Technology Assessment in Support of the Presidential Vision for Space Exploration

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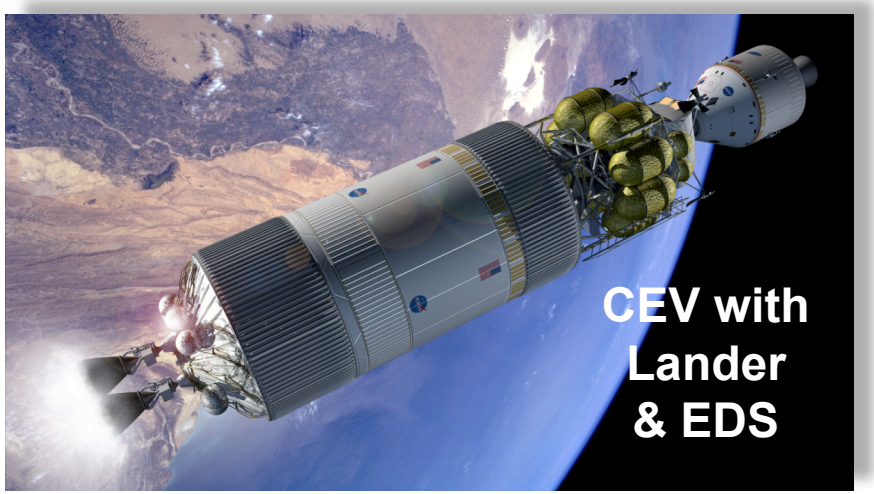
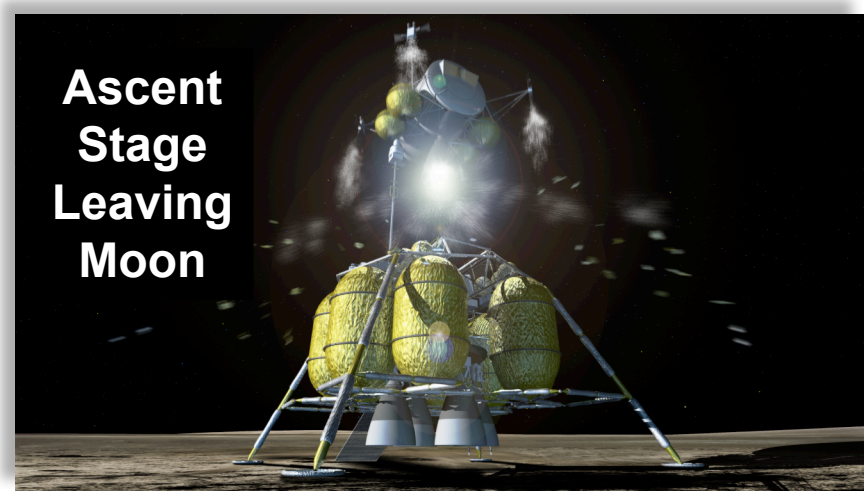
Outline

- Pictorial description of lunar context
- Definition of base case
- Optimization results
- Effects of cost uncertainties for base case and different assumed annual budget levels
- Effects of temporal optimization

Lunar Exploration



Lunar Exploration



Parachutes at Reentry

Landing on Earth

Base Case

1. **Four missions (CEV to ISS, CEV to moon – short stay; lunar outpost base; Mars outpost (to come later)) with importance weights 9, 6, 1, 0.1 respectively.**

2. **Six Figures of merit associated with each capability need**

   A. Overall criticality, safety and mission success, extensibility/ flexibility, programmatic risk reduction, affordability, and technical performance with High/Medium/Low weights taken to be 9,3,1 respectively.

   B. Individual center contributions are associated with each need; can have multiple centers contributing.

3. **Available budgets by year have been provided by HQ sponsor**

4. **Budgets and schedule to achieve performance provided and validated by HQ.**

Objective Function

5. **Benefit function (BF) is a weighted sum of expected Figures of Merit (summed per need, per weighted missions).**

$$BF = \sum_{i=1,N_{missions}} W_i \sum_{j=1,M_{needs}} P_{i,j} \sum_{k=1,R} FOM_{i,j,k}$$

$N_{missions}$	Number of missions under consideration
W_i	Weight of the ith mission
M_{needs}	Number of needs under consideration
$P_{i,j}$	Probability of fulfilling the jth need for the ith mission
R	Number of Figures of Merit
$FOM_{i,j,k}$	k^{th} Figure of Merit, of the jth need, with respect to the ith mission

