Airport Availability Modeling:
A Different Perspective

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Abstract

This study proposes a systems-level approach to airport and runway availability assessments and prediction, and addresses the problem of the aging or continuously degrading aviation infrastructure.

Although the availability block diagrams are often used in the availability assessment of aerospace and electronic systems, their application to the airport availability problem on a system-level, developed in this study, is novel. The methodology developed in this paper is intended for short-term and long-term planning of the communication, navigation and surveillance (CNS) equipment acquisition. Improved understanding of the effects of equipment outages on airport availability is valuable in determining a required level of airport equipage and equipment reliability, particularly during critical situations, such as bad weather conditions and increased traffic demand. With proposed methodology an analyst can precisely quantify the additional level of airport availability achieved by upgrading or adding new pieces of CNS equipment at airports, and therefore better accommodate critical operating conditions. Consequently, this methodology should assist the Federal Aviation Administration to improve investment and modernization decisions related to CNS equipment, particularly at airports that require additional service availability.

Keywords
Availability, airport, navigational equipment, system modeling, outages, runway

Biography

Dr. Jasenka Rakas is a principal investigator on aviation infrastructure system research at the National Center of Excellence for Aviation Operations Research, and a lecturer in the Civil and Environmental Engineering Department at the University of California at Berkeley.

Her research interests include optimization methods for management and evaluation of equipment and facilities in the National Airspace System (NAS), performance assessment and modeling of airports and airspace, and availability modeling of aviation systems. She is Vice-Chair of the Transportation Research Board Committee for Airport and Airspace Capacity and Delay, and a founder of the annual conference on NAS Infrastructure Management.
Myron Hecht is a Senior Engineering Specialist at the Aerospace Corporation where he works on software and system reliability and system safety issues on satellite and space programs. He has worked on availability, maintainability, and safety issues associated with air traffic control for more than a decade. Among his current activities is aviation safety assurance for the next generation of the Global Positioning System (GPS). His research interests include architectural and software reliability, fault tolerance, and the product liability aspects of consumer products with embedded software. He previously worked on space systems, nuclear reactor digital control systems, and transportation control systems. Mr. Hecht holds B.S., M.S., M.B.A. and J.D. degrees, all from UCLA.
1 Introduction

Commercial air transportation in the United States National Airspace System (NAS) moves more than 600 million passengers on nearly 10 million flights annually [1] and is dependent on an underlying infrastructure of facilities and services for air traffic management and communications. This infrastructure represents one of the largest integrated civil systems in the world, consisting of tens of thousands of facilities and services geographically dispersed throughout the contiguous United States, Alaska, Hawaii, commonwealths, and territories from the Caribbean Sea to the South Pacific Ocean.

Because of their safety of life significance and economic importance, services provided by the NAS infrastructure must be highly available. However, the resources that can be used for maintaining such a high level of availability are limited, as are the capital budgets for replacement of aging systems. As a result, airport managers and those responsible for the allocation of capital resources need to understand the impact of outages of individual facilities and equipment. A systems-level approach to availability assessment and prediction enables a more efficient prioritization and allocation of scarce maintenance resources.

This paper describes such a system-level approach for evaluation of airport availability using availability block diagrams (ABDs). ABDs are used in the availability assessment of aerospace and electronic systems, but their application to this problem is novel. As such, one of the contributions of this paper is a demonstration of the feasibility of this approach in this domain. Our approach is of particular relevance to the issues related to transportation disasters and degradation management because the problem of prioritization of capital replacement and operational maintenance budgets for aging or continuously degrading infrastructures are not unique to airports.

This paper first explains the importance of availability as a metric of overall airport performance. In the subsequent section, we define the concepts of airport equipment availability, weather availability and service availability and how they are considered jointly. We then identify the various factors that affect airport and runway availability, and model airport/runway availability in case of equipment outages for a hypothetical multi-runway airport and then apply the proposed methodology to the Boston Logan Airport.

2 National Airspace System and Relevant Performance Metrics

Availability is the primary measure of the performance of any system within the U.S. National Airspace (NAS) because of its impact on capacity and safety. Availability is affected by failure rates (i.e., reliability), redundancy, and repair rates (i.e., maintainability) as depicted in figure 1.

![Figure 1. Selected performance metrics and their relations.](image-url)
Capacity, as a performance metric, is needed for assessing the effect of systems unavailability upon delays and NAS capacity. Theoretically, the term capacity is usually used to “designate the processing ability of a service facility over some period of time” [2].

Maintainability is needed to estimate the effect of maintenance costs as a function of increasing failure rates. Some think of maintainability as ease or cost of keeping a system in good enough condition. The effect of maintainability on availability of air traffic control communications, navigation and surveillance systems (CNS) is direct. On average, actual repair rates, number of maintenance technicians, average maintenance rate per facility, distribution of technicians by shifts, training and travel time to facility all have an effect on equipment outage times, service availability and technician utilization.

3 Equipment Availability, Weather Availability and Service Availability

The services provided by an airport are (1) acceptance of arriving aircraft and (2) supporting the departure of aircraft, both with a high level of safety. The availability of these services is dependent on the likelihood that the landing systems and lighting equipment are functional and that the local weather enables aircraft operations. This section describes the conceptual framework for evaluation of equipment and weather availability and how they are combined to provide a service availability.

3.1 Equipment Availability

The traditional (FAA) operational availability of the NAS is defined by the FAA [3] Order 6040.15C as the ratio between

(a) the difference between the maximum available service time $t_s$, and the total time out of service, $t_{down}$, and
(b) the maximum available service time $t_s$, in the form $A_{op} = (t_s - t_{down})/t_s$.

For repairable systems such as the NAS, the “up time” is related to the mean time between failures (MTBO), and the “down time” is referred to the mean time to repair (MTTR). Hence, the traditional way of estimating (for example) a runway equipment availability is simply defined as $A = MTBO / (MTBO + MTTR)$. If a higher level of precision is required, then, the MTTR would account for the technician repair time, administrative time, technician’s travel to the site, etc.

