Interdependence and Integration among Components of the Airline Scheduling Process: A State-of-the-Art Review

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***Abstract*—Over the last few decades, the Airline Scheduling Process (ASP) has received an unprecedented attention from airliners and operations research society. Conventionally, the Airline Scheduling Process is decomposed into four sub-problems namely- Schedule Generation, Fleet Assignment, Aircraft Routing, and Crew Scheduling which are solved sequentially in order to incorporate tractability and feasibility in the overall process. However, sequential decomposition, by construct, fails to capture the inter-dependencies among these sub-problems. To overcome this limitation, the air transport research society has lately started adopting integrated models for modeling and solving the sub-problems of the ASP. But due to the limited computational power and available technology, researchers are only able to address partial-integration among these sub-problems. This paper thoroughly reviews the ASPs literature particularly in the light of the extent to which the inter-dependence has been explored through integration among its sub-problems. This review paper categorizes the existing literature in one of the 11 possible classes based on varying degree of integration among the sub-problems, and projects the research gap in the integrated airline scheduling which is ought to be bridged towards robust airline scheduling.**

***Keywords*: Integrated Airline Scheduling; Airlines Operations Research; Airline Scheduling Process; Schedule Generation; Fleet Assignment; Aircraft Routing; Crew Scheduling.**

I. Introduction

The air transport industry has seen a significant rise in the number of flight delays, owing to its sub-optimal airline operations. In 2015, a large number of flight delays (40% of the total departed flights) were recorded in the European airline industry (Manager, 2016). In the American airline industry, a 20.22% of the total flights departed got delayed and 3.61% of the flights got canceled in 2015 (of Transportation Statistics, 2017 (accessed April 20, 2017). A delay-cause analysis, carried out in (of Transportation Statistics, 2017 (accessed January 11, 2017), shows that the late-aircraft-arrival delays caused a 39.8% of the total flight delays (largest among all delay sources) and the air-carrier delays caused a 32.2% of the total flight delays (second largest). Moreover, over the past few years, a gradually increasing trend has been recorded in the number of air-carrier delays per year (of Transportation Statistics, 2017 (accessed January 11, 2017). Hence, it has become imperative to develop a better understanding of the airline operations and to remove the underlying inefficiencies in order to prevent the flight delays or to minimize them.

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The Airline Scheduling Process (ASP) is considered as one of the most crucial activities of the airline operations. Since decades, several researchers from the operations research (OR) community are trying to improve the state-of-the-practice in the ASP (Levin, 1971; Pollack, 1974; Etschmaier and Mathaisel, 1985). As a result, several optimization frameworks have been developed based on multiple OR techniques such as mathematical programming (Anbil et al., 1991, 1992), heuristics (Rubin, 1973), metaheuristics (Beasley and Chu, 1996), and many more. With tremendously increasing air travel demand and the number of airports, there is an urgent need to improve upon the existing optimization frameworks of the ASP in order to solve bigger models which involve a large number of variables and parameters. ASP is a combination of several *combinatorial optimization* sub-problems (Etschmaier and Mathaisel, 1985). In combinatorial optimization problems, the optimal solution is obtained from a finite set of mathematical objects using intelligent methods/algorithms (Ausiello et al., 2012). In such problems, an exhaustive search becomes obsolete as the number of possible combinations of these objects (size of the search-space) increases rapidly with an increase in the size of the input to the problem. Some examples of combinatorial optimization problems are the traveling salesman problem, bin-packing, job-shop scheduling, etc. (Schrijver, 2000). Similarly, the presence of a large number of decision variables, a large set of input data & restrictions that have to be incorporated, and the presence of functional relationships and inter-dependencies contribute to the complexities of the ASP.

As a result, it is difficult to formulate the ASP in a single decision model. Given this, the conventional approach of solving the ASP is to decompose it into four sub-problems and solve them sequentially. These four sub-problems are *Schedule Generation*, *Fleet Assignment*, *Aircraft Routing*, and *Crew Scheduling*. The objective of the Schedule Generation sub-problem is to generate a list of flight legs to be operated in a worldwide network. This is achieved by selecting a set of profitable origin-destination (O-D) pairs, determining the flight frequencies between such O-D pairs, and finally selecting the departure and arrival flight times. These objectives are facilitated after considering demand fluctuations, multiple fare classes, passenger spill and recapture, and other characteristics. The resulting flight network is sent as input to the *Fleet Assignment* sub-problem. The goal of this sub-problem is to assign aircraft types, called as *fleets*, to individual flights. This goal is achieved using the following objectives: minimizing operating cost, maximizing captured and recaptured passengers, and maximizing revenue and through revenue (revenue generated from premium customers that are willing to pay more for staying with the same aircraft during their whole itinerary). This sub-problem involves feasibility constraints such as balance constraints, availability constraints, flow constraints, and flight coverage constraints. This fleet assigned flight schedule is fed as a constant input to the *Aircraft Routing* sub-problem. This sub-problem is aimed to find a sequence of flight legs, called *rotations*, for each aircraft of all fleet types while simultaneously incorporating maintenance slots as imposed/regulated by FAA[1], EASA[2] and other safety agencies. Finally, the last sub-problem is the *Crew Scheduling* sub-problem which uses the output of the aircraft routing sub-problem as its input. Crew scheduling involves the generation of sequences of flight legs to be flown by cockpit and cabin crews in accordance with the rules & regulations imposed by FAA & other aviation government bodies, airlines, and labor unions. It is addressed in two stages by formulating and solving two sub-problems: crew pairing and crew rostering. The former sub-problem handles the generation of a set of *crew pairings*[3] to cover a finite set of flight legs over a particular time window in minimum cost while satisfying the legality rules & regulations as mentioned above (Aggarwal et al., 2018). The latter sub-problem deals with the assignment of particular crew members to the optimal crew pairings. The combined output of all sub-problems of the ASP is called an *airline schedule*.

