SUMMARY

AE4423 – AIRLINE PLANNING & OPTIMIZATION

CONTENTS

This summary 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 Inde-penent Consulting.
- Lecture slides *Robust Airline Scheduling* (2015/12/10) by Clarke, Georgia Institute of Technol-ogy.

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: governments reduce involvement in airline economics.
- Liberalization: private ownership, bankruptcies, mergers, take-overs, alliances.
- Changing business models: expansion of LCCs, legacy carriers adopting some LCC-strategies.
- 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

Freedoms of the air (or Air Service Agreements, or bi- or multilateral agreements) govern which airlines can operate which routes, and how. There are negotiated between countries, not between airlines themselves.

1. Right to fly over another state B without landing (*automatically granted to all ICAO-member states*).
2. Right to land in another state B for technical reasons (*automatically granted to all ICAO-member states*).
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 (*allows for hubbing; typically not specified explicitly, as this follows from 3 and 4 between A and B and A and C*).
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 (rows) and come in three variants (columns).

	Traditional 1946 –	**Open market** 1978 –	**Open skies** 1992 –
Market access Potential city pairs served and freedoms beyond 3rd and 4th	Limited to specific city-pairs	Generally open to all city-pairs	Unlimited city-pairs at both ends
Airline designation Number of airlines from each state allowed to operate	One airline from each state	Multiple airlines	Multiple airlines
Capacity Frequency + # seats	Typically 50/50, sometimes revenue pooling	No restrictions	Allows code sharing and *break of gauge*
Airfares / tariffs Manner in which fares are computed and approved by governm.	All fares require double approval	Propositions approved, unless double disapproval	Not subject to government approval

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.

Furthermore, there are smaller and/or more localized trade associations, such as **Airports Council International (ACI)**, the **International Federation of the Airline Pilots Associations (IFALPA)**, the **Regional Airlines Association (RAA)**, the **Association of European Airlines (AEA)** and the **European Low-Fares Airline Association (ELFAA)**. In the regulatory environment, there are the **European Aviation Safety Agency (EASA)** and the US **Federal Aviation Administration (FAA)** and **National Transportation Safety Board (NTSB)**.

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*. Order of 70 – 90%.
- **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 × avg. speed.*)
- **Labour Productivity**: average number of ASK in a given period of time per employee involved in airline operations.

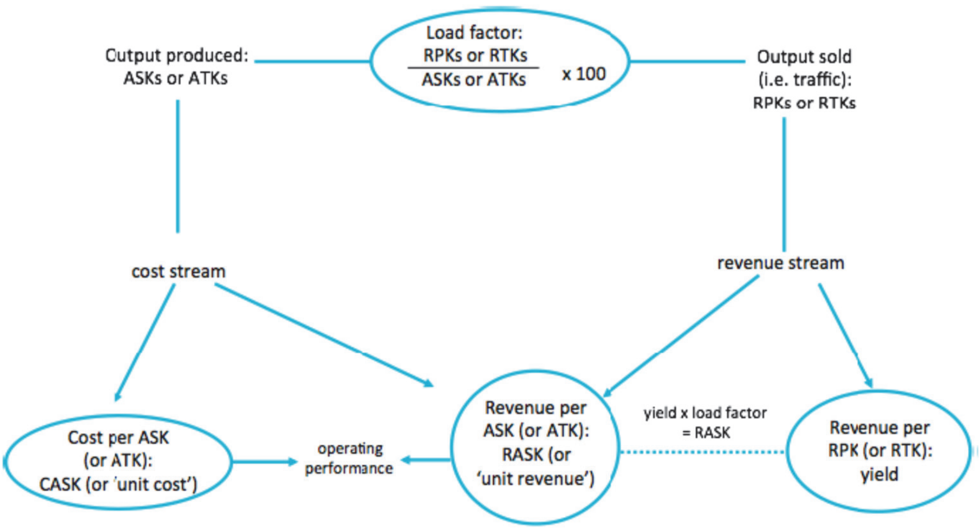
More on productivity in Lecture 3: Cost and revenue structures.

OPERATION

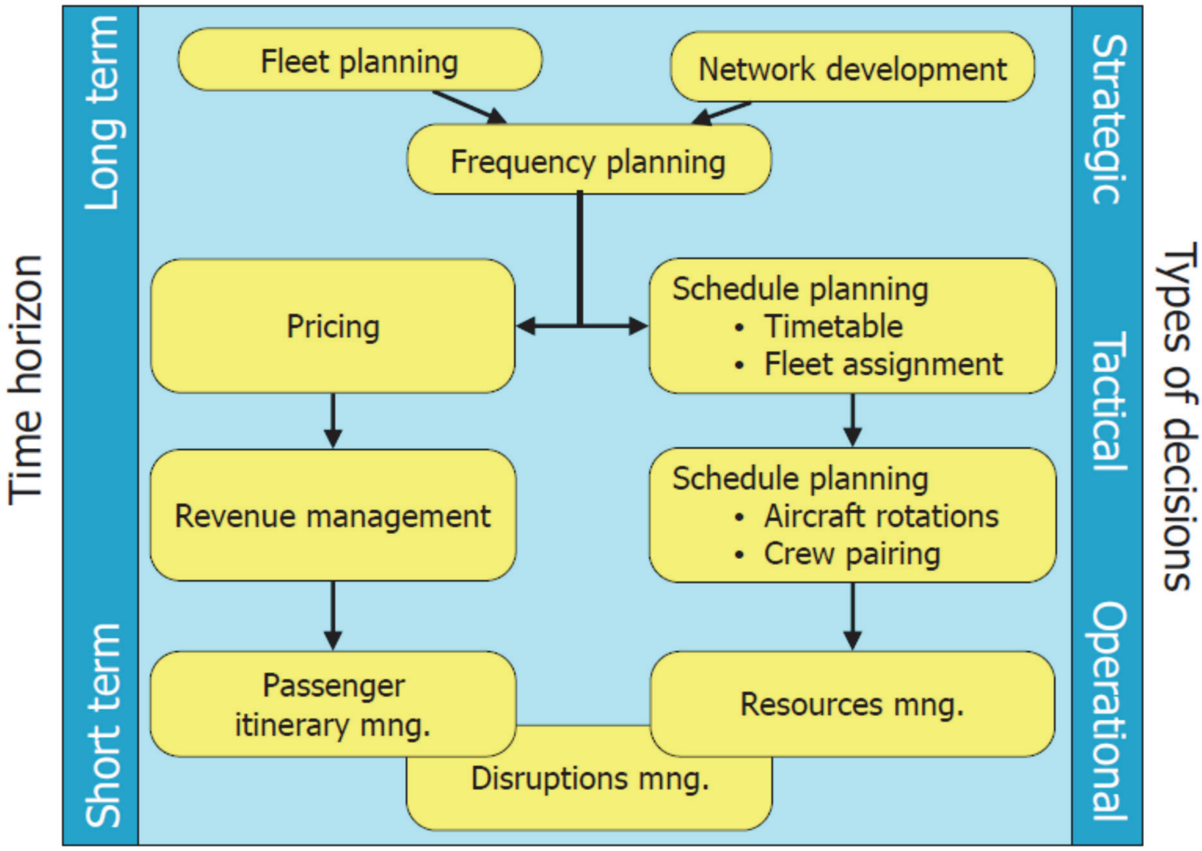
- **On Time Performance (OTP)**: % of flights in a given period, delayed for at most 15 minutes.
- **Average delay**: average difference between scheduled and actual time of (a set of) flight(s).
- **Number of missed connections**: number of *passengers* that missed their connections at a hub between 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).