For a redundant system (for example, with one back-up), defined as a s-independent (i.e., when failures of the primary and back-up system happen independently), the restoration time (i.e., the time required to switch to the back-up equipment) is also considered.

Airport availability for arrivals is different from the availability for departures because of different aircraft equipment requirements, and different modeling requirements.

3.2 Weather Availability

The statistics shows [4] that the main reasons for runway or airport closures or delays are bad weather conditions. The traditional approach for estimating the weather related availability considers the time when the airport was “up” (open), and the time when the airport was “down” (closed) because of the bad weather.
If we define the mean time between (runway or airport) closures as $MTBC$, and the mean
time to clear bad weather as $MTTC_w$, then the weather-related airport availability $A_w$ could be
defined as:

$$A_w = \frac{MTBC}{MTBC + MTTC_w}$$

(1)

The sum of $MTBC$ and $MTTC_w$ is usually equivalent to the official operational time of an
airport, considering all environmental (i.e., noise) constraints. For example, the ($MTBC$
$+ MTTC_w$) duration for the Washington National Airport (without allowing overnight operations
due to the proximity of the residential area) is less than that for the Chicago O’Hare International
Airport (24 hours in operation).

The runway can be closed for a number of weather related reasons, such as low ceiling
and visibility, or heavy snow. However, the airport availability for arrivals is different from the
availability for departures also due to different ceiling and visibility requirements, meaning that
(for example), the runway can be closed for arrival operations but open for departures during the
bad weather conditions.

Airport equipage also has an effect on weather availability. For example, during the low
ceiling or visibility conditions, precision approaches are required. Precision approaches require
Category (CAT) I, II and III type of navigational equipment, and if the airport is not adequately
equipped, and the alternative air traffic control procedures can not be used, the airport (or
runway) must be closed. Thus, it is assumed that better airport equipage yields higher weather
availability, as depicted in figure 2.

![Figure 2. Assumed relation between weather availability for arrivals and equipment availability for precision approaches.](image)

### 3.3 Service Availability

As previously stated, the traditional availability is either equipment- or weather-related and the
measures are not considered jointly. Furthermore, equipment-related availability is often related
to individual pieces of equipment or smaller equipment systems rather than to the airport-system availability. To overcome these deficiencies, we first introduce an airport arrival service availability and departure service availability as new performance metrics that consider weather conditions and equipment reliability jointly. We define these service availabilities as a percentage of time (or probability) that a service for arrivals or departures is being provided, given the availabilities of weather conditions, individual pieces of equipment, and interactions among equipment systems and runways. Figure 3 illustrates the runway arrival service availability to better understand this term.

![Figure 3. Runway arrival service availability.](image)

4 Methodology

To address the problem of airport availability estimates on a system level, an airport availability model is developed that considers the necessary navigational equipment required for each type of operation (arrivals and departures). Thus, the airport arrival and departure models cover local navigational aids, instrument landing system (ILS), and the airport tower communication, navigation and surveillance equipment. The models address multiple airport runway configurations and the following four categories of visibility conditions: unrestricted or VFR (visual flight rules) and IFR (instrument flight rules) Categories I, II, and III. The airport model uses a hierarchical approach as depicted in figure 4.

Each airport has its own unique runway layout. The physical characteristics of each of the runways influence its availability. The dominant physical characteristics are the runway length and separation, as well as the layout of the runways (parallel, converging intersecting or converging non-intersecting). Runways normally have dual directional capabilities, however, wind as well as considerations such as noise and safety often limit the directional possibilities. Under clear conditions, visual flight rules are used and the degree of navigational aids required is minimal. Under less than ideal conditions, IFR must be applied. There are three categories of IFR dependent upon visibility and ceiling, with CAT III required under the worst conditions.
Major airports have multiple runways and these are serviced partly by common facilities (VOR, DME) and partly by runway specific facilities, such as ILS. The use of multiple dual directional runways at airports necessitates a means for safe and efficient runway assignments for approaches and departures. Each physical runway has two runway numbers to differentiate direction of use. At any given time a specific runway or group of runways are assigned for approaches and a different runway or runways for departures. This set of approach and departure runways is referred to as a runway configuration. The number of acceptable runway configurations varies for different airports. The selection of a given configuration depends upon numerous variables such as wind, visibility, runway length, noise and navigational aid equipment availability.

The airport system-availability model hierarchical approach is comprised of the following levels:
- **Level 1:** Airport Level. These models depict the airport runway system departure and approach availability based upon approved runway configuration options.
- **Level 2:** Configuration Level. These models identify the configurations in terms of runways.
- **Level 3:** Runway Level. These models identify the facility equipment required for each type of approach or departure for each of the runways.

The availability calculations are performed by beginning at the lowest hierarchical level. One of the alternative methods of Hierarchy Level 3 models is used to calculate the approach and departure availability for a given runway based upon the facilities. The runway availability is determined by weighting the results in accordance with the relative utilization of the approach or departure visibility (weather) category. The Runway Level results serve as input to the Configuration Level models. Similarly, the Configuration Level model results serve as input to the Airport Level models.

### 4.1 Hierarchy Level 1: Airport Level

The airport level availability is the probability that an airport is available for arrivals and departures given that external conditions, such as weather, do not force closing of the airport due to other reasons.

At each airport a specific configuration of runways will be in use for arrivals and another configuration will be used for departures at any given time. The number of unique runway
configurations at an airport depends on existing runways, wind conditions, and noise restrictions. Configuration unavailability is defined as the probability that no runways within a configuration can be used. Because of the different facility requirements for departures and arrivals, departure and arrival configuration availabilities differ.

Each runway configuration is used for a known proportion of time. Hence, at a given airport, the availability of a runway for departure or approach can be calculated by weighting the configuration availability by the usage proportion.

