Systems Analysis

- Lecture #03 – September 5, 2023
- Rigorous decision making
- Structure of systems analysis
- Objective functions
- Trade studies
- Modeling
- Parametric design
- Decision matrices
- Analytical Hierarchy Process

Analytical Design

- Rigorously investigating options to arrive at the most appropriate choices
  - Modeling
  - Parametric analysis
  - Trade studies
  - Sensitivity analysis
- Ties into fields of decision analysis, optimization, probability

Design Reference Mission(s)

- Description of canonical mission(s) for use in design processes
- Could take the form of a narrative, storyboard, pictogram, timeline, or combination thereof
- Greater degree of detail where needed (e.g., surface operations)
- Created by eventual users of the system (“stakeholders”) very early in development cycle

Requirements Document

- The "bible" of the design and development process
- Lists (clearly, unambiguously, numerically) what is required to successfully complete the program which culminates in the Design Reference Mission
- Requirements "flow-down" results in successively finer levels of detail
- May be subject to change as state of knowledge grows
- Critical tool for maintaining program budgets

Akin's Laws of Spacecraft Design - #13

Design is based on requirements. There's no justification for designing something one bit "better" than the requirements dictate.

Space Systems Architecture

- Description of physical hardware, processes, and operations to perform DRM
- Term is used widely (e.g., “software architecture”, “mission architecture”, “planning architecture”), but refers to basic configuration decisions
- Generally result of significant trade studies to compare options

Making Good Decisions

- Define "good": does it best perform the mission?
- Define "mission": what does it have to do?
- Define "best": what is the critical figure of merit?
- Define "figure of merit": how do we measure how well it meets the requirements?
- Define "requirements": what does it need to be able to do?
- Define "able": how does it mean to "meet" a requirement?
- Define "meet": are there extra points for exceeding?

Buying a New Car

- Design Reference Mission: drive 12,000 miles/year for 15 years
- Possible figures of merit
  - Initial purchase price
  - Life cycle cost
  - Reliability
  - Payload
  - Environmental impacts
  - Safety
  - Maintainability/reliability

Buying a New Car

Honda Fit

- Can it accomplish the DRM?
- Does it meet the requirements? (Oops, we didn't do a requirements document… *yet!*)
- Is it the best solution to the problem that requires a new car?

Buying a New Car

Honda Fit | Chevy Bolt | Toyota RAV4

- You can't make an informed choice if you only have one option
- You must compete at least two options, and select the better/best fit to the requirements – this is a *trade study*

Overview of the Design Process

Program Objectives
System Requirements

Vehicle-level Estimation
(based on a few parameters
from prior art)

Basic Axiom: Relative rankings between competing systems will remain consistent from level to level

System-level Estimation
(system parameters based on
prior experience)

System-level Design
(based on discipline-
oriented analysis)

