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Applications of operations research in the airline industry: The aircraft sequencing problem

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ABSTRACT

Operations Research has seen a major breakthrough in airline industry through airplane sequencing/scheduling problem (ASP). With continual developments, airline industry has optimised air traffic management and minimized time-delays in arrival and departure of aircrafts. There has been contributions from all fields of knowledge to come up with exact solutions and implied algorithms. The objective of this paper is to highlight the analytical discourse of airline sequencing problem (ASP), outlining graphical formulations, mathematical models, theoretical perspectives and novel approaches that defines the problem and provides alternate contextual solutions. The systematic review focuses on the progress of these approaches to allow a layperson get a detailed overview of the sequencing/scheduling problem and its implication in the airline industry.

Keywords: *Aircraft Sequencing Problem, Operations Research, Aircraft Landing Problem, Runway Scheduling Problem, Mixed Integer Optimization, Dynamic Programming*

1. INTRODUCTION

The airline industry has remained multi-faceted with commercial travel surging every decade since 1920s. This trend has been complemented by ever-growing importance of Air Traffic Management (ATM) system which is centric to Air Sequencing Problem (ASP). (Mannino et al., 2014)The surge has also strengthened the correlation between airline industry and operations research. In the current scenario, the industry is highly dependent on operations research to function in day-to-day spew of operational handicaps. Recent research shows that without operations research, the efficiency of the airline industry would suffer a steep slump by 20%.

Historically, the arena of airline industry management has been constantly at a tussle with a footfall of billion passengers covering thousands of miles daily. Consequently, researchers have made channels to manage passengers and air traffic through time-sensitive assignments and capacity control systems. In this paper, we will discuss the trajectory of this interrelatedness between operations research and airline industry. The primary objective is to analyse the impacts and highlight the importance of Air Sequencing Problem (ASP). Airport runways are recognized to be one major bottleneck of the Air Traffic Management (ATM) system and one of the key factors that determine airport capacity. (Ikli et al., 2021)The aircraft-sequencing problem is a well-known operations research problem. (Caprì & Ignaccolo, 2004) In order to manage traffic flow during the last flight phase, it is concerned with creating the best possible methods for the sequencing of arriving flights at an airport.

The main scheduled carriers rely on a variety of management information systems and decision support systems, which are frequently created utilising ideas from operations research and artificial intelligence. From the pre-analysis phase of operations to the post-analysis phase, operation research (OR) approaches have remained fundamental and widespread. Application OR-based decision support systems have allowed the airline industry to operate more profitably, more efficiently, and with lower costs. There is a resilient competitive advantage to first movers who readily adopt new technological approach. The advent of improved computing capacity and developmental mathematical programming approaches has allowed airline industry to attend problems deemed impossible a decade ago. The technological advancement includes large-scale decision-making models that cover a variety of airline-related disciplines that were previously handled separately. The industry has seen a major fundamental tilt in the last 25 years. The global business has shifted from being a regulated industry to a liberalized one, driven by market forces.

The evolution of the airline business from a luxury catering for an exclusive clientele to a service industry accessible to the general public has been made possible in large part because of operations research. It supports the industry's ongoing transformation so that it may successfully compete in the market and adapt to the sophisticated needs of consumers. The third-largest domestic aviation market in the world is now in India. With an annual growth rate of 26.6%, operations research applications in the aviation industry are essential. The most recent projections, based on data from 2022, indicate that during the next 20 years, demand for air travel will rise on average by 4.3% annually. If this development trend is maintained, the global transportation sector will produce $1.5 trillion in GDP and 15.5 million direct jobs by 2036.We intend to use this paper to navigate through technological problems in aviation and find a problem statement that can encounter the industry in the near future.

2. LITERATURE REVIEW

The Aircraft Sequencing Problem (ASP) has been studied for over 40 years with constant developments and improvements filling gaps from the previous studies. As far back as the mid-80s, it was understood that the default model, i.e. First Come First Serve (FCFS), though simple to implement caused major delays. Though some models were based on FCFS such as(Wu & Liu, 1994), which used 4 scheduling schemes derived from the FCFS model. The research only attempted to bring order to the arriving aircrafts and did not try at optimality. Some of the earliest work in the field (Psaraftis, 1978) used Dynamic Programming to attempt to minimize passenger waiting time. They used 3 static models assuming no errors in ETA and constrained runway setups. (Bianco et al., 1987) discusses how the minimum permissible time interval varies in every case because of the variable nature of the constraints such as landing speed, aircraft size, etc. (Krzeczowski et al., 1995) implements a knowledge-based method that assigns runways, sequences landing times in real time by utilizing continuous updates of aircraft radar data.

