Understanding Customer Requirements

Abhishek, 2019

Overview

- **Understanding the "Voice of the Customer"**
  - **Use of Quality Function Deployment**
- **Concept Selection Methodology: Pugh Matrix**
- **LCC: Life Cycle Costs**

“Good” Design Practice

- Conserve resources, minimize total energy consumed in product life cycle
- Create recyclable products
- Increase useful operative life of product
- Minimize toxic or hazardous materials used in production
- Minimize air emissions, greenhouse gases and ozone-depleting substances during life cycle of product
- Increase percentage of recyclable materials at end of life of product

Environmentally Friendly Design

"Environmentally friendly design" implies design for:

- **Clean manufacturing**
- **Easy assembly**
- **Easy repair**
- **Upgradeability**
- **Recycling, clean disposal**
- **Minimized power consumption**
- **Low emission**

Disruptive Technologies

Clayton Christensen "The Innovator's Dilemma" 1997

- **Sustaining Technologies**
  - **Improve performance of established products. These often dominate the market, e.g. Cameras – increase MP add new modes etc.**
- **Disruptive Technologies**
  - **A disruptive technology or innovation helps create a new market and value network, and eventually goes on to disrupt an existing market and value network (over a few years or decades), displacing an earlier technology.**
  - **They are cheaper, smaller, simpler, better performing, more convenient….**

Examples of Disruptive Technologies

- **Disruptive technologies offer alternatives to established technologies and are perceived as more agile, responsive and empowering for user**
  - **Tablets or laptop vs personal computers**
  - **Internet**
    - **Music download, video download, software download**
  - **iPhone, iPod, iPad…**
  - **Digital cameras replacing photographic film.**
  - **Cell-phone vs land-line**
  - **DSL versus dial up**
  - **E-commerce rather than use retail outlets**
  - **USB memory sticks replacing CDs and floppies and zip-drives**

Strategy for Disruptive Innovations

- **Few companies can survive disruption**
  - **Analyze why people are using your product.**
  - **What do they want your product to do?**
  - **Deliver what your consumers actually want – rather than merely updating what you're already giving them – recipe for sustainable growth – digital camera vs camcorder**
- **Disruptive innovations for VTOL vehicles?**
  - **Tilt rotor, Tilt wing…**
  - **Autogyro, Gyrodyne, Compounds (X2, X3)…**
  - **Fully Autonomous Air Vehicles**
  - **Micro Air Vehicles, swarms of MAVs**

Frugal Engineering or Gandhian Engineering is the science of breaking up complex engineering processes/products into basic components and then rebuilding the product in the most economical manner possible – Tata Nano

Decision Making Under Uncertainties

- Analytic Hierarchy Process (AHP)
- House of Quality
- Pugh matrix

Importance of Early Decision Making

- Choosing architecture, mission mode, or concept of design is one of most important decisions made early in design process

- A decision must be made based on some implicit or explicit evaluation criteria

- Consciously and deliberately choosing criteria is of vital importance in decision making process

Steps in Decision Making Process

1. **Establish evaluation criteria**
2. **Establish relative importance of evaluation criteria**
3. **Develop alternative concepts that meet objectives and top-level requirements**
4. **Evaluate alternatives relative to established evaluation criteria**
5. **Alternative that best satisfies evaluation criteria represents tentative concept choice**
6. **Tentative concept choice is evaluated in more detail to identify any unforeseen drawbacks**
7. **In light of information gained from more detailed study, decision is finalized or decision maker returns to Step 3**

Analytic Hierarchy Process

Developed by SAATY:

Saaty, T.L. (1980), *The Analytic Hierarchy Process, McGraw* Hill, NY.
Saaty, T.L. (1990), *Multicriteria Decision Making: The Analytic Hierarchy Process, RWS Publications, Pittsburgh, PA.*

- **The Analytic Hierarchy Process (AHP) is a mathematical technique for Multi criteria decision making**
- **AHP is based on pairwise comparison between competing alternatives**
- **Allows consideration of both objective (e.g., cost) and subjective (e.g., product characteristic) factors**
- **The output from AHP are relative weights that can be used in House of Quality**

Steps Involved in AHP

- **Describe in summary form, alternatives under consideration**
- **Generate high-level Figures of Merit (FoM)**
- **Decompose high-level FoMs into a hierarchy of evaluation attributes (characteristics)**
- **Determine relative importance of FoMs through *prioritization matrix and pairwise comparisons***
- **Make pairwise comparisons of alternatives with respect to each of FoMs**
  - **Iterate until consensus is reached**

Paraphrased from the *NASA Systems Engineering handbook*

Ranking of Attributes

- **Example: RFP 2012**

- **Five most important attributes for a Racing Helicopter**
  1. **Maneuverability**
  2. **Speed**
  3. **Hover Capability**
  4. **Fuel Economy**
  5. **Reliability**

Pairwise Comparison of Attributes – Example

Priortization Matrix	Maneuverability	Speed	Hover Capability	Fuel Economy	Reliability
Maneuverability	1	1	1/5	5	3

Value aij Comparison description

- **Aij = 1 : Objectives i and j are of equal importance**
- **Aij = 3: Objectives i is weakly more important than j**
- **Aij = 5: Objectives i is strongly more important than j**
- **Aij = 7: Objectives i is very strongly more important than j**
- **Aij = 9: Objectives i is absolutely more important than j**

Even numbers (2, 4, 6, 8) are used to indicate intermediate importance

- **Obviously, Aii = 1;**
- **Also, if *Aij = p, Aji = 1/p***

Prioritization Matrix– Example

Priortization Matrix	Maneuverability	Speed	Hover Capability	Fuel Economy	Reliability
Maneuverability	1	1	1/5	5	3
Speed	1	1	1/5	5	3
Hover Capability	5	5	1	9	5
Fuel Economy	1/5	1/5	1/9	1	1/3
Reliability	1/3	1/3	1/5	3	1
Column Sum	7.53	7.53	1.74	23	12.2

Prioritization Matrix– Example

Priortization Matrix	Maneuverability	Speed	Hover Capability	Fuel Economy	Reliability
Maneuverability	1	1	1/5	5	3
Speed	1	1	1/5	5	3
Hover Capability	5	5	1	9	5
Fuel Economy	1/5	1/5	1/7	1	1/3
Reliability	1/3	1/3	1/5	3	1
Sum	7.53	7.53	1.71	23	12.33

Maneuverability	Speed	Hover Capability	Fuel Economy	Reliability	Normalized Priority Vector
0.13	0.13	0.12	0.22	0.24	0.17
0.13	0.13	0.12	0.22	0.24	0.17
0.67	0.67	0.58	0.39	0.41	0.54
0.03	0.03	0.06	0.04	0.03	0.04
0.04	0.04	0.12	0.13	0.08	0.08
1.00	1.00	1.00	1.00	1.00	1.00

Normalized Priority vectors for attributes used as weighting factors
Hover capability is most important (0.54); Fuel economy least important (0.04)
Maneuverability, speed, of equal importance

Consistency Check – Example

- **How to verify whether relative pairwise comparisons have been filled in random manner?**
- **Saaty proposed following procedure:**
  - **Step 1. Find highest eigenvalue of the matrix**
    - **Because of special nature of this matrix, an approximation to the highest eigenvalue can be found as product of the vector of the column sum with the vector of the normalized priority vector**

