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A SIMULATION STUDY TO INVESTIGATE RUNWAY CAPACITY USING TAAM

Massoud Bazargan
Kenneth Fleming
Prakash Subramanian

Embry Riddle Aeronautical University
600, S. Clyde Morris Blvd.
Daytona Beach, FL 32114, U.S.A.

ABSTRACT

This study outlines a method to evaluate runway layouts using simulation, to aid in the airport planning and decision making process. As a sample study, the maximum throughput capacities of proposed expansion alternatives at Philadelphia International Airport (PHL), constrained at varying levels, are identified. The objective is to compare these ultimate airport capacities achievable for each of the different layouts to estimate their respective efficiencies in terms of runway system utilization. TAAM (Total Airspace and Airport Modeller) is used to simulate each proposed alternative given its capabilities for modeling at a very high level of detail and closely representing reality in terms of applicable separation standards and air traffic control procedures.

1 INTRODUCTION

Airports hold a key role in the commercial aviation system by allowing airlines and their customers to converge. However, they now face the challenge of meeting the growing demand for air transport. In fact, a lack of airport capacity has been forecasted by the FAA to be one of the most serious constraints to the growth of commercial and private aviation (Wells, 2000). One main reason for this lack of capacity is that airport development projects are enormously capital-intensive and probably some of the largest infrastructure development projects that are undertaken. Hence, it is a challenging task for airports to keep pace with the rapidly growing demand for air transport (Dempsey, 2000). This fact also accentuates the importance of thorough analysis of the various options and their outcomes at the planning stage. Demand-capacity analysis, therefore, plays a key role in defining the physical requirement of airport facilities to meet future demand.

This simulation study investigates different runway configurations to evaluate each of the airport layout in terms of runway system capacity utilization. Indexes are computed under varying levels of ground and airspace constraints. The objective is to make a comparison between these indexes, which are essentially measures of utilization, computed for each scenario.

From a planning perspective, this would allow more informed decision making, by providing estimates of efficiency in terms of design functionality, sensitivity to technological and procedural improvements and overall utilization of potential capacity.

As a sample study of the application of the above evaluation methodology, two proposals for expansion at Philadelphia International Airport (PHL) were investigated. For each alternative the capacity measures discussed above were determined to arrive at the runway system utilization indexes described above. A comparison between these indexes was made and inferences were drawn with regard to the best alternative in terms of the factors discussed above.

2 LITERATURE REVIEW

2.1 Capacity

An airport's capacity may be broadly defined as its ability to handle a given volume of traffic (demand). Congestion occurs when demand approaches or exceeds capacity.

The Airports Council International (ACI) and International Air Transport Association (IATA) guidelines for airport capacity/demand management (1996) defines the most significant aspect of an airport's capacity, Runway System Capacity, as the hourly rate of aircraft operations which may be reasonably expected to be accommodated by a single or a combination of runways under given local conditions.

The Runway System Capacity is primarily dependent on the runway occupancy times of, and separation standards applied to successive aircraft in the traffic mix. Other key items affecting runway capacity include: availability of exit taxiways, especially that of high speed exits that help minimize runway occupancy times of arriving aircraft; aircraft type/performance; traffic mix; Air Traffic Control (ATC) and wake vortex constraints on approach separation; weather conditions [Visual Meteorological Conditions (VMC)/Instrument Meteorological Conditions (IMC)]; spacing between parallel runways; intersecting point of intersecting runways; mode of operation, i.e., segregated or mixed.

To better explain the capacity measures introduced here, we may begin with the concept of Practical Capacity. This is defined as the number of operations that can be accommodated in a given time period, considering all constraints incumbent to the airport, and with no more than a given amount of delay (Wells, 2000). On a typical delay curve, this may be depicted as in Figure 1 (Raguraman, 1999).

