Cost Evaluation of Aircraft Systems

Prof. Dr.-Ing. Dieter Scholz, MSME

2017

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Chapter 1

Introduction

Prof. Dr.-Ing. Dieter Scholz, MSME

Contents

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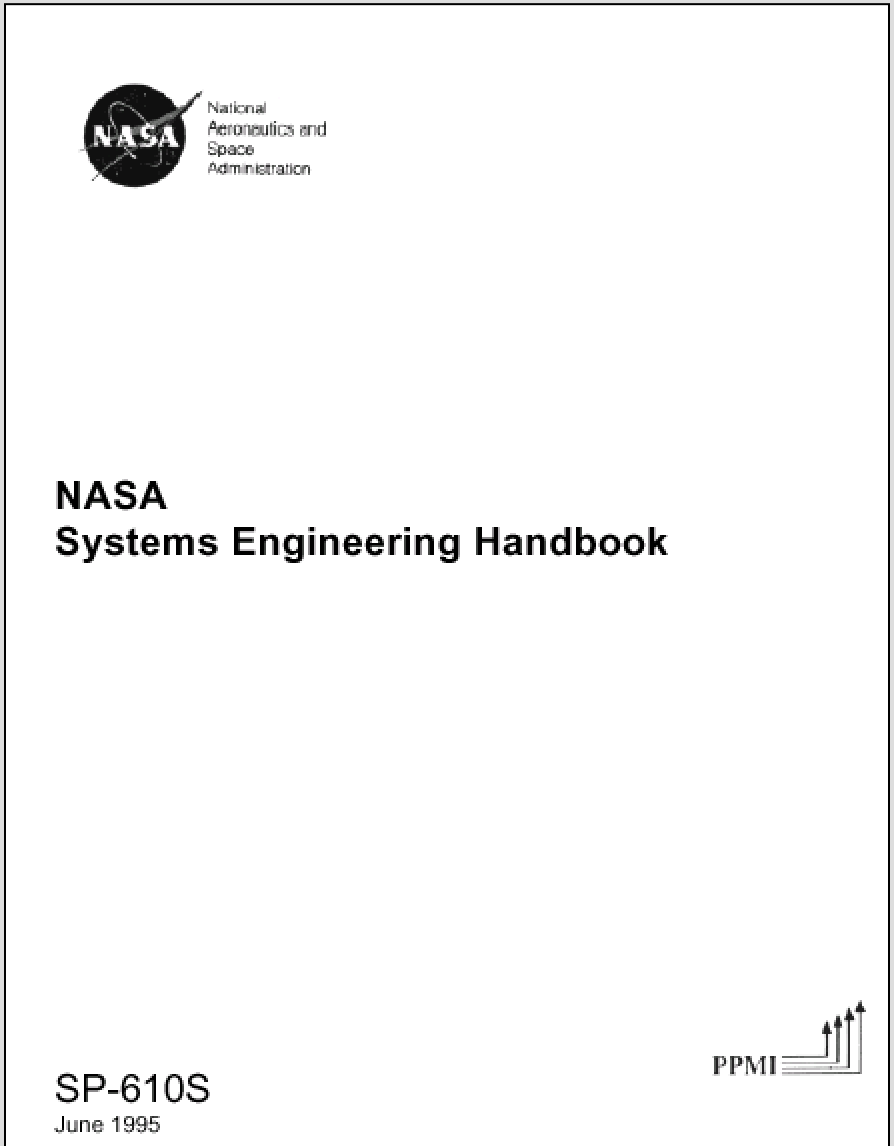
National Aeronautics and Space Administration

NASA
Systems Engineering Handbook

PPMI

SP-610S
June 1995

Main source of
Chapter 1 and Chapter 2

Systems: Definitions

A *system is* a set of interrelated components which interact with one another in an organized fashion towards a common purpose.

NASA 1995

A *system is* a combination of inter-related items arranged to perform a specific function.

WATOG 1992

Systems Approach

Essential to the *systems approach* is the recognition that a system exists, that it is embedded in a supersystem [environment] on which it has an impact, that it may contain subsystems, and that the system's objectives must be understood preferably explicitly identified.

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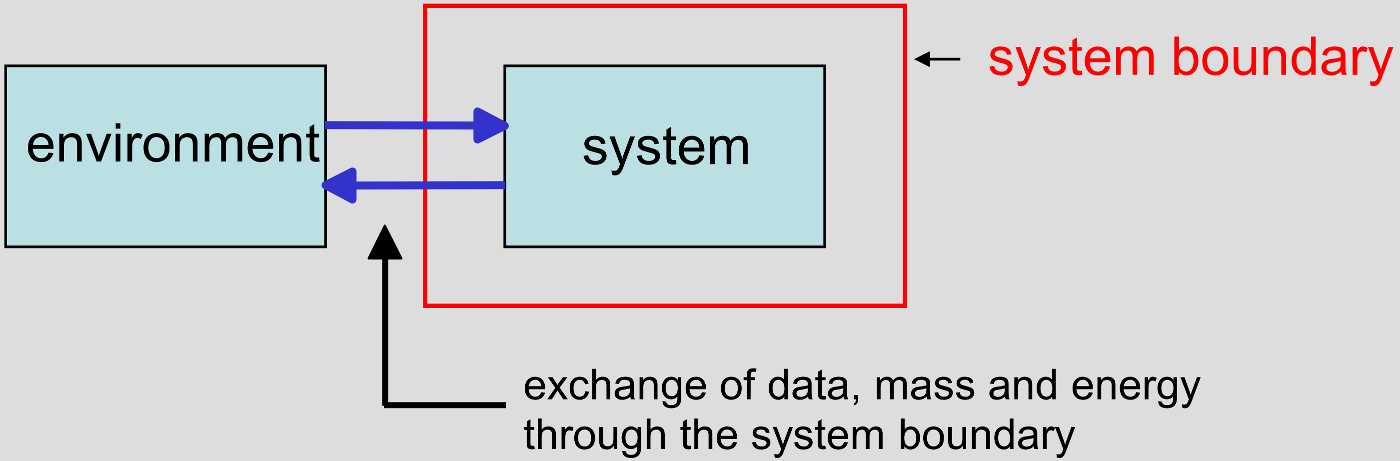
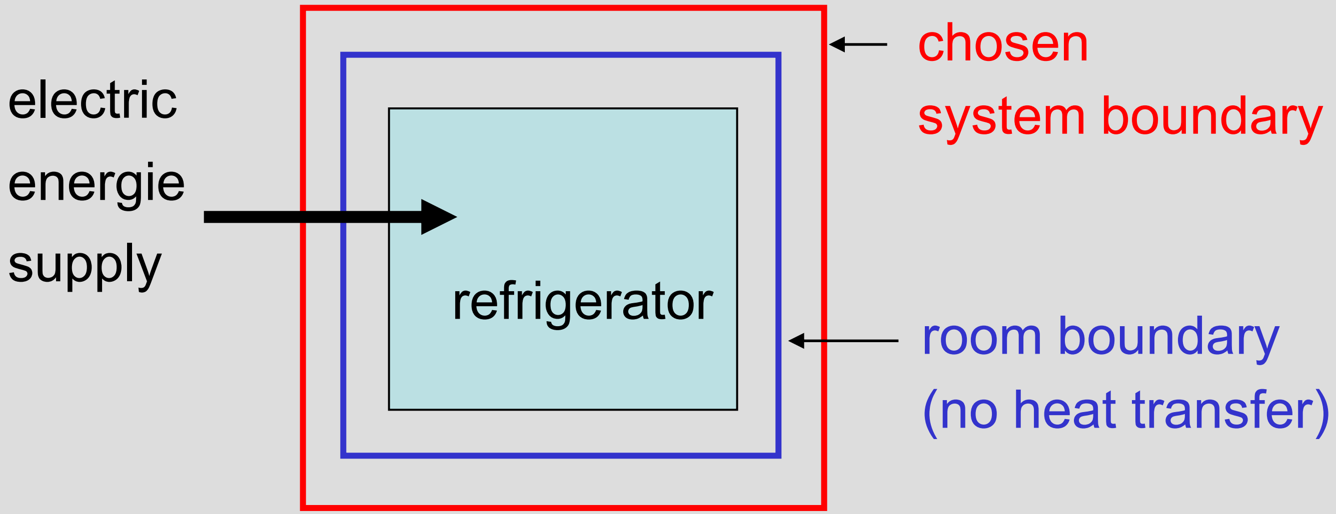
Systems: Boundary



Systems: Example



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ATA 2002

Aircraft Systems: Hierarchie

• system	(auxiliary power unit)
• subsystem	(power generator)
• component (unit)	(fuel control unit)
• subassembly	(valve)
• part	(seal)

WATOG 1992

The **identifier 29-31-03** points to

system	29
subsystem	31
unit	03

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Systems Engineering: Definition

Systems engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of **system goals**, creation of alternative **system design** concepts, performance of **design trades**, **selection** and **implementation** of the best design, **verification** that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals. The approach is usually applied repeatedly and recursively, with several increases in the resolution of the system baselines (which contain requirements, design details, verification procedures and standards, cost and performance estimates, and so on).

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Systems Engineering & Management

Systems engineering is performed in concert with *system management*. A major part of the system engineer's role is to provide information that the system manager can use *to make the right decisions*. This includes **identification of alternative design concepts**. An important aspect of this role is the creation of system models that facilitate assessment of the alternatives in various dimensions such as cost, performance, and risk.

NASA 1995

Systems Engineering & Design

Systems engineering differs from what might be called *design engineering* in that systems engineering deals with the relationships of the thing being designed to its supersystem [environment] and subsystems, rather than with the *internal details* of how it is to accomplish its objectives. The systems viewpoint is broad, rather than deep: it encompasses the system functionally from end to end and temporally from conception to disposal.

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Systems Engineering & Speciality Engineering

System engineers must also rely on contributions from the *specialty engineering* disciplines, in addition to the traditional design disciplines, for functional expertise and specialized analytic methods. These specialty engineering areas typically include reliability, maintainability, logistics, test, production, transportation, human factors, quality assurance, and safety engineering.

NASA 1995

System Design

System Design (System Synthesis) Methods

• Prognosis	(Prognose Methoden)
• State of the Art	(Stand der Technik)
• Competition	(Konkurrenzanalyse)
• Lessons Learned	
• Intuition	
• Brainstorming	
• Analogy	
• Design Methods	(Konstruktionsmethoden)
• Technical Rules	(Technische Regeln)
• Standards	(Normen)

System Analysis

Systems Analysis Methods

- Methods from Operations Research
- Methods from Economics
- Probability and Statistics
- Decision Theory
- Queueing Theory
- Game Theory
- Linear and Non-linear Programming

System Analysis

Systems Analysis Methods

- Design Review, Systemsimulation, Mock Up, Prototyp
- Safety und Reliability:
    - Fault Tree Analysis (FTA)
    - Dependence Diagrams DD or Reliability Block Diagrams (RBD)
    - Markov Analyis (MA)
    - Failure Mode and Effect Analysis (FMEA)
    - Zonal Safety Analysis (ZSA)
    - Particular Risk Analysis
    - Common Mode Analysis

Cost and Effectiveness: Definitions

The *cost* of a system is the foregone value of the resources needed to design, build, and operate it. Because resources come in many forms: work performed by ... personnel and contractors, materials, energy, and the use of facilities and equipment such as wind tunnels, factories, offices, and computers it is often convenient to express these values in common terms by using monetary units (such as dollars).

The *effectiveness* of a system is a quantitative measure of the degree to which the system's purpose is achieved. Effectiveness measures are usually very dependent upon system performance.

NASA 1995

Cost and Effectiveness: Definitions

The *cost-effectiveness* of a system combines both the cost and the effectiveness of the system in the context of its objectives. While it may be necessary to measure either or both of those in terms of several numbers, it is sometimes possible to combine the components into a meaningful, single-valued objective function for use in design optimization.

Even without knowing how to trade effectiveness for cost, designs that have lower cost and higher effectiveness are always preferred.

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Cost and Effectiveness: Application

The *objective of systems engineering* is to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering performance, cost, schedule, and risk.

A cost-effective system must provide a particular kind of balance between effectiveness and cost: the system must provide the most effectiveness for the resources expended or, equivalently, it must be the least expensive for the effectiveness it provides.

NASA 1995

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1 Introduction

Evaluation by Trade Studies

Design *trade studies* ... attempt to find designs that provide a better combination of the various dimensions of cost and effectiveness. When the starting point for a design trade study is inside the envelope, there are alternatives that reduce costs without decreasing any aspect of effectiveness or increase some aspect of effectiveness with out decreasing others and without increasing costs.

