SUMMARY (CONDENSED)

AE4423 – AIRLINE PLANNING & OPTIMIZATION

CONTENTS

This condensed summary is based on a larger summary of this course, by the same author. To shrink it down, examples have been omitted, as well as mathematical models.

The original summary, and therefore also this document, is based on

- Course outline 2nd Quarter 2015 – 2016 AE4423 *Airline Planning & Optimization* (2015 – 2016) by Santos and Hartjes, Delft University of Technology.
- *The Global Airline Industry* (2009), 3rd edition, by Belobaba, Odoni and Barnhart (Eds.), John Wiley & Sons, ch. 1 – 9, 15;
- Lecture slides AE4423 *Airline Planning & Optimization* (2015 – 2016) by Santos and Hartjes, Delft University of Technology.
- Lecture slides *Aircraft Leasing* (2015/12/03) by Van Hövell tot Westervlier, Aviation Indepenent Consulting.
- Lecture slides *Robust Airline Scheduling* (2015/12/10) by Clarke, Georgia Institute of Technology.

Information is structured based on lecture contents, as made public by the course outline. When available, book summaries are quoted at the end of the first lecture referring to a chapter.

LECTURE 1: AIRLINE CONTEXT AND PLANNING FRAMEWORK

Airline industry (characteristics and trends), regulations, freedoms of the air, key performance indicators, airline planning process. Book chapters 1 and 2.

KEY CHARACTERISTICS AND PARADOX

Within the air transportation chain, airlines are the ones that makes the lowest profit. Contributing factors to that are underlined in the below list of key characteristics.

- Global industry
- Continuous growth
- Competitive sector
- Cyclical industry (depends on and influences larger economic trends, air travel growth is roughly twice the growth in GDP; seasonality)
- Long aircraft deliverable times (*makes planning hard, especially when faced with cyclical characteristics of industry*)
- Perishable supply (*if a flight leaves half empty, you cannot sell the empty seats a later day*)
- Technology oriented
- Capital intensive
- Marginal profitability
- High dependability on fuel prices
- Highly regulated (economically, environmentally and safety-wise)
- Government ownership
- Labour intensive
- Oligopolistic market (in terms of operators on route and suppliers, such as aircraft OEMs, GDS manufacturers, …)
- Safe(st) transport mode

TRENDS

- Deregulation
- Liberalization
- Changing business models
- Industry ‘centre of gravity’ shifts from US/EU towards the Middle East and Asia.

CHALLENGES

- Achieving sustaining airline profitability (reduce cyclical nature).
- Ensuring safety and security, while keeping good levels of service.
- Increasing operations reliability (increase resilience, schedule coordination at hubs).
- Forecasting.

AIR SERVICE AGREEMENTS / FREEDOMS OF THE AIR

1. Right to fly over another state B without landing.
2. Right to land in another state B for technical reasons.
3. Right to enplane revenue traffic from home state A to other state B.
4. Right to enplane revenue traffic from other state B to home state A.
5. Right to enplane revenue traffic from other state B to other state B as part of the continuation of a flight originating/terminating in home state A.
6. Right to transport revenue traffic between other states B and C connecting in home state A.
7. Right to transport revenue traffic between other states B and C.
8. Right to transport revenue traffic within other state B as part of the continuation of a flight originating/terminating in home state A (*continuous or fill-up* ***cabotage***).
9. Right to transport revenue traffic within other state B (*full or pure* ***cabotage***).

All EU carriers are granted all nine freedoms on intra-EU traffic.

ASAs refer to four critical aspects of the service (market access, airline designation, capacity and airfares) and come in three variants (traditional, open market and open skies).

AIRPORTS AND SLOTS

Airports and their runway systems are believed to be the most capacity constraining element in the air transportation system. Airports “where demand exceed capacity during the relevant period” are **fully coordinated**, and work with **slots**, an interval of time reserved for the arrival or departure of a particular flight. In assigning slots, airlines already present at an airport have the advantage of a **historical precedent** that entitles them to continuing their slots the next season.

KEY ORGANISATIONS

International Civil Aviation Organization (ICAO): a United Nations of civil aviation, taking care of standards and recommended practices, mostly technical. Also registers ASAs. Members are countries.

International Air Transport Association (IATA): trade association of most of the international airlines in the world. Operates tariff conferences and has a clearing house to clear inter-airline debts. Members are airlines.

KEY PERFORMANCE INDICATORS (KPIS)

There is no such thing as a single metric to assess the performance of an airline, but multiple key performance indicators (KPIs) exist.

TRAFFIC

Passenger transport:

- **Available Seat Kilometre (ASK)**: number of seats × flown kilometres.
- **Revenue Passenger Kilometre (RPK)**: number of revenue passengers transported × flown kilometres.

Cargo transport:

- **Available Tonnes Kilometre (ATK)**: number of tonnes capacity × flown kilometres.
- **Freight Tonnes Kilometre (FTK):** number of freight tonnes transported × flown kilometres.

For all kilometre-based metrics, there are also miles-based versions.

FINANCES

- **Cost per ASK (CASK)** or **Unit Cost**: amount of operational costs / ASK.
- **Revenue per ASK (RASK)** or **Unit Revenue**: amount of revenue collected / ASK.
- **Yield** or **Revenue per RPK**: amount of revenue collected / RPK. Order of 5 – 65 cents.
- **Operating profit** = **RPK × Yield – ASK × CASK**.

LOAD FACTOR

- **Load Factor (LF)**: number of passengers / number of seats = RPK / ASK *per flight*.
- **Average Leg Load Factor (ALLF):** RPK / ASK for particular flight leg.
- **Average Network Load Factor** or **System Load Factor (ANLF** or **ALF)**: RPK / ASK *for entire network.*
- **Break-Even Load Factor (BELF)**: value for LF for which RASK equals CASK. RASK = CASK = Yield × LF = Yield × BELF, or BELF = LF × CASK/Yield = LF × Cost/Revenue.

PRODUCTIVITY

- **Aircraft Productivity**: average number of ASK in a given period of time per aircraft in the fleet. (*Other definitions, e.g. Doganis, also state productivity = max. payload × av. speed.*)
- **Labour Productivity**: average number of ASK in a given period of time per employee involved in airline operations.

