A simulation based approach on robust airline job pairing

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Abstract

Job paring, i.e. the composition of duty rosters from single activities, is an important part of the airline operations planning process. With labor costs being a major factor in an airline's cost structure, such personnel schedules have to ensure efficiency to be of practical relevance. At the same time they have to improve customer acceptance by offering best possible robustness, keeping inevitable local delays from spreading through the airline's flight network.

In this paper we present a project currently in development which aims for generating robust personnel schedules for airline operations. The resulting tool set will allow us to effectively allocate flight personnel, using optimization and simulation techniques to generate and compare schedules with respect to their applicability and their demand for standby personnel, and to evaluate them prior to their implementation in the field.

This paper begins with a short introduction of the airline planning process, focusing on the job pairing problem. We then describe our project, presenting our optimization and simulation approaches.

1 Introduction

During their extensive process of operations planning airlines are challenged by a set of interdependent planning problems (see figure 1). This process starts with the design of the flight schedule and the assignment of aircraft types to the flights. It continues with the routing of individual aircrafts and the determination of crew schedules, and is concluded by short-term flight plan management and recovery measures. Within this process the construction of a valid and efficient operations schedule for flight personnel is one of the most complex tasks. A part of this task is the crew pairing procedure which is concerned with the construction and optimal combination of anonymous crew rotations in order to cover all flights of a given flight schedule while complying with a multitude of regulations coming from labor legislation (see [4]), union agreements and operational procedures.

The majority of existing studies analyzes the *crew pairing problem* (CPP) against a cost reducing background due to its high economic significance (see e.g. [2], [8]). The use of costs as exclusive quality objective however may lead to personnel schedules with a low degree of fault tolerance and a high degree of delay propagation. In order to confine occurring disruptions and to support practical applicability a personnel schedule has to be robust.

This paper describes and outlines a project in development which aims for a better understanding of robust personnel schedules. The project follows a more detailed approach than the CPP describes by not dividing tasks on crew level but on the level of individual crew members, leading to a *job pairing problem* (JPP). In the context of robustness this approach is more realistic, since delays and drop outs of individuals can be accounted for. Furthermore individual qualifications can be incorporated which enables the analysis of efficient substitution strategies and standby structures. This approach also allows a more detailed view on the fault propagation in personnel employment strategies. Schedules resulting from our optimization process are to be simulated under realistic conditions. A concurrence of results of a robustness assessment by a static objective function with those of a dynamic simulation would demonstrate a certain suitability of practical use of our approach.

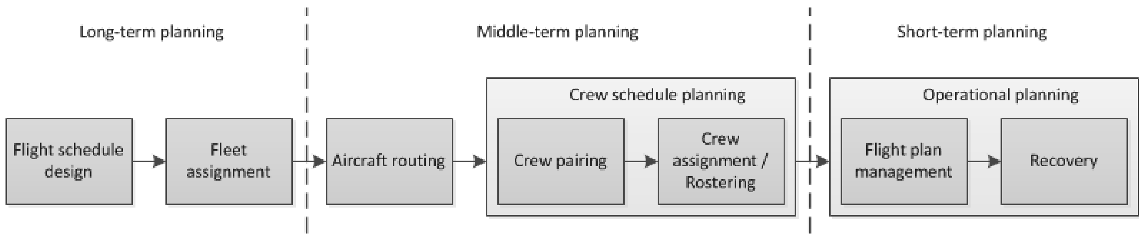

Figure 1: Operations planning process of airlines

The remainder of this paper is organized as follows. In section 2 our project is introduced. Four subsections explain technical backgrounds and give insights into different project modules with their objectives and approaches. Section 3 concludes with a summary and some thoughts on future work.

2 Project approach

Our project *Dynamic Optimization of Group Schedules (DOGS)* is build around a database containing airline schedule and network data. A network generator, simulation, optimization, and evaluation modules are connected via operations on the database and through XML configuration files (see figure 2).