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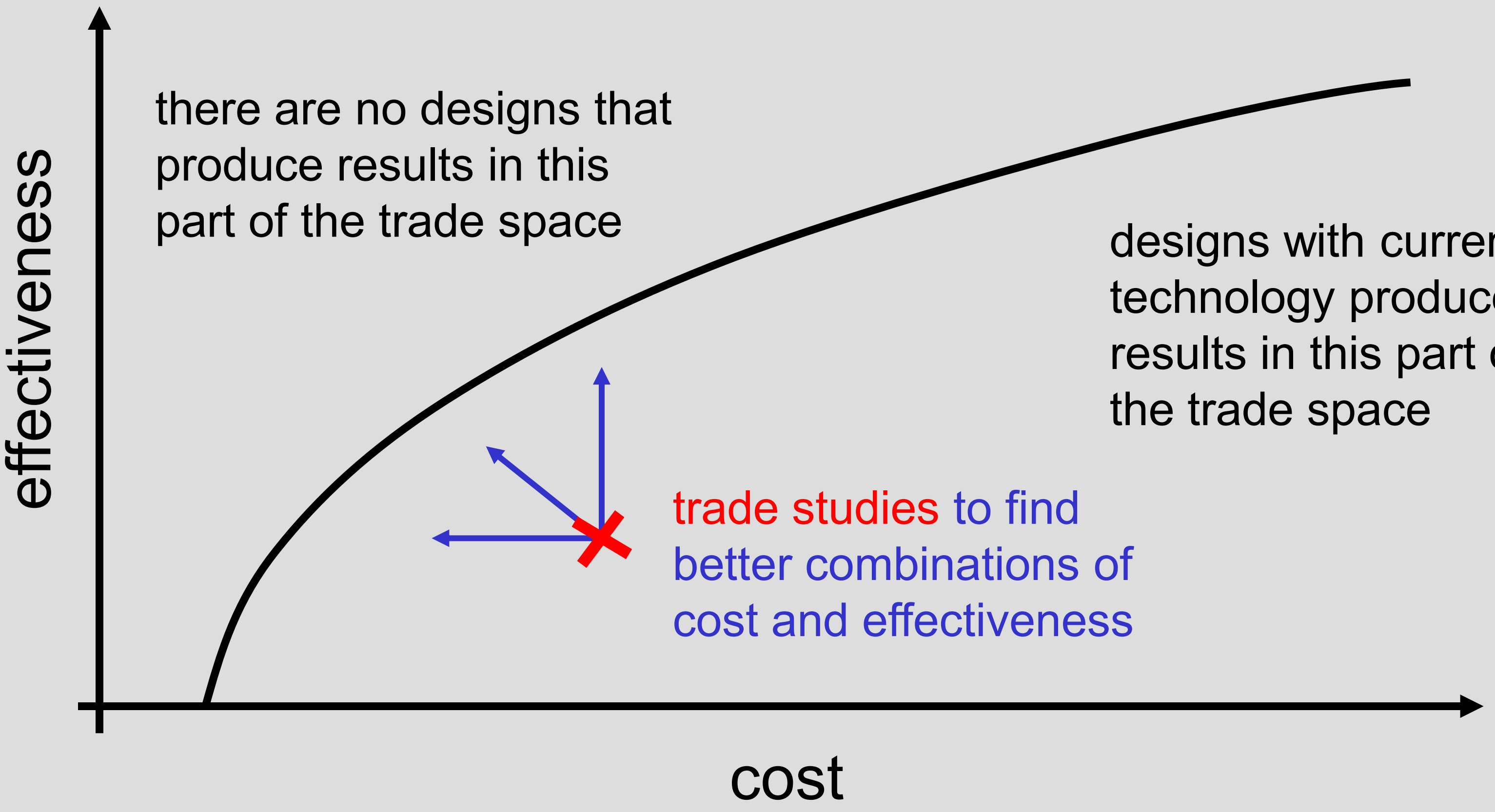
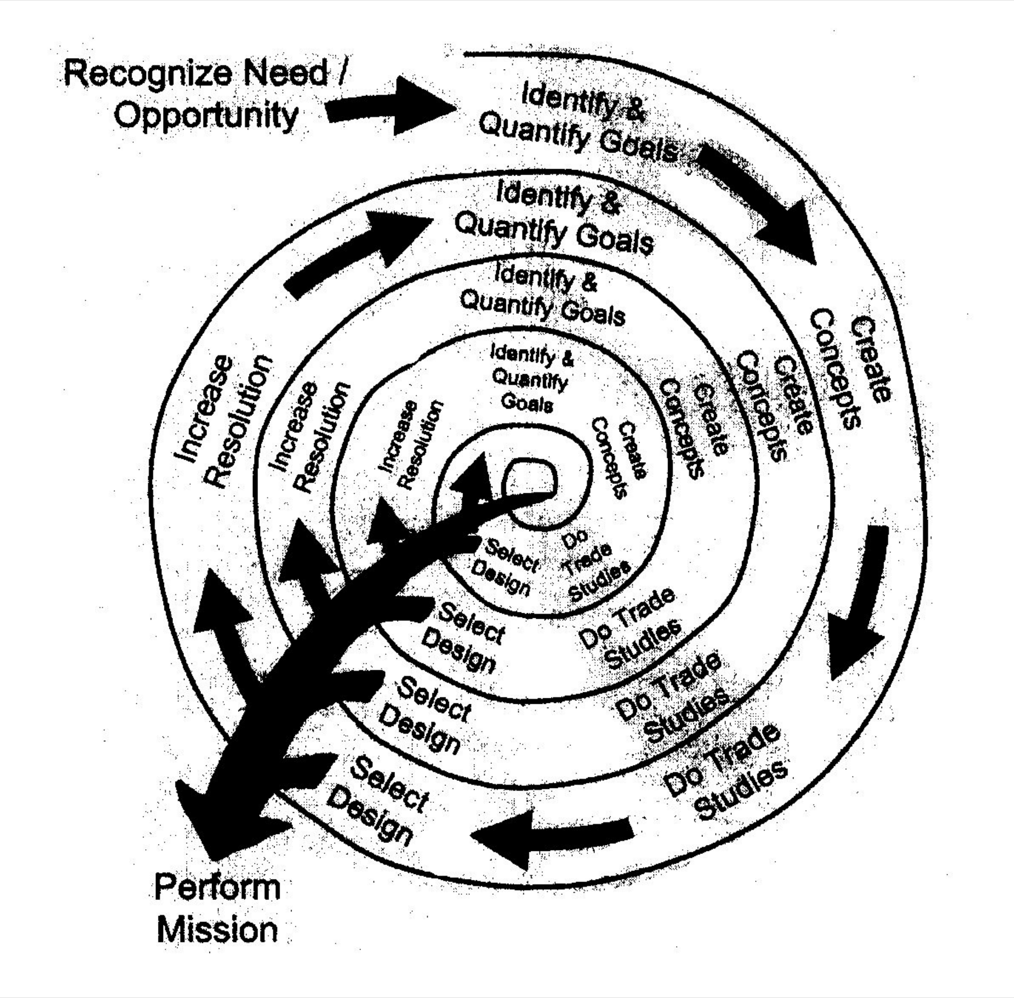
Trade Studies, Cost and Effectiveness



Doctrine of Successive Refinement



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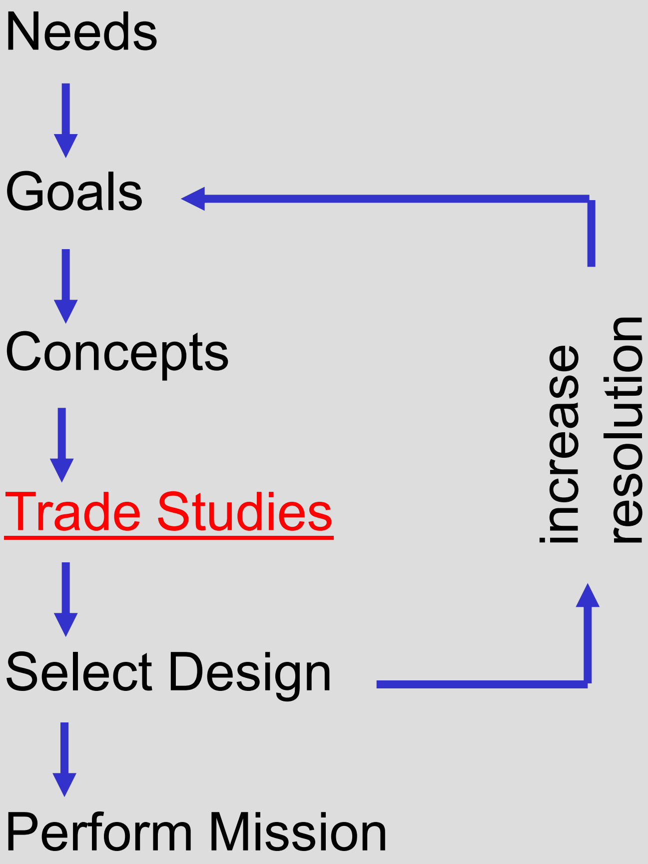
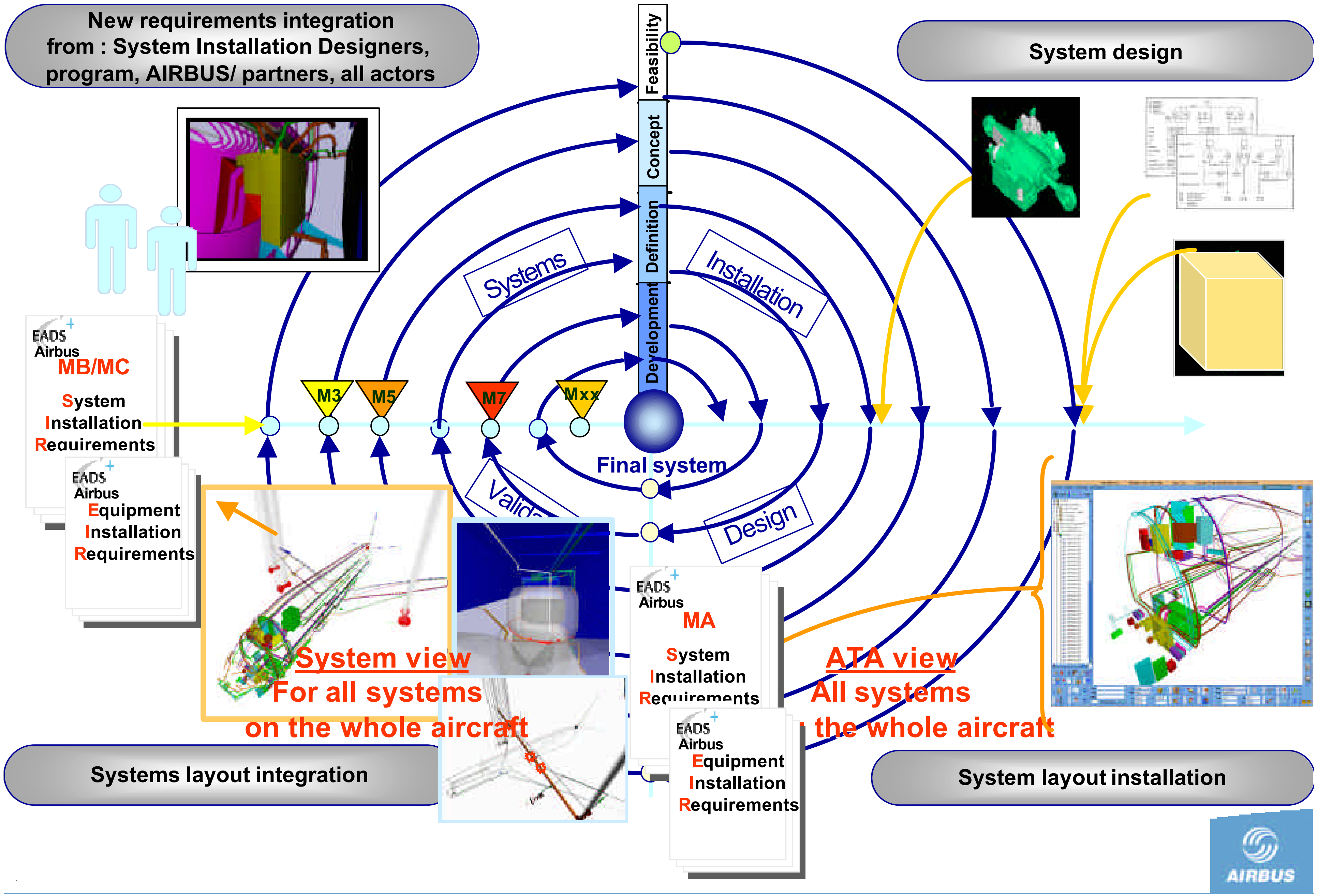


Process Principle - Systems Layout Integration process



AIRBUS

Doctrine of Successive Refinement

Identify and Quantify Goals. Before it is possible to compare the cost-effectiveness of alternative system design concepts, the *mission* to be performed by the system must be delineated. The goals that are developed should cover all relevant aspects of effectiveness, cost, schedule, and risk, and should be traceable to the goals of the supersystem.

Create Alternative Design Concepts. Once it is understood what the system is to accomplish, it is possible to devise a variety of ways that those goals can be met. Sometimes, that comes about as a consequence of considering alternative functional allocations and integrating available subsystem design options.

Do Trade Studies. Trade studies begin with an assessment of how well each of the design alternatives meets the system goals (effectiveness, cost, schedule, and risk, both quantified and otherwise). The ability to perform these studies is enhanced by the development of system models that relate the design parameters to those assessments.

Controlled modification and development of design concepts, together with such system models, often permits the use of formal optimization techniques to find regions of the design space that warrant further investigation.

Select Concept. Selection among the alternative design concepts is a task for the system manager, who must take into account the subjective factors that the system engineer was unable to quantify, in addition to the estimates of how well the alternatives meet the quantified goals (and any effectiveness, cost, schedule, risk, or other constraints).

When it is possible, it is usually well worth the trouble to develop a mathematical expression, called an *objective function,* that expresses the values of combinations of possible outcomes as a single measure of cost-effectiveness.

Doctrine of Successive Refinement

Increase the Resolution of the Design. One of the first issues to be addressed is how the system should be subdivided into subsystems. (Once that has been done, the focus changes and the subsystems become systems from the point of view of a system engineer.

Implement the Selected Design Decisions. When the process of successive refinement has proceeded far enough, the next step is to reverse the partitioning process. When applied to the system architecture, this "unwinding" of the process is called *system integration. Conceptual* system integration takes place in all phases of the project life cycle. That is, when a design approach has been selected, the approach is verified. *Physical* integration is accomplished during the finer levels of resolution, pieces must be tested, assembled and/or integrated, and tested again. The purpose of *verification* of subsystem integration is to ensure that the subsystems conform to what was designed and interface with each other as expected *Validation* consists of ensuring that the interfaced subsystems achieve their intended results. While validation is even more important than verification, it is usually much more difficult to accomplish.

Perform the Mission. Eventually, the system is called upon.

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Incremental Development

If the user requirements are too vague to permit final definition, one approach is to develop the project in predetermined incremental releases. The first release is focused on meeting a minimum set of user requirements, with subsequent releases providing added functionality and performance. This is a common approach in software development.