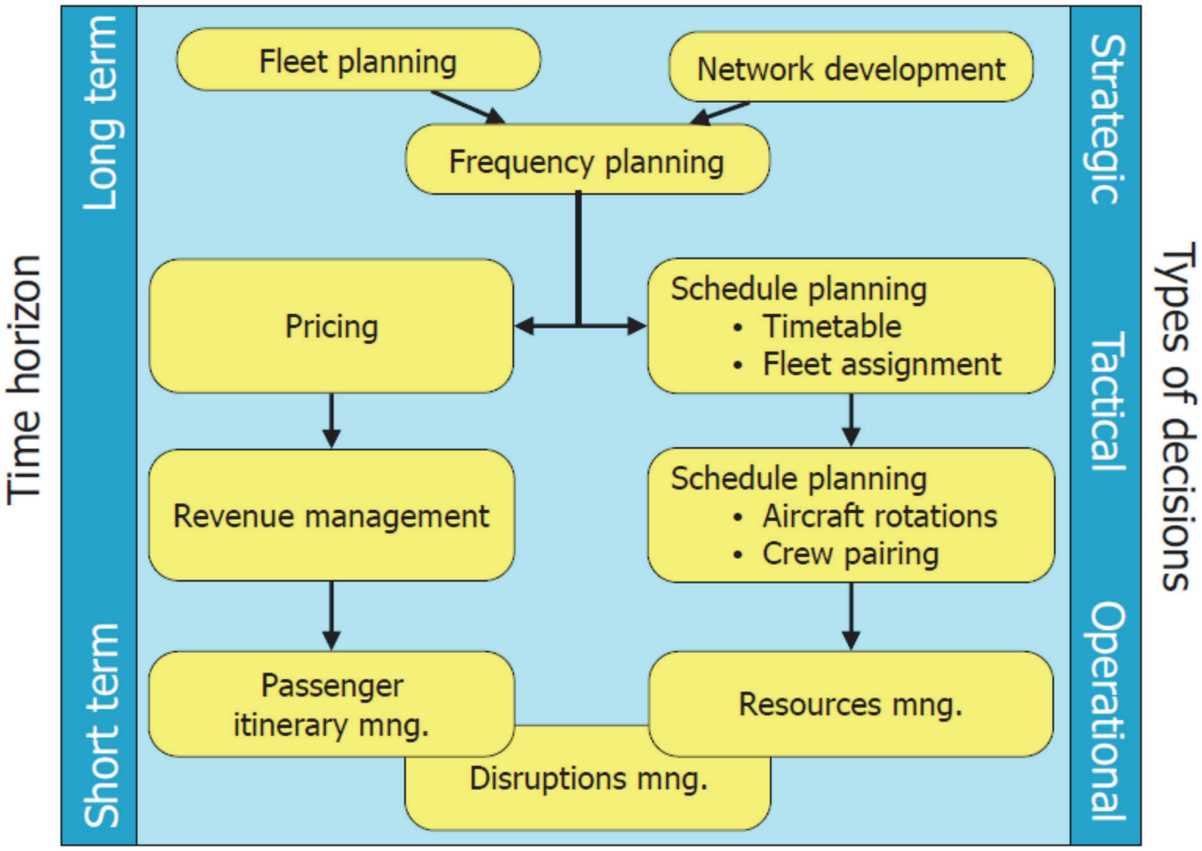
OPERATION

- **On Time Performance (OTP)**: % of flights in a given period, delayed for at most 15 minutes.
- **Average delay**: average difference between scheduled and actual time of (a set of) flight(s).
- **Number of missed connections**: number of *passengers* that missed their connections at a hub between two flights of the *same airline*.
- **Cost of delay and misconnections**: sum of costs related to delays (e.g. compensation, meals, transportation, hotels, sometimes also includes 'softer' inconvenience cost or reputational cost).

RELATION BETWEEN INDICATORS

Single KPIs can be misleading. High yield is only desirable if LF is also high and vice versa. Low CASK means little if RASK is also low. Furthermore, sales and supply should be equal. That is, required ASKs (= RPK / LF) should equal produced ASKs (# aircraft × productivity = # aircraft × capacity × distance).

PLANNING FRAMEWORK



	Long term	Medium term	Short term
Timeframe	10 – 1 years	12 – 6 months	6 months <
Uncertainty	Highest	High	Lowest
Main objective	Match supply and demand	Maximize revenue	Minimize cost
Type of decisions	Strategic (vision)	Tactical (re-adjust to market situation)	Operational (program daily ops.)

Objectives change from long-term (match demand and supply) to medium-turn (maximize revenues) to short-term (minimize costs).

LECTURE 2: DEMAND FORECASTING & MARKET SHARE

Demand uncertainty and forecasting, spill and spoilage, market share (key factors and models). Book chapter 3.

DEMAND AND SUPPLY

Passengers do not want to travel from airport to airport, but come from some 'true' origin and want to go to some 'true' destination. Air travel is a means; not an end. Each market has an **opposite market**: inbound traffic to airport B is at the same time outbound traffic from airport A. Air service markets are **distinct and separate** if their **catchment areas** (all origins of the passengers travelling through a certain airport) do not overlap. That does happen in case of **parallel markets**.

DICHOTOMY OF DEMAND AND SUPPLY

Air travel **demand** is defined for an **OD market**, but **supply** is offered by **flight leg**. Hence, there is an **inherent inability to directly compare demand and supply**. That makes it hard to say whether a market is in equilibrium (demand = supply), if a particular flight service is profitable and whether fares are (too) high or low.

Spillage	Losing demand due to lack of capacity. Leaving passengers behind.
Spoilage	Not filling complete capacity due to lack of demand. "Spoiling" passengers.

TRAVEL TIME

Total travel time includes **access and egress** time (to/from airport at O and D), **pre-departure and post-arrival processing** times (at airports), **actual flight and connection** times and **schedule displacement** (or wait time; the deviation from the actual departure time to the ideal travel time). Access and egress are **fixed** and **exogenous**, flight and connection time ("block time") depend on operations, schedule displacement depends on scheduling and *increases with decreasing frequency*.

