Examensarbete

Manpower Planning in Airlines
- Modeling and Optimization

Åsa Holm

LiTH - MAT - EX - - 2008 / 13 - - SE
Manpower Planning in Airlines
- Modeling and Optimization

Optimization, Linköpings Universitet

Åsa Holm

LiTH - MAT - EX - - 2008 / 13 - - SE

Examensarbete: 30 hp

Level: D

Supervisor: Fredrik Altenstedt, Jeppesen, Göteborg

Examiner: Torbjörn Larsson, Optimization, Linköpings Universitet

Linköping: August 2008
Crew costs are one of the largest expenses for airlines and effective manpower planning is therefore important to maximize profit. The focus of research in the field of manpower planning for airlines has mainly been on the scheduling of crew, while other areas, surprisingly, have received very little attention. This thesis provides an overview of some of the other problems facing manpower planners, such as designing a career ladder, planning transitions and making course schedules.

Mathematical models are presented for some of these problems, and for the problem of allocating training and vacation in time the mathematical model has been tested on data from SAS Scandinavian Airlines. When allocating training and vacation there are many aspects to consider, such as avoiding crew shortage, access to resources needed for training, and vacation laws. Comparisons between solutions obtained with the model and SAS Scandinavian Airlines manual plan show encouraging results with savings around 10%.

| Nyckelord | Manpower planning, Airlines, Optimization, Training allocation |
Abstract

Crew costs are one of the largest expenses for airlines and effective manpower planning is therefore important to maximize profit. The focus of research in the field of manpower planning for airlines has mainly been on the scheduling of crew, while other areas, surprisingly, have received very little attention. This thesis provides an overview of some of the other problems facing manpower planners, such as designing a career ladder, planning transitions and making course schedules.

Mathematical models are presented for some of these problems, and for the problem of allocating training and vacation in time the mathematical model has been tested on data from SAS Scandinavian Airlines. When allocating training and vacation there are many aspects to consider, such as avoiding crew shortage, access to resources needed for training, and vacation laws. Comparisons between solutions obtained with the model and SAS Scandinavian Airlines manual plan show encouraging results with savings around 10%.

Keywords: Manpower planning, Airlines, Optimization, Training allocation
Acknowledgments

This master thesis has been performed at Jeppesen during the spring and summer of 2008. Jeppesen has kindly provided me with an office at their Göteborg location and access to the systems and documents needed for the thesis work.

I would like to start by thanking my supervisor at Jeppesen, Fredrik Alтенстедт for his big help and commitment during the entire time. Also Tomas Gustafson, Eva Bengtsson and Tomas Larsson have been very helpful, patiently answering all of my questions. There are many other at Jeppesen that in different ways have helped me and I want to thank you all.

The personnel at SAS Scandinavian Airlines have helped me tremendously by answering many, many questions and providing me with the data needed to test my model, for this I am truly grateful. Especially I want to thank Lena Killander and Tom Sillfors, their knowledge have been invaluable for this thesis.

I would also like to thank my supervisor at LiU, Torbjörn Larsson. Lastly, a special thanks to Susanne Gennow and Paul Vaderlind, without you I would never have found the wonderful world of mathematics.

Åsa Holm
August 2008
# Contents

1 Introduction .................................................. 1  
   1.1 Short Description of Jeppesen ........................... 1  
   1.2 Introduction ........................................... 1  
   1.3 Outline of the Thesis ................................... 2  

2 The Planning Process ......................................... 3  
   2.1 Timetable Construction .................................. 3  
   2.2 Fleet Assignment ....................................... 4  
   2.3 Manpower Planning ..................................... 4  
   2.4 Tail Assignment ......................................... 5  
   2.5 Crew Scheduling ......................................... 5  
       2.5.1 Crew Pairing ...................................... 5  
       2.5.2 Crew Rostering .................................... 6  
   2.6 Recovery Planning ...................................... 6  

3 Manpower Planning ........................................... 7  
   3.1 Overview of the Process ................................. 7  
   3.2 Predicting Demand ...................................... 8  
   3.3 Predicting Supply ...................................... 9  
   3.4 Strategies for Closing the Gap ......................... 10  

4 Manpower Planning for Airlines ............................. 13  
   4.1 Features of the Manpower System in Airlines ........... 13  
   4.2 Support Systems ....................................... 14  
   4.3 Predicting Demand and Supply .......................... 17  
       4.3.1 Seat Ranking .................................... 18  
       4.3.2 Crew Groups ..................................... 19  
       4.3.3 Traffic Assignment ............................... 20  
   4.3.4 Reserve Crew ....................................... 21  
   4.4 Closing the Gap ....................................... 22  
       4.4.1 Transition ....................................... 22  

Holm, 2008.  

xi
Chapter 1

Introduction

1.1 Short Description of Jeppesen

Jeppesen is a subsidiary of Boeing Commercial Aviation Services with offices in the United States, Australia, Sweden, Canada, China, France, and Russia. Their portfolio includes: worldwide flight information, flight operations services, international trip planning services, aviation weather services, and aviation training systems. Jeppesen is recognized as the world’s foremost provider of information solutions in aviation with around 900 airlines as customers.

The office in Gothenburg, Sweden, conducts all of Jeppesen’s planning, scheduling, optimization and disruption management business for airlines. The software produced in Gothenburg, Carmen, is currently used to plan over 23 percent of the world’s airline crews with customers like British Airways, Virgin Atlantic and Singapore Airlines.

1.2 Introduction

The airline industry is faced with some of the largest and most difficult planning problems known today (Grönkvist [8]). In view of the fact that one major European carrier operates and plans approximately 1400 flights per day to more than 150 cities in 76 countries, using 350 aircrafts of 11 different types, and 3400 cockpit, 14000 cabin and 8300 ground crew, this is easy to understand (Grönkvist [8]). To make things even harder there is an enormous set of constraints like government and union rules, crew preferences, crew qualifications and aircraft maintenance regulations.

Since fuel consumption, other aircraft expenses and flight crew salaries typically represent the largest expenses for an airline, efficient planning of
the crew and aircrafts is important to maximize profits (Grönkvist [8]). Cost reductions of only a few percent has a major impact, for example a cost reduction of only one percent of the crew costs for an airline the size of SAS would save around $5 million per year (Andersson et al. [1]). One way of improving utilization of expensive and scarce resources is by optimization systems. Optimization is often described as the methodology to find the best solution, to the right problem as fast as possible. These three dimensions are important in any optimization system but one often has to compromise with some of the dimensions. In real-world problems such as those in the airline industry one often neglect the dimension of the right problem (Andersson et al. [1]).

The planning of flight crew begin some years in advance of operation day to make the workforce better suited for the future needs of the airline. This process of adapting the crew to future needs continues until the day of operation and is called manpower planning. One can say that it is the responsibility of the manpower planners to provide the right number of the right personnel at the right time at the minimum cost (e.g. Khoong [10]). Although manpower planners handle a variety of problems, the focus of research has according to Qi et. al [17] mainly been on crew scheduling and the related problem of pairing generation. However relatively few studies have so far investigated other areas of manpower planning in airlines, such as crew grouping, allocation of training and vacation, and course scheduling. The aim of this thesis is therefore to provide an overview of some of these other problems facing manpower planners and to show the potential of using optimization for one of them.

1.3 Outline of the Thesis

In Chapter 2 the entire planning process for airlines is described in order to supply a context in which to put manpower planning. Chapter 3 provides a definition of manpower planning and an overview of theories concerning manpower planning. In Chapter 4 the different manpower planning problems for airlines is described in detail and in Chapter 5 mathematical models are presented to some of these problems. Chapter 6 presents the method for solving and evaluating one of these models, and in Chapter 7 the results from tests of the model are provided. Finally a concluding discussion is provided in Chapter 8.
Chapter 2

The Planning Process

To make it possible to understand the manpower planning process it is necessary to understand the context in which it is found. Therefore this chapter will focus on the entire planning process by describing it’s different parts.

The planning process is divided into several subprocesses depending of the level of planning and the resources planned. Although each process solves one specific problem, they depend on each other in many complex ways. Traditionally the subprocesses are executed sequentially, but lately researchers have presented different ways to solve some of the subproblems in an integrated manner. However, no single optimization model has, due to the complexity of the problem, even been formulated to solve the entire problem (Barnhart [2]). In Figure 2.1 a schematic overview of the planning process is found. An excellent overview of the airline planning process is provided by Barnhart et. al [2].

2.1 Timetable Construction

Taking into account tactical and strategical decisions a timetable is constructed based on traffic forecasts for the period, seasonal demand variations, available fleet and possibly synchronization within airline alliances. Because of the inability of optimization models to adequately describe the entire problem the timetable is usually constructed manually by the airlines. However, as a result of recent advances in research optimization tools are beginning to play a role in the timetable construction.

A highly associated area is yield management, also referred to as revenue management, which considers the task of maximizing the company’s revenue by optimal allocation of capacity to the different fare classes. Many models also incorporate important practical issues such as overbooking, cancellations

Holm, 2008.
and no-shows. Yield management is extensively covered in literature and an excellent overview is provided by McGill and Van Ryzin [13].

2.2 Fleet Assignment

After the timetable has been constructed the next step is to decide which aircraft type is going to operate each flight; this is called fleet assignment. It is important to note that it is aircraft types that are assigned and not individual aircrafts. The goal in fleet assignment is to maximize profit while maintaining aircraft balance, i.e. an aircraft that lands at an airport must take off from the same airport, using only the available number of aircrafts. How this assignment is done is very important because it directly influences operating costs and passenger revenues, a small aircraft takes fewer passengers but costs less in fuel, landing fees and crew costs. As an example, in 1994 Delta Air Lines estimated that the use of a new system for fleet assignment would yield savings of up to $300 millions over a period of three years (Grönkvist [8]).

2.3 Manpower Planning

Since manpower planning will be discussed extensively in Chapter 3 the process will not be described here. Nevertheless it is necessary to note that
the manpower planning interacts with many of the other steps of the complete planning process.

### 2.4 Tail Assignment

In tail assignment an individual aircraft, of the type decided in the fleet assignment, is assigned to each flight. The flights assigned to an aircraft must constitute a route, i.e. they must form consecutive flights with pairwise matching arrival and departure airports. In addition to these constraints there are some other important constraints, mainly maintenance constraints, that ensure that all aircrafts undergo the needed maintenance checks with regular intervals, and restrictions on the aircraft operating a flight depending on the individual aircraft.

Since each flight is assigned an aircraft type in the fleet assignment, tail assignment falls apart to one problem per aircraft type. The way tail assignment is made varies a lot between airlines, from simplistic procedures like first-in-first out to complex optimization models. Also the time-frame is quite different between companies, some do the assignment very close to the day of operation while others do it longer in advance.

### 2.5 Crew Scheduling

Crew scheduling is the problem of deciding which crew to assign to each flight at a minimum cost. The numerous complex rules and well-defined costs of crew scheduling makes it well suited for optimization. Since it is hard to find even feasible solutions to the scheduling problem, and crew costs are one of the highest operating costs, the area have received a great deal of attention by researchers. Preferably airlines would like to solve the entire scheduling of flight crew as a single problem but so far this seems very hard to do. Therefore the problem is typically divided into two steps: crew pairing and crew rostering.

#### 2.5.1 Crew Pairing

The aim of the crew pairing is to generate minimum-cost pairings so that all flights are covered by the required number of crew members of the right type. A pairing is a multiple-day work schedule consisting of a sequence of flights operated by an anonymous crew member, starting and ending at the same base. Each pairing must respect a large number of work rules specified by the government and unions. Examples of work rules are limitations on
the maximum number of hours worked in a day and minimum length of rest periods. The costs that the optimization tries to minimize are mainly salaries and overnight expenses, but “soft” costs are often added that make the solution more robust and better suited for crew rostering.

2.5.2 Crew Rostering

The objective in crew rostering is to combine the pairings into crew schedules and assigning them to individual crew members. There are mainly two ways of doing this, preferential bidding and bidlines. When using a preferential bidding system schedules are constructed for specific crew members taking into account their needs, limitations and requests. A bidline system constructs anonymous schedules that crew members bid on and the assignment is thereafter done based on seniority. The optimization objective is not actual monetary cost but rather bid satisfaction, robustness or “quality of life”.

