
A REVIEW ON FLIGHT DELAY PREDICTION

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ABSTRACT

Flight delays hurt airlines, airports, and passengers. Their prediction is crucial during the decision-making process for all players of commercial aviation. Moreover, the development of accurate prediction models for flight delays became cumbersome due to the complexity of air transportation system, the number of methods for prediction, and the deluge of flight data. In this context, this paper presents a thorough literature review of approaches used to build flight delay prediction models from the Data Science perspective. We propose a taxonomy and summarize the initiatives used to address the flight delay prediction problem, according to scope, data, and computational methods, giving particular attention to an increased usage of machine learning methods. Besides, we also present a timeline of significant works that depicts relationships between flight delay prediction problems and research trends to address them.

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1 Introduction

Delay is one of the most remembered performance indicators of any transportation system. Notably, commercial aviation players understand delay as the period by which a flight is late or postponed. Thus, a delay may be represented by the difference between scheduled and real times of departure or arrival of a plane [117]. Country regulator authorities have a multitude of indicators related to tolerance thresholds for flight delays. Indeed, flight delay is an essential subject in the context of air transportation systems. In 2013, 36% of flights delayed by more than five minutes in Europe, 31.1% of flights delayed by more than 15 minutes in the United States, and 16.3% of flights were canceled or suffered delays greater than 30 minutes in Brazil [45, 5]. This indicates how relevant this indicator is and how it affects no matter the scale of airline meshes.

Flight delays have negative impacts, mainly economic, for passengers, airlines, and airports. Given the uncertainty of their occurrence, passengers usually plan to travel many hours earlier for their appointments, increasing their trip costs, to ensure their arrival on time [11, 55]. On the other hand, airlines suffer penalties, fines and additional operation costs, such as crew and aircrafts retentions in airports [25, 112, 51, 62]. Furthermore, from the sustainability point of view, delays may also cause environmental damage by increasing fuel consumption and gas emissions [95, 105, 102, 75, 8, 125].

Delays also jeopardize airlines marketing strategies, since carriers rely on customers' loyalty to support their frequent-flyer programs and the consumer's choice is also affected by reliable performance. There is a identified relationship between levels of delays and fares, aircraft sizes, flight frequency and complaints about airline service [39, 83, 21, 93, 133]. The estimation of flight delays can improve the tactical and operational decisions of airports and airlines managers and warn passengers so that they can rearrange their plans [40].

To better understand the entire flight ecosystems, vast volumes of data from commercial aviation are collected every moment and stored in databases. Submerged in this massive amount of data produced by sensors and IoT [86, 29, 90], analysts and data scientists are intensifying their computational and data management skills to extract useful information from each datum. In this context, the procedure of comprehending the domain, managing data and applying a model is known as Data Science, a trend in solving challenging problems related to Big Data.

Under this data deluge scenario, this paper contributes by presenting an analysis of the available literature on flight delay prediction from Data Science perspective. It seeks to summarize the most researched trends in this field, describing how this problem is addressed and comparing methods that have been used to build prediction models. This becomes more relevant as we observe an increasing presence of machine learning methods to model flight delays predictions. This analysis is conducted by establishing a flight delay research taxonomy, which organizes approaches according to the type of problem, scope, data issues, and computational methods. The paper also contributes by presenting a timeline of major works grouped by the kind of flight delay prediction problem.

Besides this introduction, the rest of this paper is structured as follows. Section 2 introduces the flight delay scenario, describing a typical operation of a commercial flight, kinds of delays and their impacts. It also structures three different ways for treating the prediction problem. In Section 3, a taxonomic analysis of the prediction is presented, showing the most researched topics, the scope of application, data and methods that authors are using to predict flight delays. Section 4 discusses the main results based on a timeline of publications grouped by the types of problems and their intersections. Finally, Section 5 concludes our analysis by presenting major highlights and trends about delay prediction problem.

2 The flight delay scenario

Commercial aviation is a complex distributed transportation system. It deals with valuable resources, demand fluctuations, and a sophisticated origin-destination matrix that need orchestration to provide smooth and safety operations. Furthermore, individual passenger follows her itineraries while airlines plan various schedules for aircrafts, pilots and flight attendants. Figure 1 illustrates a typical operation of a commercial flight. Stages can take place at terminal boundaries, airports, runways, and airspace, being susceptible to different kinds of delays. Some examples include mechanical problems, weather conditions, ground delays, air traffic control, runway queues and capacity constraints [103, 63, 3].

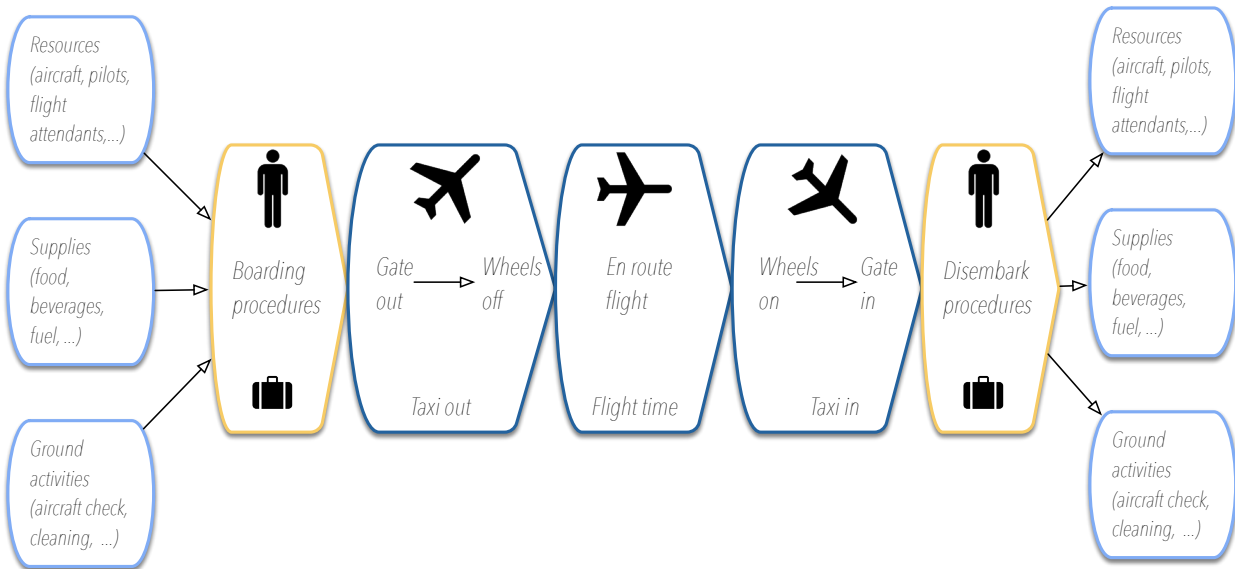


Figure 1: A typical operation of a commercial flight

This scheme is repeated several times throughout the day for each flight in the system. Pilots, flight attendants and aircrafts may have different schedules due to legal rests, duties, and maintenance plans for airplanes. So, any disruption in the system can impact the subsequent flights of the same airline [2]. Moreover, disturbances may cause congestion at airspace or other airports, creating queues and delaying some flights from other carriers [106, 123]. In this way, the prediction of flight delays is an essential subject for airlines, airports, Air Navigation Service Providers (ANSP), and network managers, like FAA [52] and Eurocontrol [46].

The flight delay prediction problem can be treated by different points of view: (i) delay propagation, (ii) root delay and cancellation. In delay propagation, one study how delay propagates through the network of the transportation system. On the other hand, considering that new problems may happen eventually, it is also important to predict further delays and understand their causes. Such occurrences, in this paper, are named as a *root* delay problem. Finally, under specific situations, delays can lead to cancellations, forcing airlines and passengers to reschedule their itineraries. So, researchers focused on cancellation analysis try to figure out which conditions lead to cancellations. Moreover, it explores the airlines' decision-making process for choosing the flights to be canceled.

3 Taxonomy

The main problems related to flight delay prediction are identified and organized in a taxonomy. It includes scopes, models, and ways of handling flight delay prediction problem. It considers flight domain features, such as *problem* and *scope*, and Data Science perspectives, such as *data* and *methods*. Figure 2 depicts the entire taxonomy while next subsections describe each component of the taxonomy and related work.

Regarding the available literature on flight delay prediction, we have conducted a systematic mapping study. The search expression string $(\text{"airport delay"} \vee \text{"flight delay"}) \wedge (\text{"predict"} \vee \text{"forecast"} \vee \text{"propagate"})$ was used to query Scopus on October 2017. Query result brought 310 references. Additionally, 29 works were added using snowballing search.