This representation of travel time shows why more frequent departures can increase demand (reduced schedule displacement), why more frequent departures are more important in short-haul than in long-haul markets (schedule displacement is a bigger portion of total time) and why hub-and-spoke networks might provide better service than one non-stop flight per day (longer flight time more than compensated by shorter displacement time).

DEMAND MODELS AND FORECASTING

There are four demand segments:

1. Time sensitive and insensitive to price: typical representation of business traveller.
2. Time sensitive but price sensitive: actual representation of business travel.
3. Price sensitive and insensitive to time: leisure/vacation travellers.
4. Insensitive to both price and time: small group, often combined with 1.

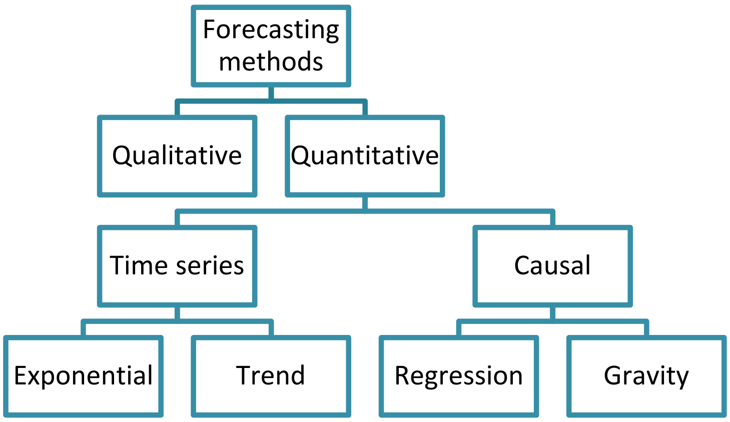
SEASONALITY

- LCC: off-peak discounts and (extra) advertising.
- Legacy: seasonal schedules and maintenance (during off-peak periods).

Seasonality can be removed from data (data can be 'deseasonalized') using **moving averages**:

1. Compute average values for all quarters (or other seasonal periods);
2. Subtract the mean value of the dataset from these averages. This yields the **cycle effect**.
3. Compute deseaonalized data by subtracting result from 2) from the dataset.

FORECASTING



Time-series projections are most widely used and establish a relationship between traffic (dependent) and time (independent). Exponential (constant relative growth) time-series come as **average rate of growth** ($D_t = D_0 + (1 + \text{average growth})^t$) or **moving-average rate of growth**; trend projections methods (constant absolute growth) are **simple linear trend** ($D_t = D_0 + x \cdot t$) **and moving average trend**.

Causal models are based on the idea that demand follows larger trends, such as (socio)economic factors. Examples are population, size of the economy (GDP), distance, average airfare, etc. The market is segmented between different levels of service quality (first/business/economy). These segments have a different elasticity to price, travel time, income variations and other factors.

Scenario-based forecasts are often used to cope with forecasting uncertainty and help to analyse whether solutions are **robust**. Forecasting x years requires $2 \cdot x$ years of historical data.

ELASTICITY

Elasticity is the percentage in total market demand that occurs with a 1% change in the average value of a certain explanatory factor. $E = \frac{\Delta D}{D} / \frac{\Delta F}{F}$. If $\%\Delta D > \%\Delta F$, demand is **elastic to $\boldsymbol{F}$**, if $\%\Delta D < \%\Delta F$, demand is **inelastic to $\boldsymbol{F}$**. If $E > 1$, an increase in e.g. price will reduce demand a lot, reducing revenues. If $E < 1$, an increase in e.g. price will decrease demand a little, increasing revenues. The demand curve w.r.t. price is usually exponential.

MARKET SHARE

Airlines compete within a market on:

- frequency / schedule;
- price;
- quality of service and products offered.

Generally, market share and frequency scale. However, there are two more complicated, but also better methods.

S-CURVE MODEL

Market share (MS) and frequency are non-linearly related through frequencies (FS) of all carriers (A, B, C, …) on a particular route. a is a scaling parameter, $a > 1$, generally $1.3 \leq a \leq 1.7$.

$$MS(i) = \frac{FS(i)^a}{FS(A)^a + FS(B)^a + FS(C)^a + \cdots}$$

QUALITY OF SERVICE INDEX (QSI) MODEL

The QSI model assigns a score to each carrier based on factors such as frequency, travel time, fare, aircraft type, etc. These scores (or indices) are computed as $Index(i) = Freq(i)^a \times Fare(i)^b \times Capacity(i)^c \times COnnection(i)^d \times$ … (with $a, b, c, d,$ … fitting parameters) and yield the following market share formulation:

$$MS(i) = \frac{Index(i)}{Index(A) + Index(B) + Index(C) + \cdots}$$

LECTURE 3: COST AND REVENUE STRUCTURES

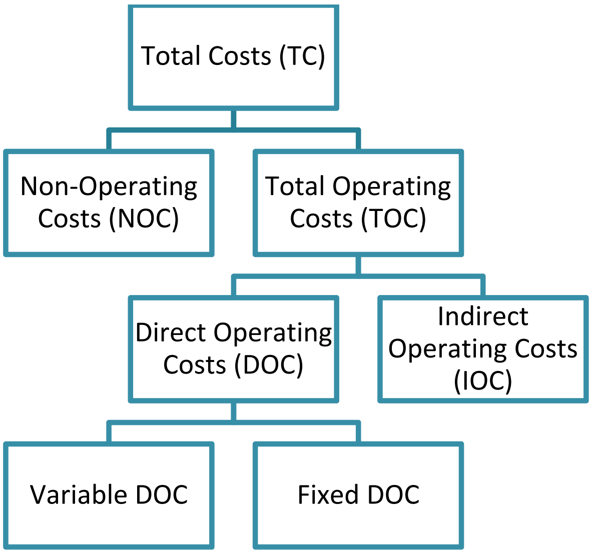
Different airline business models, structure of airlines' costs, aircraft and labour productivity. Book chapter 5.

COSTS

Airline costs information is important:

- as a general management and accounting tool;
- for supporting operating decisions;
- for developing pricing policies and making pricing decisions;
- for evaluating investments, such as new aircraft, routes and services.