Column Sum	**7.53**	**7.53**	**1.71**	**23**	**12.33**

Normalized Priority Vector
0.17
0.17
0.54
0.04
0.08

Approximate λ_{max} = [Column Sum] {Normalized Priority}

Approximate λ_{max}
= 7.53*0.17+7.53*0.17+1.71*.54+23*0.04+12.33*.08
= 5.39

Consistency Check – Example

- **STEP 2: Calculate the "Consistency Index" defined as**

Consistency Index, $$C.I. = \frac{\lambda_{max} - n}{n-1} = \frac{5.39-5}{5-1} = 0.097$$

- **STEP 3: Random Consistency Index**

Saaty randomly generated comparison matrices using 1/9, 1/8,…8, 9 and obtained a random consistency index (R.I.). The average R.I. of different sample sizes are

n	3	4	5	6	7	8
R.I.	0.58	0.90	1.12	1.24	1.32	1.41

- **STEP 4: Calculate the "Consistency Ratio" (C.R.) defined as**

$$C.R. = \frac{C.I.}{R.I.} = \frac{0.0975}{1.12} = 0.087$$

C.R. should be less than 0.1 to verify that the table has not been filled-in randomly.

List of Configurations

- **Analytical Hierarchy Process can be used to short list candidate configurations for detailed study**
  - **First, make a list of possible configurations:**
    - **Single Main Rotor Configurations (SMR)**
    - **Tilt Rotor**
    - **Sikorsky X2 Concept**
    - **Eurocopter X3 concept**

Comparison of Different Types of V/STOL Platforms

VTOL Concept	Helicopter	Compound	Compound	Compound	Compound	Tilt Rotor	Tilt Wing	Canard Rotor Wing	Fan-in-Wing	Jet Lift
Features		(Tail Rotor + Aux Prop)	(Advancing Blade Concept)	(Vectrd Thrst - Open Prop)	(Vectrd Thrst - Ducted Prop)					
Examples	AH-64, RAH-66	AH-56	Sikorsky XH-59	Sikorsky AAFSS	Piasecki VTDP	XV-3, XV-15, V-22	CL-84, TW-68, XC-142	Boeing CRW	XV-5, Grum-man ACAS	AV-8B
Hover / Loiter / Ground Ops										
Efficiency (Endurance)	Best	Good	Good	Good	Good	Good	Fair	*Low*	*Low*	*Poor*
Downwash / Temperature	Low	Low	Low	Low	Low	Moderate	*Marginal*	*Marginal*	*High*	*Extreme*
Ground Ops Protection	Optional	*Open Prop*	No Anti-Torque	*Open Prop*	Ducted Prop	---	Optional	No Anti-Torque	---	*Jet Exhaust*
Cruise / Dash										
Max Speed (Dash)	*Low*	> Helicopter	> Helicopter	> Helicopter	> Helicopter	Good	> Tilt Rotor	High	High	Highest
Cruise Efficiency (Range)	*Lowest*	*Low*	*Low*	*Low*	*Low*	Good	Good	Good	Good	Highest
Maneuverability / Agility										
Low Speed	Good	Good	Good	Good	Good	Good	Fair	*Limited*	*Limited*	*Limited*
High Speed	*Limited*	Good	Good	Good	Good	Good	Good	Good	Good	Excellent
Conversion	---	---	---	*Limited Agility*	*Limited Agility*	*Benign*	*Lmtd Corridor*	*Lmtd Corridor*	*Lmtd Corridor*	*Benign*
Attitude vs Accel (Low Speed)	*Coupled*	Independent	*Coupled*	*Coupled*	*Coupled*	Independent	Independent	Independent	Independent	Independent
Reverse Thrust Capability	---	All Speeds	---	High Speed	High Speed	---	High Speed	---	---	---
Yaw Control	Symmetrical	Symmetrical	Symmetrical	Symmetrical	*Limited / Unsymmetrical*	Symmetrical	Symmetrical	Limited in Low Speed	Symmetrical	Symmetrical
Survivability										
RCS (Low Speed Mode)	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Doors / Louvers*	*Short Inlet*
RCS (High Speed Mode)	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	*Rotating Blade*	Good	Good	*Short Inlet*
IR (Engine Exhaust)	Lowest Power	Low Power	Low Power	Low Power	Low Power	Low Power	Medium Power	High Power	High Power	*Short Exhaust*
Cost / Supportability										
Vibration Environment	*Highest*	*High*	*Very High*	*High*	*High*	*Moderate*	---	*Moderate*	Low	Low
Empty Weight	Low	*Increased*	*Increased*	*Increased*	*Increased*	*Increased*	*Increased*	*Increased*	*High*	*Moderate*
Complexity (Min # of Thrusters)	*2 Fixed*	*3 Fixed*	*2 Fixed*	*1 Fixed + 1 Vectored*	*1 Fixed + 1 Vectored*	*2 Vectored*	*1 Fixed + 2 Vectored*	*Convertible Engine*	*3 Vectored*	*1 Thruster + 8 Nozzles*

Key to Table: **Advantage** Neutral *Disadvantage*

Prioritization Matrix–Maneuverability

Maneuverability	SMR	Tilt rotor	X2	X3
SMR	1	3	1/5	1/5
Tilt rotor	1/3	1	1/7	1/7
X2	5	7	1	1
X3	5	7	1	1
Sum	7.53	7.53	1.71	23

SMR	Tilt rotor	X2	X3	Normalized Priority Vector
0.09	0.17	0.09	0.09	0.43
0.03	0.06	0.06	0.06	0.21
0.44	0.39	0.43	0.43	1.68
0.44	0.39	0.43	0.43	1.68
1.00	1.00	1.00	1.00	1.00

X2 and X3 are equally better than SMR and Tilt rotor (C.R. 0.037)

Prioritization Matrix– Speed

Speed	SMR	Tilt rotor	X2	X3
SMR	1.00	0.14	0.33	0.33
Tilt rotor	7.00	1.00	3.00	3.00
X2	3.00	0.33	1.00	1.00
X3	3.00	0.33	1.00	1.00
Sum	14.00	1.81	5.33	5.33

SMR	Tilt rotor	X2	X3	Normalized Priority Vector
0.07	0.08	0.06	0.06	0.07
0.50	0.55	0.56	0.56	0.54
0.21	0.18	0.19	0.19	0.19
0.21	0.18	0.19	0.19	0.19
1.00	1.00	1.00	1.00	1.00

Tilt rotor clear winner in Speed race (C.R. 0.001)

Prioritization Matrix– Hover Capability

I I T K A N P U R

Hover Capability	SMR	Tilt rotor	X2	X3
SMR	1.00	5.00	3.00	3.00
Tilt rotor	0.20	1.00	0.33	0.33
X2	0.33	3.00	1.00	1.00
X3	0.33	3.00	1.00	1.00
Sum	1.87	12.00	5.33	5.33

SMR	Tilt rotor	X2	X3	Normalized Priority Vector
0.53	0.42	0.56	0.56	0.52
0.11	0.08	0.06	0.06	0.08
0.18	0.25	0.19	0.19	0.20
0.18	0.25	0.19	0.19	0.20
1.00	1.00	1.00	1.00	1.00