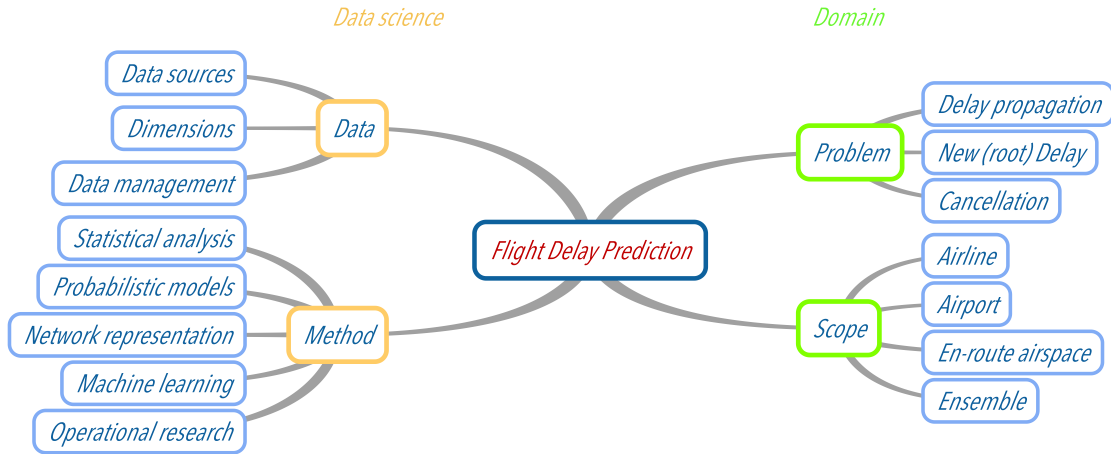


Figure 2: Taxonomy of the flight delay prediction problem

We have selected 134 to build this review due to their relevance and direct link with the flight delay prediction problem. The main criteria to be included is to have the word “delay” in the abstract, and the paper should have at least the one citation at Google Scholar per year before 2016. It means that to include a paper of 2015, it must have at least one citation, and so one.

From this study, we were able to present a taxonomy that drives the organization of the following sections.

3.1 Problem

Problem is the core feature in domain taxonomy. As seen in Section 2, there are three major concerns regarding the flight delay prediction problem: delay propagation, root delay and cancellation. Depending on the emphasis of the research, authors select one of these lines to develop their models.

3.1.1 Root delay and cancellation

Considering that new delay (root delay) may happen eventually, these root delays impair the performance of transportation network. Researchers create prediction models to tackle root delay, predicting when and where a delay will occur and what are its reasons and sources. This includes models that efficiently seek to estimate the number of minutes, probability or level of delay for a specific flight, airline or airport.

A relevant number of works focused on predicting and estimating delay duration [102]. Some approaches considered probabilistic models and innovation distribution [90, 112], whereas others find conditions for the occurrence of a root delay, such as passenger demand, fares, flight frequency, aircraft size, and taxi-out time [11, 131].

Particular circumstances, such as weather conditions, acts of God, aircraft problems, may lead airlines to cancel flights. Besides, airlines may directly cancel a flight, when factors like seat occupancy or cost savings are taking into consideration [80, 122].

3.1.2 Delay propagation

In delay propagation, the primary objective is to understand how delay propagates through airlines and airports based on the assumption that an initial delay has already occurred in the transportation system. A particular scenario happens when delays are spread to other flights of the same airline as chain reactions [24, 16, 2, 118]. Under this situations, it is important to measure how stable and reliable carriers can be to recover from delay propagation [119, 41]. Also, a delay may continue to propagate due to the scheduling of critical resources or retentions in other airports [59].

When scheduled time for take-off or landing is not fulfilled, flights need new slots that may be unavailable. In this scenario, it is important to understand the effects that a root delay in flight may produce to both departure and arrival airports [123, 100, 61]. Such phenomenon may increase the number of flights at some period, generating capacity problems and queues.

3.2 Scope

Delays can be induced by different sources and affect airports, airlines, *en route* airspace or an ensemble of them. For analysis purposes, one may assume a simplified system where only one of these actors or any combination of them is considered. It should be noted that any scope of application can be combined with any problem mentioned in Section 3.1.

Some work focused on airports to predict delays for all departs considered all airlines and *en route* airspace indifferently [106, 102]. Airports are also the focus when the objective is to investigate their efficiency based on delays of all carriers [94, 72, 100, 71]. On the other hand, only airlines are considered when comparing the performance of two airlines under the same conditions [3].

An ensemble of airport and *en route* airspace were studied to understand the relationship between congestion and delays [63, 88]. Others considered airports and airlines as well to evaluate capacity problems and airlines decisions [112]. There are many possibilities to ensemble scopes. This becomes important when studying the dynamics of air transportation systems, mainly when targeting root delay.

3.3 Data

Three fundamental questions about data are: Where to find flight data? Which attributes should be considered? Is it possible to handle each datum to obtain better results? To answer these questions, the data problem is divided into three classes: (i) data sources, (ii) dimensions, and (iii) data management.

3.3.1 Data Sources

The type of datasets from the air transportation system are mainly related to airlines, airports or ensemble. Since airlines and airports commonly do not share their databases with the entire community, they are often used by collaborators of those institutions. Ensemble datasets may include both carriers, airports, and additional information provided by governmental agencies, regulatory authorities, and service providers. Table 1 displays the type of datasets by regions. It presents the number of publications and the top three most cited papers in each category. Governmental agencies usually provide public access to their databases with different granularity. It is noticed that data from The United States Department of Transportation [44], primarily through The Federal Aviation Administration [52] and The Bureau of Transportation Statistics databases [26] are widely used to obtain information about flights. The Eurocon-

trol [46] database is provided by an intergovernmental organization in Europe. This dataset is also used intensively in flight delay studies [103].

Table 1: Number of sources of real data about the air transportation system per region

Region	Ensemble	Airline	Airport
Asia	2 [89, 111]	1 [104]	1 [121]
Brazil	2 [110, 5]	0	0
Europe	7 [30, 29, 81]	2 [109, 58]	7 [103, 27, 96]
US	11 [90, 112, 128]	7 [78, 3, 4]	16 [54, 11, 53]

Other related datasets, such as weather, may be obtained from governmental databases or service providers. This includes, for example, The National Oceanic and Atmospheric Administration of the United States [92]. In fact, authors may use more than one source to develop their models. Datasets from United States Department of Transportation [44], National Oceanic and Atmospheric Administration [92], and Weather Company [113] are commonly used to build delay prediction models.

Additionally, some researchers [130, 131] create synthetic datasets to evaluate their models instead of using real data. For example, Zou et al. [131] developed a market scenario, considering airport capacity, links, frequency, and characteristics of flights and passenger demand.

3.3.2 Dimensions

Considering the main public datasets and the papers analyzed, we have organized their main commonly attributes used into seven classes depicted in the data model of Figure 3. They abstract the main input attributes for delay prediction models. Beyond scheduled and actual times of departure and arrival, several characteristics may be considered depending on the focus of research.

