How the Passenger Aviation Industry Prepares for and Responds to Disruptions: Foundational Analysis and Current-State Assessment Part 1

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1. Overview

This report consists of three parts. The first section reviews the existing literature, both academic and commercial, on disruptions in domestic U.S. passenger aviation. We consider how carriers use robust planning to prepare pro-actively and how they use recovery mechanisms to react post-disruption. The second section presents a detailed analysis of historical data that considers severity, patterns, and trends in both root- and propagated-disruptions across the U.S. domestic flight network. The third section uses case studies to analyze some of the differences between carriers' approaches to robust planning and recovery.

2. Literature Review

There is a vast amount of research on robust planning and recovery mechanisms to be found in the academic literature. In addition, the lay press includes discussion of industry strategies and philosophies, as well as the frequency and severity of disruptions, the impact on passengers and the economy, and more. Finally, government reports summarize and synthesize industry statistics and trends.

Our focus on reviewing this literature is in understanding how the following questions have been addressed:

- What are the sources of disruption in passenger aviation?
- How do disruptions propagate and what is the resulting impact in terms of passenger delays, costs, and other factors?
- How do carriers attempt to mitigate the effects of disruption pro-actively, through robust planning, and how do they respond to disruptions and reduce the impact of propagation through recovery mechanisms?

- How do carriers differ in their approaches to robust planning and recovery, and can anything about corporate philosophy be inferred from these differences?

2.1 Causes of Root Disruption

A *root disruption* is a disruption that is in some way intrinsic to a flight itself associated with an activity, event, or condition that is directly related to the flight as a function of space, time, or resources. For example, a flight might be delayed because of a mechanical problem discovered on the assigned aircraft prior to departure. We contrast this with *propagated delay* or *propagated disruption* which is the result of a resource (e.g. aircraft, crew member, connecting passenger) that is not available at the scheduled time because of an earlier disruption in the system.

The sections below discuss several sources of root delays. More information about how the FAA reports on delays can be found at http://www.rita.dot.gov/bts/help/aviation/html/understanding.html.

Weather

Weather issues are perhaps the most relevant sources of root disruptions: hard to predict, hard to control, frequent in occurrence, and often greatly reducing flight capabilities. It is difficult (and perhaps not particularly helpful) to separate out the impact of weather on root disruptions (e.g. a flight delayed when the origin airport shuts down due to a sudden thunderstorm) versus on propagated disruptions (e.g. a flight that is delayed while awaiting in inbound aircraft that is late due to a departure delay caused by a thunderstorm). We discuss the overall impact of weather delays on the aviation system in the Section 2.2.

Note that it is very difficult to measure exactly how weather impacts delays, especially in trying to identify root causes and not propagated delays, as discussed in this U.S. Bureau of Transportation report: http://www.rita.dot.gov/bts/help/aviation/html/understanding.html .

We *do* know, however, that different weather conditions have markedly different impacts in terms of root disruptions. For example:

- **Snow and Ice Storms** often occur with multiple days' notice (although the accuracy of these forecasts improves greatly as the time of event is approached). These forecasts provide airlines with opportunity for proactive cancellations, repositioning of equipment, and re-booking of passengers. Such events usually last for extended periods of time (often hours or even days) but with varying degree of intensity. There is often a gradual diminishing of capacity (e.g. decreased take-off and landing rates, then greater reductions in capacity due to plowing or treating of runways and de-icing of aircraft) followed by gradual increasing of capacity as the storm abates (http://traveltips.usatoday.com/criteria-flight-delays-during-snow-110542.html).
  For example, in December of 2008, a holiday blizzard cancelled nearly 10,000 flights, with extensive delays to additional flights (http://www.nytimes.com/2010/12/29/nyregion/29airports.html?_r=1, http://www.cnn.com/2010/TRAVEL/12/28/airlines.weather/).
  2010 saw February storms of such significance that the FAA reported on their impact (including a record-high monthly total of more than 20,000 flight cancellations http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/special_reports_and_issue_briefs/special_report/2010_07/html/entire.html).
  Multiple storms in the winter of 2011 were crippling to the airline industry (http://www.csmonitor.com/USA/2011/0202/Winter-storm-s-airport-impact-13-000-canceled-flights), in some cases leading to more than 10,000 cancelled.
  Winter holidays seem to be particularly problematic for the airline industry, with the combination of frequent bad weather, very high load factors, and limited flexibility for passengers traveling to time-specific events, as evidenced in 2012 (http://www.usatoday.com/story/todayinthesky/2012/12/19/new-winter-storm-could-snarl-christmas-flights/1779441/).