2.6 Recovery Planning

After the aircraft and crew schedules have been planned they have to be maintained to account for late changes such as sick crew members, faulty airplanes, big changes in demand, etc. When these disruptions occur long in advance of the day of operation they can usually be solved in a way very similar to the ordinary planning, this is called maintenance or tracking. However closer to the operation day, approximately 3-5 days before and closer, other approaches are usually needed. The ordinary planning process often needs several hours to find a good solution and the closeness to the day of operation does not allow for such long time frames. Therefore the main objective in recovery planning is not to find the best solution, but at least one, preferably more, feasible solutions very fast. The closeness to the day of operation also makes the interdependence between crew, aircraft and passengers an important factor, a solution that works well with the crew might be impossible when considering aircrafts.
Chapter 3

Manpower Planning

The purpose of this chapter is to provide an insight into the manpower planning in general. The focus will be on the elements most useful for the specific problem of manpower planning for airlines, which is presented in Chapter 4.

3.1 Overview of the Process

The basic components of a manpower system are people, jobs, time and money (Grinold [7]). When deciding on a manpower policy it is important to be aware of how these components interact. Ideally the purpose of manpower planning is "to provide the right (required) number of the right (qualified) personnel at the right (specified) time at the minimum cost" (Wang [19]), but often the constrains of the system do not allow the needs to be matched perfectly (Grinold [7]).

There are many definitions and explanations of manpower planning but a common definition is that manpower planning is a process consisting of three elements:

1. Analyzing, reviewing and seeking to predict the number of personnel needed to achieve the objectives of the organization.

2. Predicting the future supply of personnel in the organization by examining current personnel stocks, future recruitment, wastage etc.

3. Considering policies to reconcile any difference between the result of 1 and 2.
Each of these elements is described further in Section 3.2, 3.3 and 3.4 and in Figure 3.1 an illustration of the stages of manpower planning can be found (Barton and Gold [3]).

![Figure 3.1: The Manpower Planning approach](image)

It is important to understand that the elements of manpower planning is not executed sequentially but rather in parallel, starting at an aggregated level and progressing to a more detailed level as the operation day comes closer. Choosing how to aggregate personnel on different levels are one of the first important decisions that manpower planners have to make (Purkiss [15]). The groups should be disjunct and represent features important for the organization; examples of features that might be of interest are entry points, growing grades, significant job steps and streams, and the boundaries of the system (Purkiss [15]).

### 3.2 Predicting Demand

Predicting the number of personnel needed in the future is the main goal of demand forecasting. This forecasting is usually the most difficult part of manpower planning. A reason for this is that demand forecasting requires customized models, since the factors in need of consideration differ considerably between companies. Output level of the company is a factor that all companies need to consider. But since this level is needed by the company
3.3. Predicting Supply

Anyway, it is usually forecasted by another department and serves as an input to manpower planners. Some other factors that usually need to be considered are productivity changes, technological changes, organizational changes, market forces and trends, corporate strategy, etc. (Bartholomew et al. [4], Edwards [6])

Some methods for prediction are extrapolation of time-series data, work study techniques, regression or factor analysis, and product life cycles (Edwards [6]). Most of these methods have frequently been used in other areas than manpower planning and are therefore only covered briefly in the manpower literature. Furthermore few of these methods are applicable for demand forecasting in airlines and will therefore not be covered in this thesis.

3.3 Predicting Supply

When studying personnel supply within an organization, manpower models are often used as an aid. The foundation of the majority of manpower models is the representation of the organization as a dynamic system of stocks and flows. The members of an organization are classified into disjunct groups based on attributes relevant for the area of study, and the number in such a group at a specific time is called the stock. Changes of the system are represented by flows which is the number of movements between groups during an interval of time. A flow can be either a “push” or a “pull” flow; the size of a ”push” flow is determined only by the origin of the flow while the size of “pull” flows are determined by the destination of the flow. A typical representation of an hierarchy organization is presented in Figure 3.2.

The manpower models of the system are used to understand how factors such as e.g. recruitment policies, wastage, promotion policies and age distribution affect the supply of personnel (Purkiss [15]). Another area of application for manpower models are to compute optimal personnel decisions (such as recruitment, promotion, training, etc.) when the situation can be clearly defined (Purkiss [15]). Literature often distinguishes between two types of models: descriptive models constructed to imitate the behavior of the manpower system and normative models which can prescribe a course of action, typically by various optimization techniques (Price et al. [14]).

The main types of descriptive models are Markov chain models, renewal models and simulation models (Price et al. [14]). Markov chain models assume that all flows are “push” flows while renewal models assume “pull” flows. In many organizations there are flows of both types and therefore models including combinations of “push” and “pull” flows have been constructed, e.g. the KENT model (Edwards [6]). Both Markov chain models
Figure 3.2: A simple hierarchy organization, boxes represent stocks and arrows represent flows.

and renewal models are extensively covered by Batholomew et al. [4], and will not be covered in this thesis since they are rarely applied in airlines. Markov and renewal models are not applicable when group sizes are too small, Edwards [6] claims that group sizes should not be less than 100 employees, however simulation models does not have this limitation (Purkiss [15]). Simulation models work at an individual level and by using stochastic simulations many possible scenarios can be achieved and evaluated (Purkiss [15]).

3.4 Strategies for Closing the Gap

There are almost as many strategies for closing the gap between supply and demand as there are companies, although the factors that are possible to affect are similar. Each of these factors have been investigated thoroughly and many are separate fields of studies. It would therefore be possible to write an essay on each of them, but only a short overview will be given here.
work flow  An obvious way to equalize the gap between supply and demand is of course to fire, hire or move personnel. It is important when using these means to consider what effects there will be on the gap in the future, for example hiring when the need is only temporary might be more expensive than being short on supply for a short while. The process of recruiting can be extensive and an overview of the process and what to consider when recruiting personnel is provided by Bratton and Gold [3, Ch.7]. Another part of managing the work flow is career and succession planning whose aim are to designing career paths and to make sure that positions have suitable occupants. Since most position requires a “learning period” a long-term view is needed.

training Training can be considered as the activities intended to enhance the skill, knowledge and capabilities of the personnel. The processes and procedures that try to provide the learning activities are often referred to as human resource development (HRD) and have been a major field of study during recent years. In Chapter 9 in [3] by Bratton and Gold the field of HRD is presented.

reward management Bratton and Gold [3] define a reward as “all the monetary, non-monetary and psychological payments that an organization provides for its employees in exchange for the work they perform”. The way employees and managers are rewarded has undergone a significant change during the past decade, from being based on hours worked and seniority to individual effort and performance. There are many objectives that a reward system must meet: support the organization’s strategy, recruit qualified employees, retain capable employees, ensure internal and external equity, be sustainable within the financial means of the organization, motivate employees to perform to the maximum of their extent, and so on (Bratton and Gold [3]). Reward management is extensively covered in literature and entire books are available on the subject, Bratton and Gold cover some important features in Chapter 10 of [3].

demand factors In Section 3.2 some factors affecting demand were presented: corporate strategy, productivity changes, technological changes, organizational changes, market forces and trends etc. When trying to find strategies to close the gap these factors are still important but from another perspective. In Section 3.2 the focus was how these factors affected demand, but here the focus is how these factors can be affected so that they in turn affect demand in the desired direction.
supply factors As with demand some factors affecting supply have been presented, in Section 3.3, namely: recruitment policies, wastage, promotion policies and age distribution. These can similarly to demand factors be affected to in turn affect supply.
Chapter 4

Manpower Planning for Airlines

This chapter starts by providing an overview of the most important features of the manpower system in airlines and thereafter continues with a short presentation of how airlines solve different manpower planning problems both historically and at presently. Finally an extensive overview of different problems in manpower planning in airlines is presented.

4.1 Features of the Manpower System in Airlines

All cabin and flight deck crew positions can be described by a few characteristics:

**base** Base is the geographic location where the crew member is stationed, i.e. where he/she starts and ends his/her trips.

**rank** There are usually three different ranks for pilots; flight captain, first officer and relief pilot. The flight captain is the commanding officer on the aircraft and hence has the overall responsibility on the bridge. The flight pilot has basically the same task as the captain but has no commanding post. A relief pilot works exclusively on long haul flights were the relief pilot replaces the captain or first officer when they are in need of a rest. The relief pilot is not allowed to take off or land the aircraft. The cabin crew are also typically divided into three levels of rank: purser, steward and flight attendant.

Holm, 2008.
qualification Most Airlines have different kinds of aircrafts and the qualifications of a crew member state which types of aircrafts the crew member is allowed to man. Pilots are generally only qualified for one type of aircraft while almost all cabin crew members are allowed to man two or more types of aircraft.

Apart from the characteristics concerning the position, each crew member has a unique seniority number based on length of service within the airline, with some reductions for long absences. The seniority number determines the priority of the crew member when promotions, vacations, etc. are allocated.

Most pilots want to move from smaller to bigger aircrafts and from first officer to captain, since pay and status are highly associated with aircraft and responsibility, hence pilots change positions many times during their careers. Manpower planners also want pilots to move between positions since the need at different positions change with time. The process of deciding which pilot to be transferred from one position to another is referred to by many names, but in this thesis the notation transition planning will be used.

Almost all pilots that are assigned to a new position require training. However, the amount of training needed depends on their previous experience and the new position. The kind of training that is required when a pilot changes position is called initial training. Initial training is the most extensive and time-consuming type of training, requiring between 5 and 8 weeks (Yu et al. [23]). There is also recurrent training and refresher training. All pilots go through recurrent training a couple of times annually to secure the quality of the pilots by both check-ups and training on abnormalities and safety. Refresher training are dedicated to pilots who have not recently flown the required number of legs needed to keep their qualification. All training types include all or some of the following elements: classroom training, ground training, simulator training, in-flight training and flight checks. Most of the training elements require an instructor that is qualified to teach for the rank, qualification and training type in question. Instructors are usually experienced senior pilots that have undergone training to become instructors.

The planning of transitions and training is two of the problems facing manpower planners in airlines but there are several others. An overview of the areas of manpower planning in airlines are presented in Figure 4.1.

4.2 Support Systems

All airlines have some means for managing their manpower such as legacy database applications, spreadsheet applications and paper-based record keeping (Yu et al. [23]). Most of these means are only a support for manual
4.2. Support Systems

Figure 4.1: The manpower planning process for airlines

planning and for many years an advanced decision-support system has been envisioned by operations research and information technology professionals. In 1991 Verbeek [18] presented a framework for such a system for a strategic manpower planning problem for airline pilots. His system, which was designed for KLM, was organized in three parts: a data preparation part, an (interactive) planning support part, and a reporting part. The system aimed at helping when solving the problem of “when to schedule transition training for pilots from one group of pilots to another and when to hire new pilots, so as to minimize surpluses and shortages of pilots and training costs”. Verbeek formulated some subproblems as mathematical models, but all subproblem were solved with heuristics in the system.

The initial ideas for the development of an integrated manpower planning decision support system at Continental Airlines were presented by Yu et al. [21] in 1998. The system contained pilot and flight attendant fleet optimization, monthly planning optimization, training administration, vaca-
tion administration, and seniority administration. The paper focuses on the training assignment problem, which will be covered in Section 4.4.2. A more complete description of the system, which had by then been implemented and tested, were published in 2003 [22] and 2004 [23]. In Figure 4.2 the modules of Yu’s system, Crew ResourceSolver, are depicted, with input/output, interactions, and communication with external systems, for each module.

The system uses advanced optimization techniques to solve the different manpower planning problems, and some of these techniques will be described in the coming sections. Even though both Yu’s and Verbeek’s systems have been designed for one specific airline, the methods used to solve the problems...
4.3 Predicting Demand and Supply

Very little research has been done specifically for demand and supply forecasting in airlines and it is therefore hard to get an overview of how different airlines solve the problem. The information presented below is therefore based on the knowledge at Jeppesen about how their clients do.

As for most companies accurate predictions of supply and demand of manpower is essential for airlines. There are some different ways of measuring supply and demand, but the most common one is block-hours. The number of block-hours is measured as the time between an aircraft is leaving the departure gate and arriving at the destination gate. The major component of demand is production, i.e. how many block-hours or production days that are needed to man all aircrafts, and added to this demand is need for free days, standbys, training, vacation, etc. For supply the major component is of course the number of employees, which is subtracted by estimates of retirements, different kinds of leave of absence, long-term sickness, etc. To get the number of available block-hours, the number of available crew members is multiplied by the utilization. Utilization is the expected amount of work from each crew member. Whether a component is considered to affect demand or supply is not obvious and differs between airlines.

A long time in advance (around 3 years) the estimate of demand is based on the expected fleet of the company. Closer in time (about 1 year) there often exists a (preliminary) timetable to base the estimates on. By making a preliminary fleet assignment and crew pairing a very good estimate of demand can be obtained, but unfortunately very few airlines do this. Close to the day of operation (1-3 months) crew schedules are available and this provide very good estimates on both supply and demand of manpower.