Single Main Rotor is best in Hover (C.R. 0.01)

Prioritization Matrix– Fuel Economy

Fuel Economy	SMR	Tilt rotor	X2	X3
SMR	1.00	0.33	5.00	5.00
Tilt rotor	3.00	1.00	7.00	7.00
X2	0.20	0.14	1.00	1.00
X3	0.20	0.14	1.00	1.00
Sum	4.40	1.62	14.00	14.00

SMR	Tilt rotor	X2	X3	Normalized Priority Vector
0.23	0.21	0.36	0.36	0.29
0.68	0.62	0.50	0.50	0.57
0.05	0.09	0.07	0.07	0.07
0.05	0.09	0.07	0.07	0.07
1.00	1.00	1.00	1.00	1.00

Tilt Rotor is best for overall fuel economy

Prioritization Matrix– Reliability

Reliability	SMR	Tilt rotor	X2	X3
SMR	1.00	3.00	5.00	5.00
Tilt rotor	0.33	1.00	3.00	3.00
X2	0.20	0.33	1.00	3.00
X3	0.20	0.33	0.33	1.00
Sum	1.73	4.67	9.33	12.00

SMR	Tilt rotor	X2	X3	Normalized Priority Vector
0.58	0.64	0.54	0.42	0.54
0.19	0.21	0.32	0.25	0.24
0.12	0.07	0.11	0.25	0.14
0.12	0.07	0.04	0.08	0.08
1.00	1.00	1.00	1.00	1.00

SMR most reliable and X3 capabilities unproven

Summary – Final Score

Final Score	Weights	SMR	Tilt rotor	X2	X3
Maneuverability	0.17	0.43	0.21	1.68	1.68
Speed	0.17	0.07	0.54	0.19	0.19
Hover Capability	0.54	0.52	0.08	0.2	0.2
Fuel Economy	0.04	0.29	0.57	0.07	0.07
Reliability	0.08	0.54	0.24	0.14	0.08
Final Scores		0.42	0.21	0.44	0.43

Relative ranking:

1. X2
2. X3
3. SMR
4. Tilt rotor

Weighting Factors are from Slide 16

Concept Selection Methodology
Life Cycle Costs
Cost Effectiveness

Concept Selection Methodology
Pugh’s Method

Pugh’s Method (Decision-Matrix Method)

- **Effective method for comparing concepts *not refined enough* to generate performance data for assessment against specifications**
- **Method involves *iterative evaluation* of each concept to meet requirements and converges to strongest concept**
- **Method is most effective when *each member performs it independently*. Results of each evaluation are compared and consensus decision results in a better concept selection**

Pugh Matrix: Step 1

Study customer's requirements and develop a list of criteria. All members should contribute. Must be debated until consensus is reached.

Example:
MARV: UMD's entry for
2000 AHS Student Competition

Selection Criteria	Weight
Compactness of folding	10
Reliability	10
Controllability	8
Aerodynamic cleanliness	6
Maturity of technology	10
Hover efficiency	8
Aerodynamic interaction	3
Vibration	8
Cruise efficiency	7
Maneuverability	3
Ease of payload packaging	9
Simplicity of structure	10
Simplicity of control system	8

Pugh Matrix Step 2

- **Concept selection**
  - Choose several possible concepts or configurations – potential candidates
  - Important that compared be made at same level of abstraction

Examples of configurations with hover capability

- Single Main Rotor w/Tail Rotor/Fenestron/NOTAR
- Co-axial (similar to Kamov)
- SMR / compound
- Co-axial/compound (Sikorsky X2)
- Tandem
- Tilt Rotor
- Tilt Wing
- Fan-in-wing
- ……………..

Pugh's Method Step 3: Assign a score

All designs compared to each other for selection criteria

- **Select one candidate configuration and assess all others with respect to it**
  - **First step could be to do a relative comparison for configurations being better (>), worse (<) or same (=) as datum / baseline for each attribute**
- **Assign scores between 1 and 9 to each attribute**
  - **Each of these scores is multiplied by weighting factor and total score of each candidate design is added up.**

Weight	Selection Criteria	Conventional (T/R)	Ducted w/ 2 propellers	Ducted w/ slipstream vanes	Tip-jet rotors
10	Compactness of folding	1	2	2	1
10	Reliability	9	5	3	5

Pugh's Method Step 4: Add up the score

- **If a concept has highest weighted score, it is a clear choice**
- **If two or more candidate concepts have similar score**
  - **Scoring should be examined more closely**
  - **It may be necessary to carry out some additional calculations or to generate more criteria for comparison**

10	Simplicity of structure	8	8	10	8
8	Simplicity of control system	6	6	6	6
	Total	646	654	760	588

Clear winner!

Example Criteria – UMD MARV

Selection Criteria	Weight
Compactness of folding	10
Reliability	10
Controllability	8
Aerodynamic cleanliness	6
Maturity of technology	10
Hover efficiency	8
Aerodynamic interaction	3
Vibration	8
Cruise efficiency	7
Maneuverability	3
Ease of payload packaging	9
Simplicity of structure	10
Simplicity of control system	8

MARV: Pugh Matrix for Single Rotor Configurations

Weight	Selection Criteria	Conventional (T/R)	Ducted w/ 2 propellers	Ducted w/ slipstream vanes	Tip-jet rotors
10	Compactness of folding	1	2	2	1
10	Reliability	9	5	3	5
8	Controllability	5	3	1	1
6	Aerodynamic cleanliness	8	2	2	3
8	Maturity of technology	10	2	5	2
8	Hover efficiency	10	7	3	8
3	Aerodynamic interaction	7	10	10	9
8	Vibration	1	2	6	3
7	Cruise efficiency	7	4	1	4
3	Maneuverability	5	1	1	3
9	Ease of payload packaging	10	5	1	10
10	Simplicity of structure	8	2	5	10
8	Simplicity of control system	6	2	2	6
	Total	659	336	297	492

Pugh Matrix: Summary

- This is a relative evaluation of concepts – there is no need to perform detailed calculations
- Assignment of scores to each concept at this stage is based on qualitative assessment
- It may be necessary to break up some criteria into sub categories (e.g., maneuverability can be broken in to agility and responsiveness)
- Assignment of weights for attributes should be based on its relevance to requirements from RFP

Aircraft LCC: Life Cycle Costs

Life Cycle Cost (LCC)

- **Research and Development 15%LCC**
  - -**Airframe, 13(1.9%LCC)**
  - -**Avionics, 25(3.7%LCC)**
  - -Propulsion, 12(1.8%LCC)
  - -System Tests, 15(2.2%LCC)
  - -Flight Tests,22(3.3%LCC)
  - -Logistics Support, 5(0.7%LCC)
  - -Government oversight, 8(1.2%LCC)
- **Production 58%LCC**
  - -**Recurring flyaway, 70(40.6)**
    - -***Airframe, 58(23.5%LCC)***
    - -***Avionics, 30(12.2%LCC)***
    - -***Propulsion, 12(4.9%LCC***)
  - -Nonrecurring flyaway, 8(4.6%)
  - -Spares, 7(4.0%LCC)
  - -Support, 15(8.7%LCC)
- **Operation and Service 27%LCC**
  - -Mission Personnel, 40(10.7%LCC)
  - -Consumables, 35(9.4%LCC)
  - -Intermediate Maintenance, 4(1.1%LCC)
  - -Depot Maintenance, 13(3.5%LCC)
  - -Support, 8(2.1%LCC)