Increasing complexity

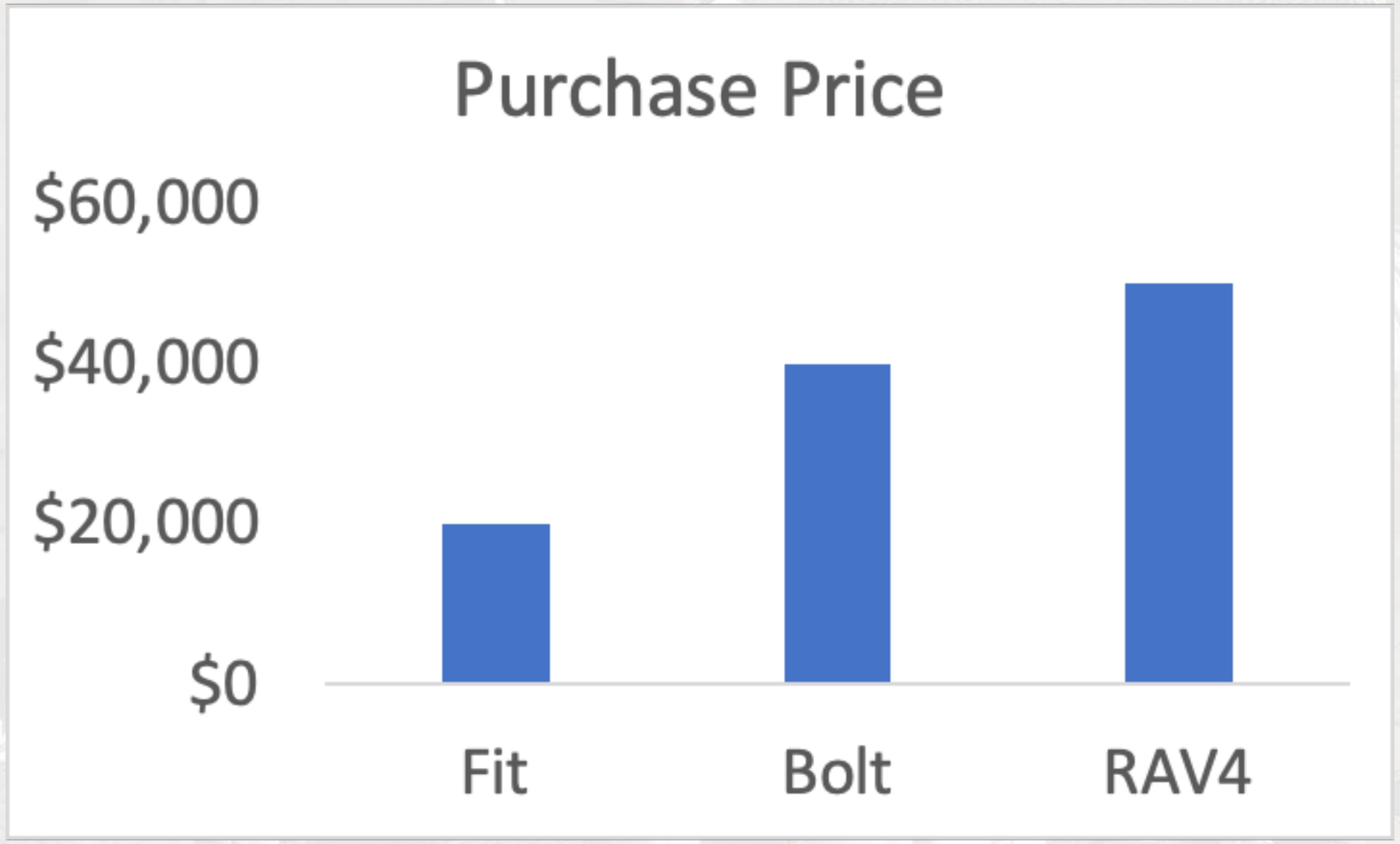
Increasing accuracy

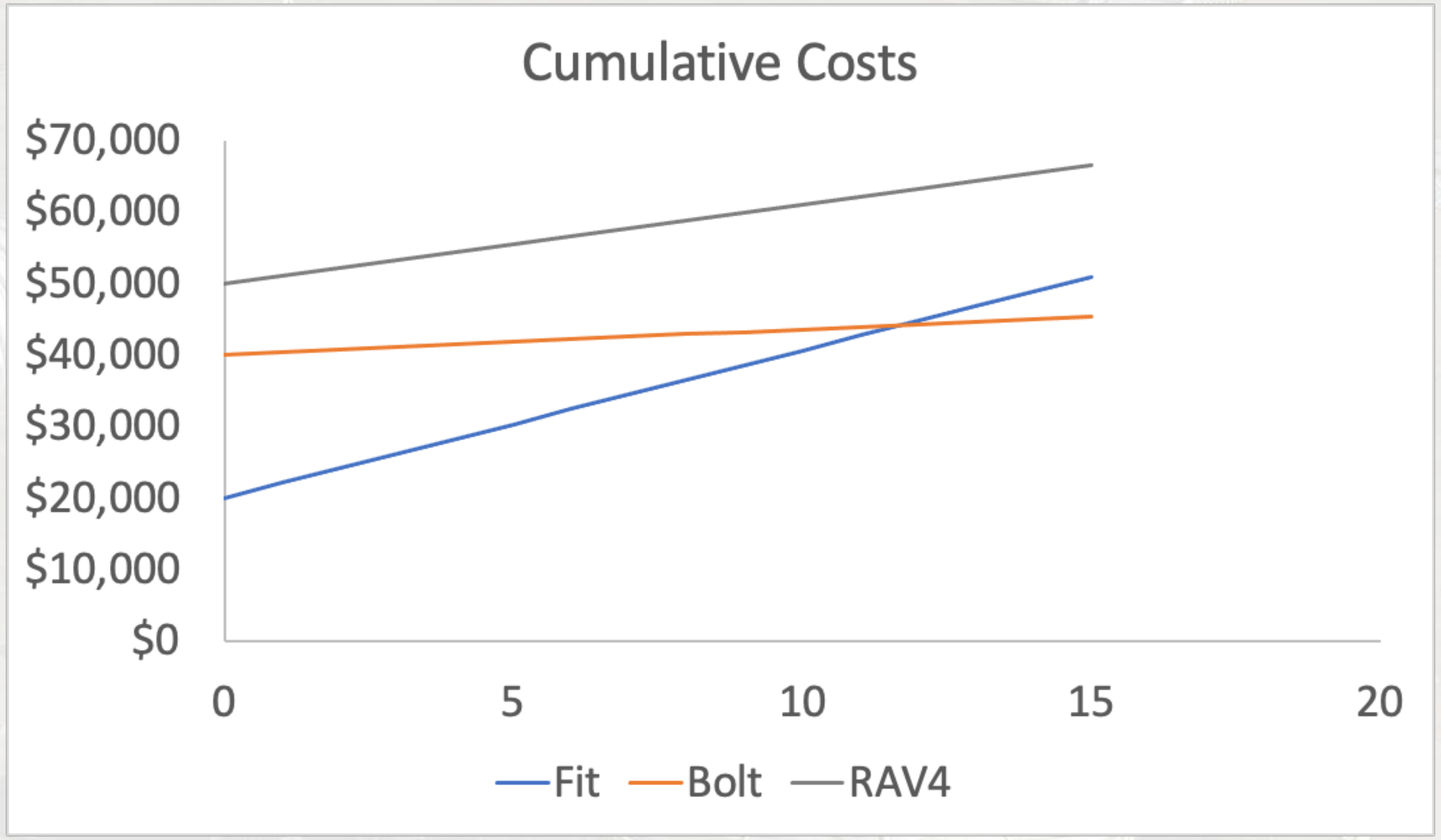
Decreasing ability
to comprehend the “big
picture”