Another sequencing technique that improved on FCFS is Constrained Position Shifting (CPS). It allows some flexibility in FCFS by shifting up to a max number of positions away from the FCFS schedule. It allows for avoidance of undesirable scenarios such as a heavy aircraft following a light one where the maximum separation would be very large. CPS is seen implemented in Roger Dear 1989 as well as modern research (Balakrishnan & Chandran, 2006, 2010; Prakash et al., 2018). As far as sequencing models go, FCFS and CPS were the most common ones.

Now to observe the different mathematical model approaches taken to the ASP. Firstly, we shall present the most cited work in this field i.e., (Beasley et al., 2000). It suggests many formulations to tackle the problem, mostly Mixed Integer Programming formulations, subject to parameters such as target landing time, penalty cost for landing before the target, penalty cost for landing after the target, the WV separation between the two aircraft when they land on the same or different runways. (Beasley et al., 2000) contains the most cited MIP approach in the field. The research also draws parallels between the ASP and other well-known problems such as the traveling salesman problem. If time windows are introduced to the TSP, it gives meaningful insight into solving the ASP as seen in (Ghoniem et al., 2014). Another example of this is parallel to the Vehicle Routing Problem where the runways correspond to the cars, and the aircraft to the customers to serve, and the separation time between landings is the distance between two customers (Briskorn & Stolletz, 2014). Many exact methods of solving the ASP have been suggested, most of them being either MIP or Dynamic Programming methods. The following section of the review focuses on research that has implemented either of these. Another interesting solution to the sequencing problem is proposed in (L. Wang et al., 2009)where he uses Gene Expression Programming (GEP), birthed by developments in Genetic Programming (GP) and Genetic Algorithms (GA). They have used methods like coding, selection, fitness function, combinatorial-specific operators to optimize sequencing and to minimize the delay time further.

Air traffic has been the biggest reason for most aircraft delays barring extreme weather conditions. Following this (Barnhart et al., 2006)gives the major determinants affecting single runway and multi-runway capacity. The objective is to not only solve the sequencing problem but the paper also highlights how capacity constraints play an important role in delays. (Ahmed & Poojari, 2008)uses fleet assignment model (FAM) approach (Hane et al., 1995)and entwines it in a two-step stochastic programming (SP) approach with recourse. (Clarke & Smith, 2004) also emphasizes on FAM and revenue management (RM) approaches and outlines other possible methods like crew scheduling and aircraft maintenance routing.

We have already discussed about (Psaraftis, 1978) which was the first paper to address the ALP as a DP problem. In their work landing, times are never assumed i.e., no restrictions can be imposed on delays. Hence the model was mostly theoretical. (Briskorn & Stolletz, 2014) extend the DP argument by adding multiple independent runways and bounded landing times. The approach proposed (Lieder & Stolletz, 2016) does not allow for landing to be earlier than the target time and deals with runways that are interdependent. It also handles the more general case and extends the approach to ensure separation during both landing and take-off.

As far as MIP goes, (Beasley et al., 2000) presented the most cited MIP approach and all the other variations on this work. (Briskorn & Stolletz, 2014) changed the way the model was computed from ELW to CPLEX and yielded better computation times. Empirical tests (Ghoniem & Farhadi, 2015) show that pre-processing isn’t optimized enough that it could be applied to even a small number of airplanes in real-time. It groups the problem into sets and partitions them to be able to solve larger problems in an acceptable computation time. A similar approach is taken by (Furini et al., 2012,)which takes a rolling horizon approach, grouping the flights into small sets that can be solved in real-time to construct a global solution from a solution of chunks. In (Dariano et al., n.d.)alternate graphical formulations are used which considers aircraft velocity to determine the safe distance or Separation Time Interval (STI) and assumes that aircrafts wouldn’t overtake each other in Terminal Manoeuvring Area (TMA). The paper underlines heuristics and accurate algorithms to solve the sequencing and scheduling problem with two alternate graphical solutions.