### 4.1.1 Airport Departure Availability

Figure 5 shows the departure availability block diagram for hierarchy level 1, and equation 2 defines the weighted departure availability, $A_D$, based on the approach defined above.

\[
A_D = \sum_{i=1}^{m} x_i \times A_{DC_i}
\]

Where:

- $A_D$ = airport availability for departures
- $x_i$ = proportion of use of runway configuration $i$
- $A_{DC_i}$ = departure availability for runway configuration $i$ (equation 3)
- $m$ = number of runway configurations
- $i$ = runway configuration

### 4.1.2 Airport Arrival Availability

Similarly, figure 6 shows the arrival availability block diagram for hierarchy level 1 and equation 3 defines the weighted arrival availability, $A_A$, based on the approach defined above.
Figure 6. Approach availability block diagram - hierarchy level 1.

\[ A_A = \sum_{i=1}^{m} x_i \times A_{AC_i} \]  \hspace{1cm} (3)

Where:

- \( A_A \) = airport availability for arrivals
- \( x_i \) = proportion of use of runway configuration \( i \)
- \( A_{AC_i} \) = arrival availability for runway configuration \( i \) (equation 4)
- \( m \) = total number of runway configurations
- \( i \) = runway configuration

4.2 Hierarchy Level 2: Runway Configuration Level

The runway configuration availability is composed of the availability of each of the component runways of the runway configuration. We discuss calculation of such availability for departure and arrival configurations respectively.

4.2.1 Departure Configuration Availability

Figure 7 shows conceptually that a departure configuration is made up of one or more runways whose availability may be considered in parallel. Because availability of a given configuration is equal to the complement of the combined unavailability of its component runways, the configuration departure, \( A_{DC} \), and arrival availability, \( A_{AC} \), can be expressed as shown in equation 4 and equation 5.
Figure 7. Departure availability block diagram - hierarchy level 2.

\[
A_{DC_i} = 1 - \prod_{j=1}^{n_i} (1 - A_{DR_{ij}}) \quad \forall i = 1, m
\]  

Where:

- \(A_{DC_i}\) = departure availability in runway configuration \(i\)
- \(A_{DR_{ij}}\) = availability for departures at runway \(j\) in configuration \(i\) (Eq. 5)
- \(n_i\) = total number of departure runways in configuration \(i\)
- \(i\) = runway configuration
- \(j\) = runway
- \(m\) = total number of runway configurations

4.2.2 Arrival Configuration Availability

Arrival configuration availability, \(A_{AC}\), as described in figure 8 and equation 5, is analogous to figure 7 and equation 4 for departure configuration availability.
4.3 Hierarchy Level 3: Runway Level

At the lowest hierarchical level there are two methods by which the runway availability can be determined. The first, called the Availability Block Diagram (ABD) method relies solely on National Airspace Performance Reporting System (NAPRS) outage data of the relevant facilities. The second, called the Fault Tree Analysis (FTA) method is based upon fault trees which can be constructed based upon NAS 6750.24C [4]. In this study, the ABD method has been used since not all of the input data required for the FTA was available for the numerical example presented in section 9.

4.3.1 Arrival and Departure Runway Availability and Availability Block Diagram (ABD) Method

The departure and arrival availability of a given runway is calculated by taking into consideration the proportion of time that each of the weather categories of approach and departure were utilized.

Runway departure availability, $A_{DR}$, is expressed by the following equation:
Where:

\[ A_{DR_j} = \sum_{l=1}^{4} y_j \times A_{DT_{lj}} \quad \forall j \]  

Equation (6)

- \( A_{DR_j} \) = departure availability for runway \( j \)
- \( y_j \) = percentage use of weather category \( l \)
- \( A_{DT_{lj}} \) = equipment-related departure availability for weather category \( l \) on runway \( j \). This parameter is calculated from the diagrams in figures 10 through 12 using ABD method.
- \( l \) = arrival or departure weather category; the 4 weather categories are VFR, CAT I, CAT II and CAT III
- \( j \) = departure runway selected

Runway arrival availability, \( A_{AR_j} \), is then expressed by the following equation:

\[ A_{AR_j} = \sum_{l=1}^{4} y_j \times A_{AT_{lj}} \quad \forall j \]  

Equation (7)

Where:

- \( A_{AR_j} \) = arrival availability for runway \( j \)
- \( y_j \) = percentage use of weather category \( l \)
- \( A_{AT_{lj}} \) = equipment-based arrival availability for weather category \( l \) on runway \( j \). This parameter is calculated from the diagrams in figures 10 through 12 using ABD method.
- \( l \) = arrival or departure weather category; the 4 categories are VFR, CAT I, CAT II and CAT III
- \( j \) = arrival runway selected

4.3.2 Summary of Airport Arrival and Departure Models

Based on equation 2, and after expressing the departure availability, \( A_{DC_i} \), for runway configuration \( i \), with equations 3 and 6, the final formula for total airport departure availability, \( A_D \), is obtained by the following expression:

\[ A_D = \sum_{i=1}^{m} \left[ 1 - \prod_{j=1}^{n_i} (1 - (\sum_{l=1}^{4} y_j \times A_{DT_{lj}})) \right), \forall i = \overline{1,m}, \ j = \overline{1,n_i} \ and \ l = 4 \]  

Equation (8)

Based on equation 3, the total airport arrival availability, \( A_A \), is now expressed by equations 4 and 7, and is described by equation 9 below:
Thus, equations 8 and 9, express arrival and departure availabilities on a much finer level of granularity, as a function of runway arrival and departure availabilities, $A_{AT}$ and $A_{DT}$, respectively.

5 Equipment Requirements for Approaches and Departures

Aircraft departures and arrivals can occur under either Visual Flight Rules (VFR) or Instrument Flight Rules (IFR) depending on the weather (visibility) conditions, the type of aircraft, and requirements of the specific aircraft operator. In order for an airport to be available, all equipment necessary for the VFR or IFR operation must be functional. Prior to building the availability block diagrams for each IFR category, it is necessary to understand weather limitations/conditions, and runway/airport equipment mandatory during each weather (visibility) conditions. Hence, the following subsections describe the derivation of availability block diagrams for VFR and IFR operations.