BOOK SUMMARY

The global airline industry operates in an international regulatory environment that ranges from strict regulation and protectionism in some countries or regions to almost complete deregulation in others. The long-term trend would seem to be in the direction of further deregulation and liberalization, with the unified market created by the EU and the proliferation of bilateral and multilateral "open skies" agreements marking major advances in this direction since the early 1990s. National ownership requirements, even in the economically developed regions of the world, persist as an important barrier to a full "globalization" of the industry. There is also a strong trend toward privatizing the many government-owned national carriers ("flag carriers") that had long dominated air travel outside the United States.

Airport capacity constraints are becoming increasingly severe in many regions of the world, resulting in serious problems of flight delays and cancellations and of low reliability of flight schedules. Using IATA's schedule coordination system, many major international airports largely rely on historical precedent as the primary criterion for allocating scarce airport "slots" among airlines that request them. This approach to airport demand management is restraining competition and is increasingly viewed as an indirect form of industry regulation. Market-based mechanisms for effecting slot allocation are currently being considered as possible alternatives to the IATA approach. Private participation in airport ownership and private-sector-style airport management is another important trend that emerged in the late 1980s and the 1990s outside the USA. US airports are owned by state or local governments, but rely heavily on outsourcing most of their financing, planning and operating activities to private companies. This approach to airport management is now being widely imitated by both privatized and government-owned airports around the world. Airport privatization has also stimulated interest in the economic regulation of airports – particularly as regards the rates they charge for aeronautical services.

In response to the growing complexity and cost of air navigation services (or "air traffic management") a number of economically developed countries have "corporatized" (or "commercialized") the provision of these services, through establishment of autonomous corporate entities that largely operate according to private-sector principles. These entities, mostly 100% government owned, have assumed responsibility for what was previously a government service. As is the case with airports, economic regulatory measures have been put in place in response to these developments.

A large number of international and national institutions and organizations, public and private, play a central role in policy making regarding economic, regulatory and technical matters that profoundly affect the air transport sector.

The study of any aspect of the global airline industry must be cognizant of the complex regulatory, legal and institutional contexts within which the industry operates.

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.

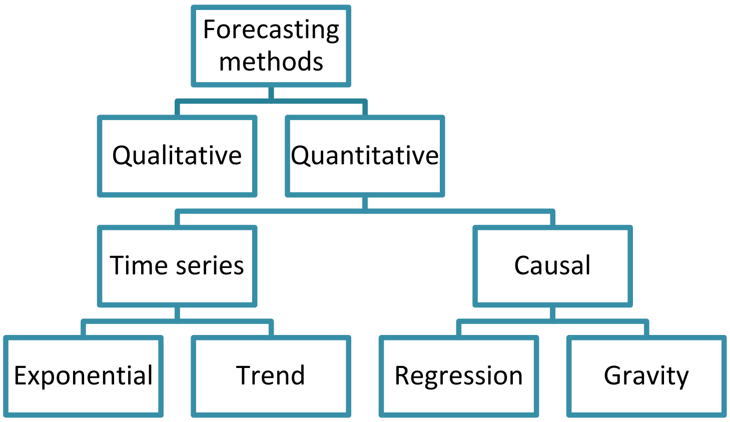
SEASONALITY

- 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.

		Qualitative methods		Time-series projections			Causal methods	
		Executive judgment	Market research	Annual average growth	Linear trend	Linear w/ moving averages	Regression analysis	Gravity model
Accuracy	Short-term (0-6 mo.)	Good	Good	Fair/good	Fair/good	Good	Good	Good
	Long-term (> 6 yrs)	Poor	Poor/fair	Poor	Poor	Poor/fair	Fair	Fair
Suitability for forecasting	Growth	Good	Good	Good	Good	Good	Good	Good
	Reaction	Fair	Good	n.a.	n.a.	n.a.	Good	Poor
	New routes	Poor	Fair	n.a.	n.a.	n.a.	Fair	Good
Ability to identify turning point		Poor/fair	Fair	Poor	Poor	Poor/fair	Good	Poor
Days required to produce forecast		1 - 2	90+	1 - 2	1 - 2	1 - 2	30 - 90	20 - 60
Cost of implementation		Very low	Very high	Low	Low	Low	High	Moderate

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:

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

BOOK SUMMARY

This chapter has introduced basic airline terminology and definitions, as well as several concepts related to air transportation markets and the demand for air travel. The most common measures of airline performance – RPK, yield, ASK, unit cost and load factor – were defined. They were then incorporated into a basic airline profit equation that illustrates the interdependence among these measures in airline management decisions.

Our discussions of markets in air transportation began with a description of a typical passenger airline trip, followed by several spatial definitions of origin-destination (O-D) markets. Different O-D markets are considered to be distinct and separate, but can be interrelated through "parallel markets". Multiple O-D markets also can share the joint supply of seats on a single flight leg, given the existence of multiple leg and connecting passenger itineraries. Because demand for air travel is generated at the level of a passenger's O-D trip, while a joint supply is provided to multiple O-D markets by a set of flight leg departures, there is an inherent inability to directly compare demand and supply in an individual O-D market.

The demand for air travel in an O-D market is affected by many different variables, including various socioeconomic characteristics of the origin and destination regions, price of air services (and competing modes) and quality of service factors. The concept of total trip time was discussed as being the most important quality of service affecting the volume of O-D market demand for air travel.

The concepts of price and time elasticity were defined, and related to the segmentation of total demand by airlines, which have traditionally separated business and leisure demand for pricing and scheduling purposes. These elasticity concepts were then incorporated into several examples of O-D market demand functions, including a model that reflected the different segments of air travel in a market and the fact that there can be more than one air travel "product" offered to travellers.

Finally, the nature of competition for market share on the basis of airline frequency of service was described. The "S-curve" relationship between airline market share and frequency share reflects that higher airline frequency shares are associated with disproportionately higher market shares in competitive markets. This model explains why competing airlines use frequency as a competitive weapon, perhaps to a greater extent than other quality of service elements, to retain market share.

