

A SIMULATION STUDY TO
INVESTIGATE RUNWAY CAPACITY
USING TAAM

by

Prakash Subramanian

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This thesis was prepared under the direction of the candidate's thesis committee chair, Dr. Massoud Bazargan, Department of Business Administration, and project co-supervisor, Dr. Kenneth Fleming, Department of Sponsored Programs, and has been approved by the members of his thesis committee. The thesis was submitted to the Department of Business Administration and was accepted in partial fulfillment of the requirements for the degree of Master of Business Administration in Aviation

THESIS COMMITTEE:

Dr. Massoud Bazargan
Chair

Dr. Kenneth Fleming
Member

Dr. Bijan Vasigh
Member

MBA/A Graduate Program Chair

Department Chair, Business Administration

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ABSTRACT

Author: Prakash Subramanian
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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 the ultimate airport capacities achievable for each of the different layouts to estimate their respective efficiencies in terms of runway system utilization. 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, TAAM (Total Airspace and Airport Modeller) is used to simulate each proposed alternative. Using the methodology proposed here, the baseline and the different alternatives were evaluated in terms of design functionality, sensitivity to technological and procedural improvements and overall utilization of potential capacity. Results indicate that the Diagonal concept layouts provide a better alternative, irrespective of the set of constraints on the airport.

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LIST OF ABBREVIATIONS

ACI	Airports Council International
ADS-B	Automatic Dependent Surveillance-Broadcast
ATC	Air Traffic Control
ATCT	Air Traffic Control Tower
ATM	Air Traffic Management
CDTI	Cockpit Display of Traffic Information
DP	Instrument Departure Procedure
ERAU	Embry-Riddle Aeronautical University
ETA	Estimated Time of Arrival
ETD	Estimated Time of Departure
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Authority
FIFO	First In First Out
FMS	Flight Management System
HERMES	Heuristic Runway Movement Event Simulation
IATA	International Air Transport Association
IFR	Instrument Flight Rules

IMC	Instrument Meteorological Conditions
LAAS	Local Area Augmentation System
LAHSO	Land and Hold Short Operations
LMI	Logistics Management Institute
NAS	National Airspace System
PHL	Philadelphia International Airport
PRM	Precision Runway Monitor
RNAV	Area Navigation
SIMMOD	Airport and Airspace Simulation Model
STAR	Standard Terminal Arrival
TAAM	Total Airspace & Airport Modeller
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions

“Ninety percent of aviation is on the ground. Only 10% is in the air.”---Glen Curtis, Aircraft Designer and Entrepreneur.

1. INTRODUCTION

Airports play a key role in the commercial aviation system by allowing airlines and their customers to converge. However, since the early 1970s, the peaking of traffic at airports has been a problem of increasing concern to airport operators around the world. Though the systems put in place by airports today are extensive and highly developed, the busiest airports still face the problems of congestion and delay. Facilities at most airports are not adequate enough to accommodate demand at all times and in all conditions of weather and visibility. The resulting delays lead to inefficiency and increased expenses to airlines, inconvenience and opportunity costs for passengers, and increased workload for the FAA air traffic control system. 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 in the planning stage. Therefore, demand-capacity analysis, a vital component of the airport planning process, is crucial in defining the physical requirement of airport facilities to meet future demand.

Airport facilities broadly include, the airfield – runway, taxiway, gates; the terminal building; and airport access / parking facilities (Mumayiz, 1999). Approaches to improving these facilities, thereby expanding airport capacity, may be categorized as,

- Techniques to increase runway operation rate and hence augment airside capacity or mitigate aircraft delay.
- Techniques to move the aircraft from the runway to the passenger loading gates and back again as quickly as possible to shorten the taxi-in and taxi-out components of delay.
- Techniques to aid in the transit of passengers through the terminal building and the flow of vehicles on airport circulation and access roads (Wells, 2000).

A prerequisite to an airport planning process is an evaluation of the existing operational environment. The next step would be to estimate the effect of proposed developments on the airport's performance. This is then compared with the performance of the existing system to justify the proposed developments. Methods used to assess airport capacity and/or delay may be broadly categorized under Observation and Simulation (IATA, 1996).

- *Observation*: Involves actual observation of traffic activity at an airport, particularly during peak periods. It may also involve comparison of the airport and its subsystems with those of another airport similar in terms of demand characteristics.
- *Simulation*: Employs computer simulation models to predict the effect of projected airline schedules on existing and improved airport facilities. Computerized simulations also provide a quantitative and visual demonstration of the benefits that are expected from physical improvements to airfields, enhancement of airspace and air traffic operation, analysis of passenger flows in the terminal area, or a policy change.

Observation is normally used to assess the static or existing situations and facilities while simulation is usually employed to study dynamic conditions.

Simulation is the process of imitating the operation of a real-world system over time. It is used to describe and analyze the behavior of a system, ask “what if” questions about the real-world system and aid in designing the system. Given the complex nature of airport systems owing to interdependence among a number of subsystems, simulation proves to be an indispensable tool in addressing the various problems that are faced here. The very process of developing the model itself often provides valuable insights into the system. Computer driven simulations provide a better understanding of the behavior of the system under various conditions, suggest ways to increase efficiency by experimenting with a range of variables in the system, and are extremely useful in identifying bottlenecks. Using simulation models in airport planning provides insight into the impact of current and future changes on the functioning of the airport.

1.1 Genesis of the project

The thesis project has evolved from an ongoing simulation analysis of Philadelphia International Airport (PHL) that is being carried out at Embry Riddle Aeronautical University (ERAU). This project uses TAAM Plus (Total Airspace and Airport Modeller), one of the most sophisticated software packages for simulation of airspace and airports. Details of the capabilities and the validity of the model are provided in section 2.3. The essence of the main project has been to compare a number of proposals for the development of PHL and to aid in decision making based on the absolute values of performance measures such as the number of

movements, delay, fuel and non-fuel costs, taxiing times, etc. Although TAAM is capable of predicting these variables fairly accurately, a problem is posed by the fact that the differences in the values being compared are often very small. This may render the comparisons between alternatives nebulous, thereby clouding decision-making.

The TAAM functionality has been developed to imitate real-world traffic patterns and behavior as well as to closely replicate actual air traffic control procedures. It is a discrete event, deterministic model that generally does not use a probability distribution in any of its inputs (although such distributions can be generated for specific inputs if so desired). All inputs required to run a valid simulation are real-world data. A more detailed list of the inputs to TAAM is provided in section 2.2 and 2.3. Though this “real-world” feature of TAAM is extremely useful in visually validating each simulation, solving tactical issues and identifying bottlenecks, it restricts the model from being effectively used for multiple iterations based on a random seed. This may be considered a weakness of the model in comparison to other simulation models such as Arena or Automod. However, it must be noted that TAAM is not a generic, statistical simulation model and is primarily suited for reliable technical evaluations of complex airside scenarios. For studies such as the PHL simulation analysis, this fundamental logic of TAAM proves to be an asset given the complexities of the various scenarios being examined. Therefore, since the model does not lend itself well to statistical analysis (such as standard hypothesis testing), it is generally validated by comparing its fidelity against existing real world conditions.

In addition to the performance measures determined for the baseline and for each proposal under a given set of operating conditions in the main study for PHL, it is also important to see the performance of each of these scenarios under different conditions and in a broader

sense. These conditions may include improvements in technology and procedures that aid in air traffic management (many of which are already in the pipeline and are discussed in section 4) or the theoretical condition of no constraints on the airport environment. Evaluation of these alternatives in a broader sense would involve looking at the functionality of the layout design, sensitivity to technological changes and overall utilization of the potential maximum capacity. Evaluating these scenarios in this fashion would be very useful in the decision making process itself. Given the uncertainty of the future at today's rate of technological change and lead times required in airport planning and development, it would also serve to help evaluate any decisions made.

1.2 Objective of the Thesis

This thesis is a simulation study that investigates different runway configurations to evaluate each of the airport layouts in terms of runway system capacity utilization. Capacity utilization is measured in the form of indexes, computed using maximum capacities at varying levels of ground and airspace constraints. The objective is to make a comparison between these indexes computed for each scenario instead of comparing the absolute values of parameters mentioned previously. From a planning perspective, this allows 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 evaluation methodology, two proposals for expansion at Philadelphia International Airport (PHL) were investigated. For each alternative the maximum capacities mentioned above were determined to arrive at the runway system utilization

indexes. A comparison between these indexes was made and inferences were drawn with regard to the best alternative in terms of the factors delineated.

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) over time (Wells, 2000). 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; and whether the mode of operation is 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). The key here is that capacity is determined at a given level of delay. This capacity level does not necessarily reflect the maximum throughput capacity of the runway configuration.

