
13	Newark Liberty International, NJ	EWR	29,431,061	405,808	874,641	24,649	1,443,044
14	San Francisco International, CA	SFO	29,313,271	334,515	573,523	9,310	400,617
15	Orlando International, FL	MCO	27,319,223	295,542	193,037	1,242	49,153
16	Seattle Tacoma International, WA	SEA	26,755,888	354,770	351,418	1,984	53,148
17	Philadelphia International, PA	PHL	24,671,075	446,529	524,485	13,627	603,247
18	Charlotte/Douglas International, NC	CLT	23,062,570	443,394	140,085	3,315	110,594
19	Boston Logan International, MA	BOS	22,791,169	373,304	363,082	3,852	176,220
20	LaGuardia, NY	LGA	22,482,770	374,952	28,402	17,898	952,634
21	Covington/Cincinnati/Northern Kentucky International, KY	CVG	21,228,402	505,557	392,695	6,980	251,496
22	Lambert-St. Louis International, MO	STL	20,427,317	379,772	115,574	4,788	203,553
23	Baltimore/Washington International, MD	BWI	20,094,756	299,469	235,576	1,736	104,975
24	Honolulu International, HI	HNL	19,732,556	319,989	421,930	13	437
25	Salt Lake City International, UT	SLC	18,466,756	400,452	216,870	772	29,183
26	Midway International, IL	MDW	18,426,397	328,035	23,266	4,994	237,807
27	Fort Lauderdale - Hollywood International, FL	FLL	17,938,046	287,593	156,449	3,893	150,190
28	Washington Dulles International, VA	IAD	16,767,767	335,397	285,352	5,845	310,871
29	Tampa International, FL	TPA	15,523,568	233,601	93,457	1,130	43,217
30	San Diego International, CA	SAN	15,260,791	203,285	135,547	779	31,318
31	Pittsburg International, PA	PIT	14,266,984	361,329	121,536	710	33,555

	Airport Name	Airport Code	Total Passengers	Aircraft Movements	Cargo (ton)	Delayed Flights	Total Time Delays (min)
32	Ronald Reagan Washington National, DC	DCA	14,214,803	250,802	5,774	1,746	93,764
33	Oakland International, CA	OAK	13,548,363	342,871	597,383	304	10,599
34	Portland International, OR	PDX	12,395,938	267,052	239,265	180	4,753
35	Memphis International, TN	MEM	11,437,307	402,258	3,390,515	1,575	54,118
36	Mineta San Jose International, CA	SJC	10,677,903	198,082	108,622	227	14,392
37	Cleveland Hopkins International, OH	CLE	10,555,387	258,460	95,761	1,467	57,693
38	Kansas City International, MO	MCI	9,715,411	170,758	136,687	36	1,822
39	Louis Armstrong New Orleans International, LA	MSY	9,275,690	137,312	80,831	218	10,312
40	John Wayne, CA	SNA	8,535,130	350,074	12,050	1,599	69,001
41	William P. Hobby, TX	HOU	7,803,330	242,635	5,775	551	26,809
42	Ontario International, CA	ONT	6,547,877	146,413	518,710	201	9,290
43	Port Columbus International, OH	CMH	6,252,061	237,979	10,766	64	2,884
44	Albuquerque International Sunport Airport, NM	ABQ	6,051,879	221,003	71,599	41	2,401
45	Palm Beach International, FL	PBI	6,010,820	171,692	18,300	1,856	98,659
46	Jacksonville International, FL	JAX	4,883,329	121,143	70,650	100	5,994
47	Anchorage International, AK	ANC	4,791,431	277,361	2,102,025	196	5,381
48	Bob Hope, CA	BUR	4,729,936	178,079	44,654	177	11,419
49	Norfolk International, VA	ORF	3,436,391	121,373	32,283	43	3,339
50	Long Beach, CA	LGB	2,875,703	338,807	50,873	80	4,133
51	Birmingham International, AL	BHM	2,672,637	154,849	34,184	68	5,781
52	Pensacola Regional, FL	PNS	1,361,758	127,197	4,569	2	107
53	Palm Spring International, CA	PSP	1,246,842	93,068	103	36	4,819
54	Jackson International,	JAN	1,215,093	79,377	10,957	1	34
55	Santa Barbara, CA	SBA	752,762	152,485	2,825	51	2,912
56	Stewart International, NY	SWF	393,530	112,284	19,024	7	197
	Total		1,094,725,865	18,781,482	22,599,243	295,606	13,334,196