Decision Criteria

- Requirements are “pass/fail” – either you meet them or you don’t
- Each design process will have an “Objective Function” – a particular figure of merit which is optimized in the trade study process
- Examples: minimize inert mass, maximize payload, minimize cost

What's the Right Objective Function?





Was the DRM Correct and Appropriate?

- 1st iteration: 12,000 mi/yr (U.S. average)
- 2nd iteration:
  – 35 mi/day x 250 working days = 8750 mi/yr
  – 300 mi/month chasing balloons = 3600 mi/yr
  – 2000 mi/yr in road trip
  – Total mileage 14,350 mi/yr
- Requirements include
  – Balloon launches include carrying 4 helium tanks ⇒ need 5ft of cargo

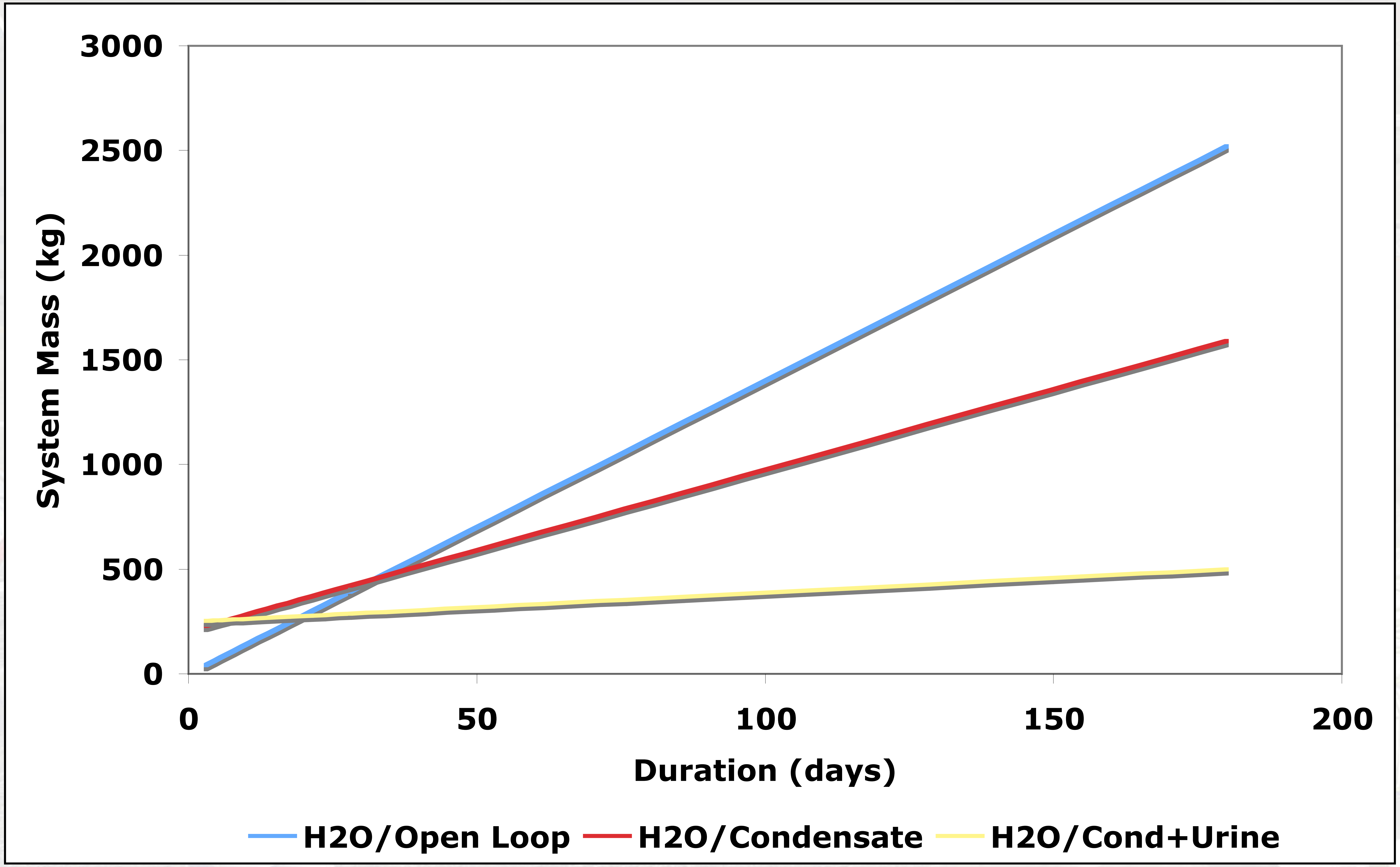
Car Decision, Revisited

- Bolt doesn't have the range for balloon launches or road trips
- Fit doesn't have the cargo space for balloon launches
- ⟹Choice defaults to RAV4 as only option that meets requirements
- Next revisit: mixed fleet solution
  - RAV4 for long range trips and cargo
  - Bolt or Fit for routine local transportation
  - Assumes purchase or life cycle cost is *not* the objective function!