Some research has also been written, drawing from seemingly unrelated areas of evolutionary genetics to improve the genetic algorithms used to solve the ASP. Since the ASP is a multi-constraint and large-scale problem, (S. Wang, 2009)proposes a hybrid algorithm which integrates Bee Evolutionary Genetic Algorithm with modified clustering method to solve the Aircraft Sequencing Problem. It assigns relative and absolute position of an aircraft as a cluster and efficiently reduces the number of infeasible permutations to improve the speed of convergence. (Zhan et al., 2010) was the first research in the field which attempted a solution of the ASP by using an ant colony system based on receding horizon control to solve. This algorithm is an efficient way to solve the problem not only because it is proven to be useful in finding optimality in other NP-hard problems of which the ASP is a part, but also because RHC can divide the computational burden and enhance the solutions quality. (Fei et al., 2008)used an artificial fish school algorithm, which is an optimization formula which was presented in 2002. AFSA has a fast convergence speed and is not sensitive to initial parameters.

After reviewing the work done in the area, these are the areas in which we believe research can go on, and where there are gaps in the literature. Refinement of aircraft categories, taking into account the 6 wake patterns as recognized by (Cheng et al., 2016) and integration of scheduling in air traffic control. But where most literature lacks, and essentially infinite optimization is possible, is the addressing of uncertainty such as weather changes, human errors, and airline-specific preferences.

3. METHODOLOGY

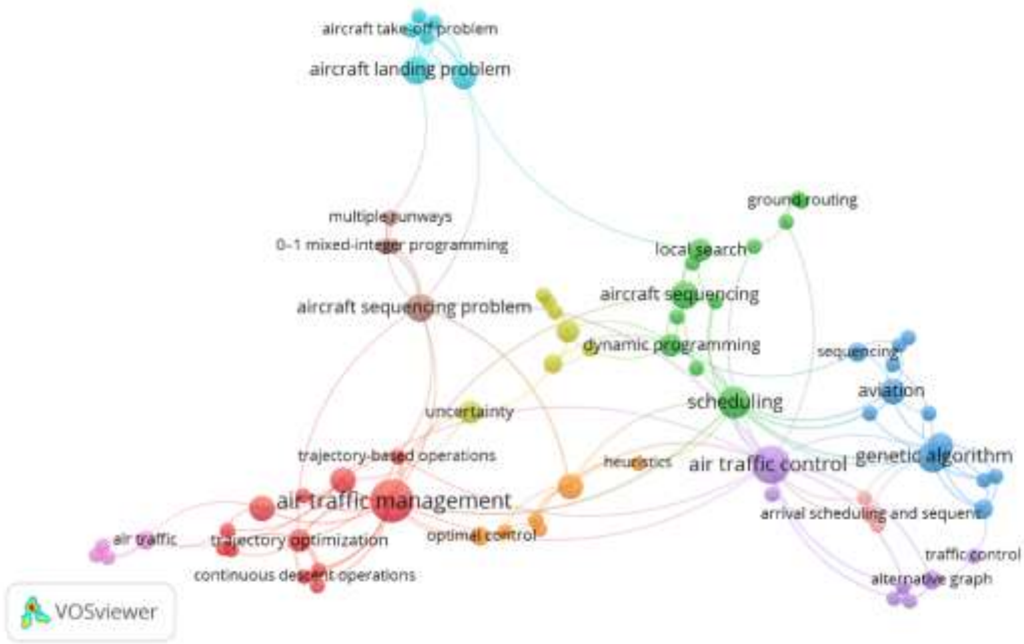
To justify the objective of this analysis, we will use a systematic literature review (SLR) method. The systematic review approach parallels exclusivity with extensivity and allows us to provide full coverage of the defined area. It allows a researcher to replicate and calibrate himself to the specific area of interest. The approach is reproducible and hence allows other authors to use the paper in a more comprehensive manner.

To achieve the aim of this study, articles and journals published between 1985-2002, classified under air sequencing problem (ASP) were taken into consideration. The papers were mainly found with the view to draw a trajectory of solutions to the issue and understand the substantial development in the area. For this, keywords like “air traffic management”, “air sequencing problem”, “airport runway systems” were used. A two-pronged simultaneous classification strategy has been used – (a) chronological and (b) categorical.

(a) The papers have been analyzed in 5-year splits. The time period taken into account conforms to the major changes in airplane industry and airport systems. The chronological classification has allowed for a timeline to be used by readers to navigate their way through the area of research.