December snow in New York in 2013 provided yet another example of major disruptions (http://www.nytimes.com/2013/12/15/nyregion/snowstorm-causes-delays-at-new-york-airports.html).

While many of the high-visibility storms in the U.S. affect the East Coast, they are by no means restricted to that area. For example, Denver experienced significant disruption in February of 2013 due to snow and associated de-icing, runway closures, etc. (http://www.denverpost.com/ci_22659461/snow-bound-passengers-camping-out-at-denver-international). A January storm in 2014 brought rare snow and ice to Atlanta, causing extensive delays and cancellations there, as well as at many other airports across the country (http://www.cnn.com/2014/01/28/travel/winter-storm-travel/). Also in January of 2014, snow storms disrupted 150,000 passengers for JetBlue Airways alone (http://money.cnn.com/2014/01/07/news/companies/jetblue/). A month later, another snow storm caused East Coast delays almost as extensive as those experienced two years earlier for Hurricane Sunday (https://skift.com/2014/02/14/winter-storm-caused-almost-as-many-flight-cancellations-as-hurricane-sandy-thursday/ , http://www.usatoday.com/story/todayinthesky/2014/02/11/another-winter-weather-headache-for-air-travelers-tuesday/5388691/). Sleet was the prime source of disruption in a January 2015 storm that led to more than 1,600 cancellations in Chicago (http://www.dailyherald.com/article/20151227/news/151229260/).

And as is discussed in http://www.nytimes.com/2016/01/24/travel/the-snow-storm-is-over-but-travel-delays-arent.html, the impact of such storms often extends many hours, and even days, beyond the end of the weather event itself. Furthermore, delays often extend well beyond the location of the storm itself, for example with Los Angeles feeling significant impacts from mid-West and East Coast storms (http://www.scpr.org/news/2016/01/23/57007/lax-flights-could-face-more-delays-due-to-winter-s/).

A lay discussion of aviation issues associated with flying in winter weather can be found at http://news.nationalgeographic.com/news/2013/11/131126-storm-airlines-travel-shutdown-weather-air-safety/.

- **Hurricanes and Tropical Storms** are similar to snow and ice storms in their level of predictability, their intensity, their wide-spread nature (across multiple airports), their duration, and their major impact. Moving aircraft away from potentially-affected airports in advance of the storm (as discussed by Barry (2008)) is common practice to avoid damage to such expensive assets, which can further delay recovery after the end of a storm as aircraft need to be repositioned.

  Although less frequent than snow storms, hurricanes and tropical storms are still common enough to greatly impact the airline industry. For example, Hurricane Irene led to several thousand flight cancellations, in addition to wide-spread delays, in 2011 (http://articles.latimes.com/2011/aug/27/local/la-me-0827-flights-cancel-20110828 , http://www.bloomberg.com/news/articles/2011-08-25/airlines-cancel-180-flights-as-hurricane-irene-approaches-u-s-east-coast-, http://www.npr.org/sections/thetwo-way/2011/08/26/139979801/2-400-flights-cancelled-ahead-of-hurricane-irene).

  Hurrican Sandy, in 2012, is reported to have caused more than 20,000 flight cancellations, including disruption to many international flights to/from Europe (http://www.wsj.com/articles/SB10001424052970204840504578086833916411390 , http://www.flightstats.com/company/20254-flights-canceled-due-to-hurricane-sandy/, http://www.dailymail.co.uk/news/article-2224417/Hurricane-Sandy-2012-path-Airlines-cancel-7-000-flights.html , http://www.bbc.com/news/uk-20120019), http://www.huffingtonpost.com/2012/10/30/flight-cancellations-superstorm-sandy_n_2044102.html).

