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Framework for the Assessment of Capacity and Throughput Technologies

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ABSTRACT

The demand for air travel is expanding beyond the capacity of existing airports and air traffic control. This excess traffic often results in delays and compromised safety. Therefore, a number of initiatives to improve airport capacity and throughput have been proposed. However, in order to assess the impact of these technologies on commercial air traffic one must move beyond the vehicle to a system-of-systems point of view. This top-level point of view must include consideration of the aircraft, airports, air traffic management and airlines that make up the airspace system. In addition to the analyses of each of these components and their interactions, a thorough investigation of capacity and throughput technologies requires due consideration of other pressures such as economics, safety and government regulations. Furthermore, the air traffic system is inherently variable with constant changes in everything from fuel prices to the weather. Thus, the development of a modeling environment that encompasses all these sources of uncertainty and the methodology to be used in a probabilistic evaluation of technological impacts are the subject of this paper.

INTRODUCTION

The globalization of the worldwide economy coupled with airline deregulation and trade expansion have caused a boom in air travel. Market forecasts by major commercial airplane manufacturers indicate that this increase in demand is expected to continue for the next 20 years with a world average growth of nearly 5% [1]. However, many airports are quickly approaching maximum capacity and delays have become an everyday occurrence. The projected growth in air cargo, which is expected to triple in the next twenty years due to the increase in e-commerce, and the favoring of single-aisle and regional jets to meet demand through increased departure frequency further aggravate the capacity problem [1][2][3]. Failure to address capacity concerns and the subsequent delays could lead to loss of revenue and eventually to a loss of market-share to other transportation methods such as high speed rail [1][2].

A number of approaches have been suggested to remedy congestion problems ranging from the introduction of runway independent aircraft to radical changes in airline and Federal Aviation Administration (FAA) policies. All of these tactics show promise of significant benefits, but they also involve significant risk. The realization of those benefits and the assessment of those risks can often only be estimated from a total airspace point of view. Therefore, a methodology capable of assessing quantitatively and qualitatively the effects of proposed capacity improvements, while considering safety and cost, and accounting for the variability of the airspace environment, is of outmost importance.

INTERDEPENDANT RESEARCH AREAS

The National Airspace System is made up of a number of entities with conflicting interests. Airline strategies often conflict with airport and Air Traffic Control (ATC) concerns. As an example, the recent increase in regional jet departures at peak times in the LaGuardia airport, and the resulting delays, have forced the airport authorities to impose a limit on the number of flights that can use the airport at those times of the day [4]. Unfortunately, when analyzing solutions to the NAS congestion problem researchers often focus on a single aspect of the problem, without thoroughly considering the effects a change in one of the NAS components will have on the other pieces of the air transportation puzzle. One of the solutions to limited airport capacity and increased demand currently being pursued by the European aircraft manufacturer Airbus is the use of very large aircraft capable of carrying more than 400 passengers per departure. In developing this aircraft Airbus has considered the airline tendency to favor increased frequency rather than increased seats per departure, and has even attempted to address some of the airport compatibility issues raised by such a large aircraft. However, due consideration must also be paid to the vortices being shed by heavy aircraft, and the impact such an airplane would have in the arrival stream of a particular airport. If arrival separations have to be increased to maintain safety and comply with ATC rules, the advantages of the increased seats per departure may be offset by the decreased arrival capacity.

Figure 1 illustrates the various components of the NAS, and adds three considerations which are vital when assessing capacity and throughput technologies: Safety, Environment and Economics.

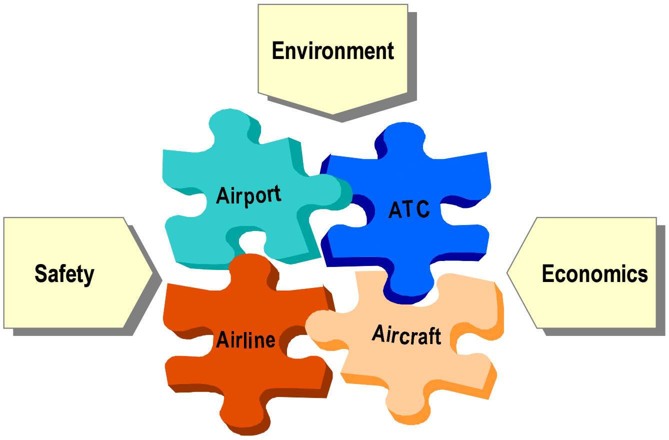

Figure 1: Interdependent NAS components

Economics are the driver behind the capacity problem. The increase in demand is directly related to the economic well-being of the communities being served and their Gross Domestic Product (GDP) [1][2]. Profit and market-share drive the airline schedules and fares. It is, in fact, the fear of lost revenues due to delays that has brought capacity concerns to the forefront.

The environment in terms of governmental and community pressures can also influence airport capacity greatly. Community noise has become an increasing concern in the neighborhoods surrounding major airports to the point that arrival paths are being diverted to avoid populated areas, with the subsequent efficiency loss [5]. On the other hand, the community needs for air travel can prompt government action such as the recent approval of the AIR21 bill that provides funds for airport improvement and the inclusion of runway independent aircraft in ATC procedures [6][7][8].

Safety can be viewed as a capacity constraint. It is safety that dictates aircraft separation on arrival, a major traffic volume limitation. It is also safety that prescribes bad weather procedures further straining system capacity. New technologies designed to relieve congestion will not be implemented unless they demonstrate a good safety record. Even more, safety must be improved if capacity is to increase; today's accident rates would result in a major accident occurring every three days at 2005 demand levels [9]. Thus, an assessment of capacity and throughput technologies without due consideration to safety issues would not only be incomplete, but entirely unacceptable.