In the classical ASP, these sub-problems are solved independently in a sequential order, addressing the intractability and infeasibility issues involved in the combined model. In a sequential approach, the solution of a former sub-problem becomes a constant input for the subsequent sub-problems, as shown in Figure 1. In some scheduling models, few sub-problems are grouped together, forming cumulative phases. Suggestions from numerous researchers in the past explore possible ways of decomposing the ASP, grouping its disciplines, and ordering them in the sequential order (Barnhart and Talluri, 1997; Gopalan and Talluri, 1998; Barnhart et al., 2003; Lohatepanont and Barnhart, 2004). However, such models fail to account for inter-dependencies among the sub-problems of the ASP. Hence, it was imperative for researchers to develop advanced models in order to capture the interdependencies involved in the ASP.

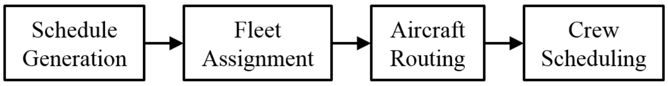

FIG. 1: SEQUENTIAL DECOMPOSITION OF THE ASP

Since 1950, substantial efforts have been made in developing stand-alone planning tools for each of the sub-problems of the ASP. With advancements in computational power and optimization techniques, researchers have lately started adopting integrated airline scheduling (IAS) to capture the inter-dependencies while solving the ASP. In other words, IAS is a scheduling method to capture the inter-dependencies of the sub-problems, implemented using models having more than one sub-problems coupled together. The existing IAS models are only able to partially integrate the sub-problems of the ASP and to the best of authors' knowledge, no planning tool has been developed that could solve all the sub-problems in one integrated model. Hence, it is imperative to develop a better understanding of the existing IAS models from the IAS literature which builds the rationale for the development of fully-integrated IAS models. This research paper reviews the existing IAS literature by presenting the research trend over the last few decades and highlighting the research gap which could guide new researchers in identifying the crucial yet unexplored IAS models.

The outline of this paper is as follows: In Section II, an overview of IAS is presented by defining it and presenting a system for classification of existing IAS models from the literature. This is followed by a detailed overview of salient features and limitations of existing IAS models, belonging to each class. In Section III, observations from this state-of-the-art review are presented in order to explain the research trend in IAS and to highlight possible future directions for new researchers.

II. Integrated Airline Scheduling Process

A. Overview

Primarily, researchers and airliners opted for the sequential decomposition of the ASP in order to bring

[1] Federal Aviation Authorities.

[2] European Aviation Safety Agency.

[3] A crew pairing is a sequence of flights to be flown by a crew that starts and ends at the same crew base (home airport of the crew).

tractability in the complete model. However, sequential decomposition limits the flexibility of later scheduling steps, the rationale being the solution of former sub-problems serving as constant input for the subsequent sub-problems. This leads to sub-optimal and less-reliable airline schedules (Barnhart et al., 1998a; Cordeau et al., 2001; Barnhart et al., 2003). For instance, fleet assignment sub-problem does not consider maintenance requirements and may lead to crew schedules with increased costs, and Schedule Generation sub-problem does not consider availability and assignment costs of resources like aircraft and crew (Clarke et al., 1996, 1997; Barnhart et al., 1998a; Klabjan et al., 2002; Barnhart et al., 2003).

To account for inter-dependencies among the sub-problems of the ASP, partially-integrated models have been developed by the researchers and airliners. In the existing research, mainly two types of IAS models have been developed. In the first type of IAS models, a feedback-loop, from latter sub-problems to former sub-problems, has been implemented. In the other types of IAS models, an iterative cycle of re-scheduling and re-evaluation is performed among the sub-problems of the ASP. In this process, the solutions of later scheduling steps (Fleet Assignment, Aircraft Routing, and/or Crew Scheduling) are sent to the previous scheduling steps (e.g. Schedule Generation) where slight adjustments and modifications are carried out in order to improve the overall solution quality (Rexing et al., 2000; Sriram and Haghani, 2003). However, the associated improvement in a schedule's quality by using iterations within the ASP comes at a larger cost and time-span. Second, the other IAS models have solved some of the sub-problems together (considering as a single bigger problem) instead of sequentially solving them (Sherali et al., 2006). Moreover, IAS builds the rationale for incorporating robustness[4] in the ASP. The rationale behind this is the strong correlation among the robustness objectives (e.g. schedule's flexibility, sensitivity, etc.) from multiple sub-problems, jointly influencing the overall airline schedule's operational performance. For example, with the onset of an uncertain event in a schedule with a smaller number of integrated sub-problems, the play of cascading effects and inter-dependencies could lead to the infeasibility of those sub-problems that are not integrated into that model. Also, the extent of integration among the sub-problems of the ASP directly influences the degree of original performance that can be recover. Hence, with more sub-problems integrated into the same model, a more robust ASP could be achieved. In this paper, all of the existing IAS models (belonging to either of the above-mentioned directions of the IAS research) are reviewed. In the following subsection, IAS is defined and a classification system is presented to categorize the literature instances on the basis of the extent of integration among the sub-problems of the ASP.

[4]Robustness is the ability of the system to retain original performance by absorbing disruptions.