ICAO breaks down costs as follows:



NOC	Property or equipment, interests (paid and received), profits/losses from affiliated companies, exchange transactions, sales of shares, government subsidies or taxes.
DOC	Flight operations, maintenance and overhaul, depreciation and amortization.
VDOC	Allocated to individual flights or routes and directly escapable in the short turn by cancelling a flight. Typically 30 – 45% of TOC.
FDOC	Costs that are not directly escapable by cancelling a flight. Typically 25 – 30% of TC
IOC	All costs which remain unaffected by a change of aircraft type: station and ground expenses, passenger services, ticketing, sales and promotion, and general and administration. Route-specific IOC are typically 5 – 10% of TOC; generic IOC typically 25 – 35% of TC.

The **trend in airline costs** is a high dependency on fuel prices, increasing airport fees and increased leasing of aircraft.

PROFITABILITY

Profitability is difficult to assess because of the network effects. Profitability of a flight leg consists of incremental revenues and costs (direct and connecting passengers, TOC) and network contributions and costs.

There are two approaches to estimating the profitability of (new) routes.

- **Traditional**: all costs and revenues of a flight leg basis and treats flight legs independent of the network. Pro: easy. Con: does not capture important network effects, allocation schemes subjective.
- **Trial-and-error**: adjust network with one flight leg, re-optimize and compare profitability before and after change. Pro: captures network effects. Con: difficult, requires good network model.

PRODUCTIVITY

Productivity is measured by assessing the added value between input (labour and capital) and output (ASKs). Well-known metric of productivity is **utilization**.

BUSINESS MODELS

- Network / flag / legacy carriers
- Regional airlines
- Charter airline
- Low cost carrier
- Business class airlines
- Business charter / air taxi
- Cargo airline

LECTURE 4: OPTIMIZATION AND OPERATIONS

MILP examples, CPLEX (& MATLAB). No related book chapters.

Decision variables	quantities (independent variables) that need to be determined in order to solve the problem.
Parameters	quantities (input values, constants or dependent variables) that define system characteristics.
Objective function	defines the goal of the problem, either maximization or minimization.
Constraints	can be either *hard constraints* which set conditions for the variables that must be satisfied, or *soft constraints* which have some slack, but are penalized.

LECTURE 5: NETWORK PLANNING

Route profitability, network structure (hub-and-spoke versus point-to-point), current trends, network optimization model. Book chapter 6.

Where to fly the aircraft profitably, subject to fleet availability constraints?

There are economic and practical considerations to route development. Even the practical considerations often have an economic basis.

Economic considerations:
- potential demand: not only O-D demand, but also connecting flights;
- current and expected future competition;
- incremental profitability in the short run.

Practical considerations:
- technical capability;
- characteristics of aircraft;
- airport facilities and staff re-location;
- regulatory issues.

PLANNING SEQUENCES

Currently, network, fleet and schedule planning decisions are made sequentially. Future trends probably go towards integrated airline planning, allowing for joint optimization. This, however, is and will remain difficult, given the different time horizons for the different planning stages.

NETWORK TYPES

Point-to-point networks connect city pairs in direct flights. **Hub-and-spoke networks**, on the other hand, feature indirect transfer flights and are based on the concept of a wheel, with a central hub and multiple spokes.

Working with a hub is more profitable if the costs savings associated to operating fewer flights with larger aircraft and higher load factors are greater than the revenue loss associated to losing passengers choosing a non-stop flight (if one exists).

Hubs work with **connecting banks** or **waves** of flights. In large airports, these last from 1 to 2 hours, giving passengers and cargo the time to make the connection between incoming (arriving at the start of the wave) and outgoing (leaving at the end of the wave) flights. This results in an uneven use of resources, as much capacity is required during the peak times, but only little is used off-peak. **Continuous hubs** (or **rolling hubs**) (nearly) eliminate the waves to achieve a more balanced utilization of e.g. runways, gates, ground resources, etc. This also improves aircraft utilization, as aircraft depart as soon as they can be turned around. The downside (for passengers) is that it increases connecting times, especially for low demand routes.

Low-cost carriers operate point-to-point networks to explore the revenue of non-stop flights, prevent connectivity costs, reduce airport operating costs by going to (non-hub) secondary airports and/or reduce service needs at primary airports. Furthermore, LCCs rather have more lower-capacity O-D flights than only one large one so they can compete on frequency.

RECENT TRENDS

The main trend towards bigger hub development continues. This is especially true in periods of slow economic times (and/or weak demands and/or high fuel costs), when airlines rely on the economic benefits of load consolidation at hubs. Non-hub flights are then often terminated, and sometimes even smaller hubs are shut down.

NETWORK MODELS

Below, two network models are shown. They contain a few simplifications:

- static demand, independent of frequency and flight type;
- no competition (market share is incorporated in demand numbers);
- no passenger choice;
- possible aircraft routing discontinuity;
- single scenario for a static future.

LECTURE 6: FLEET PLANNING

Commercial aircraft characteristics, planning criteria and models. Book chapter 6.

What type of aircraft to acquire, when and how many of each?

Fleet planning strategies look far into the future and often define multiple periods in that long-term strategy. Given long-term uncertainty, contingencies are important to incorporate in the plans. A good fleet plan is adaptable (aircraft size, performance, economics), flexible (reconfiguration, operational flexibility, phase-in / -out) and continuous/coherent.

Fleet planning generally follows network planning. The figure below summarized the economic evaluation process.

INPUT

Various information sources are used as input to the fleet planning process:

- network data;
- route data;
- airport data;
- current fleet;
- product requirements.

METHODS

- Macro or top-down approach.
- Micro or bottom-up approach.