A Swedish airline, that uses production days (number of crew members needed per day) as a measurement, estimates that each aircraft will need two crew members per position during one day to cover the flights. They also estimate that to produce one production day of flying they need 7.3\(^1\) production days to cover free days, vacations, etc. This means that if they

---

\(^1\)7.3 is not the true number with respect to the company
have 15 aircrafts of one type they estimate that the demand for production days on that type of aircraft is $15 \cdot 2 \cdot 7.3 = 219$ per position.

Most airlines have extensive information about their crew in a personnel system. From these systems data on current numbers of crew members at different positions, and to some extent also trends for sickness, child-nursing, etc. can be derived. Wastage is, in contrast to other industries, a very small problem in airlines. Few pilots change company, probably because of the benefits of being a senior pilot. There is however one problem associated with predicting supply, namely the multitude of different contracts used, stipulating when and how much the crew is to work.

### 4.3.1 Seat Ranking

Until now the ways that crew members want to move between positions have been considered to be fixed. This is probably true to some extent, since big planes often fly to exotic destinations while the small carry domestic travelers. The career ladder that most pilot follow is different at different airlines. For example pilots at SAS change position approximately six times during their career, and they change from first officer to captain at the same aircraft type before they change to a bigger aircraft. At Lufthansa, on the contrary, pilots change from first officer on one aircraft to first officer on another aircraft, and when they reach the top of aircrafts they change to captains on the smallest aircraft, and so on. Some airlines have managed to put some positions in parallel and by that reducing the number of changes a pilot makes during a career; we have seen an example of an airline were a pilot only changes position approximately 2.4 times, although the number of aircraft types is greater.

By trying to affect the pilots’ choices there might be money to save by less trainings, which lead to less time away from production. The major means of influence is of course the salary on different positions. By evaluating how different salary settings influence pilot wishes, and how these wishes influence training costs and salary costs, a career ladder that is cheaper might be found, even if the salaries become more expensive. An example of how putting aircraft types in parallel can influence the number of trainings can be found in Figure 4.3. The goal of the seat ranking is to find a salary distribution that leads to a career ladder with minimal total cost.

In Section 5.1 a model of how to evaluate different career ladders can be found.

To my knowledge there is no published research in this area.
4.3.2 Crew Groups

Most manpower problems presented in this thesis focuses on planning of pilots; there is however, an interesting problem almost unique to manpower planning of cabin crew, namely crew grouping. When predicting demand and supply all crew members have to be grouped into disjunct groups, were members of a groups are considered as equal for planning purposes. For pilots this is easy to do since they rarely have more than one qualification and therefore can be grouped by qualification and rank. For cabin crew however, creating disjunct groups becomes more difficult since they often have at least two qualifications. When deciding which groups of qualification to use and how to size each of the groups used there are a few things to keep in mind:

(a) Crew groups with many qualifications are easier to allocate in the crew pairing, leading to a better and cheaper solution.

(b) It costs more to hold several qualifications since the crew members need training for maintaining all their qualifications.

(c) If the groups are too big or the usage of qualifications in a group is very
unbalanced, problems with recency may arise, i.e. the crew members
 cannot fly the required number of flights to keep their qualification.

(d) Multi-qualified crew members make the recovery phase much easier
since the degree of freedom is greater. If however recency is a problem,
it might be hard to find a recovery solution that admit crew members
to fly enough to keep their qualification.

(e) If there is interdependence between bases, the groups should be similar
at all bases, while if there is no interdependence one grouping per base
could be used.

The aim of the crew grouping problem is to choose and size the groups to use
while minimizing the total cost for training and salaries under the restrictions
given by (a)-(e). In Section 5.2 a mathematical model for one time period
and base, that do not consider (a) and (d), is presented.

To my knowledge there is no published research in this area.

4.3.3 Traffic Assignment

Strategic and tactical decisions such as introducing a new fleet, expanding
a current fleet, changing destinations, making a timetable, etc., all influence
the demand of crew. So when considering such decisions the impact of these
on the crew must be determined to correctly estimate changes in crew costs.
As a consequence of this, manpower planners are often consulted during the
decision process to estimate potential changes in crew costs. To do these
estimates manpower planners consider one or often more of the problems
described in this chapter, but with a scenario instead of the reality.

An example can be found at SAS Scandinavian Airlines where a pro-
cess called “snurran” is used for strategic decisions such as constructing a
timetable. This process starts with the construction of a timetable by per-
personel responsible for flights and customer market. The manpower planners
then do a consequence analysis to find what crew changes would be neces-
sary and what the cost would be. The results are sent to the traffic planning,
that tries to create a timetable that balances the customers’ wishes to costs.
This timetable is then sent back to the personnel responsible for flights and
customer market, and the process start all over again until a timetable that
works well for both crew and customers have been constructed.
4.3.4 Reserve Crew

In Chapter 2 the planning process which results in a schedule for crew and fleet was described. This schedule does however rarely operates as planned. Disruptions due to maintenance problems or severe weather conditions are usual and during a typical day several flights may be delayed or cancelled causing aircrafts and crew to miss the rest of their assigned flights. The problem of dealing with disruptions is the object of recovery planning, described in Section 2.6. It is often not possible to resolve the problems using only regular crew, and airlines therefore keep reserve crew members. The reserve crew members work on call and are assigned to those flights where the assigned regular crew can not fly the aircraft due to disruptions.

Airlines using the bidline system also assign reserve crew to “uncovered trips”. During the bidding process crew members are allowed to bid for schedules that conflict with their individual vacation and training assignments. This creates bidding-invoked conflicts causing pairings to be dropped from the individuals’ schedule and hence become uncovered. For airlines using the bidline system these “uncovered trips” contribute to a major portion of reserve crew demand; for a major U.S. Airline such as Delta it can contribute to more than 60% of the reserve demand (Sohoni et al. [16]). Airlines using preferential bidding systems do not have uncovered trips, since they prevent conflicts with training and vacation assignments during the rostering process.

Estimating the demand of reserve crew is hard. It resembles the general estimation of demand in that it can to some extent be derived from company fleet or timetable, but variations are far greater. By experience airlines usually get some idea of how much reserve crew they need. A problem when deriving estimates based on historical data is that reserve crew is then almost always used, since the aim of recovery planning is to find a solution immediately and not minimizing crew use, but in many cases there might have been a solution that did not require much reserve crew at all.

Different strategies for reserve crew are applied by different airlines. For some airlines reserve crew are a special group that always flies flights that for some reason have been reassigned from the regular crew; this strategy is common in the U.S. The reserve crew schedules do not consist of pairings like for the regular crew, but of groups of consecutive on-duty and off-duty days and are called reserve patterns. A pattern type is determined by the total number of, and grouping of the off-duty days, one example of a pattern type used by a large U.S. carrier is 4-3-3-2:6-3 which is a reserve pattern with one grouping of four off-days, two of three off-days and one two off-day, all separated by at least three days and with at most six consecutive
on-days (Sohoni et al. [16]). How to choose which patterns to use have been a field subject to some research, and Dillon and Kontogiorgis [5] presented in 1999 a deterministic model which had been implemented at US Airways with success. In 2004 Sohoni et al. [16] presented a stochastic optimization formulation minimizing involuntary flying hours and cost over a finite number of scenarios. Their model is presented in Section 5.3.

Not all airlines have special crew for reserve duty; there are companies that use the ordinary crew for reserve duty as well. These companies schedule reserve duty the exact same way as flights, and planning of reserve duty is hence done by the crew paring and rostering.

\section{Closing the Gap}

For airlines the factors that are easiest to decide over and plan for are transitions, i.e. who are going to get promoted or transferred, training, i.e. when are the required training going to take place, and vacation, i.e. how many is going to have vacation at a certain time.

\subsection{Transition}

As mentioned in Section 4.1 one way of adapting supply to demand is transferring pilots from one seat to another. The process of deciding which pilot to be transferred from one position to another differs between companies but one can typically distinguish two different strategies: system bid award and preferential bidding. As a part of the process the number of new hires and pilot releases are also decided.

When using a system bid award the airline offers positions to the pilots, based on forecasted needs for the company. The pilots then bid on the positions they desire and position are awarded in seniority order. If there is not enough pilots wanting a position, assignments will be made in reverse-seniority order. In an average system bid award at Continental Airlines 15-20 percent of the pilots change position. Preferential bidding is similar, but here the pilots first order the positions in the order they desire them, then the planners award transitions based on forecasted need, desires and seniority. Both systems assign all transferees for a period (often 6-12 months) and have an effective date when all pilots who been assigned to a new position shall have been transfered to their new positions.

In some airlines it is possible to break the seniority order in special cases, this is however associated with a cost called pay-protection. Pay-protection means that the more senior pilot that did not get the transfer he wanted,
due to breaking of seniority rules, receives the same pay as he would have had if transferred, from the day that the less senior pilot is transferred.

Since initial courses are very expensive manpower planners do not want pilots to spend too short times in a certain seat. Most airlines therefore have a rule that force pilots to spend a minimum amount of time in the new seat before changing again. This time is called the binding period. It is different between airlines and depends both on the new and old seat, but is usually 2-3 years.

Currently most companies do transition planning for only one period of time, e.g. a year. Since training and hiring take a long time, e.g. Air France cadets get hired 26 months before they are ready to go into production, it would be desirable to take several time periods into account when creating the transition plan. Manpower planners also want the plan to keep training costs at a low level, have a low level of transfers and fulfill crew wishes. The seniority-order awarding does however not leave room for adjustments that would reduce number of transfers and training costs. To my knowledge there is no research on how to make a good transition plan and only a little on how to make a transition plan at all.

4.4.2 Training and Vacation

When transition planning has been made the next step is to plan when the transitions, new hires and pilot releases are going to take place. When creating such a plan there are many restrictions that need to be considered:

1. A very important goal when creating a plan is to ensure that the demand of pilots at each time and position can be covered by those available. This is however not always possible and then the blockhour-shortage should be minimized.

2. Resources for training, such as instructors and simulators, are limited and the training plan must make sure that all resources needed for a pilot’s initial training are available.

3. Pilots may have pre-assigned activities, such as vacation, preventing them from going through training at a specific time. Since however the plan at many airlines is made a long time in advance, the number of such activities should be relatively few.

4. All pilots that were awarded a transition must be transferred within the required period.
5. There might be seniority rules restricting the order of transitions, such as pay-protection (described in Section 4.4.1) or rules forcing transitions to be in seniority or reverse-seniority order.

Yu et al. ([22], [23]) have built and implemented a model considering all these restrictions for Continental Airlines. There are however a few aspects that their model do not consider in a way that may be desirable:

- Recurrent courses are only considered to block resources and capacity, no optimization of when to place recurrent courses is made. This would however be desirable since recurrent courses use the same resources as the initial training. Furthermore pilots in recurrent courses are not available for production. This implies that planning of recurrent courses at the same time as initial training makes it easier to meet the constraints on resource availability and block-hour shortage minimization.

- A vacation budget is considered an input to the model. Since vacation takes away pilots from production in much the same way as training courses do, it would make it easier to prevent block-hour shortage if the vacations were planned at the same time as the courses.

Laws and union regulations determine rules on when and how vacation can be placed, and on how often and which kind of recurrent training that is needed. This results in a variety of rules that differ a lot between airlines. An example of a law that affects vacation allocation is the Swedish vacation law that stipulates that if nothing else has been agreed-on, for example in union regulations, personnel have the right to four consecutive weeks of vacation during the summer (SFS [27]). An example of laws concerning recurrent training is EU OPS 1.965 that stipulates what kind of recurrent training that is needed in a commercial airline within the countries of the European Union, an example from this law is that all flight crew members undergo a line check\(^2\) every 12 months [25].

While finding a plan that meets all restrictions and rules the goal is of course to minimize the costs. The costs that should be considered are:

**Transition costs** When a pilot changes position the costs for that pilot, mainly the salary but perhaps also training costs, etc. often change.

**Course costs** There is of course a cost associated with holding the required courses, and the cost of the course can often be divided into two parts, a cost for holding it and a cost per participant.

\(^2\)An instructor checks pilots during one of their ordinary flights.
4.4 Closing the Gap

Shortage costs When lacking manpower the airline has to solve the problem of this in some way, which is often associated with costs that have to be considered. It is however difficult to know what the costs actually are and therefore finding a good estimate is important.

Pay-protection costs If pay-protection is used the costs of that should be considered.