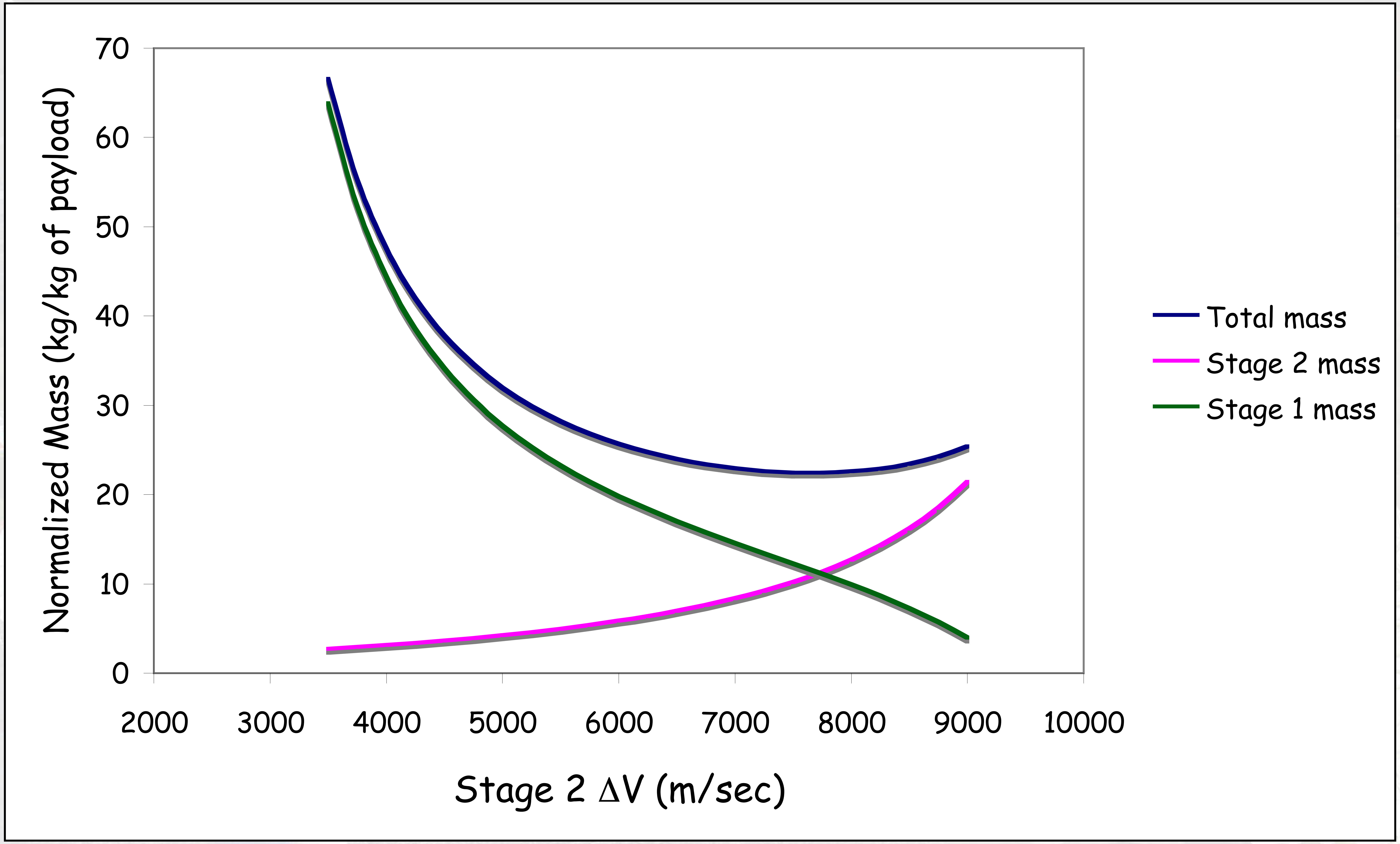
Summary of the Trade Study Process

- Always develop at least two options to satisfy requirements
- Compare options on the basis of an objective function to find which is maximally beneficial to the decision criteria