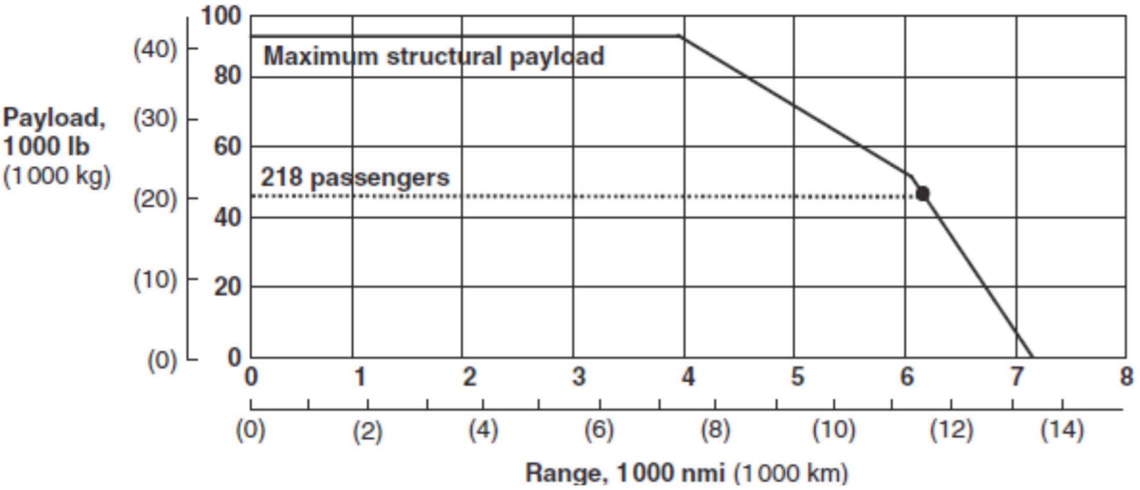
SELECTION CRITERIA

Aircraft are selected based on several criteria:

- financial and economic issues;
- technical and performance characteristics;
- comfort;
- commonality;
- environmental regulations;
- market and infrastructure;
- political issues;
- marketing.

PERFORMANCE

A **payload range diagram** looks as follows and shows the dependence of range on payload. This allows “trading fuel for passengers”, i.e. reduce capacity to be able to fly a longer range flight.



Extended-range Twin-engine Operational Performance Standards (ETOPS) allow twin-engined aircraft to fly over large bodies of airportless terrain (or water), as long as they stay within 120 to 207 minutes of the closest airport.

AIRCRAFT WEIGHT BREAKDOWN

- **Operating Empty Weight (OEW)**
- **(Maximum) Zero Fuel Weight (MZFW)**
- **Maximum (Design) Take-Off Weight (MDTOW)**
- **Maximum Landing Weight (MLW)**

The amount of runway length required (**Take-Off Distance Required**, TODR) by an aircraft depends on actual take-off weight (TOW), and is equal to the **Accelerate-Stop Distance Required** (ASRD).

MANUFACTURERS

In aircraft and engine manufacturing, there are only a few OEMs (original equipment manufacturers), depending on the specific market:

- aircraft, 150 seats and over: Airbus, Boeing;
- aircraft, regional: Embraer, Bombardier, ATR;
- engines: Rolls-Royce, General Electric, CFM International, project-based alliances.

LECTURE 8: AIRCRAFT LEASING

Guest lecture by Gilles van Hövell tot Westervlier, Managing Partner of Aviation Independent Consulting.

Leasing is becoming much more important, with 0.5% of aircraft leased in 1970 and over 35% in 2015.

(In most cases) leasing separates **ownership** from **control**. There are various types of leasing arrangements, with a spilt between <u>financial</u> and <u>operational</u> lease. The latter is further divided in three categories:

- <u>dry lease</u>: excluding crew;
- <u>wet lease</u>: including crew;
- <u>damp lease</u>: hybrid of dry and wet lease.

The **lessor** owns the aircraft and is looking for a return on his investment (financing and procuring the aircraft) and the **lessee** uses the aircraft, desiring efficient operations. The lessor has to monitor the asset value and often transfers the responsibility for continued airworthiness to the lessee. The lessee has to operate the aircraft under an Air Operator Certificate (AOC) and ensure that maintenance is done by an Approved Maintenance Organisation (AMO).

The **lease rate** is generally between 0.5% and 0.8% of the total asset value ($50 - $400 million) per month. The exact lease rate however depends on duration, creditworthiness of the lessee, customization costs, strategic importance, and many other factors.

The **lease cycle** looks as follows:

1. negotiations, resulting in a (binding) lease agreement;
2. aircraft delivery;
3. aircraft operation;
4. end of lease and aircraft redelivery (“repossession”).

Without documentation (that show airworthiness, configuration, etc), an aircraft is practically worthless, as this paperwork is required by authorities.

LECTURE 7 + 9: SCHEDULING PLANNING (I + II)

Schedule development, timetable issues and constraints, fleet assignment, aircraft rotation, crew scheduling. Book chapters 7 and 9, and §6.3.

How frequently and at what times on each route should flights be operated, subject to operational and aircraft limitations?

Schedule development consists of five[1] interrelated tasks, not taking into account maintenance needs:

- **Frequency planning**: how often should flights on specific routes be operated?
- **Timetable development**: at what times should flights depart?
- **Fleet assignment:** what type of aircraft should be used for each departure time?
- **Aircraft rotation planning**: how should each specific aircraft (tail number) fly the airline's network?
- **Crew scheduling**: how to assign crew (pilots and cabin crew), guaranteeing the operation and satisfying work rules (over 1 month periods)?

Frequency planning follows network and fleet planning, done based on forecasts made 2 – 5 years in advance. Timetable and aircraft rotation planning then follows from 1 year in advance, but is finalized up to 2 months before departure. Final revisions are made until the flight departs.

FREQUENCY PLANNING

More frequent departures (generally) increase market share, but this is constrained by available resources, connection banks at hub airports, demand peaks (from a customer point of view, i.e. 09:00 and 17:00) and time zone differences. However, this goes to say that frequency has an influence on demand. (This explains that due to competition, airlines are sometimes forced to operate more expensive lower-capacity aircraft in relatively large markets).

Airlines cope with this chicken-and-egg-problem as follows:

1. Estimate demand based on "baseline" frequency.
2. Calculate frequency to satisfy demand, while remaining profitable.
3. Compute new potential demand, based on new frequency.
4. Update frequencies and iterate.

TIMETABLE DEVELOPMENT

The goal is to provide flights at peak periods, but resource constraints make that not all flights can be in a peak. There is a trade-off between minimum **turnaround time** (good for utilization, but little flexibility) and 'wait for peak' turnaround time (flights adjusted to demand at cost of lower utilization). Furthermore, there are timetable constraints from hub operations, time zone differences, airport slot times and crew schedules and routine maintenance.

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[1] The lecture slides (lecture 7, p. 5) and book (section 6.3, p. 192) disagree on these exact elements. As the lecture slides on subsequent slides follow the four steps in the book, these form the basis of the list. The fifth element is added from the lecture slides.