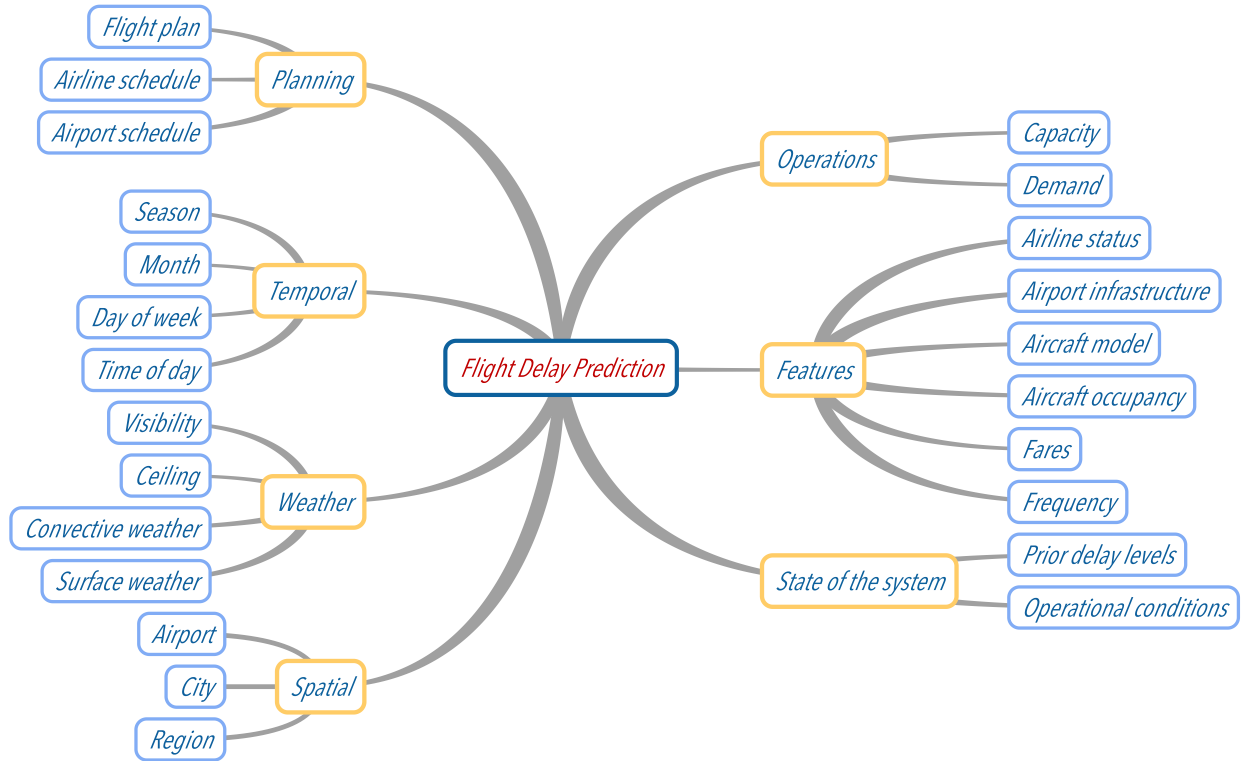


Figure 3: Data model of the flight delay prediction

Spatial dimension is related to the positions taken by the aircraft, such as departure and arrival airports, their cities, regions, and countries [61, 102]. The temporal dimension is often used to capture seasonality or periodic patterns

of data. These elements contain both date (season, month, and day of the week) and time (the day or time of the day) characteristics [90, 1, 112]. Weather dimension expresses external and environmental conditions in a particular moment [50]. It may represent specific features, such as ceiling and visibility [103] that defines, for example, if take-off or landing is going to happen under visual or instrumental conditions. Additionally, *en route* airspace weather situation (known as convective weather) and airport weather situation (known as surface weather) contain several momentaneous parameters [63].

Planning describes what airlines, airports, and air traffic controllers intend to do with critical resources involved in their operations. This dimension includes (i) airline schedules, (ii) airport schedules and (iii) flight plans. Arline schedules define all origin and destination points, their frequency and sequence, and aircrafts and crew allocations for each flight [24, 16, 119, 3, 41]. Airport schedules indicate the time each flight takes-off and lands, while flight plans indicate all *en route* parameters, such as distance, route, speed, and high [59].

Features represent characteristics of airlines, airports or aircrafts. Airlines status may indicate if a carrier is a major or an affiliate one or if it is a traditional hub-and-spoke or a low-cost point-to-point. Aircrafts characteristics show their size, their number of seats and occupancy, which may be a constraint to some operations because they affect market decisions. Finally, airport infrastructure may represent the number of runways, gates and service providers in an airport facility [94, 109, 122].

The state of the system indicates in which conditions airlines, airports or *en route* airspace are operating at a specific moment. Some examples correspond to prior levels of delay or airports closures [130]. The information about the state of the system is used to predict its behavior. Finally, operations are related to capacity and demand of airports and *en route* airspace. When demand exceeds capacity, a congestion scenario is formed, which enables occurrence of delays [88].

3.3.3 Data Management

Since the use of databases to store a massive amount of data have been increasing over the last years, data management techniques are becoming more and more crucial to provide a convenient and efficient query processing. Data management tasks contemplate design of database structure to enable data integration from different sources, elimination of inconsistencies, and data transformation. The development of a data warehouse supported by online analytical processing (OLAP) and data management techniques may be useful for this purpose. As mentioned in Section 3.3.1, multiple sources of data may be used. Thus, the usage of data warehouses combined with Extract, Transform and Load (ETL) procedures are commonly used to link the datasets of different sources [126].

There are many data management preprocessing procedures that can be applied to flight delay prediction datasets. They include data cleaning, feature selection, data transformation, and clustering. One of the main tasks of data cleaning is outlier removal. Extreme conditions may result in outliers that are not interesting if one is concerned about regular operations [112]. Feature selection is the process of identifying attributes that are less correlated. Correlated and irrelevant attributes may provide model over-fitting or decrease prediction performance [118]. These preprocessing procedures are essential since the better the preprocessing is conducted on input data, the better the prediction models may be developed from it.

Data transformation is also an important activity to empower prediction models. Some examples of transformations include normalization and discretization. Normalization reduces the range of possible values to a particular interval, such as -1 to 1 or 0 to 1. It gives equal strength for different variables and let machine learning methods identify which are the most relevant ones. Discretization consists of replacing numerical values by representative labels. It includes the transform of time periods into bins of a fixed time [11, 72], binning of values to cope with limitations in computational packages [24, 123] or to better train prediction models [16], especially when using machine learning models.

Clustering means grouping elements of the dataset in a way that similar observations stay together in the same group and dissimilar items stay in different groups. Many works compute clustering techniques, such as k-means or agglomerative hierarchical clustering, to support preliminary steps for further prediction models [102].

3.4 Method

The flight delay prediction problem may be modeled in many ways, depending on the objectives of the research. Methods were divided into five groups, according to Figure 4. The numbers next to each category represent the number of related papers.

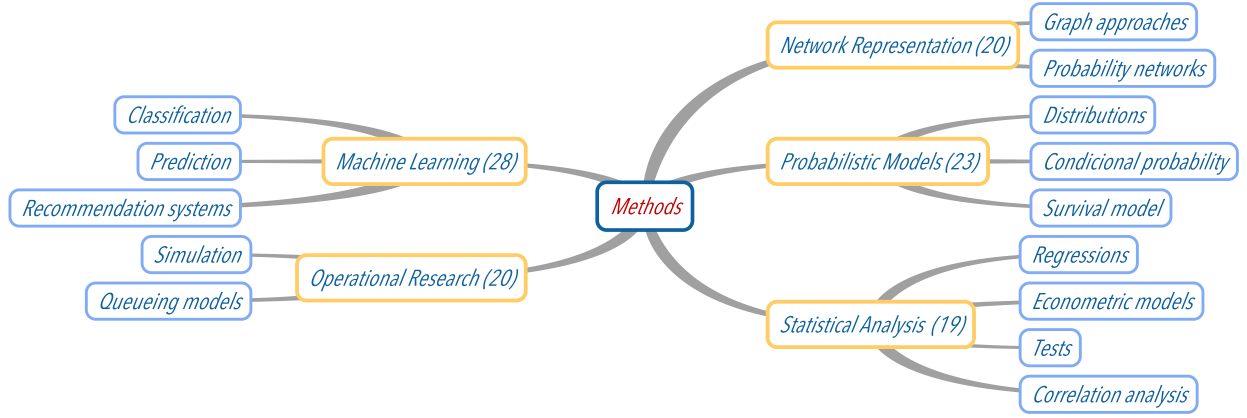


Figure 4: Categories of methods used to model the flight delay prediction

3.4.1 Statistical Analysis

Statistical analysis usually encompasses the use of regression models, correlation analysis, econometric models, parametric tests, non-parametric tests, and multivariate analysis (MVA). When it comes to regression models, both delay multiplier and recursive models can help airlines to understand delay propagation effects through the network and to estimate the costs of delays [16, 115, 84, 124, 127].

Many econometric models are also build to evaluate the efficiency flight systems, such as the analysis of the investments done by a governmental agency [88] or to evaluate the equilibrium point considering the relationship between delays and passenger demand, fares, frequency and size of the aircrafts [131]. Xiong et al. [122] built an econometric model based on pre-existing delays, potential delay savings, distance, characteristics of the destination airport and airline, frequency, aircraft size, occupancy rate and fare to understand which reasons lead airlines to cancel their flights. Qin et al. [101] studied the periodicity of flight delay rate, whereas Mofokeng et al. [87] studied the impact of aircraft turnaround time during maintenance check. Finally, Hao et al. [61] built a model to quantify how delays originated at New York are propagated to other airports.

Some works focus on statistical inference. Pathomsiri et al. [94] used a non-parametric function to evaluate the efficiency of airports of the United States regarding delays. Reynolds et al. [103] computed the correlation between levels of delays and capacities of the European airports. They also suggested different approaches to deal with the congestion problem, describing their advantages and disadvantages. Finally, Abdel-Aty et al. [1] calculated daily average of delays to detect correlations to understand the principal causes of delays at Orlando International Airport.