- Revisit components (DRM, requirements, objective function) periodically to ensure the solution made is still the most favorable
- This works on every level of the design process (components, subsystems, systems, vehicles, architectures…)

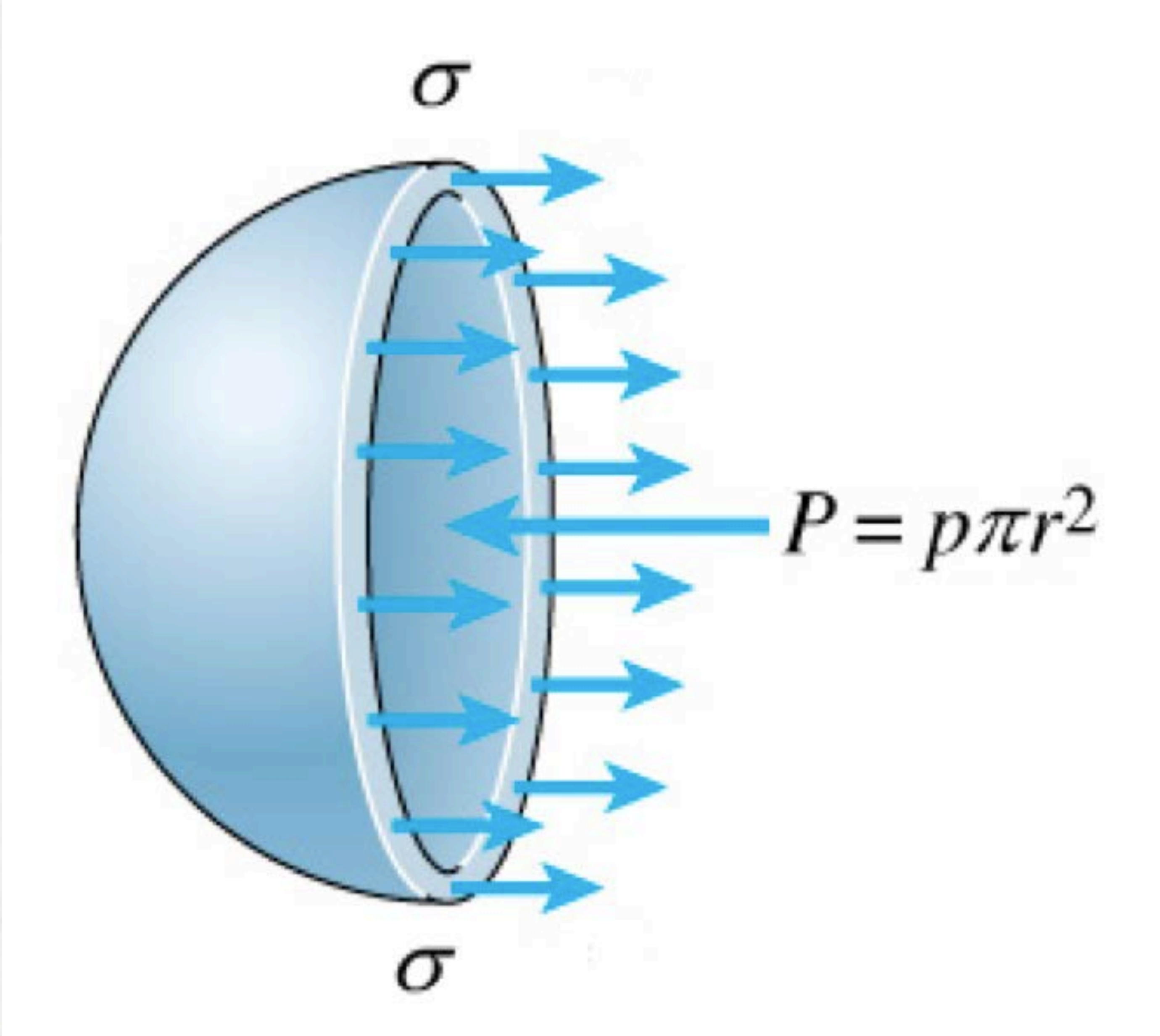
Trade Study – Comparison of Life Support Options