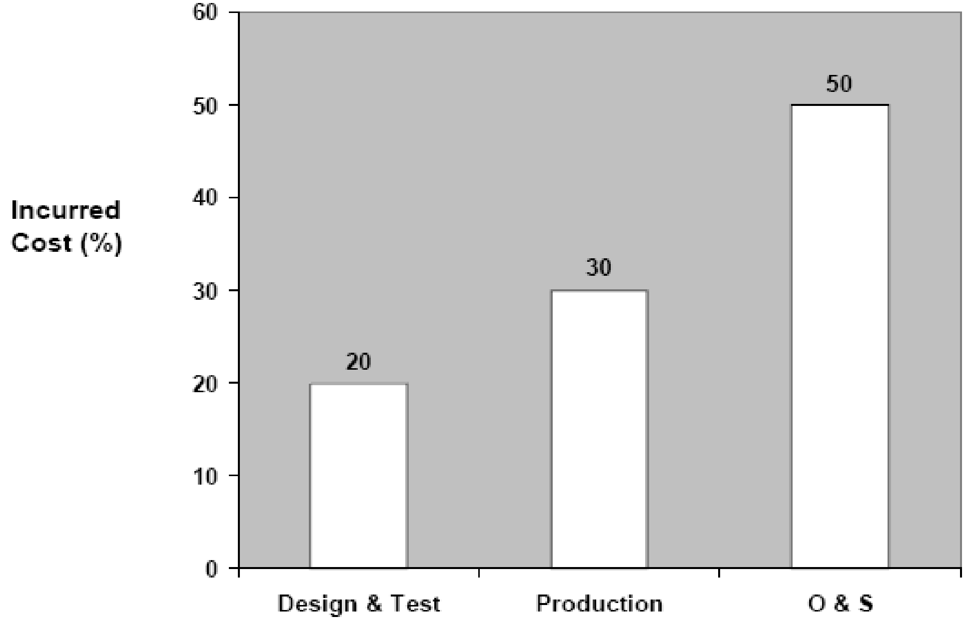
Life Cycle Cost Distribution

I I T K A N P U R

Measure of Affordability

LOCKHEED MARTIN
Aeronautical Systems
Marietta, GA

Life Cycle Cost (LCC) or "Cradle-to-Grave" Incurred Cost



Production + Operation & Support Costs—80% of LCC!

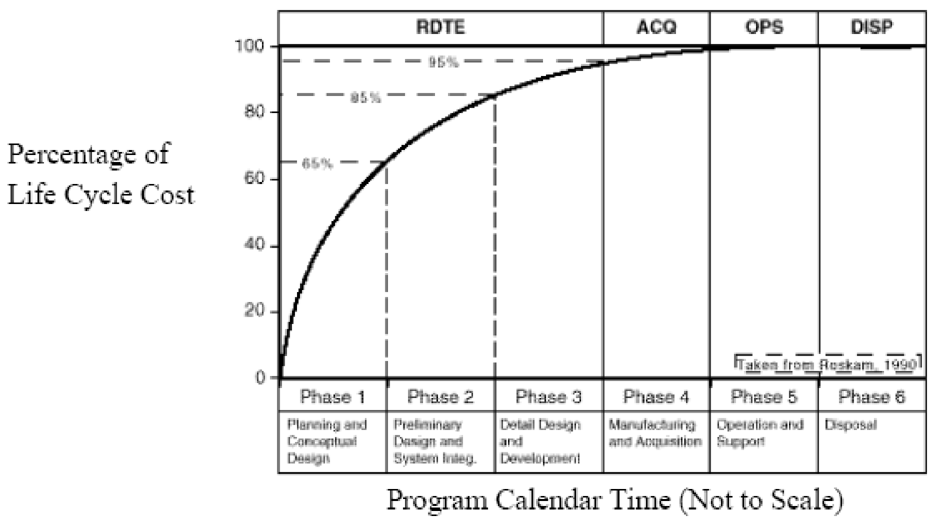
Impact of Design on Life Cycle Cost

I I T K A N P U R

Design and LCC

LOCKHEED MARTIN
Aeronautical Systems
Marietta, GA

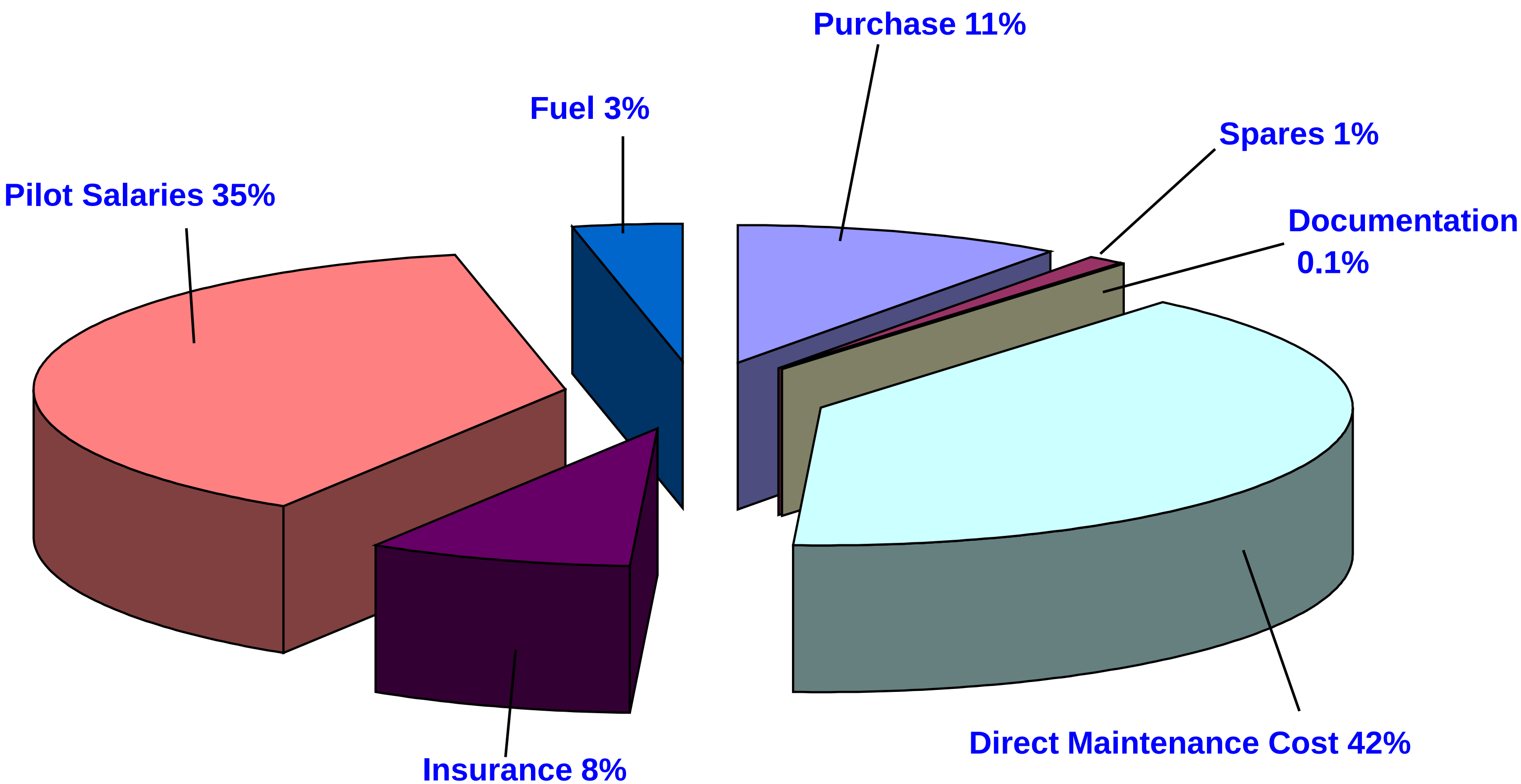
Design Activities Have Disproportionately Large Impact on LCC