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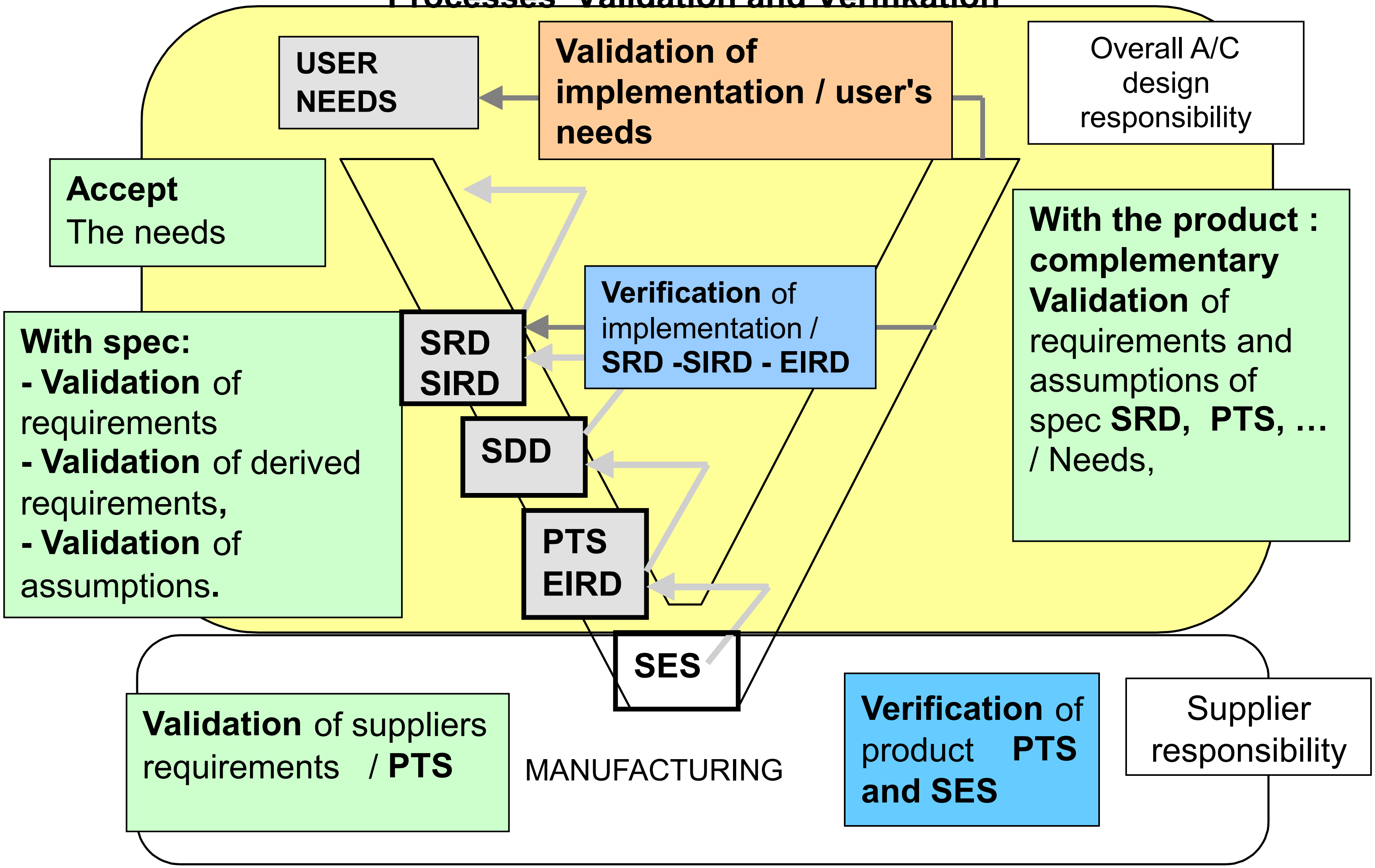
Requirements Engineering

V-Model

Processes Validation and Verifikation



Summery - Chapter 1

An **Evaluation of Aircraft Systems** ...

- takes on a systems approach
- takes place within systems engineering
- looks at cost, performance and risk ...
- typically includes reliability and maintainability
- with a broad viewpoint
- evaluation by trade studies to find better design combinations for cost and effectiveness

Chapter 2

Trade Studies

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2 Trade Studies

- Objective, Levels, Process
- Alternatives
- Characteristics, Parameters, Criteria
- Measurement Methods
- Selection Rules
- Report, Lessons Learned
- Example

Objective and Levels of Formality

Objective of Trade Studies

Trade studies provide an objective foundation for the selection of one or two or more alternative approaches to solutions of an engineering problem.

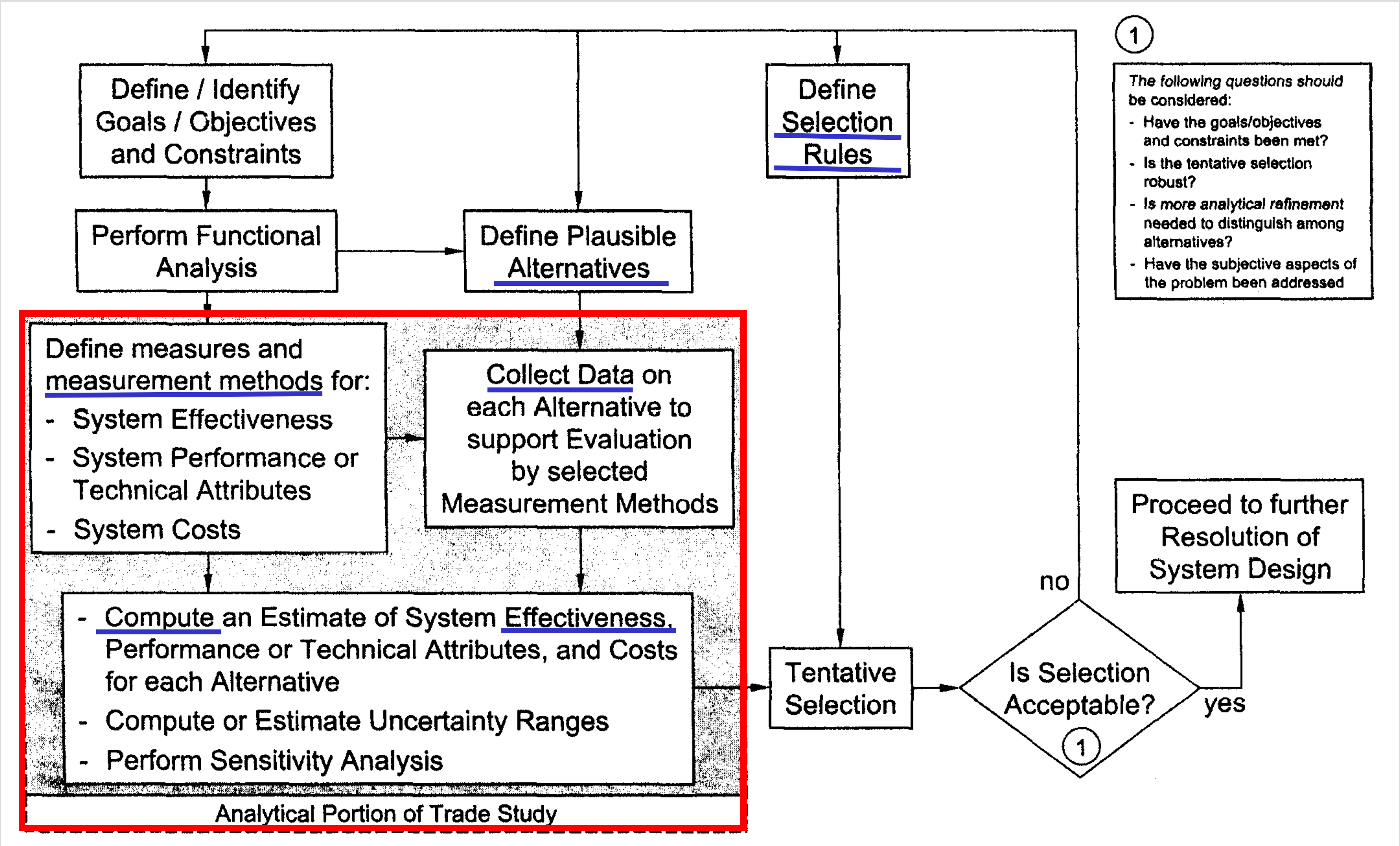
Trade Study Levels of Formality

Formal: Formally conducted with results reviewed at technical reviews.

Informal: Follows the same methodology as a formal trade study but is not documented as formally since it is of less importance.

Mental: A selection made based on the judgement of the analyst or designer which does not require the rigour of a more formal study and for which the consequences are not too important, one alternative clearly outweighs others, and/or time is not available for a more formal approach.

Trade Study Process



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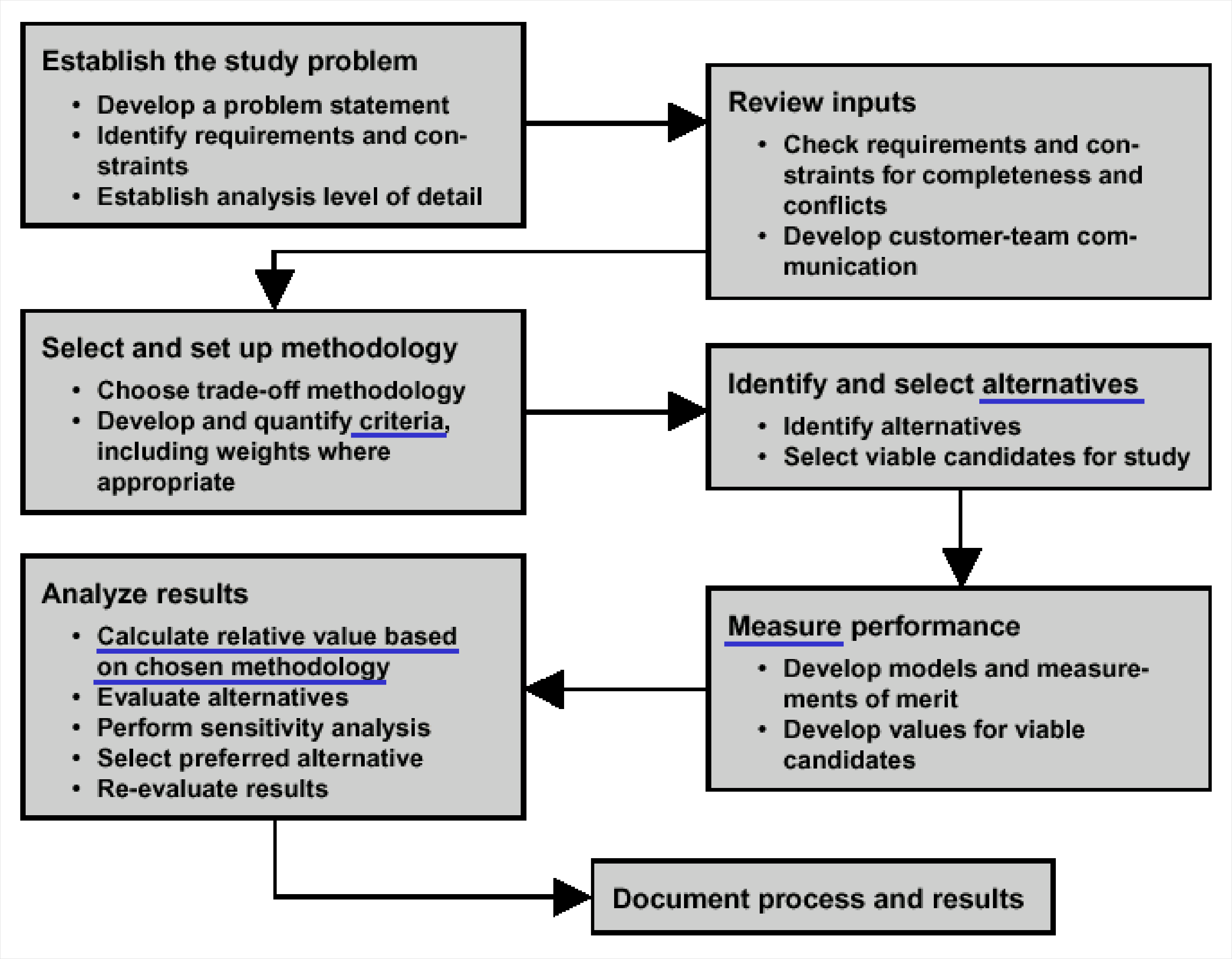
Trade Study Process



DOD 2001

Contents

2 Trade Studies

- Objective, Levels, Process
- <u>Alternatives</u>
- Characteristics, Parameters, Criteria
- Measurement Methods
- Selection Rules
- Report, Lessons Learned
- Example

Alternatives

- A trade study should consider between 4 and 7 alternatives.
- Design alternatives should be comparable in completeness.
- All alternatives have to meet minimum specification.
- Inform management, if no alternative is going to meet minimum specification.

Alternatives

	1.)	2.)	3.)
Subsystem 1	Principle alpha	Principle beta	---
Subsystem 2	Principle A	Principle B	Principle C
Subsystem 3	Principle 1	Principle 2	---
Subsystem 4	Principle I	Principle II	Principle III

The system consist of subsystems.