4.4.3 Course Scheduling

In the training allocation a plan for when pilots shall go through training is produced taking into account limitations on resources, such as instructors and simulators. To get a complete schedule however, there needs to be a plan for which pilots/courses use which resource and when. This problem is called course scheduling, and schedules all course activities while assigning necessary resources to each activity.

The constraints on a schedule that need to be considered are:

- There are rules regarding the order of the activities within a course, often the activities require that one or more of the activities have been performed prior. Sometimes there are also restrictions that some activities must be scheduled consecutively without days-off in between. With each course a template is therefore associated, defining which the activities are and the mutual order of them.

- Resources can be assigned only once every device period$^3$.

- Pilots that are scheduled on consecutive days must day 2 be scheduled in the same or a later device period than day 1.

- Pilots are entitled to days-off that have to be scheduled. At Continental Airlines the general rule is that for every 7 consecutive days there must be at least 1 day-off, and for every 14 consecutive days there must be at least 4 days off (Qi et al. [17]).

Qi et al. [17] have presented a complex heuristic to solve the course scheduling problem and this heuristic is included in the Crew ResourceSolver implemented at Continental Airlines, and described by Yu et al. ([22], [23]). These are the only attempts to solve the course scheduling problems for airlines known to me. There are however closely related problems such as course $^3$The time available in a simulator (training device) during a day is often divided into periods referred to as device periods.
timetabling, resource-constrained project scheduling, and machine scheduling but all of these are different in some way that make them unsuitable for application to the course scheduling problem (Qi et al. [17]).

4.4.4 Reward Decisions

All strategies for closing the gap presented above use some kind of force. The planners decide what the crew should do and when. There is however other ways to make the crew fulfill the wishes of the company by simply awarding the “right” decisions. A few examples of this is presented here.

- By Swedish law all personnel have the right to at least 4 weeks of connected vacation during June, July and August. This can be somewhat of a problem to an airline that can not shut down during the summer. One airline does therefore give their employees the following offer. If you move out vacation from the summer to another part of the year you gain 0.5 extra days for every day moved. The opposite is also true, if you want to have more vacation during the summer than the 4 weeks required by law you have to pay 1.5 vacation days for each extra vacation day during the summer. This means that if you move 6 day from the summer you can have 9 days of vacation at another time, but if you want to move 6 days from the autumn to the summer you will only get 4 vacation days.

- An airline that have a problem with redundancy have considered giving their employees the following offer. If taking a leave of absence there will be no loss of seniority, i.e. the pilot will keep his/her place on the seniority list even though not working. Furthermore the airline will keep paying for your future pension as if you were working. By giving this offer the airline can retain their pilots in the company for later times when they might be needed, while paying very little for them.
Chapter 5
Mathematic Models

In this chapter the mathematical models of the problems described in Chapter 4 will be presented. Some of the models presented here have been published by other authors and some of them are my work.

5.1 Seat Ranking

Below a model constructed by me for the seat ranking problem, described in Section 4.3.1, is presented. It is mainly a model for calculating the costs of different formations of the career path. The optimization is done by choosing the cheapest of the evaluated formations, and this can be done since the number of possible formations is very small. For each formation estimates of pilot bidding and seniority must be done to find the distribution of transfers between seats, and thereafter the problem can be formulated as follow.

**Sets**

$I$ = available seats, i.e. all possible combinations of qualification and rank.

$T$ = time periods.

**Parameters**

$a_{ijt} =$ share of pilots transferring to seat $j$ who is coming from seat $i$

during period $t$

$d_{it} =$ demand for pilots qualified for seat $i$ during period $t$

$s_{it} =$ cost for a pilot qualified for seat $i$ during period $t$: salaries, recurrent training, etc.
\( r_{it} = \) number of pilots retiring from seat \( i \) during period \( t \)
\( t_{ij} = \) percent of utilization loss due to training from seat \( i \) to seat \( j \)
\( c_{ijt} = \) cost for training one pilot from seat \( i \) to seat \( j \) during period \( t \)

**Variables**

\( y_{it} = \) supply of pilots qualified for seat \( i \) during period \( t \)
\( O_{it} = \) number of pilots trained from seat \( i \) to another seat during period \( t \)
\( N_{it} = \) number of pilots trained to seat \( i \) from another seat during period \( t \)
\( x_{ijt} = \) number of pilots trained from seat \( i \) to seat \( j \) during period \( t \)

**Objection function**

\[
\min \sum_{t \in T} \sum_{i \in I} s_{it} y_{it} + \sum_{t \in T} \sum_{i \in I} \sum_{j \in I: i \neq j} c_{ijt} x_{ijt}
\]

**Subject to:**

Keeping demand satisfied:

\[
y_{it} - \sum_{j \in I} l_{ij} x_{ijt} \geq d_{it} \quad \forall i \in I, t \in T \quad (5.1.1)
\]

Crew balance:

\[
y_{i,t-1} + N_{it} - O_{it} - r_{it} = y_{it} \quad \forall i \in I, t \in T \quad (5.1.2)
\]

Translating share to number:

\[
x_{ijt} = a_{ijt} N_{jt} \quad \forall i, j \in I, t \in T \quad (5.1.3)
\]

All transferring from a seat should come to a specific seat:

\[
\sum_{j \in I} x_{ijt} = O_{it} \quad \forall i \in I, t \in T \quad (5.1.4)
\]

Variable restrictions:

\[
y_{it}, O_{it}, N_{it} \in \mathbb{R}^2_+ \quad \forall i \in I, t \in T \quad (5.1.5)
\]
\[
x_{ijt} \in \mathbb{R}^3_+ \quad \forall i, j \in I, t \in T \quad (5.1.6)
\]

Since this is a very long term planning problem the time period should be long, probably around 1 year.
5.2 Crew Grouping

The mathematical formulation presented here is constructed for the problem described in Section 4.3.2 and is my work. It does not include all aspects presented and it include only one time period and one base.

Sets

\[ I = \text{all available seats, i.e. combinations of rank and qualification} \]
\[ G = \text{all possible groups of seats, i.e. } G \subseteq \mathcal{P}(I) \]
\[ G(i) = \text{all groups containing seat } i \in I \]
\[ G^0 = \text{all groups currently used} \]

Parameters

\[ a_g = \text{current number of employees in group } g \]
\[ d_i = \text{demand for employees with certification for seat } i \]
\[ cb_g = \text{cost for using group } g \]
\[ cc = \text{cost for adding a new group} \]
\[ cr_g = \text{salary and training cost for one employee in group } g \]
\[ cl_i = \text{cost for shortage of seat } i \]
\[ ct_{gh} = \text{cost for initial training when transferring from group } g \text{ to group } h \]
\[ \bar{g} = \text{maximal number of groups allowed} \]
\[ e = \text{minimal number of employees in a used group} \]
\[ t_i = \text{maximal number of employees who can be trained to have certification for seat } i \]
\[ M = \text{big number} \]

Variables

\[ x_g = \text{number of employees assigned to group } g \]
\[ y_g = 1 \text{ if group } g \text{ should be used, otherwise } 0 \]
\[ u_{gh} = \text{number of employees who will be trained from group } g \text{ to group } h \]
\(s_i = \) shortage of employees certified for seat \(i\)

**Objective function**

\[
\begin{align*}
\text{min} & \quad \sum_{g \in G} cr_g x_g + \sum_{g \in G} \sum_{h \in G} cl_{gh} u_{gh} + \sum_{i \in I} cl_i s_i + \sum_{g \in G} cb_g y_g + \sum_{g \in G \setminus G^0} cc \cdot y_g \\
\text{Crew costs} & \quad \text{Initial training costs} & \quad \text{Shortage costs} & \quad \text{Group costs}
\end{align*}
\]

**Subject to:**

**Crew balance:**

\[
a_g + \sum_{h \in G} u_{hg} - \sum_{h \in G} u_{gh} = x_g \quad \forall g \in G \tag{5.2.1}
\]

**Cover crew demand:**

\[
\sum_{i \in J} s_i + \sum_{g \in \bigcup_{i \in J} G(i)} x_g \geq \sum_{i \in J} d_i \quad \forall J \in \mathcal{P}(I) \tag{5.2.2}
\]

**Do not train more crew members to a qualification than possible:**

\[
\sum_{g \in G \setminus G(i)} \sum_{h \in G(i)} u_{gh} \leq \bar{t}_i \quad \forall i \in I \tag{5.2.3}
\]

**At least the minimum allowed number of crew members must be in a group:**

\[
\underline{\xi} \cdot y_g \leq x_g \quad \forall g \in G \tag{5.2.4}
\]

**If the group is not used no crew member can be in that group:**

\[
x_g \leq M \cdot y_g \quad \forall g \in G \tag{5.2.5}
\]

**Limit the number of used groups:**

\[
\sum_{g \in G} y_g \leq \bar{y} \tag{5.2.6}
\]

**Variable restrictions:**

\[
\begin{align*}
n_g, y_g & \in \{0, 1\} & \forall g \in G \\
u_{gh} & \in \mathbb{Z}_+^2 & \forall g, h \in G \\
x_g & \in \mathbb{Z}_+ & \forall g \in G \\
s_i & \geq 0 & \forall i \in I
\end{align*}
\]
5.3 Reserve Crew

This model for selecting patterns for reserve crew, a problem described in Section 4.3.4, was presented by Sohoni et al. [16]. The aim is to cover all uncovered trips in each scenario either by reserve crew or by involuntary overtime flying, while minimizing involuntary flying hours and costs. Pairings that are disrupted by weather or unplanned maintenance are for this model regarded as uncovered trips as well. A scenario specifies the number of uncovered trips that operate on each day. The model assumes that it is always possible to find a regular pilot to cover a trip day not covered by reserves.

Sets

\[ P = \text{all possible legal reserve patterns} \]
\[ P_k = \text{all reserve patterns of type } k \]
\[ S = \text{all scenarios} \]

Parameters

\[ m = \text{number of days in the planning period} \]
\[ N = |P| \]
\[ M = \text{vector of length } m, \text{ containing the minimum numbers of off-duty reserves required on each day} \]
\[ L_k = \text{minimum number of patterns of type } k \]
\[ R = \text{maximum number of patterns to be selected} \]
\[ A = \text{matrix of dimension } m \times N, \text{ where element } a_{dp} \text{ is } 1 \text{ if pattern } p \]
\[ \text{has an on-duty day on day } d, \text{ otherwise} \]
\[ B = \text{matrix of dimension } m \times N, \text{ element } b_{dp} \text{ is } 1 \text{ if pattern } p \]
\[ \text{has an off-duty day on day } d, \text{ otherwise} \]
\[ r_s = \text{vector of length } m, \text{ containing the number of reserves required during day } d \text{ in scenario } s \]
\[ C = \text{cost per reserve crew} \]
\[ q = \text{cost for a trip day covered by regular crew} \]
\[ p_s = \text{probability for scenario } s \]
Variables

\[ x = \text{vector of length } N, \text{ where the value of } x_j \text{ is the frequency of pattern } j \]
\[ y_s = \text{number of trip days not covered by reserves in scenario } s \]

Objective function

\[
\min \sum_{j=1}^{N} x_j C + q \sum_{s \in S} p_s y_s
\]

Reserve crew costs \[+\] Costs for covering days with regular crew

Subject to:

Demand/supply balance:

\[ r_s - Ax = y_s \] (5.3.1)

Limit on the number of used patterns:

\[ \sum_{j=1}^{N} x_j \leq R \] (5.3.2)

Cover the required number of reserve crew on an off-day:

\[ Bx \geq M \] (5.3.3)

Cover the demand of patterns of a specific type:

\[ \sum_{j \in P_k} x_j \geq L_k \quad \forall k \in K \] (5.3.4)

Variable restrictions:

\[ y_s, x_s \geq 0 \] (5.3.5)
\[ x \in \mathbb{Z}^N \] (5.3.6)
5.4 Training and Vacation

In this section a model for the training and vacation allocation problem described in Section 4.4.2 is presented. The model is my work but it has been influenced to a great deal by the model presented by Yu et al. [23] for training allocation (called “The Pilot-Transitioning Model”).