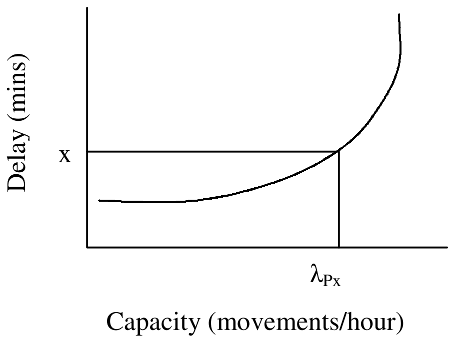

Figure 1: Practical Capacity: λ_P

Maximum throughput capacity or Saturation capacity may be measured as the number of operations that can be accomplished in a given period of time disregarding any delay that aircraft might experience and assuming that the aircraft will always be present, waiting to land or take-off (Wells, 2000, Ashford and Wright, 1992). This may be depicted as in Figure 2.

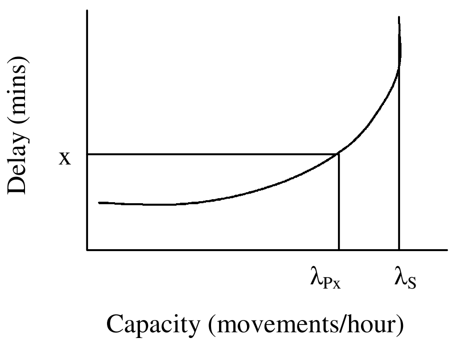

Figure 2: Saturation Capacity: λ_S

In this study, three measures of capacity are determined for each scenario. These are essentially saturation capacities of each layout constrained at varying levels. Each of these is discussed below.

Fully constrained capacity (λ_{S1}), takes into account all constraints that exist in an airport environment. These include both layout/ground factors as well as airspace factors. Ground constraints include the location of runway exits and taxiway and apron capacity. Airspace constraints arise from factors such as increased controller workloads due to the absence of sufficient procedural and technological support. This measure of capacity is similar to what is described by Reynolds-Feighan and Button (1999) as Ultimate capacity.

The second measure of capacity (λ_{S2}), which may be called semi-constrained capacity, assumes that technological and procedural improvements are in place. These improvements aid in maintaining separation standards more precisely thereby increasing runway throughput. However, the airport layout constraints discussed above, are still considered in determining this measure of capacity.

Finally, Unconstrained capacity (λ_U), assumes away all constraints except those posed by safety requirements. In particular, it is assumed that sufficient high speed runway exits exist allowing significant reduction of runway occupancy times, taxiway and apron constraints are absent and procedures to support high intensity runway operations are implemented. This concept may be represented diagrammatically as in Figure 3. The concept of unconstrained capacity has been advanced by IATA and represents the maximum possible capacity of a given runway configuration (Pitfield and Jerrard, 1999).

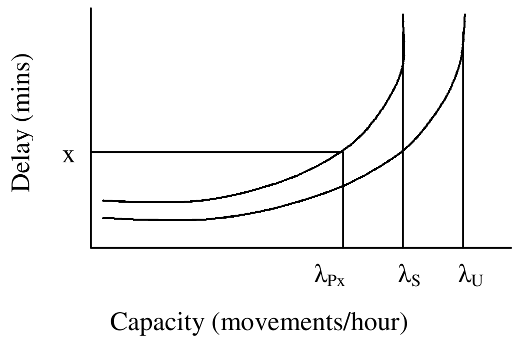

Figure 3: Unconstrained Capacity: λ_U

2.2 Capacity Estimation Models

A distinction between analytical and simulation models may be made based on the methodology used to compute capacity, delay or other such metrics. Analytical models are primarily mathematical representations of airport and airspace characteristics and operations and seek to provide estimates of capacity by manipulation of the representation formulated. These models tend to have a low level of detail and are mainly used for policy analysis, strategy development and cost-benefit evaluation (Odoni et al., 1997).

Most earlier analytical models generated to estimate runway capacity such as that proposed by Harris (1972), subsequently extended by Amodeo, Haines and Sinha (1977) aimed to compute the average interarrival time between aircraft over the runway threshold given a certain mix of lead and trail aircraft. The inverse of this would yield the runway arrival capacity per unit of the interarrival time, using which, the hourly arrival capacity of the runway could be computed.