LECTURE 3: COST AND REVENUE STRUCTURES

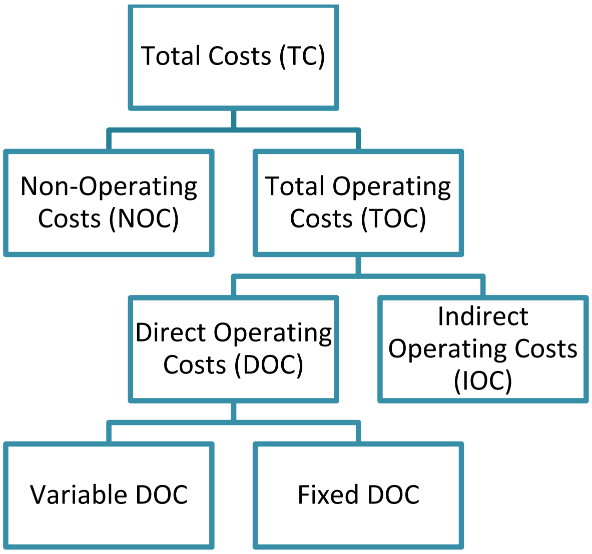
Different airline business models, structure of airlines' costs, aircraft and labour productivity. Book chapter 5.

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 All costs which are associated with and dependent on the type of aircraft being operated:

- Flight operations: crew salaries and expenses, fuel and oil, airport and en-route charges, insurance of flight equipment, rental/lease of equipment and crew. Approximately \$20 – 30 per seat-hr.
- Maintenance and overhaul: labour costs, spare parts, maintenance administration (sometimes IOC).
- Depreciation (periodic deduction from income of a portion of the difference between purchase cost and spare cost and residual value) and amortization (allocation of a lump sum amount to different time periods, such as crew training costs).

VDOC Allocated to individual flights or routes and directly escapable in the short turn by cancelling a flight. Includes fuel and service costs, DOC-fees and charges, passenger service costs, most MRO. Salaries are not part of VDOC, as these are (normally) fixed per period.
Typically 30 – 45% of TOC.

FDOC Costs that are not directly escapable by cancelling a flight. Expressed per block hour and then allocated to flights/routes. Includes depreciation, lease rentals, insurance, maintenance, fixed crew costs.
Typically 25 – 30% of TC

IOC All costs which remain unaffected by a change of aircraft type:
- Station and ground expenses: ground staff salaries and expenses, buildings, ground equipment, handling fees (aircraft cleaning, check-in, baggage, …)
- Passenger services: cabin crew salaries and expenses, direct passenger services (in-flight catering, hotels, meals on the ground, …), passenger insurances.
- Ticketing, sales and promotion: salaries and expenses for staff, fees to travel agents and Global Distribution Systems (GDSs), advertising.
- 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

- Wide network
- Enhanced airport facilities
- Brand building
- Frequent flyer programs
- Alliances
- Mergers and takeovers
- Use GDSses

KLM, Lufthansa, American Airlines, Iberia

REGIONAL AIRLINES

- Short and thin routes
- Regional aircraft, < 100 passengers
- Three types: feeder, commuter and independent regional airlines.

KLM CityHopper, American Eagle, SkyWest

CHARTER AIRLINE

- Vertically linked to tour operators
- Both B2C and B2B
- Entire aircraft rather than individual seats are chartered / sold
- Seasonal schedule
- Low cost operation
- Small fleet

TUIfly, Thomas Cook

LOW COST CARRIERS

- (Generally) no long-haul routes
- Fleet commonality
- (Generally) avoid hub airports
- Low fares, passengers pay for extra services
- Low IOC
- Low yield + high volume = profit

Ryanair, easyJet, Southwest Airlines

BUSINESS CLASS AIRLINES

- Business travellers
- High quality of service
- Luxurious cabin
- Business routes

Open Skies (British Airways), Privatair

BUSINESS CHARTER / AIR TAXI

- On demand
- Point-to-point
- High / low quality of service
- High / low cost

CARGO AIRLINE

Different types of operations, all with different aircraft types:

- Freight forwarding
- Parcel services
- Airline subsidiaries
- Specialized cargo

Martinair, FedEx, Volga-Dnepr, Kalitta

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. Examples are passenger flows, frequency per route, aircraft-route pairings.

Parameters quantities (input values, constants or dependent variables) that define system characteristics. Examples are costs, fares, fleet composition, aircraft characteristics, demand values.

Objective function defines the goal of the problem, either maximization or minimization.

Minimize costs associated with flying (per class):

$$\min C = \sum_{k \in K} \sum_{i \in N} \sum_{j \in N} c_{ij}^k \cdot pax_{ij}^k$$

Maximize revenues:

$$\max R = \sum_{i \in N} \sum_{j \in N} yield_{ij} \cdot pax_{ij} \cdot dist_{ij}$$

Maximize demand served

$$\max D = \sum_{i \in L} pax_i$$

Minimize spillage

$$\min S = \sum_{i \in N} \sum_{j \in N} \left(Dem_{ij} - pax_{ij}\right)$$

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.

Flow continuity at the node (per class)

$$\sum_{j \in N} pax_{ij}^k - \sum_{j \in N} pax(ji)^k = Dem_i^k, \quad \forall i \in N, k \in K$$

Demand constraints

$$\sum_{j \in N} pax_{ij}^k = Dem_i^k, \quad \forall i \in N, k \in K$$

Capacity constraints

$$\sum_{k \in K} pax_{ij}^k \leq Cap_{ij}, \quad \forall i, j \in N$$

Budget constraint

$$\sum_{n \in AC} Cost_n \cdot AC_n \leq Budget$$

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 (*is there a net profit in sacrificing another route/lowering another frequency to free up the resources (= aircraft, crew, …) required for this new route?*).

Practical considerations:
- Technical capability: availability of aircraft, range capability of aircraft, etc.
- Characteristics of aircraft: performance, operating cost, etc.
- Airport facilities and staff re-location (only in case of new destination).
- Regulatory issues: ASAs, limited airport slots.

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. This allow airlines to serve many O-D markets with fewer flight departures, requiring fewer aircraft generated fewer ASKs at a lower total operating costs as compared to point-to-point networks. This also makes it easier to justify adding a small new route, as long as it connects to a hub.

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.