5.1 VFR Availability Block Diagram

For VFR operations, there are no equipment requirements during the day and only the medium intensity runway lights (MIRL) are required to perform a night time approach or departure. MIRL are the responsibility of the local airport authorities. Thus, no outages of FAA facilities affect runway availability under VFR. Therefore, for the purposes of this analysis, it is assumed that the MIRL availability is equal to 1.

![Figure 9. Availability block diagram: hierarchy level 3 - VFR Conditions.](image)

5.2 IFR Availability Block Diagrams

For IFR operations (i.e., those in lower visibility weather conditions), an Instrument Landing System (ILS) is used. The ILS is classified into 3 categories (designated as I, II and III), where each category has progressively lower visibility and decision height altitudes. ILS systems provide both horizontal and vertical position information to aircraft as they land. Arrival operations utilizing both vertical and horizontal guidance are referred to as precision approaches.

The most common ILS is a Category I (CAT I) system, which provides accurate guidance information in visibilities as low as 0.5 mile and ceilings as low as 200 feet [5]. CAT II allows a properly equipped aircraft (and trained pilots) to utilize the ILS in the visibility conditions of

$$A_i = \sum_{i=1}^{m} x_i \times \left[ 1 - \prod_{j=1}^{p_i} \left( 1 - \sum_{l=1}^{4} y_l A_i^{AT} \right) \right], \forall i = 1, m, j = 1, p_i \text{ and } l = 4$$ (9)
1,200 ft and ceiling of 100 ft. The additional equipment required for CAT II includes more effective localizer and glide slope monitoring equipment, an inner marker and additional approach lighting. CAT III ILS equipment is more expensive because it requires completely redesigned localizer and glide slope equipment. Approaches under CAT III can be conducted when the ceiling (i.e., decision height) is zero, and the visibility is 700, 150, and 0, for CAT IIIa, b, and c, respectively. Thus, different approach categories result in different runway performance outcomes during equipment outages [6,7].

Figure 10 identifies the runway availability block diagrams for IFR CAT I approaches and departures (generally, runway visual range (RVR) > 1800 feet) when the runways are CAT I precision runways. All of the series facilities are essential for runway availability. The facilities appearing in dotted blocks do not have outages reported in NAPRS. They are included for the sake of model completeness but are not included in the availability calculations. Under these diminished visibility conditions it is necessary to have the upgraded high intensity runway lights and the additional lighting provided by the centerline lights (CL) and Touchdown Zone Lights (TZL). The runway visual range capabilities are required for CAT I instrument approaches if the visibility is less than one-half mile. Because weather data did not permit a distinction based on that criterion it was assumed that RVR is required for all approaches. As for departures, neither ILS nor the additional lighting and RVR are required for departures. The departure diagram in figure 10 includes VOR and DME as associated with runway availability although these facilities usually serve more than one runway. As shown in the diagram, there are multiple alternatives for obtaining distance along the approach path, and therefore the availability of these facilities is considered perfect in our model.

Figure 10. Availability block diagram: hierarchy level 3 (CAT I equipped runways).

Figure 11 is the runway availability block diagram for precision approaches and departures when the runways are CAT II precision runways. The only difference in this diagram from the previous diagram is that the approach lighting system is the ALSF-2 high intensity system rather than the medium intensity system MALSR, which is used for CAT I precision runways.
Figure 11. Availability block diagram: hierarchy level 3 (CAT II equipped runways).

Figure 12 is the availability block diagram for CAT III approach and departure. Since CAT III approaches are used under the worst visibility conditions the Airport Surface Detection Equipment (ASDE) is an additional requirement. The departure facility requirements are identical with those of a CAT II departure.

Figure 12. Availability block diagram: hierarchy level 3 runway (CAT III equipped runways).
6 Numerical Example: Boston Logan (BOS) International Airport Availability

This section describes an application of the methodology for Boston Logan International Airport (BOS). BOS is the 19th busiest airport in the country that handled 405,370 aircraft operations and 10,731,523 passenger enplanements in fiscal year 2002 [8]. Figure 14 illustrates the runway geometry and location of terminal buildings [9] for Boston Logan International Airport. The airport has a total of five runways. Runways 4L/22R and 4R/22L are parallel North/West-South/East runways, which intersect another set of parallel runways 15R/33L and 15L/33R, which run in an almost perpendicular direction. The fifth runway 6/27 is an East-West runway which crosses runways 4R/22L and 15R/33L. Only four bi-directional runways are considered in the availability models. Runway 15L/33R is used for turboprop commuter aircraft but is not long enough for commercial jets. A new runway 14/32 is planned to be completed in 2006, with the objective to relieve the current traffic congestion. This runway has not been completed yet and therefore has not been considered in the airport availability estimation. Table 1 summarizes current capabilities by runway. Two directions of a given physical runway are considered as two separate runways. For this reason we indicate 8 runways in table 1.

![Figure 14. Boston Logan International Airport](image)

Table 1

<table>
<thead>
<tr>
<th>Runway Number</th>
<th>Length (feet)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>4L/22R</td>
<td>10,000</td>
<td>East-West</td>
</tr>
<tr>
<td>4R/22L</td>
<td>10,000</td>
<td>East-West</td>
</tr>
<tr>
<td>15R/33L</td>
<td>10,000</td>
<td>East-West</td>
</tr>
<tr>
<td>15L/33R</td>
<td>10,000</td>
<td>East-West</td>
</tr>
<tr>
<td>6/27</td>
<td>10,000</td>
<td>East-West</td>
</tr>
<tr>
<td>14/32</td>
<td>10,000</td>
<td>East-West</td>
</tr>
<tr>
<td>10</td>
<td>10,000</td>
<td>East-West</td>
</tr>
<tr>
<td>13</td>
<td>10,000</td>
<td>East-West</td>
</tr>
</tbody>
</table>

This table shows the current lengths of all relevant runways at Boston Logan International Airport.
Table 1. Boston Logan runway IFR capability.