For mixed operations, the probability of releasing a departure between arrivals could be factored into the model for the arrivals only configuration assuming that departures occur only when permissible by the separation between arriving aircraft. If perfect interleaving of arrivals and departures was assumed, then the separation between arrivals would have to be the greater of the minimum separation required between arrivals and the minimum runway occupancy time of the departure released between the two arrivals. Error correction factors were applied to these models where appropriate. Most computer based models for runway capacity estimation in the late 70s and early 80s were based on this fundamental logic (Weiss, 1978).

The primary analytical models that are used currently to estimate runway capacity include, The LMI Runway Capacity Model and the FAA Airfield Capacity Model (Odoni et al., 1997). A hybrid of these two models, with the logic of the LMI model and the extension to multiple runways featured in the FAA model has been recommended and is expected to be very useful in providing quick estimates of runway system capacity (Odoni et al., 1997).

Simulation of the airport environment has been increasingly used recently to obtain more realistic estimates of capacity by randomizing the various input parameters. In fact, meteoric improvements in computer technology, especially in the areas of computer graphics; human-computer interaction; computer networks; and the world wide web, have had a significant impact on modeling and simulation (Nance and Sargent, 2002). Fishburn and Stouppe (1997) have suggested that simulation modeling and analysis be integrated into the airport planning process rather than being simply used for final evaluations.

Monte-Carlo simulations have been used extensively to study the airport environment. This tool was used by Pitfield and Jerrard (1999) to estimate the unconstrained airport capacity – taking only safety requirements into consideration, and assuming all other factors such as air traffic management and control procedures and best pilot practices as "ideal" - at the Rome Fiumucino International Airport. Pitfield, Brooke and Jerrard (1998) have also used Monte-Carlo simulation to analyze potentially conflicting ground movements at a new airport proposed in Seoul, Korea. This is a common simulation tool for sampling from cumulative distributions using random numbers until a steady state evolves. Given known or reasonable distributions, as the number of simulations increase, the results match the distributions and predict the likely outcome.

In comparison to the above, microscopic simulation models dedicated to airport or airspace types of simulation seek to generate traffic flows through the airspace segments and airports which are modeled and are configured to represent actual constraints and uncertainties. Observations from these flows allow appropriate measures of capacity and/or delay to be computed. Microscopic simulations tend to have a much higher level of detail including conflict resolution, airport taxiway and gate selection, pushback maneuvering, etc., to deal with more tactical issues (Odoni et al., 1997).

Microscopic models, can be either node-link or 3-dimensional (3-D). Node-link models such as SIMMOD and the Airport Machine separate the airport and airspace into a number of nodes and links over which aircraft move. Conflict occurs when more than one aircraft try to pass one node. 3-D models such as TAAM and HERMES (Heuristic Runway Movement Event Simulation), allow flight over random 3-dimensional routes (Odoni et al., 1997).

A detailed compilation of all existing and required modeling capabilities for ATM systems and concepts is provided by Odoni et al. (1997). This study also presents an exhaustive list of airport capacity estimation models together with extensive insights into and comparisons between these.

To summarize, a variety of techniques may be used to evaluate runway capacity. These may range from basic analytical models, through more sophisticated Monte-Carlo and other random number probabilistic models, to complex computer-intensive discrete event models requiring extensive input data. The compromise in the choice of a technique lies between "the higher reliability of the results of the higher-order model versus the increased effort and cost" (Mumayiz, 1997).

2.3 TAAM Review

Developed by The Preston Group (now Preston Aviation Solutions) in cooperation with the Australian Civil Aviation Authority, TAAM (Total Airspace & Airport Modeller) is a large scale detailed fast-time simulation package for modeling entire air traffic systems. The model is a four dimensional flight path simulator and allows greater realism than mesh based simulations such as SIMMOD (Odoni et al., 1997). A number of factors may be randomized in the simulation to reflect day-to-day fluctuations. A versatile simulation model, TAAM has been used in a wide variety of applications including airport capacity estimation (gate, taxiway, runway capacity), planning airport improvements, extensions, de-icing, noise impact, effect of severe weather, design of terminal area procedures (SIDs/STARs) and terminal area ATC sectors, controller workload assessment, impact of new ATC rules, system wide delays and cost/benefit studies.