Sets

\[
\begin{align*}
H &= \text{available positions} \\
K &= \text{courses} \\
K_i &= \text{initial courses} \\
K_r &= \text{recurrent courses} \\
K_r(h) &= \text{recurrent courses for position } h \\
I &= \text{pilots to be transferred or released} \\
I_k &= \text{pilots who need course } k \\
I_q &= \text{pilots who will be let go, sorted in backward seniority order} \\
O(h) &= \text{pilots whose initial position is } h \\
N(h) &= \text{pilots whose future position is } h \\
P &= \text{pair of pilots } (i, j) \text{ where pilot } i \text{ is pay-protected by pilot } j \\
SS &= \text{pair of pilots } (i, j) \text{ where pilot } i \text{ by seniority rules must move before pilot } j \\
R &= \text{training resources}
\end{align*}
\]

Parameters

\[
\begin{align*}
N &= \text{number of time periods} \\
BI_h &= \text{initial supply of block-hours for position } h \text{ in period } t \\
B_{ht} &= \text{demand of block-hours for position } h \text{ in period } t \\
u_{ht} &= \text{pilot utilization per position } h \text{ in period } t \\
rs_{rt} &= \text{supply of resource } r \text{ in period } t \\
dp_{kp} &= \text{demand of resource } r \text{ per person, } p \text{ periods into course } k \\
dc_{kp} &= \text{demand of resource } r \text{ per course, } p \text{ periods into course } k
\end{align*}
\]
\[ dv_{htu} = \text{vacation demand for position } h \text{ between periods } t \text{ and } u \]
\[ dl_{ktu} = \text{demand for recurrent courses of type } k \text{ between periods } t \text{ and } u \]
\[ l_i = \text{length of course for pilot } i \]
\[ l_k = \text{length of course } k \]
\[ b_k = \text{maximal number of participants in course } k \]

\[ ct_{it} = \text{cost if pilot } i \text{ is transferred or released in period } t \]
\[ cm_i = \text{pay-protection cost per period for pilot } i \]
\[ cc_k = \text{cost for holding a course of type } k \]
\[ cr_k = \text{cost per participant on course } k \in K_r \]
\[ cl_h = \text{cost per block-hour shortage in position } h \]

**Variables**

\[ y_{it} = 1 \text{ if pilot } i \text{ is transferred or released in period } t \]
\[ x_{kt} = \text{number of pilots starting course } k \text{ in period } t \]
\[ a_{kt} = \text{number of courses of type } k \text{ starting in period } t \]
\[ v_{ht} = \text{number of pilots at position } h \text{ with vacation in period } t \]
\[ p_i = \text{number of periods with pay-protection for pilot } i \]
\[ s_{ht} = \text{block-hour shortage for position } h \text{ in period } t \]

**Objective function**

\[
\min \sum_{k \in K} \sum_{t=1}^{N} (cc_k a_{kt} + cr_k x_{kt}) + \sum_{i \in I} \sum_{t=1}^{N} ct_{it} y_{it} + \sum_{i \in I} cm_i p_i + \sum_{h \in H} \sum_{t=1}^{N} cl_h s_{ht}
\]

**Subject to:**

All pilots awarded a transition must be moved:

\[
\sum_{t=1}^{N} y_{it} = 1 \quad \forall i \in I
\]  
([5.4.1])
5.4. Training and Vacation

Tracking of the number of periods with pay-protection for each pilot:

\[ \sum_{t=1}^{N} ty_{it} - \sum_{t=1}^{N} ty_{jt} \leq p_{i} \quad \forall (i, j) \in P \] (5.4.2)

Transitions in strict seniority order can be enforced in many ways, 5.4.3 is my way and 5.4.4 is the way of Yu et al. [23] (their model only used strict seniority order for furloughs):

\[ \sum_{t=1}^{N} ty_{jt} - \sum_{t=1}^{N} ty_{it} \geq 0 \quad \forall (i, j) \in SS \] (5.4.3)

\[ \sum_{t=u}^{N} y_{it} - \sum_{t=u}^{N} y_{i-1t} \geq 0 \quad \forall i \in I_{q}, u \in \{1, 2, \ldots, N\} \] (5.4.4)

Allocation of enough vacation within required periods:

\[ \sum_{t=u}^{w} v_{ht} \geq dv_{hzu} \quad \forall h \in H, (u, w) \in \{1, 2, \ldots, N\}^{2} : u < w \] (5.4.5)

Allocation of enough courses of correct types in the right periods:

\[ \sum_{t=u}^{w} x_{kt} \geq dt_{kzu} \quad \forall k \in K_{r}, (u, w) \in \{1, 2, \ldots, N\}^{2} : u < w \] (5.4.6)

Connecting pilots with the courses given:

\[ \sum_{i \in I_{k}} y_{it} = x_{kt} \quad \forall k \in K_{i}, t \in \{1, 2, \ldots, N\} \] (5.4.7)

Limit the number of participants in each course:

\[ x_{kt} \leq b_{k}a_{kt} \quad \forall k \in K, t \in \{1, 2, \ldots, N\} \] (5.4.8)

Limit the use of resources for each period:

\[ \sum_{k \in K} \sum_{p=0}^{l_{k}} (dp_{kpr}x_{k(t-p)} + dc_{kpr}a_{k(t-p)}) \leq r_{srt} \quad \forall r \in R, t \in \{1, \ldots, N\} \] (5.4.9)
Chapter 5. Mathematic Models

Tracking block-hour shortages:

\[
BI_h - \sum_{i \in O(h)} \sum_{u=1}^{t} u_{ht} y_{iu} + \sum_{i \in N(h)} \sum_{u=1}^{t-l_i} u_{ht} y_{iu} - \sum_{k \in K(h)} \sum_{u=t-l_k}^{t} u_{ht} x_{ku} - u_{ht} v_{ht} \geq B_{ht} - s_{ht} \quad \forall h \in H, t \in \{1, \ldots, N\} \quad (5.4.10)
\]

Variable restrictions:

\[
y_{it} \in \{0, 1\} \quad v_{ht}, x_{kt}, a_{kt}, p_{i} \in \mathbb{Z}^+ \quad s_{ht} \geq 0
\]
Chapter 6

Method

The choice of a model to implement and test ended up with the training and vacation allocation, since the data needed for testing this model was less difficult to obtain than for the other models. This chapter will start with presenting the method for solving and evaluating the training and vacation allocation model. Thereafter the adaptations of the model to the specific case studied are presented and at the end I will shortly refer interested readers to where to read about the implementation and results of the other models that have been implemented by others.

6.1 Solution Technique

For solving the problem the model was first implemented using a modeling language called zimpl (Kosh [11]) and thereafter a computer software called XPRESS-Optimizer [24] was used to solve it. XPRESS uses a sophisticated branch and bound algorithm to solve mixed integer problems such as the training and vacation allocation problem [24]. The solution to the problem, a plan, obtained by this process will in the reminder of the report be called an automatic plan.

Branch and bound is an algorithm for finding an optimal solution by systematic enumeration of candidate solutions. For clearness, assume that the problem to solve is \( z = \min \{ cx : x \in S \} \). The idea behind the branch and bound algorithm is that if \( S = \bigcup_{k=1}^{K} S_k \) is a decomposition of \( S \) into smaller sets and \( z^k = \min \{ cx : x \in S_k \} \), \( k \in \{1, 2, \ldots, K\} \) then \( z = \min_k z^k \). The algorithm can be described by three keywords:

**Branching** Decomposing the feasible region \( S \) into subsets is referred to as branching. The decomposition can be made in many different ways, in most cases a division into two subsets is done (binary branching), but
division into more branches is possible. A typical way to represent this technique of decomposition is via an enumeration tree such as the one found in Figure 6.1. Each subset is referred to as a node.

Bounding Some information on $z^k$ must be obtained but it is not necessary to find $z^k$ explicitly for each node. Bounds on $z^k$ are however needed. These bounds can be found in the same way as for all optimization problems, upper bounds from feasible solutions and lower bounds from duality or relaxation (for the case of minimization). Thereafter one can use that if $\bar{z}^k$ is an upper bound for $z^k$ and $\underline{z}^k$ is a lower bound, then $\bar{z} = \min_k \bar{z}^k$ is an upper bound for $z$ and $\underline{z} = \min_k \underline{z}^k$ is a lower bound.

Pruning Based on the bounds some nodes can be pruned, meaning the investigation of them can be stopped, since it is sure that better solutions can not be found by a continued investigation. A node can be pruned for one of three reasons:

1. Due to infeasibility, that is $S_i = \emptyset$
2. Due to optimality, that is $z^i = \{\min cx : x \in S_i\}$ has been found
3. Due to bounds, that is $\underline{z}^i \geq \bar{z}$.

To use branch and bound one has to decide a couple of things, first how to branch, second how to find bounds for each subproblem, and lastly in which order the nodes shall be investigated.

A common branch and bound version for integer problems, that is usually used in commercial systems, uses linear programming relaxations to provide the bounds, since linear problems are easily solved. The branching is done by choosing a variable that is fractional in the linear programming solution.
and split the feasible set into two around this fractional value, that is if \(x_j\) has the fractional value \(\bar{x}_j\), \(S\) is split in the following way:

\[
S_1 = S \cap \{x : x_j \leq \lfloor \bar{x}_j \rfloor\} \\
S_2 = S \cap \{x : x_j \geq \lceil \bar{x}_j \rceil\}.
\]

A downside with this technique becomes very clear when a sum of binary variables should equal one, that is a sum of the form \(\sum_{j=1}^{k} x_j = 1\). If one of these binary variables, say \(x_i\), has a fractional value in the linear programming solution the branching would create the following subsets: \(S_1 = S \cap \{x : x_i = 0\}\) and \(S_2 = S \cap \{x : x_i = 1\}\). This branching leaves \(k - 1\) possibilities in the \(S_1\) subset and only one in the \(S_2\) subset, leaving an unbalanced tree which is undesirable. A better way, that can be user-defined in many commercial softwares, is to use GUB (generalized upper bound) branching that provides a more balanced division into \(S_1\) and \(S_2\) by splitting \(S\) into the following subsets;

\[
S_1 = S \cap \{x : x_j = 0 \ j = 1, \ldots, r\} \\
S_2 = S \cap \{x : x_j = 0 \ j = r + 1, \ldots, k\},
\]

where \(r = \min\{t : \sum_{j=1}^{t} x_j^* \geq \frac{1}{2}\}\), with \(x_j^*\) being the linear programming solution. A GUB branching is in many cases much more efficient and reduces the number of nodes in the tree significantly. The \(y\) variables in the training and vacation allocation model in Section 5.4 are binary variables with sum one, and GUB branching has therefore been applied to make the solver more efficient.

Ideally the entire tree is investigated until all nodes have been pruned, however this is hardly ever possible when problems are large, since the time it would take would be very long. Therefore some kind of termination rule is needed. One termination rule often used is to stop the algorithm when the relative gap between upper and lower bounds is sufficiently small, i.e.

\[
\frac{UBD - LBD}{LBD} < \epsilon
\]

where a typical value for \(\epsilon\) is 0.01. An other termination rule used is running time, i.e. the time for which the algorithm is allowed to work is limited. We have used time as a termination rule, since time is in real world application often scarce.

The presentation of branch and bound above is a short summary of the descriptions presented by Lundgren et al. [12] and by Wolsey [20].
Chapter 6. Method

6.2 Evaluation

For the evaluation of the model one authentic case from SAS Scandinavian Airlines (presented below) was tested with some different rules. The different rules that were tested concerned the order of transitions:

1. No restrictions on transitions
2. Pay-protection is applied
3. Strict seniority

The rule used by planners were rule 1. Although they tried to keep transitions in seniority order, there were no rules forcing them to do this. When evaluating the potential of an automatic plan compared to a manual plan constructed by planners at SAS Scandinavian Airlines, rule 1 will therefore be used. Comparisons, mainly of different costs, between the manual plan and the automatic plan have been made to obtain some insights into the potential gains and losses. Comparisons have also been made between the rules to see which effect they have on the final result.

6.2.1 Case

Data for testing the model have been provided by SAS Scandinavian Airlines. SAS comprises four different companies: Scandinavian Airlines Denmark, Scandinavian Airlines Norway, Scandinavian Airlines Sweden, and Scandinavian Airlines International. Together these companies used 7 types of aircrafts during 2006-2007. The fleet distribution between the different companies can be found in Figure 6.2.

For our study only Scandinavian Airlines Sweden, in the future referred to as SAS Sweden, has been considered, due to difficulties in achieving data. Out of consideration for Scandinavian Airlines, all costs have been scaled so that only the relationship between costs are presented.

During 2006 SAS Sweden had approximately 1600 employees, of which the average number of pilots during the year was 360, and in 2006 a total of 5.9 million passengers were transported to 45 destinations [26]. The fleet used by SAS Sweden in 2006 comprised 19 Boeing 737, 16 MD-80 and 7 deHavilland Q400 [26]. At SAS Sweden relief pilots are not used, so that pilots are either captains or first officers, which means that the available positions in SAS Sweden are:
In the promotion ladder three more seats are available, namely captain, first officer and relief pilot at A340. The A340 fleet is used by Scandinavian Airlines International and transitions between SAS Sweden and Scandinavian Airlines International is a part of the career path. As for almost all airlines the cost per pilot (mainly the salary cost and taxes) varies with position. In Table 6.1 the average pilot cost per position and week is presented.