Trade Study – Variation of LV Design Parameters



Modeling for Design Parameters



$$\pi r^2 P = 2\pi r t \theta \qquad rP = 2t\theta$$

$$t = \frac{rP}{2\sigma} \qquad V_{tank} = 4\pi r^2 t$$

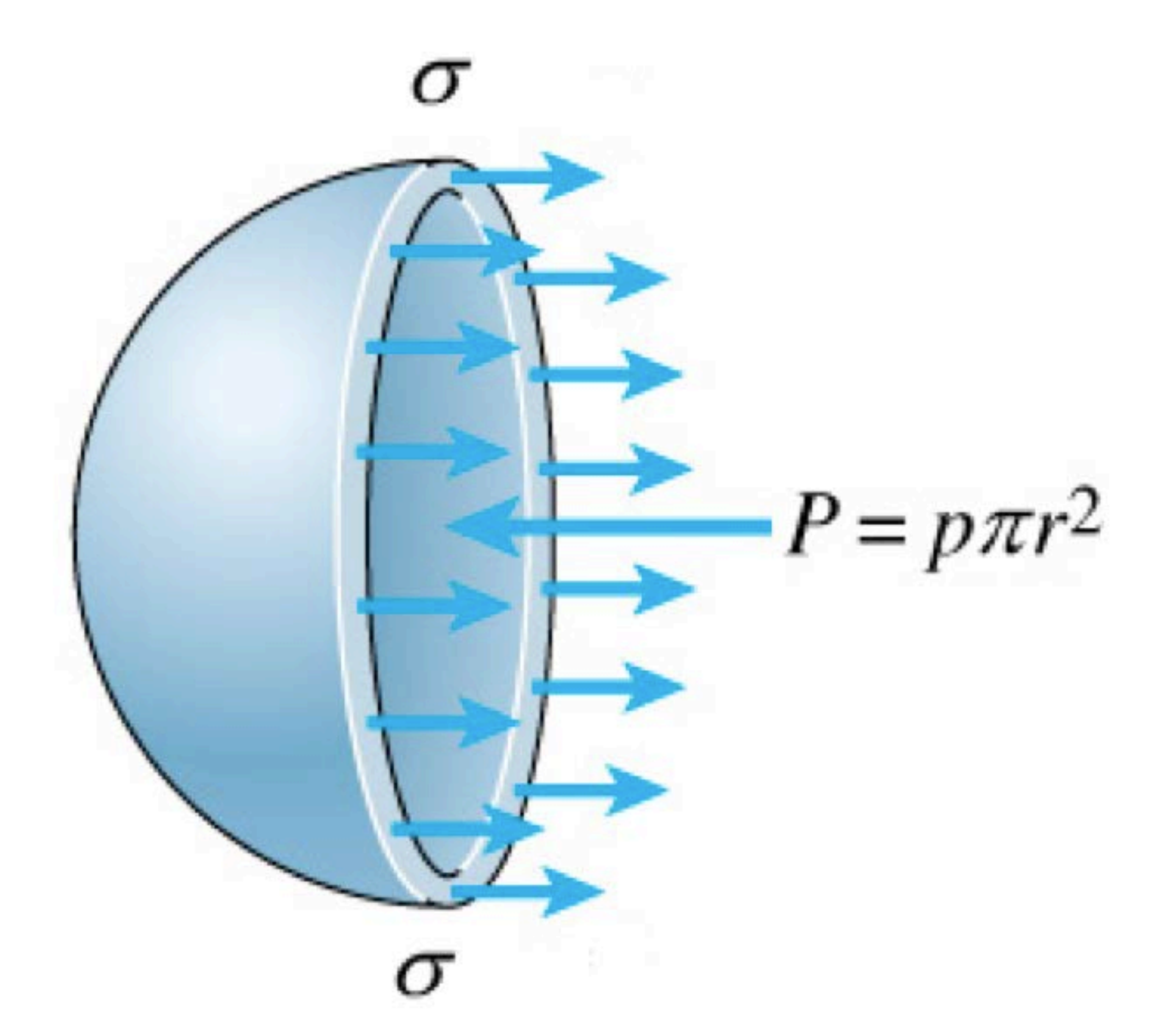
$$m_{tank} = V_{tank}\rho_t = 4\rho_t \pi r^2 \frac{rP}{2\sigma} = 2\rho_t \pi r^2 \frac{rP}{\sigma}$$