Schedules can be graphically represented in schedule maps. One change has influences throughout the entire network. Therefore, airlines often keep to incremental changes, also in order not to upset loyal customers (that are accustomed to a particular timetable).

FLEET ASSIGNMENT

After the timetable has been made, aircraft types have to be assigned to flights, aiming to minimize operational cost, maximize profits or reduce spillage. Flight networks are modelled using **time-space networks**. These extend the schedule map shown above (showing **flight arcs**) with **ground arcs** (or **wraparound arcs**). Finding a feasible flight assignment then becomes analogous to selecting a path through the time-space network. There are a few differences between time-space networks and schedule maps:

- different networks for different aircraft types;
- “overnight” ground arcs exist at airports;
- *possible* flight and ground arcs link nodes;
- each node represents a combination of time and space.

To count the number of aircraft (of a particular type) required, count all the arcs that cross the **count time** line. It doesn’t matter where that count time line is drawn in the diagram, as long as it’s vertical.

SPILL EFFECT

Spill costs can be taken into account by setting the cost of the passengers not flying equal to the price of the passengers if they would fly. These costs are computed stochastically given a demand distribution and a known capacity.

Recapture	Passengers that are recaptured back to the airline after being spilled from another flight leg.

AIRCRAFT ROTATION PLANNING

Aircraft rotation planning (or **aircraft routing planning**) determines which specific aircraft in the fleet (which tail number) operates each flight leg, aiming to:

- cover each flight leg by only one aircraft;
- balance aircraft utilization;
- comply with maintenance requirements.

To the actual optimization problem, there are multiple possible objective functions:

- minimize TOC for a specific type;
- maximize the ‘through values’, i.e. flights that sequentially perform a pair of flight legs on a route;
- maximize maintenance opportunities.

This is subject to the constraints of flight coverage (cover each flight once) and number of available aircraft.

CREW SCHEDULING

Crew costs are the second largest contributor to overall costs. Therefore, crew scheduling is often performed before aircraft routing planning, because an optimal crew assignment is more valuable than an optimal aircraft assignment.

Crew scheduling problems are solved in two phases: crew pairing and crew rostering.

CREW PAIRING

In crew pairing, airlines pair crew-sets to a sequence of flights that starts and ends at the same base. The objective is to minimize crew costs. Airlines often try to keep a crew and its aircraft tail number with each other, to avoid delay-stacking (crew for flight A is delayed on inbound flight B) or dead-heading (transporting crew as passengers).

Crew pairing is similar to aircraft rotation planning, although crews require no turnaround time, have limited daily utilization and should get back where they started at the end of a trip.

CREW ROSTERING

Crew rostering is about assigning individual crew to pairings, with the objective to maximize crew satisfaction and minimize the time a crew doesn't generate production. Ensuring that each crew pairing gets one crew also ensures that each flight leg gets only one crew. Crew rosters are usually made on a monthly basis.

FUTURE TRENDS

1. Integrated schedule planning, as mentioned in Lecture 5: Network Planning, page 12.
2. Operations recovery and robustness, as discussed in Lecture 10: Robust Airline Scheduling, page 20.

LECTURE 10: ROBUST AIRLINE SCHEDULING

Guest lecture by John-Paul Clarke, Director of Air Transportation Laboratory at Georgia Tech.

SCHEDULE ROBUSTNESS

(Static) Robustness	The ability of a system to resist change without adapting its initial stable configuration.
Dynamic robustness	Robustness where a system senses and then changes its configuration in order to mitigate the ill-effects of disturbances. (*Comparable to disturbance rejection in control theory.*)

The goal is to make airline schedules that are insensitive to delays and cancellations. The objective of robustness can thus be one of the following:

- minimize cost;
- minimize aircraft/passenger delays and disruptions;
- easy to recover (aircraft, crew, passengers);
- isolate disruptions, limit downstream impact.

There are two ways to achieve robustness in airline operations: adapt schedule after disruptions occur (purely dynamic robustness) or build robustness into the schedule (combination of static and dynamic robustness).

Flight leg delay is built up from propagated delay and independent delay. Appropriately allocated slack can reduce propagated delay.

FLEET ASSIGNMENT ROBUSTNESS

Fleet assignment can also be made more robust, for example by improving **station purity** (smaller range of aircraft that visit particular airports, so that swapping is easier). This also reduces operational costs, because each fleet/station combination increases costs, and makes crew scheduling more efficient.

RESEARCH EXAMPLES

- **Robust Maintenance Routing** aims to reduce the propagation of delays by combining flight legs in an optimal (from the point of view of follow-on delays) maintenance routings.
- **Flight Schedule Retiming** aims to reduce passenger misconnections by adjusting departure times so that passenger connection times are correlated with the likelihood of a missed connection.
- **Degradable Airline Scheduling** aims to develop a robust schedule with isolated delays that, in case of disturbances, prioritizes certain passenger / flight groups.
- **Virtual Spares** aims to reduce propagated delay by decoupling inbound and outbound tail numbers at hubs, such that these can be swapped.
- **Robust Fleet Assignment**
- **Sub-Route Switching**

LECTURE 11: PRICE & REVENUE MANAGEMENT

Pricing structure, revenue strategies, EMRS model. Book chapters 4 and 15.

PRICING

Pricing	the process of determining the fare levels and service amenities and restrictions for a set of fare products in an O-D market.

There are three pricing strategies:

- Cost-based pricing: micro-economical of marginal cost pricing (pricing based on the costs incurred to provide a service), or global average-cost pricing.
- Demand-based pricing: based on **willingness to pay (WTP)**, price discrimination.
- Service-based pricing, product differentiation through service levels.

Price discrimination	Charging different prices for the same (or very similar) products (with same service and production costs), based solely on willingness to pay.
Product differentiation	Charging different prices for products with a different quality of service and (associated) different costs of production.

Airline usually combine these two concepts in a practice called **differential pricing**. Low-cost carriers take the opposite approach of setting fares first, and then match costs to that (**price-based costing**).

DIFFERENTIAL PRICING

In differential pricing schemes, people with a high willingness to pay are only offered the most expensive tickets, saving the cheaper ones for people that have a low willingness to pay. The success of this approach depends on the airline's ability to identify different demand groups (**market segmentation**).