3.4.2 Probabilistic Models

Probabilistic Models encompass analysis tools that estimate the probability of an event based on historical data. Tu et al. [112] developed a probabilistic model based on expectation-maximization combined with genetic algorithms to predict the distribution of departure delay at Denver International Airport.

Boswell et al. [24] expressed delay classes by a probabilistic mass function and used a transition matrix to verify delay propagation to subsequent flights. They made a cancellation analysis computing the conditional probability to cancel a flight given that its previous flight was delayed. Mueller et al. [90] modeled departure, *en route* and arrival delays using density functions. The authors verified that Normal distribution fitted better to departure delays, while *en route* and arrival delays were better described by Poisson distribution. Concerned about the total duration of a root delay, Wong et al. [118] studied delay propagation through a survival model.

Evans et al. [49] built a theoretical routing networks that integrated flight routing and scheduling model. Kotegawa et al. [74] built a series of algorithms that forecast restructuring of the US commercial airline network to reduce both flight delay and total delay. Pfeil et al. [98] a probabilistic forecasts of whether or not a terminal area route will be blocked based on raw convective weather forecasts. Finally, Zhong et al. [129] build a Monte Carlo simulations to estimate airports' runway capacity.

3.4.3 Network Representation

Network representation encompasses the study of flight systems according to a graph theory. Abdelghany et al. [2] built direct acyclic graphs to model the schedule of an airline (including flight times and resources availability) to detect disruptions and their impacts on the rest of the network. They used the classical shortest path algorithm to evaluate propagation effects.

Ahmadbeygi et al. [3] built propagation trees to compare two different airlines, one operating in a conventional hub-and-spoke scheme and the other in a low-cost point-to-point system. Xu et al. [123] and Wu et al. [120] built a Bayesian network to model delay propagation. Baspinar [14] built a network-epidemic process using historical flight-track data of Europe to create a novel delay propagation model.

3.4.4 Operational Research

Operational Research includes advanced analytical methods (such as optimization, simulations, and queue theory) to help key-players make better decisions. Simulations may analyze airport capacity data, considering departure and arrival delays under different weather conditions [106, 63]. They may also evaluate the cost of, each delayed flight of an airline schedule [109]. Moreover, simulations through queuing models were applied by Wieland [117] to predict root delay, by Kim and Hansen [72] to study the effects of capacity and demand on delay levels at the airports of New York area, and by Pyrgiotis et al. [100] to study delay propagation between some airports.

Other simulations were done to analyze delay propagation concerning schedule stability [41] and reliability [119]. Through simulations, different scenarios were commonly explored, such as reliability or flexibility of airports under external conditions. Hansen et al. [59] considered the congestion problem and designed a simple deterministic queuing model to analyze propagation effects for subsequent flights of an airline and at Los Angeles International Airport.

3.4.5 Machine Learning

Machine learning is the research that explores the development of algorithms that can learn from data and provide predictions based on it. Works that study flight systems are increasing the usage of machine learning methods. The methods commonly used include k-Nearest Neighbor, neural networks, SVM, fuzzy logic, and random forests. They were mainly used for classification and prediction.

Rebollo et al. [102] applied random forests to predict root delay. They compared their approach with regression models to predict root delay in airports of the United States considering time horizons of 2, 4, 6 and 24 hours. Their test errors grew as the forecast horizon increased.

Khanmohammadi et al. [69] created an adaptive network based on fuzzy inference system to predict root delay. The predictions were used as an input for a fuzzy decision-making method to sequence arrivals at JFK International Airport in New York.

Balakrishna et al. [10, 11] used a reinforcement learning algorithm to predict taxi-out delays. The problem was modeled through a Markov decision process and solved by a machine learning algorithm. When running their model 15 minutes before the scheduled time of departure, authors achieved good performances at JFK International Airport in New York and Tampa Bay International Airport.

Lu et al. [130] built a recommendation system to forecast delays at some airports due to propagation effects. The prediction was based on the k-Nearest Neighbor algorithm and used historical data to recognize similar situations in the past. The authors noticed fast response time and easy, logical comprehension as the main advantages of their method.

4 Results and discussion

Since flight delays cause economic consequences to passengers and airlines, recognizing them through prediction may improve marketing decisions. Due to that, several forecast models have been built over the last twenty years. These models have sought to understand how delays propagate through the network of flights or airports, to predict root delay in the system or to comprehend the cancellation process. Beyond these three points of view for treating the flight delay prediction problem, models could also differ by their scope of application, data issues and methods.

The number of papers has increased in the late 2000s since 87.5% of the works had been published between 2007 and 2017. Regarding only the documents considered in this analysis, Figure 5.a displays the number of publications grouped by methods. It can be observed a significant growth in machine learning [6] and data mining [17, 77] in the last decade. Also, Figure 6 depicts the complete timeline of papers, showing most cited authors per period and

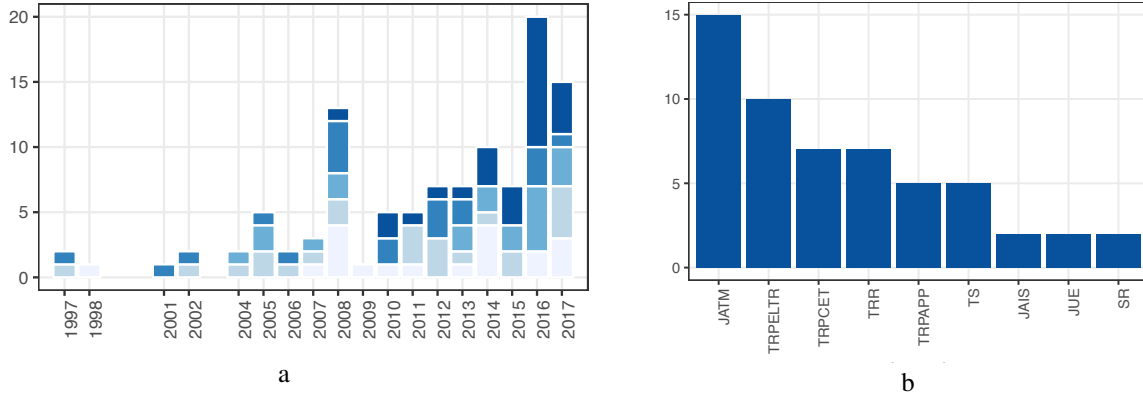


Figure 5: (a) Publication in years according to main methods: Statistical Analysis, Probabilistic Models, Network Representation, Operational Research, Machine Learning; (b) Journals of with major published papers in the subject

Years	root delay or cancellation	delay propagation
1997-2000	Wieland [117] Boswell [24]	Beatty [16]
2001-2004	Hansen [59] Mueller [90] Evans [51]	Schaefer [106] Abdelghany [2]
2005	Hsiao [62] Hansen [60]	Wu [119] Xu [123]
2006	Sim [107]	Lan [78]
2007	Wan [114] Biesiada [22] Abdel-Aty [1]	
2008	Balakrishna [9] Soomer [109]	Lapp [79] AhmadBeygi [3]
2009	McCrea [85] Tu [112] Pathomsiri [94]	
2010	Pejovic [96]	Ahmadbeygi [4]
2011	Balakrishna [11] Ganesan [56] Klein [73]	Nayak [91]
2012	Gürbüz [58] Evans [47]	Dück [41] Wong [118]
2013	Wang [116] Zou [132] Azadian [7]	Pyrgiotis [100] Fleurquin [54]
2014	Kulkarni [76] Kim [72] Evans [48]	Campanelli [29] Hao [61]
2015	Xiong [122]	Ciruelos [35] Cheng [32]
2016	Rebollo [102] Lin [82] Baumgarten [15]	Khanmohammadi [70] Cong [36]
2017	Bloem [23] Cai [28] Jacquillat [65]	Belkoura [18] Ben Ahmed [19]
	Choi [34] Castaing [31] Bertsimas [20] Simaiakis [108]	
	Takeichi [111] Ding[43] Baluch[13]	
	Jayam [67] Jacquillat [66]	
	Pérez-Rodríguez [99]	

Figure 6: Time line of flight delay prediction publications: Statistical Analysis, Probabilistic Models, Network Representation, Operational Research, Machine Learning

categories of methods. Pondering the way for tackling the delay problem, it was seen a balance between the number of papers that consider delay propagation and root delay, while few works deemed sole the cancellation analysis. Also, Figure 5.b indicates the foremost journals in which flight delay material was published.