  And Mexican traffic and tourism was substantially impacted by Hurricane Patricia in October of 2015 (http://www.cntraveler.com/stories/2015-10-26/hurricane-patricia-the-storm-that-canceled-1000-flights, http://www.latimes.com/business/la-fi-hurricane-patricia-impact-on-travel-20151023-story.html, http://www.latimes.com/local/lanow/la-me-ln-hurricane-patricia-flight-cancellations-20151023-story.html).

- **Thunderstorms, Fog, and Wind** are quite different from blizzards and hurricanes in many ways. They are harder to anticipate, shorter in duration, more localized, and more frequent. As such even relatively limited weather events can have great impact on flights operations (http://articles.sun-sentinel.com/2011-06-19/news/fl-summer-flight-delays-20110619_1_airline-delays-winter-storms-thunderstorms-move).
  In Allan et al (2001)'s three-year empirical study of Newark International Airport, they found convective weather, reduced ceiling, and visibility to be the primary cause of large delays. Such events, at EWR and elsewhere, are often somewhat localized in duration and limited in time, but at times can be as wide-spread and high-impact as a major snow or tropical storm. For example, thunderstorms on the East Coast, ranging from Florida to New York, caused more than 4,000 flights to be delayed on May 15, 2014 http://www.usatoday.com/story/todayinthesky/2014/05/15/storms-snarl-flights-create-thousands-of-delays/9136361/ . On June 13, 2014 there were delays of as long as four hours on many flights in and out of New York due to thunderstorms http://nypost.com/2014/06/13/thunderstorms-rock-ny-delay-flights-at-all-airports/ .
  Morning fog in San Francisco often causes delays (both locally and through ground delay programs), as discussed by http://crankyflier.com/2010/10/14/san-franciscos-fog-and-runway-problems-give-the-airport-a-dubious-honor/ . And airports in Chicago ("The Windy City") are frequently plagued by high winds, as evidenced by news stories such as http://chicago.suntimes.com/news/high-winds-cancel-delay-hundreds-of-flights-at-ohare/ .
  The FAA website provides information here about how thunderstorms affect aircraft enroute (https://www.faa.gov/nextgen/programs/weather/faq/#faq4) and when approaching landing (https://www.faa.gov/nextgen/programs/weather/faq/#faq5).
  We provide greater detail in Section 3 about the frequency, geographic distribution, and severity of such weather events.

Air Traffic Control/Congestion

Congestion in the airspace is another cause of root delays (as well as propagated delays). Such delays take two primary forms. The first is the immediate impact of congestion – for example, an over-abundance of planes in the airspace leading to longer delays on approach and departure as managed by Air Traffic Control. While this is often immediately impacted spatially, it can also be more removed (e.g. delays in Philadelphia resulting from the volume of traffic flying out of the New York metro area).

The second related type of ATC delays is associated with *ground delay programs* and *ground stop programs.* In these cases, congestion in one location (which can be strictly a function of volume or may be congestion resulting from weather disruptions) motivates ATC to delay departures *to* that location to avoid further build up of congestion in the air. For example, fog in San Francisco may decrease arrival rates, leading to congestion. As a result, flights from many other airports to SFO may be delayed on the ground at their airport of origin (because delays are safer on the ground than in the air, as well as being less expensive with respect to fuel burn).

There is also significant scholarly work on the issue of congestion and its impacts, all of which recognizes the tremendous challenges associated with modeling these questions and much of which focuses on either congestion-based pricing or air traffic flow management as a means to reduce congestion-induced costs and delays. For example, Ghobrial and Fleming (1992) investigated the impact of congestion on passenger delays and in particular focused on how the movement several decades ago towards hubbing, while having many advantages, also significantly (negatively) impacted congestion issues. Glockner (1996) focuses on how ATC manages traffic flow, balancing safety and efficiency, and specifically considers how different approaches to air traffic flow management (e.g. ground delay programs) impact delays. Johnson and Fleming (2006) modeled the relationship between congestion and delays, focusing on the example of Chicago O'Hare, especially after the elimination of slot controls in 2002. In particular, they model how bad weather (including weather of minimal severity) can greatly exacerbate congestion issues. Ison et al (2015) discuss the steady growth in volume in the past decade, the associated congestion-based delays, and the role of air traffic management tools in mitigating this. Wang and Kulkarni (2011) present machine learning approaches to predicting GDP parameters as a function of weather and operating conditions.