INHERENTLY UNCERTAIN SYSTEM

A thorough analysis of the NAS is further complicated by the variability it is subject to. The economic environment can fluctuate widely with periods of economic boom alternating with phases of recession, influencing GDP values accordingly, and affecting not only the demand for air travel, but also the revenue yield that can be obtained without loss of market-share. Furthermore, many of the day-to-day costs in the NAS are driven by factors beyond an analyst's control, such as OPEC fuel production levels or labor union agreements. Government policies, often driven by electoral polls, can also have a great influence on the funds available for ATC improvements. These factors influence both demand and capacity, but capacity is even more deeply affected by weather, which judging by weather forecasts is completely unpredictable.

The inherent uncertainty in the system alone would justify a statistical approach to the capacity problem, yielding results in terms of probabilities, rather than deterministic values. But an additional degree of imprecision is also induced by the fidelity of the modeling codes used, as accuracy is traded off with model efficiency and technologies push the system beyond existing databases. Furthermore, the forecasted impacts of technologies which are still in the development stage are often not entirely reliable, and a probability associated to the potential improvement is often preferred to a deterministic impact prediction. This uncertainty in the potential effect of a technology also applies to its negative impacts, which are often overlooked or not researched as thoroughly.

MODELING THE NAS

The need for a comprehensive NAS model that places aircraft within airline fleets, and those airlines within a competitive environment under airport and ATC restrictions has been established. It has been further determined that such a model must also include economic, safety and environmental impact assessments. And the model must be versatile enough to accept a statistical treatment of the variability existing within the NAS.

The approach taken by the authors involves both existing sub-models and new model creation. It is the interactions among these sub-models and their compatibility that will present the foremost challenge in the establishment of an integrated NAS model, as well as the collection of data for the design of the new models.

A description of the models under consideration follows including their strong and weak points, and certain interactions.

Aircraft

The two basic options for meeting increased demand at a particular airport are to increase the number of operations, assuming this does not signify more small aircraft, or to increase the number of seats served per operation. Both of these approaches are being investigated from the aircraft point of view. The aircraft manufacturer, Airbus, is developing a range of very large aircraft serving over 400 passengers per departure, as well as cargo and combi configurations. NASA is sponsoring the Short Haul Civil Tilt-Rotor (SHCTR) program, which aims to introduce runway independent aircraft as a way to increase the number of operations possible at an airport without changes to the airport infrastructure or the air traffic control system. Although both of these alternatives are sound congestion solutions, they both entail a number of issues to be resolved when considering the NAS as a whole.

Very large aircraft have raised concerns when considering airport compatibility in terms of runway length and strength, as well as taxiway and gate suitability [10][11]. Another point raised by such a heavy aircraft is vortex generation and its effect on arrival and departure separations. This directly affects ATC and safety. Furthermore, noise restrictions will have to be met introducing another constraint in the design. This noise constraint is one shared by the SHCTR; in fact, low-noise rotors will be necessary if the CTR is to be integrated into the NAS. Safety introduces a further difficulty in the design of this V-STOL aircraft due to its unique design, especially in terms of contingency power [12]. The operation of the tilt-rotor may also pose challenges to ATC if these aircraft are to operate at existing airports.

These are just two examples of aircraft under development whose benefits and potential drawbacks can only be assessed from a system of systems point of view. But modeling of the aircraft is not only important when considering new aircraft types such as these. Many of the technologies proposed for the improvement of ATC, or for environmental concerns such as noise, require that additional equipment be placed in aircraft within the NAS. This equipment adds cost and weight to the aircraft, a negative effect that is often overlooked when considering the impact of these technologies. Thus, the ability to model both new and existing aircraft to a good level of detail is necessary to define the aircraft operating within the NAS and assess capacity related technologies.

The authors propose to use FLOPS (FLight OPtimization System) as the model of choice for the definition of fixed wing aircraft. This synthesis and sizing code originally developed by NASA has been extensively modified at the Aerospace Systems Design Laboratory (ASDL) to expand its capabilities. Currently FLOPS is capable of scaling aircraft configurations, in terms of geometry, weights, and propulsion requirements, to meet a specified mission. Beyond this basic sizing capability FLOPS also includes a detailed takeoff and landing module which includes all current FAA safety requirements. Furthermore, this model is also linked to a noise module capable of calculating the noise footprint area of a given aircraft. This information is invaluable when considering the introduction of new aircraft to airports surrounded by residential areas. And the economic impact of changes on the aircraft is accounted for through the link of FLOPS with ALCCA (Aircraft Life Cycle Cost Analysis). FLOPS has also been used by ASDL in previous technology assessment projects, and contains a number of technology dials referred to as Kappa Factors. These Kappa factors represent a percent increase or decrease in a particular performance measure. All of these capabilities coupled with the authors' familiarity with the FLOPS code make it a candidate to model the aircraft portion of the NAS.

Airports

One of the most obvious options to relieve congestion at an airport is the construction of additional runways. However, runway construction is an expensive proposition, and the capacity added may be jeopardized when the interaction with other runways, especially in bad weather conditions, is taken into account. Furthermore, the construction of a new runway may result in longer transit to the gates and complication to the ground traffic at the airport. Noise restrictions and community pressures may also limit the feasibility of such an option in terms of land availability and air traffic paths. In addition, the airport ATC may need to expand to absorb the additional traffic arriving and departing from the new runway, an additional cost that must be accounted for.