From Figures 6 and 7, it is possible to observe the leading authors in the field. Figure 7 displays the main collaboration graph from authors in our systematic review that had three or more publications. The radius of each vertex indicates the number of papers published by each author, whereas the strength of the edge indicates the degree of collaboration among the pair of authors. Some authors do not contain connected edges, meaning that none of their collaborators achieved three publications in our review.

According to data perspective, we divided our analysis into three parts: data sources, dimensions and data management. From our review analysis, the adoption of data sources depends mostly on the country or region where the study

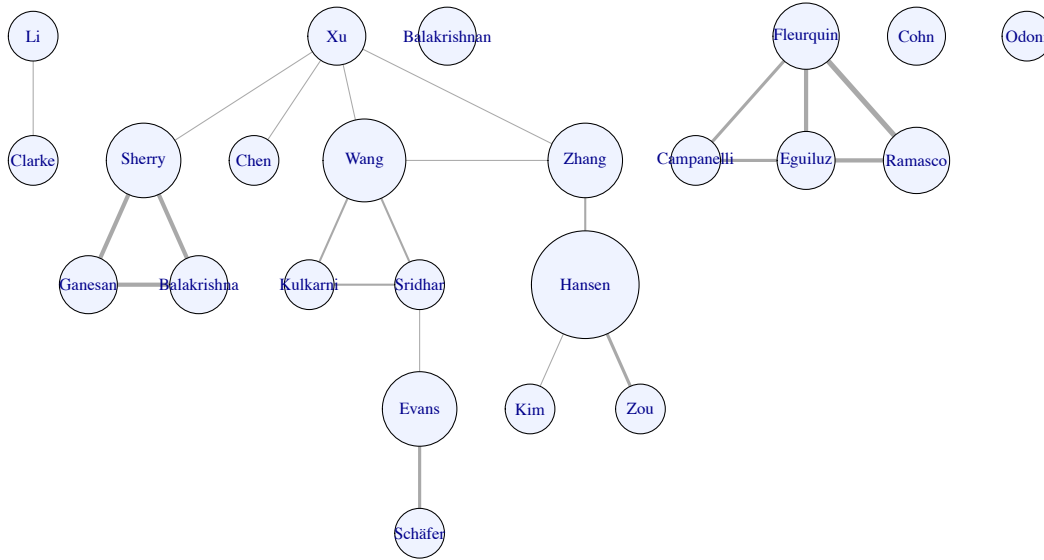


Figure 7: Collaboration network of main authors in subject

has been taken place. For example, in China, most works were based on airport data, while in the United States the primary source was The United States Department of Transportation [44].

Dimensions were not directly related to the type of problem, but to the scope of application. This characteristic is notable in this case. Attributes such as weather, capacity, and demand were characteristics of airport or *en route* airspace scopes. On the other hand, airlines schedules indicated scopes that considered airlines elements. It was also observed several ensembles of different dimensions, showing that prediction models may be improved through the selection of different attributes.

Data management was not specific to any problem or scope of application, and its use is steadily growing. In fact, it is present in most of the machine learning models adopted, primarily through data transformation. Most of the probabilistic models also considered outlier removal and data transformations techniques. A small percentage of the statistical analysis, network representation, and operational research methods applied general data management techniques as well.

Regarding the methods used to develop the prediction models, statistical analysis, and operational research were the most applied in the past. These approaches were well spread between the three ways of treating the prediction problem. This same balance was also verified for probabilistic models. On the other hand, network representation was mostly employed for delay propagation.

It is worth mentioning that machine learning approaches experienced a notable growth in the late 2000s, especially in root delay. In fact, both machine learning and data management are positively correlated. The more machine learning is used, the more data management is required. Especially, due to a trend in which extensive data is collected from sensors and IoT devices [68, 42, 97, 122, 128]. In fact, this can be confirmed in Figure 8 that presents the cloud word from papers published between 2015 and 2017 related to flight delays and machine learning. Terms such as algorithm [12], big data [38, 33], data model [37], learn [57], train-test [64] are becoming more frequent. Such terminology is day-by-day becoming a trend for the next years.

5 Conclusion

Flight delays are an important subject in the literature due to their economic and environmental impacts. They may increase costs to customers and operational costs to airlines. Apart from outcomes directly related to passengers, delay prediction is crucial during the decision-making process for every player in the air transportation system.

In this context, researchers created flight delay models for delay prediction over the last years, and this work contributes with an analysis of these models from a Data Science perspective. We developed a taxonomy scheme and classified models in respect of detailed components.

Mainly, the taxonomy includes domain and Data Science branches. The former branch categorizes the problem (flight delay prediction) and the scope. The last branch groups methods and data handling. It was observed that the flight delay prediction is classified into two main categories, such as delay propagation and root delay and cancellation. Besides, the scope determines one of the three specific extents: airline, airport, en-route airspace or an ensemble of them.

Besides the taxonomic scheme, we also presented a timeline with all articles to spot trends and relationships involving the main elements in the taxonomy. In the light of the domain-problem classification, this timeline showed a dominance of delay propagation and root delay over cancellation analysis. Researchers used to focus on statistical analysis and operational research approaches in the past. However, as the data volume grows, we noticed the use of machine learning and data management is increasing significantly. This clearly characterizes a Data Science trend.

Acknowledgments

Conflict of interest

References

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- [2] K. F. Abdelghany, S. S. Shah, S. Raina, and A. F. Abdelghany. A model for projecting flight delays during irregular operation conditions. *Journal of Air Transport Management*, 10(6):385–394, Nov. 2004. ISSN 0969-6997.
- [3] S. AhmadBeygi, A. Cohn, Y. Guan, and P. Belobaba. Analysis of the potential for delay propagation in passenger airline networks. *Journal of Air Transport Management*, 14(5):221–236, Sept. 2008. ISSN 0969-6997.
- [4] S. Ahmadbeygi, A. Cohn, and M. Lapp. Decreasing airline delay propagation by re-allocating scheduled slack. *IIE Transactions (Institute of Industrial Engineers)*, 42(7):478–489, 2010.
- [5] ANAC. Agência Nacional de Aviação Civil. Technical report, <http://www.anac.gov.br/>, 2017.
- [6] C. Ariyawansa and A. Aponso. Review on state of art data mining and machine learning techniques for intelligent Airport systems. In *Proceedings of 2016 International Conference on Information Management, ICIM 2016*, pages 134–138, 2016.
- [7] F. Azadian, A. E. Murat, and R. B. Chinnam. Dynamic routing of time-sensitive air cargo using real-time information. *Transportation Research Part E: Logistics and Transportation Review*, 48(1):355–372, Jan. 2012. ISSN 1366-5545.
- [8] E. Balaban, I. Roychoudhury, L. Spirkovska, S. Sankararaman, C. Kulkarni, and T. Arnon. Dynamic routing of aircraft in the presence of adverse weather using a POMDP framework. In *17th AIAA Aviation Technology, Integration, and Operations Conference, 2017*, 2017.
- [9] P. Balakrishna, R. Ganesan, and L. Sherry. Airport taxi-out prediction using approximate dynamic programming: Intelligence-based paradigm. *Transportation Research Record*, (2052):54–61, 2008.
- [10] P. Balakrishna, R. Ganesan, L. Sherry, and B. S. Levy. Estimating Taxi-out times with a reinforcement learning algorithm. In *2008 IEEE/AIAA 27th Digital Avionics Systems Conference*, pages 3.D.3–1–3.D.3–12, Oct. 2008.
- [11] P. Balakrishna, R. Ganesan, and L. Sherry. Accuracy of reinforcement learning algorithms for predicting aircraft taxi-out times: A case-study of Tampa Bay departures. *Transportation Research Part C: Emerging Technologies*, 18(6):950–962, Dec. 2010. ISSN 0968-090X.
- [12] H. Balakrishnan. Control and optimization algorithms for air transportation systems. *Annual Reviews in Control*, 41:39–46, 2016.
- [13] M. Baluch, T. Bergstra, and M. El-Hajj. Complex analysis of united states flight data using a data mining approach. In *2017 IEEE 7th Annual Computing and Communication Workshop and Conference, CCWC 2017*, 2017.
- [14] B. Baspinar and E. Koyuncu. A Data-Driven Air Transportation Delay Propagation Model Using Epidemic Process Models. *International Journal of Aerospace Engineering*, 2016, 2016.
- [15] P. Baumgarten, R. Malina, and A. Lange. The impact of hubbing concentration on flight delays within airline networks: An empirical analysis of the US domestic market. *Transportation Research Part E: Logistics and Transportation Review*, 66(Supplement C):103–114, June 2014. ISSN 1366-5545.
- [16] R. Beatty, R. Hsu, L. Berry, and J. Rome. Preliminary evaluation of flight delay propagation through an airline schedule. *2nd USA/Europe Air Traffic Management R&D Seminar*, 7(4):259–270, 1998.
- [17] L. Belcastro, F. Marozzo, D. Talia, and P. Trunfio. Using scalable data mining for predicting flight delays. *ACM Transactions on Intelligent Systems and Technology*, 8(1), 2016.
- [18] S. Belkoura, J. Peña, and M. Zanin. Beyond linear delay multipliers in air transport. *Journal of Advanced Transportation*, 2017, 2017.
- [19] M. Ben Ahmed, W. Ghroubi, M. Haouari, and H. Sherali. A hybrid optimization-simulation approach for robust weekly aircraft routing and retiming. *Transportation Research Part C: Emerging Technologies*, 84:1–20, 2017.
- [20] D. Bertsimas and M. Frankovich. Unified optimization of traffic flows through airports. *Transportation Science*, 50(1):77–93, 2016.
- [21] D. Bhadra. You (expect to) get what you pay for: A system approach to delay, fare, and complaints. *Transportation Research Part A: Policy and Practice*, 43(9):829–843, Nov. 2009. ISSN 0965-8564.
- [22] M. Biesiada and A. Piórkowska. Gamma-ray burst neutrinos, Lorenz invariance violation and the influence of background cosmology. *Journal of Cosmology and Astroparticle Physics*, (5), 2007.
- [23] M. Bloem and N. Bambos. Ground delay program analytics with behavioral cloning and inverse reinforcement learning. *Journal of Aerospace Information Systems*, 12(3):299–313, 2015.
- [24] S. B. Boswell and J. E. Evans. *Analysis of downstream impacts of air traffic delay*. Lincoln Laboratory, Massachusetts Institute of Technology, 1997.