B. Definition

IAS is the method of modeling *downstream* and *upstream* dependencies between the sub-problems of the ASP by solving one or more of these sub-problems in an integrated architecture. In the sequential ASP, the subsequent sub-problems depend on the solution of their previous sub-problems such as the solution of schedule generation is essential for assigning fleets to the scheduled flights, etc. These dependencies are called *downstream* dependencies. Moreover, in sequential ASP, a solution of a former sub-problem becomes a constant input for subsequent sub-problems, limiting their flexibility, resulting in a sub-optimal airline schedule. However, consideration of scheduling decisions from latter sub-problems (which comes later in the sequential order) while optimizing/re-optimizing a former sub-problem may result in a better airline schedule. For example, incorporating crew scheduling decisions/constraints while solving fleet assignment, aircraft routing or schedule generation sub-problems may lead to a cost-effective airline schedule, etc. The consideration of such scheduling decisions are called *upstream* dependencies. (Burke et al., 2010) have also defined IAS as the modeling of downstream relations between the scheduling steps and developing fully integrated scheduling models by exploring the inter-dependencies of two or more sub-problems. In this paper, the existing IAS models from the literature are classified into 11 possible classes, based on the varying degree of integration among the sub-problems. This classification system and the absolute frequencies of the relative classes is shown in Table I. Classes ranging from 1 to 6 represent integrated models jointly solving two sub-problems of the ASP together. Similarly, classes ranging from 7 to 10 represents IAS models solving any three sub-problems together, and Class 11 represents the IAS model solving all of the four sub-problems in one integrated framework. Reviewing the existing IAS models, in accordance with the proposed classification system, helps in developing a better understanding of the IAS and its research trend. It also helps in finding the answers to the following questions:

- What are the possible ways of integrating the sub-problems of the ASP?
- Which sub-problems have been integrated frequently by the researchers?
- What is the research gap (unexplored IAS models) in the IAS which may become the prime focus or the starting point of the future researchers?

This understanding, in return, helps toward the development of new IAS models which can solve more of these sub-problems in one integrated model.

TABLE I: Classification of the IAS models based on the extent of integration among the sub-problems of the ASP and their respective absolute frequencies

Classification[a]	Class Labels	Count
SG + FA	1	11
SG + AR	2	5
SG + CS	3	1
FA + AR	4	6
FA + CS	5	2
AR + CS	6	6
SG + FA + AR	7	7
SG + AR + CS	8	4
SG + FA + CS	9	0
FA + AR + CS	10	8
SG + FA + AR + CS	11	0
		50

[a] SG- Schedule Generation sub-problem; FA- Fleet Assignment sub-problem; AR- Aircraft Routing sub-problem; CS-Crew Scheduling sub-problem

C. Existing Integrated Airline Scheduling Models

In this subsection, a thorough review (respective advantages and limitations) of the existing IAS models from the literature is presented. Table II presents the research gap of these IAS models, in the light of the extent of integration achieved among the sub-problems of the ASP. To the best of the authors' knowledge, a total of 50 instances of these IAS models have been proposed by researchers in the past. The authors would appreciate receiving additional instances of IAS models that have not been captured in this review paper. These IAS models are categorized using the classification system, proposed in Table I. The presentation order of the review of these IAS models is in accordance with the order of classes given in Table I, starting with the IAS models integrating only two sub-problems (Class 1-6) of the ASP and concluding with the IAS models that integrate three of these sub-problems.

Class 1: Schedule Generation and Fleet Assignment Sub-problems
Numerous contributions have been made by the researchers from the OR society in developing integrated models for solving schedule generation and fleet assignment sub-problems. Such 11 contributions have been recorded from the existing literature. Most of these publications solved an enhanced fleet assignment model (FAM) by incorporating important aspects of schedule generation decisions in it. (Rexing et al., 2000; Belanger et al., 2006; Jiang and Barnhart, 2009; Sherali et al., 2013a; Pita et al., 2013, 2014) considered flexible departure times by using narrow time windows. The width of these time windows is kept narrow so as to nullify the effect of passenger demand variations. (Barnhart et al., 2002; Lohatepanont and Barnhart, 2004; Jiang and Barnhart, 2009; Sherali et al., 2013a) integrated a Passenger Mix Model (PMM) into the basic FAM, leading to an Itinerary-based FAM (IFAM). (Rexing et al., 2000; Barnhart et al., 2002; Pita et al., 2012) minimized the passenger spill costs in order to avoid spill of passengers due to the assignment of smaller aircraft. (Sherali et al., 2010, 2013a) also considered demand and price variations associated with multiple-fare classes. (Jiang and Barnhart, 2009) adopted a dynamic scheduling approach to constructing weekly flight schedules. All of the publications used a time-space network based multi-commodity flow formulation (TMCF) to model their integrated approach. (Barnhart et al., 2002) used a row and column generation heuristic approach to solve their integrated model. (Belanger et al., 2006) adopted a branch-and-price algorithm embedded with branch-and-bound strategies. A Bender's decomposition method is applied by (Sherali et al., 2010, 2013a) to solve their models. Other publications developed direct and iterative heuristic approaches to solve the integrated models. All of these 11 publications demonstrated the performance of their IAS models on real-world airline data. Two out of these 11 instances used homogeneous aircraft type whereas the other nine used heterogeneous fleets.