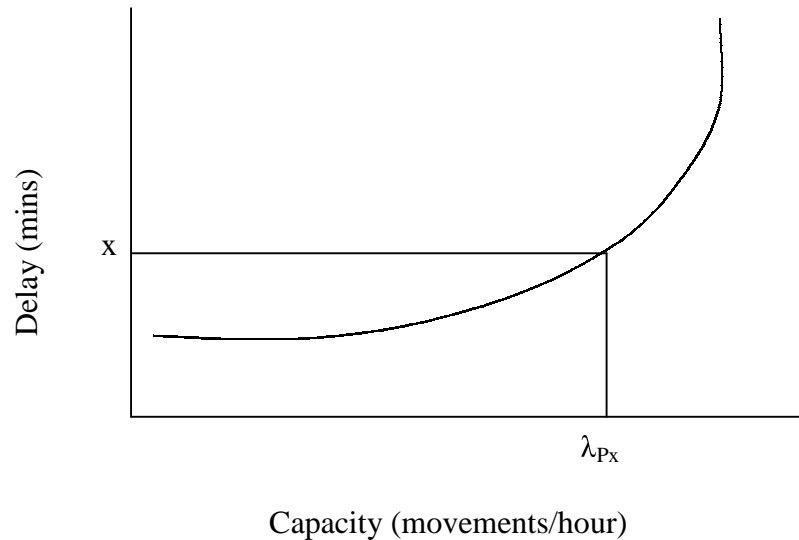


Figure 1: Practical Capacity: λ_p

As an illustration of Practical Capacity, we may consider the following example. Let us assume that capacity at 10 minutes of delay is 100 movements per hour and that at 20 minutes of delay is 125 movements per hour. On a typical delay curve, this could be represented as in Figure 2. From the figure, it may be observed that, at 20 minutes of delay the airport has almost reached its maximum capacity. However, capacity at 10 minutes of delay does not represent the maximum throughput capacity of the airport.

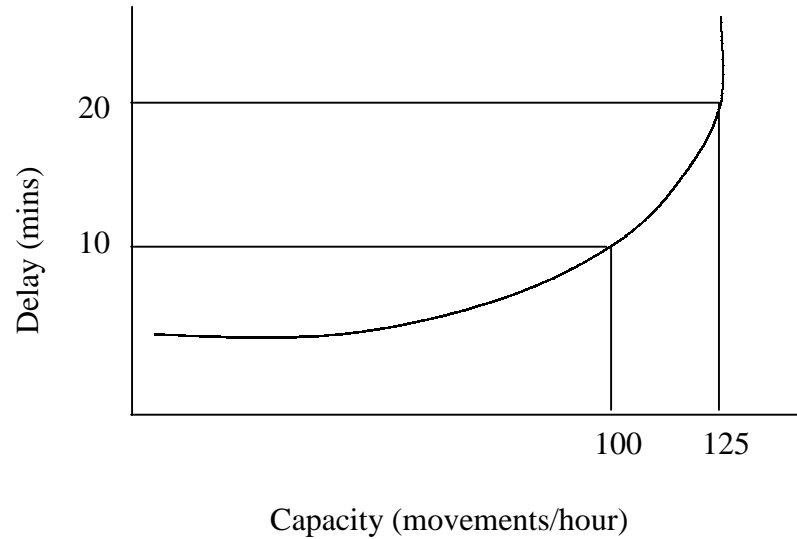


Figure 2: Practical Capacity: Example

Expanding on the concept of Practical Capacity, if we were to disregard delay, the airport's capacity would only increase until a certain maximum level. In the above example, this would be about 125 movements per hour. Every movement above this level in the same hour would contribute more to delay than to the airport's capacity. This level may be regarded as the point of negative returns, beyond which every additional movement would only contribute to the overall delay without improving capacity; this concept is called the Maximum throughput capacity or Saturation capacity. It can 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 concept is depicted as in Figure 3. Put simply, this is the capacity level where the layout gets saturated.

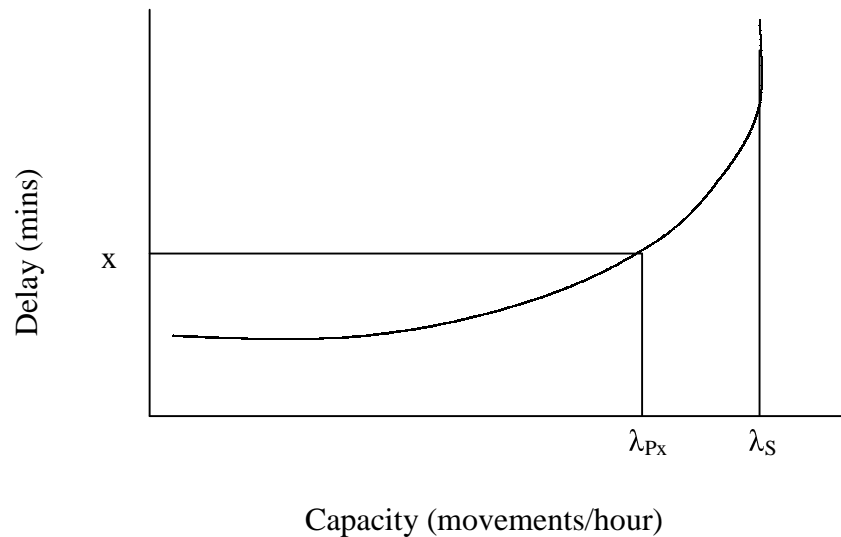


Figure 3: Saturation Capacity: λ_S

Saturation capacity is the key concept for this study and it is used for three different measures of capacity for each proposed runway configuration. The capacity measures differ in the sense that each one represents a capacity that has a separate set of constraints associated with it. Each of these is discussed below.

λ_{S1} : 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.

λ_{S2} : **Semi-constrained capacity:** The second measure of capacity (λ_{S2}), which may also be called semi-constrained capacity, assumes that technological and procedural improvements are in place. A detailed explanation of these improvements and the impact of each of them are provided in Section 4, which also explains the details of the sample study. 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.

λ_{SU} : **Unconstrained capacity:** Finally, Unconstrained capacity (λ_{SU}), assumes away all constraints except those posed by safety requirements. These would broadly include separation standards established in order to allow for wake turbulence and runway occupancy rules. 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). The main assumptions in determining this measure of capacity are,

- 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.

These three concepts may be represented diagrammatically as in Figure 4. Again, note that each of these is essentially a saturation capacity. They fall on different curves because each one represents a different level of constraints on the system and is hence a separate scenario. As the

constraints on the system decrease, capacity increases and the curve moves in the positive-x direction.

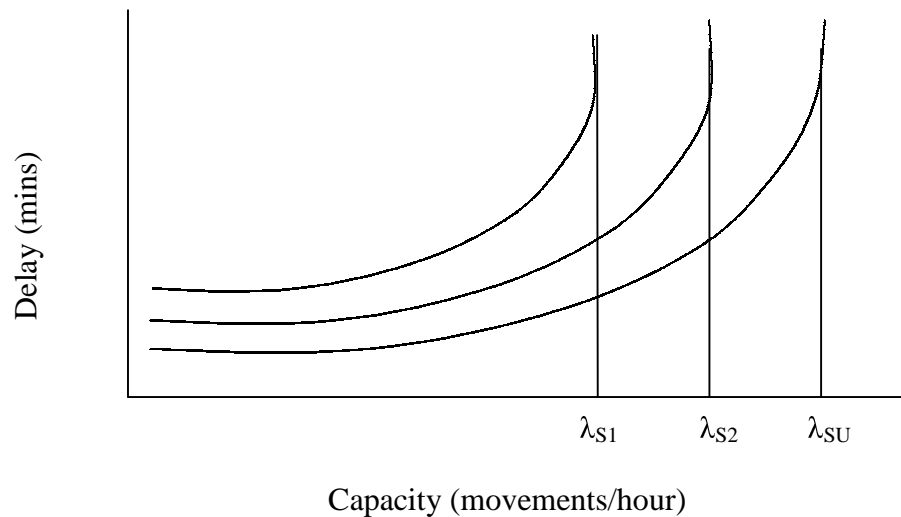


Figure 4: Capacity Measures Determined in This Study: λ_{S1} , λ_{S2} & λ_{SU}

For example, for a particular layout, the fully constrained saturation capacity λ_{S1} , may be 110 movements per hour. For the same scenario, the semi-constrained capacity λ_{S2} , could be 130 movements per hour and the unconstrained capacity λ_{SU} , could be 160 movements per hour.

2.2 Capacity Estimation Models

A distinction between analytical and simulation models is 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 used 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, was 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 Stoupe (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 Fiumicino 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 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 was provided by Odoni et al. (1997). This study also presented 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 three-dimensional flight path simulator and allows greater realism than mesh based simulations such as SIMMOD (Odoni et al., 1997). 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 PROPOSED AIRPORT LAYOUT EVALUATION

3.1 Airport Layouts in General

Most airport layouts are customized to represent the most useful configuration given the airport environment. The airport's environment is characterized by,

- *Airfield characteristics*: Basic determinants of the airfield's ability to accommodate different types of aircraft and the handling rate. These include the physical layout of the runways, taxiways, aprons etc.
- *Airspace characteristics*: The situational relationship of the airfield to other airports and to natural and manmade obstacles and the navigable airspace hence developed.
- *Air traffic control*: ATC rules and procedures.
- *Meteorological conditions*: Visual Meteorological Conditions (VMC), atmospheric conditions, which allow pilots to land and take-off visually and Instrument Meteorological Conditions (IMC), atmospheric conditions, which do not allow visual reference and require ATC rules and procedures for safe conduct of operations.
- *Demand characteristics*: The number of aircraft seeking service, their performance characteristics and their usage of the airport. (Wells, 2000)

As a result, airport operations, including, 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 saturation 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 existed. Also in the sample study, for each configuration, only the westerly flow was considered as this represents the majority of the annual usage of the airport.