- [25] R. Britto, M. Dresner, and A. Voltes. The impact of flight delays on passenger demand and societal welfare. *Transportation Research Part E: Logistics and Transportation Review*, 48(2):460–469, Mar. 2012. ISSN 1366-5545.
- [26] BTS. The Bureau of Transportation Statistics databases. Technical report, <http://www.rita.dot.gov/bts/home>, 2017.
- [27] B. Bubalo and J. Daduna. Airport capacity and demand calculations by simulation-the case of Berlin-Brandenburg International Airport. *NETNOMICS: Economic Research and Electronic Networking*, 12(3):161–181, 2011.
- [28] K. Cai, Y. Jia, Y. Zhu, and M. Xiao. A novel biobjective risk-based model for stochastic air traffic network flow optimization problem. *Scientific World Journal*, 2015, 2015.
- [29] B. Campanelli, P. Fleurquin, V. Eguíluz, J. Ramasco, A. Arranz, I. Extebarria, and C. Ciruelos. Modeling reactionary delays in the European air transport network. In *SIDs 2014 - Proceedings of the SESAR Innovation Days*, 2014.
- [30] F. Carr, G. Theis, J.-P. Clarke, and E. Feron. Evaluation of improved pushback forecasts derived from airline ground operations data. *Journal of Aerospace Computing, Information and Communication*, (JAN.):25–43, 2005.
- [31] J. Castaing, I. Mukherjee, A. Cohn, L. Hurwitz, A. Nguyen, and J. Müller. Reducing airport gate blockage in passenger aviation: Models and analysis. *Computers and Operations Research*, 65:189–199, 2016.
- [32] F. Cheng, B. Baszczewski, and J. Gulding. A hybrid optimization-simulation approach for itinerary generation. In *Proceedings - Winter Simulation Conference*, volume 2015-January, pages 1885–1896, 2015.
- [33] J. Cheng, C. Rong, H. Ye, and X. Zheng. Risk management using big real time data. In *Proceedings - IEEE 7th International Conference on Cloud Computing Technology and Science, CloudCom 2015*, pages 542–547, 2016.
- [34] S. Choi, Y. Kim, S. Briceno, and D. Mavris. Prediction of weather-induced airline delays based on machine learning algorithms. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, volume 2016-December, 2016.
- [35] C. Ciruelos, A. Arranz, I. Extebarria, S. Peces, B. Campanelli, P. Fleurquin, V. Eguiluz, and J. Ramasco. Modelling delay propagation trees for scheduled flights. In *Proceedings of the 11th USA/Europe Air Traffic Management Research and Development Seminar, ATM 2015*, 2015.
- [36] W. Cong, M. Hu, B. Dong, Y. Wang, and C. Feng. Empirical analysis of airport network and critical airports. *Chinese Journal of Aeronautics*, 29(2):512–519, 2016.
- [37] J. Cox and M. Kochenderfer. Ground delay program planning using markov decision processes. *Journal of Aerospace Information Systems*, 13(3):134–142, 2016.
- [38] L. Cruciol, L. Weigang, J.-P. Clarke, and L. Li. Air traffic flow management data mining and analysis for in-flight cost optimization. *Computational Methods in Applied Sciences*, 38:73–86, 2015.
- [39] J. I. Daniel and K. T. Harback. (When) Do hub airlines internalize their self-imposed congestion delays? *Journal of Urban Economics*, 63(2):583–612, Mar. 2008. ISSN 0094-1190.
- [40] A. D’Ariano, M. Pistelli, and D. Pacciarelli. Aircraft retiming and rerouting in vicinity of airports. *IET Intelligent Transport Systems*, 6(4):433–443, 2012.
- [41] V. Dück, L. Ionescu, N. Kliwer, and L. Suhl. Increasing stability of crew and aircraft schedules. *Transportation Research Part C: Emerging Technologies*, 20(1):47–61, Feb. 2012. ISSN 0968-090X.
- [42] T. Diana. Validating delay constructs: An application of confirmatory factor analysis. *Journal of Air Transport Management*, 35(Supplement C):87–91, Mar. 2014. ISSN 0969-6997.
- [43] Y. Ding. Predicting flight delay based on multiple linear regression. In *IOP Conference Series: Earth and Environmental Science*, volume 81, 2017.
- [44] DOT. The United States Department of Transportation. Technical report, <http://www.dot.gov/>, 2017.
- [45] EUROCONTROL. CODA Digest - Delays to Air Transport in Europe. Technical report, <https://www.eurocontrol.int/articles/coda-publications>, 2017.
- [46] EUROCONTROL. European Organisation for the Safety of Air Navigation. Technical report, <https://www.eurocontrol.int/>, 2017.
- [47] A. Evans and A. Schäfer. The impact of airport capacity constraints on future growth in the US air transportation system. *Journal of Air Transport Management*, 17(5):288–295, 2011.