In addition, government efforts to mitigate delay (specifically through NextGen) are discussed at https://www.faa.gov/nextgen/programs/weather/faq/.

Mechanical Issues

Mechanical issues are a prime source of root delays, with a scheduled flight (and associated tail assignment) unable to operate according to plan. They can cause delays in a number of ways – the time required to fix the problem, certainly, but also sometimes the need to wait for parts to be flown in from another airport and the potential case where the initial mechanical delay leads to an associated crew time-out and the need to swap crews or bring in a reserve.

We have found virtually no published information to help quantify the frequency or severity of mechanical delays, however. The U.S. government delay statistics, as self-reported by the airlines, simply bundle mechanical delays in with the broader category of "air carrier delay," which also includes crew problems and ground operations (cleaning, fueling, catering, etc.) delays (http://www.rita.dot.gov/bts/help/aviation/html/understanding.html). And very little appears in the lay press about mechanical issues, presumably because they do not cluster like weather events.

Crew Availability

Unavailable crew members are a common source of propagated delay. If a pilot or flight attendant is on a flight that is delayed for any of the reasons above, then unless there is sufficient buffer before their next flight, they will be unavailable at the scheduled time of this flight, resulting in either a propagated delay or the need for recovery action to avoid this delay. In addition, delays can lead to crews at risk of exceeding duty hours, requiring them to be replaced for later flights in their duty or pairing.

It is less common for crew members to be a source of root delay, but happens on some occasions. For example, traffic congestion and other non-aviation transportation issues can prevent a crew member from reaching the airport on time to check in before their duty starts.

Crew members who commute by air to their crew base (e.g. living in one city but domiciled at another) may experience delays if they are unable to find an available seat on an early enough flight. A crew member's illness can require the calling in of reserve crews, with possible delays as well.

Finally, somewhere "in between" root delays and propagated delays for crew members are rest issues. If a crew is delayed on the last flight of their duty, and this is not the last duty of their pairing, then they may have insufficient rest time in between duties. This can result in the need to either delay the first flight of their next duty or bring in a reserve crew.

A more detailed investigation of the link between crew scheduling and flight delays in the U.S. can be found in a 2008 report to the Government Accountability Office entitled "Commercial Aviation: Impact of Airline Crew Scheduling on Delays and Cancellations of Commercial Flights" (http://www.gao.gov/products/GAO-08-1041R). This report highlights the fact that crew-only root delays are rare but that crews play a significant role in the propagation of root delays.

Computer issues: We conclude with a less-recognized but not insignificant source of delays: computer malfunctions. These may be airline software crashes, hardware failures, FAA system issues, and more. As one op-ed put it, "Airlines are flying computers … Increased reliance on technology has enabled (airlines) to become a much more successful and efficient business, and that also creates an exposure." (http://fortune.com/2015/07/10/airlines-computer-glitches/)

While we have not been able to identify a source for statistics on their frequency or severity, computer-caused disruptions are by no means extremely rare events, as can be seen by just a quick search of the general press. Furthermore, while they typically seem to be relatively short in nature (e.g. on the order of hours or shorter), they often impact multiple locations (in some cases, a carrier's entire operations) and thus a large number of flights. The result, of course, is significant propagation of the root delays and a much longer period of time to reach full recovery.