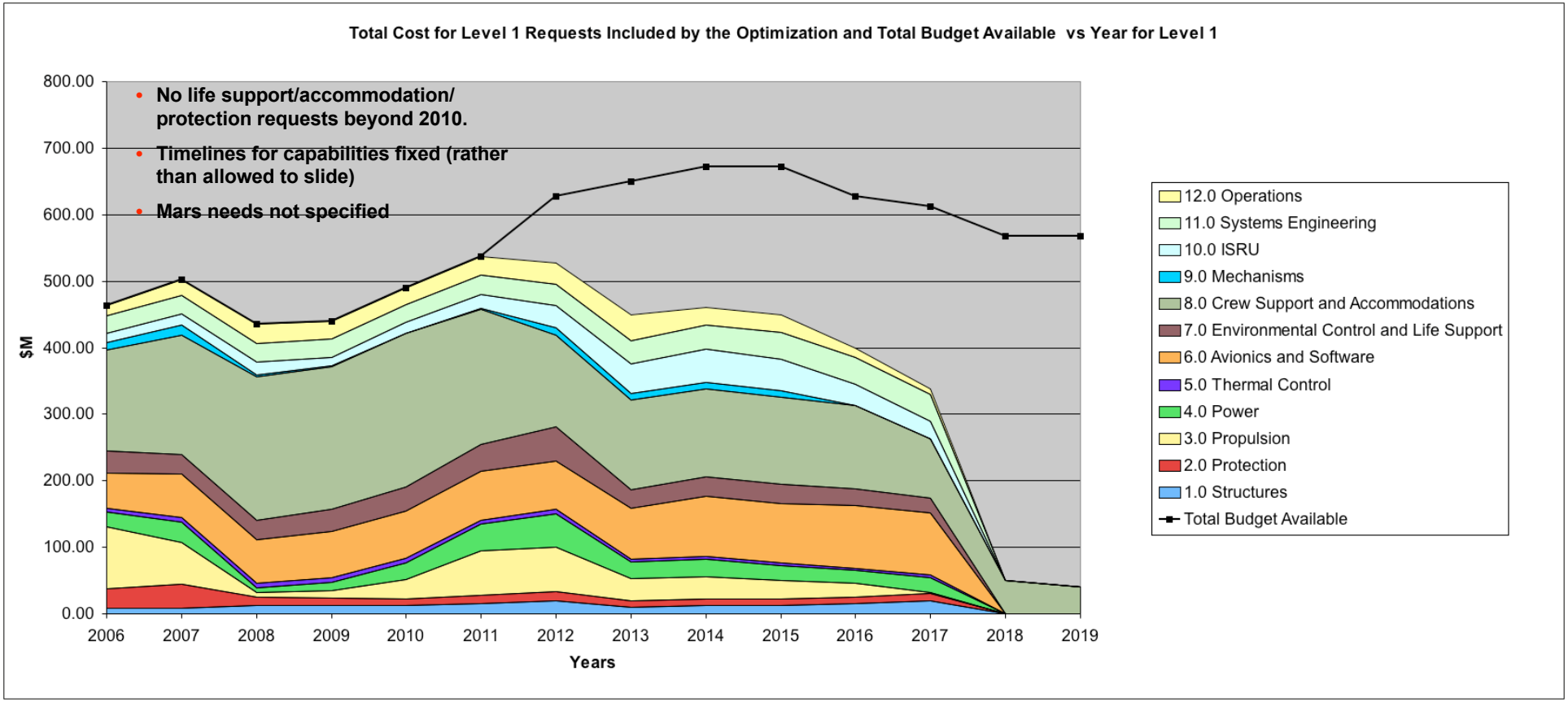
Optimization

6. System is optimized (i.e. maximize total Figure of Merit achieved) subject to specified costs per year allowable by sponsor, and full investment in a capability once selected (i.e. no partial funding)

7. Outputs are selected investments by year and associated sensitivity analysis

Total Budget Available and Total Budget Allocated ($M) per Level 1 Capability Optimized to Fit per Year