NOTATION

Sets

N airports, i and j
H hubs, m
K aircraft types, k (omitted in single fleet models)

Decision variables

${z_{ij}}^k$ flights from i to j
x_{ij} (direct) passenger flow from i to j
${w^i}_{mj}$ passenger flow from m to j, originally coming from i
y_{im} passenger flow from i to m, intending to continue beyond m

Parameters

d_{ij} distance between i and j
$Yield$ revenue per RPK flown (average yield)
s^k number of seats per aircraft
q_{ij} demand between i and j
AC^k number of aircraft type k
$CASK^k$ unit operation cost per ASK flown of aircraft type k
sp^k speed of aircraft type k
R^k range of aircraft type k
LTO^k extra landing and take-off time for aircraft type k
LF average load factor
BT^k block time of aircraft type k
h_k $= 1$ if hub at airport k, $= 0$ otherwise
O_i total demand with origin at airport i
oc^k unit operation cost of aircraft type k

SIMPLE NETWORK MODEL

Objective function

$$\max Profit = \sum_{i \in N} \sum_{j \in N} \Big(\underbrace{Yield \times d_{ij} \times x_{ij}}_{revenue} - \underbrace{CASK \times d_{ij} \times s \times z_{ij}}_{cost} \Big)$$

Subject to constraints

Flow cannot be more than demand

$$x_{ij} \leq q_{ij}, \quad \forall i, j \in N$$

Flow cannot be more than aircraft capacity (i.e., capacity verification)

$$x_{ij} \leq z_{ij} \times s \times LF, \quad \forall i, j \in N$$

Number of inbound aircraft should equal number of outbound aircraft (i.e., balance)

$$\sum_{j \in N} z_{ij} = \sum_{j \in N} z_{ji}, \quad \forall i \in N$$

Aircraft cannot be used for more time than they are available (i.e., productivity)

$$\sum_{i \in N} \sum_{j \in N} \left(\frac{d_{ij}}{sp} + LTO \right) \times z_{ij} \leq BT \times AC$$

HUB-AND-SPOKE MODEL

Objective function

$$\max Profit = \sum_{i \in N} \sum_{j \in N} \left(\underbrace{Yield \times d_{ij} \times \left(x_{ij} + \sum_{m \in H} w^i{}_{mj} \right)}_{revenue} - \underbrace{CASK \times d_{ij} \times s \times z_{ij}}_{cost} \right)$$

Subject to constraints

Flow leaves the airport on a direct flight or on a hub flight

$$\sum_{j \in N} x_{ij} + \sum_{j \in N} y_{ij} \leq O_i, \quad \forall i \in N$$

Flow arrives at an airport on a direct flight or on a hub flight

$$x_{ij} + \sum_{m \in N} w^i{}_{mj} \leq q_{ij}, \quad \forall i, j \in N$$

Flow cannot be more than aircraft capacity (i.e., capacity verification)

$$x_{ij} + y_{ij} + \sum_{n \in N} w^n{}_{ij} \leq z_{ij} \times s \times LF, \quad \forall i, j \in N$$

Flow has to be conserved in hubs

$$y_{im} = \sum_{j \in N} w^i{}_{mj}, \quad \forall i \in N, m \in H$$

Maximum number of passengers leaving to hub j

$$y_{ij} \leq O_i \times h_j, \quad \forall i, j \in N$$

Maximum number of passengers arriving from i to j through hub n

$$w^i{}_{nj} \leq q_{ij} \cdot h_n, \quad \forall i, j, n \in N$$

Number of inbound aircraft should equal number of outbound aircraft (i.e., balance)

$$\sum_{j \in N} z_{ij} = \sum_{j \in N} z_{ji}, \quad \forall i \in N$$

Aircraft cannot be used for more time than they are available (i.e., productivity)

$$\sum_{i \in N} \sum_{j \in N} \left(\frac{d_{ij}}{sp} + LTO \right) \times z_{ij} \leq BT \times AC$$

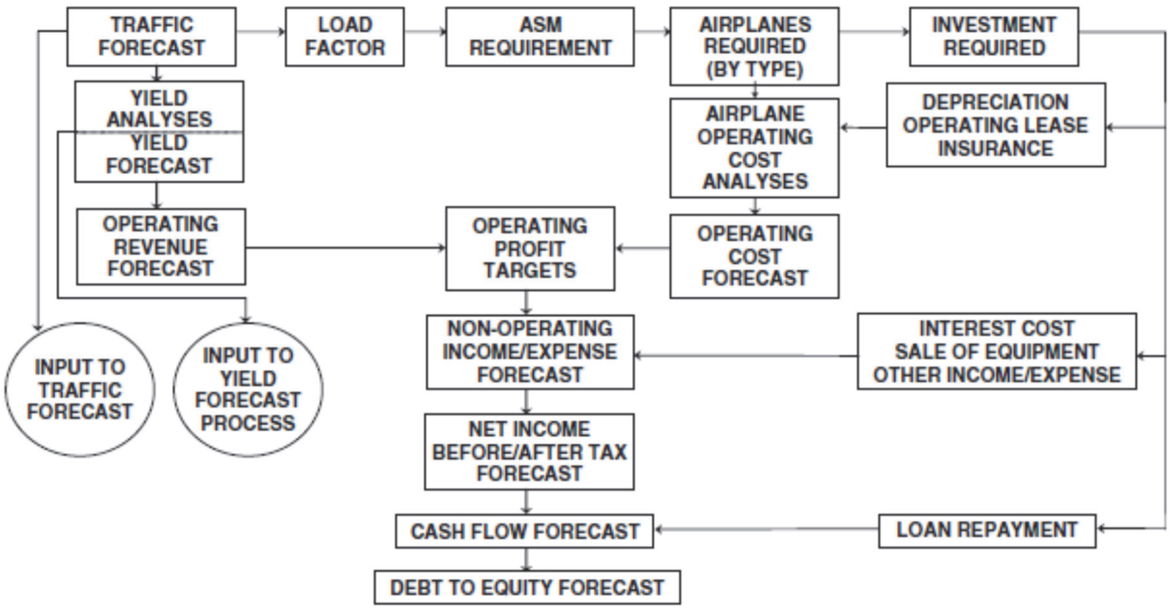
LECTURE 6: FLEET PLANNING

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

The **macro approach** (or **top-down approach**) is based on high-level aggregate analysis. Demand for required RPKs is based on historical data and projected traffic growth. Combined with an expected/assumed load factor this yields the amount of ASKs required, which can be solved for the number of aircraft. This is further iterated to take aircraft utilization into account.

The **micro approach** (or **bottom-up approach**) is much more detailed and looks at demand and market share per route or per flight. This is much more complex and time consuming (i.e., costlier) than the macro approach and can only be used for short-term planning due to tremendous forecasting errors on the long term.

AIRCRAFT TYPES

Aircraft are mainly categorized in terms of size (payload capacity) and range. The table below shows these two characteristics on the horizontal and vertical axes, and provides some example aircraft in the cells.