- [48] A. Evans and A. Schäfer. The rebound effect in the aviation sector. *Energy Economics*, 36:158–165, 2013.
- [49] A. Evans, A. Schäfer, and L. Dray. Modelling airline network routing and scheduling under airport capacity constraints. In *8th AIAA Aviation Technology, Integration and Operations (ATIO) Conference*, 2008.
- [50] A. Evans, B. Sridhar, and D. McNally. Improving operational acceptability of dynamic weather routes through analysis of commonly used routings. In *16th AIAA Aviation Technology, Integration, and Operations Conference*, 2016.
- [51] J. Evans, S. Allan, and M. Robinson. Quantifying delay reduction benefits for aviation convective weather decision support systems. In *Conference on Aviation, Range, and Aerospace Meteorology*, pages 39–70, 2004.
- [52] FAA. Federal Aviation Administration. Technical report, <http://www.faa.gov/>, 2017.
- [53] P. Fleurquin, J. Ramasco, and V. Eguiluz. Data-driven modeling of systemic delay propagation under severe meteorological conditions. In *Proceedings of the 10th USA/Europe Air Traffic Management Research and Development Seminar, ATM 2013*, 2013.
- [54] P. Fleurquin, J. Ramasco, and V. Eguiluz. Systemic delay propagation in the US airport network. *Scientific Reports*, 3, 2013.
- [55] P. Fleurquin, B. Campanelli, V. Eguiluz, and J. Ramasco. Trees of reactionary delay: Addressing the dynamical robustness of the US air transportation network. In *SIDs 2014 - Proceedings of the SESAR Innovation Days*, 2014.
- [56] R. Ganesan, P. Balakrishna, and L. Sherry. Improving quality of prediction in highly dynamic environments using approximate dynamic programming. *Quality and Reliability Engineering International*, 26(7):717–732, 2010.
- [57] E. George and S. Khan. Reinforcement learning for taxi-out time prediction: An improved Q-learning approach. In *2015 International Conference on Computing and Network Communications, CoCoNet 2015*, pages 757–764, 2016.
- [58] F. Gürbüz, L. Özbakir, and H. Yapici. Data mining and preprocessing application on component reports of an airline company in Turkey. *Expert Systems with Applications*, 38(6):6618–6626, 2011.
- [59] M. Hansen. Micro-level analysis of airport delay externalities using deterministic queuing models: a case study. *Journal of Air Transport Management*, 8(2):73–87, Mar. 2002. ISSN 0969-6997.
- [60] M. Hansen and Y. Zhang. Operational consequences of alternative airport demand management policies case of LaGuardia Airport, New York. *Transportation Research Record*, (1915):95–104, 2005.
- [61] L. Hao, M. Hansen, Y. Zhang, and J. Post. New York, New York: Two ways of estimating the delay impact of New York airports. *Transportation Research Part E: Logistics and Transportation Review*, 70(Supplement C): 245–260, Oct. 2014. ISSN 1366-5545.
- [62] C.-Y. Hsiao and M. Hansen. Air transportation network flows: Equilibrium model. *Transportation Research Record*, (1915):12–19, 2005.
- [63] G. Hunter, B. Boisvert, and K. Ramamoorthy. Advanced national airspace traffic flow management simulation experiments and validation. In *2007 Winter Simulation Conference*, pages 1261–1267, Dec. 2007.
- [64] L. Ionescu, C. Gwiggner, and N. Kliewer. Data Analysis of Delays in Airline Networks. *Business and Information Systems Engineering*, 58(2):119–133, 2016.
- [65] A. Jacquillat and A. Odoni. Endogenous control of service rates in stochastic and dynamic queuing models of airport congestion. *Transportation Research Part E: Logistics and Transportation Review*, 73:133–151, 2015.
- [66] A. Jacquillat, A. Odoni, and M. Webster. Dynamic control of runway configurations and of arrival and departure service rates at jfk airport under stochastic queue conditions. *Transportation Science*, 51(1):155–176, 2017.
- [67] H. Jayam and L. Nozick. Understanding the trade-off between maximum passenger throughput and airline equity in allocating capacity under severe weather conditions. *Transportation Research Record*, 2626:18–24, 2017.
- [68] B. Karakostas. Event Prediction in an IoT Environment Using Naïve Bayesian Models. In *Procedia Computer Science*, volume 83, pages 11–17, 2016.
- [69] S. Khanmohammadi, C. A. Chou, H. W. Lewis, and D. Elias. A systems approach for scheduling aircraft landings in JFK airport. In *2014 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*, pages 1578–1585, July 2014.
- [70] S. Khanmohammadi, S. Tutun, and Y. Kucuk. A New Multilevel Input Layer Artificial Neural Network for Predicting Flight Delays at JFK Airport. In *Procedia Computer Science*, volume 95, pages 237–244, 2016.

- [71] A. Kim. The impacts of changing flight demands and throughput performance on airport delays through the Great Recession. *Transportation Research Part A: Policy and Practice*, 86:19–34, 2016.
- [72] A. Kim and M. Hansen. Deconstructing delay: A non-parametric approach to analyzing delay changes in single server queuing systems. *Transportation Research Part B: Methodological*, 58(Supplement C):119–133, Dec. 2013. ISSN 0191-2615.
- [73] A. Klein. Airport delay prediction using weather-impacted traffic index (WITI) model. In *29th Digital Avionics Systems Conference*, pages 2.B.1–1–2.B.1–13, Oct. 2010.
- [74] T. Kotegawa, D. De Laurentis, K. Noonan, and J. Post. Impact of commercial airline network evolution on the U.S. air transportation system. In *Proceedings of the 9th USA/Europe Air Traffic Management Research and Development Seminar, ATM 2011*, pages 572–580, 2011.
- [75] T. Krstić Simić and O. Babić. Airport traffic complexity and environment efficiency metrics for evaluation of ATM measures. *Journal of Air Transport Management*, 42(Supplement C):260–271, Jan. 2015. ISSN 0969-6997.
- [76] D. Kulkarni, Y. Wang, and B. Sridhar. Data mining for understanding and improving decision-making affecting ground delay programs. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, pages 5B11–5B18, 2013.
- [77] D. Kulkarni, Y. Wang, and B. Sridhar. Analysis of airport ground delay program decisions using data mining techniques. In *AIAA AVIATION 2014 -14th AIAA Aviation Technology, Integration, and Operations Conference*, 2014.
- [78] S. Lan, J.-P. Clarke, and C. Barnhart. Planning for robust airline operations: Optimizing aircraft routings and flight departure times to minimize passenger disruptions. *Transportation Science*, 40(1):15–28, 2006.
- [79] M. Lapp, S. AhmadBeygi, A. Cohn, and O. Tsimhoni. A Recursion-based Approach to Simulating Airline Schedule Robustness. In *Proceedings of the 40th Conference on Winter Simulation, WSC '08*, pages 2661–2667, Miami, Florida, 2008. Winter Simulation Conference. ISBN 978-1-4244-2708-6.
- [80] L. Le, G. Donohue, K. Hoffman, and C.-H. Chen. Optimum airport capacity utilization under congestion management: A case study of New York LaGuardia airport. *Transportation Planning and Technology*, 31(1): 93–112, 2008.
- [81] T. Lehouillier, F. Soumis, J. Omer, and C. Allignol. Measuring the interactions between air traffic control and flow management using a simulation-based framework. *Computers and Industrial Engineering*, 99:269–279, 2016.
- [82] L. Lin, Q. Wang, and A. Sadek. Border crossing delay prediction using transient multi-server queueing models. *Transportation Research Part A: Policy and Practice*, 64:65–91, 2014.
- [83] B. Manley and L. Sherry. Impact of ground delay program rationing rules on passenger and airline equity. In *IMETI 2008 - International Multi-Conference on Engineering and Technological Innovation, Proceedings*, volume 1, pages 325–330, 2008.
- [84] D. Markovic, T. Hauf, P. Röhner, and U. Spehr. A statistical study of the weather impact on punctuality at Frankfurt airport. *Meteorological Applications*, 15(2):293–303, 2008.
- [85] M. V. McCrea, H. D. Sherali, and A. A. Trani. A probabilistic framework for weather-based rerouting and delay estimations within an Airspace Planning model. *Transportation Research Part C: Emerging Technologies*, 16 (4):410–431, Aug. 2008. ISSN 0968-090X.
- [86] M. Mellat-Parast, D. Golmohammadi, K. McFadden, and J. Miller. Linking business strategy to service failures and financial performance: Empirical evidence from the U.S. domestic airline industry. *Journal of Operations Management*, 38:14–24, 2015.
- [87] T. Mofokeng and A. Marnewick. Factors contributing to delays regarding aircraft during A-check maintenance. In *2017 IEEE Technology and Engineering Management Society Conference, TEMSCON 2017*, pages 185–190, 2017.
- [88] S. A. Morrison and C. Winston. The effect of FAA expenditures on air travel delays. *Journal of Urban Economics*, 63(2):669–678, Mar. 2008. ISSN 0094-1190.
- [89] J. Mou, C. Liu, S. Chen, G. Huang, and X. Lu. Temporal Characteristics of the Chinese Aviation Network and their Effects on the Spread of Infectious Diseases. *Scientific Reports*, 7(1), 2017.
- [90] E. R. Mueller and G. B. Chatterji. Analysis of aircraft arrival and departure delay characteristics. In *AIAA aircraft technology, integration and operations (ATIO) conference*, 2002.