TABLE 2 Descriptive Statistics of Sample 2000 – 2003

Statistics	Input			Desirable Outputs			Undesirable Outputs	
	Land area (acre)	Number of runways	Runway area (acre)	Total passengers	# of non delayed flights	Cargo throughput (ton)	# of delayed flights	Time delays (minutes)
Minimum	501	1.00	24.60	362,017	79,376	74	1	20
Maximum	33,422	7.00	305.87	80,162,407	874,203	3,390,800	96,346	5,398,921
Range	32,921	6.00	281.26	79,800,390	794,827	3,390,726	96,345	5,398,901
Mean	4,381	3.35	104.21	20,009,558	343,324	401,667	5,818	259,558
Median	2,650	3.00	99.56	16,225,655	326,086	171,349	1,355	57,200
Standard deviation	5,298	1.21	51.65	16,924,416	176,881	591,702	11,917	611,968

TABLE 3 Efficiency Scores for With and Without Consideration of Undesirable Outputs

Airport Code	2000		2001		2002		2003	
	w/o	w	w/o	w	w/o	w	w/o	w
ABQ	2.6026	0.2034	2.3279	**0.0000**	2.1394	**0.0000**	2.5656	0.1459
ANC	0.2314	**0.0000**	0.0506	**0.0000**	0.2719	**0.0000**	0.1607	**0.0000**
ATL	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
BHM	2.0490	**0.0000**	1.8211	**0.0000**	1.8425	**0.0000**	1.7062	**0.0000**
BOS	0.9495	0.5044	1.0133	0.5901	1.1142	0.5707	1.1994	0.5366
BUR	1.4154	0.0108	1.3685	**0.0000**	1.2516	**0.0000**	0.9675	**0.0000**
BWI	1.7999	**0.0000**	1.6086	**0.0000**	1.6914	**0.0000**	1.7879	**0.0000**
CLE	1.4892	0.4323	1.7279	0.4745	2.1009	0.6814	1.9452	0.5329
CLT	0.6097	0.3502	0.4057	0.1170	0.4162	0.2693	0.4722	0.2139
CMH	1.0697	**0.0000**	0.7945	**0.0000**	0.7010	**0.0000**	0.8564	**0.0000**
CVG	0.5496	0.4044	0.7237	0.3123	0.3720	0.2028	0.3526	0.1445
DCA	0.7610	0.0102	0.9666	0.3270	1.0714	0.0831	0.8962	**0.0000**
DEN	1.2381	0.2956	1.2805	0.0263	1.2264	0.0723	1.4323	0.0370
DFW	0.9718	0.7486	0.9455	0.6133	1.0190	0.7380	1.0848	0.5632
DTW	1.2993	0.6938	1.1319	0.4017	1.6990	0.6783	1.7536	0.5520
EWR	0.0892	**0.0000**	0.2055	**0.0000**	0.1541	0.0362	0.1417	**0.0000**
FLL	0.8739	0.5941	0.7538	0.1505	0.7183	0.3577	0.7067	0.3649
HNL	1.6907	**0.0000**	1.6235	**0.0000**	1.5242	**0.0000**	1.5904	**0.0000**
HOU	2.0979	0.3367	2.0753	0.3014	2.0687	0.4408	2.0455	0.3063
IAD	0.6289	0.4777	0.6822	0.2531	0.7778	0.4155	1.0388	0.4017
IAH	0.8696	0.5179	0.8391	**0.0000**	0.9481	0.5056	0.9998	0.6074
JAN	4.2904	**0.0000**	3.6530	**0.0000**	4.1563	**0.0000**	4.4356	**0.0000**
JAX	2.2758	0.5331	2.2219	0.3636	2.4574	0.5007	2.6094	0.4274
JFK	0.3469	0.3099	0.4730	0.2767	0.4246	0.3642	0.3759	0.2737
LAS	0.6444	0.5919	0.6896	0.0045	0.6718	0.2138	0.6483	0.4974
LAX	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
LGA	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
LGB	1.1960	**0.0000**	1.2235	**0.0000**	1.2579	**0.0000**	1.2281	**0.0000**
MCI	2.4069	0.2827	2.1817	0.1933	2.4846	0.2980	2.9981	0.3422
MCO	0.9268	0.2619	1.0137	**0.0000**	1.1632	0.0383	1.1712	0.1094
MDW	0.3364	0.0118	0.2882	**0.0000**	0.1665	**0.0000**	0.1177	**0.0000**
MEM	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**