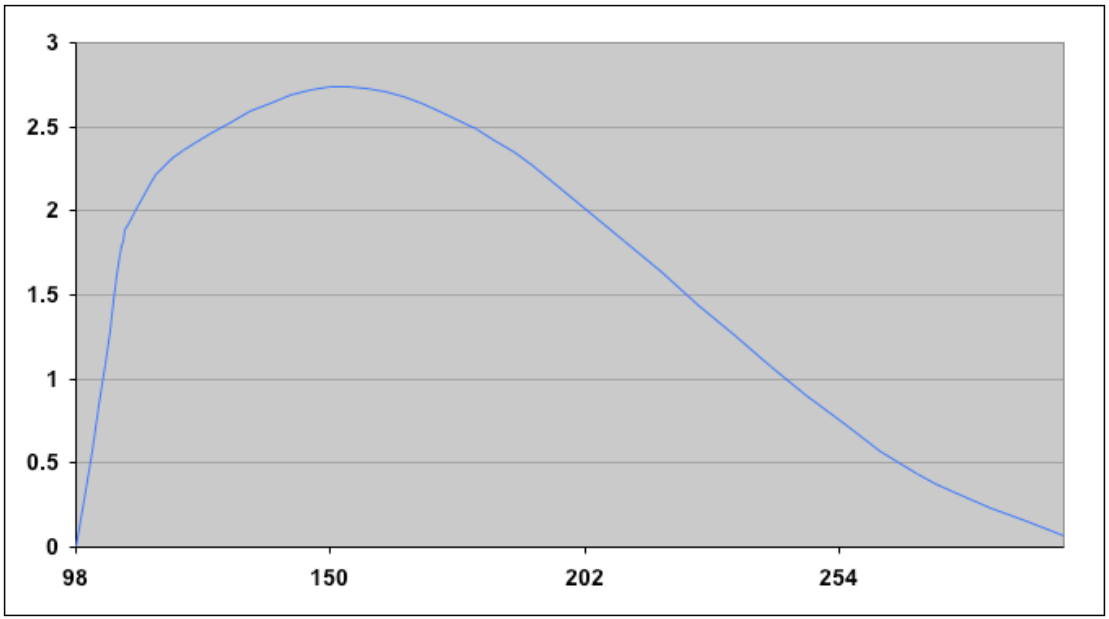
- Used data set provided by HQ
- Optimized benefit function subject to cost constraint
- Optimization is trivial since our input data was constructed such as to have all capabilities fit under available annual budgets



Cost Uncertainties

- **Examine effects of uncertain cost estimates**
  - Beta density function used to model the cost uncertainties
- **Monte Carlo simulation sampled from capability cost space and input to optimization**
- **Optimization used to identify portfolio of capabilities that fit under available budget levels**

Beta sampling function



Beta function parameters
$\alpha = 1.5$
$\beta = 3$
Lower bound = 98 %
Upper bound = 300 %

Percent cost variation from nominal

Method and Interpretation of Results

- **Used Monte Carlo simulation with 1000 runs**
- **Optimization performed on each run**
  - Maximize the weighted sum of FOMs of selected capabilities
  - While constrained by the available annual budget levels
- **Enabling and enhancing distinction not available in the input data**
  - Selection of capabilities based on FOM and cost alone may not be valid for enabling technologies
- **Percentage of time each capability was chosen in the optimization was tabulated**
  - With 1000 runs the 95% confidence interval for true percentage is +/- 1.5%

0%-10%
10%-20%
20%-30%
30%-40%
40%-50%
50%-60%
60%-70%
70%-80%
80%-90%
90%-100%

Results based on input data. Changes in dependency, prioritization, FOM or cost will affect results.

Impact of Cost Uncertainties

- **Used full available annual budget levels**

- Large budget
- FOM not proportionally higher

Crew healthcare systems (medical tools & techniques, countermeasures, exposure limits)	0.0%
Habitability systems (waste management, hygiene)	5.1%
EVA Suit (surface including portable life suppport system)	32.7%
Surface heat rejection	36.6%
Low temperature electronics & systems (permanent shadow region ops)	46.2%
Autonomous precision landing and GN&C (Lunar & Mars)	73.2%
Demonstration of polar volatile collection and seperation	73.2%
Advanced environmental monitoring & control	74.7%
In space engine and propulsion system, human rated, (CM for ISS orbital ops, lunar ascent and TE	77.9%
Advanced air & water recovery systems	83.2%
Detachable, human-rated, ablative environmentally compliant TPS - ISS and lunar sortie.	87.4%
Long-term, cryogenic, storage, management and transfer (for lunar surface module)	87.8%