Being a large scale simulation of an air traffic system, TAAM requires comprehensive input data files describing the entire Air Traffic system. The level of detail, however, is variable and can be adapted to suit individual project needs. Typical inputs include, the airport layout, air traffic schedule, environment description, aircraft flight plans and air traffic control rules. These are used to investigate the usage of the airport and airspace, conflict detection and resolution, and to compute aggregate metrics using TAAM's internal algorithms and user specified rules (Odoni et al., 1997). These aggregated metrics include system delay and its distribution; costs: fuel, non-fuel, and total; airport movements; operations on taxiways and runways; runway occupancy and airspace operation metrics such as usage of routes, sectors, fixes and coordination.

TAAM has been verified by many users on many different scenarios. TAAM simulation outputs have been compared with some FAA studies on aspects of new ATM concepts and have shown comparable results. In fact, the four dimensional movement of aircraft can be simulated in TAAM to get within 3 - 4% of the actual aircraft profiles. Airport movement rates and other characteristics can be modeled with similar accuracy (Odoni et al., 1997). An operational evaluation of TAAM by the Eurocontrol Experimental Center (Sillard, Vergne and Desart, 2000), has provided detailed evaluation of the different aspects of the model. The study identified a number of discrepancies and limitations, however, experts in the field of airports, whose opinions were solicited during the course of this study, were in agreement that the model was responding to particular events or scenarios in a manner that reflected day-to-day fluctuations in airport operations.

The evaluation also concluded that TAAM demonstrates a significant capability to simulate an airport and its environment in a manner that can be very close to reality. Besides being recognized by ATC controllers who examined the baseline, this relative accuracy has been measured through different sensitivity analyses.

3 AIRPORT LAYOUT EVALUATION

3.1 Airport Layouts in General

Most airport layouts are customized to represent the most useful configuration given the airport environment. As a result, the runway dependencies, airspace procedures and limitations, and other characteristics are usually unique to every airport. A more generic description of runway configurations and their corresponding dependencies has been laid out by the FAA. These configurations include the following:

1. Single runway
2. Close parallels (distance between runway centerlines, less than 2500 feet)
3. Intermediate parallels (distance between runway centerlines, 2500 – 4300 feet)
4. Far Parallels (distance between runway centerlines greater than 4300 feet)
5. Dual lane (two pairs of close parallel runways separated by more than 4300 feet)

Under instrument flight conditions, simultaneous independent approaches are permissible on far parallels. Intermediate parallels can employ simultaneous dependent approaches, requiring a diagonal separation between approaching aircraft. Close parallels are treated as a single runway and simultaneous operations are not permitted (Burnham, Hallock and Greene, 2001).

Airport layouts may correspond with one of the above configurations or may be a combination of two or more of them.

3.2 Evaluation Methodology

To begin with, the three capacity measures (λ_i) described in section 2.1 are determined for each of the layouts. A standard assumption in the determination of these measures was that visual meteorological conditions exist. Also in each of the configurations studied, only the westerly flows were considered. Hence we have,

1. λ_{S1}: Capacity as influenced by all constraints incumbent at an airport – ground as well as airspace constraints,
2. λ_{S2}: Capacity under procedural and technological constraints – only Airspace constraints,
3. λ_U: Capacity in an unconstrained environment– considering only safety related constraints such as separation standards.

Based on the above measures of capacity, the following ratios are computed for each layout,

1. λ_{S1}/λ_U: indicates the runway system utilization owing to all constraints incumbent at an airport. This would show where the layout stands, in capacity terms, in light of its maximum potential. Hence, $[(\lambda_U-\lambda_{S1}) / \lambda_{S1}]$ indicates the potential for maximum runway system utilization.
2. $\lambda_{S1}/\lambda_{S2}$: provides an estimate of the utilization as a result of airspace constraints. Therefore, the sensitivity of the layout to technological and procedural changes that improve the traffic flow in and out of the airport is indicated by $[(\lambda_{S2}-\lambda_{S1}) / \lambda_{S1}]$.
3. λ_{S2}/λ_U: indicates the utilization constrained by the airport layout design factors affecting taxiing, gate usage etc., thus throwing light on the layout's functionality or what may be called its design efficiency. Here again, $[(\lambda_U-\lambda_{S2}) / \lambda_{S2}]$, shows the

potential for runway system utilization by improving airport design.