	Single aisle / narrow-body	**Twin-aisle / wide-body**
Short range	A320, B737, MD80	
Medium range	B757	A330, B767
Long range		A340, A380, B747, B777

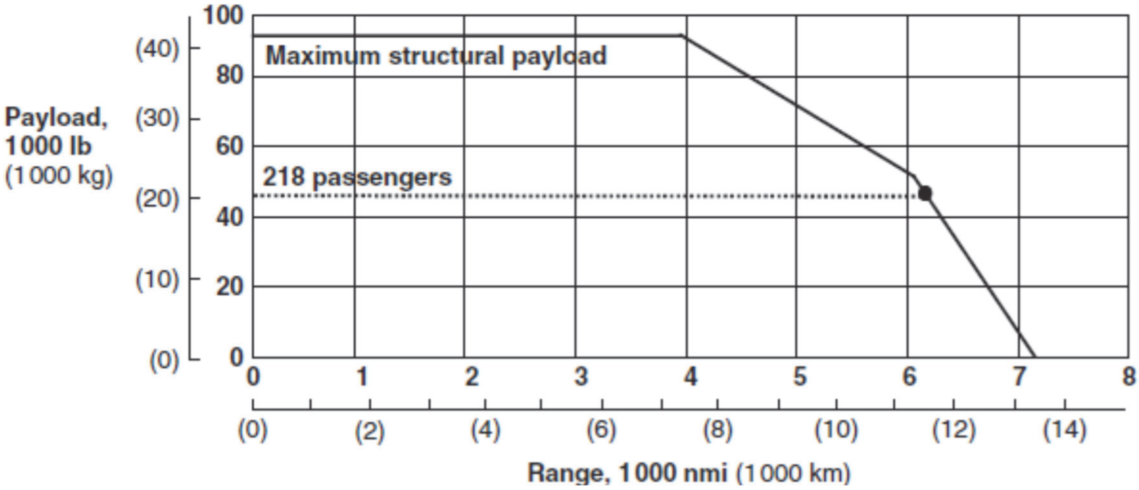
SELECTION CRITERIA

Aircraft are selected based on several criteria:

- Financial and economic issues: lease vs. ownership, new vs. second-hand aircraft, costs of acquisition, spare parts, supplementary equipment.
- Technical and performance characteristics: payload-range diagram, speed.
- Comfort.
- Commonality: fleet (crew flexibility, lower spare stocks, lower training costs to transfer to other aircraft of same manufacturer), engine manufacturer (across aircraft types).
- Environmental regulations: emissions, noise.
- Market and infrastructure: airport deployability (runway lengths, ground equipment compatibility, etc.), delivery times.
- Political issues: political influences (*Air France will buy Airbus if they can*), international trade issues.
- Marketing: first operator of particular type can have marketing advantage (has happened recently with A380 and B787).

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.



Originally, only aircraft with more than 2 engines were allowed to cross oceans, as the probability of engine failures was still relatively high. Since 1985, this has changed with the introduction of **Extended-range Twin-engine Operational Performance Standards** (ETOPS). This limits twin-engined aircraft to fly everywhere within 120 (1985), 180 (1988) or 207 (2001) minutes of the closest airport. Currently, this means that only the poles and the South Pacific cannot be reached. Furthermore, both the aircraft and the airline need an ETOPS-certification.

AIRCRAFT WEIGHT BREAKDOWN

- **Operating Empty Weight (OEW)**: aircraft structural weight excluding fuel and payload, including operators' items (includes flight crew!).
- **(Maximum) Zero Fuel Weight (MZFW)**: OEW + payload weight.
- **Maximum (Design) Take-Off Weight (MDTOW)**: maximum weight at which an aircraft is allowed to take-off.
- **Maximum Landing Weight (MLW)**: maximum weight at which an aircraft can land.

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). That means that pilots are able to abort the take-off up to the **decision speed** (V_1) and still stop before they run out of runway. Subsequent speeds are V_R (**rotation speed**) and V_2, the **take-off safety speed** (speed required to clear a 35 ft. obstacle at the end of the runway).

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.

MULTI-FLEET NETWORK MODEL

The multi-fleet network model is based on the hub-and-spoke network model on page 20.

Objective function

$$\max Profit = \sum_{i\in N}\sum_{j\in N}\left(\underbrace{Yield \times d_{ij} \times \left(x_{ij} + \sum_{m\in H} w^{i}{}_{mj}\right)}_{revenue} - \sum_{k\in K}\underbrace{CASK^{K} \times d_{ij} \times s^{k} \times z_{ij}^{k}}_{cost}\right)$$

Subject to constraints

Flow leaves the airport on a direct flight or on a hub flight

$$\sum_{j\in N} x_{ij} + \sum_{j\in N} y_{ij} \leq O_i, \quad \forall i \in N$$

Flow arrives at an airport on a direct flight or on a hub flight

$$x_{ij} + \sum_{m\in N} w^{i}{}_{mj} \leq q_{ij}, \quad \forall i,j \in N$$

Flow cannot be more than aircraft capacity (i.e., capacity verification)

$$x_{ij} + y_{ij} + \sum_{n\in N} w^{n}{}_{ij} \leq \sum_{k\in K} z_{ij}^{k} \times s^{k} \times LF, \quad \forall i,j \in N$$

Flow has to be conserved in hubs

$$y_{im} = \sum_{j\in N} w^{i}{}_{mj}, \quad \forall i \in N, m \in H$$

Maximum number of passengers leaving to hub j

$$y_{ij} \leq O_i \times h_j, \quad \forall i,j \in N$$

Maximum number of passengers arriving from i to j through hub n

$$w^{i}{}_{nj} \leq q_{ij} \cdot h_n, \quad \forall i,j,n \in N$$

Number of inbound aircraft should equal number of outbound aircraft (i.e., balance)

$$\sum_{j\in N} z_{ij} = \sum_{j\in N} z_{ji}, \quad \forall i \in N$$

Aircraft cannot be used for more time than they are available (i.e., productivity)

$$\sum_{i\in N}\sum_{j\in N}\left(\frac{d_{ij}}{sp^{k}} + LTO^{k}\right) \times z_{ij}^{k} \leq BT^{k} \times AC^{k}, \quad \forall k \in K$$

Aircraft cannot fly flight legs longer than their range

$$z_{ij}^{k} \leq a_{ij}^{k} \quad \rightarrow \quad a_{ij}^{k} = \begin{cases} 10000, & if\ d_{ij} \leq R_k \\ 0, & otherwise \end{cases}$$

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 financial and operational lease. The latter is further divided in three categories:

- dry lease: excluding crew;
- wet lease: including crew;
- damp lease: 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:

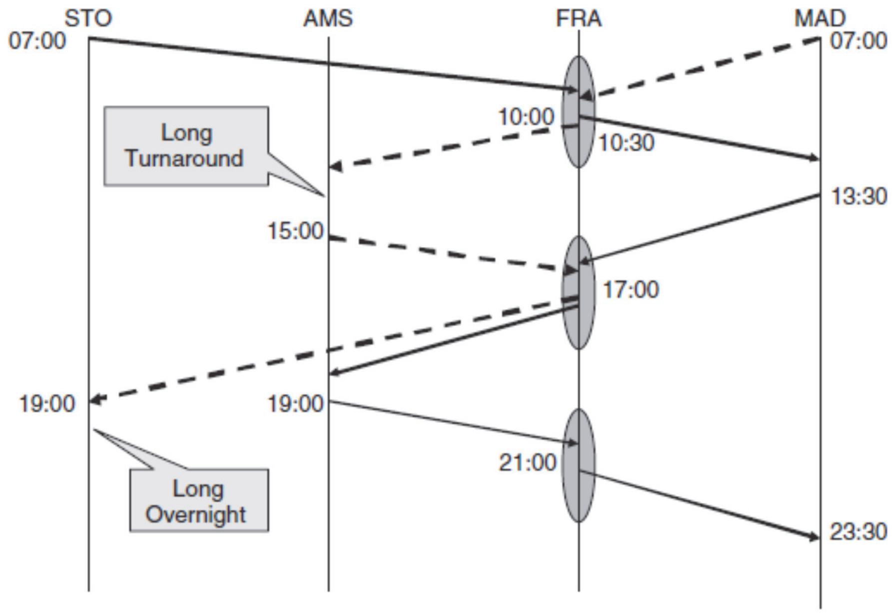
1. Estimate demand based on "baseline" frequency.
2. Calculate frequency to satisfy demand, while remaining profitable.
3. Compute new potential demand, based on new frequency.
4. Update frequencies and iterate.