The situation at each airport is as different as their prevailing winds and surrounding landscape. Therefore, in modeling the airports it is not reasonable to use a generic 'landing strip' model. The number of runways and their orientation, the terminal layout, the approach and departure paths, are all factors that affect the capacity of an airport. Therefore, the authors intend to utilize the capacity and delay models for major hub airports developed at the Logistics Management Institute (LMI). These models are similar in structure, but differ from airport to airport in terms of noise restrictions and runway combinations.

The first step in using the capacity LMI models is to provide information about the aircraft mix utilizing the airport, the environment that the airport is subject to, and the separation matrices dictated by ATC. An initial calculation is done to find single runway capacities based on the probability dictated aircraft sequencing, the approach, departure speeds and Runway Occupancy Times (ROT) of the aircraft types defined, and the separations that must be maintained to comply with FAA rules. When noise or other restrictions dictate longer approach or departure paths this is also taken into account. The single runway occupancies are subsequently combined according to the airport runway configurations, not simply in an additive manner. The configurations that yield the highest capacity are then used to generate airport Pareto frontiers for each weather condition. The Pareto frontiers are displayed as a curve of departures vs. arrivals generally defined by a number of points (see Figure 2). The arrivals push, the departure push, the balanced arrival/departure point, the free arrivals point and the free departures point are some of these points. The arrivals push represents the maximum number of aircraft that can land under a given meteorological condition when no departures are allowed. The free departures point takes advantage of the natural gaps between arriving aircraft to generate some departures within the arrival stream. Similarly the free arrivals point allows a number of aircraft to arrive without disturbing the maximum departures. The departures push represents maximum departures when no arrivals are allowed. And the balanced arrival/departure point estimates the maximum arrivals/departures possible when there is no emphasis on either.

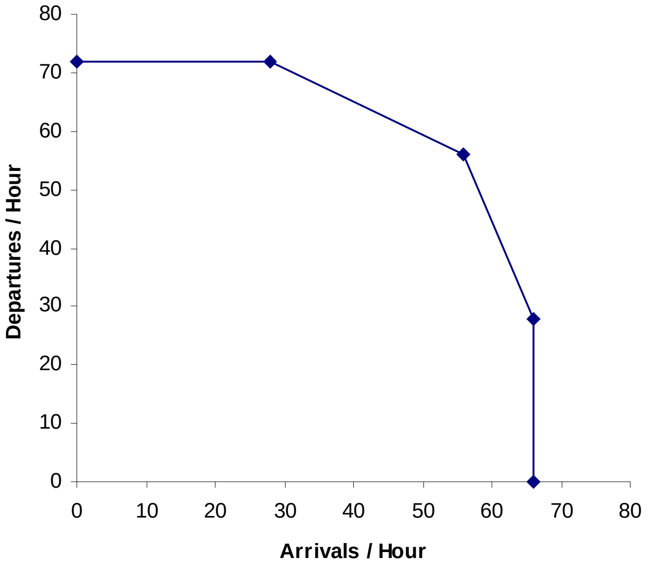

Figure 2: Sample Airport Capacity Pareto Frontier

The delay models generally run through a number of days, selecting the Pareto frontiers to define capacity according to weather conditions, and comparing that capacity to the forecasted demand for that day. The weather data is taken in hourly increments from a typical weather year. The demand is generated by taken the current airline schedules and incrementing them according to an input percentage increase in demand while accounting for the average number of seats per flight [12]. The authors are currently considering generating the demand estimates from another LMI code which is grouped with the capacity and delay models under the Aviation System Analysis Capability (ASAC) environment: the Air Carrier Investment Model (ACIM). The ACIM generates demand for air travel estimates based on econometric data such as GDP and unemployment rates. As it was mentioned earlier, the demand for air travel is closely related to economic conditions, and the authors feel it is important to capture this link in order to accurately reflect the impending capacity problems.

The models mentioned so far calculate the delays generated at particular airports, but the system-wide capacity problems are also important since many of the technologies proposed could affect the entire system, and it is this type of generalized effect that raises public interest and government funding. LMINet includes a net of 64 airports and the en-route sectors between them and has the ability to calculate cumulative delays accounting for the routes generally flown in current airline schedules. However, this net does not account for the interdependency of flights, and the ripple effects a delay early in the morning can have on that day's schedule [15]. As general rule, a delay in the first flight of the morning will have had four times its impact by the end of the day. Thus, it is extremely important, as well as extremely difficult, to capture this effect.

Airlines

Airline policies also play a significant part in the current congestion problems at major airports. They tend to favor frequency over number of seats as a way to serve demand. This approach results in a larger variety of flight times and a larger market-share capture. However, this attitude also results in an increased number of flights with a reduced seat capacity. Another frequent airline strategy involves the clustering of flights around certain times of the day. This is based on customer preferred flight times, but it is detrimental to serving the overall demand at a particular airport. Since airline business procedures are profit driven, they will continue these non-capacity increasing trends until such time as the costs of delays outweigh the benefits of increased market-share. Thus, an accurate estimate of the revenue lost due to delays and cancellations is essential. This will be further discussed in the economics section.