$$m_{gas} = V_{gas}\rho_g = \frac{4}{3}\pi r^3 \rho_g$$

$$\frac{m_{tank}}{m_{gas}} = \frac{2\rho_t \pi r^3 P/\sigma}{4/3\rho_g \pi r^3} = \boxed{\frac{3}{2}\frac{\rho_t}{\rho_g}\frac{P}{\sigma}}$$

However…

Modeling for Design Parameters



$$P = \rho_g RT \;\Rightarrow\; \frac{\rho_g}{\rho_{g,ref}} = \frac{P}{P_{ref}} \;\Rightarrow\; \rho_g = P\frac{\rho_{g,ref}}{P_{ref}}$$

$$\frac{m_{tank}}{m_{gas}} = \frac{3}{2}\frac{\rho_t}{\rho_g}\frac{P}{\sigma} = \frac{3}{2}\frac{\rho_t}{P}\frac{P_{ref}}{\rho_{g,ref}}\frac{P}{\sigma} = \boxed{\frac{3}{2}\frac{\rho_t}{\rho_{g,ref}}\frac{P_{ref}}{\sigma}}$$

For a spherical tank, the ratio between optimized tank mass and pressurized gas mass is invariant with tank pressure

Decision Analysis Tools

- A number of different approaches exist, e.g.
  - Decision Matrices (such as Pugh Method)
  - Quality Function Deployment
  - Six Sigma
  - Analytic Hierarchy Process (details following)
- Generally provide a way to make decisions where no single clear analytical metric exists - “quantifying opinions”
- Allows use of subjective rankings between criteria to create numerical weightings
- **Not** a substitute for rigorous analysis!

Pugh Matrix

Criterion	Weight	Fit	Bolt	RAV4
Purchase price	2	5	3	2
Price/yr	3	2	5	4
CO2 emissions	1	1	5	4
Totals		17	26	20

This is NOT engineering!!!

Decision Matrix Using Real Numbers

Criterion	Weight	Fit	Bolt	RAV4
Purchase price	2	$20,000	$40,000	$50,000
Price/yr	3	$2063	$359	$1104
CO2 emissions	1	3188	1794	2277
Totals		49,377	82,871	105,589

This is bad mathematics

Decision Matrix Using Normalized Numbers

Criterion	Weight	Fit	Bolt	RAV4
Purchase price	0.3	0.4	0.8	1
Price/yr	0.4	1	0.174	0.535
CO2 emissions	0.3	1	0.549	0.714
Totals	1	0.820	0.474	0.728

Conclusion on Decision Matrices

- Use of the Pugh method (arbitrarily assigning numbers with implicit weighting of subjective evaluations) may produce a "reasonable" answer, but is *NOT* meaningful analysis and should *NOT* be presented or used as such
- Use of quantitative values in a decision matrix *CAN* be used to evaluate given multiple different decision criteria
- Quantitative data and weights should be normalized to prevent inadvertent weighting bias across criteria