Comparison between different layouts are made based on these indexes to arrive at the best configuration, primarily in terms of,

1. Efficiency in terms of design functionality;
2. Sensitivity to technological and procedural improvements and;
3. Overall utilization of potential capacity.

3.3 Sample study: Philadelphia International Airport

The FAA Capacity Benchmark Report (2001) has estimated the current capacity benchmark at Philadelphia International Airport (PHL) to be 100-110 flights per hour in good weather (VFR conditions) and 91-96 flights (or fewer) per hour in adverse weather conditions (IFR conditions), which could include poor visibility or low cloud base. Figure 4 represents a westerly usage of the runways in VFR conditions. In the figures, the callouts provide the runway names. The arrows present the usage of the runways. An arrow toward a runway represents arrivals to that runway while an arrow away from the runway represents departures from that runway.

One of the current problems faced at PHL is that of significant delays. For example, in 2000, over 4% of all flights at Philadelphia experienced significant delay (defined by the FAA as more than 15 minutes of delay). Under IFR conditions, capacity is exceeded for about 3 1/2 hours of the day resulting in about 14% of the flights experiencing significant delay. Moreover, traffic at PHL is expected to increase by 23% over the next decade, which will further increase delays. The capacity estimates in the FAA report assume that the short runways 17/35 and 8/26 provide for 25% of airport traffic operations. The airport's capacity stands to decrease if this percentage declines.

Because of these current capacity problems, a number of enhancement initiatives are being undertaken by the airport authorities. Technological and procedural improvements to be implemented include:

- Automatic Dependent Surveillance-Broadcast / Cockpit Display of Traffic Information with Local Area Augmentation System [ADS-B/CDTI (with LAAS)], which would provide a cockpit display of the location of other aircraft thus helping pilots maintain desired separations more precisely;
- Flight Management System/Area Navigation (FMS/RNAV) Routes, to enable a more consistent flow of aircraft to the runway;
- Land and Hold Short Operations (LAHSO), allowing independent arrivals for specific aircraft types on intersecting runways and
- Precision Runway Monitor (PRM), a sophisticated radar system that allows simultaneous instrument approaches to parallel runways as close as 3000 feet apart.

According to the Capacity Benchmark Report, these changes will improve Philadelphia's capacity in good weather by 17% (to 117-127 flights per hour) over the next 10 years, while capacity under adverse weather is expected to increase by 11% (to 101-106 flights per hour).

Besides these, major expansions involving the construction of new and/or expansion of existing runways and taxiways, improved and/or new terminal area and cargo handling facilities are being planned. These expansion plans may be categorized under two broad concepts,

1. The Parallel concept, which is an extension of the current layout, and
2. The Diagonal concept, which involves a complete change of the layout including new runway orientations, new terminal area design, new apron and taxiway designs.

Under each of these concepts, two proposed full-build layouts were chosen for purpose of this analysis. The Parallel concept layouts chosen were:

1. Full-Build Parallel Layout With Crosswind Runway (Parallel-1) –The baseline layout altered to have 09L/27R shifted to the south and west, 17/35 and 08/26 extended and a new runway, 09R/27L built to the south of the airfield. The existing 09R/27L would also be extended and would now be called 09C/27C. Figure 5 represents the full build of this layout and also explains its usage.
2. Baseline Layout with 4th Parallel Runway (Parallel-2)– This configuration is essentially the same as the Parallel-2 except that here the crosswind runway, 17/35 is converted to a taxiway in order to provide for easier taxiing to and from the

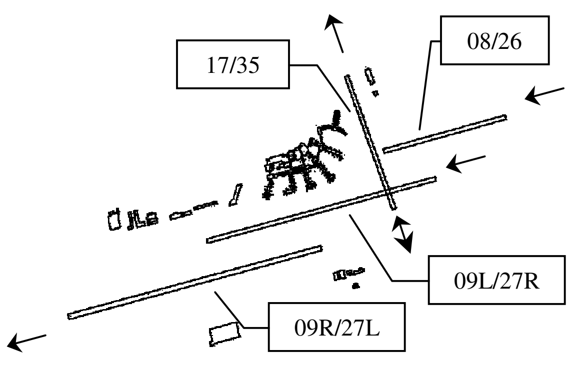

Figure 4: Current West-VFR Operations at PHL

northern aprons. Also, 27R/09L is as in the baseline scenario and not shifted south and west as in Parallel-1. Figure 6 depicts this configuration and explains its westerly usage.