- [91] N. Nayak and Y. Zhang. Estimation and comparison of impact of single airport delay on national airspace system with multivariate simultaneous models. *Transportation Research Record*, (2206):52–60, 2011.
- [92] NOAA. National Oceanic and Atmospheric Administration. Technical report, <http://www.noaa.gov/>, 2017.
- [93] V. Pai. On the factors that affect airline flight frequency and aircraft size. *Journal of Air Transport Management*, 16(4):169–177, July 2010. ISSN 0969-6997.
- [94] S. Pathomsiri, A. Haghani, M. Dresner, and R. J. Windle. Impact of undesirable outputs on the productivity of US airports. *Transportation Research Part E: Logistics and Transportation Review*, 44(2):235–259, Mar. 2008. ISSN 1366-5545.
- [95] T. Pejovic, R. B. Noland, V. Williams, and R. Toumi. A tentative analysis of the impacts of an airport closure. *Journal of Air Transport Management*, 15(5):241–248, Sept. 2009. ISSN 0969-6997.
- [96] T. Pejovic, V. Williams, R. Noland, and R. Toumi. Factors affecting the frequency and severity of airport weather delays and the implications of climate change for future delays. *Transportation Research Record*, (2139):97–106, 2009.
- [97] E. Peterson, K. Neels, N. Barczy, and T. Graham. The economic cost of airline flight delay. *Journal of Transport Economics and Policy*, 47(1):107–121, 2013.
- [98] D. Pfeil and H. Balakrishnan. Identification of robust terminal-area routes in convective weather. *Transportation Science*, 46(1):56–73, 2012.
- [99] J. Pérez-Rodríguez, J. Pérez-Sánchez, and E. Gómez-Déniz. Modelling the asymmetric probabilistic delay of aircraft arrival. *Journal of Air Transport Management*, 62:90–98, 2017.
- [100] N. Pyrgiotis, K. M. Malone, and A. Odoni. Modelling delay propagation within an airport network. *Transportation Research Part C: Emerging Technologies*, 27(Supplement C):60–75, Feb. 2013. ISSN 0968-090X.
- [101] Q. Qin and H. Yu. A statistical analysis on the periodicity of flight delay rate of the airports in the US. *Advances in Transportation Studies*, 3:93–104, 2014.
- [102] J. J. Rebollo and H. Balakrishnan. Characterization and prediction of air traffic delays. *Transportation Research Part C: Emerging Technologies*, 44(Supplement C):231–241, July 2014. ISSN 0968-090X.
- [103] A. J. Reynolds-Feighan and K. J. Button. An assessment of the capacity and congestion levels at European airports. *Journal of Air Transport Management*, 5(3):113–134, July 1999. ISSN 0969-6997.
- [104] F. Rong, L. Qianya, H. Bo, Z. Jing, and Y. Dongdong. The prediction of flight delays based the analysis of Random flight points. In *Chinese Control Conference, CCC*, volume 2015-September, pages 3992–3997, 2015.
- [105] M. S. Ryerson, M. Hansen, and J. Bonn. Time to burn: Flight delay, terminal efficiency, and fuel consumption in the National Airspace System. *Transportation Research Part A: Policy and Practice*, 69(Supplement C): 286–298, Nov. 2014. ISSN 0965-8564.
- [106] L. Schaefer and D. Millner. Flight delay propagation analysis with the Detailed Policy Assessment Tool. In *2001 IEEE International Conference on Systems, Man and Cybernetics. e-Systems and e-Man for Cybernetics in Cyberspace (Cat.No.01CH37236)*, volume 2, pages 1299–1303 vol.2, 2001.
- [107] K. Sim, H. Koh, and S. Shetty. Some potential issues of service quality reporting for airlines. *Journal of Air Transport Management*, 12(6):293–299, 2006.
- [108] I. Simaiakis and H. Balakrishnan. A queuing model of the airport departure process. *Transportation Science*, 50(1):94–109, 2016.
- [109] M. J. Soomer and G. J. Franx. Scheduling aircraft landings using airlines’ preferences. *European Journal of Operational Research*, 190(1):277 – 291, 2008. ISSN 0377-2217.
- [110] A. Sternberg, D. Carvalho, L. Murta, J. Soares, and E. Ogasawara. An analysis of Brazilian flight delays based on frequent patterns. *Transportation Research Part E: Logistics and Transportation Review*, 95:282–298, 2016.
- [111] N. Takeichi, R. Kaida, A. Shimomura, and T. Yamauchi. Prediction of delay due to air traffic control by machine learning. In *AIAA Modeling and Simulation Technologies Conference, 2017*, 2017.
- [112] Y. Tu, M. O. Ball, and W. S. Jank. Estimating flight departure delay distributions—a statistical approach with long-term trend and short-term pattern. *Journal of the American Statistical Association*, 103(481):112–125, 2008.
- [113] TWC. The Weather Company. Technical report, <http://www.theweathercompany.com/>, 2017.
- [114] Y. Wan and S. Roy. A scalable methodology for evaluating and designing coordinated air traffic flow management strategies under uncertainty. In *Collection of Technical Papers - AIAA Guidance, Navigation, and Control Conference 2007*, volume 1, pages 674–698, 2007.

- [115] P. Wang, L. Schaefer, and L. Wojcik. Flight connections and their impacts on delay propagation. In *Digital Avionics Systems Conference, 2003. DASC '03. The 22nd*, volume 1, pages 5.B.4–5.1–9 vol.1, Oct. 2003.
- [116] Y. Wang. Prediction of weather impacted airport capacity using RUC-2 forecast. In *AIAA/IEEE Digital Avionics Systems Conference - Proceedings*, pages 3C31–3C312, 2012.
- [117] F. Wieland. Limits to growth: results from the detailed policy assessment tool [air traffic congestion]. In *16th DASC. AIAA/IEEE Digital Avionics Systems Conference. Reflections to the Future. Proceedings*, volume 2, pages 9.2–1–9.2–8 vol.2, Oct. 1997.
- [118] J.-T. Wong and S.-C. Tsai. A survival model for flight delay propagation. *Journal of Air Transport Management*, 23(Supplement C):5–11, Aug. 2012. ISSN 0969-6997.
- [119] C.-L. Wu. Inherent delays and operational reliability of airline schedules. *Journal of Air Transport Management*, 11(4):273–282, July 2005. ISSN 0969-6997.
- [120] W.-W. Wu, T.-T. Meng, and H.-Y. Zhang. Flight plan optimization based on airport delay prediction. *Jiaotong Yunshu Xitong Gongcheng Yu Xinxi/Journal of Transportation Systems Engineering and Information Technology*, 16(6):189–195, 2016.
- [121] G. Xiangmin and M. Li. Departure capacity prediction for hub airport in thunderstorm based on data mining method. In *Proceedings of the 29th Chinese Control and Decision Conference, CCDC 2017*, pages 6004–6009, 2017.
- [122] J. Xiong and M. Hansen. Modelling airline flight cancellation decisions. *Transportation Research Part E: Logistics and Transportation Review*, 56(Supplement C):64–80, Sept. 2013. ISSN 1366-5545.
- [123] N. Xu, G. Donohue, K. B. Laskey, and C.-H. Chen. Estimation of delay propagation in the national aviation system using Bayesian networks. In *6th USA/Europe Air Traffic Management Research and Development Seminar*. Citeseer, 2005.
- [124] N. Xu, L. Sherry, and K. Laskey. Multifactor model for predicting delays at U.S. airports. *Transportation Research Record*, (2052):62–71, 2008.
- [125] Y. Xu, R. Dalmau, and X. Prats. Maximizing airborne delay at no extra fuel cost by means of linear holding. *Transportation Research Part C: Emerging Technologies*, 81:137–152, 2017.
- [126] R. Yao, W. Jiandong, and D. Jianli. RIA-based visualization platform of flight delay intelligent prediction. In *2009 ISECS International Colloquium on Computing, Communication, Control, and Management*, volume 2, pages 94–97, Aug. 2009.
- [127] J. Zhang, X.-H. Xu, F. Wang, and D.-X. Wei. Airport delay performance evaluation based on fuzzy linear regression model. *Jiaotong Yunshu Gongcheng Xuebao/Journal of Traffic and Transportation Engineering*, 10(4):109–114, 2010.
- [128] W. Zhang, M. Kamgarpour, D. Sun, and C. Tomlin. A hierarchical flight planning framework for air traffic management. *Proceedings of the IEEE*, 100(1):179–194, 2012.
- [129] Z. Zhong, D. Varun, and Y. Lin. Studies for air traffic management R&D in the ASEAN-region context. *Journal of Air Transport Management*, 64:15–20, 2017.
- [130] L. Zonglei, W. Jiandong, and Z. Guansheng. A New Method to Alarm Large Scale of Flights Delay Based on Machine Learning. In *2008 International Symposium on Knowledge Acquisition and Modeling*, pages 589–592, Dec. 2008.
- [131] B. Zou and M. Hansen. Flight delays, capacity investment and social welfare under air transport supply-demand equilibrium. *Transportation Research Part A: Policy and Practice*, 46(6):965–980, July 2012. ISSN 0965-8564.
- [132] B. Zou and M. Hansen. Impact of operational performance on air carrier cost structure: Evidence from US airlines. *Transportation Research Part E: Logistics and Transportation Review*, 48(5):1032–1048, 2012.
- [133] B. Zou and M. Hansen. Flight delay impact on airfare and flight frequency: A comprehensive assessment. *Transportation Research Part E: Logistics and Transportation Review*, 69(0):54 – 74, 2014. ISSN 1366-5545.