A Large Amount of LCC—more than 80%—is Committed in Early Stages of Design

Unless Principal Objectives of <u>Design</u> Include Reducing Production and O&S Costs, Affordability Will Remain an Elusive Goal

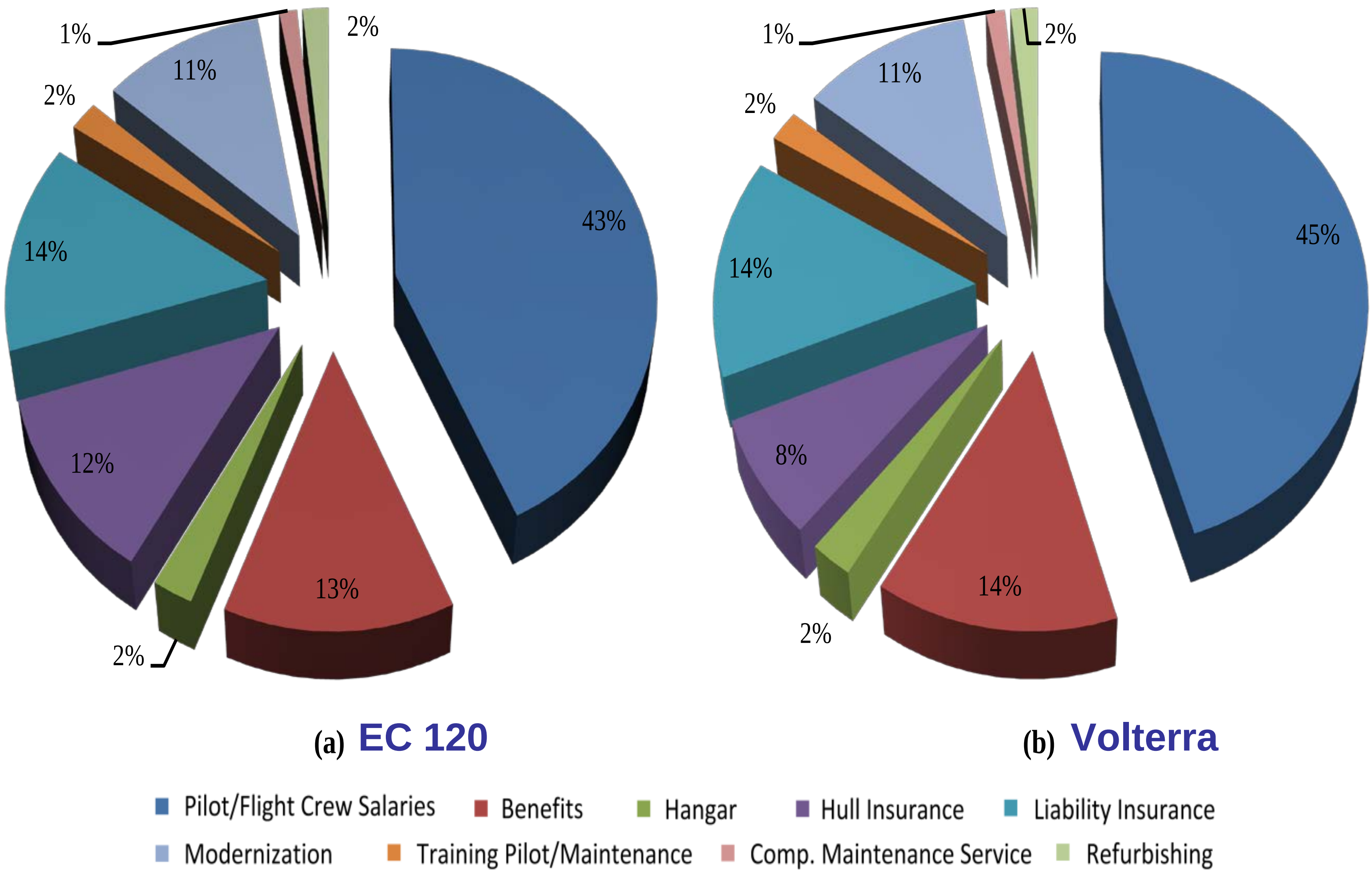
Helicopter Life Cycle Cost Components



Ref: J. F. Boer: “Helicopter Life Cycle Cost reduction through pre-design optimization”, VIVACE Forum 1, 2005.