Pilots outside SAS Sweden are considered to cost nothing, but this is only true if you consider SAS Sweden to be an independent company. If the interdependence between the different parts of Scandinavian Airlines are taken into consideration, it is easy to see that costs for pilots outside SAS
Sweden just influence another part of Scandinavian Airlines. Unfortunately, the cost for pilots on deHavilland Q400 were not available so these have been estimated.

At Scandinavian Airlines transition planning is made during the spring once a year with a preferential bidding system. The demand used to decide transitions is expectations of the demand at the end of the following year. Pilots awarded a transition must undergo the required training between the 1 of July and the 31 of October the following year. In the transition planning for the year 2007, 498 pilots belonged to SAS Sweden, either before or after the transition, and of these 72 were awarded a new position. The numbers of transitions between different positions are found in Table 6.2.

<table>
<thead>
<tr>
<th>To From</th>
<th>FPQ4</th>
<th>FPM8</th>
<th>FP36</th>
<th>FCQ4</th>
<th>FCM8</th>
<th>FC36</th>
<th>OUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPQ4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FPM8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FP36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCQ4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCM8</td>
<td>11</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>FC36</td>
<td></td>
<td></td>
<td>12</td>
<td></td>
<td></td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>OUT</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>9</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.2: Number of pilots transitioning between different seats

To change position training is needed. Unfortunately I have not been able to get information about which exact courses each pilot needed, but I have however been able to get the exact dates of when they trained. By considering the lengths of their training, and which positions they change between, I have grouped those likely taking the same course and given that course an appropriate name. Some pilots changing both qualification and rank must do the transition training in two steps, which I will refer to as split training, changing qualification first and thereafter rank, with a 3 month long period of flying in between. In the transition planning for 2007 there was 16 pilots in need of split training. There were also 10 pilots that were trained via SAS Norway, and this was also considered as split training. In Table 6.3 number of pilots taking each course, together with length and cost of the
courses are presented. The maximum number of pilots attending a course is 2, since this is the maximum number of pilots in a simulator. Each course requires 1 instructor.

<table>
<thead>
<tr>
<th>Course</th>
<th>Pilots</th>
<th>Length (weeks)</th>
<th>Cost (per course)</th>
<th>Cost (per participant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36 Refresher 1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>36 Refresher 2</td>
<td>5</td>
<td>4</td>
<td>1149</td>
<td>198</td>
</tr>
<tr>
<td>36 Refresher 3</td>
<td>10</td>
<td>2</td>
<td>226</td>
<td>67</td>
</tr>
<tr>
<td>36 Conversion</td>
<td>2</td>
<td>6</td>
<td>1385</td>
<td>330</td>
</tr>
<tr>
<td>36 Commander 1</td>
<td>2</td>
<td>1</td>
<td>311</td>
<td>129</td>
</tr>
<tr>
<td>36 Commander 2</td>
<td>7</td>
<td>2</td>
<td>311</td>
<td>129</td>
</tr>
<tr>
<td>M8 Conversion</td>
<td>13</td>
<td>7</td>
<td>981</td>
<td>425</td>
</tr>
<tr>
<td>M8 Commander 1</td>
<td>15</td>
<td>2</td>
<td>268</td>
<td>129</td>
</tr>
<tr>
<td>M8 Commander 2</td>
<td>5</td>
<td>3</td>
<td>268</td>
<td>129</td>
</tr>
<tr>
<td>M8 Refresher</td>
<td>9</td>
<td>5</td>
<td>939</td>
<td>286</td>
</tr>
<tr>
<td>Out</td>
<td>29</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.3: Demand, length and cost of initial courses. Pilots undergoing split training requires two of these courses.

Due to a deal between Scandinavian Airlines and the pilot union, some pilots awarded a captain seat had longer time to complete their training, with a due date of 30 of June 2008 instead of 31 of October 2007. To deal with this, since I only plan the ordinary transition period, I chose to only plan the training that these pilots had performed before 31 of December 2007. All pilots had by then been through at least the first step of their training, but 15 pilots had the second part of their split training left.

The pilots also go through recurrent training, at SAS each pilot needs one training session in a simulator once every 6 months, called OPC or PC, and one training on security, called PGT, each year. All pilots have a due month when their OPC/PC must be made, or they will be grounded; they can do the training in their due month or in the two prior months. The maximum number of pilots in a OPC/PC course is 2 and each course requires 1 instructor. The two students should be one captain and one first officer for the fleet type in question, it is however possible to have two captains but this results in a higher cost. The PGT is joint for flight deck and cabin crew, each course takes around 20 students, and no flying instructor is needed. In Table 6.4 the total numbers of pilots attending the courses and course costs are presented.
Table 6.4: Recurrent courses. Prices are per course regardless of the number of participants.

A pilot at SAS Sweden has the right to 42 vacation days per year, i.e. 6 weeks. The vacation year extends from 1 of June to the last of May. In addition to the vacation days, 8 days called F7-days are provided as vacation days to compensate for work done by the pilots on their free time. During the summer (June 1 to August 31) each pilot has the right to 3 weeks of vacation. The summer vacation at SAS Sweden follows a rotating schedule that determines when each crew member will receive his or her vacation, this system has however not been implemented since it reduces many levels of freedom for both crew and planners. The total numbers of weeks to distribute for the periods are presented in Table 6.5.

Table 6.5: Required number of vacation weeks in different periods

<table>
<thead>
<tr>
<th>Period</th>
<th>Position</th>
<th>FPQ4</th>
<th>FPM8</th>
<th>FP36</th>
<th>FCQ4</th>
<th>FCM8</th>
<th>FC36</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-69</td>
<td></td>
<td>401</td>
<td>453</td>
<td>936</td>
<td>425</td>
<td>1140</td>
<td>1220</td>
</tr>
<tr>
<td>1-9 (summer)</td>
<td></td>
<td>75</td>
<td>78</td>
<td>182</td>
<td>76</td>
<td>174</td>
<td>215</td>
</tr>
<tr>
<td>49-61 (summer)</td>
<td></td>
<td>100</td>
<td>112</td>
<td>223</td>
<td>110</td>
<td>325</td>
<td>319</td>
</tr>
<tr>
<td>1-48</td>
<td></td>
<td>261</td>
<td>297</td>
<td>628</td>
<td>271</td>
<td>682</td>
<td>773</td>
</tr>
<tr>
<td>49-69</td>
<td></td>
<td>140</td>
<td>157</td>
<td>308</td>
<td>154</td>
<td>458</td>
<td>447</td>
</tr>
</tbody>
</table>

Scandinavian Airlines uses the production day measurement when estimating supply and demand of manpower. The data received from SAS of these estimates were monthly averages and to suit the model, which applies weeks, an assumption was made that the monthly average is a good estimate of the weekly averages. The estimates of demand and supply of manpower for the planning period are presented in Figure 6.3. A rule that is important to take into account when considering the balance between demand and supply, is that at Scandinavian Airlines pilots are allowed to fly below rank, which means that captains can fly as first officers.
When lacking manpower one possibility at SAS is to buy back free days\(^1\). This possibility is often used instead of keeping many pilots on standby. The cost of buying back a free day is approximately 100, and this cost is used as an estimate of the shortage cost. The maximum number of days possible to buy back has been estimated to be 30% of the available free days.

---

\(^1\)A free day is a day when the crew member is scheduled as off-duty, like Saturdays and Sundays at ordinary work places.
6.3 Model Adaptations

The model presented in Section 5.4 is general and needs to be adapted to the specific rules of the airline using it. To be able to use the model for the case presented above (Section 6.2.1) the following changes must be done:

- Since training only takes away production capacity when a crew member is not flying we choose not to include the LIFUS\textsuperscript{2} time in the time for the training. Since however the entire training has to be made before the expiration date a variable \( l_{fi} \) is added which is the LIFUS time for pilot \( i \) and the constraint:

\[
\sum_{t=(N-l_i-l_{fi})}^{N} y_{it} = 0 \quad \forall i \in I
\]

- The extra cost resulting from two captains taking an OPC/PC course together is managed by:

  1. adding the variable \( \beta_{kt} \) which states the number of courses of type \( k \) in period \( t \) that have two captains
  2. adding the parameter \( c_{\beta_k} \) for the extra cost for course \( k \)
  3. adding an index \( \alpha \) to the variable \( x \), that separates captains (FC) from first officers (FP). For initial courses all pilots taking the course are considered to be captains. In most old constraints I summerize over this new index
  4. adding the term \( \sum_{k \in K_i} \sum_{t=1}^{N} c_{\beta_k} \times \beta_{kt} \) to the objective function
  5. adding the the constraint

\[
x_{kt}^{FC} - x_{kt}^{FP} = \beta_{kt} \quad \forall k \in K_r, t \in \{1, 2, \ldots, N\}
\]

- Taking split training into account requires some changes:

  1. adding a set \( I_r \) for all pilots going through split training
  2. adding a set \( I_{zk} \) for all pilots taking course \( k \) as step 2. For pilots going through split training they also belong to the set \( I_k \) representing their training in step 1.
  3. adding the sets \( L(h) \) for all pilots whose position after both steps is \( h \)

\textsuperscript{2}LIFUS is a commonly used name for in-flight training.
4. a pilot $i$ in $I_x$ belongs to the set $N(h)$, where $h$ is the pilot’s position between step 1 and 2 of training

5. letting $l_i$ be the length of step 1 of the training for pilots in $I_x$

6. adding the parameter $l_i^2$ for the length of step 2 of the training, and a parameter $lf_i^2$ for the length of the LIFUS training of step 2.

7. adding the variable $\mu_{it}$ that is 1 if pilot $i$ starts training step 2 in time period $t$

8. adding a constraint so that all that are supposed to go through step 2 of their training will actually do so:

$$\sum_{t=1}^{N} \mu_{it} = 1 \quad \forall i \in I_x$$  \hspace{1cm} (6.3.3)

9. adding the following constraints to make the period between trainings long enough:

$$\sum_{t=1}^{u+lf_i+li} \mu_{it} \leq \sum_{t=1}^{u} y_{it} \quad \forall i \in I_x, u \in \{1, 2, \ldots, N\}$$  \hspace{1cm} (6.3.4)

$$\sum_{t=1}^{12+lf_i+li} y_{it} = 0 \quad \forall i \in I_x$$  \hspace{1cm} (6.3.5)

10. adding a constraint to make sure that training is done on time:

$$\sum_{N-l_i^2-lf_i^2}^{N} \mu_{it} = 0 \quad \forall i \in I_x$$  \hspace{1cm} (6.3.6)

11. changing constraint 5.4.7 to include the courses in step 2:

$$\sum_{i \in I_x} y_{it} + \sum_{i \in I_x} \mu_{it} = x_{kt} \quad \forall k \in K_i, t \in \{1, 2, \ldots, N\}$$  \hspace{1cm} (6.3.7)

- Split training and the rule allowing below-rank flying require changing
constraint 5.4.10 to this:

\[
\begin{align*}
\sum_{h \in H_a} & \left( B I_h - \sum_{i \in O(h)} \sum_{u=1}^{t} u_{ht} y_{iu} + \sum_{i \in N(h)} \sum_{u=1}^{t-l_i} u_{ht} y_{iu} - \right. \\
& \left. - \sum_{i \in N(h) \cap I_x} \sum_{u=1}^{t} u_{ht} \mu_{iu} + \sum_{i \in L(h)} \sum_{u=1}^{t-l_i} u_{ht} \mu_{iu} - \right. \\
& \left. - \sum_{k \in K_r(h)} \sum_{u=t-l_k}^{t} \sum_{f \in \{FC\} \text{ if } |H_a|=1} u_{ht} x_{ku}^f - u_{ht} v_{ht} \right) \\
& \geq \sum_{h \in H_a} (B_{ht} - s_{ht}) \quad \forall H_a \in H^*, t \in \{1, \ldots, N\} \quad (6.3.8)
\end{align*}
\]

where \( H^* \) is the union of all sets containing exactly one captain position and one set per fleet type having both first officer and captain.

In Appendix A the entire model as it has been implemented is presented.

### 6.4 Methods used by Others

Since research into manpower planning for airlines has been scarce there have been only few attempts in finding methods to solve the resulting problems. First was Verbeek [18] with his decision support system for KLM. As mentioned above his system only used heuristics to solve the problems’ and unfortunately these heuristics have not been presented. No results from the implementation at KLM has to my knowledge been published, but after using the system for approximately two months the planners at KLM were enthusiastic about many of the features.