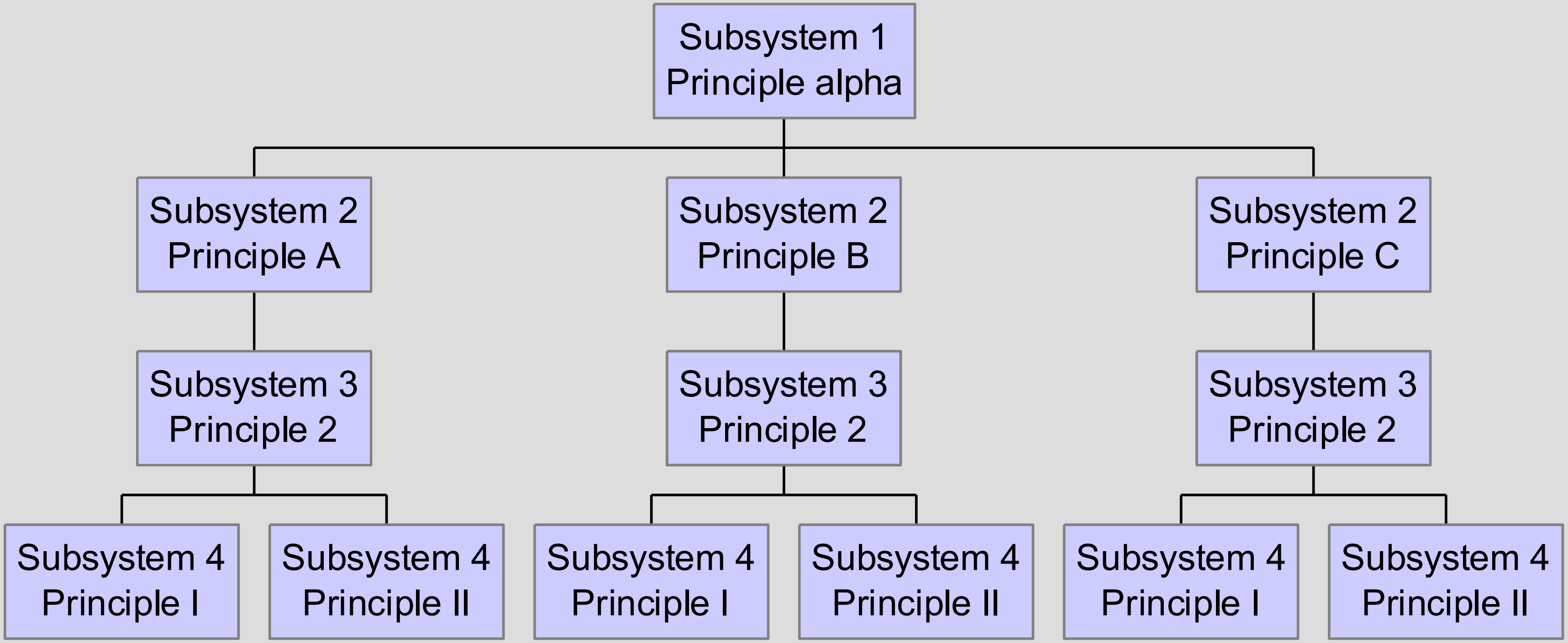
For each subsystem several technical principles can be applied.

The most promising principles are highlighted.

They form the basis of the trade tree (see next page).

Alternatives

Trade Tree



One way to represent the trade study alternatives under consideration is by a trade tree.

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2 Trade Studies

- Objective, Levels, Process
- Alternatives
- <u>Characteristics, Parameters, Criteria</u>
- Measurement Methods
- Selection Rules
- Report, Lessons Learned
- Example

Characteristics, Parameters, Criteria

- Main **characteristics** are:
  - Performance characteristics. They shall be independent of each other. Performance **parameters** are e.g.: payload, range, fuel consumption
  - Cost characteristics. They include: development, production, maintanance.
  - Risk. It may be decomposed into: cost riks, schedule risk, performance risk.
- Prefer to select *quantifiable* characteristics!
- Select only those characteristics that reflect *needs* of your system!
- Characteristics and parameters form the evaluation **criteria**. Key criteria are: performance, cost, risk

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2 Trade Studies

- Objective, Levels, Process
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- Characteristics, Parameters, Criteria
- <u>Measurement Methods</u>
- Selection Rules
- Report, Lessons Learned
- Example

Measurement Methods

- Measurement methods describe how to assign **scores** to *characteristics* (*parameters*).
- Assigning scores can be very subjective. You can get more objective results with:
  - asking **several experts** and calculate an average score
  - define a **mathematical relationship** between the parameter value and the score
  - **break scoring tasks into subtasks**:
    - subdivide a characteristic into several separate characteristics
    - define measurement methods for each of these characteristics
    - combine the sub-scores

Contents

2 Trade Studies

Selection Rules

Defining the selection rule is the step of explicitly determining **how** the outcome variables will be used **to make a selection** of the preferred alternative.

As an example, a selection rule may be to choose the alternative with the highest estimated system effectiveness that costs less than x dollars, meets safety requirements, and possibly meets other political or schedule constraints.

Selection rules can define how **alternatives are sequenced** from most preferred to least preferred.

The selection should not be accepted blindly. There is usually a need to **subject the results to a "reality check"** by considering a number of questions. Have the goals, objectives, and constraints truly been met? Is the tentative selection heavily dependent on a particular set of input values to the measurement methods, or does it robust?

Selection Rules

Choose the alternative ...

... that **maximizes net benefits** (benefits minus costs) - requires that benefits can be measured in the same units as the costs. This rule is used in cost-benefit analyses.

... that **maximizes effectiveness** for a given level of cost - requires that each of the alternatives be placed on an equal cost basis.

... that **minimizes cost** for a given level of effectiveness - requires that each of the alternatives be put on an equal effectiveness basis. This selection rule will be expended in Chapter 3 to the method DOCsys.

... with the **highest value of the cost-effectiveness** objective function.

Selection Rules

Linear Combination of Scores (**Nutzwertanalyse**) NASA 1995

Calculating a figure of merit for each alternative by *linearly combining* its scores computed for each of the objectives: **compute a weighted sum of the scores** (see example).

The weights used in computing the figure of merit can be

a) assigned a priori or

b) determined using other trade methods:

- Analytic Hierarachy Process (AHP) (pair-wise comparisons)
- Multi Attribute Utility Theory (MAUT) (not explained here).

Nutzwertanalyse nach: Zangemeister 1976

Selection Rules

Analytic Hierararchy Process (AHP)

NASA 1995

AHP is a decision technique in which a figure of merit is determined for each of several alternatives through a series of pair-wise comparisons.

1. Describe the alternatives under consideration.
2. Develop a set of high-level evaluation objectives
3. Decompose each high-level evaluation objective into a hierarchy of evaluation attributes that clarify the meaning of the objective.
4. Determine from evaluators ("experts") the relative importance of the evaluation objectives and attributes through pair-wise comparisons. (=> objective weights)
5. Have each evaluator make separate pair-wise comparisons of the alternatives with respect to each evaluation attribute. This produces with objective weights from step 4 a single figure of merit for each alternative.
6. Iterate the questionnaire and AHP evaluation process until a consensus ranking of the alternative is achieved.

Selection Rules

Selection Rules When Uncertainty Predominates

NASA 1995

The selection of the best alternative may need to be handled differently if uncertainty predominates. This is because of the general propensity of decision makers to show risk-averse behavior when dealing with large variations in cost and/or effectiveness outcomes. In such cases, the mean value is not a satisfactory point measure, because it does not take the probabilities into account.

1. Maximum of expected value (Erwartungswert):

$$E(X) = \sum_{i=1}^{n} X(\omega_i) \cdot P(\omega_i)$$

X : score $\quad P$: probability $\quad \omega$: characteristic

2. Minimum of maximum loss (minimax rule).

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2 Trade Studies

Trade Study Report

Trade study reports should be prepared for each trade study. At a minimum, each trade study report should identify:

- The system under analysis
- System goals and objectives (requirements) and constraints
- The measurement methods (models) used
- All data sources used
- The alternatives chosen for analysis
- The selection rule used
- The computational results, including uncertainty ranges and sensitivity analyses performed
- The recommended alternative.

Trade Study Lessons Learned

- Individual evaluators may tend to reflect the institutional biases and preferences of their respective organizations. The results, therefore, may depend on the mix of evaluators.
- If the wrong weights, objectives, or attributes are chosen in either technique, the entire process may obscure the best alternative.
- In a group of evaluators, agree on the weights that should be assigned to the characteristics in a first step. Do not change the weights according to the outcome of the trade study.

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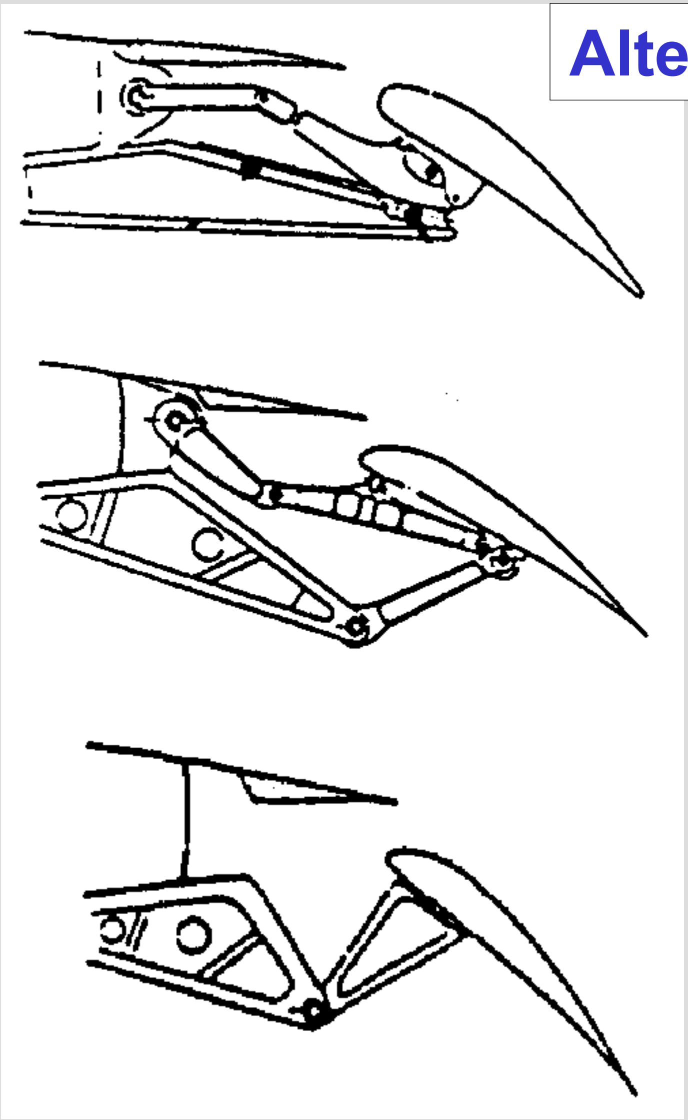
Example



Alternatives

Track

Linkage

Pivot Point

Evaluation of three High-Lift Systems

Method:

Linear Combination of Scores

Scholz 1991

Example

Data Collection

	Pivot Point	Linkage	Track	Bemerkungen
Start	+ 311 ft	– 83 ft	Basis	Denver, ISA +31°C, TOW für 1000 nm, X – 200 ER: Startstrecke.
Landung und Anflug: Anfluggeschwindigkeit v_{app}	139 kts	135 kts	135 kts	
				Für X–200 ER mit MLW = 51730 kg.
Dispatch Reliability	$1.0 - 3.0 * 10^{-4}$ (2 Syst.) $1.0 - 4.8 * 10^{-4}$ (1 Syst.)	$1.0 - 5.4 * 10^{-4}$	$1.0 - 6.0 * 10^{-4}$	
Ausfallwahrscheinlichkeit ("flap–less landing")	$2.8 * 10^{-5}$ (2 Syst.) $1.7 * 10^{-4}$ (1 Syst.)	$1.7 * 10^{-5}$	$1.7 * 10^{-5}$	
Zuverlässigkeit , relativ	1.0 (2 Syst.) 0.8 (1 Syst.)	0.9	1.0	Beeinflußt die Wartungskosten; abgeschätzt für MPC 75.
RC	0.85 Mio DM	0.96 Mio DM	1.26 Mio DM	
F NRC	5.6 Mio DM	4.6 Mio DM	5.3 Mio DM	
E NRC	2.	2.	1.	
DMC	1.56 DM/FH	2.34 DM/FH.	4.43 DM/FH	Berechnet nach MTBUR existierender Flugzeuge.
Gewicht	689.4 kg	752.9 kg	930.2 kg	
Tankvolumen / Kraftstoffmasse	Basis	Δ = + 720 kg	Δ = + 720 kg	720 kg entsprechen einer Hinterholmverschiebung von 3 %. Annahme: gleicher Füllfaktor.
Kommunalität der Flap–/Slat–Antr.	2.	1.	1.	
Weiterentwicklungspotential	2.	1.	1.	
Platzbedarf hinter Hinterholm	keine Unterschiede	keine Unterschiede	keine Unterschiede	
Verbräuche im Antrieb	keine Unterschiede	keine Unterschiede	keine Unterschiede	
Probleme bei der Zulassung	2.	1..	1.	
Entwicklungsrisiko	3.	2.	1.	
Termine des Programms	3.	2..	1.	

1. ; 2. ; 3. : Abschätzung einer Bewertungsrangfolge bei Mangel an Daten.

Scholz, EV52

Example

Measurement Method & Selection Rule

Linear Combination of Scores (Nutzwertanalyse)

	Bewertungsfaktor			Pivot Point		Linkage		Track	
				Punkte	Produkt	Punkte	Produkt	Punkte	Produkt
Start	80	40	20	0	0	2	40	1	20
Landung und Anflug			10	1	10	2	20	2	20
Dispatch Reliability			5	2	10	1	5	0	0
Ausfallwahrscheinlichkeit ("flap–less landing")			5	1	5	2	10	2	10
RC		40	8	2	16	1	8	0	0
F NRC			4	0	0	2	8	1	4
E NRC			4	1	4	1	4	2	8
DMC			8	2	16	0	0	0	0
Gewicht			16	2	32	1	16	0	0
Tankvolumen / Kraftstoffmasse	20	20	5	0	0	1	5	1	5
Kommunalität der Flap–/Slat–Antr			2.5	0	0	1	2.5	1	2.5
Weiterentwicklungspotential			5	0	0	2	10	2	10
Platzbedarf hinter Hinterholm			2.5	1	2.5	1	2.5	1	2.5
Verbräuche im Antrieb			2.5	1	2.5	1	2.5	1	2.5
Probleme bei der Zulassung			2.5	1	2.5	2	5	2	5
Entwicklungsrisiko	Diese Bewertungskriterien sind einer systematischen Betrachtung entzogen.								
Termine des Programms									
Summe	100	100	100		100.5 (2.)		138.5 (1.)		89.5 (3.)