In 2015 alone, there were several highly-visible events, including:

- In July of 2015, United Airlines experienced a disruption to its computer system that led to the grounding of flights for nearly two hours, ultimately leading to more than 60 cancellations and more than 1,100 flight delays. http://www.nytimes.com/2015/07/09/business/united-airlines-grounds-flights-citing-computer-glitch.html
- In August of 2015, computer issues (hypothesized to be caused by a software upgrade) at the Northern Virginia air traffic control center affected East Coast flights for several hours, with impact felt from New York to Florida, most heavily in the DC area. http://www.nytimes.com/2015/08/16/business/technical-problem-suspends-flights-along-east-coast.html?_r=0
http://www.pcworld.com/article/2971752/software-upgrade-could-be-cause-of-us-airline-disruption.html
https://www.theguardian.com/technology/2015/aug/17/air-traffic-control-software-upgrade-grounds-hundreds-of-flights-us-east-coast
http://www.cnn.com/2015/08/15/travel/flight-delays-dc-new-york/
- In September of 2015, American Airlines experienced computer issues that led to ground stops at a number of airports across the country, with particular impact on their hubs in Miami, Dallas, and Chicago.
http://www.hngn.comIn Se/articles/130865/20150917/american-airlines-flights-grounded-due-computer-problems-breaking.htm
http://loyaltylobby.com/2015/09/18/american-airlines-computer-issues-ground-all-flights-in-dallas-chicago-and-miami/
http://abcnews.go.com/US/computer-glitch-grounds-american-airlines-flights-major-cities/story?id=33835682
- In October of 2015, a Department of Homeland Security computer system that checks passengers against watch lists went down. This caused delays at airport security and screening which in turn propagated to cause flight delays at JFK, ATL, CLT, and other airports.

http://www.nbcnews.com/business/travel/system-checks-air-passengers-against-terror-list-experiencing-disruptions-n444831
http://venturebeat.com/2015/10/14/customs-computer-systems-reportedly-down-at-multiple-u-s-airports/

http://www.nydailynews.com/new-york/computer-glitch-chaos-jfk-article-1.2397825

- Another October 2015 event was caused by problems with the Southwest Airlines computerized check-in service, delaying some 100 flights resulting from long lines for manual check-in.
  http://www.ibtimes.com/southwest-airlines-technical-glitch-causes-national-service-disruptions-travelers-2136349

Such events are not a new phenomenon, however. For example:

- In 2007, failure in a computer system at the FAA that processes flight plans, in conjunction with inclement weather, led to lengthy delays and cancellations, particularly along the East Coast.
  http://usatoday30.usatoday.com/travel/flights/2007-06-08-faa-glitch-delays_N.htm
- In 2011, a nationwide system failure at United Airlines caused substantial delays due to disruptions to its flight departures, airport processing, and reservation systems.
  http://technology.inquirer.net/1546/computer-failure-disrupts-united-airlines-operations
  http://www.cleveland.com/business/index.ssf/2011/06/united_airlines_computer_outag.html
- United Airlines also experienced several computer-related disruptions in 2012, including one in November with a two-hour outage.
  http://chicago.cbslocal.com/2012/11/15/computer-problems-causes-havoc-for-united-passengers/
- In April of 2013, computer issues caused American Airlines to ground all flights for several hours, leading to delays and the cancellation of more than 400 flights.

http://www.nytimes.com/2013/04/17/business/american-airlines-cancels-flights-after-outage.html?_r=0

- In 2014, an employee set fire to the Chicago FAA center, grounding more than 2000 flights in a single day, with ongoing disruptions until repairs were made. http://www.chicagotribune.com/news/local/breaking/chi-flights-grounded-at-midway-ohare-as-fire-crews-called-to-radar-facility-20140926-story.html

Nor are these events unique to the U.S. airline industry. For example, significant disruptions were caused in the United Kingdom during a software upgrade, as outlined in this government report: http://www.nats.aero/wp-content/uploads/2014/08/ATC%20Disruption%207%20Dec%2013%20-%20Report.pdf. (http://www.computerweekly.com/news/2240210656/Computer-system-failure-delays-hundreds-of-UK-flights) And in December of 2014, a failure at the UK air traffic control center caused substantial delays and cancellations at LHR and many other airports across the UK. (http://www.bbc.com/news/uk-30454240); a second malfunction just two weeks later also caused lengthy delays (http://www.dailymail.co.uk/news/article-109001/Computer-failure-leads-flight-chaos.html ; http://www.telegraph.co.uk/news/aviation/11290489/UK-flights-grounded-as-London-airspace-closed-live.html)

These disruptions are perhaps most similar to thunderstorms in their timing and impact, often appearing without little warning, resulting in near or complete shutdown (although often to a much larger set of airports for any given event), and fairly short in duration but with widespread propagating effects.