The Diagonal concept layouts chosen were:

1. Full-Build Diagonal Layout With 4 Runways (Diagonal-1)- two pairs of close parallel runways separated by more than 4300 feet with the runways oriented 30 degrees clockwise from 09C/27C. The terminal area in this concept is also redesigned to a more symmetric one allowing more structured taxi patterns. Figure 7 represents the westerly usage of this configuration.
2. Full-Build Diagonal Layout With 3 Runways (Diagonal-2) – This configuration is the same as the Diagonal-1with the exception of the northernmost runway. Figure 8 depicts this layout and explains its usage.

In computing λ_{S1}, the measure of fully constrained capacity, ground constraints were simulated by turning taxiing on to see the effect of the taxiway and apron design on capacity. Airspace constraints were simulated by setting the terminal area radar separation to 3 nautical miles (nm).

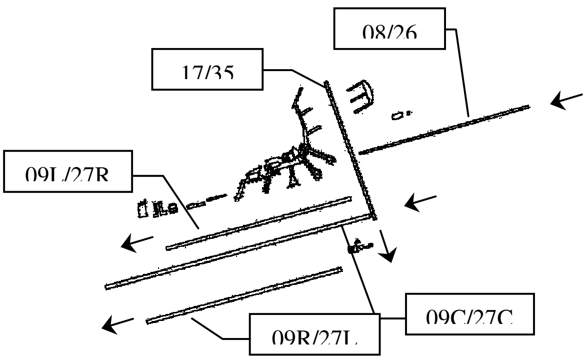

Figure 5: Parallel-1: West VFR Operations

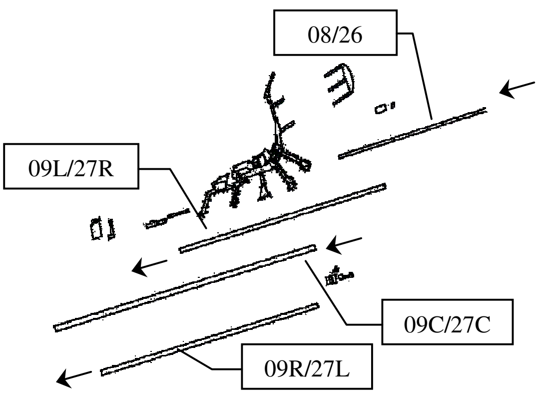

Figure 6: Parallel-2: West VFR Operation

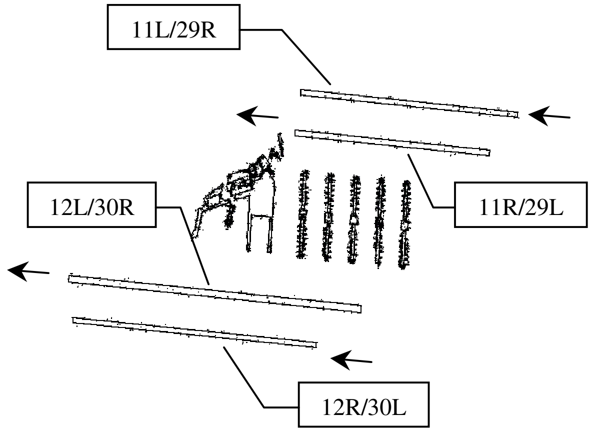

Figure 7: Diagonal-1: West VFR Operations

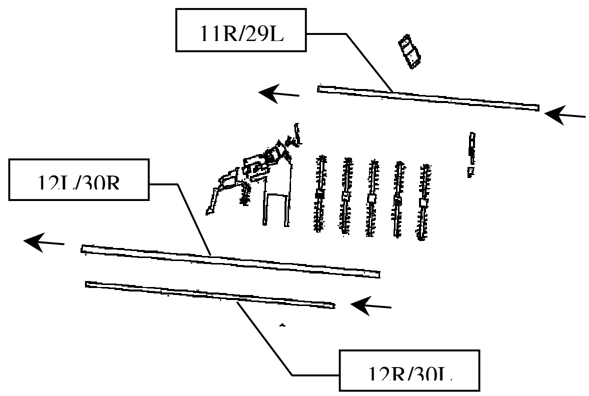

Figure 8: Diagonal-2: West VFR Operations

This separation distance has been arrived at as a result of calibration of TAAM simulations to represent reality. Although 2.5nm separation is authorized in VFR conditions, where permissible by wake turbulence separation requirements, between aircraft on the final approach course within 10 miles of the landing runway (U.S. Department of Transportation, 2000), in reality, air traffic controllers tend to leave a "buffer" of typically an extra half mile in order to ensure that separation standards are met.

The net effect of the technologies and procedural improvements discussed above is that these separation standards can be closely met. In other words, the "buffer" can be significantly reduced, thereby increasing runway throughput.

Finally, the departure sequencing strategy is set as a First In First Out (FIFO) strategy, which is also TAAM's default departure sequencing strategy.