<table>
<thead>
<tr>
<th>Runway</th>
<th>Max IFR Runway Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>4L</td>
<td>CAT III</td>
</tr>
<tr>
<td>4R</td>
<td>CAT III</td>
</tr>
<tr>
<td>9</td>
<td>CAT I</td>
</tr>
<tr>
<td>15R</td>
<td>CAT I</td>
</tr>
<tr>
<td>22L</td>
<td>CAT I</td>
</tr>
<tr>
<td>22R</td>
<td>CAT I</td>
</tr>
<tr>
<td>27L</td>
<td>CAT I</td>
</tr>
<tr>
<td>33L</td>
<td>CAT I</td>
</tr>
</tbody>
</table>

Table 2 shows the BOS IFR runway configurations and relative frequencies of the use of these configurations based on information [10]. Weather conditions reported in the International Station Meteorological Climate Summary [11] are summarized in table 3, and show the proportion of restricted visibility conditions based on these data. The airport weather conditions permit VFR operations 87% of the time, and the IFR conditions, with restricted visibilities and low ceilings, are present 13% of the time. The source for outage data is the National Airspace Performance Reporting System (NAPRS) as defined in [3], FAA Order 6040.15C. The outage data used for this analysis were obtained from the NAPRS data base covering the period from January, 1996 through May, 1997.

Table 2. Runway configuration information.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Departure Runways</th>
<th>Arrival Runways</th>
<th>Parameter Name</th>
<th>Proportion</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4L,4R and 9</td>
<td>4R</td>
<td>$x_1$</td>
<td>31.5%</td>
<td>Based on [10]</td>
</tr>
<tr>
<td>2</td>
<td>22Rand 22L</td>
<td>22L</td>
<td>$x_2$</td>
<td>30.1%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>33L</td>
<td>33L</td>
<td>$x_3$</td>
<td>34.1%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15R and 9</td>
<td>15R</td>
<td>$x_4$</td>
<td>4.3%</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Frequency of visibility conditions at BOS.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Symbol</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>VFR</td>
<td>$y_0$</td>
<td>87%</td>
</tr>
<tr>
<td>CAT I</td>
<td>$y_1$</td>
<td>8%</td>
</tr>
<tr>
<td>CAT II</td>
<td>$y_2$</td>
<td>3%</td>
</tr>
<tr>
<td>CAT III</td>
<td>$y_3$</td>
<td>2%</td>
</tr>
</tbody>
</table>

In the following sections of this paragraph the general availability model equations were used for the specific conditions at the Boston Logan International Airport. Subsection 8.1 describes the relationship between airport availability and possible runway configurations at the airport (hierarchy level 1). Subsection 8.2 further decomposes the configuration availability to those of individual runways (hierarchy level 2), and subsection 8.3 describes runway availability.
as a function of the individual facilities defined as essential for runway availability under various visibility conditions (hierarchy level 3).

6.1 Airport Level (Hierarchy Level 1)

Based on the analysis of the airport operations at BOS, it is found that the airport has four alternative runway configurations available for IFR arrivals and departures. Equations 10.1 and 10.2 are the BOS specific departure, \(A_D\), and arrival, \(A_A\), availability equations adapted from equations 2 and 3.

\[
A_D = x_1A_{DC_1} + x_2A_{DC_2} + x_3A_{DC_3} + x_4A_{DC_4} \quad (10.1)
\]
\[
A_A = x_1A_{AC_1} + x_2A_{AC_2} + x_3A_{AC_3} + x_4A_{AC_4} \quad (10.2)
\]

Variables \(x_1\) through \(x_4\) represent the proportion of use of the four configurations shown in table 2, while availabilities \(A_{DC_1}\) through \(A_{DC_4}\) are the availabilities of departure configurations 1 through 4, and \(A_{AC_1}\) through \(A_{AC_4}\) are the availabilities of arrival configurations 1 through 4.

6.2 Configuration Level (Hierarchy Level 2)

The runway IFR arrival and departure configurations for BOS are shown in table 2. Equations 11.2 through 11.4, adopted from equation 4, show the availability, \(A_{DC}\), of the four departure configurations as a function of runway availability, \(A_{DR}\).

\[
A_{DC_1} = 1 - (1 - A_{DR_{4L}}) \times (1 - A_{DR_{4R}}) \times (1 - A_{DR_{9}}) \quad (11.1)
\]
\[
A_{DC_2} = 1 - (1 - A_{DR_{22L}}) \times (1 - A_{DR_{22R}}) \quad (11.2)
\]
\[
A_{DC_3} = A_{DR_{33L}} \quad (11.3)
\]
\[
A_{DC_4} = 1 - (1 - A_{DR_{15L}}) \times (1 - A_{DR_{15R}}) \quad (11.4)
\]

Availabilities \(A_{DR_{4L}}, A_{DR_{4R}}, A_{DR_{9}}, A_{DR_{22L}}, A_{DR_{22R}}, A_{DR_{33L}}\) and \(A_{DR_{15L}}, A_{DR_{15R}}\) are the departure availabilities for runways 4L, 4R, 9, 22L, 22R and 33 defined in section 6.