2.2 Propagation of Disruption

The airline industry is prone to many sources of disruption that are at least in part out of their control (weather, air traffic control, mechanical and human issues, etc.). The inter-connectedness of an airline's network structure further exacerbates these disruptions due to the extent to which resources (aircraft; ground, cockpit, and cabin crew; the airspace; etc.) are shared.

For example, if an early morning flight is delayed, this can lead to a second delay (a flight awaiting the inbound aircraft), a third delay (a flight awaiting the inbound cabin crew), a fourth delay (a flight awaiting the inbound cockpit crew), and additional delays if connecting flights await inbound passengers (this is most common for the last flight of the day to a given destination or for international flights with limited re-booking alternatives). Each of these delayed flights can, in turn, delay subsequent flights, leading to a snowball of delay propagations. Furthermore, because of the high cost of assets such as aircraft, schedules are often built with limited buffer in order to maximize the utilization of these assets. A negative consequence of this is the absence of adequate slack to absorb disruptions.

There is significant literature from the academic and industrial communities attempting to understand, quantify, and mitigate propagation (planning and recovery strategies are discussed in the next section).

Abdelghany, et al (2004) present a model to predict propagation of delays during irregular operations. Specifically, they look at how flights that are disrupted due to Ground Delay Programs may lead to downstream delays (due to delayed aircraft, crew, or other impacted resources), with advance knowledge of this information enabling airlines to better prepare to handle these propagated delays.

AhmadBeygi, et al (2008) use the notion of a *propagation tree* as the framework for analysis comparing the propagation of delays in hub-and-spoke vs. point-to-point carriers.

Allan, et al (2001) focus on Newark International in their analysis of weather related delays and associated propagation, noting significant differences between departure and arrival delays as a function of weather type.

Beatty, et al (1998) present the idea of a “delay multiplier” which uses the original delay, the time of occurrence, and airline schedule structure to derive this factor. The motivation is to show how different delays propagate in a variety of ways, and to therefore help triage which disruptions to prioritize in recovery.

Churchill, et al (2010) look at delay propagation analytically, over an extended time period, focusing on both temporal and spatial components. In particular, they observe both the propagation of delays across an individual aircraft and over time within and across airports.

Fleurquin, et al (2013) model the propagation of primary delays throughout a U.S. aviation network. They focus on passenger and crew connectivity as primary areas of concern.

Pyrgiotis, et al (2013) study delay propagation from a queueing perspective, with both modeling and empirical analysis used to study interactions between airports across the U.S.

Schaefer and Millner (2001) present a “Delay Propagation Assessment Tool” that allows them to simulate propagation of initial disruptions across a network.

Wang et al (2003) develop an analytic model that allows them to look at “controllable” factors from “random” factors as they propagate through a flight network.

In one of a limited number of papers focusing on propagation on non-U.S. networks, Wong and Tsai (2012) consider delays propagate in a Taiwanese domestic airline.

Wu (2005) discusses delay propagation in the context of evaluating the impact of stochasticity and limited buffer time on airline performance.

Finally, Xu, et al (2005) propose the use of Bayesian networks as a tool for understanding delay propagation across an aviation flight network.

2.3 Impact of Disruptions

Clearly, the impacts of disruptions in the aviation industry are significant. The most directly measurable costs include crew overtime costs, excess fuel burn, and passenger re-accommodations (e.g., hotel and meal vouchers), but as flight delays propagate so do the delay costs. Furthermore, costs such as lost productivity, loss of good will, and other less tangible impacts are nonetheless quite sizable.

As such, many in the industrial, government, and academic communities have attempted to quantify these impacts, with scopes ranging from single carriers/single airports to nationwide statistics.

For example, Robinson (1989) undertook a study of a single carrier at ATL (Atlanta Hartsfield International Airport) and estimated local costs of $6 million annual attributable to weather delays alone.

Reynolds, et al (2007) presented an ambitious integrated modeling approach to analyze environmental and economic impacts in aviation policy making, based on a modularized system that allows interaction between different levels of the aviation system.