Bewertungspunkte: *0 = unterdurchschnittlich ; 1 = durchschnittlich ; 2 = überdurchschnittlich*

Scholz, EV52

Analytic Hierarchy Process (AHP)

	Evaluation Criteria Weighting											Ranking				
Example Attribute	Low NRC	Low RC	Low Weight	Low Risk	Less Operational impact	Good Operational reliability	Maintainability	No Impact on flying fleet	LowDMC	Low Certification risk	Weighting Factor		Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
Low NRC		0	0	0	0	0	5	0	0	0	5		0,75	0,75	0,00	0,25	1,00
Low RC	10		0	0	0	0	5	0	0	0	15		1,00	1,00	0,25	0,50	1,00
Low Weight	10	10		5	5	5	10	5	5	0	55		1,00	1,00	0,25	0,00	1,00
Low Risk	10	10	5		5	0	10	0	5	0	45		1,00	1,00	0,00	0,25	0,00
Less Operational impact	10	10	5	5		0	10	0	0	0	40		0,00	0,25	1,00	1,00	1,00
Good Operational reliability	10	10	5	10	10		10	5	10	0	70		0,25	0,25	1,00	1,00	1,00
Maintainability	5	5	0	0	0	0		0	0	0	10		1,00	1,00	0,75	1,00	1,00
No Impact on flying fleet	10	10	5	10	10	5	10		10	5	75		0,50	0,25	1,00	0,75	0,25
Low DMC	10	10	5	5	10	0	10	0		0	50		1,00	1,00	0,50	0,25	1,00
Low Certification risk	10	10	10	10	10	10	10	5	10		85		1,00	0,00	0,00	0,25	0,00
												Ranking	318,75	225,00	235,00	230,00	263,75

Summery - Chapter 2

The purpose of **Trade Studies** is to...

- look at various alternatives
- its characteristics and parameters
- define measurement method in order to convert the characteristics and parameters into scores
- define selction rules to combine the scores to cost and efficiency values
- from which the alternatives can be placed into a sequence
- and a selction of the best alternative can be made.

Chapter 3

Direct Operating Costs for Aircraft Systems

DOCsys

Prof. Dr.-Ing. Dieter Scholz, MSME

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3 Direct Operating Costs for A/C systems

- Introduction
- Equations
- DOCsys Program
- DOCsys Example

Introduction

DOCsys ...

- is a method to perform **trade studies** for **aircraft systems**, subsystems or parts
- is based on the selection rule "**minimizing costs**" for a given level of effectiveness
- calculates a single figure of merit: US$
- assumes that alternatives have equal effectiveness
- is derived from
  - Direct Operating Cost methods (DOC) for aircraft
  - Cost Of Ownership methods (COO)
  - further research
- **eliminates subjectively weighted criteria**
- is based as much as possible on **readily available basic input parameters**.

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3 Direct Operating Costs for A/C systems

- Introduction
- Equations
- DOCsys Program
- DOCsys Example

Equations

Fundamental DOCsys:

$$DOC_{SYS} = Depr_{SYS} + Fuel_{SYS} + DMC_{SYS}$$

Extended DOCsys:

$$DOC_{SYS,ext} = Depr_{SYS} + Fuel_{SYS} + DMC_{SYS} + Delay_{SYS} + SHC_{SYS}$$

Equations

Depreciation

$$Depr_{SYS} = \frac{Price - Residual}{N} = \frac{Price \cdot \left(1 - \frac{Residual}{Price}\right)}{N}$$

N depreciation period
(as in aircraft DOC; often: 15 years)

Equations

Fuel Costs

$$Fuel_{SYS} = Fuel_{mf} + Fuel_{mv} + Fuel_{P} + Fuel_{B} + Fuel_{R} + Fuel_{D}$$

due to: fixed mass, variable mass, power off-takes from the engines, bleed air off-takes, ram air off-takes, additional drag

$$Fuel_X = m_{fuel,X} \cdot FuelPrice \cdot NFY$$

$m_{fuel,X}$ mass of fuel consumed due to cause X during the whole flight
NFY Number of Flights per Year

$$m_{fuel,X} = \sum_{i=1}^{7} m_{fuel,i,X}$$

calculated for 7 flight phases.
For details and references: see paper !!!

Equations

The fuel consumption is calculated for 7 **flight phases** i :

$i = 1$, engine start,

$i = 2$, taxi,

$i = 3$, take-off,

$i = 4$, climb,

$i = 5$, cruise,

$i = 6$, descent,

$i = 7$, landing, taxi, engine shut down.

Equations

Fuel consumption due to **fixed mass** m_i during flight phase i

$$m_{fuel,i,X,m} = m_{i,X} \cdot \left(e^{t_i \cdot k_{E,i}} - 1 \right)$$

Fuel consumed due to **variable mass** $\dot{m}_{i,mv}$ during flight phase i

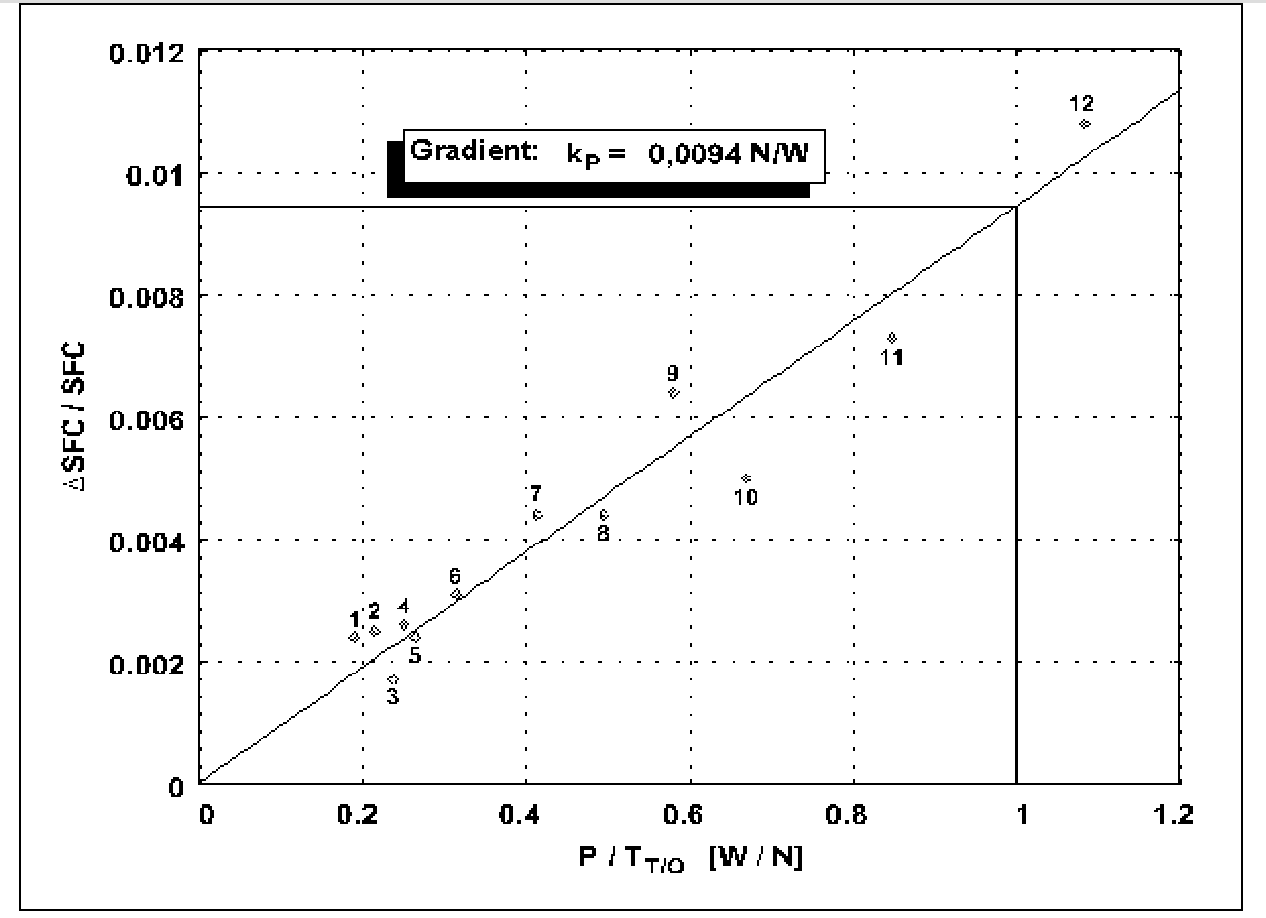
$$m_{fuel,i,mv,f} = \frac{\dot{m}_{i,mv}}{k_{E,i}} \left(e^{t_i \cdot k_{E,i}} - 1 \right) - \dot{m}_{i,mv} \cdot t_i$$

Fuel consumed due to **power off-takes** P_i during flight phase i

$$m_{fuel,i,P,f} = \frac{P_i \cdot k_p \cdot m_{A/C}}{n \cdot T_{T/O}} \left(e^{t_i \cdot k_{E,i}} - 1 \right)$$

$T_{T/O}$ take-off thrust
n number of engines

Equations



Gradient

k_p

for power off-takes

k_p from Gasturb-Examples (AHLEFELDER): 0.0116 N/W

Equations

Fuel consumed due to **power off-takes** P_i during flight phase i

Simple calculation as often applied:

$$m_{fuel,i,P,f} = P_i \cdot k_p^* \cdot t_i$$

k_p^*		
	Mittelwert:	0,097 kg/kWh (SCHOLZ)
	A300:	0,125 kg/kWh (DECHOW)
	A400M:	0,167 kg/kWh (BRIX)
	Gasturb-Examples:	0,176 kg/kWh (AHLEFELDER)

Equations

Fuel consumption due to **bleed air off-takes** during flight phase i

$$m_{fuel,i,B,f} = \frac{k_B \cdot T_{tb} \cdot \dot{m}_B}{k_{E,i}} \left(e^{t_i \cdot k_{E,i}} - 1 \right)$$

$\dot{m}_B$ bleed air mass flow

T_{tb} turbine inlet temperature (1100 K)

$k_B = 3.015 \cdot 10^{-5} 1/K$

Fuel consumption due to **ram air off-takes** during flight phase i

$$m_{fuel,i,R,f} = \frac{SFC_i \cdot \rho_i \cdot Q_i \cdot v_i}{k_{E,i}} \cdot \left(e^{t_i \cdot k_{E,i}} - 1 \right)$$

Q required air flow rate

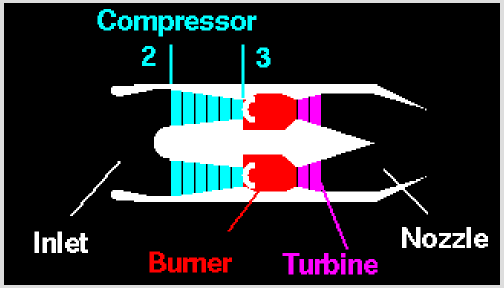
ρ air density; v true air speed

SFC Specific Fuel Consumption

Equations

Fuel consumption due to **bleed air off-takes** during flight phase i

$$\dot{m}_{fuel,i,B,f} = k_B \cdot T_{tb} \cdot \dot{m}_B = k_B^* \cdot \dot{m}_B$$



k_B^* 0,0335 (AIR 1168/8)

$$k_B^* = k_{BB} \left(\frac{p_3}{p_2} \right)^y$$

$\frac{p_3}{p_2}$ is compressor (overall) pressure ratio
CFM56-5C: 37,4

k_{BB} : 4,99 · 10^{-3} 1/K

y : 0,475

(at relative enthalpy of 0,63)

k_B^* 0,028 (AHLEFELDER, CFM56-5C)

Equations

Fuel consumption due to **additional drag** D_i during flight phase i

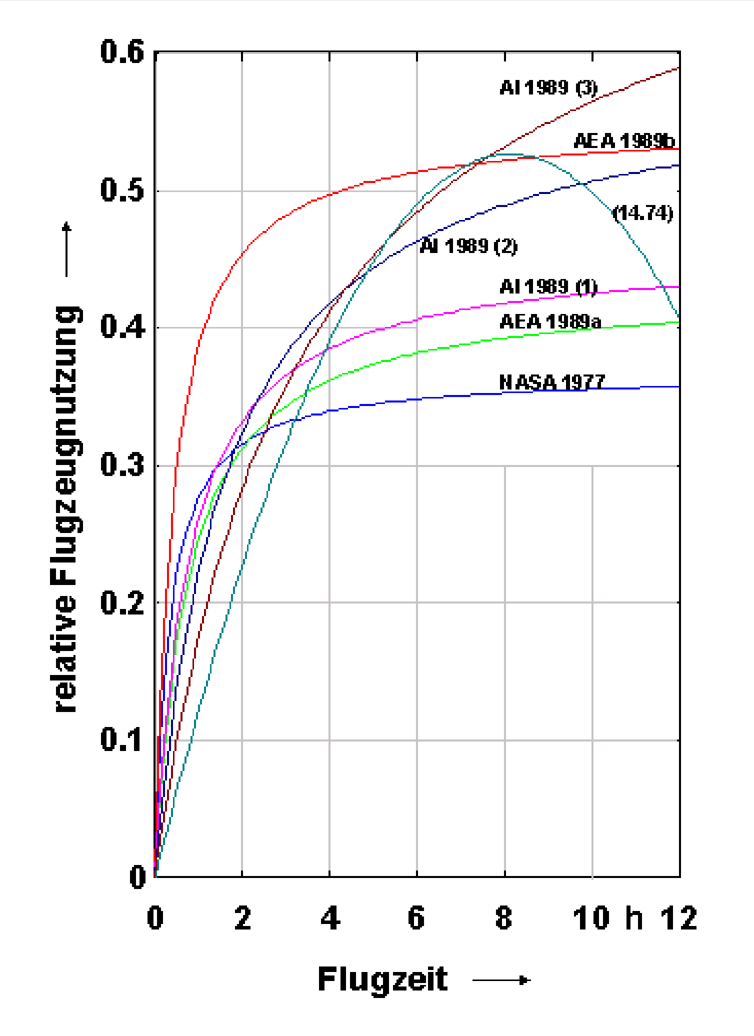
$$m_{fuel,i,D,f} = \frac{SFC_i \cdot D_i}{k_{E,i}} \left(e^{t_i \cdot k_{E,i}} - 1 \right)$$