Airlines have several methods of coping with delays. A very popular one in recent years has been to pad schedules with built in delays. This gives customers the illusion that the aircraft arrived on time or even early on good weather days, and the delays recorded for bad weather days are not as significant. Other potential reactions previously mentioned are the smoothing of schedules to avoid peak time delays or the increase in average seats per flight by using larger aircraft. Airlines also have the option of moving away from the hub-andspoke system to utilize less congested airports. This last alternative is under investigation at LMI by modeling a large number of small aircraft landing facilities. Thus, the ability to model these reactions is in place, however, it would also be of interest to investigate what options will be most likely to be pursued, and what will be the deciding factors in choosing a particular approach. The authors have recently reviewed work under way at the MITRE Corporation dealing with both airline and ATC behavior. In their IMPACT (Intelligent agent-based Model for Policy Analysis of Collaborative TFM) code the airlines are modeled as agents driven by market-share or profit depending on the airline personality chosen. These agents are then placed within a system with other agents representing ATC. A disruption such as a bad weather day is introduced in the system and the agents are allowed to react to the event and to each other's decision according to their predefined personalities. Unfortunately, the reaction of the ATC seems to be limited to the activation of Ground Delay Programs which do not allow aircraft to depart if their destination airport is congested to avoid airborne delays [16]. The MITRE Corporation has also developed a model named ACSEM (Air Carrier Service Evolution Model) that models airline behavior in more detail. Within this model economic conditions, airport capacities, demand and costs are translated into a flight schedule, RPM, load factors, and passengers serviced along with average delays. Within this model transfer flights can be used to serve two cities not directly connected and passengers can have either a time or a cost priority. Passenger sets with similar destination and time preferences are grouped together and matched to potential flights which are purchased based on a balance between the closeness with which they match customer desires, and the cost per ticket. The airline agents within the model have the ability to make changes to their strategies, such as varying fares and schedules, the size of the aircraft flown or the number of aircraft owned. As the airlines make changes, the flights in the schedule are flown, delays are calculated and translated into costs, and these costs are then balanced with the profits made. As long as the profit (or the market-share) increases, airlines will continue to make the same type of decisions [17]. The authors feel this model closely mimics airline behavior, and they hope to obtain access to it.

ATC

A number of the technologies being proposed for the improvement of airport capacity are related to improvements of the Air Traffic Control system in terms of easing controller workloads, improving communication between pilots and the tower, or allowing for the reduction of inter-arrival separations.

NASA is currently sponsoring two programs that are investigating capacity and throughput oriented technologies: the Terminal Area Productivity (TAP) program, and the Advanced Air Transportation Technologies (AATT) program [12].

The TAP includes technologies such as DROM (Dynamic Runway Occupancy Measurement), ROTO (Rool-Out Turn Off), AVOSS (Aircraft Vortex Sensing System) and CTAS (Center-TRACCON Automation System)/FMS (Flight Management System) integration. DROM could estimate actual ROTs, and thus allow for the removal of current buffers in place to avoid having two aircraft on the same runway, which, when combined with the ROTO program that is expected to decrease the actual ROTs, may allow for clear weather operations on bad weather days. The TAP program is also attempting to reduce miles-in-trail restrictions by using actual vortex persistence to determine separation, rather than using a standard separation requirement for all cases, through the development of the AVOSS system. The CTAS/FMS integration will enable the controller to obtain more accurate information as to the location, speed and flight direction of incoming aircraft, thus allowing for the removal of built in buffers that decrease efficiency. The intended effect of these technologies is easily modeled within the ASAC airport capacity models since they use ROTs, separation matrices, and position uncertainty as inputs [18]. However, these technologies also require the installation of software and hardware on all the aircraft operating within their areas of application, or additional airport infrastructure. The impact of this equipment in terms of cost and weight is often overlooked.

Economics

Economics are the driver behind the capacity problem as well as behind the congestion alleviation projects. Economics drive demand for air traffic. When trade increases the need for air transportation follows. When passengers have higher incomes they will often choose the convenience of flying over other modes of transportation. But this is only true as long as air transportation is affordable and convenient. As delays increase airline costs surge, facility and crew charges go up and more fuel is spent. There are also indirect costs associated with delays such as passenger dissatisfaction and rerouting. To preserve passenger good-will and thus market-share, airlines often incur in the cost of meals and accommodations for delayed passengers, as well as future flight vouchers or other forms of compensation for their lost time [19]. Delays readily translate into cost, and provide a reason to fund the alleviation of the problem. If the capacity limitations are not solved and delays are allowed to grow unchecked air travel may decay. Just like economic welfare drives demand for air transportation, a sharp decrease in air travel demand would result in fewer aircraft and associated services being required. This could be severe enough to have a negative impact on the economy, thus closing the supply and demand loop.

The authors have already mentioned the potential of the ACIM tool to forecast demand based on economic factors. This tool also has the capability of translating demand into the number of new aircraft required to fulfill the air transportation need, accounting for the age of the fleet. This aircraft demand can then be used in conjunction with a tool such as ALCCA to estimate the costs of new aircraft to the airline. ALCCA also translates this purchase price into a direct cost for the airline which will directly interact with how many aircraft the airline can afford to purchase [20][21]. The ACIM uses the estimate of aircraft needed to estimate employment within the aerospace industry, and the effect this has on the overall economy. In view of these economic results the estimate for air travel demand could then be revised as well.

ALCCA, originally developed at NASA, and subsequently improved at ASDL, considers both aircraft and airline costs in detail, furthermore, it includes a number of features that make it well suited for this task. Specifically, the airline costs account for the indirect effects of delays and lack of aircraft availability through the revenue loss module added in-house. However, this revenue loss module is currently based on some basic assumptions about airline schedules and could benefit from actual estimates of delays such as those generated by the ASAC models previously mentioned [22].

The authors feel that, as a number of capacity solutions involve expansion of airport and ATC facilities, and the economic models mentioned thus far include only the airline and aircraft manufacturer, the current economics capability is not sufficient. Therefore, an estimate of the costs of new runways or AVOSS equipment will require a new model whether it is based on raw data or an existing capability. Furthermore, the new navigation equipment required within the aircraft will be costly, but the estimation of this type of equipment within the chosen aircraft cost estimation code, ALCCA is not sufficiently detailed. Thus, data on this type of costs must also be collected and analyzed.