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_{SU} : 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. $\lambda_{S1}/\lambda_{SU}$: 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, $[(\lambda_{SU}-\lambda_{S1}) / \lambda_{S1}]$ 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. $\lambda_{S2}/\lambda_{SU}$: 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, $[(\lambda_{SU}-\lambda_{S2}) / \lambda_{S2}]$, 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.

To illustrate the use of these ratios, we may build on the example provide on page 12 in Section 2.1. Let us assume the values provided in Table 1a as the capacity measures determined for two proposed alternatives.

Table 1a: Example of proposed methodology: Capacity measures

	λ_{S1}	λ_{S2}	λ_{SU}
Alternative 1	110	130	160
Alternative 2	120	140	160

The ratios associated with these capacity values would be as in Table 1b.

Table 1b: Example of proposed methodology: Ratios

	$\lambda_{S1}/\lambda_{SU}$	$\lambda_{S1}/\lambda_{S2}$	$\lambda_{S2}/\lambda_{SU}$
Alternative 1	68.8%	84.6%	81.3%
Alternative 2	75%	85.7%	87.5%
	$(\lambda_{SU} - \lambda_{S1})/\lambda_{S1}$	$(\lambda_{S2} - \lambda_{S1})/\lambda_{S1}$	$(\lambda_{SU} - \lambda_{S2})/\lambda_{S2}$
Alternative 1	45.5%	18.2%	23.1%
Alternative 2	33.3%	16.7%	14.3%

From Table 1a, it may seem as if the two alternatives are equivalent in terms of their maximum achievable capacity (λ_{SU}). However, on computing the ratios as in Table 1b, it becomes evident that Alternative 2 is the better one since,

1. It is less sensitive to technological change (comparing λ_{S1} with λ_{S2}),
2. Provides better design efficiency (comparing λ_{S2} with λ_{SU}), and
3. Provides better overall utilization of potential capacity (comparing λ_{S1} with λ_{SU}).

4. SAMPLE STUDY: PHILADELPHIA INTERNATIONAL AIRPORT

4.1. Overview

The FAA Capacity Benchmark Report (2001) 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 5 represents a westerly usage of the runways in VFR conditions. In this figure, the callouts provide the runway names. The arrows show 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 it.

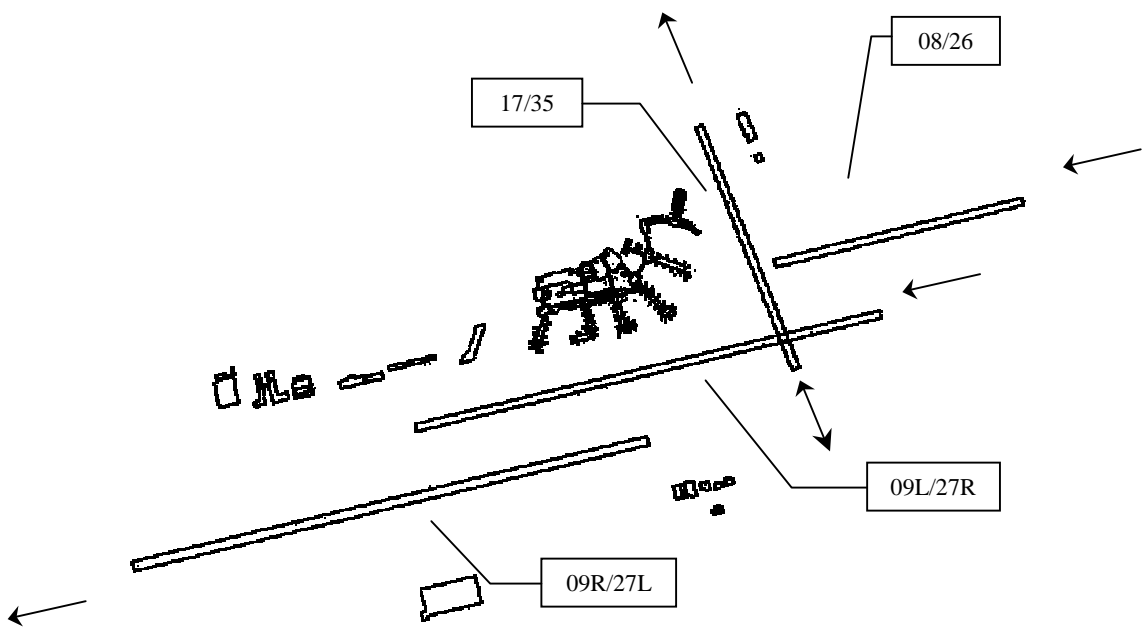


Figure 5: Current West-VFR Operations at PHL

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 (Federal Aviation Administration, 2001).

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 (Federal Aviation Administration, 2001).

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. Therefore, in total, five layouts were examined in this study – the baseline or the airport layout, as it exists, two Parallel concept layouts and two Diagonal concept layouts.

4.2 Parallel concept layouts:

4.2.1 Full-Build Parallel Layout With Crosswind Runway (Parallel-1):

- Runway 09L/27R to be shifted to the south and west, to provide more taxiways closer to the apron area just above the runway.
- Runways 17/35 and 08/26 to be extended to enable turboprops and jets other than widebodies to use these runways.
- New runway, 09R/27L, built to the south of the airfield to be used as a departure runway.
- The existing southerly runway, 09R/27L would also be extended and would then be called 09C/27C. This would be the primary arrival runway.

Figure 6 represents the full build of this layout and also explains its usage.

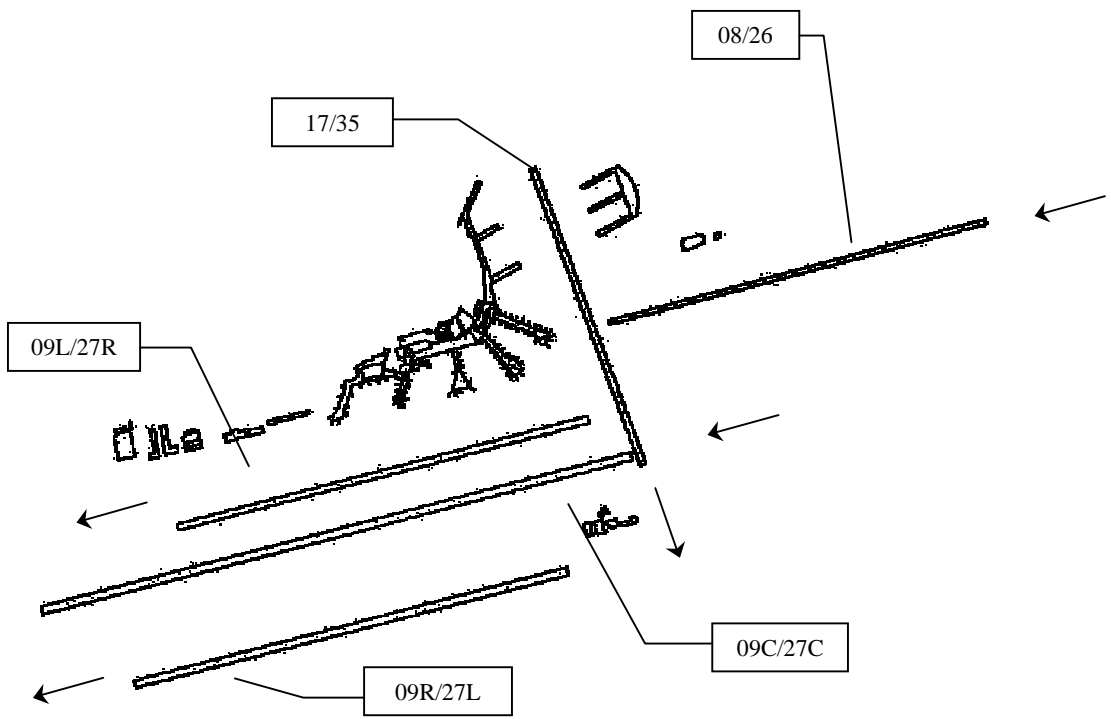


Figure 6: Parallel-1: West VFR Operations

4.2.2. Baseline Layout with 4th Parallel Runway (Parallel-2): This configuration is essentially the same as the Parallel-1 except that

- The crosswind runway, 17/35 would be converted to a taxiway in order to provide for easier taxiing to and from the northern aprons. Other advantages from avoiding the use of this runway would include the removal of the dependencies associated with it.
- 27R/09L would be as in the baseline scenario and not shifted south and west as in Parallel-1.
- Runway 08/26 would not be built to the full length as in Parallel-1 and would hence be unavailable for use by jets.