Equations 12.1 through 12.4 are the configuration level arrival equations adapted from equation 5 for the four BOS configurations based on [10]. Since all of the arrival configurations consist of only one runway, the arrival configuration, \(A_{AC}\), equals the runway availability, \(A_{AR}\).

\[
A_{AC_1} = A_{AR_{4L}} \quad (12.1)
\]
\[
A_{AC_2} = A_{AR_{22L}} \quad (12.2)
\]
\[
A_{AC_3} = A_{AR_{33L}} \quad (12.3)
\]
\[
A_{AC_4} = A_{AR_{15R}} \quad (12.4)
\]

Therefore, availabilities \(A_{AR_{4L}}, A_{AR_{22L}}, A_{AR_{33L}}\) and \(A_{AR_{15R}}\) are the arrival availabilities for runways 4R, 22L, 33L and 15R defined in the next subsection.
### 6.3 Runway Level (Hierarchy Level 3)

Based on the block diagrams shown in figures 10 through 12, and equation 7, it is possible to derive the following relationships for equipment-related runway arrival availabilities, $A_{AT}$. Equations 13.1 through 13.3 show the equipment-related runway arrival availability, $A_{AT}$, for Category I through III visibility conditions.

$$A_{AT_{\text{CATI}}} = A_{\text{GS}} \times A_{\text{DME}} \times A_{\text{RVR}} \times A_{\text{LOC}} \times A_{\text{MALSR}} \times A_{\text{VOR}}$$  \hspace{1cm} (13.1)

$$A_{AT_{\text{CATII}}} = A_{\text{GS}} \times A_{\text{DME}} \times A_{\text{RVR}} \times A_{\text{LOC}} \times A_{\text{ALSF}} \times A_{\text{VOR}}$$  \hspace{1cm} (13.2)

$$A_{AT_{\text{CATIII}}} = A_{\text{GS}} \times A_{\text{DME}} \times A_{\text{RVR}} \times A_{\text{LOC}} \times A_{\text{ALSF}} \times A_{\text{ASDE}} \times A_{\text{VOR}}$$  \hspace{1cm} (13.3)

Availabilities $A_{AT_{\text{CATI}}}$, $A_{AT_{\text{CATII}}}$, and $A_{AT_{\text{CATIII}}}$ respectively refer to Category I, II, and III arrival availability, and availabilities on the right hand side of each equation refer to the availability of specific runway equipment derived from NAPRS data.

In order to translate these equipment-related runway arrival availabilities into weather-related runway arrival capabilities, it is necessary to consider the IFR and VFR capabilities of the individual runways as shown in table 3. A runway is available if it is equipped to handle the minimum visibility conditions and all required pieces of equipment are operational. Thus, for Runway 4R, a Cat III runway, the availability is:

$$A_{AR_{4R}} = y_0 + y_1 \times A_{AT_{\text{CATIII}}} + y_2 \times A_{AT_{\text{CATII}}} + y_3 \times A_{AT_{\text{CATI}}}$$  \hspace{1cm} (14.1)

Variable $y_0$ refers to the proportion of time of VFR conditions, and $y_1$, $y_2$, and $y_3$ respectively refer to the proportion of Category I, II and III visibility conditions. For Runway 15R, a Category I runway, the availability can not exceed the proportion of VFR and Category I visibility conditions, i.e.,

$$A_{AR_{15R}} = y_0 + y_1 \times A_{AT_{\text{CATI}}}$$  \hspace{1cm} (14.2)

The same is true for runways 22L and 33L, which are also Category I runways.

$$A_{AR_{22L}} = A_{AR_{33L}} = y_0 + y_1 \times A_{AT_{\text{CATI}}}$$  \hspace{1cm} (14.3)

Under VFR conditions, only runways 4L, 9, 22R, and 27 are used, and the arrival availability is equal to the proportion of time that VFR weather conditions are experienced, thus:

$$A_{AR_{4L}} = A_{AR_{9}} = A_{AR_{22R}} = A_{AR_{27}} = y_0$$  \hspace{1cm} (14.4)

For departures, the block diagrams, shown in figures 10 through 12, indicate that only the VOR and DME are required. The departure availability is then the proportion of VFR conditions (when no NAS facilities are required) and combined availability of a VOR and a DME when any IFR conditions are present. Thus, for runway 4R the departure availability is:

$$A_{DR_{4R}} = y_0 + (A_{\text{DME}} \times A_{\text{VOR}}) \times (y_1 + y_2 + y_3)$$  \hspace{1cm} (15.1)
The first term, \( y_0 \), accounts for VFR conditions when no runway facilities are required. The second term, \( (A_{DME} \times A_{VOR}) \times (y_1 + y_2 + y_3) \), addresses the proportion of time when any IFR condition is present.

For the Category I runways 15R, 22L and 33L, the following formula apply for departure availability:

\[
A_{DR_{15}} = A_{DR_{22}} = A_{DR_{33}} = y_0 + (A_{DME} \times A_{VOR}) \times y_1
\]  \hspace{1cm} (15.2)

The departure availability for the VFR runways 4L, 9, 22L and 27 is the same as the arrival availability, and is equal to the proportion of VFR weather conditions. Thus,

\[
A_{DR_{4L}} = A_{AR_9} = A_{DR_{22}} = A_{AR_{27}} = y_0
\]  \hspace{1cm} (15.3)

### 6.4 Numerical Results

This section presents the results of the model using NAPRS data and the airport specific models described in previous section. Section 8.4.1 discusses the baseline results and section 8.4.2 discusses the impacts of runway ILS upgrades on runway and airport availabilities.