The IAS models, in this class, are built on multiple unrealistic assumptions, one such assumption is the consideration of deterministic demands. Moreover, some of the authors targeted a daily scheduling problem instead of a weekly flight schedule and assumed that all days of week are equivalent but it is unrealistic to consider each day of the week as equivalent. Many of them considered a single-fare class, ignoring demand fluctuations due to different fare-classes. Most importantly, many IAS models incorporated important aspects of schedule generation sub-problem in fleet assignment sub-problem, enhancing the latter sub-problem, and solving this enhanced sub-problem. Hence, this integration leads to a uni-directional flow of information leading to a pseudo-integrated framework of two sub-problems captured.

Class 2: Schedule Generation and Aircraft Routing Sub-problems
Multiple contributions are made by the OR society in developing integrated models to jointly solve schedule generation and aircraft routing sub-problems. In this class, five instances have been recorded from the existing literature. Most of the publications in this class integrated airline routing and schedule generation sub-problems. (Levin, 1971; Pollack, 1974; Burke et al., 2010; Faust et al., 2017) addressed the inter-dependencies between schedule generation and aircraft routing sub-problems by including discrete departure times

TABLE II: Research Gap in the literature of the IAS

Authors	Year	Title	Extent of Integration				Class
			SG	FA	AR	CS	
Levin	1971	Scheduling and fleet routing models for transportation systems	Yes	No	Yes	No	2
Pollack	1974	Some aspects of the aircraft scheduling problem	Yes	No	Yes	No	2
Balakrishnan et al.	1990	Selecting aircraft routes for long-haul operations: a formulation and solution method	Yes	No	Yes	No	2
Subramanian et al.	1994	Coldstart: fleet assignment at delta air lines	No	Yes	Yes	Yes	10
Clarke et al.	1996	Maintenance and crew considerations in fleet assignment	No	Yes	Yes	Yes	10
Yan and Young	1996	A decision support framework for multi-fleet routing and multi-stop flight scheduling	Yes	Yes	Yes	No	7
Desaulniers et al.	1997	Daily aircraft routing and scheduling	Yes	Yes	Yes	No	7
Rushmeier and Kontogiorgis	1997	Advances in the optimization of airline fleet assignment	No	Yes	Yes	Yes	10
Yan and Tu	1997	Multifleet routing and multistop flight scheduling for schedule perturbation	Yes	Yes	Yes	No	7
Barnhart et al.	1998a	Flight string models for aircraft fleeting and routing	No	Yes	Yes	No	4
Barnhart et al.	1998b	Integrated airline schedule planning	No	Yes	No	Yes	5
Ioachim et al.	1999	Fleet assignment and routing with schedule synchronization constraints	Yes	Yes	Yes	No	7
El Moudani and Mora-Camino	2000	A dynamic approach for aircraft assignment and maintenance scheduling by airlines	No	Yes	Yes	No	4
Rexing et al.	2000	Airline fleet assignment with time windows	Yes	Yes	No	No	1
Cordeau et al.	2001	Benders decomposition for simultaneous aircraft routing and crew scheduling	No	No	Yes	Yes	6
Barnhart et al.	2002	Itinerary-based airline fleet assignment	Yes	Yes	No	No	1
Klabjan et al.	2002	Airline crew scheduling with time windows and plane-count constraints	Yes	No	Yes	Yes	8
Yan and Tseng	2002	A passenger demand model for airline flight scheduling and fleet routing	Yes	Yes	Yes	No	7
Cohn and Barnhart	2003	Improving crew scheduling by incorporating key maintenance routing decisions	No	No	Yes	Yes	6
Sriram and Haghani	2003	An optimization model for aircraft maintenance scheduling and re-assignment	No	Yes	Yes	No	4
Lohatepanont and Barnhart	2004	Airline schedule planning: integrated models and algorithms for schedule design and fleet assignment	Yes	Yes	No	No	1
Mercier et al.	2005	A computational study of benders decomposition for the integrated aircraft routing and crew scheduling problem	No	No	Yes	Yes	6
Belanger et al.	2006	Periodic airline fleet assignment with time windows, spacing constraints, and time dependent revenues	Yes	Yes	No	No	1
Schaefer and Nemhauser	2006	Improving airline operational performance through schedule perturbation	Yes	No	No	Yes	3
Mercier and Soumis	2007	An integrated aircraft routing, crew scheduling and flight retiming model	Yes	No	Yes	Yes	8
Sandhu and Klabjan	2007	Integrated airline fleeting and crew-pairing decisions	No	Yes	Yes	Yes	10

Extent of Integration: Schedule Generation (SG), Fleet Assignment (FA), Aircraft Routing (AR), and Crew Scheduling (CS) sub-problems of the ASP. Legend: ( ) Yes, ( ) No.