Figure 7 depicts this configuration and explains its westerly usage. Essentially, the usage of this configuration would be the same as that of Parallel-1 with the exception of runway 17/35.

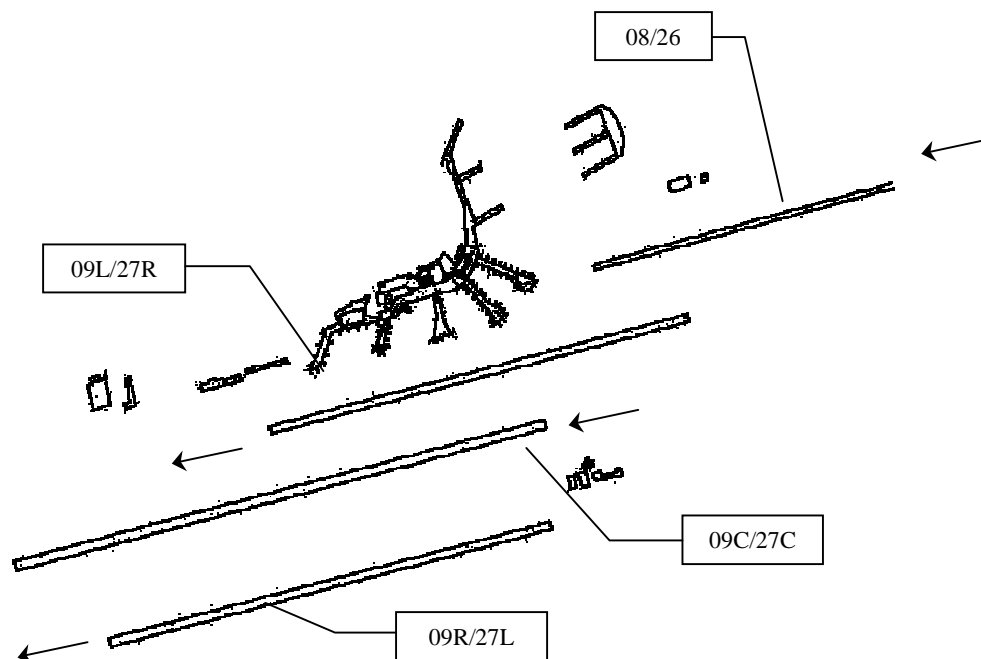


Figure 7: Parallel-2: West VFR Operations

4.3 Diagonal concept layouts:

4.3.1. Full-Build Diagonal Layout With 4 Runways (Diagonal-1):

- Two new pairs of close parallel runways separated by more than 4300 feet.
- The new runways would be oriented 30 degrees clockwise from 09C/27C.
- The terminal area in this concept would also be redesigned to a more symmetric one allowing more structured taxi patterns.
- The two inner runways, 11R/29L and 12L/30R would be used as departure runways.
- 11L/29R and 12R/30L, the two outer runways would be used as arrival runways.

Figure 8 represents the westerly usage of this configuration.

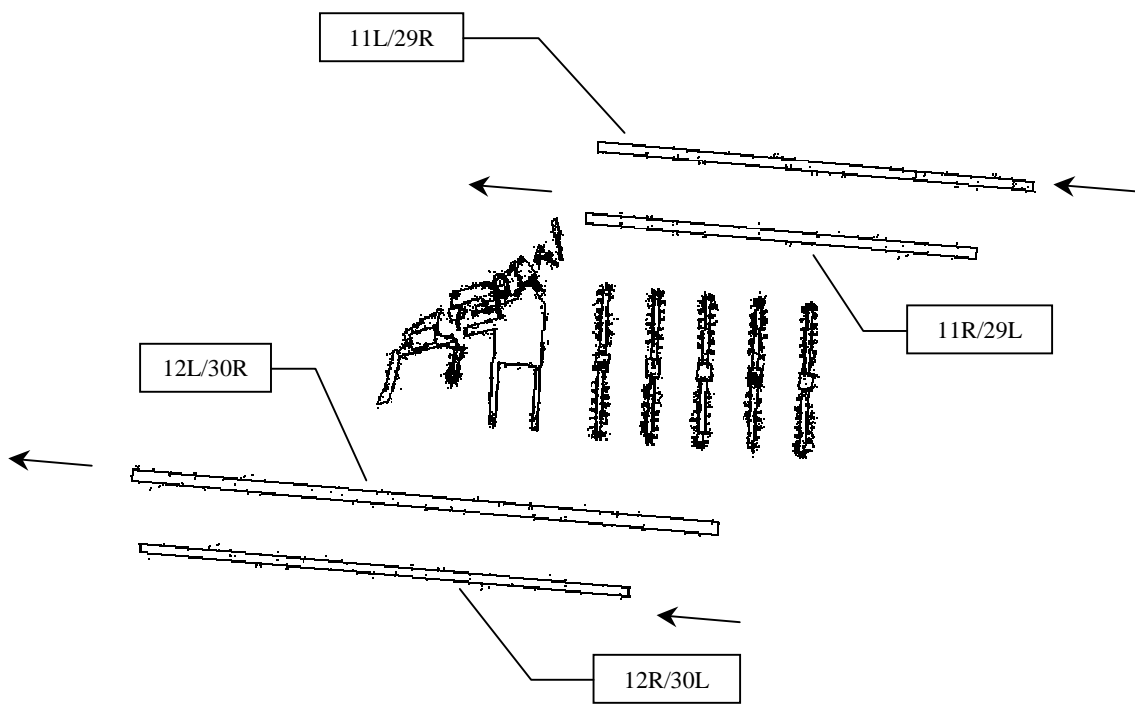


Figure 8: Diagonal-1: West VFR Operations

4.3.2. Full-Build Diagonal Layout With 3 Runways (Diagonal-2):

- This configuration is the same as the Diagonal-1 with the exception of the northernmost runway.
- Runway usage is similar to that of Diagonal-1 with runway 11R/29L being used as a dual use runway. Dual usage of a runway means the runway is used for arrivals as well as for departures. Departures are normally interleaved between arrivals.

Figure 9 depicts this layout and explains its usage.

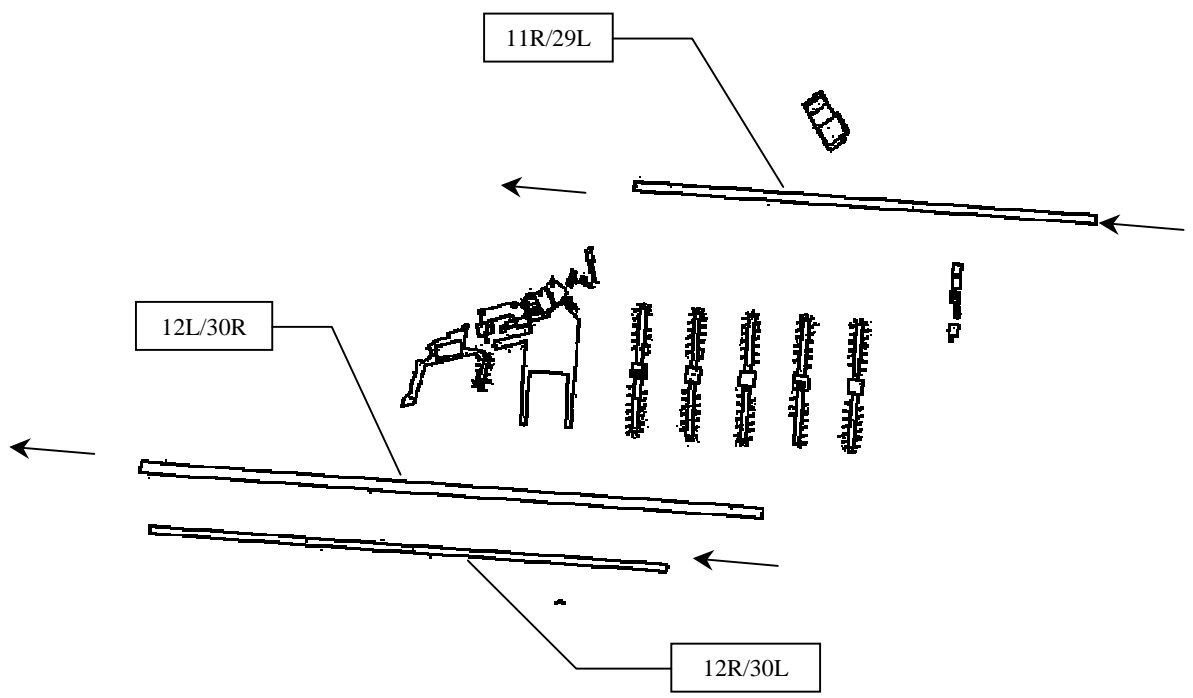


Figure 9: Diagonal-2: West VFR Operations

4.4 Simulation Methodology

4.4.1 Inputs

In TAAM, a number of inputs are required to carry out a simulation as indicated in section 2.3. The inputs, common to all the scenarios evaluated, were the routes, airports, waypoints and the traffic schedule. The routes, airports and waypoints are files in TAAM format that represent those in the current National Airspace System (NAS). Each of these inputs may be found in Appendix B.