#### 6.4.1 Baseline Results

Airport availability estimates are presented in table 4. An interpretation of the results for airport departure availability is that at least one departure runway configuration is available all but 7.18 days per year (\( A_d = 0.9803 \)) and one arrival runway configuration is available all but 13.41 days per year (\( A_a = 0.9632 \)). On the average, there will be 20.60 days per year when the runway configurations in operation will not have its full compliment of runways. When availabilities for primary runway configurations are analyzed, it is found that Configuration 1 has the highest arrival (\( A_{AC_1} = 0.9961 \)) and departure (\( A_{DC_1} = 0.9999 \)) configuration availability. The high level of Configuration 1 availability is explained by the fact that its primary arrival runway, 4R, is the CAT III runway, and therefore can accommodate the worst weather conditions. The runway itself has the highest runway arrival (\( A_{AR_{4R}} = 0.9967 \)) and runway departure (\( A_{DR_{4R}} = 0.9984 \)) availabilities, compared to that of the other runways. Configuration 4 has the lowest arrival (\( A_{AC_4} = 0.9479 \)) and departure (\( A_{DC_4} = 0.9934 \)) availabilities, which is intuitively expected because of a very low use of runways 15R and 9 for arrivals and departures, and the lack of IFR equipage at runway 9. A relatively low value of runway arrival and departure availabilities for runways 4L, 27R and 27 is also explained by the lack of IFR equipage. However, the most surprising finding is that Configuration 3 does not have the highest level of availability, although it has a higher (34%) utilization when compared to Configuration 1 (31.5%). In the next section we further analyze this intriguing finding.
Table 4. Arrival and departure availability estimates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_A$</td>
<td>Airport Arrival Availability</td>
<td>0.9632</td>
</tr>
<tr>
<td>$A_D$</td>
<td>Airport Departure Availability</td>
<td>0.9803</td>
</tr>
<tr>
<td>$A_{AC_1}$</td>
<td>Arrival Availability for Configuration 1</td>
<td>0.9961</td>
</tr>
<tr>
<td>$A_{DC_1}$</td>
<td>Departure Availability for Configuration 1</td>
<td>0.9999</td>
</tr>
<tr>
<td>$A_{AC_2}$</td>
<td>Arrival Availability for Configuration 2</td>
<td>0.9479</td>
</tr>
<tr>
<td>$A_{DC_2}$</td>
<td>Departure Availability for Configuration 2</td>
<td>0.9934</td>
</tr>
<tr>
<td>$A_{AC_3}$</td>
<td>Arrival Availability for Configuration 3</td>
<td>0.9479</td>
</tr>
<tr>
<td>$A_{DC_3}$</td>
<td>Departure Availability for Configuration 3</td>
<td>0.9490</td>
</tr>
<tr>
<td>$A_{AC_4}$</td>
<td>Arrival Availability for Configuration 4</td>
<td>0.9479</td>
</tr>
<tr>
<td>$A_{DC_4}$</td>
<td>Departure Availability for Configuration 4</td>
<td>0.9934</td>
</tr>
<tr>
<td>$A_{AR_{4L}}$</td>
<td>Arrival Availability, Runway 4L</td>
<td>0.8700</td>
</tr>
<tr>
<td>$A_{DR_{4L}}$</td>
<td>Departure Availability, Runway 4L</td>
<td>0.8700</td>
</tr>
<tr>
<td>$A_{AR_{4R}}$</td>
<td>Arrival Availability, Runway 4R</td>
<td>0.9967</td>
</tr>
<tr>
<td>$A_{DR_{4R}}$</td>
<td>Departure Availability, Runway 4R</td>
<td>0.9984</td>
</tr>
<tr>
<td>$A_{AR_9}$</td>
<td>Arrival Availability, Runway 9</td>
<td>0.8700</td>
</tr>
<tr>
<td>$A_{DR_9}$</td>
<td>Departure Availability, Runway 9</td>
<td>0.8700</td>
</tr>
<tr>
<td>$A_{AR_{15R}}$</td>
<td>Arrival Availability, Runway 15R</td>
<td>0.9479</td>
</tr>
<tr>
<td>$A_{DR_{15R}}$</td>
<td>Departure Availability, Runway 15R</td>
<td>0.9490</td>
</tr>
<tr>
<td>$A_{AR_{22L}}$</td>
<td>Arrival Availability, Runway 22L</td>
<td>0.9479</td>
</tr>
<tr>
<td>$A_{DR_{22L}}$</td>
<td>Departure Availability, Runway 22L</td>
<td>0.9490</td>
</tr>
<tr>
<td>$A_{AR_{22R}}$</td>
<td>Arrival Availability, Runway 22R</td>
<td>0.8700</td>
</tr>
<tr>
<td>$A_{DR_{22R}}$</td>
<td>Departure Availability, Runway 22R</td>
<td>0.8700</td>
</tr>
<tr>
<td>$A_{AR_{27}}$</td>
<td>Arrival Availability, Runway 27</td>
<td>0.8700</td>
</tr>
<tr>
<td>$A_{DR_{27}}$</td>
<td>Departure Availability, Runway 27</td>
<td>0.8700</td>
</tr>
<tr>
<td>$A_{AR_{33L}}$</td>
<td>Arrival Availability, Runway 33L</td>
<td>0.9479</td>
</tr>
<tr>
<td>$A_{DR_{33L}}$</td>
<td>Departure Availability, Runway 33L</td>
<td>0.9490</td>
</tr>
</tbody>
</table>

6.4.2 Sensitivity Analysis: Impact of Runway ILS Upgrades on Availability

The calculated airport arrival and departure availability for Boston Logan, as documented in table 4, have relatively low values ($A_A = 0.9632$ and $A_D = 0.9803$). The reason for the low availability values is largely due to runway IFR capability limitations. This section examines the availability...
benefit that can be achieved by upgrading the IFR capability of selected runways. At BOS only runway 4R has CAT III capability, runways 15R, 22L and 33L have CAT I capability and the remaining runways 4L, 9, 22R and 27 have only VFR visibility capability. Runway 4R is used in Configuration 1 for arrivals and departures. However, since Configuration 1 is only used 31.5%, during the remaining 68.5% of the time the airport has only CAT I capability and can not accommodate the worse visibility conditions, which historically occur 5% of the time. It is interesting to explore the availability gain which could be achieved if runway visibility equipment upgrading were performed. It is postulated that the IFR upgrading to runways 22L and 33L would yield the greatest airport arrival and departure availability improvements, and therefore these options are analyzed first separately, and then in combination. The three upgrade possibilities are:

- Upgrade 1: Upgrading runways 22L from a maximum capability of CAT I to CAT III
- Upgrade 2: Upgrading runways 33L from a maximum capability of CAT I to CAT III
- Upgrade 3: Performing both upgrade 1 and 2.