Airport Code	2000		2001		2002		2003	
	w/o	w	w/o	w	w/o	w	w/o	w
MIA	0.0301	**0.0000**	**0.0000**	**0.0000**	0.0229	**0.0000**	0.1650	**0.0000**
MSP	0.3488	0.1833	0.2947	0.0393	0.2750	0.2002	0.2884	0.1709
MSY	2.6039	0.1553	2.4819	**0.0000**	2.4938	**0.0000**	2.6035	0.1366
OAK	0.5276	**0.0000**	0.5457	**0.0000**	0.6508	**0.0000**	0.7313	**0.0000**
ONT	1.2123	**0.0000**	1.2000	0.2388	1.0546	**0.0000**	1.0359	0.1085
ORD	0.5309	0.2600	0.4958	0.1223	0.4646	**0.0000**	0.4776	**0.0000**
ORF	2.5854	0.2944	2.4231	**0.0000**	2.2075	0.0331	2.2866	0.1202
PBI	2.2824	0.6936	2.1645	0.2441	2.5192	0.6013	2.4350	0.6686
PDX	1.1367	**0.0000**	1.1653	**0.0000**	1.2548	**0.0000**	1.3765	**0.0000**
PHL	0.6512	0.7166	0.6293	0.5415	0.5628	**0.0000**	0.5875	0.6064
PHX	**0.0000**	**0.0000**	0.1491	**0.0000**	0.1590	**0.0000**	0.1739	**0.0000**
PIT	1.2968	0.2264	0.9713	0.1214	1.0942	0.3194	1.5232	0.3257
PNS	2.7395	0.1525	2.4767	**0.0000**	2.0497	**0.0000**	2.0909	**0.0000**
PSP	4.0613	0.4099	3.7163	0.7247	3.5666	**0.0000**	3.0955	**0.0000**
SAN	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
SBA	2.4880	**0.0000**	2.5483	**0.0000**	2.4674	**0.0000**	2.4552	**0.0000**
SEA	0.0821	**0.0000**	0.0873	**0.0000**	0.1816	**0.0000**	0.2607	**0.0000**
SFO	0.7716	0.5650	0.9830	0.4686	1.1199	0.7539	1.2892	0.7767
SJC	0.8666	**0.0000**	0.8341	**0.0000**	1.1352	0.3169	1.3895	**0.0000**
SLC	1.6591	0.6842	1.3735	0.2175	1.1670	0.1123	1.2490	0.1898
SNA	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**
STL	0.3992	**0.0000**	0.3213	0.2189	0.4253	0.3945	0.6358	0.5103
SWF	2.5810	0.0147	2.8170	0.0512	2.4968	**0.0000**	2.9040	**0.0000**
TPA	1.5896	0.4392	1.4895	0.0294	1.6490	0.1627	1.8012	0.3630
Average score	1.1813	0.2208	1.1296	0.1326	1.1591	0.1672	1.2168	0.1792
Number of efficient airports	7	23	7	29	6	29	6	28

Note: An efficient airport has a zero score as labeled by bold typeface. The input set of both without (w/o) and with (w) consideration of undesirable outputs are the same. The output set of w/o cases consist of passengers, aircraft movements, and cargo throughput. The output set of w cases include passengers, non-delayed flights, cargo throughput, delayed flights, and time delays.