Authors	Year	Title	Extent of Integration				Class
			SG	FA	AR	CS	
Mercier	2008	A theoretical comparison of feasibility cuts for the integrated aircraft-routing and crew-pairing problem	No	No	Yes	Yes	6
Gao et al.	2009	Integrated airline fleet and crew robust planning	No	Yes	No	Yes	5
Haouari et al.	2009	Network flow-based approaches for integrated aircraft fleeting and routing	No	Yes	Yes	No	4
Jiang and Barnhart	2009	Dynamic airline scheduling	Yes	Yes	No	No	1
Papadakos	2009	Integrated airline scheduling	No	Yes	Yes	Yes	10
Weide	2009	Robust and integrated airline scheduling	Yes	No	Yes	Yes	8
Burke et al.	2010	A multi-objective approach for robust airline scheduling	Yes	No	Yes	No	2
Sherali et al.	2010	Integrated airline schedule design and fleet assignment: polyhedral analysis and benders decomposition approach	Yes	Yes	No	No	1
Weide et al.	2010	An iterative approach to robust and integrated aircraft routing and crew scheduling	No	No	Yes	Yes	6
Cadarsoa and Marín	2011	Integrated robust airline schedule development	Yes	Yes	No	No	1
Haouari et al.	2011	Exact approaches for integrated aircraft fleeting and routing at Tunisair	No	Yes	Yes	No	4
Zeghal et al.	2011	Flexible aircraft fleeting and routing at Tunisair	Yes	Yes	Yes	No	7
Dunbar et al.	2012	Robust airline schedule planning: minimizing propagated delay in an integrated routing and crewing framework	No	No	Yes	Yes	6
Pita et al.	2012	Integrated flight scheduling and fleet assignment under airport congestion	Yes	Yes	No	No	1
Cacchiani and Salazar-González	2013	A heuristic approach for an integrated fleet-assignment, aircraft-routing and crew-pairing problem	No	Yes	Yes	Yes	10
Liang and Chaovalitwongse	2013	A network-based model for the integrated weekly aircraft maintenance routing and fleet assignment problem	No	Yes	Yes	No	4
Pita et al.	2013	Setting public service obligations in low-demand air transportation networks: application to the Azores	Yes	Yes	No	No	1
Sherali et al.	2013a	A benders decomposition approach for an integrated airline schedule design and fleet assignment problem with flight retiming, schedule balance, and demand recapture	Yes	Yes	No	No	1
Sherali et al.	2013b	An integrated approach for airline flight selection and timing, fleet assignment, and aircraft routing	Yes	Yes	Yes	No	7
Dunbar et al.	2014	An integrated scenario-based approach for robust aircraft routing, crew pairing and re-timing	Yes	No	Yes	Yes	8
Pita et al.	2014	Socially-oriented flight scheduling and fleet assignment model with an application to Norway	Yes	Yes	No	No	1
Salazar-González	2014	Approaches to solve the fleet-assignment, aircraft-routing, crew-pairing and crew-rostering problems of a regional carrier	No	Yes	Yes	Yes	10
Cacchiani and Salazar-González	2016	Optimal solutions to a real-world integrated airline scheduling problem	No	Yes	Yes	Yes	10
Faust et al.	2017	Demand-oriented integrated scheduling for point-to-point airlines	Yes	No	Yes	No	2

Extent of Integration: Schedule Generation (SG), Fleet Assignment (FA), Aircraft Routing (AR), and Crew Scheduling (CS) sub-problems of the ASP. Legend: ( ) Yes, ( ) No.

and varying them in a narrow time window. Whereas the (Balakrishnan et al., 1990) did not include flexible departure times, instead solved the aircraft routing problem for a long-haul network airline aiming to maximize the profit. They incorporated passenger revenues and traffic estimates of each O-D pair, aircraft operating costs, and their seating capacities in order to integrate the decisions of schedule generation sub-problem. Two publications from the 1970s proposed a simplified integer linear programming model (ILP) for their integrated models whereas the authors of other three publications formulated a mixed-integer linear programming model (MIP) based on a time-space network based multi-commodity flow formulation (TMCF). A branch-and-bound algorithm (Levin, 1971), an LP-based heuristic procedure (Balakrishnan et al., 1990) and a column generation heuristic (Faust et al., 2017) are used to solved their respective integrated models. (Burke et al., 2010) targeted the integration of robustness objectives (e.g. schedule's flexibility and reliability) from aircraft routing and schedule generation sub-problems respectively. They formulated a multi-objective optimization problem for re-routing and re-timing, and solved it using a multi-meme genetic algorithm.

In practical, aircraft have to go under frequent maintenance checks in order to get certified for flying and these maintenance visits are usually scheduled in the aircraft routing phase. Out of all the IAS models mentioned in this class, authors of three publications (Pollack, 1974; Burke et al., 2010; Faust et al., 2017) incorporated aircraft maintenance requirements while the other two solved their integrated models without the maintenance requirements. Integration of only two robustness objectives is solved by (Burke et al., 2010), whereas more robustness objectives like prioritizing strategic flights, time-space based robustness etc may lead to better solutions. Computational experiments are performed by the last three approaches to show the efficacy of their models whereas the first two approaches captured the theoretical aspects. Moreover, some of the developed solution methods such as branch-and-price strategy (Faust et al., 2017) failed for larger real-world airline instances.

Class 3: Schedule Generation and Crew Scheduling Sub-problems

To the best of author's knowledge, only one instance of integration among schedule generation and crew scheduling sub-problems is recorded so far. (Schaefer and Nemhauser, 2006) proposed an integrated model to perturb the original schedule's departure and arrival times in order to reduce the operational costs of a given crew schedule. Authors have used a set partitioning problem formulation (SPP) to model the crew scheduling problem. They have employed a push-back schedule recovery and, using computational experiments, demonstrated that changing the flight schedule after the crew schedule has been prepared may lead to improved on-time performance as well as reduced operational crew costs. Although push-back recovery has no adverse effects, more realistic recovery strategies are required to be tested with this model to give the same or improved results. More work is required for relaxation of assumptions about the availability of planes, dependency of block-time and ground-time error distributions on the time of day, and delays prior to the beginning of each pairing.