In determining λ_{S2}, the semi-constrained capacity, ground constraints are again simulated as before, by turning taxiing on. The assumption that technological and procedural improvements are implemented is simulated by setting terminal area radar separation at 2.8nm. This is again a pessimistic estimate but has a noticeable impact on runway throughput. Departure sequencing strategy is set as optimized.

When departure sequence is optimized, TAAM examines all possible combinations of departures, in light of the arrivals to the particular runway and the spacing required. The combination that provided the shortest total delay in the line-up queue is then chosen (Preston Aviation Solutions, 2001). Essentially, runway capacity is increased by interleaving departures going in different direction. This has been endorsed a "best in class" ATM procedure (Pitfield and Jerrard, 1999)

Finally, in determining λ_U, the unconstrained capacity, the assumption of no ground constraints is simulated by turning taxiing off. The lack of airspace constraints is simulated as in λ_{S2}, by setting the terminal area radar separation to 2.8nm and the departure sequencing strategy as optimized.

To satisfy the assumption of an ever-present traffic flow, a one-hour traffic schedule with a total of 364 flights - equal arrivals and departures, was generated. The traffic mix representing the forecast for the year 2020 for PHL was used. The arrivals, departures and different types of aircraft were evenly distributed through the one hour time period. The year 2020 was chosen as this is the expected date of completion of the full-build layouts in either concept.

3.4 Observations

The ratios obtained from the simulation results are presented in the following tables.

Table 1: λ_{S1} Vs. λ_U

	λ_{S1}/λ_U	$[(\lambda_U-\lambda_{S1}) / \lambda_{S1}]$
Baseline	86%	16.2%
Parallel-1	93.7%	6.7%
Parallel-2	93.2%	7.3%
Diagonal-1	82.4%	21.4%
Diagonal-2	90.1%	11.0%

Table 2: λ_{S1} Vs. λ_{S2}

	$\lambda_{S1}/\lambda_{S2}$	$[(\lambda_{S2}-\lambda_{S1}) / \lambda_{S1}]$
Baseline	90%	11.1%
Parallel-1	94.8%	5.5%
Parallel-2	95.8%	4.4%
Diagonal-1	93.5%	6.9%
Diagonal-2	97.3%	2.7%

Table 3: λ_{S2} Vs. λ_U

	λ_{S2}/λ_U	$[(\lambda_U-\lambda_{S2}) / \lambda_{S2}]$
Baseline	95.6%	4.6%
Parallel-1	98.9%	1.2%
Parallel-2	97.3%	2.8%
Diagonal-1	88.1%	13.5%
Diagonal-2	92.6%	8%

3.5 Inferences

Inferences have been drawn based on comparisons between the layouts within each concept and between the different concepts themselves.