Table 5 summarizes the effect of each ILS equipment upgrade on arrival and departure availability for runways 22L and 33L. As expected, availability has increased significantly at both runways. At runway 22L, arrival availability, $A_{AR_{22L}}$, increased from 0.9479 to 0.9967, while departure availability, $A_{DR_{22L}}$, increased from 0.9490 to 0.9984. Similarly, runway 33L experienced significant gains in both, arrival availability, $A_{AR_{33L}}$, from 0.9479 to 0.9967, and in departure availability, $A_{DR_{33L}}$, from 0.9490 to 0.9984.

<table>
<thead>
<tr>
<th>Availability</th>
<th>Present Value</th>
<th>With Upgrade 1</th>
<th>With Upgrade 2</th>
<th>With Upgrade 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{AR_{22L}}$</td>
<td>0.9479</td>
<td>0.9967</td>
<td>0.9479</td>
<td>0.9967</td>
</tr>
<tr>
<td>$A_{DR_{22L}}$</td>
<td>0.9490</td>
<td>0.9984</td>
<td>0.9490</td>
<td>0.9984</td>
</tr>
<tr>
<td>$A_{AR_{33L}}$</td>
<td>0.9479</td>
<td>0.9479</td>
<td>0.9967</td>
<td>0.9967</td>
</tr>
<tr>
<td>$A_{DR_{33L}}$</td>
<td>0.9490</td>
<td>0.9490</td>
<td>0.9984</td>
<td>0.9984</td>
</tr>
</tbody>
</table>

The logical question is then to explore the impact of the runway availabilities on configuration availabilities, and then on the overall airport arrival, $A_A$, and departure, $A_D$, availabilities. As shown in table 6, the airport arrival and departure availabilities are substantially improved by upgrading the runway equipment to CAT III level. As a first priority, runway 33L should be updated since it yields the greatest airport availability improvement, with airport arrival availability increasing from 0.9632 to 0.9799, and airport departure availability increasing from 0.9803 to 0.9972.
Table 6. Impact of possible ILS upgrades on BOS airport availability.

<table>
<thead>
<tr>
<th>Upgrade Option</th>
<th>Arrival Availability (A_A)</th>
<th>Departure Availability (A_D)</th>
<th>Total Hours</th>
<th>Percent Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>No upgrades (Current Configuration)</td>
<td>0.9632</td>
<td>0.9803</td>
<td>494.3</td>
<td></td>
</tr>
<tr>
<td>1 Upgrading runway 22L from a maximum capability of CAT 1 to CAT III</td>
<td>0.9779</td>
<td>0.9823</td>
<td>348.8</td>
<td>29.4%</td>
</tr>
<tr>
<td>2 Upgrading runway 33L from a maximum capability of CAT I to CAT III</td>
<td>0.9799</td>
<td>0.9972</td>
<td>201.1</td>
<td>59.3%</td>
</tr>
<tr>
<td>3 Performing both above upgrades</td>
<td>0.9946</td>
<td>0.9991</td>
<td>55.5</td>
<td>88.8%</td>
</tr>
</tbody>
</table>

For better clarity, figure 15 shows only the availability improvements offered by the 3 options. Option 2 is preferable to Option 1 for improving both arrival and departure availabilities. Option 1 only offers a dramatic improvement to the arrival availability. By selecting both upgrades, Option 3, the airport arrival availability increases from 0.9632 to 0.9946, and the airport departure availability rises from 0.9803 to 0.9991.

Figure 15. Availability Improvements with IFR equipment upgrades.

Figure 16 identifies only the total of arrival and departure downtime experienced with the present runway IFR capabilities and the potential downtime reduction that the various options offer. A runway 33L upgrade offers a significantly higher reduction in downtime (from 494.3 hours to 201.1 hours) when compared to the reduction in downtime of runway 22L upgrade to CAT III (348.8 hours per year).
When the downtime reduction is expressed in terms of the percentage downtime reduction, figure 17 shows possible improvements for each of the options. Hence, Option 3 offers a 88.8% reduction in total downtime from 494.3 hours to 55.5 hours.

Another, more practical interpretation of availability improvements for both airport arrival and departure availabilities is that, with Option 1, one arrival runway configuration is available all but 8.06 days per year, and airport departure availability is available all but 6.26 days per year. On the average, with Option 1, there would be 14.52 days per year when the runway configurations in operation would not have its full compliment of runways. Option 2 further reduces the number of inoperable days to 7.34 for arrivals and 1.022 for departures, while Option 3 offers almost an amazing reduction to only 1.97 inoperable days for arrivals and only 0.328 inoperable days for departures.

7 Conclusions and Recommendations

The methodology developed in this paper is intended for short-term and long-term planning of the CNS equipment acquisition. Improved understanding of the effects of equipment outages on airport availability is valuable in determining a required level of airport equipage and equipment reliability, particularly during critical situations, such as bad weather conditions and increased traffic demand. With proposed methodology an analyst can precisely quantify the additional
level of airport availability achieved by upgrading or adding new pieces of CNS equipment at airports, and therefore better accommodate critical operating conditions (such as bad weather). Consequently, this methodology should assist the FAA to improve investment and modernization decisions related to CNS equipment, particularly at airports that require additional service availability.

The developed methodology is also useful in estimating airport effectiveness, a performance metric used to measure a level of airport (or runway) capacity that can be reached at each level of airport equipment-related availability. Airport capacity is usually affected by equipment outages due to the additional spacing that air traffic controllers impose on mile-in-trail separation, due to the change in ATC procedures and reduced safety, or due to the use of alternative runways, in order to compensate for the lack of necessary pieces of navigational equipment. We strongly recommend further research in the area of airport effectiveness because of its usefulness to the estimation of expected capacity – and estimations of the necessary airport modernization required to meet continual increase in traffic demand.

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