Class 4: Fleet Assignment and Aircraft Routing Sub-problems

Numerous contributions are made by the OR society in developing integrated models to jointly solve fleet assignment and aircraft routing sub-problems. In this class, six instances have been recorded from the existing literature. All of these publications incorporated maintenance requirements in their integrated models. (El Moudani and Mora-Camino, 2000) proposed a dynamic approach to integrating the fleet assignment and aircraft maintenance routing sub-problems in order to face real-time airline operating conditions. (Sriram and Haghani, 2003; Liang and Chaovalitwongse, 2013) targeted a weekly maintenance routing problem so as to incorporate less frequent long maintenance checks. (Barnhart et al., 1998a) modeled the problem as a string-based set partitioning problem formulation (SSPP) for a long-haul network airline whereas authors of all other publications formulated the problem as a time-space network based multi-commodity flow formulation (TMCF). Various solution methodologies are developed to solve these models. A heuristic approach is developed by (El Moudani and Mora-Camino, 2000; Sriram and Haghani, 2003; Liang and Chaovalitwongse, 2013); a Bender's decomposition approach is proposed by (Haouari et al., 2011); a branch-and-price algorithm is proposed by (Barnhart et al., 1998a; Haouari et al., 2011); and a fast optimization based approximate algorithm is developed by (Haouari et al., 2009) to solve their integrated models.

Decisions involved in crew scheduling and schedule generation sub-problems, and *yield management* problem (an important aspect of airline scheduling which is aimed at maximizing an airline's profitability by efficiently managing its flights' reservations inventory in the given fare structure and the flight schedule (Smith et al., 1992)) are not integrated into these proposed models restricting their application in real-time operations. Most of these publications provided maintenance opportunities in the night assuming that no flights are flown in the night. Additionally, some of them incorporated maintenance routing constraints in a fleet assignment model leading to the pseudo-integration of the sub-problems. (Liang and Chaovalitwongse, 2013) anticipated uniform distribution of demand over all the routes which is an unrealistic assumption. Moreover, some of the approaches formulated simple costs in their respective objective functions whereas considering more complex costs and requirements may yield better solutions. Some of the publications conducted computations with small real-world airline instances which are insufficient in measuring the true potential of their proposed models.

Class 5: Fleet Assignment and Crew Scheduling Sub-problems

Two integrated models are proposed by the OR society to jointly solve fleet assignment and crew scheduling sub-problems. Both (Barnhart et al., 1998b; Gao et al., 2009), enhanced the fleet assignment model by incorporating crew scheduling constraints. However, the former approach considered crew duty periods, whereas the latter approach included crew connections for the relaxation of crew scheduling sub-problem. Both of these integrated problems are modeled using a time-space network based multi-commodity flow formulation (TMCF) for fleet assignment sub-problem, and an SPP formulation for crew scheduling sub-problem. (Barnhart et al., 1998b) solved these sub-problems in a sequential process whereas (Gao et al., 2009) solved their integrated model using a mixed-integer programming solver.

Crew duty period and crew connections, instead of more important crew pairings, are considered as the criteria for relaxing crew scheduling decisions. Moreover, TAFB[5] crew costs are incorporated in the objective function by (Barnhart et al., 1998b) which are only dominant in a long-haul airline network.

Class 6: Aircraft Routing and Crew Scheduling Sub-problems

Numerous contributions are proposed by the OR society to jointly solve aircraft routing and crew scheduling sub-problems in an integrated model. In this class, six instances have been recorded from the existing literature. All of these models used an SPP formulation for the crew pairing sub-problem, and five out of these six models modeled their problem using a connection-network based multi-commodity flow formulation (CMCF). Only (Mercier, 2008) used a time-space network based multi-commodity flow formulation (TMCF) for modeling this problem. All of them incorporated maintenance requirements as soft constraints in their respective models. Moreover, (Weide et al., 2010; Dunbar et al., 2012) aimed to incorporate robustness in the process against the flight delays by minimizing the flight delay propagation costs. A branch-and-price solution strategy is suggested by (Cohn and Barnhart, 2003) whereas a Bender's decomposition method is adopted by (Cordeau et al., 2001; Mercier et al., 2005). In these Bender's decomposition methods, (Cordeau et al., 2001) formulated aircraft routing as a master problem and crew scheduling as a sub-problem, whereas (Mercier et al., 2005) did opposite of this. (Mercier, 2008) carried out a theoretical study of different feasibility cuts and proposed a procedure of applying these cuts to accelerate the solution process adopted in (Mercier et al., 2005; Weide et al., 2010; Dunbar et al., 2012) solved their integrated models using an iterative heuristic approach.

Integration of departure time windows in the above-mentioned IAS models may further reduce the crew cost and hence it is advisable to explore this approach. Most of these models considered an unrealistic assumption that all aircraft in a fleet have equal operating costs. Moreover, the classification of fleets in crew-compatible groups is ignored which could have eased the overall problem. Some of the approaches incorporated aircraft maintenance requirements implicitly as constraints in the crew pairing sub-problem. Although the primary goal of an aircraft routing sub-problem is to assign feasible rotations to all aircraft, sometimes it is desirable to choose the cost-efficient routing out of many feasible ones. Such costs could be related to:

- a routing's through-values. Sometimes, passengers demand direct flight connections in their itineraries and in return, are ready to pay more. This extra cost associated with a flight-pair that are flown in sequence by the same aircraft is called a through-value. In (Weide et al., 2010), authors did not use any routing costs explicitly but used implicit penalty costs, defined by a non-robustness measure (NRM), in order to restrict the aircraft changes whose sit-time exceeds the minimum sit-time by $\geq$ 30 minutes.
- a routing's robustness towards cascading flight delays. In (Dunbar et al., 2012), costs of total aircraft delay in a 24-hour period are considered in the aircraft routing model.
- the costs incurred in performing unnecessary aircraft maintenance checks (before the actual date of maintenance in order to achieve feasible routing).