The model for reserve crew planning has been tested on historical data from a large U.S. carrier (Sohoni et al. [16]), but has to my knowledge not been implemented at any airline. The model is solved with the commercial software ILOG CPLEX 7.0, and the results were used to estimate a function for the value of reserve crew members to use when making long-term manpower decisions (Sohoni et al. [16]). No information on possible cost savings using the model were presented.

The system that has been tested the most and implemented at Continental Airlines is the Crew ResourceSolver. As mentioned in Section 4.2 it uses advanced optimization to solve the different manpower planning problems,
but it is only for the training allocation problem and the course scheduling problem that the techniques have been published. Below I describe the solution technique which can be found in [22] and [23].

The training allocation problem is modeled in a way similar to mine and thereafter solved in two steps. In step one the linear programming relaxation is solved using a high block-hour shortage cost, to get an estimate of the best block-hour shortage that can be achieved and to find the cost coefficient to be used in the mixed-integer program in order to ensure that block-hour shortage will be near the minimum. In step two the mixed-integer problem is solved, with the shortage cost decided in step one, using commercial software libraries with predetermined ordering to direct the mixed-integer program branching.

Using the result from the training allocation as input the system can solve the course scheduling problem using a specially designed technique. First a schedule that decides which part of which course is to be performed at which day is produced. Thereafter each activity is assigned a specific time during the day to which it was assigned in the first step, creating a hourly schedule for pilots and resources. The daily schedule is created using a branch and bound procedure over subsets of the courses to schedule, and then applying a rolling horizon approach to cover all courses. Each level in the branch and bound tree represents a calendar day and each node at a specific level, say $t$, represents a partial schedule where all days up until day $t$ have been scheduled. The branches are produced by scheduling the next day, and each node therefore has many branches. This is only a very brief description of the procedure and a much more detailed description can be found in the article published by Qi et al. in 2004 [17]. The assignment of activities to specific resources to create a detailed hourly schedule is made by solving a mixed-integer programming assignment model.

Continental Airlines uses the system and estimates that they save more than $10 million annually by creating their training plans with the system. Comparisons between two automatic training plans and a manual one showed that savings for one automatic training plan was approximately $7.5 millions or 15%.
Chapter 7

Results

In this chapter the results from using the model on the SAS case study are presented. First comparisons between automatic and manual solutions are presented and thereafter the impact of different transition rules on the costs.

7.1 Automatic versus Manual Solution

The model for the SAS case study presented in Section 6.2.1 has approximately 11 thousands variables and 119 thousands constraints. As mentioned in section 6.1 the problem was solved with XPRESS. The solution time was limited to 18 hours since more time seems to improve the result very little, and the gap between the upper and lower bounds by then is relatively small. How the upper and lower bounds change during the branch and bound search is presented in Figure 7.1. As one can see most improvements happen during the first couple of hours, therefore the runs with some changes to the rules are limited to 2.5 hours. One can also see that the gap between the upper and lower bounds is quit small, at the end it is only 0.61%.

The manual plan constructed by manpower planners used for comparisons is based on their planned values for everything except transition dates, these are based on when the actual transitions took place since planned values have not been available. It is however believed to be very few differences between the plan and the outcome for transitions, since booking of the transition training has to be done a long time in advance. The costs calculated for the plan are based on the costs from Section 6.2.1 and can therefore only be seen as an estimate of the actual cost, since for example salaries are averages per position and not exact per pilot.

In Table 7.1 costs for both the plan made by the SAS manpower planners and the automatic plan are presented. From the figures one can conclude that
there is a gain of almost 18.4% using my models and that most of the gain comes from lower shortage costs. That shortage cost is so large for the manual solution seems a little bit strange, however almost all of the shortage comes from a lack of manpower at MD-80 during week 1 to 26, and the average shortage during these weeks is 11.8 pilots. This means that SAS might have planned for this shortage in a way that is unknown to us. Therefore this part of the cost might be overestimated. A run where a shortage of at most 10 pilots at MD-80 during weeks 1–26 is allowed without cost was therefore done to see how this would affect the solution. The result of this run is presented in Table 7.2. As one can see the automatic solution is much cheaper even when shortage costs are not considered, and almost 10% of the transition costs could be saved if the automatic solution was applied.
### 7.1. Automatic versus Manual Solution

<table>
<thead>
<tr>
<th></th>
<th>Shortage allowed at MD-80</th>
<th>Manual solution, shortage allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>727,234</td>
<td>833,188</td>
</tr>
<tr>
<td><strong>Transition costs</strong></td>
<td>595,122</td>
<td>656,659</td>
</tr>
<tr>
<td><strong>Course costs</strong></td>
<td>127,172</td>
<td>127,844</td>
</tr>
<tr>
<td><strong>Shortage costs</strong></td>
<td>4,940</td>
<td>48,685</td>
</tr>
</tbody>
</table>

Table 7.2: Costs for the solution where a shortage of 10 pilots at MD-80 were allowed without cost during week 1–26

When presenting the case in Section 6.2.1 I made the assumption that pilots used outside of SAS Sweden cost nothing. This might result in moving cost from SAS Sweden to other parts of Scandinavian Airlines. Since almost all moves of pilots to other parts of Scandinavian Airlines is to Scandinavian Airlines International (below referred to as SAS Intercont), the major impact of these transfers of costs would be to them. To investigate whether this has happened in my solution, the total numbers of weeks that pilots spend at different positions at SAS Intercont, in both the manual and the automatic solution (still allowing shortage), have been counted and the result is presented in Table 7.3. As can be seen there are significant differences, mainly that the number of weeks at SAS Intercont has increased. The decrease for relief pilots can be compensated by first pilots or captains flying below rank. The total difference in weeks is 321, which corresponds to around 76,700 units in salaries. An even more worrying fact was however that the placement of weeks was a bit different, which might lead to shortage some weeks and excess other weeks. Two runs with locking of pilots to SAS Intercont in different ways have therefore been done to see how the solution would be affected by taking SAS Intercont into account. In the first of these runs the total number of weeks at each position at SAS Intercont was forced to be the same as in the manual solution, and in the second all transfers to and

<table>
<thead>
<tr>
<th>Position</th>
<th>Manual solution</th>
<th>Automatic solution</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relief pilot at A330/340</td>
<td>526</td>
<td>461</td>
<td>-65</td>
</tr>
<tr>
<td>First officer at A330/340</td>
<td>675</td>
<td>863</td>
<td>188</td>
</tr>
<tr>
<td>Captain at A330/340</td>
<td>862</td>
<td>1060</td>
<td>198</td>
</tr>
</tbody>
</table>

Table 7.3: Number of weeks spent by transitioning pilots at different positions at SAS Intercont
from SAS Intercont were locked to exactly the same period as in the manual solution. Both runs allowed for shortage in the same way as the solutions presented in Table 7.2. The results from these runs are presented in Table 7.4

<table>
<thead>
<tr>
<th></th>
<th>Locked weeks</th>
<th>Locked transfers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (Upper bound)</td>
<td>764550</td>
<td>833032</td>
</tr>
<tr>
<td>Lower bound</td>
<td>756255</td>
<td>832153</td>
</tr>
<tr>
<td>Transition costs</td>
<td>636786</td>
<td>656463</td>
</tr>
<tr>
<td>Course costs</td>
<td>126344</td>
<td>125719</td>
</tr>
<tr>
<td>Shortage costs</td>
<td>1420</td>
<td>50850</td>
</tr>
</tbody>
</table>

Table 7.4: Comparison of costs

As one can see the costs increase, especially when transfers are locked. The locked weeks solution is approximately 8% cheaper than the manual, but the solution with locked transfers costs almost the same. That the locked transfer solution is not performing better than the manual is mainly because the number of remaining decisions to influence are few. The locked weeks solution does not move any salaries to or from SAS Intercont, so the only costs that might be moved are shortage costs and some course costs, and this implies that if the entire Scandinavian Airline was considered at the same time, cost would probably not rise much.

A concern I had during the implementation was that the allocation of vacation would become very unbalanced between weeks. To investigate this concern the vacation allocation for the automatic solution with some shortage allowed was studied. In Figure 7.2 the allocation of vacatoin for MD-80 is shown, the allocations for the other fleet types are very similar. As can be seen the allocation is very unbalanced if considering a specific position, however if only fleet type is considered the allocation seems to be far more balanced. The reason for this is that the block-hour shortage for first officers depends on supply of both first officers and captains, since captains can fly below rank. This implies that vacation can probably be moved between first officers and captains without any major influence on the objective value. The allocation is of course not totally balanced throughout the entire period, but the irregularities are small enough not to aggravate planning, and the two major peaks are for the two summer periods where much vacation is required.

Another concern regarding vacation was that not implementing the rolling schedule used at SAS would give an unfair advantage, since the manual solution uses a rolling schedule. To investigate this concern comparisons
between the manual plan and the automatic with shortage allowed were
done for the summers. In Figure 7.3 the total vacation allocation for MD-80
during summer number two (weeks 49–61) for the automatic solution, the
manual solution, and the actual outcome for SAS Sweden are presented. The
allocation is very similar for other fleets and summers. As can be seen the
automatic solution allocated more vacation during almost all of these weeks
than both the manual solution (budget) and the actual outcome did, so not
implementing the rolling schedule does not seem to be a weakness in reality.

Figure 7.3: Vacation allocation during summer 2
7.2 Different Transition Rules

In Section 6.2 the three tested transition rules were presented. In Table 7.5 the results for these tests are presented.

<table>
<thead>
<tr>
<th></th>
<th>Automatic solution</th>
<th>With pay-protection</th>
<th>With strict seniority¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>818 161</td>
<td>862 131</td>
<td>883 150</td>
</tr>
<tr>
<td>Lower bound</td>
<td>813 231</td>
<td>849 035</td>
<td>863 113</td>
</tr>
<tr>
<td>Gap</td>
<td>0.61%</td>
<td>1.54%</td>
<td>2.32%</td>
</tr>
<tr>
<td>Transition costs</td>
<td>688 634</td>
<td>714 725</td>
<td>743 154</td>
</tr>
<tr>
<td>Course costs</td>
<td>126 017</td>
<td>126 486</td>
<td>132 096</td>
</tr>
<tr>
<td>Shortage costs</td>
<td>3 510</td>
<td>6 270</td>
<td>7 900</td>
</tr>
<tr>
<td>Pay-protection</td>
<td></td>
<td>14 650</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.5: Comparison of costs

As one can see all types of costs rise when a stricter transition rule is applied, and this is not at all surprising since a stricter transition rule is a restriction of the feasible region. One fact worth noting is that even when the strict seniority rule is applied the total cost is 11.9% lower than for the manual solution. The most interesting fact however is to compare pay-protection with strict seniority, since airlines often use strict seniority because pay-protection to them seem troublesome. As seen in Table 7.5, using pay-protection instead of strict seniority as transition rule results in a saving of around 2%, and pay-protection is therefore probably well worth the extra work it might cause.

¹Due to a bug in XPRESS the branch and bound stopped after 1.2 hours
Chapter 8

Discussion

The purpose of this thesis was twofold. The first was to provide an overview of some of the problems facing manpower planners. As we have seen there is a variety of different problems that manpower planners have to deal with in different ways. Some require making plans of different types while others require investigations of what will be the effects of different decisions. Few automatic decision tools are available to assist manpower planners in their work and the goal for manpower planners therefore often becomes to find a solution that complies with rules and regulations rather then finding a solution that is optimal in some sense. My overview gives insight into what the problems are and hopefully this will lead to the development of some helping tools.

The second part of the purpose was to investigate the potential of using optimization methodology for one of the problems described. The problem chosen was the allocation of training and vacation, and for this problem a model that produces plans with low total costs has been suggested. The results show a potential for savings around 10%, the only test that did not show potential for savings close to this figure was the one with all transfers to and from SAS Intercont locked. This test did however depend heavily on the manual solution, and could influence very few decisions. One factor that might result in lower savings is that transition costs are calculated from average salaries, and the difference between average salaries for positions are probably greater than the change in salary that a pilot gets when transferring, since salaries besides position often depend on age or seniority. My guess is that savings from using the model is at least 5% but could be as much as 20%. The higher number is supported by the fact that the model by Yu et al. that was presented in Section 6.4 yielded savings around 15%. Their model does on one hand consider the detail course schedule as well, but does not allocate vacation or recurrent courses, so my model has both weaknesses and
advantages compared to theirs.