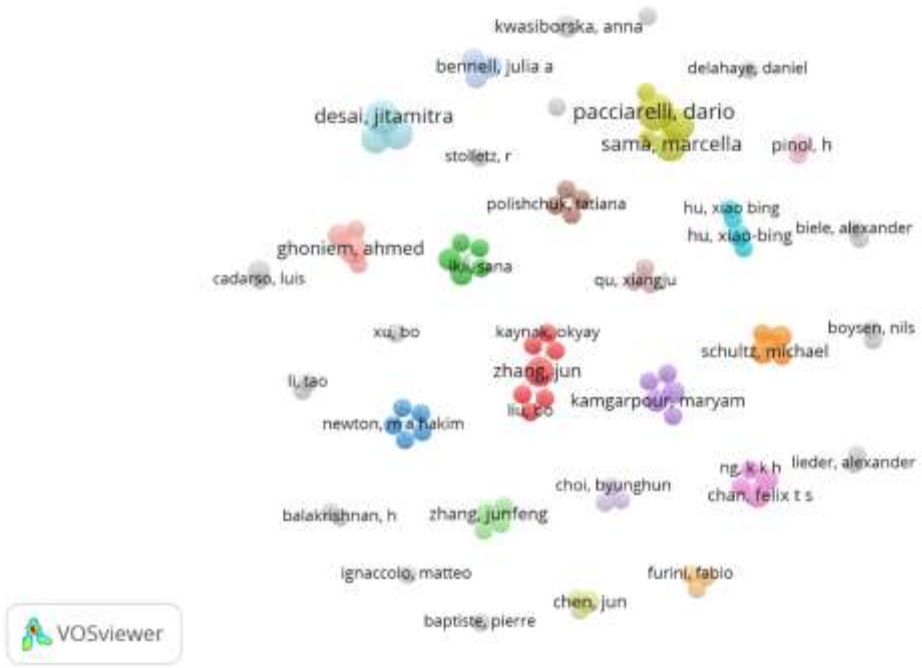
(b) In categorical classification, we have distributed papers according to their classification as research papers. The analytical research papers have been taken separately to analyze the different approaches used and formulas ideated. These research papers give a sight of different formulas used to solve the sequencing problem in different places at different times. The literature reviews have done justice by providing us with insights into the industry and outside the industry where similar sequencing problem has risen and solved.

The papers include a diverse knowledge of sequencing problems to optimize arriving and departing airplanes; on-boarding and off-boarding passengers and loading and unloading cargos. To make our study well-defined we have excluded research papers that are majorly related to operations inside an airport. The keyword “airport systems” has incited a lot of discussion of passenger movement inside airport which stays outside the perimeter of our study. The focus of study remains at the movement on runways in single and multi-runway airports.



Graph 1

Graph 1 shows a keyword analysis from the research in the field of the Aircraft Scheduling Problem.



Graph 2

Graph 2 shows an analysis of authors that have frequently co authored for research in the field of the Aircraft Sequencing Problem.

4. CONCLUSION AND FUTURE WORK

Airplane sequencing is a well discussed and well tackled program with strong algorithms providing channels to optimize operations at airline industry. The approaches used are both definitive and practical, and have proved their significance in multi-runway systems and single-runway systems at established airports. Despite the success of algorithms, current statistics show that the delay minimization has decreased gradually and showed a surge in certain years. This implies that the current algorithms are absolute and provide exact solutions but the industry encounters dynamicity in its operations. The papers summons research to widen the practical implication of aircraft sequencing solutions from its theoretical nature, to suit better to the dynamic environment. The airline industry is placed at the heart of two changing phenomenon – weather cycles and technology and therefore a generic and inclusive approach becomes imperative.

Delay Cause by Year, Percent of Total Delay Minutes (%)

	Air Carrier Delay	Aircraft Arriving Late	National Aviation System Delay	Security Delay	Extreme Weather
(Jun-Dec)	26.3	30.9	36.5	0.3	6.1
2004	25.8	33.6	33.5	0.3	6.9
2005	28.0	34.2	31.4	0.2	6.2
2006	27.8	37.0	29.4	0.3	5.6
2007	28.5	37.7	27.9	0.2	5.7
2008	27.8	36.6	30.2	0.1	5.4
2009	28.0	36.2	30.6	0.1	5.0
2010	30.4	39.4	25.7	0.2	4.4
2011	30.1	40.8	24.8	0.1	4.1
2012	31.9	41.4	22.5	0.1	4.0
2013	29.4	42.1	24.2	0.1	4.1
2014	30.2	41.9	23.5	0.1	4.3
2015	32.2	39.8	22.9	0.1	5.0
2016	32.6	39.2	23.7	0.1	4.4
2017	31.2	39.4	25.1	0.1	4.3
2018	30.1	39.6	24.5	0.1	5.6
2019	30.6	39.7	24.0	0.1	5.5
2020	41.0	30.2	21.6	0.2	6.9

SOURCE: Bureau of Transportation Statistics

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