Hence, a fully-integrated model belonging to this class would be the one that incorporates both crew-operating and aircraft-routing costs in the objective function of the integrated model. Such IAS models, categorized in this class, are (Weide et al., 2010; Dunbar et al., 2012) where authors have incorporated the aircraft routing costs too in the objective function of the integrated model. However, in other IAS models (Cordeau et al., 2001; Cohn and Barnhart, 2003; Mercier et al., 2005; Mercier, 2008), the aircraft routing sub-problem has been reduced to a feasibility problem, resulting in partially-integrated IAS

[5]Time-away-from-base is the time for which the crew is away from its home airport i.e. the crew base.

models.

Class 7: Schedule Generation, Fleet Assignment, and Aircraft Routing Sub-problems

Numerous contributions are made by the OR society in developing integrated models for schedule generation, fleet assignment, and aircraft routing sub-problems. In this class, seven instances have been recorded from the existing literature. From these seven instances, (Yan and Tu, 1997; Yan and Tseng, 2002) are not included as they are identical to the (Yan and Young, 1996) with slight variations. (Sherali et al., 2013b) is the only integrated model in this class which employed itinerary-based demands, multiple-fare classes, passenger recapture, optional and through flights. In all of these integrated models, inter-dependencies of schedule generation sub-problem are incorporated via implementing departure time windows. (Yan and Young, 1996; Zeghal et al., 2011) used a TMCF formulation whereas other three publications used a CMCF formulation for modeling their respective integrated problems. Most of them also used an SPP formulation for modeling aircraft routing sub-problem. Multiple solution methodologies are proposed such as a branch-and-bound algorithm (Desaulniers et al., 1997; Ioachim et al., 1999), a Lagrangian heuristic approach (Yan and Young, 1996), a column generation based heuristic (Zeghal et al., 2011), and a Bender's decomposition method (Sherali et al., 2013b).

Out of all the IAS models discussed in this class, (Zeghal et al., 2011; Sherali et al., 2013b) incorporated aircraft maintenance requirements whereas (Yan and Young, 1996; Desaulniers et al., 1997; Ioachim et al., 1999) did not consider the maintenance constraints. Moreover, (Zeghal et al., 2011) proposed two integrated approaches, solving two sub-problems at a time instead of solving all of them in one integrated system. Some of the publications conducted computations with small real-world airline instances which are insufficient in measuring the true potential of their proposed models.

Class 8: Schedule Generation, Aircraft Routing, and Crew Scheduling Sub-problems

Multiple contributions are made by the OR society in developing integrated models for solving schedule generation, aircraft routing, and crew scheduling sub-problems. In this class, four instances have been recorded from the existing literature. In all of these integrated models, inter-dependencies of schedule generation sub-problem are incorporated via implementing departure time windows. (Weide, 2009) incorporated robustness in their model by penalizing the number of aircraft changes for which crew connection time is lower than a particular restricted time. All of these publications used an SPP formulation for their crew pairing model and a CMCF formulation for modeling aircraft routing sub-problem. A branch-and-bound approach (Klabjan et al., 2002), a Bender's decomposition method (Mercier and Soumis, 2007), and a heuristic (Dunbar et al., 2014) to solve their respective integrated models.

Out of all of these publications, only (Dunbar et al., 2014) incorporated maintenance requirements implicitly in their integrated model whereas other only incorporated plane-count constraints. In addition to this, aircraft routing costs (as explained in the limitations of the Class 6 IAS models) are not incorporated into the objective function of some of these above-presented IAS models, leading to a pseudo-integration among the three sub-problems. (Dunbar et al., 2014) focused only on minimizing delay propagation costs and did not explore the effect of other costs. Moreover, flexible departure times are incorporated but the incorporation of passenger flow may further improve the solutions. (Klabjan et al., 2002) proposed a re-timing model for a fixed aircraft and crew assignment instead of solving all of them in a single integrated model.

Class 10: Fleet Assignment, Aircraft Routing, and Crew Scheduling Sub-problems

Various contributions are made by the OR society in developing integrated models that solve fleet assignment, aircraft routing, and crew scheduling sub-problems. In this class, eight instances have been recorded from the existing literature. Out of these eight publications, (Cacchiani and Salazar-González, 2013) is not included in this paper as it is identical to (Salazar-González, 2014). (Subramanian et al., 1994; Clarke et al., 1996; Sandhu and Klabjan, 2007) formulated the aircraft routing sub-problem using a TMCF formulation, whereas (Rushmeier and Kontogiorgis, 1997; Papadakos, 2009) formulated it as a CMCF formulation. In addition to this, (Sandhu and Klabjan, 2007; Papadakos, 2009) used an SPP formulation for their crew pairing sub-problem. (Salazar-González, 2014) transformed a multi-criteria routing problem into a single objective problem and formulated their integrated model using an arc-variable based mixed integer programming formulation (MIP). Similarly, (Cacchiani and Salazar-González, 2016) used two MIP formulations (called as arc-path and path-path models) to model their integrated problem. Solution methodologies such as a branch-and-price (Clarke et al., 1996; Rushmeier and Kontogiorgis, 1997; Cacchiani and Salazar-González, 2016), a column generation based heuristic (Sandhu and Klabjan, 2007; Cacchiani and Salazar-González, 2016), a iterative heuristic approach (Salazar-González, 2014), and a Bender's decomposition (Sandhu and Klabjan, 2007; Papadakos, 2009) are proposed to solve their integrated models.