3.5.1 Comparison between the Diagonal Concept Layouts - Diagonal-1 Vs. Diagonal-2:

1. Both layouts are largely similar with respect to the parameters evaluated.
2. Diagonal-1 is marginally better than Diagonal-2 with respect to,
   a. Runway system capacity utilization,
   b. Efficiency in terms of taxiing and gate usage

3.5.2 Comparison between the Parallel Concept Layouts – Parallel-1 Vs. Parallel-2:

1. Parallel-2 is better than Parallel-1 with respect to,
   a. Runway system capacity utilization and
   b. Efficiency in terms of taxiing and gate usage

Probable reasons as observed from the simulation include the absence of the crosswind runway in Parallel-2 and hence the elimination of related dependencies, and the use of the crosswind runway as taxiway, which provides for more efficient taxiing.

3.5.3 Comparison between the Baseline and the Two Proposed Concepts:

1. The Diagonal concept layouts were found to be better than either the baseline or the parallel concept layouts, with respect to,
   a. Runway system capacity utilization, and
   b. Efficiency in terms of taxiing and gate usage.

This may be due to a more structured and symmetric taxiway and terminal design in the diagonal concept, which facilitates more structured flow of traffic on the ground. Besides, the fact that no runway crossing is required for departures ensures a continuous feed to the departure runways, which is not influenced by the arrival flow.

2. The Baseline is better than either parallel concept layout with respect to design factors affecting taxiing and gate usage.

This could be as a result of the constraints posed by the number of runways that departures have to cross in either parallel concept layout. For example, departures on 27L, have to cross the departure runway 27R, as well as, the arrival runway 27. In the event of continuous arrival and departure flows on these runways, the feed to 27L is greatly constrained. The solution to this would involve holding the departures on 27R and arrivals on 27 periodically in order to let aircraft cross these runways. However, this would negatively affect the overall runway system throughput.

3. Parallel-1 and Baseline are more sensitive to technological and procedural improvements.

This is primarily caused by the use of the crosswind runway 17/35 in both these configurations. Using this runway, imposes dependencies on arrivals and departures, which are eliminated in the other configurations.

In summary, the Diagonal concept layouts provide the best alternative as a result of this analysis. Between the two full build diagonal layouts evaluated, the Diagonal-1 configuration with the four parallel runways would be more preferable, simply because, the extra runway in this layout provides more absolute capacity.

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AUTHOR BIOGRAPHIES

MASSOUD BAZARGAN is currently an Associate Professor of Business at Embry-Riddle Aeronautical University - Daytona Beach Campus. He teaches Production Operations Management, Operations Research, Simulation and Optimization. Dr. Bazargan received his Ph.D. in Manufacturing Engineering, MA in Operations Research and a B.Sc. in Mathematics and Economics. He has spent his last 15 years of employment in consulting, research, teaching and supervising. He has research/consulting experiences with aviation, household appliances, mining, electronics, food, packaging and timber industries. Dr. Bazargan has published two book chapters and more than 20 technical papers in international journals. His research interests include facilities design, cellular manufacturing, warehousing, material handling, scheduling, Simulation, and Optimization. His email address is <bazargam@erau.edu>

KENNETH FLEMING is the Director of Modeling and Simulation at Embry Riddle Aeronautical University and received his Ph.D. in Economics from the University of California. A former military pilot with over 3,000 hours in nine different aircraft, he holds an FAA Commercial Pilot Airplane Single and Multi-engine Instrument Rating. During the past five years, he has been involved in many programs where modeling and simulation technologies were used to assess and evaluate airspace and airport operations, delay and capacity, efficiencies and processes. These initiatives included funded research programs for Lockheed Martin Corporation, Harris Corporation, NASA Ames Research Center and NASA Langley Research Center, as well as numerous other requirements for operations research-oriented experiments in aviation systems and facilities. He has also led the development of a number of ERAU proprietary airspace and airport modeling and analysis tools used in the study of system efficiency and operational capacity. He is a published and recognized expert in aviation economics as well as the modeling and simulation of airspace and airport operations. His email address is <flemingk@erau.edu>

PRAKASH SUBRAMANIAN is currently pursuing the Master of Business Administration in Aviation at Embry Riddle Aeronautical University. In 2000 he received the Link Foundation Scholarship for work that is partially documented in this paper. His research interests are in operations management and simulation modeling in the areas of airport operations management and air traffic management. His email address is <subramap@erau.edu>