Dealing with Opinions

- There will be times when you have to take human opinions into account
  - Assessment of human factors or operational protocols
  - Impact of prior experience
- The goal is to collect and use the data in a rigorous manner
- The need is to quantify the strength of the opinions spread among potential options
- One valuable approach: the Analytical Hierarchy Process

Analytical Hierarchy Process (AHP)

- Considering a range of options, e.g., ice cream
  - Vanilla (V)
  - Peach (P)
  - Strawberry (S)
  - Chocolate (C)
- Could ask for a rank ordering, e.g. (1) vanilla, (2) strawberry, (3) peach, (4) chocolate - but that doesn’t give any information on how firm the rankings are
- Use pairwise comparisons to get quantitative evaluation of the degree of preference

Pairwise Comparisons

- Ideally, do exhaustive combinations
  - Vanilla >> chocolate (strongly agree)
  - Vanilla >> peach (agree)
  - Vanilla >> strawberry (agree)
  - Peach >> chocolate (strongly agree)
  - Peach >> strawberry (disagree)
  - Strawberry >> chocolate (strongly agree)
- Number of required pairings out of N options is (N)(N-1)/2 - e.g., N=20 requires 190 pairings!
- Can use hierarchies of subgroupings to keep it manageable

Evaluation Metric

- Create a numerical scaling function, e.g.
  - "strongly agree" = 9
  - "agree" = 3
  - "neither agree nor disagree" = 1
  - "disagree" = 1/3
  - "strongly disagree" = 1/9
- Numerical rankings are arbitrary, but often follow geometric progressions
  - 9, 3, 1, 1/3, 1/9
  - 8, 4, 2, 1, 1/2, 1/4, 1/8

Evaluation Matrix

- Fill out matrix preferring rows over columns

	C	S	P	V
C				
S	9			
P	9	1/3		
V	9	3	3	

Note: if you have multiple people performing an AHP evaluation, populate a matrix like this for each of them, then add the matrices together and use that summary matrix as you proceed with the rest of the analysis.

Evaluation Matrix

- Fill out matrix preferring rows over columns
- Fill opposite diagonal with reciprocals

	C	S	P	V
C				
S	9			
P	9	1/3		
V	9	3	3	

⟹

	C	S	P	V
C		1/9	1/9	1/9
S	9		3	1/3
P	9	1/3		1/3
V	9	3	3	

Normalization of Matrix Elements

- Normalize columns by column sums

	C	S	P	V
C		1/9	1/9	1/9
S	9		3	1/3
P	9	1/3		1/3
V	9	3	3	
	27	3.44	6.11	0.78

$\Longrightarrow$

	C	S	P	V
C		0.032	0.018	0.143
S	0.333		0.491	0.429
P	0.333	0.097		0.429
V	0.333	0.871	0.491	

Evaluation of Hierarchy Among Options

- Average across the populated row elements

	C	S	P	V	
					⇓ These rankings should sum to 1.0
C		0.032	0.018	0.143	0.048
S	0.333		0.491	0.429	0.313
P	0.333	0.097		0.429	0.215
V	0.333	0.871	0.491		0.424 ⇐ Top ranking

Akin's Laws of Spacecraft Design - #38

Capabilities drive requirements, regardless of what the systems engineering textbooks say.

Term Project 1

- Everyone will be assigned to a team of 4-5 people
  - Grad students and hypersonic capstone will each form their own team
- The project will be to design an Earth launch vehicle
  - Details will be provided shortly
  - Focus will be on systems engineering, trade studies, and cost analysis
  - Each team will be required to submit detailed CAD images
  - Report will be in the form of presentation slides
  - Grad and hypersonic teams will go into greater depth and continue project throughout this term

Team Project 2

- Team project 2 will be to start work on 484 projects for next term
- Based on feedback from first day survey, projects will be
  - Long-Duration Mars Simulation at the Moon (RASC-AL)
  - Sustained Lunar Evolution (RASC-AL)
  - Large-Scale Lunar Crater Prospector (RASCAL)
  - Collaborative Robotic Lunar Rovers (GSFC)
- You will be assigned to a project and a specialty group, based on your preferences (survey coming shortly)

Specialty Teams (Matrix Organization)

- Systems Analysis and Engineering
- Mission Planning and Analysis
- Crew Systems (as appropriate)
- Loads, Structures, and Mechanisms
- Power, Propulsion, and Thermal
- Avionics, Flight Software, and Simulation
- Additional assignment: Hardware team (as appropriate)