Subsequently preventing the diversion from 'rich' passengers to 'cheap' tickets is difficult. **Fare product restrictions** help with that, by requiring more advance purchase and have minimum stay requirements for cheaper tickets, and scare business travellers away by introducing cancellation/change fees. Although to a lesser extent, low-cost carriers also employ these tactics.

Several trends have impacted this strategy:

- Internet: allows customers to compare prices.
- Lower business travel demand.
- Emergence of low-cost carriers, increasing (cheap) travel alternatives.
- Cost reductions following 9/11.
- Big data solutions for real-time (re-)optimization.
- Unbundling: charging separately for extra services (introduced by LCCs).
- Customer tailored offerings, based on knowledge gained about a particular customer.
- Increasing complexity.

Overall, airlines have been moving towards **fare simplification**.

REVENUE MANAGEMENT

The main objective of revenue management (or **yield management**) is to protect seats for later-booking and more-paying passengers. Techniques that help with that are:

- overbooking;
- fare class mix (flight leg optimization);
- O-D traffic flow control (network optimization).

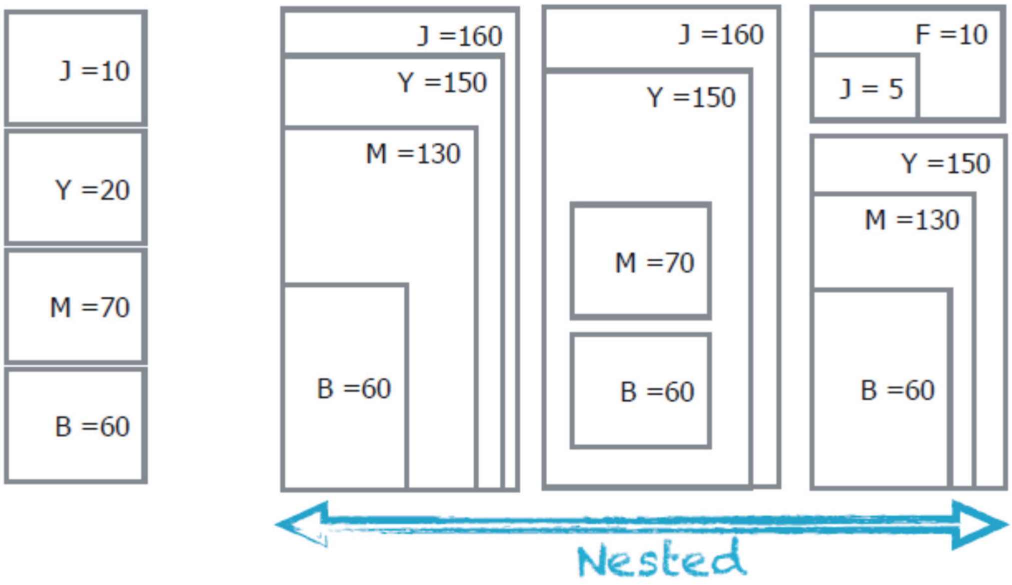
Due to the size and complexity of this inventory, airlines need computerized revenue management (CRM) systems. The 4th generation of these systems (currently introduced) are extending flight leg-based metrics with O-D metrics and takes the revenue value of the passengers' entire (network) itinerary into account.

OVERBOOKING

Based on an expected **no-show rate (NSR)**, airlines sell more tickets than there are seats available. Airlines minimize the total combined costs and risks of denied boarding (lower NSR than expected) and spoilage (higher NSR than expected, resulting in lost revenue). The overbooking capacity is normally based on probabilistic models.

BOOKING LIMITS

Booking limits can be partitioned (left) or nested in a variety of ways (right).



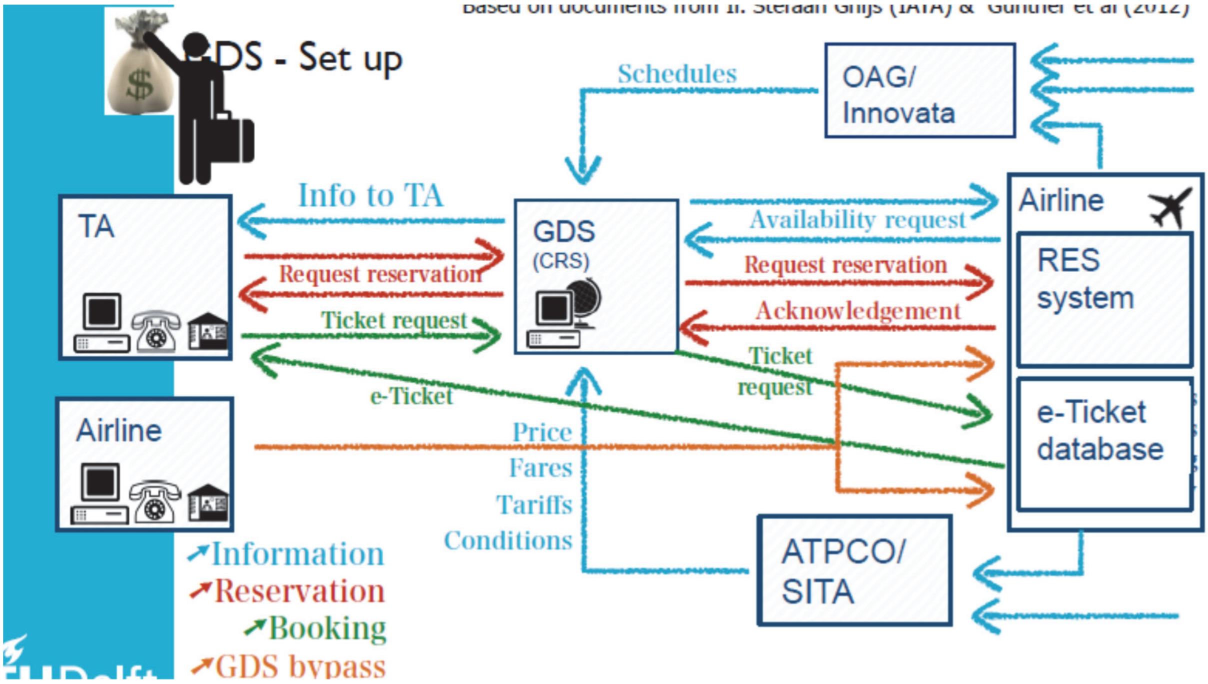
The **expected marginal seat revenue** (EMSR or, updated, EMSRb) is a system to set booking limits, that takes into account that demand is uncertain (and deterministic limits will not be optimal). It assumes:

- demand for each class is separate and independent from other classes;
- demand for each class is stochastic (often normal distribution);
- booking goes from lowest class (entirely) to highest class;
- booking limits are only set ones (no re-optimization).