Environment

The analysis of government budgets and motivations is much too complex to include in this modeling effort. However, the tangible effects of government policies such as noise regulations can and should be modeled in detail. Therefore, the aircraft noise modules within FLOPS can be used to assess whether new aircraft designs will meet the established regulations, and the noise module within ASAC can then be used to calculate aggregate airport noise footprints and analyze how the community noise restrictions affect approach and departure paths. The effect of these paths on airport efficiency can be very significant and cannot be overlooked if an accurate estimate of system capacity and average delays is to be obtained.

Safety

The NASA approach to safety is based on a three prong approach. The first step in the approach is the modeling and simulation of past accidents to identify their causes. These simulation environments could then be used to model potentially dangerous situations. Once the causes for accidents are understood an effort can be made to prevent those accidents. A number of technologies currently being developed to improve capacity in poor meteorological conditions could also be of assistance in the avoidance of weather induced accidents. The third step in the NASA approach is accident mitigation and crashworthiness [12]. However, it is the first step that would be useful in the assessment of congestion relief technologies. In order to implement many of the capacity solutions being suggested, safety must be guaranteed. But safety seems to be an elusive concept to model, with a particularly difficult balance in the detail captured vs. the complexity of the code. Perhaps the most reasonable approach to this concept is to consider the various scenarios that can occur, attach a probability of occurrence to each possibility, and then estimate what the effects would be in each situation. For example, if one were to reduce separation between incoming aircraft, at the simplest level we could have a ‘nothing happens’ scenario, a ‘recoverable vortex disturbance’, and a ‘fatal vortex disturbance’. Systems such as AVOSS are designed to ensure that only the first situation is probable. However, the system may become inoperable, or the pilots and controllers may not react to the warnings on time. In general several ‘wrong’ actions will be required to cause a fatal accident, due to the redundancies built in the system. Thus, a fault tree type of analysis could lead to all the possible situations from the time the aircraft approaches the runway, to the time it has landed safely. Work is underway at the Logistics Management Institute to develop a safety model based on a similar idea. The authors hope to incorporate this model into the NAS simulation environment proposed thus far [23].

Integration

The intention of this task is to obtain an estimate of technological effects throughout the NAS, rather than in a particular research area. Therefore, it is the integration of the models chosen that becomes the central piece of the problem. Throughout this modeling effort the interactions between the codes under consideration has been a foremost concern, thus many of the interrelationships among them have already been discussed. These relationships are summarized in Figure 3.