Based on 2005 prices, 10 helicopters for 20 years

Indirect Operating Cost Breakdown

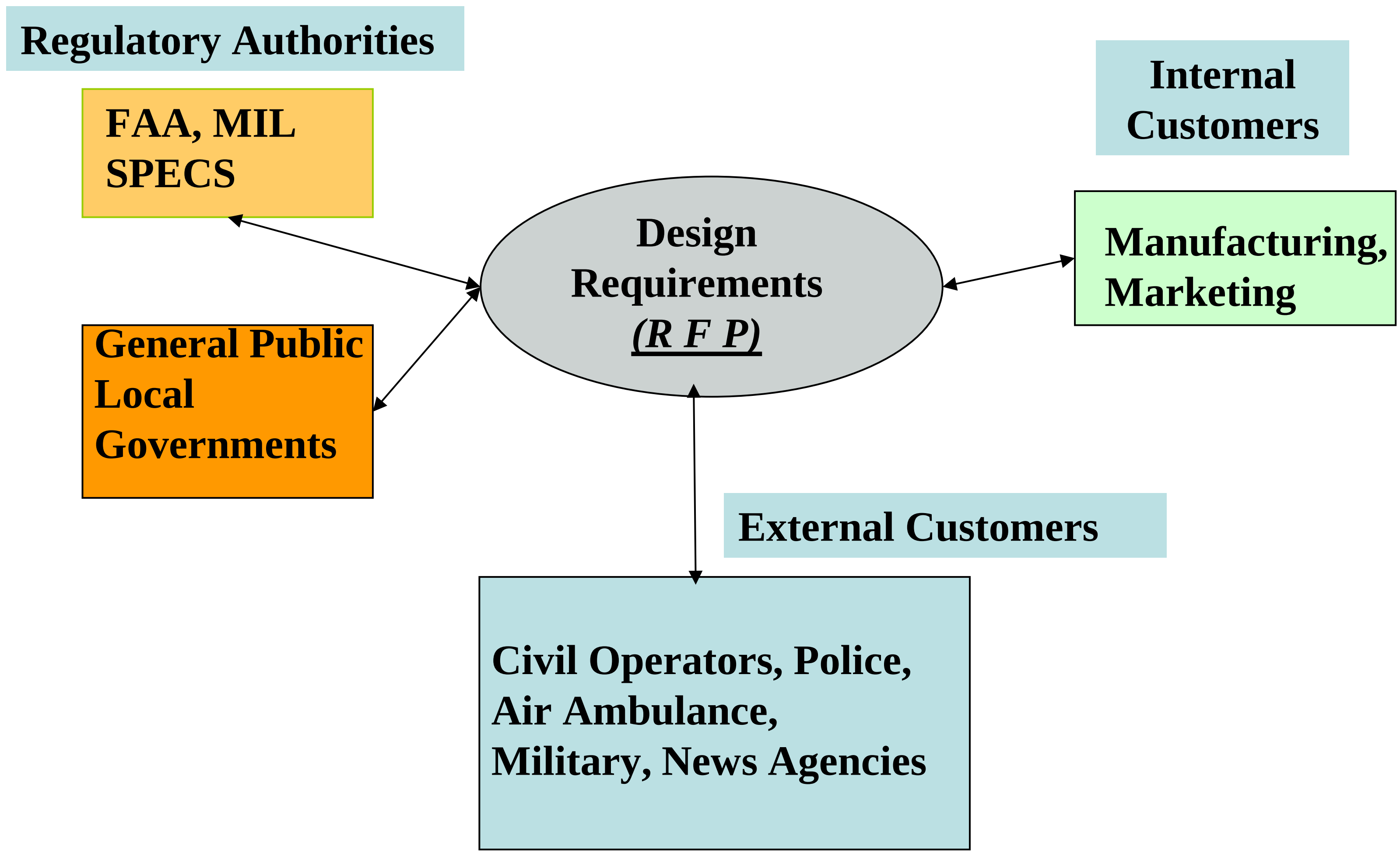


House of Quality

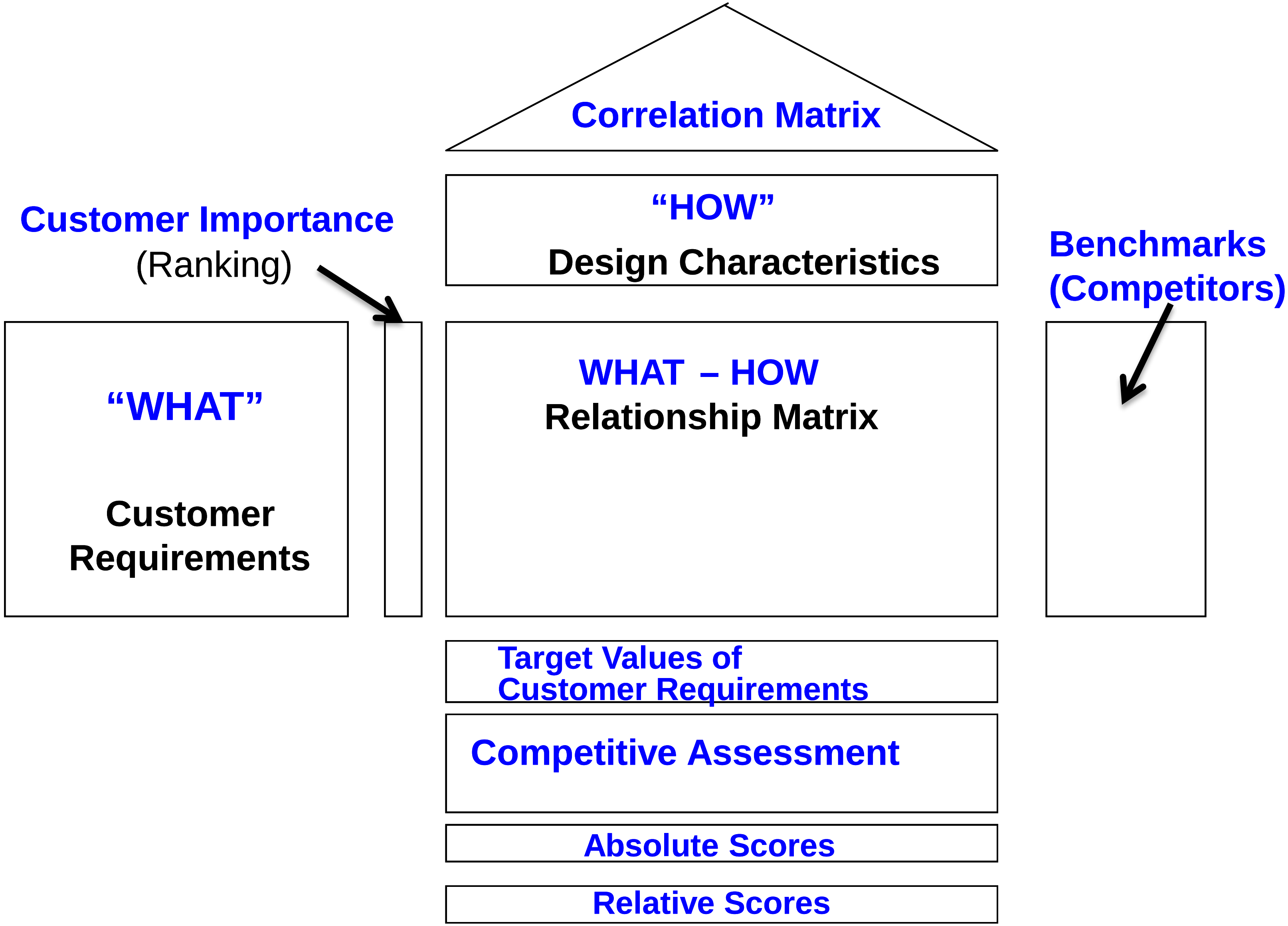
Quality Function Deployment

- **Basis: Necessary to listen to the "*Voice of the Customer*" right from onset of design process**
- **A formal method that captures the customer's requirements *("Whats")* and translates them to engineering targets *("Hows")***

Identification of Customers



House of Quality



Rooms in the House of Quality: “What”

“WHAT”

Customer Requirements (From Analysis of RFP)

Customer Needs	Customer Weights
Cruise Speed 130 knots (minimum)	5
HOGE @ 1500 m, ISA+20	5
1 Pilot + 4 Pax or 500 kg freight	5
Range = 300 n.m.	5
Low Noise	4

"How": Design Characteristics

Customer Needs	Customer Weights		Empty Weight	Disc Loading	Power Loading	Hover Figure of Merit	Blade Twist	Cabin Size	Use ofCompostie materials	Use ofMetallilc materials	Fuel density
Cruise Speed 100 knots (minimum)	5		6		6	5	6	7			
HOGE @ 1500 m, ISA+20	5		9	9	9	9	6				
1 Pilot + 4 Pax or 500 kg freight	5							9			5
Range = 300 n.m.	5		6								9
Low Noise	5		3	8	2	5	6	5			