Hansen, et al (2001) looked at the relationship between the capacity of the National Air Space (NAS) and the cost associated with delays and disruptions, in an attempt to predict the potential benefits of increased investments in the NAS.

The dissertation of M. Ishutkina (2009) focuses specifically on the question of the economic impacts of air transportation, including delay factors.

And in perhaps one of the most comprehensive academic studies undertaken, Ball et al (2010) considered costs to airlines, cost to passengers, and even lost demand due to passengers opting out of air travel due to fear of delays. They estimated $32.9 billion for 2007, with $8.3 billion being attributed to airlines, $16.7 billion to passengers, and $3.9 billion to lost demand.

Likewise, there is much in the lay press and in government reports associated with the issues of delay impact. For example, an article (http://thehill.com/policy/transportation/199707-study-winter-flight-delays-cost-economy-58-billion) reporting on a masFlight internal report cites a $5.8 billion dollar impact associated with winter weather delays in 2013/2014.

A report under the Joint Economic Committee Majority Staff Chairman (http://www.jec.senate.gov/public/_cache/files/47e8d8a7-661d-4e6b-ae72-0f1831dd1207/yourflighthasbeendelayed0.pdf) analyzed more than 10 million domestic flights in 2007 with more than 400 carriers flying through more than 1100 airports, also estimating delay costs (both direct and indirect) of more than $40billion.

Similarly, a report from Eurocontrol (https://www.eurocontrol.int/eec/gallery/content/public/document/other/other_document/201006_D2Y2_Quantifying_delay.pdf) considered not only the direct and indirect costs of delays but included the "lost opportunity cost" associated with buffer in airline systems.

The European and U.S. aviation industries are compared, with respect to how delay costs are modeled, in (http://catsr.ite.gmu.edu/pubs/ICRAT_Cost_of_Delay.pdf).

Finally, although much of the focus on delay impacts has been on weather-induced delays, congestion is also a major factor, as is discussed in (https://research.stlouisfed.org/publications/review/03/05/Cohen_Coughlin.pdf).

2.4 Robust Planning

It will never be possible to eliminate all sources of variability, both in the availability of resources (e.g. due to equipment failure, crew illness, etc.) and in the duration of flight times. Therefore, airlines have to develop methods for mitigating the impact of this variability. There are two primary ways in which to do so: *robust planning* and *recovery mechanisms*.

Robust planning is when airline plans (flight schedules, fleet assignments, crew schedules, aircraft routing, etc.) are designed with the recognition of variability and the anticipation of disruptions during the implementation of the plan. Key to this are opportunities such as the strategic use of buffer (for example, longer ground time between two consecutive flights on the same aircraft to absorb delays) and the pairing of resources (for example, keeping crews and aircraft together for multiple sequential flights to reduce the exponential propagation of delays).

There is a vast body of academic research on the topic of robust planning, including surveys in Barnhart and Cohn (2004) and Belobaba, Odoni, and Barnhart (2009), and we do not attempt to exhaustively review this literature here. We do, however, note a few demonstrative examples of this body of this work.

For example, in the 2004 masters thesis of Sarmadi (http://18.7.29.232/handle/1721.1/29401), the focus is on minimizing the impact of disruptions on passengers, specifically through the integration of flight scheduling and aircraft routing.

A similar line of research is also explored in the work of Lan, Clarke, and Barnhart (2006), which looks at passenger impacts to be gained by integrating routing and flight scheduling.

Integration is also used by Dunbar, et al (2012), with a focus on linking routing and crew decisions to reduce delay propagation, and by Gao, et al (2009) who focus on linking fleeting and crew scheduling.

AhmadBeygi, et al (2010) propose a redistribution of buffer within the flight network to maintain existing aircraft utilization while decreasing the propagation of delay.

Another time of approach is demonstrated in Shebalov and Klabjan (2006) in which the goal is to reduce disruptions due to crew time-outs during periods of propagated delay, with the method being to maximize the number of opportunities to recover, i.e. the number of "move-up" crews available for re-assignment.