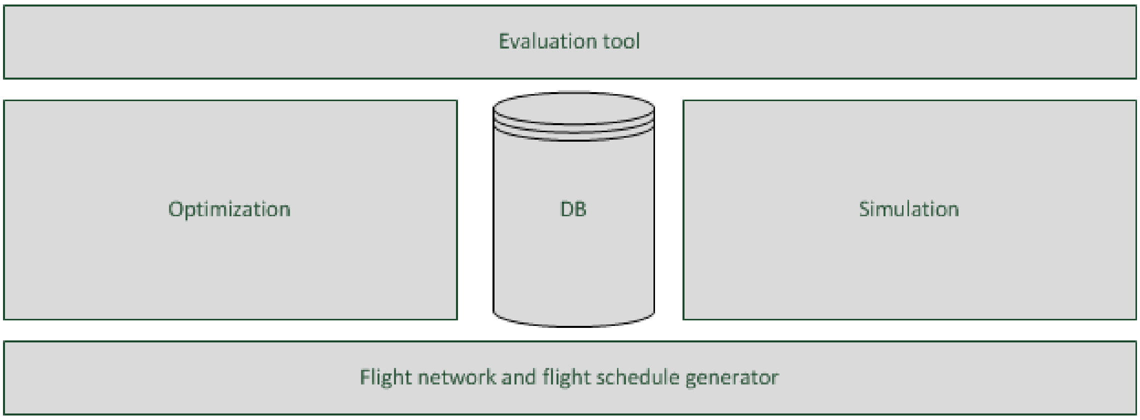

Figure 2: Modular project architecture

2.1 Technical background

The development of aircraft rotations is preceded by flight schedule design and fleet assignment which are both based upon passenger demand forecasts (see figure 1). Results of these planning steps are an airline's flight connections as well as the allocation of aircraft types to these connections. *Flight connections* are defined by their origin and destination airports as well as by their departure and arrival times. Aircraft types differ e.g. in passenger capacities and personnel requirements. All this information merges into the flight schedule which serves as input to the crew scheduling process. During the job pairing, which is part of crew scheduling, tasks combined and packaged. In the following crew assignment or rostering phase these work packages are assigned to members of the flight personnel.

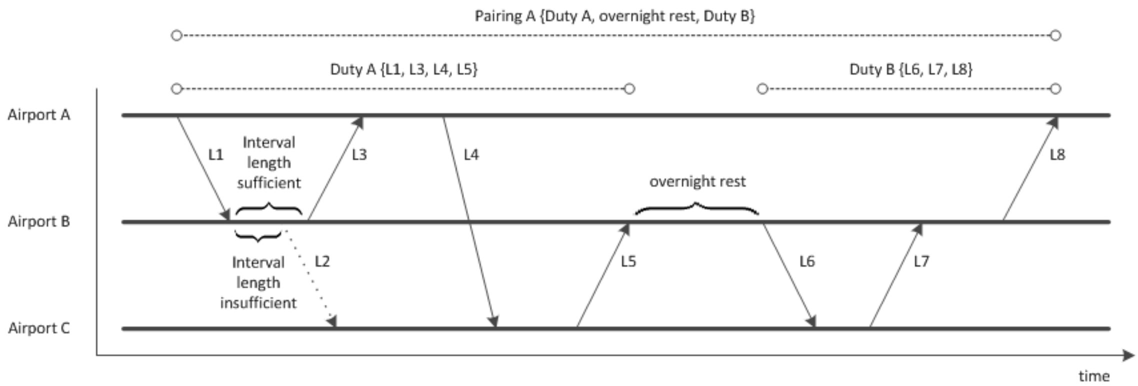

Figure 3: Diagram of a flight schedule fragment

A *flight schedule* provides detailed information about flight connections, informing about the time intervals and weekdays a connection is carried out. Connections in a schedule are identified by flight numbers while individual flights are identified by their connections and days of departure. There are different types of connections to be found in a schedule, depending on their number of *flightlegs*. Figure 3 shows a diagram of a flight schedule fragment in which flightlegs are pictured as arrows. A non-stop connection, also called *non-stop flight*, has no stops between its airports of origin and destination and therefore only one flightleg. A direct connection, also called *direct flight*, has at least one intermediate stop and thus consists of two or more flightlegs. It does not include any changes of aircraft and its flightlegs operate under a single flight number. Examples can be found in figure 3, connecting the airports A and C. A non-stop flight between these airports consists only of flightleg L4, while a direct flight stopping at airport B consists of flightlegs L1 and L2. Within a schedule the type of a connection is denoted by the number of stops it includes.