TABLE 4 Maximum Possible Passengers, Aircraft Movements and Cargo throughput in 2003

Airport	Total Passengers				Aircraft Movements				Cargo (ton)			
Code	w/o	% add	w	% add	w/o	% add	w	% add	w/o	% add	w	% add
ABQ	54,411,318	799.08	6,935,011	14.59	788,011	256.56	253,241	14.59	331,992	363.68	133,954	87.09
ANC	11,266,457	135.14	4,791,431	0.00	321,940	16.07	277,361	0.00	2,439,876	16.07	2,102,025	0.00
ATL	79,086,792	0.00	79,086,792	0.00	911,723	0.00	911,723	0.00	798,501	0.00	798,501	0.00
BHM	31,529,895	1,079.73	2,672,637	0.00	419,055	170.62	154,849	0.00	233,382	582.72	34,184	0.00
BOS	50,127,482	119.94	35,020,347	53.66	821,054	119.94	569,476	52.55	798,572	119.94	943,554	159.87
BUR	12,125,357	156.35	4,729,936	0.00	350,368	96.75	178,079	0.00	87,856	96.75	44,654	0.00
BWI	59,299,554	195.10	20,094,756	0.00	834,883	178.79	299,469	0.00	656,757	178.79	235,576	0.00
CLE	38,512,358	264.86	16,180,712	53.29	761,211	194.52	394,639	52.69	282,033	194.52	272,944	185.03
CLT	50,223,775	117.77	31,635,406	37.17	652,776	47.22	536,801	21.07	485,352	246.47	334,987	139.13
CMH	35,419,757	466.53	6,252,061	0.00	441,793	85.64	237,979	0.00	347,759	3,130.16	10,766	0.00
CVG	59,315,094	179.41	38,539,652	81.55	683,792	35.26	576,589	14.05	598,876	52.50	449,437	14.45
DCA	26,953,931	89.62	14,214,803	0.00	475,568	89.62	250,802	0.00	37,820	555.01	5,774	0.00
DEN	105,449,056	181.16	38,894,115	3.70	1,215,631	143.23	541,268	8.30	1,064,668	227.24	884,820	171.96
DFW	138,401,886	159.89	83,244,552	56.32	1,595,515	108.48	1,185,676	54.93	1,397,377	109.32	1,043,533	56.32
DTW	115,815,897	254.56	50,696,543	55.20	1,352,208	175.36	756,815	54.11	1,157,774	425.67	710,246	222.48
EWR	33,602,832	14.17	29,431,061	0.00	463,330	14.17	405,808	0.00	998,619	14.17	874,641	0.00
FLL	30,614,102	70.67	24,484,401	36.49	490,823	70.67	389,706	35.51	267,005	70.67	226,674	44.89
HNL	67,258,823	240.85	19,732,556	0.00	828,895	159.04	319,989	0.00	1,092,962	159.04	421,930	0.00
HOU	38,225,686	389.86	10,193,688	30.63	738,946	204.55	316,623	30.49	56,298	874.86	155,183	2,587.15
IAD	59,315,094	253.74	28,154,745	67.91	683,792	103.88	465,444	38.77	598,876	109.87	399,990	40.17
IAH	82,382,075	141.20	54,898,411	60.74	949,711	99.98	743,930	56.65	831,772	117.78	683,510	78.96
JAN	32,391,557	2,565.77	1,215,093	0.00	431,462	443.56	79,377	0.00	309,945	2,728.74	10,957	0.00
JAX	34,088,414	598.06	6,970,535	42.74	437,251	260.94	172,836	42.67	331,134	368.70	104,553	47.99
JFK	43,660,391	37.59	40,417,649	27.37	565,144	101.62	570,852	103.66	2,238,198	37.59	2,071,962	27.37
LAS	62,644,718	72.64	54,332,887	49.74	825,834	64.83	743,556	48.41	523,744	537.52	510,720	521.67
LAX	54,982,838	0.00	54,982,838	0.00	622,378	0.00	622,378	0.00	1,833,300	0.00	1,833,300	0.00
LGA	22,482,770	0.00	22,482,770	0.00	374,952	0.00	374,952	0.00	28,402	0.00	28,402	0.00
LGB	18,447,560	541.50	2,875,703	0.00	754,909	122.81	338,807	0.00	113,352	122.81	50,873	0.00
MCI	58,998,549	507.27	13,040,110	34.22	682,712	299.81	229,168	34.21	594,923	335.24	265,216	94.03
MCO	59,315,094	117.12	30,308,286	10.94	683,792	131.37	380,232	28.66	598,876	210.24	860,080	345.55
MDW	20,595,835	11.77	18,426,397	0.00	366,656	11.77	328,035	0.00	26,160	12.44	23,266	0.00
MEM	11,437,307	0.00	11,437,307	0.00	402,258	0.00	402,258	0.00	3,390,515	0.00	3,390,515	0.00