To satisfy the assumption of an ever-present traffic flow the traffic schedule was restricted to a one-hour time frame with a total of 364 flights - equal arrivals and departures. The following represent the basis on which the schedule 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.

Appendix B provides the entire traffic schedule used including, flight number, aircraft type, market segment, origin and destination, cruising altitude, Estimated Time of Departure (ETD), Estimated Time of Arrival (ETA) and filed flight plan for each flight.

Inputs that were unique to each scenario included the airport layout, and rules governing the airport usage such as Air Traffic Control (ATC) and sequencing rules and taxiway, gate and runway usage rules. Instrument Departure Procedure (DP)/Standard Terminal Arrival (STAR) were input to guide aircraft to and from the departure and arrival runways. Again, the details of these inputs may be found in Appendix B.

4.4.2 Baseline Generation and Validation

The baseline was generated by gathering data and information for PHL from the contractors and the FAA at the airport. Gate allocation information was obtained to develop accurate aircraft terminal parking rules. Information from the tower was used to design accurate arrival and departure procedures and runway usage rules and assumptions.

The traffic schedule was developed from archived Enhanced Traffic Management System (ETMS) data for a day in 2001. Using a parsing utility developed at ERAU, the actual filed flight plans were extracted and converted into TAAM format. Timetables generated in this way provide an accurate departure to destination representation of flights that flew on that particular day.

The baseline scenario was validated in two ways:

1. *Face Validation*: Air traffic controllers at PHL Air Traffic Control Tower (ATCT) validated the model after observing the movement of aircraft in the baseline simulation. They agreed that the simulation reasonably represented operations as they are conducted in the usage configurations modeled.

2. *Empirical Validation*: Delay, arrival and departure rates, and taxi-in and taxi-out times from the simulation were compared with the actual values for the particular day simulated. These values were found to be comparable with an acceptable level of variance.

Mr. John Lane, ATC research specialist and TAAM expert at ERAU has acknowledged that this method of validation is widely accepted by airport operators. Past simulation analyses using TAAM, which have been validated in this manner, have proven very beneficial to a number of entities. More information on the benefits of using TAAM and case studies that illustrate these may be found at

<http://www.preston.net/products/TAAMcaseStudies.htm>. The above validations were achieved in the course of the primary simulation analysis. The validated simulation model has been used in the thesis with the necessary changes made to simulate the desired conditions.

4.4.3 Alternative Generation

The alternative simulations were performed with predicted 2020 activity levels and with a series of inflated timetables to measure activity. Basic runway operational configurations were discussed with PHL staff. Proposed layouts were developed from drawings provided by the contractor for both the diagonal and parallel concept.

This phase required a timetable that would represent 2020 activity levels and aircraft fleet mix. Predicted traffic levels and fleet mix were taken from the PHL Master Plan Forecast. Using an ERAU cloning utility, a timetable was generated using the baseline 2001 timetable as the

starting point. The original arrival and departure bank structure was generally maintained and exaggerated to accommodate the extra number of daily movements within the constraints imposed by accommodating the new fleet mix. Gate allocation information for 2020 was not available. However, new terminal layouts were included into the airport layouts and, where possible, aircraft were parked in the appropriate areas.

4.4.4 Determination of Capacity Metrics

The following is a description of the methodology used to simulate each of the previously discussed capacity measures. Table 1 provides a summary of the key differences in the simulation of each of these measures.

λ_{S1} : 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). This separation distance has been arrived at as a result of calibration of TAAM simulations to represent reality. 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). However, 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 previously 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. This simply means that aircraft depart in the order in which they arrive at the runway threshold. This is also TAAM’s default departure sequencing strategy.

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

When departure sequencing 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)

λ_{SU} : Finally, in determining λ_{SU} , the unconstrained capacity, the assumption of no ground constraints is simulated by turning taxiing off. The implementation of technological and procedural improvements is simulated as in λ_{S2} , by setting the terminal area radar separation to 2.8nm and the departure sequencing strategy as optimized. As mentioned before the only

constraints considered in computing this measure are those that are safety related. In TAAM, wake turbulence data and the associated separation standards are used to satisfy this assumption. The wake turbulence and separation standard information used in this project may be found in Appendix B.

Table 2: Key Differences in Simulation Methodology of the Capacity Measures

	λ_{S1}	λ_{S2}	λ_{SU}
Taxiing and gate usage	Yes	Yes	None
Radar Separation	3.0NM	2.8NM	2.8NM
Departure Sequencing Strategy	FIFO	Optimized	Optimized

5 RESULTS AND ANALYSIS

5.1 Results

Table 2 summarizes the saturation capacities under varying constraint levels for each of the scenarios evaluated. The detailed outputs from TAAM, showing the movements per hour and split up into aircraft categories, may be found in Appendix A

Table 3: Results

	λ_{S1}			λ_{S2}			λ_{SU}		
	Arrs	Deps	All	Arrs	Deps	All	Arrs	Deps	All
Baseline	56	61	117	69	61	130	69	67	136
Diagonal-1	77	86	163	84	88	172	84	90	174
Diagonal-2	75	62	137	78	65	143	78	69	147
Parallel-1	76	69	145	82	73	155	81	95	176
Parallel-2	77	69	146	80	70	150	80	82	162

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

Table 4: λ_{S1} vs. λ_{SU}

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

Table 5: λ_{S1} vs. λ_{S2}

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

Table 6: λ_{S2} vs. λ_{SU}

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

5.2 Analysis

As discussed in Section 1.1, TAAM does not lend itself well to running multiple iterations based on a random seed. The way randomization works in TAAM is to render a number of aircraft performance characteristics such as take-off mass, cruising level, fuel consumption, etc. as randomly variable between preset limits. Details of the randomization parameters may be found in Appendix B. Given the relationship between these various parameters and the extent to which each is varied, randomizing a TAAM simulation may end up constituting an entirely different scenario. Moreover, being randomized, it would be almost impossible to replicate the exact same conditions for each alternative being evaluated and as a result the samples of outputs would not be comparable.

In light of the above, statistical analysis has been excluded from this study. However, a possible method of conducting valid statistical analyses of TAAM simulation outputs are discussed in Section 7.

The following inferences are based on comparisons between the layouts within each concept and between the different concepts themselves.

5.2.1 Comparison between the Diagonal concept layouts - Diagonal-1 Vs. Diagonal-2:

1. Both layouts are largely similar with respect to the ratios evaluated.
2. Diagonal-1 is marginally better than Diagonal-2 with respect to,
 - a. Runway system capacity utilization (Figure 10) and

b. Efficiency in terms of taxiing and gate usage, as shown in Figure 11

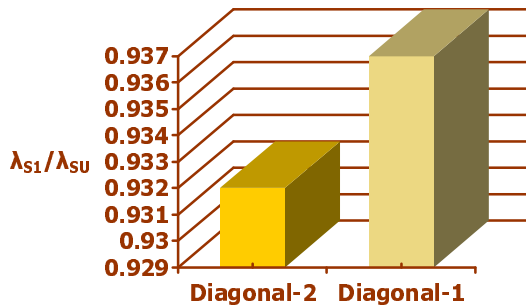


Figure 10: Diagonal Concept: $\lambda_{s1}/\lambda_{su}$

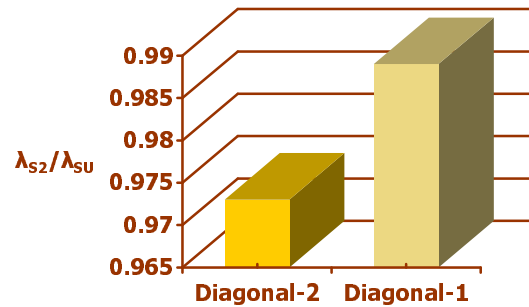


Figure 11: Diagonal Concept: $\lambda_{s2}/\lambda_{su}$

The fact that Diagonal-1 is marginally better than Diagonal-2 may be attributed to the presence of the extra northern runway in the former. This four parallel runway configuration eliminates the dual usage of the northern runway 11R/29L (as in Diagonal-2) and the related dependencies and runway occupancy restrictions. Furthermore, this allows for steady arrival and departure streams and lesser congestion in the arrival and departure lineup queues.

3. The Diagonal-2 configuration is marginally less sensitive to technological and procedural improvements in comparison to the Diagonal-1 as depicted in Figure 12.

This may be again explained by the dual usage of runway 11R/29L. In Diagonal-2 this runway is used for both arrivals and departures, which mitigates the effect of these improvements. The reason for this is that arrivals and departures on this runway are interdependent besides being governed by other technological and procedural constraints. These improvements have a greater impact on the Diagonal-1 configuration, since only dedicated

arrival and departure runways are used here. Consequently, the practice of departure optimization and the reduction in the “buffer” in aircraft separation (explained in Section 4.4.4) have a more noticeable effect on this configuration.