For the JPP not all connections found in a flight schedule are considered. To avoid redundant information direct flights are ignored since they are composed of non-stop flights already named in the schedule. An airline schedule often contains connections actually carried out by alliance partners. This way a flight might be offered by different airlines under more than one flight number, allowing customers to book at their preferred airline in their own language and currency. Those *code share flights* have to be disregarded since we only want to solve the JPP for single airlines.

The connections an airline offers form its *flight network* which can be viewed as a graph with airports being nodes and flight connections being directed edges. Flight networks of large airlines often show hub and spoke structures which support efficient operations (see [7]). Coordinated with adequate schedules they provide passengers with a manifold choice of connections and short waiting times. Commonly airlines choose large airports with strategically favorable positions within their networks to serve as *hubs*. Hubs are usually fully interconnected. *Spokes* connect the hubs to all other airports which are accessed by the airline. Within such a network structure the surrounding airports are normally not interconnected with the possible exception of *shuttle connections* extending spokes to other smaller airports which have no connections to a hub themselves.

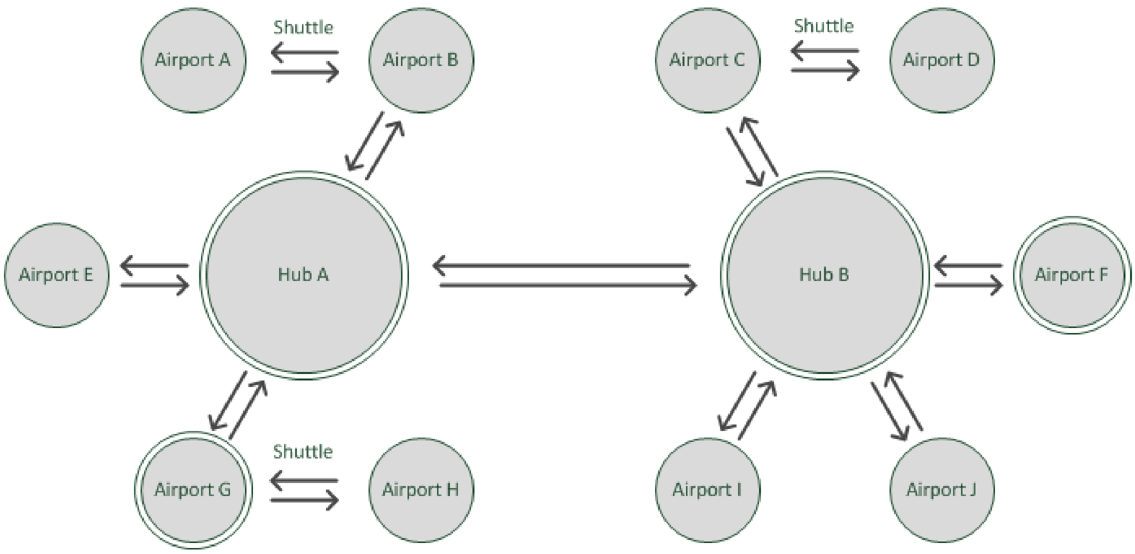

Figure 4: Example of an airline hub and spoke network structure (double lined circles picture crew bases)

Also depending on their relative position within the network airlines choose at least one airport to serve as crew base. An airport is called a *crew base* if it is the place of employment of airline's personnel. Another term used by airline personnel is *home base* which is the employees' view on a crew base. Each employee has exactly one home base while a crew base must be home base to at least one employee. Figure 4 illustrates the described network structure including crew bases.

2.2 Modeling

Following our job pairing approach, each flightleg brings up a number of *jobs*, i.e. single tasks, all requiring individual combinations of professions and qualification profiles. Depending on aircraft type, number of passengers and flight distance, different sizes of flight deck and cabin crews are mandatory. Different aircraft types and countries of origin and destination require different piloting, language and service skills.