Airport Code	Total Passengers				Aircraft Movements				Cargo (ton)			
	w/o	% add	w	% add	w/o	% add	w	% add	w/o	% add	w	% add
MIA	34,479,734	16.50	29,595,618	0.00	486,310	16.50	417,423	0.00	1,907,475	16.50	1,637,278	0.00
MSP	54,502,729	64.16	41,741,976	25.72	657,595	28.84	595,117	16.60	529,522	67.58	370,000	17.09
MSY	33,425,071	260.35	10,542,505	13.66	494,806	260.35	156,040	13.64	291,276	260.35	253,278	213.34
OAK	23,456,948	73.13	13,548,363	0.00	593,629	73.13	342,871	0.00	1,034,279	73.13	597,383	0.00
ONT	17,639,338	169.39	7,258,006	10.85	298,085	103.59	162,248	10.82	1,056,052	103.59	574,965	10.85
ORD	103,836,235	49.39	69,508,672	0.00	1,372,264	47.76	928,691	0.00	2,232,328	47.76	1,510,746	0.00
ORF	24,266,049	606.15	3,849,419	12.02	398,907	228.66	135,951	12.01	174,884	441.72	36,821	14.06
PBI	31,753,180	428.27	10,029,678	66.86	589,762	243.50	284,004	65.41	254,710	1,291.86	175,200	857.38
PDX	47,653,087	284.43	12,395,938	0.00	634,652	137.65	267,052	0.00	568,616	137.65	239,265	0.00
PHL	39,166,142	58.75	39,631,312	60.64	708,879	58.75	700,772	56.94	832,637	58.75	842,526	60.64
PHX	49,730,463	32.93	37,412,165	0.00	635,974	17.39	541,771	0.00	415,223	44.00	288,350	0.00
PIT	79,086,792	454.33	18,913,688	32.57	911,723	152.32	478,550	32.44	798,501	557.01	294,139	142.02
PNS	22,273,756	1,535.66	1,361,758	0.00	393,148	209.09	127,197	0.00	157,215	3,340.92	4,569	0.00
PSP	20,361,442	1,533.04	1,246,842	0.00	381,163	309.55	93,068	0.00	95,380	92,501.67	103	0.00
SAN	15,260,791	0.00	15,260,791	0.00	203,285	0.00	203,285	0.00	135,547	0.00	135,547	0.00
SBA	13,319,297	1,669.39	752,762	0.00	526,873	245.52	152,485	0.00	24,526	768.17	2,825	0.00
SEA	38,400,771	43.52	26,755,888	0.00	447,256	26.07	354,770	0.00	443,031	26.07	351,418	0.00
SFO	67,104,325	128.92	52,079,506	77.67	767,885	129.55	600,665	79.56	1,312,916	128.92	1,682,768	193.41
SJC	25,514,563	138.95	10,677,903	0.00	473,312	138.95	198,082	0.00	259,549	138.95	108,622	0.00
SLC	75,830,984	310.64	21,972,152	18.98	900,616	124.90	476,174	18.91	757,846	249.45	402,086	85.40
SNA	8,535,130	0.00	8,535,130	0.00	350,074	0.00	350,074	0.00	12,050	0.00	12,050	0.00
STL	47,057,418	130.37	35,870,254	75.60	621,218	63.58	568,680	49.74	378,835	227.79	299,115	158.81
SWF	34,412,038	8,644.45	393,530	0.00	438,355	290.40	112,284	0.00	335,175	1,661.85	19,024	0.00
TPA	50,687,729	226.52	21,158,079	36.30	654,359	180.12	317,570	35.95	491,146	425.53	649,238	594.69
Total	2,556,136,266	133.50	1,346,865,126	23.03	35,868,503	90.98	22,573,542	20.19	39,051,395	363.68	30,404,043	34.54