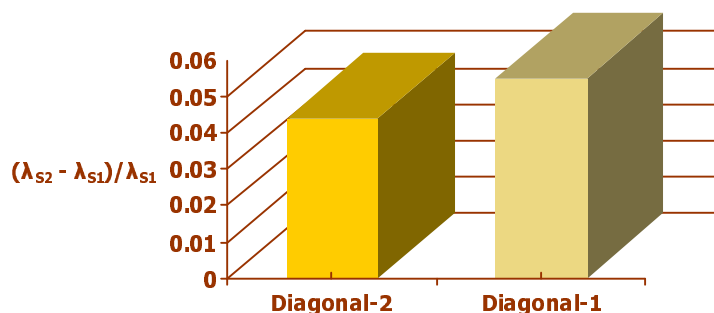
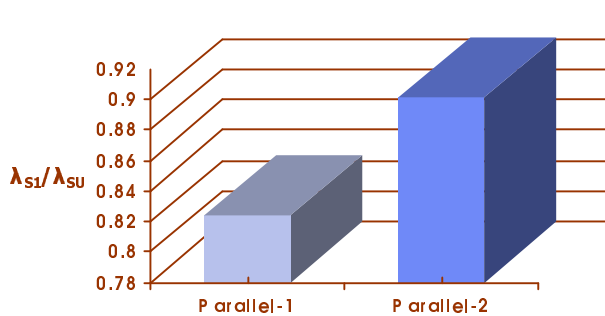
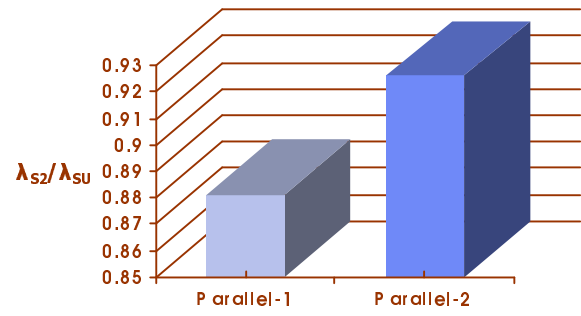


Figure 12: Diagonal Concept: $(\lambda_{S2} - \lambda_{S1}) / \lambda_{S1}$

5.2.2 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 (Figure 13) and
 - b. Efficiency in terms of taxiing and gate usage (Figure 14).

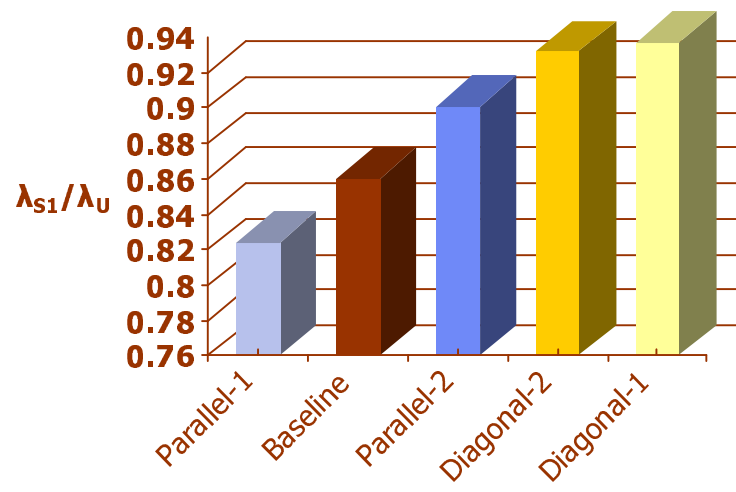
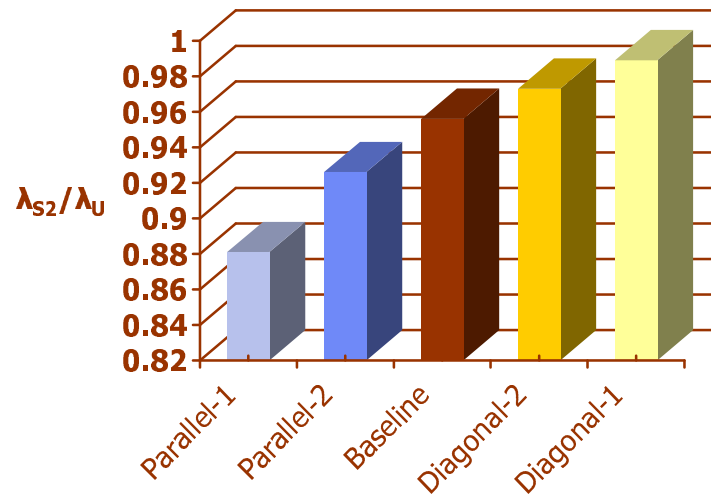
Parallel-2 is better in terms of overall utilization of potential capacity because of the absence of the crosswind runway 17/35. This eliminates the related dependencies, which in the fully constrained scenario of Parallel-1 restrict arrivals to 08/26 and 09C/27C as well as departures from 17/35.

Figure 13: Parallel Concept: $\lambda_{s1}/\lambda_{su}$ Figure 14: Parallel Concept: $\lambda_{s2}/\lambda_{su}$

The use of the crosswind runway 17/35 as a taxiway provides for more efficient taxiing to and from the northern aprons. Further, not using this runway for departures also eliminates the lineup queues associated with it. Because the runway 17/35 threshold is so close to the northern aprons, these lineup queues can cause a significant amount of congestion in Parallel-1. As a result, the Parallel-2 configuration emerges as more efficient in terms of taxiing and gate usage in comparison to Parallel-1.

5.2.3 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, as may be seen in Figure 15, and
 - b. Efficiency in terms of taxiing and gate usage (Figure 16).

Figure 15: All: $\lambda_{S1}/\lambda_{SU}$ Figure 16: All: $\lambda_{S2}/\lambda_{SU}$

This is 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. In either Diagonal concept layout no runway crossing is required for aircraft that are departing. This ensures a continuous feed to the departure runways, which is not influenced by the arrival flow. In contrast, in the baseline as well as in both Parallel layouts, departures from runway 09R/27L are required to cross other active runways. During non-peak hours, runway crossing does not pose a problem. However, during periods of heavy traffic, this causes considerable congestion.

2. The Baseline is better than either parallel concept layout with respect to design factors affecting taxiing and gate usage, which is again depicted by Figure 16.

This is a result of the greater number of runways that departures have to cross in either parallel concept layout. For example, in both Parallel layouts, departures on 27L have to cross the departure runway 27R, as well as, the arrival runway 27C. In the baseline, these departures have to cross only the arrival runway 27R. In the event of continuous arrival and departure flows on these runways, the feed to 27L is greatly constrained in the Parallel layouts. The solution to this would involve holding the departures on 27R and arrivals on 27C 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 most sensitive to technological and procedural improvements as may be seen in Figure 17.

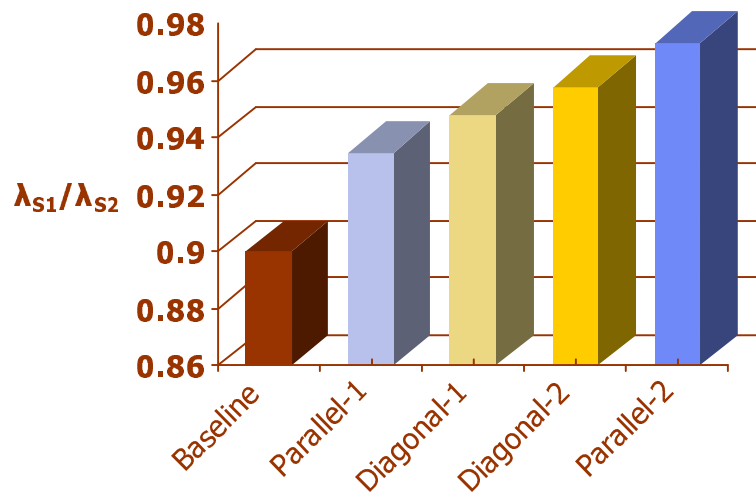


Figure 17: All: $\lambda_{s1}/\lambda_{s2}$

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.

As discussed in Section 2.1, the concept of unconstrained capacity represents the maximum possible capacity of a given runway configuration. Figure 18 shows the absolute values of this measure as determined for each of the scenarios evaluated here.