Correlation factor

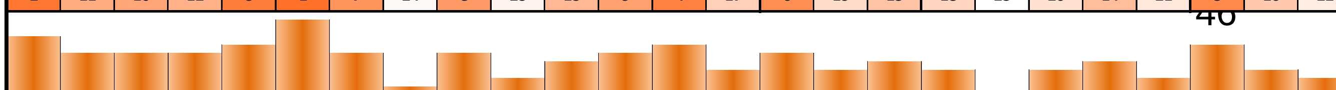
- **Question: e.g.**
  - **How does Empty Weight help to achieve V_{cruise} = 100 knots?**
  - **How does engine power decide max rate of climb?**
- **What is the degree of correlation? Strong, Medium, None?**

Engineering Design Parameters

Legend
- ✓ Strong Impact
- ! Mid-Level Impact
- ✗ Minimal Impact

Customer Requirements

		Customer Weights (0-5) 0=unimportant; 5=very imp	Aerodynamic Performance														Fuselage			Safety, Comfort, Reliability					Environmental Impact		
			Empty Weight	Cruise Speed	Tip Speed	Disc loading	Power Loading	Engine Selection	Engine SFC	Hinge Offset	Blade Design	Autorotative Index	Flat Plate Area	Auxilliary Power	Rotor Morphing	Landing Gear Morphing	Fuselage Geometry	Cabin Modularity	Avionics	Vehicle Monitoring (HUMS)	Sun Protection	Active/Passive Noise Suppression	MTBF, MTBR	Vibration/crash worthy seats	Alternate fuels	Material Selection	Manufacturability
Operational Requirements	Capable of take-off within 10 mins of positioning	5	!	✗	!	!	!	!	!	!	!	✗	!	!	!	!	!	!	!	✓	✗	!	!	✗	!	!	✗
	Cruise speed 100 kts target 120 kts	5	✓	✓	✓	!	✓	✓	!	!	✓	!	✓	!	✓	!	✓	!	!	!	✗	!	✗	✗	!	!	✗
	HOGE (15 min) with MTOW @ 1500m, ISA+20	5	✓	!	✓	✓	✓	✓	!	!	✓	!	!	!	!	✗	!	✗	✗	✗	✗	✗	!	✗	!	!	✗
	Range: 300 nautical miles	5	✓	✓	✓	!	✓	✓	!	!	!	!	✓	!	!	!	✓	!	✗	✗	✗	✗	✗	!	!	!	✗
	1 Pilot + 4 passengers with luggage or 500 kg freight	5	✓	!	!	!	!	!	!	✗	!	!	!	!	!	!	!	!	!	✗	✗	✗	✗	!	!	!	✗
	Minimum internal volume H=1.1 m,L=1.4 m,W=1.0 m	5	!	!	!	!	!	!	!	✗	✗	✗	✓	!	✗	!	✓	!	!	✗	✗	✗	✗	!	✗	!	!
	Multi-role capabilities	5	✓	✓	!	✓	!	!	!	!	!	!	!	!	!	!	!	✓	!	!	✗	!	!	!	!	!	!
Design Considerations	Low system complexity	4	!	!	!	!	!	!	!	!	!	!	!	!	✓	✓	!	!	✓	✓	!	!	✓	!	!	!	!
	Minimum operational noise	5	!	✓	✓	!	!	!	!	!	✓	!	!	!	!	✗	!	✗	!	✗	✗	✓	✗	✗	!	✗	✗
	Use of alternative fuels/hybrid energy	4	!	!	!	!	!	✓	✓	!	✗	✗	!	✓	✗	✗	✗	✗	!	✗	✗	✗	!	✗	✓	✗	!
	Operation in devastated/ground inaccessible areas	5	!	!	!	!	!	!	!	!	!	!	!	!	!	✓	!	!	!	!	!	!	!	!	!	!	!
	Semi-auto take-off and landing	4	!	✗	!	!	!	!	!	!	!	!	!	!	!	!	!	✗	✓	!	✗	!	!	✗	!	✗	✗
	Rotor morphing	3	!	!	✓	✓	!	✗	✗	!	✓	!	!	!	✓	✗	!	✗	!	!	✗	!	!	✗	✗	!	!
	Comfort/ascetics	4	!	!	!	!	!	!	✗	!	!	!	!	!	!	!	✓	✓	!	!	✓	✓	✗	!	!	!	!
	Initial operational capability (IOC) in 2020	3		!	✗	✗	!	!	!	✗	!	✗	✗	!	!	!	!	!	!	!	!	!	!	!	✓	!	✓
Cost and Energy Considerations	Selling price	4	!	!	!	!	✓	✓	!	!	!	!	!	!	✓	!	!	!	!	!	!	✓	!	!	!	✓	✓
	Sustainment costs	4	!	!	✗	!	!	!	✓	✗	!	✗	!	!	!	!	!	!	!	!	!	!	✓	!	!	!	!
	Total life-cycle costs	5	!	!	!	!	!	✓	!	!	!	!	!	!	!	!	!	!	!	!	!	!	✓	!	✓	!	✓
	Operational / recurring costs	4	!	!	!	!	!	✓	✓	!	!	✗	!	!	!	!	!	!	!	!	!	!	✓	!	✓	!	!
	RDTE costs	3	!	!	!	!	!	✓	!	!	!	!	!	!	✓	!	!	!	✓	✓	!	!	!	!	✓	!	✓
	Energy consumption: Hover	4	✓	!	✓	✓	!	✓	✓	!	!	!	!	!	!	✗	!	✗	!	!	✗	!	✗	✗	!	!	✗
	Energy consumption: 1 hour cruise	5	✓	✓	✓	✓	!	✓	✓	!	!	!	✓	!	!	!	✓	✗	!	!	✗	!	✗	✗	!	!	✗
	Energy harvesting	3	!	!	✗	✗	✗	!	!	✗	✗	✗	!	!	!	!	!	✗	!	!	!	!	!	✗	!	!	!
	End-of-life recyclability	4	!	✗	✗	✗	!	✓	!	✗	!	✗	!	!	!	!	!	!	!	!	✗	✗	!	!	!	✓	!
	Low maintenance	5	!	!	!	!	!	✓	!	!	!	✗	!	!	✓	!	!	!	!	✓	!	✓	✓	!	!	!	!
	Primary metric: Fuel or energy consumption	5	✓	✓	!	!	!	✓	✓	!	!	!	✓	✓	!	!	!	!	!	!	!	!	!	✗	✓	!	!
	Primary metric: Nox, Pollution	5	!	!	!	!	!	✓	!	!	!	!	!	!	!	✗	!	✗	!	!	!	!	!	✗	✓	!	!
	Maneuverability	3	!	!	✓	!	✓	!	!	!	✓	!	!	!	✓	!	!	!	!	✗	✗	✗	✗	✗	!	✗	✗
Safety	Operational safety	5	!	!	!	!	!	!	!	!	!	✓	!	!	!	!	!	!	!	✓	!	!	!	✓	!	!	!
	Crash worthiness	5	!	!	!	!	!	!	!	!	!	✓	!	✗	!	!	✓	!	!	!	✗	✗	!	✓	✗	✓	!
	Post-Impact survivability	4	!	!	!	!	!	!	✗	!	!	!	!	!	!	!	✓	!	!	!	✗	✗	!	✓	✗	✓	!
	Raw Score		144.1	107.9	108.3	107.1	137.6	173.6	114	44.13	112.8	57.63	96.13	108.6	134.5	82.5	119.6	76.63	90	80	19	71	90.5	62.13	124.3	86.38	61.38
	Percent Score (%)		6.0	4.5	4.5	4.4	5.7	7.2	4.7	1.8	4.7	2.4	4.0	4.5	5.6	3.4	5.0	3.2	3.7	3.3	0.8	2.9	3.8	2.6	5.2	3.6	2.5
	Relative Score		0.83	0.62	0.62	0.62	0.79	1.00	0.66	0.25	0.65	0.33	0.55	0.63	0.77	0.48	0.69	0.44	0.52	0.46	0.11	0.41	0.52	0.36	0.72	0.50	0.35
	Relative Rank (Importance to Design)		2	11	10	12	3	1	7	24	8	23	13	9	4	17	6	19	15	18	25	20	14	21	5	16	22