During the job pairing the jobs of all flightlegs have to be assorted into work packages which will be assigned to flight personnel in the following rostering process. Jobs are bundled into *duties* which can be viewed as single workdays. The work packages, called *pairings*, again are bundles of duties with overnight rest periods in between (see figure 3). They are round trips, starting and ending at the same crew base. The allowed numbers of take-offs and landings within duties and pairings, maximum flying and service times, minimum rest periods and other work rules concerning the packaging process are determined by public authorities and are further subject to operational procedures and union agreements. During the pairing process it may become necessary to reallocate flight personnel to other airports. The transportation of off duty personnel is called *deadhead*.

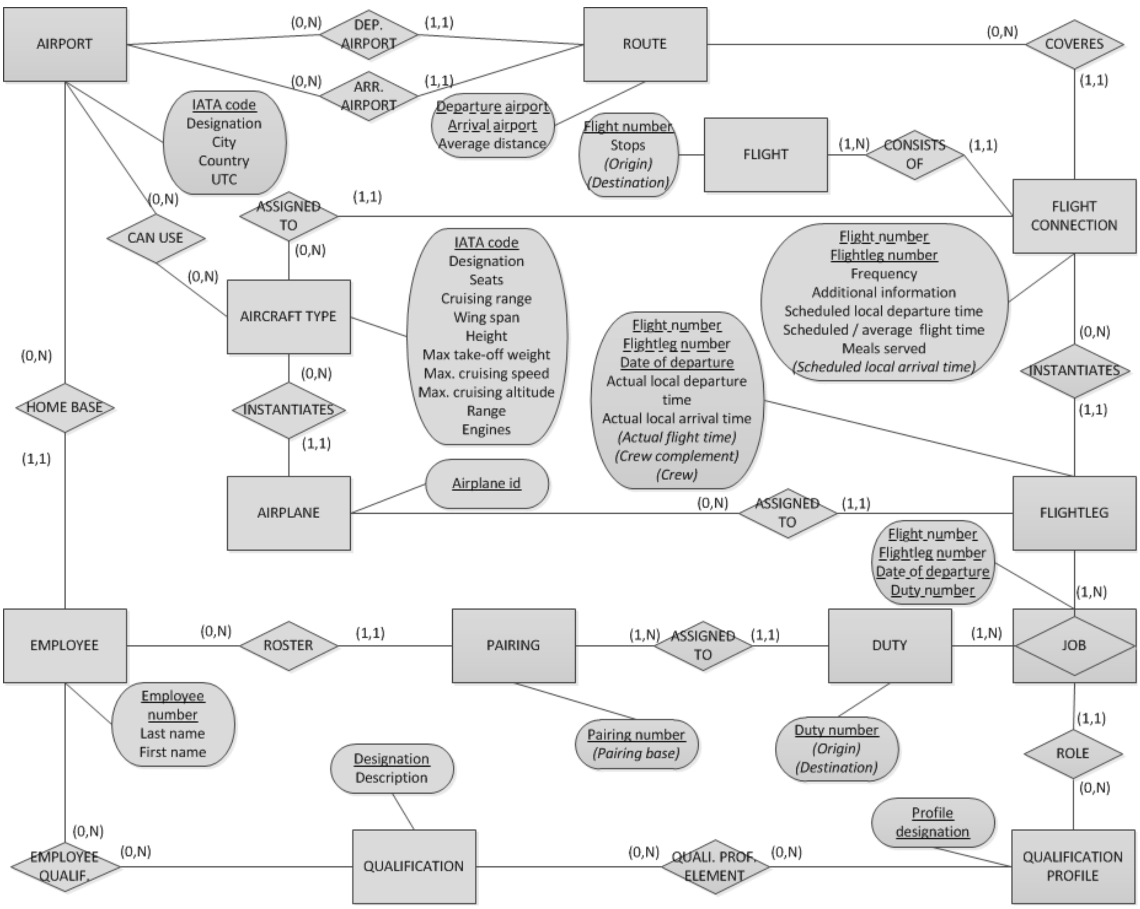

Figure 5: Entity relationship diagram of fundamental data elements within an airline operations planning process

The current state of our project's data model is pictured in figure 5. The entity relationship diagram (see [6]) illustrates the composition and relationships of the entities substantial for an airline operations planning process. The structure of the project's database is derived from this diagram.