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.

Schedules can be graphically represented in schedule maps, as shown below:

[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.



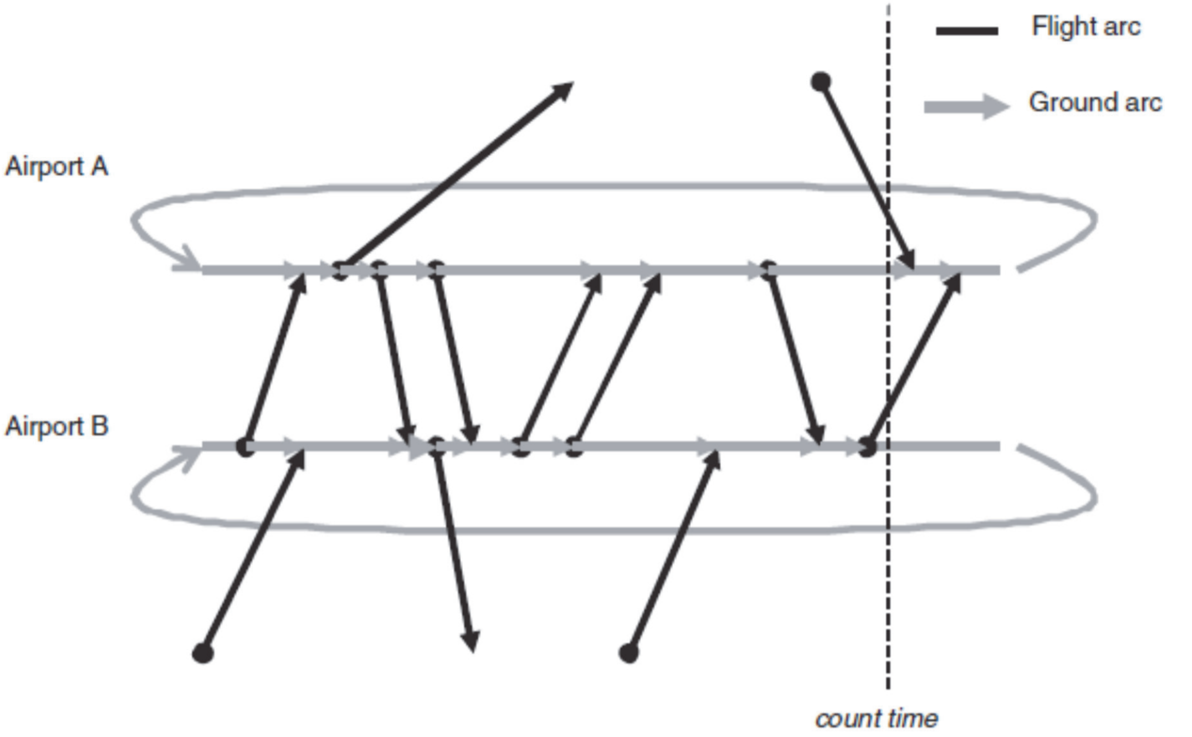
This also shows that one change has influences throughout the entire network. Therefore, airlines often keep to incremental changes, also in order not to upset loyal customers (that are accustomed to a particular timetable).

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;
- <u>each node represents a combination of time and space</u>.

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.

FLEET ASSIGNMENT MODEL

Sets

F	flights, i
$O(k,n)$	flight legs originating at node n in fleet k
$I(k,n)$	flight legs terminating at node n in fleet k
G	ground arcs, a
NG^k	overnight ground arcs
n^+	ground arcs originating at any node n
n^+	ground arcs terminating at any node n

Decision variables

f_i^k	$= 1$ if flight i is assigned to aircraft type k, $= 0$ otherwise
y_a^k	number of aircraft type k on the ground arc a

Parameters

d_i	distance of flight i
rev	revenue per RPK flown (average yield)
s	number of seats per aircraft
q_i	demand in flight i
AC^k	number of aircraft type k
oc_i^k	unit operation cost per ASK flown of aircraft type k for flight i
p_i^k	rejected demand
b_i	recapture rate
R^k	range of aircraft type k

Objective function

Minimize costs

$$\min \sum_{i \in F} \sum_{k \in K} oc_i^k \times s^k \times d_i \times f_i^k + \text{ground arc costs}$$

Maximize profit

$$\max \sum_{i \in F} \sum_{k \in K} \left[\left(\underbrace{rev \times d_i \times \min(q_i; s^k)}_{revenues} - \underbrace{oc_i^k \times d_i \times s^k}_{operating\ cost} \right) \times f_i^k \right]$$

Maximize profit, including spill cost

$$\max \sum_{i \in F} \sum_{k \in K} \left[\left(\underbrace{rev \times d_i \times \min(\overline{q_i}; s^k)}_{revenues} - \underbrace{oc_i^k \times d_i \times s^k}_{operating\ cost} - \underbrace{\boldsymbol{rev \times d_i \times \overline{p_i^k}}}_{\boldsymbol{spill\ cost}} \right) \times f_i^k \right]$$

Maximize profit, including spill cost and recapture (20%)

$$\max \sum_{i \in F} \sum_{k \in K} \left[\left(\underbrace{rev \times d_i \times \min(\overline{q_i}; s^k)}_{revenues} - \underbrace{oc_i^k \times d_i \times s^k}_{operating\ cost} - \underbrace{(\mathbf{1} - \boldsymbol{b_i}) \times rev \times d_i \times \overline{p_i^k}}_{spill\ cost} \right) \times f_i^k \right]$$

Subject to constraints

Each flight covered exactly once by one fleet type. Equality can also be $\leq$, if network planning is included.

$$\sum_{k \in K} f_i^k = 1, \quad \forall i \in F$$

Number of inbound aircraft should equal number of outbound aircraft (i.e., balance)

$$y_{n^+}^k + \sum_{i \in O(k,n)} f_i^k - y_{n^-}^k - \sum_{i \in I(k,n)} f_i^k = 0, \quad \forall n \in N^k, k \in K$$

Number of aircraft assigned cannot be more than number of aircraft available

$$\sum_{a \in NG^k} y_a^k \leq AC^k, \quad \forall k \in K$$

Aircraft cannot fly flight legs longer than their range

$$oc_i^k = \begin{cases} 10000, & if\ d_i \geq R_k \\ oc_i^k, & otherwise \end{cases}$$

Constraints on type of variables

$$f_i^k \in \{0,1\}, \quad \forall i \in F, k \in K$$
$$y_a^k \geq 0, \quad \forall a \in G^k, k \in K$$

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.