The **protection level** π is found using $EMSR(\pi_{1,2}) = F_1 \times P_1(\pi_{1,2}) \geq F_2$, with F the average fare and P the probability that demand for seats is larger than supply. The **booking limit** then follows as (authorized) capacity minus protection level.

DISTRIBUTION SYSTEMS

The figure below shows how (global) distribution systems (GDSs) are set up.



Travel agencies, having access to the CRS, see less information than an airline itself, concerning e.g. exact seat availability.

LECTURE 12: GROUND OPERATIONS

Ground operations. Book chapter 8.

LANDSIDE

Airport landside extends up to the terminal buildings, excluding the apron-gate area. Landside operations are **passenger operations**:

- passenger processing;
- goods handling;
- interlining services.

AIRSIDE

Airside involves all aspects of aircraft handling at the airport as well as aircraft moment around the aerodrome except when on active runways:

- on-board services;
- aircraft services.

Much of the airside operations are outsourced. Airside operations can be time-constrained by scheduled turnaround times.

PERT-MODEL

The PERT-model schematizes the activities that need to be completed during turnaround, showing dependencies and duration. The **critical path** is that path of activities that, when delayed, delays the entire turnaround process. The durations can be translated into start-times, working forward ($ES_j = ES_{j-1} + D_{j-1}$, earliest start equals earliest completion of the previous task) or backward ($LC_{j-1} = LC_j - D_j$, latest completion equals the last completion of the following task). The **slack** is the difference between $S_j = LS_j - ES_j$. These times are shown in diagrams like the one depicted on the right. The PERT model thus tells:

- planned **turnaround time (TAT)**;
- critical activities in TAT;
- slack times in TAT.

TURNAROUND TIME IMPROVEMENTS

Improvements to turnaround time can be made in various types of activities:

- passenger handling;
- catering;
- cleaning;
- goods handling;
- fuelling.

BOARDING

Seat interference	situation when window passenger has to pass already seated aisle passenger.
Aisle interference	situation where someone is blocking the aisle.

There are different boarding systems, in order of reduced average boarding time:

- rotating-zone boarding;
- back-to-front boarding;
- random boarding;
- block boarding;
- outside-in boarding;
- reverse-pyramid boarding.

If the passenger interarrival time increases, the speed differences disappear.

AIRLINES OPERATIONS CONTROL

Airlines operations control (AOC) investigates resilience in air transportation and decides how to resolve conflicts / recover from disruption.

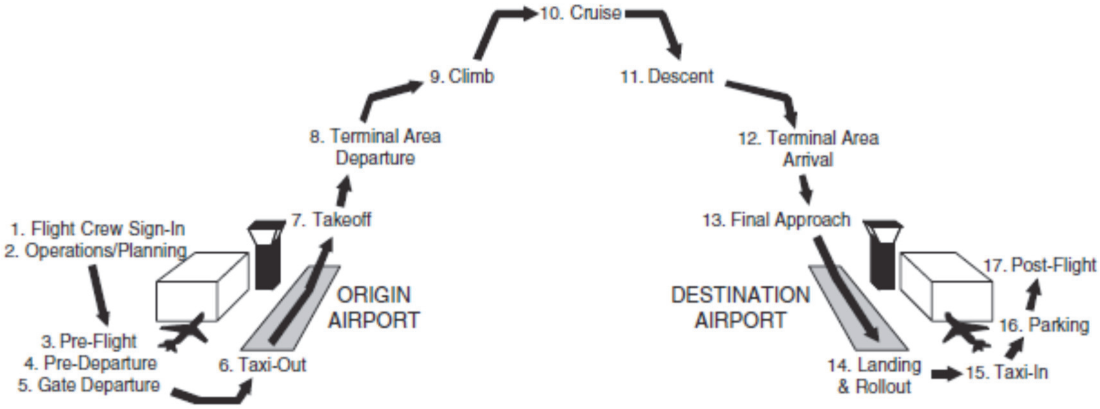
LECTURE 13: FLIGHT OPERATIONS

Flight operations, cost index. Book chapter 8.

FLIGHT PLANNING

Flight planning, done at the airline's operations control centre, tries to minimize cost, subject to constraints on aircraft performance, weather conditions, ATC, schedule and operation. They can vary vertical flight profile, airspeed profile, initial fuel load and aircraft routing.

A flight looks as follows:

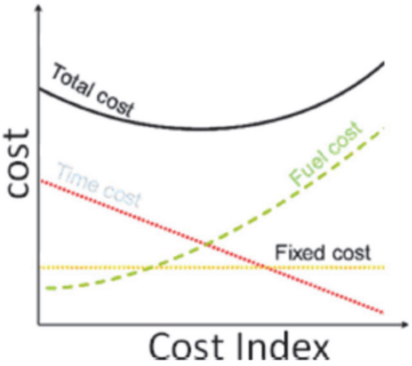


FLIGHT PROFILE

Maximum cruise range is attained at maximum $\frac{V}{F}$, with V airspeed and F fuel flow. This shows that ρ should be minimized (i.e., altitude maximized), C_L/C_D^2 should be maximized and lower weight is better.

COST INDEX

The **cost index** (CI), the ratio of time-related costs to fuel-related costs, is used by airlines to choose between **Long Range Cruise** (quicker, less fuel efficient) versus **Maximum Range Cruise** (slower, more efficient). Note that speed also directly influences other costs besides fuel, such as crew costs and cost of items that are leased per unit of time.



ROUTING

Finding the optimal route is influenced by:

- weather conditions;
- en-route charges of countries overflown;
- distance;
- avoiding geographical areas;
- ATC requirements.