The scope of the project includes the development of a flight network and flight schedule generator (see figure 2). With this tool a set of realistic and hypothetical test instances are to be generated to support the robustness analysis. Assessing diverse instances may yield information about the underlying graph structures' influences on the robustness potential. The network graphs of past flight schedules undergo a structural analysis regarding connectivity, reachability and distance measures. Once adequate parameters and realistic specifications have been found the algorithm's method of operation has to be determined. After applying a few modifications the R-MAT generator described in [3] might be a promising candidate.

2.3 Optimization

The JPP is a large scheduling problem whose complexity grows with each additional variable representing jobs, qualification requirements and types of work shifts. Due to its combinatorial structure the number of possible solutions is huge. Problem instances with over 1,000 flights a day and a monthly coordination of over 15,000 crew members are not uncommon. In addition a wide spectrum of government regulations upholding aviation safety have to be respected (see [4]).

Cost reduction is the traditional motivation of research on this topic. Personnel costs account for the second highest part of an airline's overall expenses, right after fuel costs which hardly can be impaired (see [7]). The primary aim of the project presented in this paper however is not to reduce the costs of a flight schedule but to improve its robustness. A robust schedule is to be distinguished by a low rate of delay propagation and a high fault tolerance. Delays and drop outs of personnel members or flightlegs cannot be fully avoided, but measures can be taken to reduce their occurrence probabilities and possible consequences for the flight schedule.

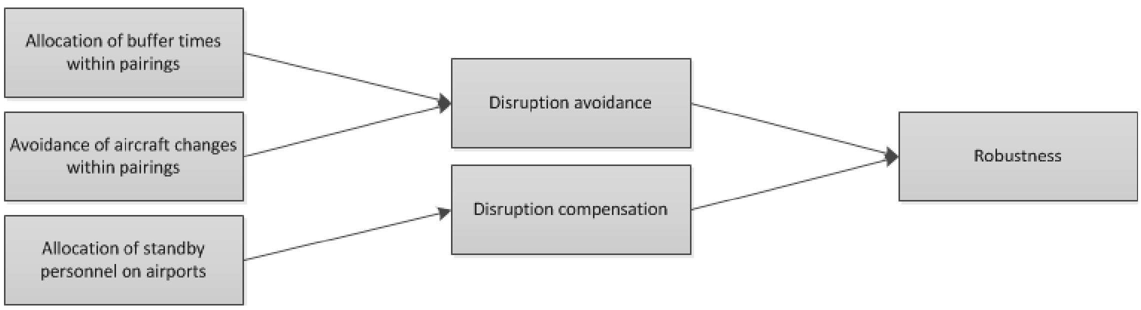

Figure 6: Overview over robustness improving measures during crew pairing

Each step of the airline operations planning process has its own options to account for disruptions. Crew pairing provides measures to avoid disruptions as well as to compensate for them (see figure 6). Our project's optimization approach focuses on disruption avoidance. One policy to create flight schedules with a maximum of stability is to demand a minimum time interval between two consecutive jobs to buffer delays. Figure 3 illustrates that a job of flightleg L2 cannot follow a job of L1 within one personnel member's duty because of the insufficient length of the intermediate time interval. Another measure is the minimization of the number of personnel's aircraft changes within a pairing, reducing dependencies between aircraft rotations and hence delay propagation.