Performance Indices - 1

1. Mission Capability or Productivity Index

$$\frac{Payload * Cruise\ Speed}{W_{Empty} + W_{fuel}}$$

2. Availability Index

$$\frac{\mathrm{MTBF}}{\mathrm{MTBF} + \mathrm{MTBR}}$$

3. Maneuverability Indices

$$\frac{M.R.\ Hinge\ offset}{Blade\ Radius};\ Power\ Loading;\quad Blade\ Loading$$

MTBF: Mean Time Between Failures **MTBR: Mean Time Between Repairs**

Performance Indices - 2

4. Safety Index

= Autorotation Index

$\equiv f$(Blade inertia, tip speed, disk loading)

5. Life Cycle Cost

= Cost of (Research, Development, Test and Engineering

+ Production

+ Retirement/Disposal

+ Operation/Support)

Measures of “Effectiveness”

I I T K A N P U R

REF: Maynard L. Marquis and George Price

“Affordability and Performance in Rotorcraft Design
A Guide for the Perplexed”

AHS 53rd Annual Forum, Virginia Beach, VA, April 29-May 1, 1997

pp. 515-538

- Measures of Effectiveness and their relation to design attributes
- Analysis oriented towards military helicopters

System Effectiveness

Availability
- MTBF
- MTBR
- ADT*

Dependability
- Target Detection
- Target Kills
- Survivability
  - Stealth
  - Maneuverability
  - Crash Survivability
- Maneuverability/Agility

Capability

<u>Performance</u>
- Payload
- Range
- Speed
- HOGE
- Loiter

<u>Mission Eqpt</u>
- Nav/Comm
- Sensors
- Counter-measures
- Load handling
- Furnishing
- Armament

**ADT=Administrative down time*

System Effectiveness= Availability x Dependability x Capability

Cost Effectiveness

- **Cost Measures: Investment cost, Maintenance cost, Cost to Environment, Operating cost, Retirement cost**

- **Effectiveness or Benefits: Characteristics that are of most interest to customer**

- **Cost – Effectiveness: used to resolve system tradeoffs by using explicit relationships that link costs and effectiveness**

Cost Effectiveness

- **Cost Index (Life cycle cost) is a sum of**
  1. **Research, Development, Test & Engineering cost**
  2. **Procurement cost**
  3. **Operating and support cost (DOC for commercial helicopters)**
- **Effectiveness Index**

  = (Productivity index)

  x (Operational availability)

  x (Battlefield win probability)

  x (Inventory factor)

Productivity Index

- Productivity Index is a function of HOGE at Gross weight, Payload capability, Mission equipment, Range capability, Speed capability, Hover time and Loiter time.

$$\text{Productivity Index} = (\text{Payload} + \text{Equipment}) * \text{Range parameter} * \left(1 + \frac{\mathrm{T_{base}}}{\text{Mission Time}}\right)$$

$$\text{Range Parameter} = \text{Range}_{\text{Max Speed}} + \text{Range}_{\text{VBR}} + V_{BR} * (t_{loiter} + t_{hover})$$

$$T_{base} : \text{Weighting factor; some desired mission time}$$

VBR : Velocity for Best Range

Operational Availability & Win Probability

Operational Availability

$$Operational\ Availability = 1 - \frac{FH\ \ per\, day * (MTTR + ADT)}{24 * MTBF}$$

$$FH\ \ per\ day = Flight\ Hours\ per\ Day$$

$$MTTR = Mean\ Time\text{-}to\text{-}Repair$$

$$ADT = Administrative\ Down\ Time$$

$$MTBF = Mean\ Time\ Between\ Failures$$

Battlefield Win Probability

(This factor can be set to 1 for commercial helicopters)

- ***Very important to Attack and Reconnaissance Rotorcraft***
- ***Non-ignorable factor for utility or cargo missions***
- ***For military helicopters, this factor is a function of***
  - ***Probability of Survival***
  - ***Probability of Enemy Kills***

Inventory Factor

Inventory Factor

Measure of program/fleet management and consists of:

-Time to market

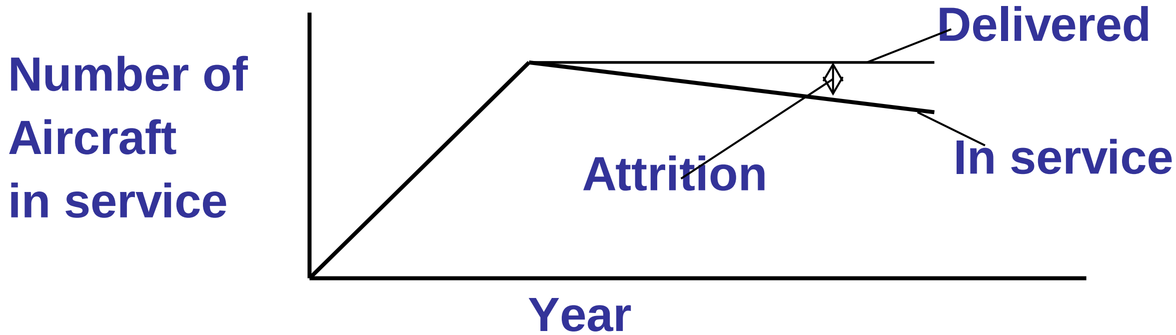
- Fleet size

- Aircraft delivery rate

- Service life

- Attrition

Defined as the area under the curve of Number of aircraft in service over the number of years in service



Sensitivity Analysis: Example

- **Influence of Mission Attributes on Rotorcraft Effectiveness (Ref: Marquis and Price, 53rd AHS Annual Forum, 1997)**

- **Baseline Mission:**
  - **10 minutes hover + 40 minutes loiter**
  - **Cruise at VBR (= 125 knots) for 175 nautical miles + 30 nautical miles at maximum cruise speed**
  - **Payload = 5000 lbs**

Sensitivity Analysis

I I T K A N P U R

Attribute	% change in Effectiveness Index due to 10% change in attribute
Productivity Index	10.00%
Inventory Factor	10.00%
Operational Availability	12.66%
Payload + Equipment	10.00
Mission range	5.45%
Range at VBR	4.66%

10% change in (Payload + Equipment) changes Effectiveness Index by 10%

Sensitivity Analysis

Attribute	% change in Effectiveness Index due to 10% change in attribute
Maximum Speed	0.98%
Hover Time	0.55%
Loiter Time	2.65%
MTBF	2.39%
Aircraft Production Rate	1.48%

Effectiveness Index more sensitive to Payload + Equipment (10% for 10% change) than to Mission Range (5.45% for 10% change in Range)