The notion of reducing the potential for propagation/increasing the opportunities for recovery is also found in Rosenberger, et al (2004). In this research hubs are isolated (i.e. aircraft rotations leaving one hub return to that hub without visiting any other hub) and short cycles (limited numbers of flights before re-visiting a common airport) are incentivized. Both cases provide the opportunity for cancelling a small number of flights in order to return to regularly scheduled operations after a period of disruption.

Similarly, Smith and Johnson (2006) develop models to impose "station purity" in which the number of fleet types flying to an individual station are limited, providing greater flexibility for recovering from disruptions.

2.5 Recovery Mechanisms

Decisions made in the context of robust planning are designed to either prevent delays (e.g. by reducing propagation) or to provide opportunities for recovery when delays cannot be avoided.

Recovery mechanisms are the options by which the airline returns from a state if disruption back to the original plans of operations. There are several ways in which this can be done, and decisions depend not only on short term impact but long-term goals and philosophies as well. For example, if a delay is allowed to propagate, several flights may be affected, but each in a progressively smaller way. Conversely, if a small sequence of flights are cancelled, the airline may return to regular operations much more quickly, but with a significantly higher impact on the passengers on the cancelled flights.

Rosenberger, et al (2003) focus on rescheduling legs and re-routing aircrafts to recover from disruptions. The more specific case of recovering from a hub closure is considered by Thengvall, et al (2003).

In Lettovsky, et al (2000), the concern is with recovering disrupting crew pairings, with a focus on computational tractability and viable run times. Crew recovery is also the focus of Yu, et al (2003), with a particular emphasis on major disruptions.

Eggenberg, et al (2010) look at both the aircraft recovery problem (with emphasis on maintenance issues) and the passenger recovery problem in a column generation modeling approach that allows for specific operational considerations.

A key challenge in making recovery decisions is the ultimate need to simultaneously coordinate multiple resources – aircraft, crews, passengers, and more. Petersen, et al (2016) present an integrated recovery model that simultaneously considers multiple resources, showing significant improvement within their computational experiments over sequential approaches. Bratu and Barnhart (2006) prioritize the accommodation of disrupted passengers in their integrated recovery models. Abdelghany, et al (2008) also consider an integrated approach, using a rolling horizon modeling framework. Most recently, Maher (2016) presents new computational approaches to achieving tractable solutions to large-scale, real-time recovery problems. For more, see the survery paper of Clausen, et al (2010).

2.6 Carrier Philosophies

When disruptions occur, carriers need to make changes to their operations to address these disruptions and return to normal operations. Disruptions can be addressed in many different ways, however. For example, consider the simple case where an aircraft is scheduled to fly from BOS to DTW to LAX, with 15 minutes of extra buffer time between the two flights. Furthermore, suppose that the BOS to DTW flight will arrive 45 minutes late. There are three immediate options for the carrier: 1) Allow the delay to propagate, with the DTW to LAX flight leaving 30 minutes late; 2) Swap another available aircraft to be used for the DTW to LAX flight; 3) Cancel the DTW to LAX flight. Depending on the circumstances, any one of these might be the “right” decision.

More broadly, what constitutes “right”? This largely depends on corporate philosophy. For example, one approach is to return to the original plan as quickly as possible while another approach is to do so at the lowest cost, even if the recovery time horizon is longer. A good example of this is in how airlines handle delayed connecting passengers. Holding a flight for connecting passengers has immediate impact (and associated goodwill) on those connecting passengers, but may negatively impact a much larger number of passengers downstream as the delay propagates. Clearly, holding the last flight of the day to a particular destination will have significant positive effect on those passengers (who would otherwise be stranded for the night) with perhaps minimal impact on other passengers (who are most likely terminating at the destination). On the other hand, holding a flight early in the day can lead to significant delay propagations, not only for passengers on the held flight, who themselves have future connections to make, but also in the propagation of delay through the cockpit crew, cabin crew, and aircraft.

Not surprisingly, there is very little publically available to demonstrate how different carriers take different approaches to recovering from disruption. It is possible, however, to tease out certain characteristics through analysis of publically available flight delay data. We discuss this further in Part 3.

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