Note: w and w/o represent with and without consideration of undesirable outputs respectively. % add is the percentage increase from current level of the corresponding output.

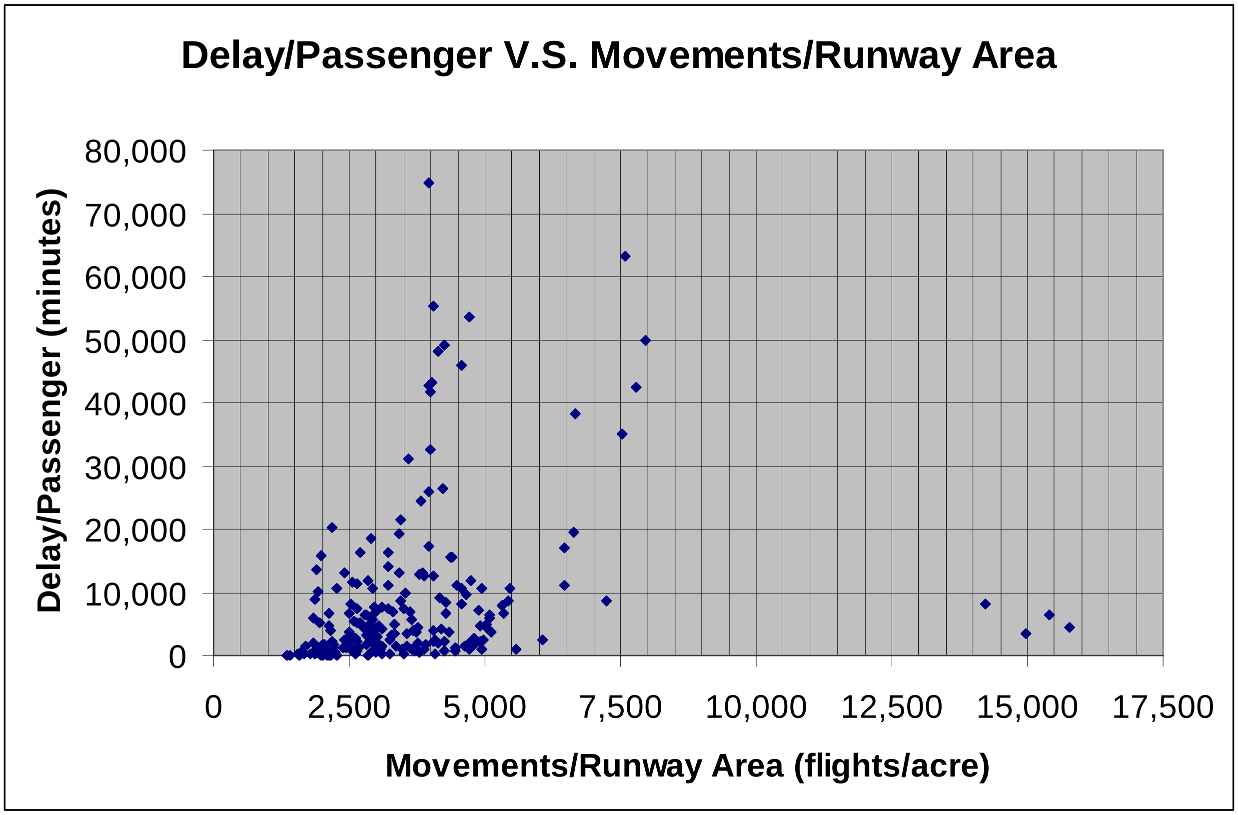