Incorporating flexible departure times in the above-discussed IAS models may improve the quality of solutions and reduce the operating costs. Apart from (Sandhu and Klabjan, 2007), all of these models incorporated maintenance requirements implicitly into their integrated models. In addition to this, aircraft routing and crew costs are not incorporated into the objective function of some of these models leading to a pseudo-integration among the three sub-problems. (Sandhu and Klabjan, 2007) used leg-based fleeting solutions, but using a Passenger Mix Model (PMM) along-with it may lead to better revenues. (Salazar-González, 2014; Cacchiani and Salazar-González, 2016) transformed a multi-criteria routing problem into a single objective problem without exploring their dependencies on decision variables.

III. Observations, Conclusion and Future Research

Optimal airline schedule is an outcome of the combination of a large number of decision variables, their mutual interactions, constraints and objective functions along-with their inter-dependencies in an integrated framework. Traditional decomposition of the ASP and sequential solution approach of its sub-problems restricts the freedom of latter sub-problems because the solutions of former sub-problems serve as constant inputs for them. Hence, the overall solution is either sub-optimal or infeasible. To address this, airlines have started using integrated airline scheduling techniques. These IAS techniques are either implemented using feedback loops and iterations which is a costlier and time-consuming approach, or solving multiple sub-problems together in one integrated model. This, in turn, helps in incorporating flexibility in the ASP. In this review paper, the developed IAS models from the literature are reviewed, highlighting their salient feature and the research gap between the previous decades' and the present-day's IAS modeling techniques.

In Table III, the evolution of the research interest among the respective classes of the IAS models is presented along with their corresponding absolute frequencies. From the research trend shown in Table III, it is observed that initially, researchers started integrating two sub-problems at a time in a tractable model, either by solving them simultaneously or by solving a sub-problem while incorporating important aspects of the other sub-problem. However, with the advancements in technology and computational resources, researchers started integrating more than two sub-problems in a tractable model. The interesting observations that could be drawn from this review paper are as follows:

1) From Table III, it could be concluded that the research trend is, in fact, growing towards the integration of more than two sub-problems.
2) While 11 levels of integration among the sub-problems of the ASP are possible, existing literature relates to only nine of these.

TABLE III: Research trend in the existing IAS models

Year	Classification of IAS models										
	1	2	3	4	5	6	7	8	9	10	11
1971		■									
1972											
1973											
1974		■									
1975											
1976											
During 1978-1986, no IAS models were developed											
1987											
1988											
1989											
1990		■									
1991											
1992											
1993											
1994										■	
1995											
1996							■			■	
1997							■			■	
1998				■	■						
1999							■				
2000	■			■							
2001						■					
2002	■						■	■			
2003				■		■					
2004	■										
2005						■					
2006	■		■								
2007								■		■	
2008						■					
2009	■			■	■			■		■	
2010	■	■				■					
2011	■			■			■				
2012	■					■					
2013	■						■			■	
2014	■							■		■	
2015											
2016										■	
2017		■									
Count	11	5	1	6	2	6	7	4	0	8	0

Legend: The class of IAS models being focused upon in each year is highlighted in ■ (green), and their respective frequencies over the timeline are highlighted in ■ (purple).

- No research publication addresses the integration of schedule generation, fleet assignment and crew scheduling sub-problems (Class 9 IAS models).
- The fully-integrated model (Class 11 IAS models), jointly addressing all sub-problems, remains largely unexplored.

3) Dominant focus of the research community has been on the integration of two sub-problems: schedule generation and fleet assignment (Class 1 IAS models). Moreover, a majority of these IAS models have been recorded in the last decade, indicating a deviation from the general research trend of integrating more than two sub-problems. This deviation could be linked to the following reasons:
   - As shown in Table IV, in most of these IAS models, the maximization of an airline's profitability has been linked with interdependencies between the schedule generation and fleet assignment sub-problems.
   - With the deregulation of the air transportation industry, low-passenger demand regions have been negatively affected. Hence, in rest of these Class 1 IAS models (Pita et al., 2013, 2014), the authors have assisted the government authorities in order to provide subsidy schemes in these low-demand regions.
4) Integration among sub-problems of the ASP directly impacts a schedule's robustness as the extent of integration achieved between these sub-problems directly increases the opportunities for robustness construction.

TABLE IV: INTERDEPENDENCIES ADDRESSED IN THE RECENT CLASS 1 IAS MODELS

Class 1 IAS models	Interdependencies addressed
(Belanger et al., 2006)	Penalized the spacing between two consecutive flights serving the same pair of origin-destination airports
(Jiang and Barnhart, 2009)	Addressed demand stochasticity
(Sherali et al., 2010)	Incorporated the simultaneous consideration of optional flight legs with the fleet assignment sub-problem
(Cadarsoa and Marín, 2011)	Constructed a robust integrated model, ensuring the availability of enough time for passengers' in order to perform flight-connections
(Pita et al., 2012)	With airport congestion being a major cause of the large flight delays, the authors in (Pita et al., 2012) accounted for aircraft and passenger delay costs explicitly into the integrated model
(Sherali et al., 2013a)	Incorporated schedule balance issues, flexible flight time-windows, multiple fare classes, path/itinerary-based passenger demands along with demand recapture issues, and assignment of optional flights into the integrated model

There may be two major reasons that could account for Observations 3 & 4. First, the absence of exact or approximate modeling and solution techniques that could address the inter-dependencies of these sub-problems. Second, the interests of airlines (rather the challenges faced by them) till now are not associated with these sub-problems. Both ways, these classes of integration (Class 9 & 11) requires further investigation by researchers in order to construct overall robust schedules with improved cost savings. In fact, these classes of IAS models could become the topics of research or starting points for the future researchers.

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