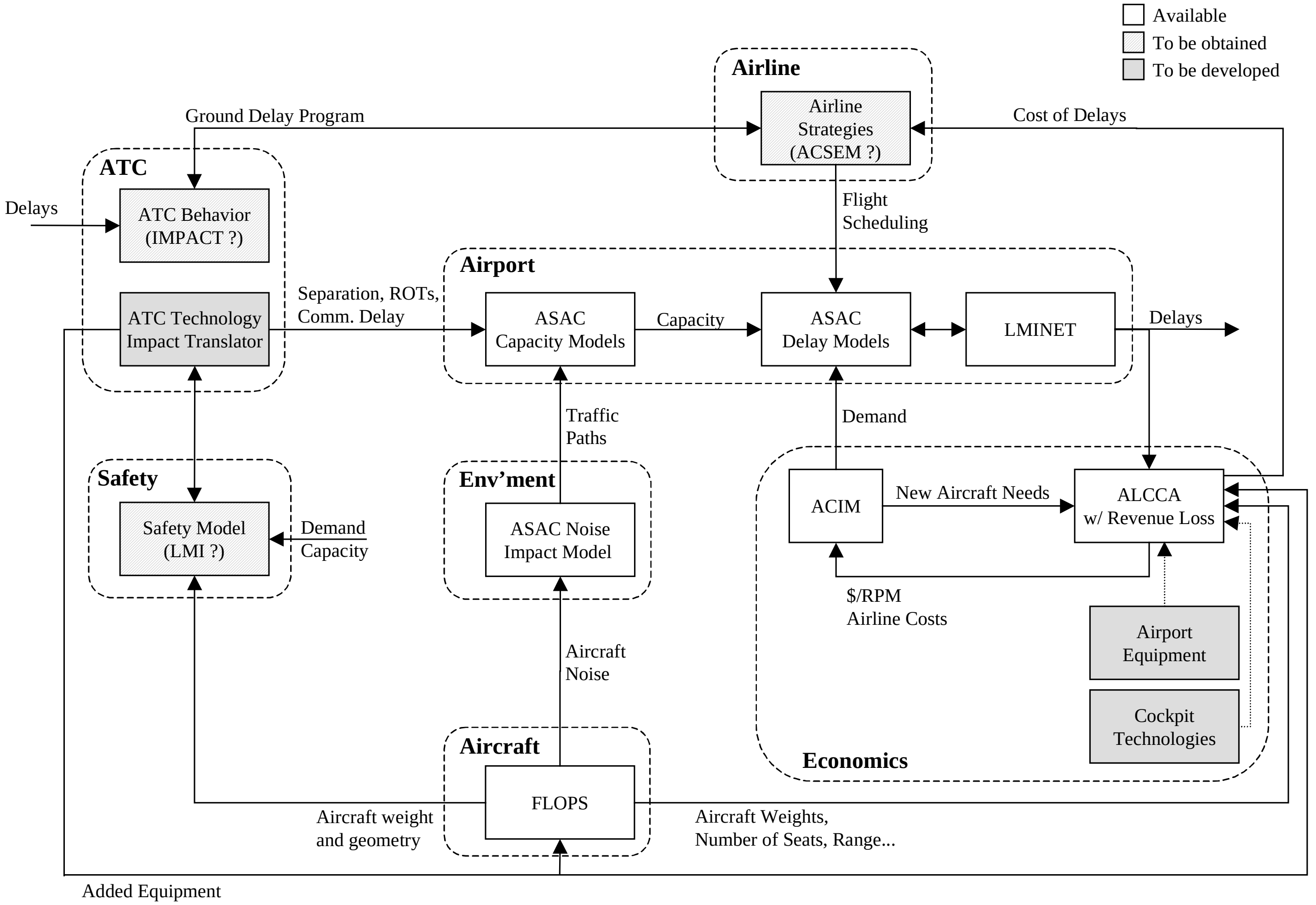

Figure 3: NAS Modeling Flowchart

The models in this chart are classified as available, to be obtained or to be developed. The authors have had the opportunity to work with those that are classified as available. The codes classified as 'to be obtained' have been identified as candidates to fulfill a modeling need, but are either not fully developed, or the authors have not dealt with them thus far. Those modules labeled as 'to be developed' identify a modeling need that is not currently covered to the knowledge of the authors. The ATC technology translator is only a placeholder for the need of translating proposed ATC technologies, such as Synthetic Vision, into their expected economic, weight and airport operations impacts. This will be done through research and expert opinion, rather than an actual code, but it still represents a vital part of the technology assessment process.

Figure 3 represents the information being transferred between the various codes within the modeling environment. However, a number of methods may be chosen to actually implement these links. This is also a key element of modeling the NAS. A balance must be attained between the amount of information captured, and the complexity of the system created. This is particularly important when the intent is to carry out a statistically based analysis since a large number of code executions may be required.

The link between FLOPS and ALCCA, the aircraft and economics codes, is a direct code link, where ALCCA is a subroutine of the sizing code. Since both codes are written in FORTRAN, and a large amount of information is required to define the aircraft within the cost estimation code, this was a feasible option. However, many of the other codes under consideration are written in different languages, run on different platforms, and may have long run-times even as stand-alone models. Thus, a direct code link may not be a practical option. The linkage between such codes could also be implemented through an integration environment such as IMAGE (Integration Modeling and Analysis Graphical Environment) [24], developed at ASDL, or a commercially available toolbox such as iSIGHT. The Logistics Management Institute uses a similar approach in their Executive Assistant, to link a number of their tools. Alternatively, if a faster high level analysis is possible the models can be replaced by Response Surface Equations (RSE's) [25], quadratic polynomial approximations of the form

$$Metric = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} b_{ij} x_i x_j$$

These RSE’s can also be used in conjunction with a Monte Carlo simulation to generate probability distributions for the metrics of interest according to the uncertainties associated with the parameters considered, this makes them particularly interesting when considering a probabilistic approach to technology impact estimation [26]. For a more in depth analysis, where all potential sources of uncertainty must be addressed and the model representation cannot be limited to a few parameters, fast probability integration techniques, such as those available within FPI, can be used to generate an approximation of the metric probability distributions [27]. This would mean approximating probabilities directly, rather than approximating the model and then applying probabilistic methods.

PROBABILISTIC TECHNOLOGY ASSESSMENT

The development of a suitable NAS modeling and simulation environment is only the first step toward analyzing the potential of certain technologies to solve the delay problem. A methodology to identify and evaluate the impacts of these technologies in a structured manner and with due attention to the inherent variability of the system is also necessary. The proposed technique follows the TIES (Technology Identification, Evaluation and Selection) methodology developed at the Aerospace Systems Design Lab [28][29][30][31][32]. A basic flowchart of the TIES methodology is displayed in Figure 4.

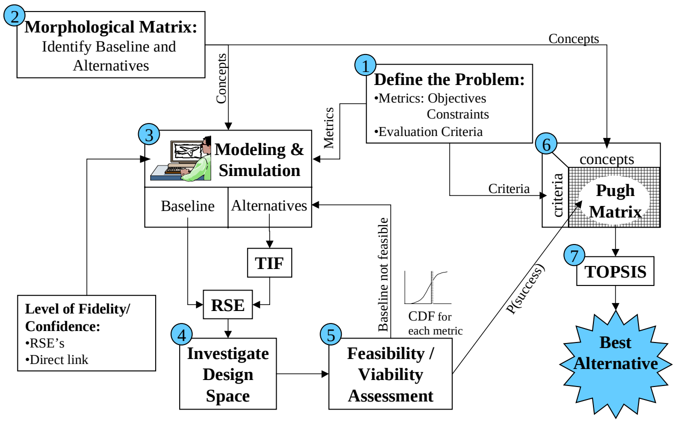

Figure 4: Technology Identification, Evaluation and Selection (TIES) Methodology [29]

As an example, the steps in this methodology will be notionally applied to the modeling environment previously described.

Step 1: Define the problem

This step involves understanding what limitations and expectations a potential customer would impose on the system being studied. These desires and requirements are then translated into metrics that will measure the customer satisfaction and targets and constraints that must be met. In this case metrics such as added equipment weight, number of seats preferred, new aircraft required and noise restrictions might capture the interest of aircraft manufacturers. Airlines, however, would be interested in results such as Revenue Passenger Miles (RPM), total block time and fuel for a flight segment, the delays accumulated, and the resulting costs and revenues. Safety measures such as accident rates and capacity measures such as number of operations or passengers served would be of interest both to the airport authority and to air traffic control. Some of these metrics could, on the other hand be treated as constraints. Accident rates are to be kept below today’s values, or in accordance with NASA goals reduced by a factor of 5. EPNL (Effective Perceived Noise Level) limits are already in place and must be treated as a constraint on aircraft generated noise. This type of brainstorming must be thoroughly explored, if all aspects of the capacity problem are to be captured.