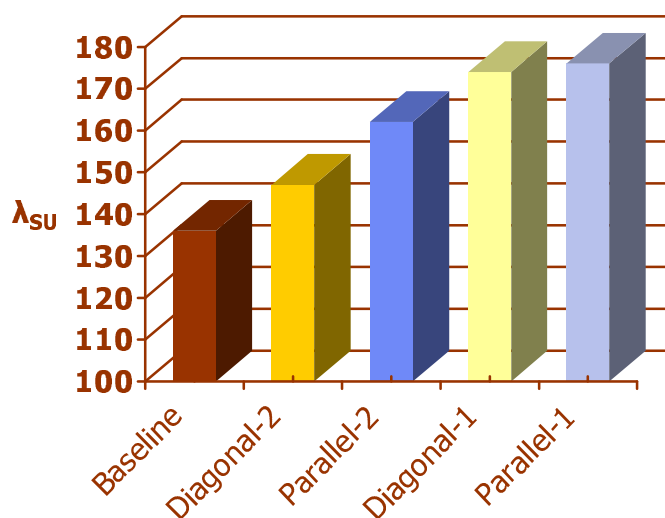


Figure 18: All: λ_{SU}

From this figure it is obvious that the best candidate for implementation is either the Diagonal-1 or the Parallel-1 layout. However, from the analysis presented in Section 5.2.3 using Figure 16, the Parallel-1 layout is the worst with regard to design efficiency in terms of taxiing and gate usage. Unless the taxiway and terminal/apron designs are changed, the Parallel-1 would not be a good option despite it delivering the maximum attainable capacity among the layouts evaluated. The point here is that the ratio analyses done in this study use theoretical concepts such as unconstrained capacity to evaluate the practical viability of the layouts. Considered in isolation, each of the capacity measures determined here could possibly portray an incomplete picture of the relative performance of the layouts being evaluated.

6. CONCLUSIONS

This study leads to conclusions in the specific context of PHL as well as on a more generic scale. With respect to Philadelphia International Airport, the main conclusion is that, the best expansion alternative based on the aspects studied here, lies in the Diagonal concept. Between the two full build Diagonal layouts evaluated, the Diagonal-1 configuration with the four parallel runways would be more preferable for two reasons. First, the extra runway in this layout provides more absolute capacity. Second, the four parallel runway configuration of Diagonal-1 allows runways to be dedicated to either arrivals or departures and provides for a smooth flow of traffic.

On a more generic scale, this study indicates that the dependencies imposed on a layout by a crosswind runway render it more sensitive to reductions in airborne separation between aircraft. Another important conclusion may be made from the viewpoint of taxiway and terminal design. A symmetric design seems to ease the flow of traffic on the ground in a considerable manner. Also a layout design that eliminates or at least minimizes runway crossing has a positive impact on both taxiing as well as on runway throughput as discussed in Section 5.2.3.

7. SCOPE FOR FUTURE WORK

Building on the discussions in Sections 1.1 and 5, reliable samples of TAAM simulation outputs may be generated by using discrete sets of inputs. For example, a set of discrete traffic schedules may be used to generate a sample of TAAM outputs. Using the same set of traffic schedules for the different alternatives being evaluated would provide comparable samples, as a set of discrete conditions would have been replicated for each scenario. Other inputs such as the routes, waypoints, airports, etc. may also be varied based on realistic or theoretical predictions of the future of these. Generating discrete inputs to TAAM is a time consuming proposition and has been excluded from the scope of this study. This may be undertaken as a separate study and might provide more insight into the impact of different airport layout designs and ATM technologies and procedures.

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APPENDIX A

Scenario: Baseline

1. Fully Constrained Capacity (λ_{S1})

a. Arrivals

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	2	0	2	0	4
10:00-11:00	7	25	1	19	4	56
11:00-12:00	5	20	5	18	3	51
12:00-13:00	4	26	0	19	5	54
13:00-14:00	6	9	0	4	2	21
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	7	22	6	26	0	61
11:00-12:00	11	20	8	17	0	56
12:00-13:00	2	35	9	7	0	53
13:00-14:00	0	1	4	0	0	5
Total	20	78	27	50	0	175

c. All Movements

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	2	0	2	0	4
10:00-11:00	14	47	7	45	4	117
11:00-12:00	16	40	13	35	3	107
12:00-13:00	6	61	9	26	5	107
13:00-14:00	6	10	4	4	2	26
Total	42	160	33	112	14	361

2. Semi Constrained Capacity (λ_{S2})

a. Arrivals

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	2	0	4	0	6
10:00-11:00	8	29	3	23	6	69
11:00-12:00	6	30	3	29	6	74
12:00-13:00	8	21	0	6	2	37
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	7	24	6	24	0	61
11:00-12:00	12	23	4	10	0	49
12:00-13:00	1	27	17	14	0	59
13:00-14:00	0	4	0	2	0	6
Total	20	78	27	50	0	175

c. All Movements

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	2	0	4	0	6
10:00-11:00	15	53	9	47	6	130
11:00-12:00	18	53	7	39	6	123
12:00-13:00	9	48	17	20	2	96
13:00-14:00	0	4	0	2	0	6
Total	42	160	33	112	14	361

3. Unconstrained Capacity (λ_{SU})

a. Arrivals

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	0	0	1	0	1
10:00-11:00	8	30	2	25	4	69
11:00-12:00	5	24	4	20	5	58
12:00-13:00	9	28	0	16	5	58
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	6	35	4	22	0	67
11:00-12:00	8	16	21	20	0	65
12:00-13:00	6	26	2	8	0	42
Total	20	77	27	50	0	174

c. All Movements

TAAM Report: KPHL Movements: Baseline						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	0	0	1	0	1
10:00-11:00	14	65	6	47	4	136
11:00-12:00	13	40	25	40	5	123
12:00-13:00	15	54	2	24	5	100
Total	42	159	33	112	14	360

Scenario: Parallel-1

1. Fully Constrained Capacity (λ_{S1})

a. Arrivals

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	0	0	1	1	2
10:00-11:00	8	31	2	30	5	76
11:00-12:00	6	42	4	21	4	77
12:00-13:00	8	9	0	10	4	31
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	9	33	5	22	0	69
11:00-12:00	11	14	1	4	0	30
12:00-13:00	0	7	8	12	0	27
13:00-14:00	0	22	13	11	0	46
Total	20	76	27	49	0	172

c. All Movements

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	0	0	1	1	2
10:00-11:00	17	64	7	52	5	145
11:00-12:00	17	56	5	25	4	107
12:00-13:00	8	16	8	22	4	58
13:00-14:00	0	22	13	11	0	46
Total	42	158	33	111	14	358

2. Semi Constrained Capacity (λ_{S2})

a. Arrivals

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	1	1	0	3	1	6
10:00-11:00	7	37	2	31	5	82
11:00-12:00	6	41	4	21	6	78
12:00-13:00	8	3	0	7	2	20
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	12	33	6	22	0	73
11:00-12:00	7	26	4	7	0	44
12:00-13:00	1	19	14	17	0	51
13:00-14:00	0	0	2	4	0	6
Total	20	78	26	50	0	174

c. All Movements

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	1	1	0	3	1	6
10:00-11:00	19	70	8	53	5	155
11:00-12:00	13	67	8	28	6	122
12:00-13:00	9	22	14	24	2	71
13:00-14:00	0	0	2	4	0	6
Total	42	160	32	112	14	360

3. Unconstrained Capacity (λ_{SU})

a. Arrivals

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	0	0	1	1	2
10:00-11:00	6	37	2	31	5	81
11:00-12:00	8	40	4	19	5	76
12:00-13:00	8	5	0	11	3	27
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	12	49	10	24	0	95
11:00-12:00	8	20	12	14	0	54
12:00-13:00	0	9	5	12	0	26
Total	20	78	27	50	0	175

c. All Movements

TAAM Report: KPHL Movements: Parallel-1						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	0	0	1	1	2
10:00-11:00	18	86	12	55	5	176
11:00-12:00	16	60	16	33	5	130
12:00-13:00	8	14	5	23	3	53
Total	42	160	33	112	14	361

Scenario: Parallel-2

1. Fully Constrained Capacity (λ_{S1})

a. Arrivals

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	1	0	5	1	7
10:00-11:00	1	36	7	30	3	77
11:00-12:00	4	36	1	8	4	53
12:00-13:00	7	19	2	4	5	37
13:00-14:00	3	6	0	3	1	13
Total	15	98	10	50	14	187

b. Departures

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	6	34	16	13	0	69
11:00-12:00	6	29	25	15	0	75
12:00-13:00	8	15	4	0	0	27
13:00-14:00	0	0	0	4	0	4
Total	20	78	45	32	0	175

c. All Movements

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	1	0	5	1	7
10:00-11:00	7	70	23	43	3	146
11:00-12:00	10	65	26	23	4	128
12:00-13:00	15	34	6	4	5	64
13:00-14:00	3	6	0	7	1	17
Total	35	176	55	82	14	362

2. Semi Constrained Capacity (λ_{S2})

a. Arrivals

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	1	0	6	0	7
10:00-11:00	1	36	7	31	5	80
11:00-12:00	4	38	1	10	3	56
12:00-13:00	9	23	2	2	5	41
13:00-14:00	1	0	0	1	1	3
Total	15	98	10	50	14	187

b. Departures

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	5	33	20	12	0	70
11:00-12:00	7	31	25	14	0	77
12:00-13:00	8	14	0	5	0	27
13:00-14:00	0	0	0	1	0	1
Total	20	78	45	32	0	175

c. All Movements

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	1	0	6	0	7
10:00-11:00	6	69	27	43	5	150
11:00-12:00	11	69	26	24	3	133
12:00-13:00	17	37	2	7	5	68
13:00-14:00	1	0	0	2	1	4
Total	35	176	55	82	14	362