AIRCRAFT PAIRING MODEL

This model does not take balanced aircraft utilization into account.

Sets

R possible routings
F flights, j

Decision variables

x_j $= 1$ if flight j is selected, $= 0$ otherwise

Parameters

m_j number of maintenance opportunities for route j
$a_{i,j}$ $= 1$ if flight i is covered by route j, $= 0$ otherwise
N total number of aircraft in fleet

Objective function

$$\max \sum_{j=1}^{R} m_j x_j$$

Subject to constraints

Each flight operated exactly once

$$\sum_{j=1}^{R} a_{i,j} x_j = 1, \quad \forall i \in F$$

Number of selected routes cannot be more than number of aircraft available

$$\sum_{j=1}^{R} x_j \leq N$$

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. The model, however, is very similar to the aircraft pairing model.

Sets

P feasible pairings, j
K crew bases
F flights, i

Decision variables

x_j $= 1$ if pairing j is selected, $= 0$ otherwise

Parameters

c_j cost of crew for pairing j
$a_{i,j}$ $= 1$ if flight i is covered by pairing j, $= 0$ otherwise
$h_{k,j}$ $= 1$ if flight i is starts and ends at base k, $= 0$ otherwise
N_k total number of crew at base k

Objective function

$$\min \sum_{j=1}^{P} c_j x_j$$

Subject to constraints

Each flight operated exactly once

$$\sum_{j=1}^{P} a_{i,j} x_j = 1, \quad \forall i \in F$$

Number of selected routes cannot be more than number of crew available

$$\sum_{j=1}^{P} h_{k,j} x_j \leq N_k$$

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.

The crew rostering model is very similar to the aircraft and crew pairing models.

Sets

P feasible pairings over available roster days, i

R valid rosters, j

Parameters

h_j flight hours of roster j

$a_{i,j}$ $= 1$ if paring i is covered by roster j, $=$ 0 otherwise

Decision variables

x_j $= 1$ if pairing j is selected, $= 0$ otherwise

Objective function

Minimize deviation from 20 weekly hours

$$\min \sum_{j=1}^{R} |h_j - 20| x_j$$

Subject to constraint

Each paring (and therefore: each flight leg) covered exactly once

$$\sum_{j=1}^{P} a_{i,j} x_j = 1, \quad \forall i \in P$$

FUTURE TRENDS

1. Integrated schedule planning, as mentioned in Lecture 5: Network Planning, page 17.
2. Operations recovery and robustness, as discussed in Lecture 10: Robust Airline Scheduling, page 33.

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, airlines aim to catch as much revenue potential as possible. That is: 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 current, 3rd generation, systems have been introduced after the late `80s and:

- collect/maintain historical booking data (per flight, fare class and departure date);
- forecast future booking demand and no-show rates (per flight, fare class and departure date);
- computes expected show-up rates;
- calculates seats' limits for revenue maximization.

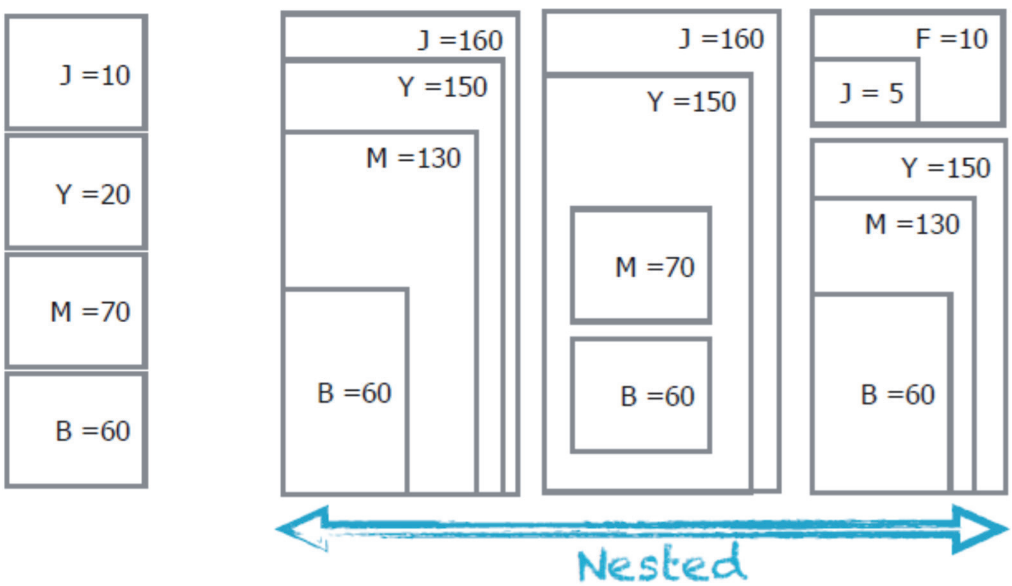
4th generation systems (currently introduced) are extending leg-based metrics with O-D metrics and takes the revenue value of the passengers' entire (network) itinerary into account.

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).



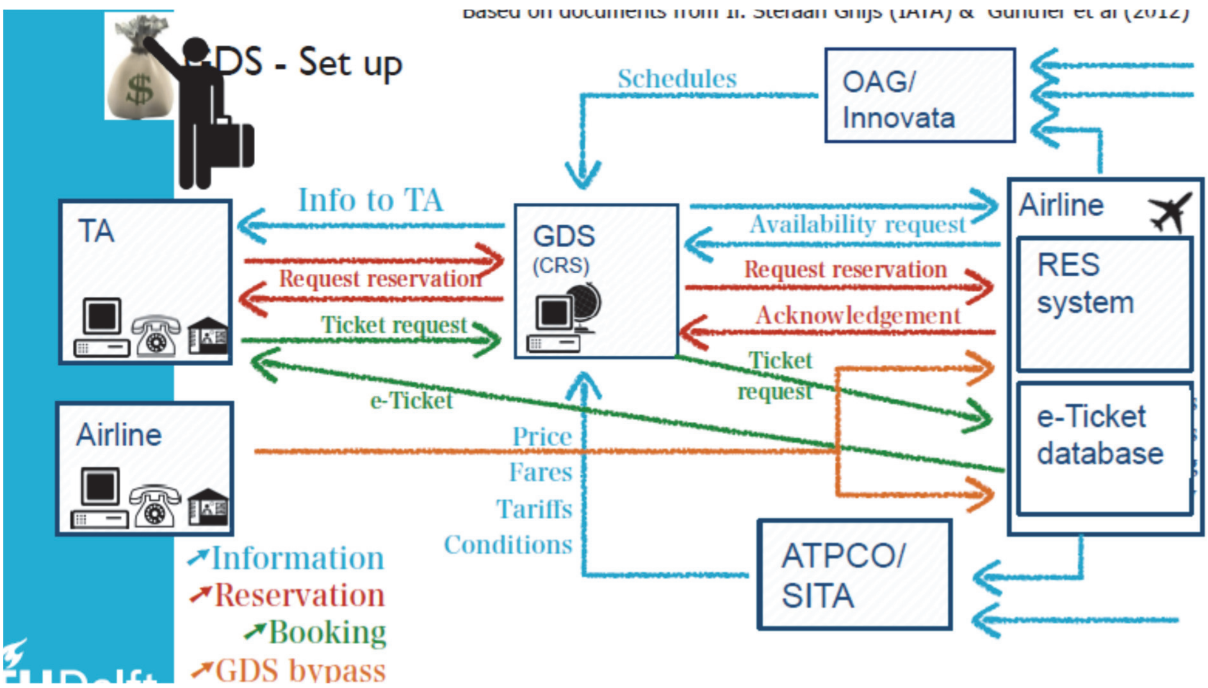
The **expected marginal seat revenue** model (EMSR or, updated, EMSRb) is a model to set booking limits, that takes into account that demand is uncertain (and deterministic limits will not be optimal). It assumes:

- 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: check-in, immigration, security, boarding / disembarkation, immigration, baggage claim.
- Goods handling: baggage check-in, security checks, sorting and loading / unloading, baggage claim.
- Interlining services: connecting passengers and cargo.

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: cleaning, catering (re-stocking), in-flight entertainment (loading magazines, newspapers, audio, video).
- Aircraft services: refuelling, routine maintenance checks, crew change, de-icing (if necessary).

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 (use more doors, use boarding schedule);
- catering (parallel catering, extra resources);
- cleaning (extra resources);
- goods handling (smooth supply of baggage, no surprises at the aircraft);
- fuelling (digital communication, connect as soon as possible).

BOARDING

Seat interference situation when window passenger has to pass already seated aisle passenger.

Aisle interference situation where someone is blocking the aisle.

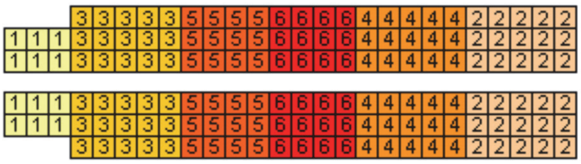
There are different boarding systems, in order of reduced average boarding time:

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

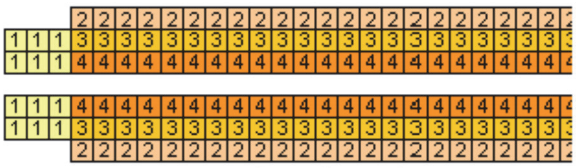
If the passenger interarrival time increases, the speed differences disappear.

Back-to-front boarding
(contingous rows from the back to the front)

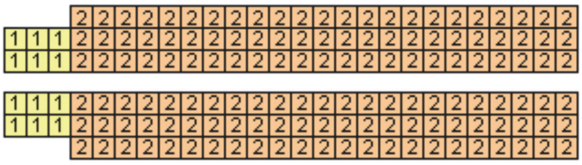
Block boarding
(window seats then middle and aisle seats)



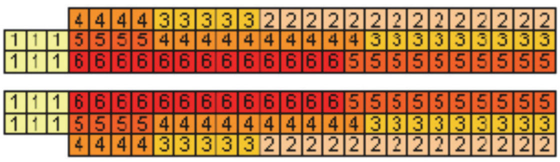
Rotating-zone boarding
(contingous rows alternating back and front)



Outside-in boarding
(window seats, then middle seats, then aisle seats)



Random boarding
(first class seats then all seats in economy)



Reverse-pyramid boarding
(Outside-in combined with back-to-front)

AIRLINES OPERATIONS CONTROL

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

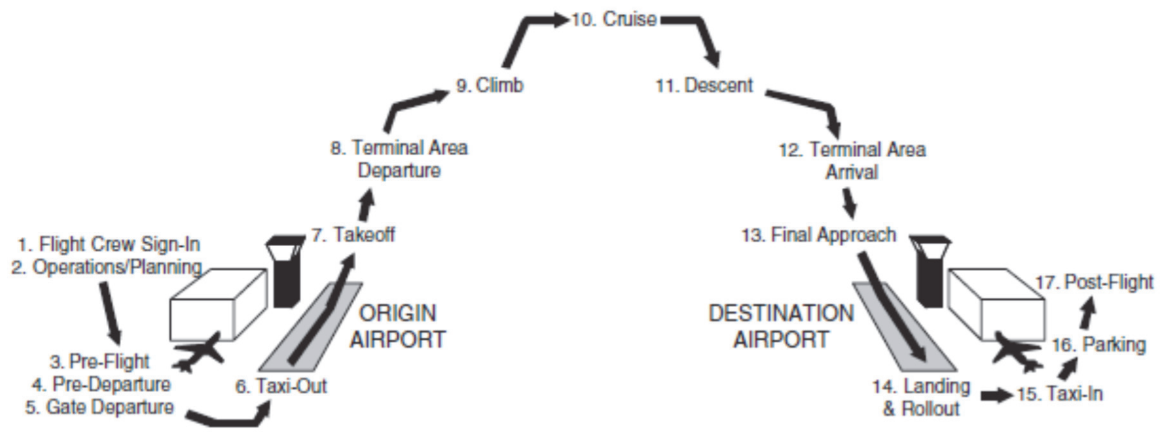
LECTURE 13: FLIGHT OPERATIONS

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. These follow from the below equations:

$$L = C_L \cdot \frac{1}{2}\rho V^2 S = W \Leftrightarrow V = \sqrt{\frac{W}{S}\frac{2}{\rho}\frac{1}{C_L}}$$

$$D = C_D \cdot \frac{1}{2}\rho V^2 S = T \Leftrightarrow T = \frac{C_D}{C_L}W$$

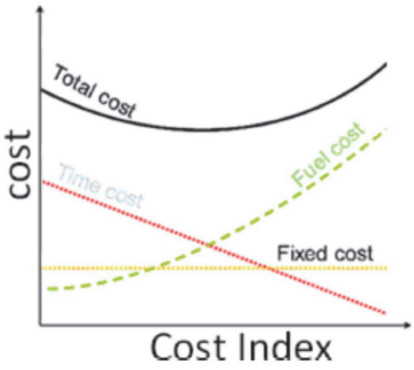
$$F = C_T \cdot T$$

$$\frac{V}{F} = \frac{1}{C_T W}\sqrt{\frac{W}{S}\frac{2}{\rho}\frac{C_L}{C_D^2}}$$

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: temperature deviations from standard conditions, local winds.
- En-route charges of countries overflown, depending on weight, distance flown, and price set by government.
- Distance.
- Avoiding geographical areas (war zones).
- ATC requirements, such as sticking to certain tracks.

Similarly, ATC requirements often prevent continuous climbs (beneficial as the aircraft gets lighter by burning fuel).