Step 2: Identify baseline and alternatives

The baseline in this case would be the current situation at a particular airport. Potential alternatives could include a vortex sensing system to set safety buffer zones that are no larger than the vortices shed require, a synthetic vision cockpit for low visibility operations, a surface movement decision support tool for controllers, or even a combination thereof. These technologies would then have to be translated into potential benefits and drawbacks. For example, the vortex sensing system would reduce the distance needed between approaching aircraft. However, it would also have a negative impact in airport costs, which are often translated into raised landing fees for the airlines. A synthetic vision system would enable good weather operations even in low visibility conditions. However, it would significantly raise the cost of aircraft navigation equipment, and it would require additional equipment at the airport and within ATC to communicate the location of other air and ground traffic.

Step 3: Modeling and Simulation

The creation of a modeling environment for the NAS has been a large part of the discussion in this paper. The environment would have to be capable of generating the metrics of interest. The overall model must also be capable of capturing the changes that would be induced by the introduction of new technologies. In fact, since the NAS is inherently variable, the modeling environment would also have to include statistical techniques such as Response Surfaces and Monte Carlo simulation. Alternatively, if the decision-maker desires a more in depth analysis tracking all potential sources of uncertainty, fast probability integration techniques, such as those implemented in FPI [27], can be used to approximate the metric probability distributions.

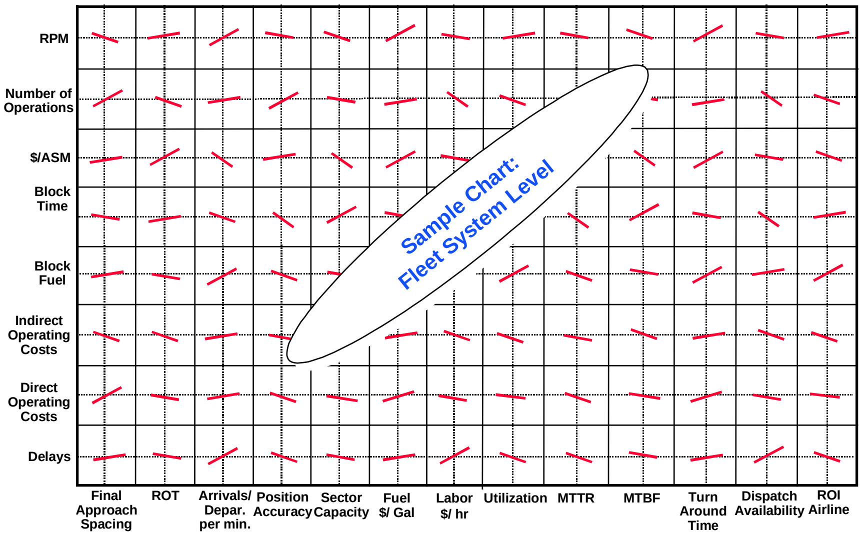

Figure 5: Notional system prediction profile [35]

Step 4: Design Space Exploration

This step involves the creation of a metamodel of the NAS. This metamodel is obtained by varying the most influential inputs to the NAS environment according to a design of experiments and analyzing the results through Analysis of Variance. If the number of inputs to the model is too large and the expertise to identify the most influential factors is not immediately available, a screening test also employing design of experiments and ANOVA techniques can be used to identify the main factors [25][26]. This analysis results in a quadratic approximation of the metrics chosen that will change parametrically as the inputs vary. A dynamic what-if environment, called a prediction profile, can then be created using the statistical package JMP [33]. This environment represents the sensitivity of the model to the inputs chosen see Figure 5 for a notional example of such an environment. This Metamodel / Monte Carlo approach may not be feasible with a model as large as that for the NAS, and an FPI approach where the probability distributions are approximated directly may be preferable. However, the prediction profile dynamic environment is very useful from the decision maker's point of view and thus the previously mentioned approach is preferred when possible.

Step 5: System Feasibility and Viability

Once a metamodel of the design space has been created, a Monte Carlo simulation can be run using a package such as Crystal Ball [34]. This will use a random number generator to produce varying inputs according to specified probability distributions. The output for each set of inputs is collected and a histogram of the results is created. This yields a probability distribution for each metric under consideration. If the metrics will not meet the targets or constraints defined in step 1 with a high degree of probability, technology infusion is warranted. Figure 6 portrays such a situation where a desired target is not met with high confidence.

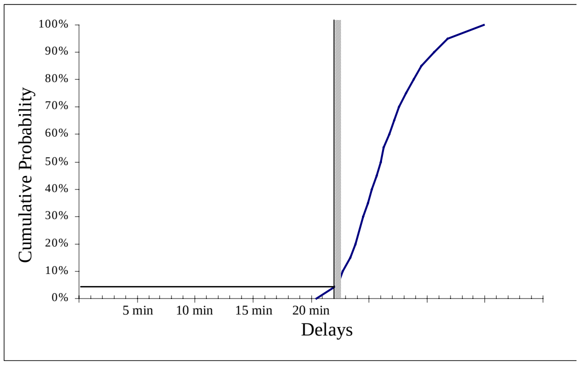

Figure 6: Metric and not-achieved target [35]

If technology infusion is required, the expected impacts of each technology must be determined. A similar procedure is carried out, but in this case the inputs are fixed, and it is a series of kappa factors which represent technology impacts that are changing. Once again a series of prediction profiles is created which can also be used for reverse engineering. The k-factors can be changed until the desired metric values are achieved. These k-factor values represent the target changes that must be addressed through technology infusion. Figure 7 depicts an example of such a prediction profile.