2. Unconstrained Capacity (λ_{SU})

a. Arrivals

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	1	0	6	0	7
10:00-11:00	1	36	7	31	5	80
11:00-12:00	4	38	1	10	3	56
12:00-13:00	9	23	2	2	5	41
13:00-14:00	1	0	0	1	1	3
Total	15	98	10	50	14	187

b. Departures

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	9	39	18	16	0	82
11:00-12:00	8	30	22	11	0	71
12:00-13:00	3	9	5	5	0	22
Total	20	78	45	32	0	175

c. All Movements

TAAM Report: KPHL Movements: Parallel-2						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	1	0	6	0	7
10:00-11:00	10	75	25	47	5	162
11:00-12:00	12	68	23	21	3	127
12:00-13:00	12	32	7	7	5	63
13:00-14:00	1	0	0	1	1	3
Total	35	176	55	82	14	362

Scenario: Diagonal-1

1. Fully Constrained Capacity (λ_{S1})

a. Arrivals

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	0	0	2	0	2
10:00-11:00	8	32	3	25	5	73
11:00-12:00	8	34	3	27	5	77
12:00-13:00	6	16	0	8	4	34
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	9	35	5	17	0	66
11:00-12:00	5	39	14	28	0	86
12:00-13:00	6	3	8	5	0	22
Total	20	77	27	50	0	174

c. All Movements

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	0	0	0	2	0	2
10:00-11:00	17	67	8	42	5	139
11:00-12:00	13	73	17	55	5	163
12:00-13:00	12	19	8	13	4	56
Total	42	159	33	112	14	360

2. Semi Constrained Capacity (λ_{S2})

a. Arrivals

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	1	1	0	3	0	5
10:00-11:00	9	32	4	32	5	82
11:00-12:00	10	39	2	24	9	84
12:00-13:00	2	10	0	3	0	15
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	11	32	4	20	0	67
11:00-12:00	7	38	16	27	0	88
12:00-13:00	2	8	6	2	0	18
Total	20	78	26	49	0	173

c. All Movements

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	1	1	0	3	0	5
10:00-11:00	20	64	8	52	5	149
11:00-12:00	17	77	18	51	9	172
12:00-13:00	4	18	6	5	0	33
Total	42	160	32	111	14	359

3. Unconstrained Capacity (λ_{SU})

a. Arrivals

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	1	2	0	3	0	6
10:00-11:00	10	34	4	31	5	84
11:00-12:00	9	37	2	26	9	83
12:00-13:00	2	9	0	2	0	13
Total	22	82	6	62	14	186

b. Departures

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
10:00-11:00	10	43	7	30	0	90
11:00-12:00	10	28	18	20	0	76
12:00-13:00	0	7	2	0	0	9
Total	20	78	27	50	0	175

c. All Movements

TAAM Report: KPHL Movements: Diagonal-1						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	1	2	0	3	0	6
10:00-11:00	20	77	11	61	5	174
11:00-12:00	19	65	20	46	9	159
12:00-13:00	2	16	2	2	0	22
Total	42	160	33	112	14	361

Scenario: Diagonal-2

1. Fully Constrained Capacity (λ_{S1})

a. Arrivals

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
8:00- 9:00	0	0	0	4	0	4
9:00-10:00	3	39	3	22	5	72
10:00-11:00	4	40	4	21	6	75
11:00-12:00	8	19	3	3	3	36
Total	15	98	10	50	14	187

b. Departures

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	4	29	18	6	0	57
10:00-11:00	3	29	18	12	0	62
11:00-12:00	13	13	9	11	0	46
12:00-13:00	0	1	0	0	0	1
Total	20	72	45	29	0	166

c. All Movements

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
8:00- 9:00	0	0	0	4	0	4
9:00-10:00	7	68	21	28	5	129
10:00-11:00	7	69	22	33	6	137
11:00-12:00	21	32	12	14	3	82
12:00-13:00	0	1	0	0	0	1
Total	35	170	55	79	14	353

2. Semi Constrained Capacity (λ_{S2})

a. Arrivals

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
8:00- 9:00	0	1	0	3	0	4
9:00-10:00	2	44	3	24	4	77
10:00-11:00	7	38	6	20	7	78
11:00-12:00	6	15	1	3	3	28
Total	15	98	10	50	14	187

b. Departures

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	4	27	13	9	0	53
10:00-11:00	4	26	26	9	0	65
11:00-12:00	12	24	5	10	0	51
Total	20	77	44	28	0	169

c. All Movements

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
8:00- 9:00	0	1	0	3	0	4
9:00-10:00	6	71	16	33	4	130
10:00-11:00	11	64	32	29	7	143
11:00-12:00	18	39	6	13	3	79
Total	35	175	54	78	14	356

3. Unconstrained Capacity (λ_{SU})

a. Arrivals

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, Arrivals						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
8:00- 9:00	0	1	0	3	0	4
9:00-10:00	2	44	3	24	4	77
10:00-11:00	7	38	6	20	7	78
11:00-12:00	6	15	1	3	3	28
Total	15	98	10	50	14	187

b. Departures

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, Departures						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
9:00-10:00	8	28	16	7	0	59
10:00-11:00	5	32	12	20	0	69
11:00-12:00	7	18	17	5	0	47
Total	20	78	45	32	0	175

c. All Movements

TAAM Report: KPHL Movements: Diagonal-2						
All Categories, All Market Segments, All Movements						
Time	Widebody Jets	Narrowbody Jets	Light Jets	Turboprops	Piston Engine	All Categories
8:00- 9:00	0	1	0	3	0	4
9:00-10:00	10	72	19	31	4	136
10:00-11:00	12	70	18	40	7	147
11:00-12:00	13	33	18	8	3	75
Total	35	176	55	82	14	362

APPENDIX B

All the inputs to the TAAM simulations have been provided in the attached CD-ROM. Listed below are the file names of the individual inputs that are provided separately in the CD-ROM. Besides these, the project files of each of the scenarios simulated are also provided. Note, these projects can only run on a machine that has an active TAAM license.

Inputs:

1. Traffic Schedule: Thesis.ACF
2. Routes: Thesis.RTS
3. Airports: Thesis.APT
4. Waypoints: Thesis.WPT
5. Wake Turbulence Characteristics: wake_turb.data
6. Separation Standards: sep_stand.data
7. Randomization: randomization.dat

Projects:

1. Baseline:
 - i. base_fullyconstrained.prj
 - ii. base_semiconstrained.prj
 - iii. base_unconstrained.prj

2. Parallel-1:
 - i. P1_fullyconstrained.prj
 - ii. P1_semiconstrained.prj
 - iii. P1_unconstrained.prj
3. Parallel-2:
 - i. P2_fullyconstrained.prj
 - ii. P2_semiconstrained.prj
 - iii. P2_unconstrained.prj
4. Diagonal-1:
 - i. D1_fullyconstrained.prj
 - ii. D1_semiconstrained.prj
 - iii. D1_unconstrained.prj
5. Diagonal-1:
 - i. D2_fullyconstrained.prj
 - ii. D2_semiconstrained.prj
 - iii. D2_unconstrained.prj

APPENDIX C

This study has been accepted for publishing in the *Proceedings of the 2002 Winter Simulation Conference*, E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, eds. The study will be presented in San Diego, California between the 8th and 11th of December 2002.

Following is the email received from WSC confirming acceptance of the paper for presentation.

-----Original Message-----

From: wsc02@ku.edu [mailto:wsc02@ku.edu]
Sent: Friday, June 14, 2002 10:23 AM
To: bazargam@erau.edu
Subject: Paper Status for WSC 2002

Title: A SIMULATION STUDY TO INVESTIGATE RUNWAY CAPACITY USING TAAM

Paper ID: bazarganm-1

Congratulations!! Your paper titled above has been accepted for presentation at the 2002 Winter Simulation Conference (WSC'02) to be held in San Diego, CA, USA, December 8-11. Included with this message are the reviewers' comments and suggested changes, if any.

To complete the final submission of your paper for presentation at WSC'02, you must submit an electronic version of the paper in the native word processor (Microsoft Word or LaTeX) format. We would like to receive your paper by July 8, and absolutely no later than July 15, 2002. In preparing your final paper, we encourage you to use the templates and checklist provided in the author kit on the Winter Simulation Conference website, www.wintersim.org. Papers not conforming to the WSC specifications will be returned to the author for modification.

Your final paper will be submitted via the conference website, www.wintersim.org. The native word processor electronic file (Microsoft Word or LaTeX) is required for your paper to be included in WSC'02 Proceedings. Please also submit a PDF file, which will be used to aid the Proceedings editors in their work.

At the time of submittal, you will also fill out forms to provide author contact information and paper title and abstract. The final conference program and abstract book will be prepared using the information on the website.

If you have any questions regarding completing your WSC'02 submission, please contact one of the Proceedings Editors, Enver Yucesan (enver.yucesan@insead.edu) or Chun-Hung Chen (cchen9@gmu.edu).

Thank you for your contribution to the conference. I look forward to seeing you at WSC'02.

John Charnes
Program Chair, WSC'02
wsc02@ku.edu