In excess of saving money the model save a lot of time for the planners, in only a couple of hours a plan can be produced instead of working several days on the plan. This saves time but also make it possible to evaluate different scenarios easily to better understand how costs are affected by choices of the planners.

The model which have been built is quite easy to adapt to different rules and circumstances that might exist in an airline. The most commonly used transition rules have been implemented and tested, sometimes the rules are used in combination for different groups but this does not cause a problem for the model. Many vacation rules and regulations can be implemented by constraints of the form 5.4.5 that are already used, even the rolling summer schedule that Scandinavian Airline uses could be implemented with constraints of this type. For our test we decided not to include the in-flight training (LIFUS); the model is however constructed to be able to handle also this aspect. Another example of a possible adaptation is that for most airlines, course activities that require a simulator require two pilots even though there might be only one student. A regular pilot will then be taken from production to fill one of the seats in the simulator, and this could be implemented with only a few changes. A last example of possible adaptations that can be made are the addition of training for instructors, since they go trough training in a way very similar to that for ordinary pilots, and the training of an instructor could be modeled in the same way as for a transitioning pilot.

There are of course some possible expansions of the model and solution technique. An obvious one is to try to customize the solution technique to the problem under consideration instead of using standardized software, in order to make the gap between the upper and lower bounds even smaller. Another one is to try to integrate course scheduling and/or transition planning into the model in order to try to find a global optimum instead of two or three suboptima.

An expansion of the model, that I wanted to do but did not have the time for, is to take pilots’ wishes for vacation into account. The idea would then be to solve the problem in two steps, the first step being the same approach as that used in this thesis. Thereafter in a second step lock all transitions ($y$ variables) to the period decided in the first step one solving the problem again, with a constraint that limits the old objective function to a value that is acceptably much above the one from the first step step and then maximize pilot satisfaction with the a new objective function. This would provide planners with a plan that is good in their eyes, since it is cheap and pilots, would be content since they would easier get the vacation they wanted.

To sum up, there are expansions and adaptations that might make the
model better, but it is my belief that the model could in many cases be used as it is, generating satisfactory results.
Bibliography


Appendix A

Entire Model for Training and Vacation at SAS

Sets

\[ H = \text{Available positions} \]
\[ H^\ast = \{ \{\text{FCM8}\}, \{\text{FPM8,FCM8}\}, \{\text{FC36}\}, \} \]
\[ \{\text{FP36,FC36}\}, \{\text{FCQ4}\}, \{\text{FPQ4,FCQ4}\} \}\]
\[ K = \text{courses} \]
\[ K_i = \text{initial courses} \]
\[ K_r = \text{recurrent courses} \]
\[ K_r(h) = \text{recurrent courses for position } h \]
\[ I = \text{pilots to be transferred or released} \]
\[ I_x = \text{pilots going through split training} \]
\[ I_k = \text{pilots who need course } k \]
\[ I_x k = \text{pilots who need course } k \text{ as step 2 of their training} \]
\[ I_q = \text{pilots who will be let go, sorted in backward seniority order} \]
\[ O(h) = \text{pilots whose initial position is } h \]
\[ N(h) = \text{pilots whose future position is } h \]
\[ L(h) = \text{pilots whose position after step 2 of training is } h \]
\[ P = \text{pair of pilots } (i, j) \text{ where pilot } i \text{ is pay protect by pilot } j \]
\[ SS = \text{pair of pilots } (i, j) \text{ where pilot } i \text{ by seniority rules must move before pilot } j \]

Holm, 2008.
$R = \text{training resources}$

**Parameters**

$N = \text{number of time periods}$
$BI_h = \text{initial supply of block-hours for position } h \text{ in period } t$
$B_{ht} = \text{demand of block-hours for position } h \text{ in period } t$
$u_{ht} = \text{pilot utilization per position } h \text{ in period } t$

$rs_{rt} = \text{supply of resource } r \text{ in period } t$
$dp_{kp} = \text{demand of resource } r \text{ per person, } p \text{ periods into course } k$
$dc_{kp} = \text{demand of resource } r \text{ per course, } p \text{ periods into course } k$

$dv_{h} = \text{vacation demand for position } h \text{ between periods } t \text{ and } u$
$dt_{kt} = \text{demand for recurrent courses of type } k \text{ between periods } t \text{ and } u$

$l_i = \text{length of course for pilot } i$
$l_i^2 = \text{length of part two of training for pilot } i$
$lf_i = \text{length of LIFUS training for pilot } i$
$lf_i^2 = \text{length of LIFUS in part 2 of training for pilot } i$

$l_k = \text{length of course } k$
$b_k = \text{maximal number of participants in course } k$

$ct_{it} = \text{cost if pilot } i \text{ is transferred or released in period } t$
$cm_i = \text{pay-protection cost per period for pilot } i$
$cc_k = \text{cost for holding a course of type } k$
$cβ_k = \text{extra cost if two captains take course } k \text{ together}$
$cr_k = \text{cost per participant of course } k \in Kr$
$dl_h = \text{cost per block-hour shortage in position } h$

**Variables**

$y_{it} = 1 \text{ if pilot } i \text{ is transferred or released in period } t$
$μ_{it} = 1 \text{ if pilot } i \text{ start step 2 of his/her transfer in period } t$
\(x_{kt}^{\alpha}\) = number of pilots starting course \(k\) in period \(t\) with rank \(\alpha^1\)

\(a_{kt}\) = number of courses of type \(k\) starting in period \(t\)

\(\beta_{kt}\) = number of courses of type \(k\) starting in period \(t\) with two captains

\(v_{ht}\) = number of pilots at position \(h\) with vacation in period \(t\)

\(p_{i}\) = number of periods with pay-protection for pilot \(i\)

\(s_{ht}\) = block-hour shortage for position \(h\) in period \(t\)

Objective function

\[
\min \left( \sum_{k \in K} \sum_{t=1}^{N} \sum_{f \in \{FC, FP\}} (cc_k a_{kt} + cr_k x_{kt}^f) + \sum_{k \in K} \sum_{t=1}^{N} c_{\beta_k} \beta_{kt} + \sum_{i \in I} \sum_{t=1}^{N} cl_{ht} y_{ht} + \sum_{i \in I} cm_i p_i + \sum_{h \in H} \sum_{t=1}^{N} cl_{ht} s_{ht} \right)
\]

Subject to:

All pilots awarded a transition must be moved:

\[
\sum_{t=1}^{N} y_{it} = 1 \quad \forall i \in I \quad (A.0.1)
\]

\[
\sum_{t=1}^{N} \mu_{it} = 1 \quad \forall i \in I_x \quad (A.0.2)
\]

Training and LIFUS must be done in time

\[
\sum_{t=(N-l_i-l_{f_i})}^{N} y_{it} = 0 \quad \forall i \in I \quad (A.0.3)
\]

\[
\sum_{N-l_i-l_{f_i}}^{N} \mu_{it} = 0 \quad \forall i \in I_x \quad (A.0.4)
\]

\(^1\)For initial courses all pilots are considered captains locking \(x_{kt}^{FP}\) to zero
The time between two trainings need to be long enough:

$$\sum_{t=1}^{u+12+l_i} \mu_{it} \leq \sum_{t=1}^{u} y_{it} \quad \forall i \in I_x, u \in \{1, 2, \ldots, N\}$$

(A.0.5)

$$\sum_{t=1}^{12+l_i} y_{it} = 0 \quad \forall i \in I_x$$

(A.0.6)

Tracking of the number of periods with pay-protection for each pilot:

$$\sum_{t=1}^{N} t y_{it} - \sum_{t=1}^{N} t y_{jt} \leq p_i \quad \forall (i, j) \in P$$

(A.0.7)

Forcing transition to follow strict seniority order:

$$\sum_{t=1}^{N} t y_{jt} - \sum_{t=1}^{N} t y_{it} \geq 0 \quad \forall (i, j) \in SS$$

(A.0.8)

Allocation of enough vacation within required periods:

$$\sum_{t=u}^{w} v_{ht} \geq d v_{hw} \quad \forall h \in H, (u, w) \in \{1, 2, \ldots, N\}^2 : u < w$$

(A.0.9)

Allocation of enough courses of correct types in the right periods:

$$\sum_{t=u}^{w} \sum_{f \in \{FC, FP\}} x_{kt}^f \geq d b_{kw} \quad \forall k \in K_r, (u, w) \in \{1, 2, \ldots, N\}^2 : u < w$$

(A.0.10)

Connecting pilots with the courses given:

$$\sum_{i \in I_k} y_{it} + \sum_{i \in I_{sk}} = x_{kt}^{FC} \quad \forall k \in K_i, t \in \{1, 2, \ldots, N\}$$

(A.0.11)

Limit the number of participants in each course:

$$\sum_{f \in \{FC, FP\}} x_{kt}^f \leq b_k a_{kt} \quad \forall k \in K, t \in \{1, 2, \ldots, N\}$$

(A.0.12)
Calculate number of captains taking a course together

\[ x_{kt}^{FC} - x_{kt}^{FP} = \beta_{kti} \quad \forall k \in K_r, t \in \{1, 2, \ldots, N\} \]  

(A.0.13)

Limit the use of resources for each period:

\[ \sum_{k \in K} \sum_{p=0}^{l_k} \sum_{f \in \{FC, FP\}} \left( dp_{kpr} x_{k(t-p)}^f + dc_{kpr} a_{k(t-p)} \right) \leq r s_{rt} \quad \forall r \in R, t \in \{1, \ldots, N\} \]  

(A.0.14)

Tracking block-hour shortages:

\[
\begin{align*}
\sum_{h \in H_a} \left( & BI_h - \sum_{i \in O(h)} \sum_{u=1}^{t} u_{ht} y_{iu} + \sum_{i \in N(h)} \sum_{u=1}^{t-l_i} u_{ht} y_{iu} - \\
& - \sum_{i \in N(h) \cap I_{au}} \sum_{u=1}^{t} u_{ht} \mu_{iu} + \sum_{u \in \{FC\}} \sum_{i \in L(h)} \sum_{u=1}^{t-l_i} u_{ht} \mu_{iu} - \\
& - \sum_{k \in K_r(h)} \sum_{u=t-l_k}^{t} \sum_{f \in \{FC\}} \text{if } |H_a|=1 \text{ or } |H_a|=2 \left( u_{ht} x_{ku}^f - u_{ht} v_{ht} \right) \right) \\
\geq \sum_{h \in H_a} (B_{ht} - s_{ht}) \quad \forall H_a \in H^*, t \in \{1, \ldots, N\} \]  

(A.0.15)

Variable restrictions:

\[ y_{it} \in \{0, 1\} \quad v_{ht}, x_{kt}^f, a_{kt}, p_i \in \mathbb{Z}_+ \quad s_{ht} \geq 0 \]
Copyright

The publishers will keep this document online on the Internet - or its possible replacement - for a period of 25 years from the date of publication barring exceptional circumstances. The online availability of the document implies a permanent permission for anyone to read, to download, to print out single copies for your own use and to use it unchanged for any non-commercial research and educational purpose. Subsequent transfers of copyright cannot revoke this permission. All other uses of the document are conditional on the consent of the copyright owner. The publisher has taken technical and administrative measures to assure authenticity, security and accessibility. According to intellectual property law the author has the right to be mentioned when his/her work is accessed as described above and to be protected against infringement. For additional information about the Linköping University Electronic Press and its procedures for publication and for assurance of document integrity, please refer to its WWW home page: http://www.ep.liu.se/

Upphovsrätt

Detta dokument hålls tillgängligt på Internet - eller dess framtida ersättare - under 25 år från publiceringsdatum under förutsättning att inga extraordinära omständigheter uppstår. Tillgång till dokumentet innebär tillstånd för var och en att läsa, ladda ner, skriva ut enstaka kopior för enskilt bruk och att använda det oförändrat för ickekommersiell forskning och för undervisning. Överföring av upphovsrätten vid en senare tidpunkt kan inte upphäva detta tillstånd. All annan användning av dokumentet kräver upphovsmannens medgivande. För att garantera äktheten, säkerheten och tillgängligheten finns det lösningar av teknisk och administrativ art. Upphovsmannens ideella rätt innefattar rätt att bli nämnad som upphovsman i den omfattning som god sed kräver vid användning av dokumentet på ovan beskrivna sätt samt skydd mot att dokumentet ändras eller presenteras i sådan form eller i sådant sammanhang som är kränkande för upphovsmannens litterära eller konstnärliga anseende eller egenart. För ytterligare information om Linköping University Electronic Press se förlagets hemsida http://www.ep.liu.se/

© 2008, Åsa Holm