1 / BREGUET-Time-Factor for flight path angle γ_i during flight pahse i

$$k_{E,i} = SFC_i \cdot g \cdot \left(\frac{\cos\gamma_i}{L/D_i} + \sin\gamma_i \right)$$

Equations

Number of Flights per Year *NFY*



A/C DOC methods:

$$U_{a,f} = t_f \frac{k_{U1}}{t_f + k_{U2}}$$

Quelle	k_{U1} h	k_{U2} h
AA 1980 / NASA 77	3205	0.327
AEA 1989a	3750	0.750
AEA 1989b	4800	0.420
AI 1989 [a]		
R < 1000 nm	3994	0.754
1000 nm ≤ R ≤ 2000 nm (2)	5158	1.650
2000 < R nm	6566	3.302

Recommended for DOCsys

$$U_{h,f} = k_{U,A} (t_f - k_{U,B})^2 + k_{U,C}$$

$k_{U,A}$ = - 0.00796 1/h²

$k_{U,B}$ = 8.124 h

$k_{U,C}$ = 0.525

$$NFY = U_{a,f} / t_f$$

$$U_{a,f} = U_{h,f} \cdot 24 \cdot 365$$

t_f flight time

Equations

Direct Maintenance Costs for Systems DMC_{SYS}

$$DMC_{SYS} = \left(MMH_{on} + MMH_{off} \right) \cdot LR + MC$$

MMH_{on} Maintenace Man Hours On Aircraft

MMH_{off} Maintenace Man Hours Off Aircraft

LR Labor Rate

MC Material Costs

The Direct Maintenance Costs DMC_{SYS} can be calculated with the Airbus Industrie Comparison Method (AICM). For details see paper !!!

Equations

Capital Costs Caused by Spare Parts on Stock for Systems SHC_{SYS}

$$SHC_{SYS} = \frac{SPF \cdot SPR}{RED} \cdot Price \cdot \frac{RQS_{req}}{FS} \cdot r$$

SPF	Spare Part Factor: Spare part price divided by initial purchase price
SPR	Spare Part Ratio: Portion of costs of spare parts in total amount of parts for the aircraft system, or subsystem
RED	average redundancy level (resulting in equal parts) in the system or subsystem
$RQSreq$	required amount of spare parts (depends on the "on average" required amount of spare parts and the required probability of having a required spare part on stock)
FS	fleet size
r	interest rate

Equations

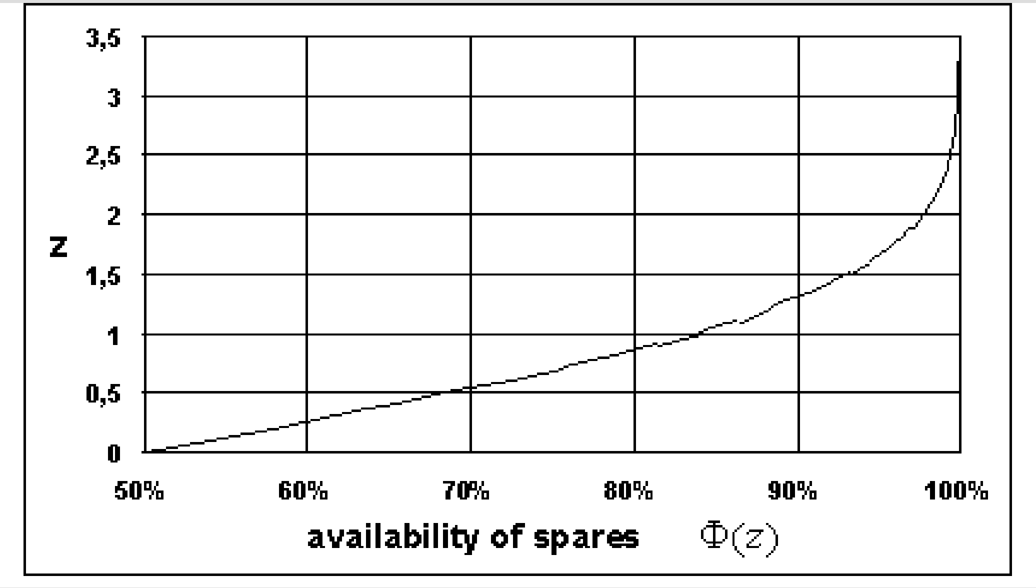
$$RQS_{req} = RQS_{av} + z \cdot \sqrt{RQS_{av}}$$

$$RQS_{av} = RED \cdot TATR \cdot FS \cdot \frac{FT \cdot NFY}{MTBUR}$$

$TATR$ Turn Around Time Ratio

$MTBUR$ Mean Time Between Unscheduled Removals

FT flight time



availability factor z
for spare parts on stock

Equations

Delay and Cancellation Costs caused by Systems $Delay_{SYS}$

$$Delay_{SYS} = \left(D_I \cdot C_I + D_{II} \cdot C_{II} + D_{III} \cdot C_{III} + D_C \cdot C_C\right) \cdot NFY$$

$$C_j = m_j \cdot x + b_j$$

parameter	C_I	C_{II}	C_{III}	C_C
	delay 0-29 min	delay 30-59 min	delay >=60 min	cancellation
m_j	0.291	0.753	2.251	2.900
b_j	82.2	207.2	1125.7	1499.4
r	0.989	0.963	0.953	0.950

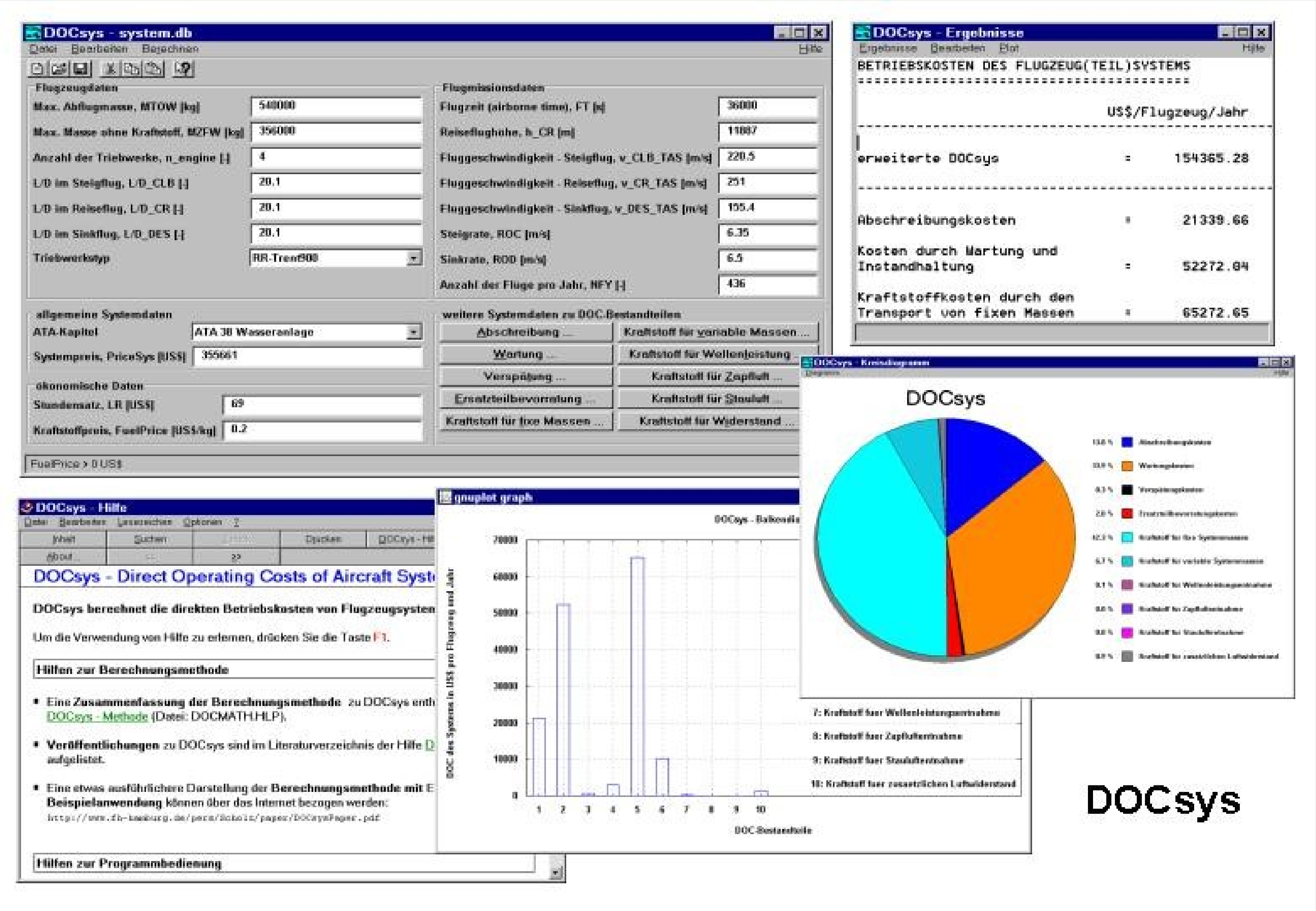
Parameters m and b for calculating delay and cancellation costs as 1992US$. Compare with article in FAST No 26!

$$C_{year} = C_{method} \cdot k_{INF}$$

$$k_{INF} = (1 + p_{INF})^{n_{year} - n_{method}}$$

Contents

DOCsys Program



Example see Notes

DOCsys Rules of Thumb

With these Inputs ...

SFC	1,60E-05	kg/N/s
g	9,81	m/s²
L/D	20	
k_E	7,85E-06	1/s
n_DEP	15	years
P_res/P_tot	0,1	
P_F	0,2	US$/kg
t_f	10	h
t_f	36000	s
NFY	436	

We get this Output:

ΔP_total/Δm	474	US$/kg

With these further Inputs:

m_A/C	540000	kg
T_T/O	331000	N
k_P	0,0094	N/W
n_E	4	

We get this Output:

ΔP_total/ΔP	1,82	US$/W
ΔP_total/ΔP	1819	US$/kW

From both results we get:

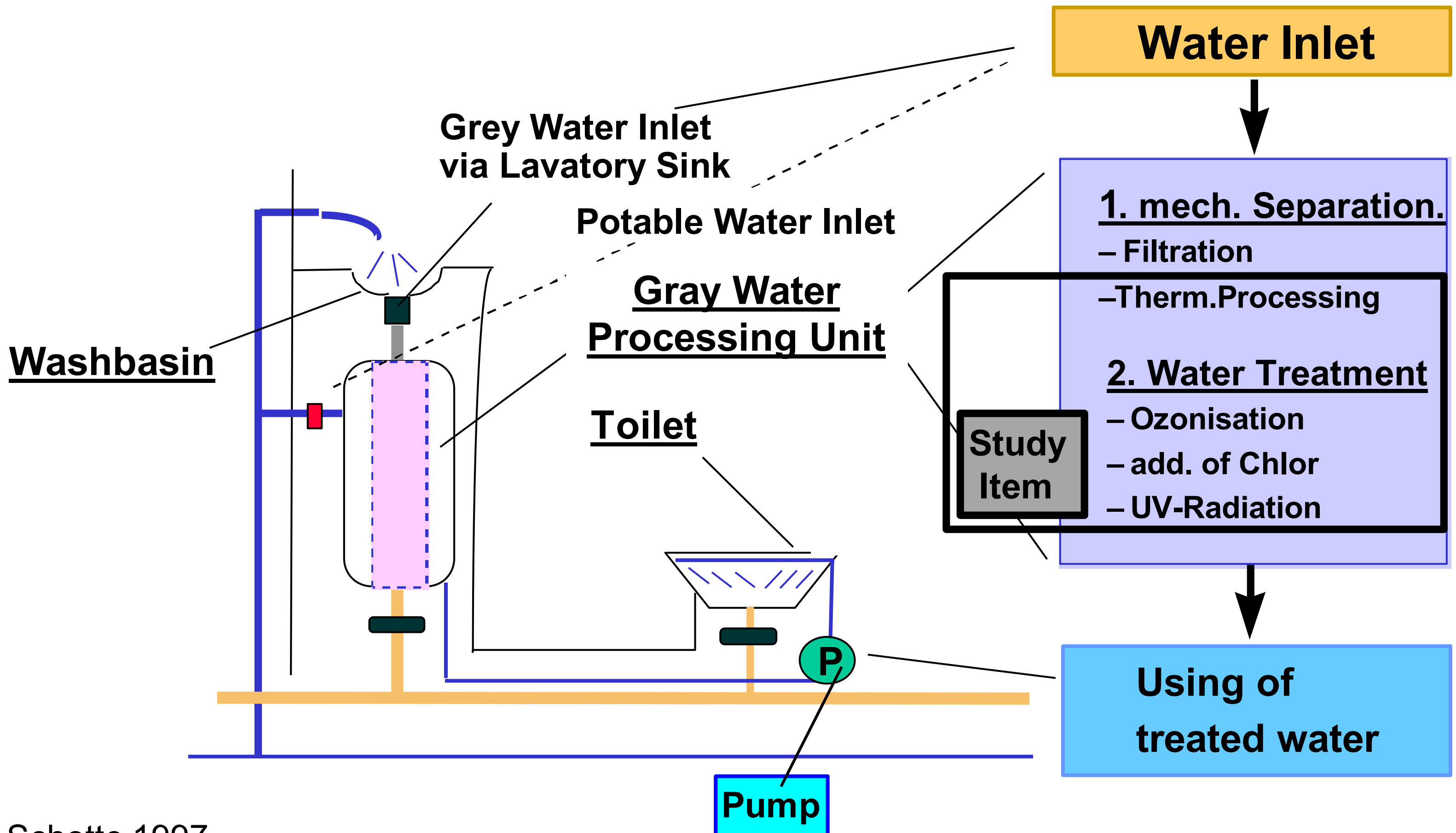
Δm/ΔP	3,84	kg/kW

Contents

3 Direct Operating Costs for A/C systems

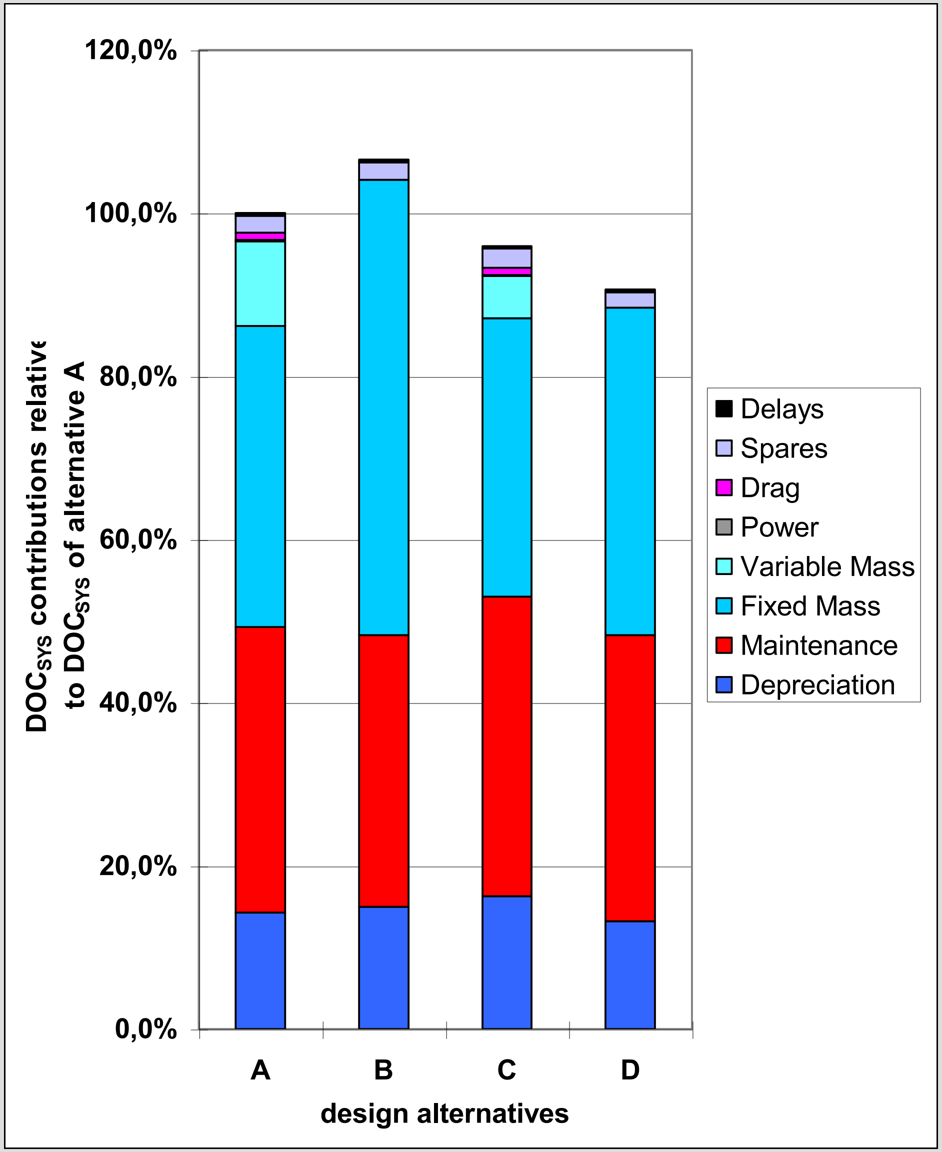
DOCsys Example

gray water system



Schotte 1997

DOCsys Example



Trade Study of gray water system with DOCsys

Contributions of different cost elements to total DOC_{SYS} of four water/waste system design alternatives. FT = 10h.

A	system **without** gray water treatment system; **with** drain mast (**open** system)
B	system **without** gray water treatment system; **without** drain mast (**closed** system)
C	system **with** gray water treatment system; **with** drain mast (**open** system)
D	system **with** gray water treatment system; **without** drain mast (**closed** system)

Scholz 1998

Chapter 4

Introduction to Reliability Calculations

Prof. Dr.-Ing. Dieter Scholz, MSME

See Lecture Notes

Chapter 5

Maintenance Costs

Prof. Dr.-Ing. Dieter Scholz, MSME

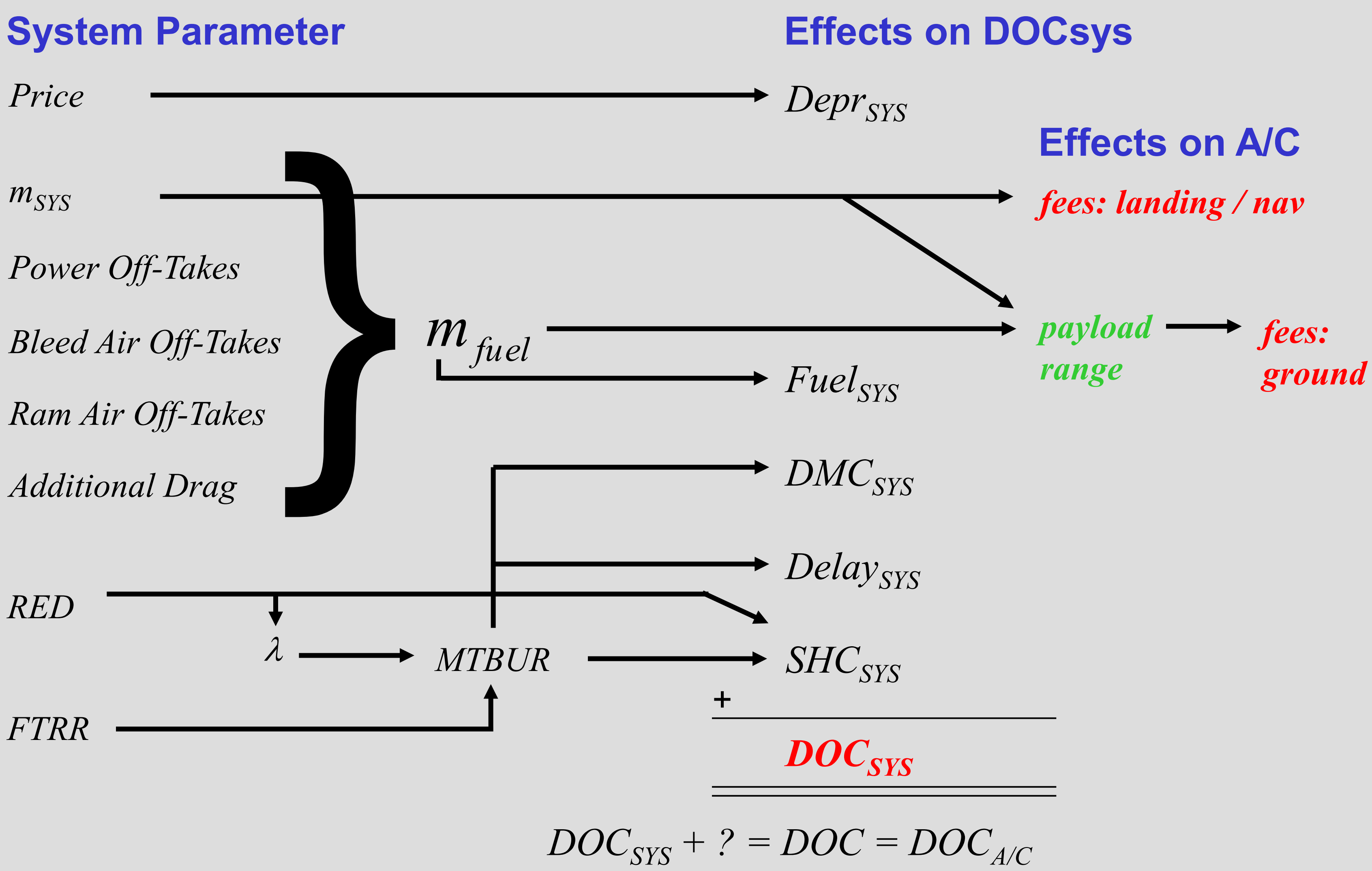
See Lecture Notes

Chapter 6

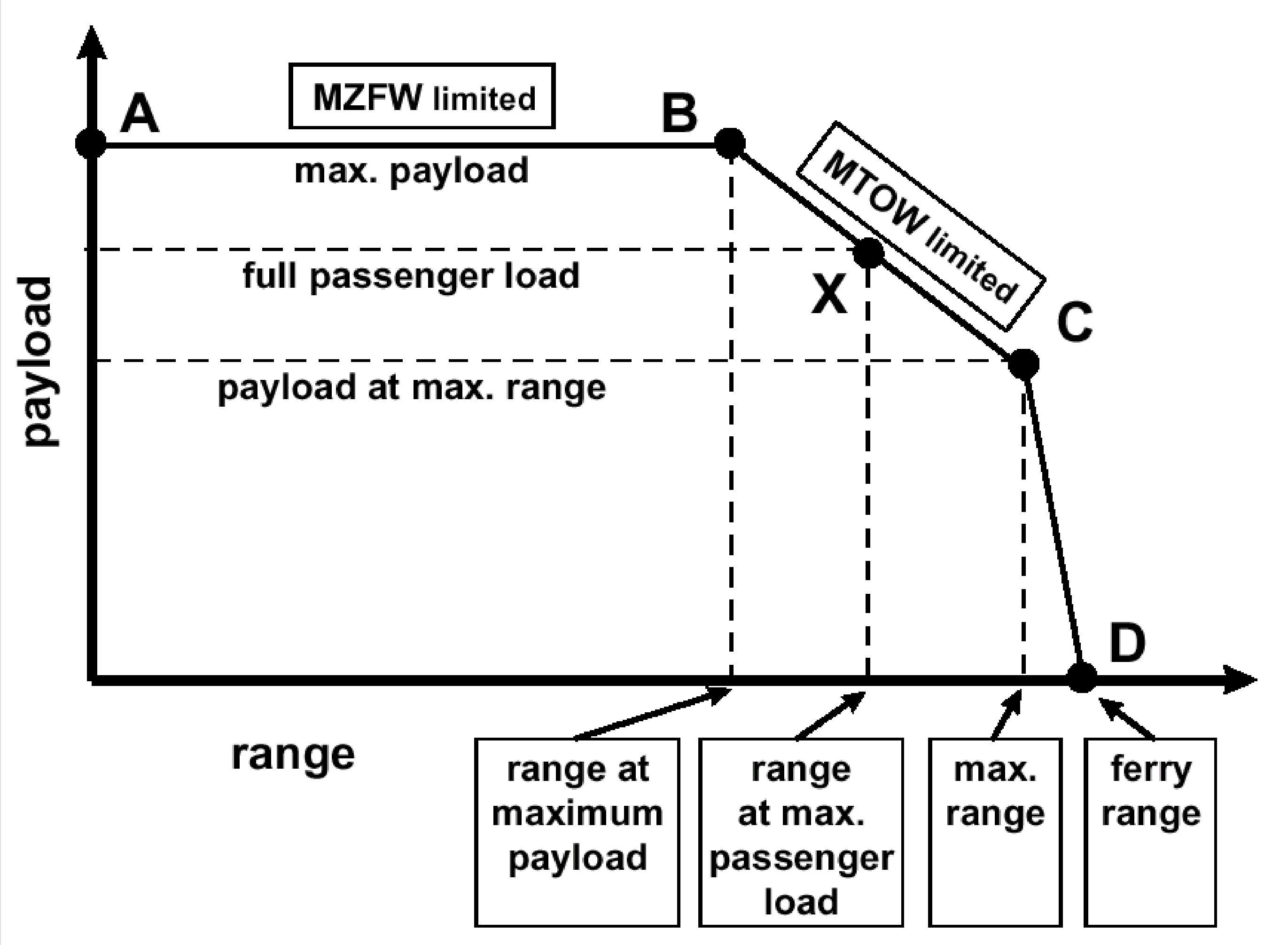
System Design Parameters and Their Effects

Prof. Dr.-Ing. Dieter Scholz, MSME

Parameter Relationship



Payload Range Diagram



Range and Mass Equations

$$R = \frac{L/D \cdot v}{SFC \cdot g} \ln\left(\frac{m_{TO}}{m_L}\right)$$

L/D	"lift over drag"
v	cruise speed
SFC	spcific fuel consumption
g	9.81 m/s^2
m_L	landing mass

$$m_{TO} = m_{OE} + m_{PL} + m_F$$

m_{OE}	operating empty weight
m_{PL}	payload
m_F	fuel mass

Customer Dependant System Design Optimization

Different operators will aim for different system designs:

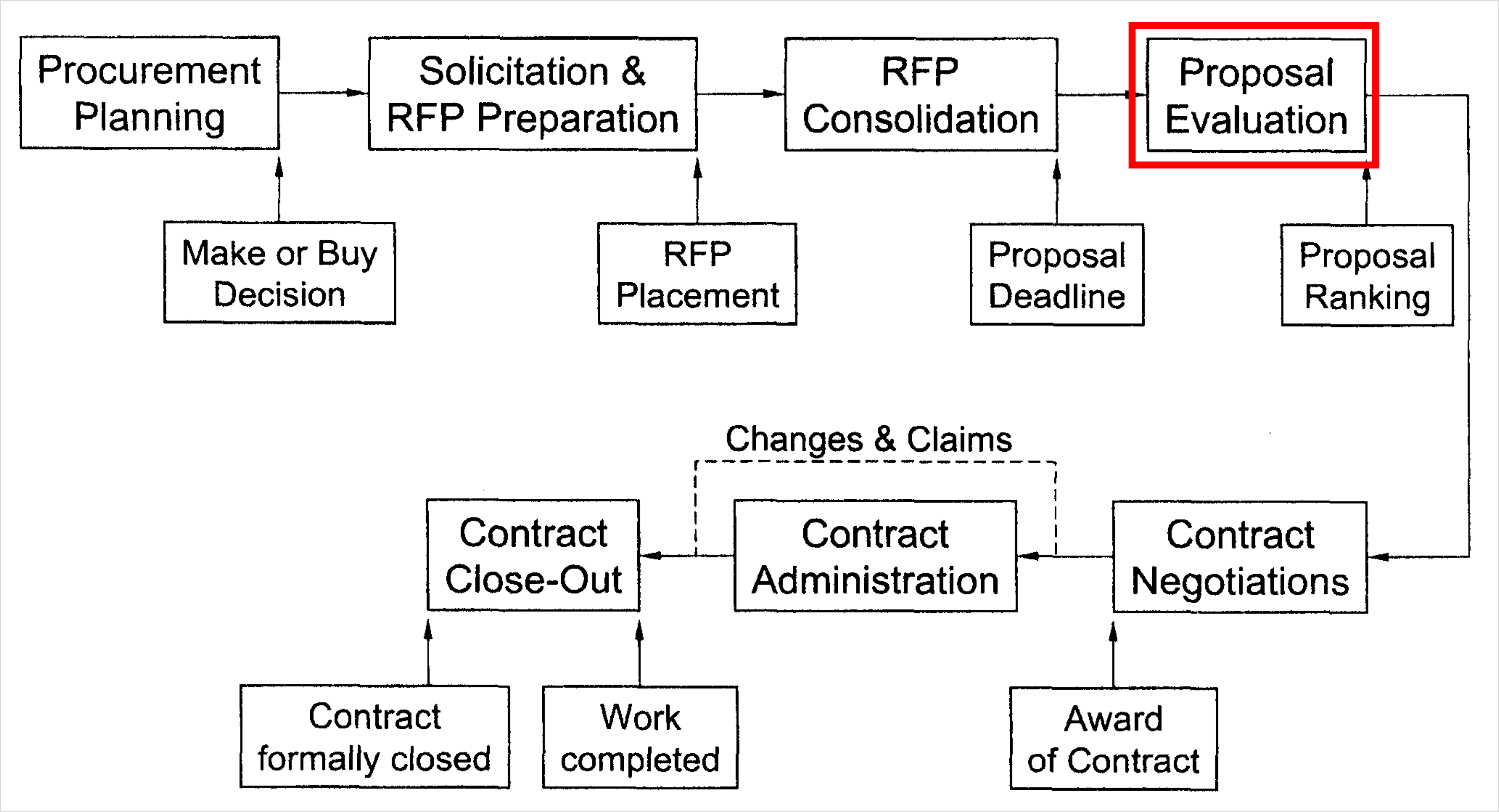
- **Low cost operators** will require
  - minimum DOCsys, minimum fees
  - maximum range
  - maximum payload
- **High end operators** will require
  - minimum delays and cancellations
    (even at higher DOCsys) ...

Chapter 7

Vendor Selection

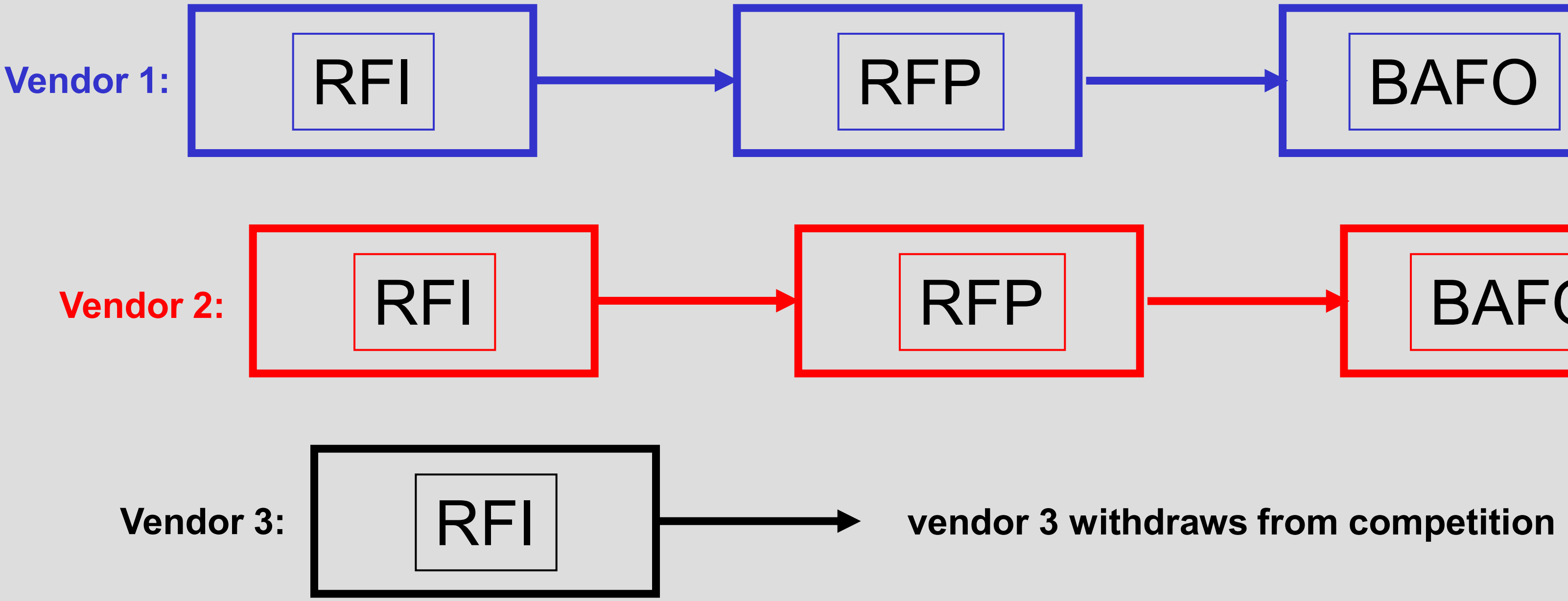
Prof. Dr.-Ing. Dieter Scholz, MSME

Procurement Process



RFP = Request For Proposal

Procurement Process



RFI	Request For Information
RFP	Request For Proposal
BAFO	Best And Final Offer

Proposal Evaluation

1. System Overview
2. Architecture / System Scheme
3. **Technical assessment**
   - Supplier experience
   - Functional comparison
   - Architecture weight comparison
   - Lead Time / Schedule
   - Supplier Development Plan
   - Safety / Reliability
   - Technical conclusion
4. Industrial Performance
5. Product Support Assessment
6. Commercial Assessment
7. Strategy
8. Risks
9. Total Conclusion

Source: Airbus

The selection criteria 3 ... 8 have 2 ... 6 sub criteria each.

With Linear Combination of Scores (Nutzwertanalyse) a score for the effectiveness is determined for each of the main criteria like "3. Technical Assessment".

(Nutzwertanalyse) is used again in "9. Total Conclusion" in order to come up with an end result.

Proposal Evaluation

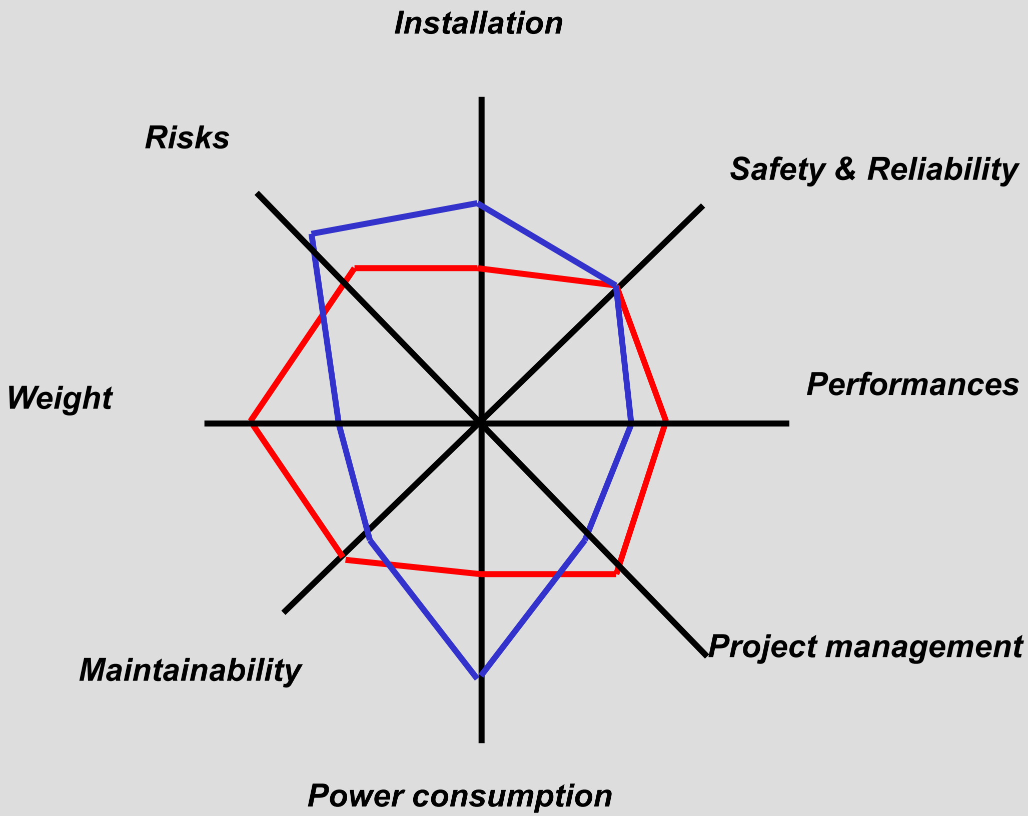
Linear Combination of Scores

Evaluation Criteria	WT. Factor (%)	Proposal A		Proposal B		Proposal C	
		Rating	Score	Rating	Score	Rating	Score
A. Technical Requirements:	25						
1. Performance Characteristics	6	4	24	5	30	5	30
2. Effectiveness Factors	4	3	12	4	16	3	12
3. Design Approach	3	2	6	3	9	1	3
4. Design Documentation	4	3	12	4	16	2	8
5. Test and Evaluation Approach	2	2	4	1	2	2	4
6. Product Support Requirements	4	2	8	3	12	2	8
B. Production Capability	20						
1. Production Layout	8	5	40	6	48	6	48
2. Manufacturing Process	5	2	10	3	15	4	20
3. Quality Control Assurance	7	5	35	6	42	4	28
C. Management	20						
1. Planning (Plans/Schedules)	6	4	24	5	30	4	24
2. Organization Structure	4	4	16	4	12	4	16
3. Available Personnel Resources	5	3	15	3	20	3	15
4. Management Controls	5	3	15	3	20	4	20
D. Total Cost	25						
1. Acquisition Price	10	7	70	5	50	6	60
2. Life Cycle Cost	15	9	135	10	150	8	120
E. Additional Factors	10						
1. Prior Experience	4	4	16	3	12	3	12
2. Past Performance	6	5	30	5	30	3	18
Grand Total	100		476		516*		450

* Select Proposal B

DOD 2001

Proposal Evaluation



Visualisation of proposal evaluation results.

During contract negotiation manufacturer tries to eliminate apparent weaknesses of the vendor.

Source: Airbus

Literature

- **ATA 2002**

  AIR TRANSPORT ASSOCIATION OF AMERICA: *ATA iSpec 2200 : Information Standards for Aviation Maintenance*. Washington D.C. : ATA, 2002.
- **DOD 2001**

  SYSTEMS MANAGEMENT COLLEGE, DEPARTMENT OF DEFENSE: *Systems Engineering Fundamentals*. Fort Belvoir, VA : Defense Aquisition University Press, 2001
- **NASA 1995**

  NATIONAL AERONAUTICS AND SPACE AGENCY: *NASA Systems Engineering Handbook.* NASA, 1995 (SP-610S)
- **Scholz 1991**

  SCHOLZ, Dieter: *MPC 75: Landeklappenvergleich: Pivot Point / Linkage / Track* . Hamburg : Deutsche Airbus, 1991 (TN-EV52-145/91)
- **Scholz 1998**

  SCHOLZ, D.: *Design Concepts of Water/Waste Systems for New Aircraft Projects*. Bd. 2 : *Evaluation of Water/Waste System Baseline and Alternative Concepts*. Neu Wulmstorf : Applied Science, 1998 (Bericht 2-98)

Literature

- **Schotte 1997**

  SCHOTTE, H.: *Das Wassersystem des Megaliners* (Statusseminar Flugführung, Flugsteuerung und Systeme, Braunschweig, 1./2. Oktober 1997), Bonn : bmb+f, 1997
- **WATOG 1992**

  AIR TRANSPORT ASSOCIATION OF AMERICA: *Airline Industry Standard, World Airlines Technical Operations Glossary (WATOG)*. Washington : ATA, 1992.
- **Zangemeister 1976**

  ZANGEMEISTER, C.: *Nutzwertanalyse in der Systemtechnik*. München : Wittmann, 1976

Appendix

Papers related to these notes:

- SCHOLZ, D.:
  DOCsys - A Method to Evaluate Aircraft Systems

- POUBEAU, J.-P.; HERINCKX, E.:
  Methodology for Analysis of Operational Interruption Costs

- BRINK, K.B.; RIECK, G.:
  Wartungsaufwandsanalyse auf Systemebene