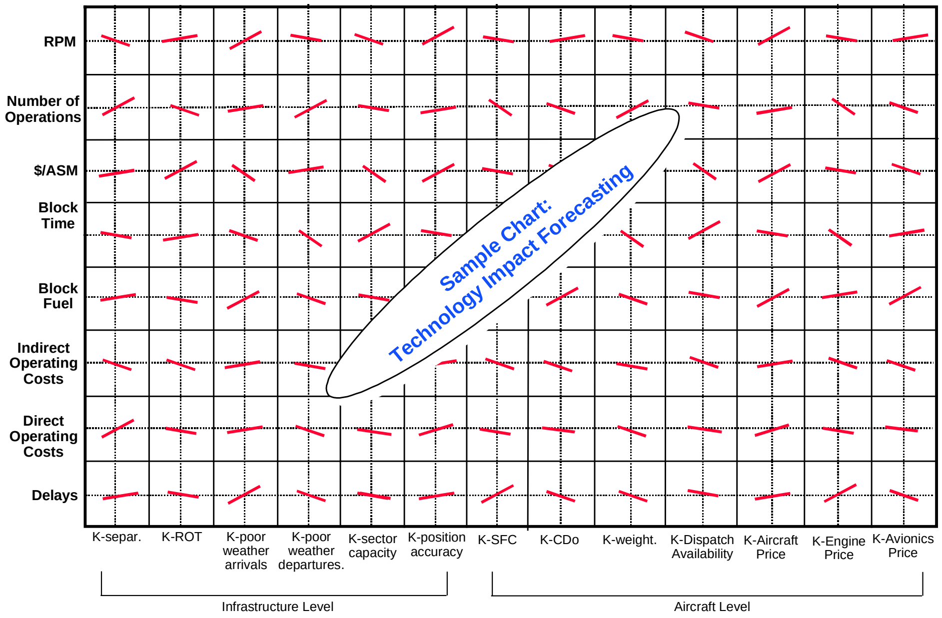

Figure 7:Technology Impact Forecasting [35]

Once this metamodel has been created a Monte Carlo simulation is run to assess the impact of each technology. Due to technology readiness issues, technological impacts are often not known with full certainty, therefore the expected impacts of each technology or technology combination are modeled as a probability distribution. The result, as before, is a probability distribution for each metric of interest.

Step 6: Technology Evaluation

The cumulative probability distributions generated in the previous step are used to estimate the confidence of meeting the set targets each alternative will yield. This information is tabulated for each metric and each technology combination. The information collected can then be used to select the most promising technologies. However, recent research at the Aerospace Systems Design Lab implies the probability distributions for each metric individually may not be indicative of an overall solution. Rather, joint probabilities that include several metrics and account for their positive or negative correlation may be more accurate. The authors regard this as an important caveat, and will consider the use of JPDM (Joint Probability Decision Making) methods along with those previously mentioned [36].

Step 7: Technology Selection

A multi-attribute decision-making technique can finally be used to determine which technologies meet all desired targets with the highest degree of probability. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) has been used in the past to fulfill this purpose due to its ability to include a weighting of the different metrics according to their importance to the customer.

CONCLUSION

Economic welfare has prompted an increase in demand for air travel beyond the capacity of existing infrastructure. Technologies have been proposed to ease the capacity problem and reduce delays. In order to assess these technologies a model of the NAS which includes all the interested parties (aircraft, airport, airline and ATC), and accounts for environment, economic and safety pressures is needed. Certain codes and models have been identified as potentially representative of each of these concerns and steps have been taken to identify their pros and cons, as well as their interactions. A technology evaluation methodology capable of including an assessment of the variability within the NAS has also been investigated. However, this is only a start in estimating the effect of capacity related technologies. Future work will involve the acquisition of the codes mentioned and their integration into a cohesive simulation environment. Still to be investigated is also the applicability of the TIES methodology to the problem at hand.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AATT Advanced Air Transportation Technologies

ACSEM Air Carrier Service Evolution Model

ALCCA Aircraft Life Cycle Cost Analysis

ASAC Aviation Systems Analysis Capability

ASDL Aerospace Systems Design Laboratory

ATC Air Traffic Control

AVOSS Aircraft Vortex Sensing System

CTAS Center-TRACCON Automation System

DROM Dynamic Runway Occupancy Measurement

EPNL Effective Perceived Noise Level

FAA Federal Aviation Administration

FAST Final Approach Spacing Tool

FLOPS FLight OPtimization System

FMS Flight Management System

GDP Gross Domestic Product

IMAGE Integration Modeling and Analysis Graphical Environment

IMPACT Intelligent agent-based Model for Policy Analysis of Collaborative TFM

JPDM Joint Probability Decision Making

LMI Logistics Management Institute

NAS National Airspace System

ROT Runway Occupancy Times

ROTO Roll-Out Turn Off

SHCTR Short Haul Civil Tilt Rotor

SMA Surface Movement Advisor

TAP Terminal Area Productivity

TFM Traffic Flow Management

TIES Technology Identification, Evaluation and Selection

TMA Traffic Management Advisor

TOPSIS Technique for Order Preference by Similarity to Ideal Solution

V-STOL Vertical - Short Take Off and Landing