FIGURE 1 Scatter Plot between Delay/Passenger and Density of Movements, 2000 – 2003

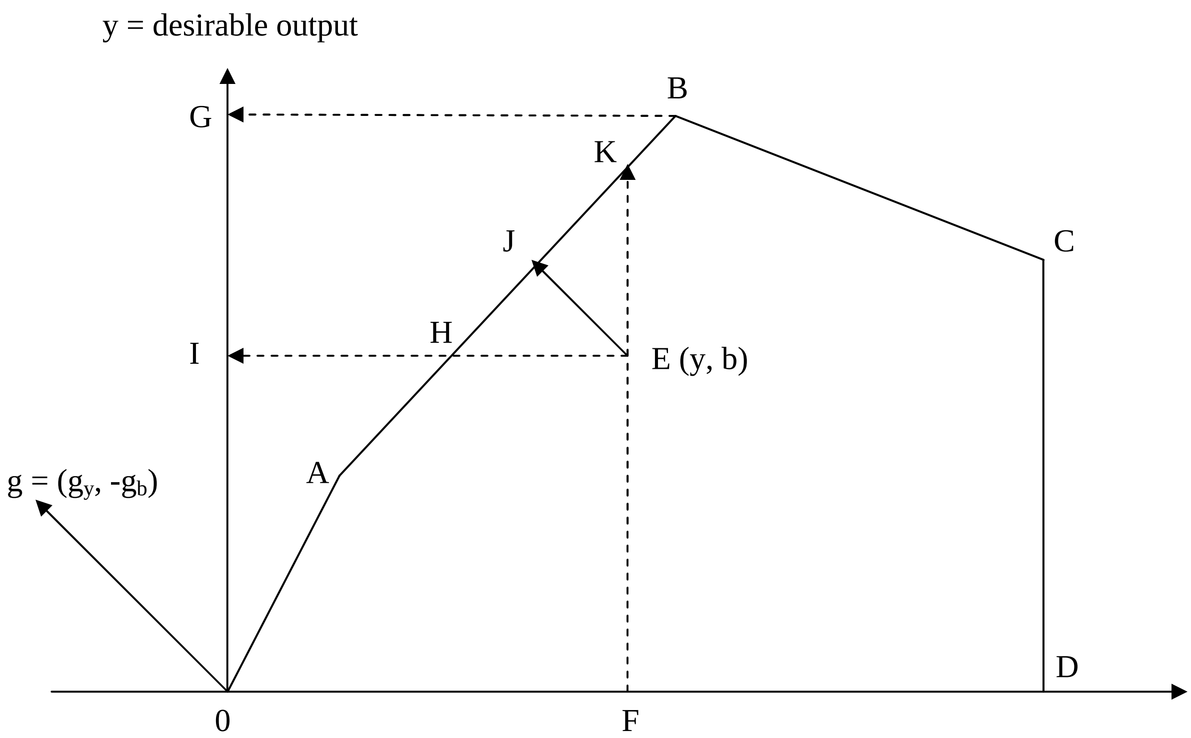

FIGURE 2 Graphical Illustration of Directional Output Distance Function