The CPP is often discussed in literature, and a plurality of mathematical models and solution approaches are presented. For our project we haven't yet decided which approaches to adjust to our JPP. Thus we describe a common crew pairing procedure at this point. Crew pairing divides all flightlegs of a given flight schedule into pairings. The problem of covering each flightleg exactly once by a single pairing is described by the *set partitioning problem* (see [2]). In order to include deadheads into the process of optimization the coverage of a flightleg by more than one crew, and hence more than one pairing, must be allowed. The formulation as a *set covering problem* includes the condition to cover each flightleg at least once (see [7]). Solving the CPP for a major airline includes a large set of pairings which leads to a huge number of possible combinations.

Because of its large scale the CPP is often divided into a master problem and a subproblem. The subproblem, including only a manageable amount of pairings, is solved and then iteratively expanded by column generation. Applying the local search heuristic 2-opt (described in [8]), the size of the subproblem stays constant because promising new pairings replace pairings of the previous solution. A common approach for approximating a global optimum is described by the *restricted shortest path problem* (see [9]). Here a problem's graph structure is used to evaluate the quality of all pairings outside the current subproblem so that only the most promising pairings have to be calculated in the next iteration.

Commonly these procedures are used to optimize a cost function. The costs of a pairing can be determined by measuring its time consumption. Gopalakrishnan et. al. define the costs by the difference between the *time away from base* and the *flying time* (see [7]). The time away from base is the time interval between leaving and returning to a crew base. The flying time is the summation of the differences between the arrival and departure times of all the pairing's legs. This calculation determines non-productive waiting times of pairings. Analogous to [5] we want to treat the aspect of robustness using penalty costs for insufficient intervals between flightlegs and for aircraft rotation changes. The formulation of the robustness objective as a cost reduction problem allows the use of already approved optimization procedures.

2.4 Simulation

We plan to develop a model and implement an application to simulate flight schedules. This will enable us to evaluate given personnel schedules prior to their implementation in the field and to compare schedules generated by optimization methods with respect to their applicability. Schedules considered feasible by a static objective function, can be evaluated for their dynamic applicability, and thus lead to a higher degree of validity.

Another focus of the simulation system lies on disruption compensation, i.e. to evaluate a given personnel schedule for its recoverability characteristics (see figure 6). For this, we simulate a personnel schedule under a predefined flight schedule, as well as given fault tolerance policies, and take note of requested numbers and qualifications of standby or reserve personnel. After an adequate number of simulation runs, we thus can recommend standby policies for each airport and time slot. A further aim is to assess different scenarios' impact on schedules to reveal consequences of temporary resource losses, e.g. damaged runways or raised probabilities of staff shortage in certain personnel clusters.

The simulation system currently under development is based on the event-based simulation approach (as described in [1]). Here, events of certain types yield state changes, which manifest at discrete points in time. The events are administrated in a priority queue, ordered by the time stamp of their occurrence. In a loop, the simulation engine extracts the event with the lowest time stamp, advances the simulation time accordingly, processes the event, updates the affected entities' states, and generates appropriate follow-up events, which are again entered into the priority queue. This is repeated until the priority queue is empty, i.e. all scheduled actions of the operational period are processed, and no more follow-up events are generated. Using this technique, scenarios and occurrences of rare events can be handled by injecting corresponding simulation events into the priority queue prior to the simulation run.

In our simulation system airplanes encapsulate most of the simulation dynamics. Planes change their state at events like landing or opening doors. Main attributes are specified by the plane type, which holds functions for capacity, number and position of doors, avionic capabilities, etc. Combined with requirements of flight types, e.g. the number and qualifications of flight attendants, the demand for personnel is calculated. While processing these state changes, the simulation engine takes note of statistical data about delays and dynamic requests for standby personnel.

3 Conclusion and future work

In this paper we presented our project currently in development on robust airline job pairing. After explaining the context of the general airline operations planning process we gave an insight into the modules of the intended project architecture. The models and approaches presented differ from other models of airline personnel planning by considering single crew members instead of whole crews. We illustrated the common graph structure of flight networks and its potential influence on the JPP.

Since this project is still in its beginnings a lot of work has yet to be done. At the moment the real-world model, the setup of the database and a robust optimization program are refined in parallel. We look forward to our next milestone, the completion of the flight network and flight schedule generator, and to the comparison of the potentials of different graph structures on options of robust job pairing.

Acknowledgments

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