Impact of Cost Uncertainties

- **Used full available annual budget levels minus $100 M/year**

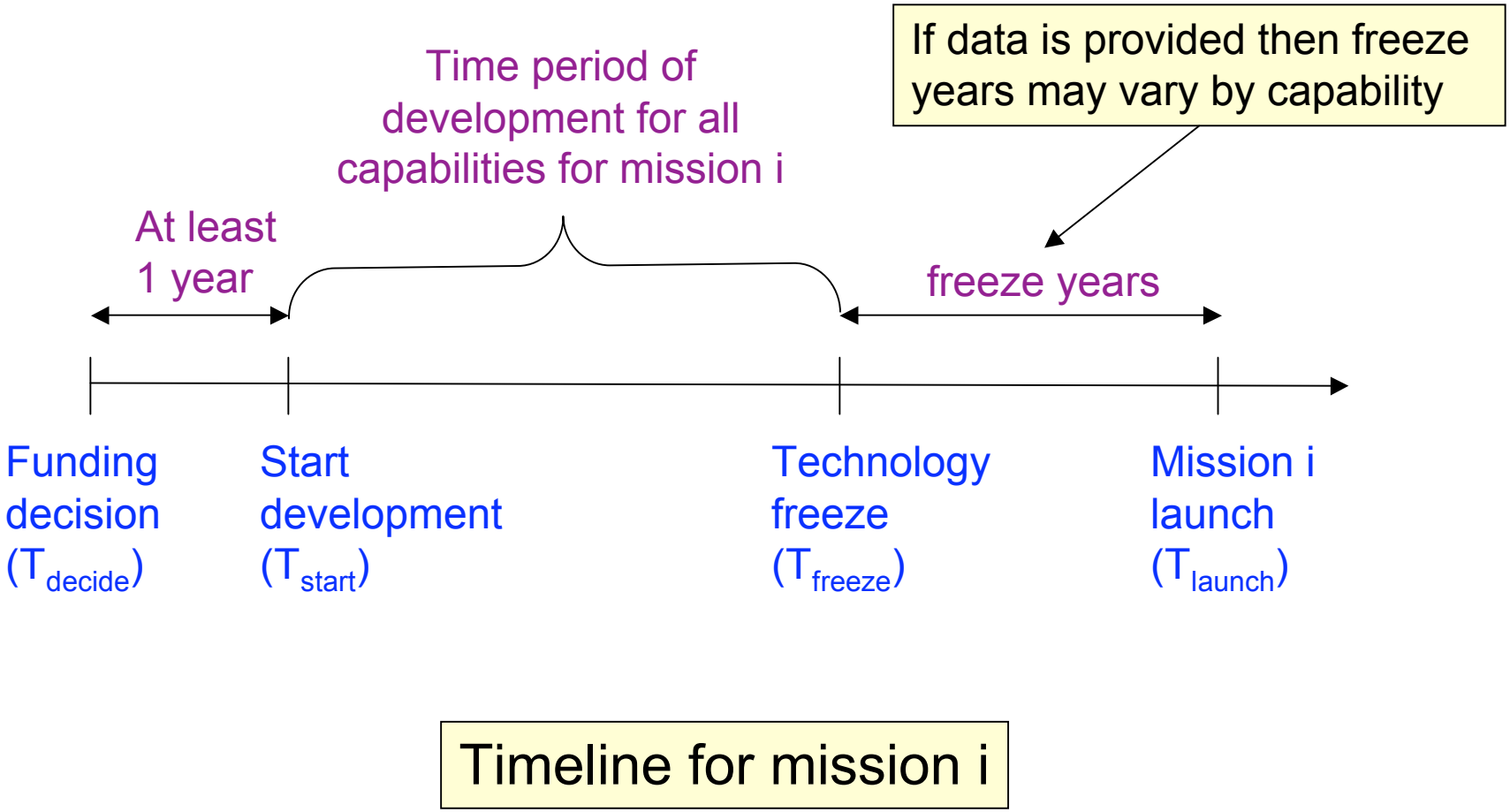
Crew healthcare systems (medical tools & techniques, countermeasures, exposure limits)	0.0%
Habitability systems (waste management, hygiene)	0.1%
EVA Suit (surface including portable life suppport system)	0.6%
In space engine and propulsion system, human rated, (CM for ISS orbital ops, lunar ascent and TE	13.3%
Low temperature electronics & systems (permanent shadow region ops)	16.2%
Surface heat rejection	17.0%
Long-term, cryogenic, storage, management and transfer (for lunar surface module)	24.5%
Autonomous precision landing and GN&C (Lunar & Mars)	25.8%
Advanced air & water recovery systems	52.1%
Demonstration of polar volatile collection and seperation	56.1%
Deep throttle-able engine, human rated (lunar descent)	71.9%
Surface handling, transportation, and operations equipment (Lunar or Mars)	72.0%
Advanced environmental monitoring & control	75.2%
Detachable, human-rated, ablative environmentally compliant TPS - ISS and lunar sortie.	85.2%
Extraction of water/hydrogen from lunar polar craters	86.8%
Fuel Cells (surface systems)	88.4%

Impact of Cost Uncertainties

- **Used full available annual budget levels with capability 8e reserved**

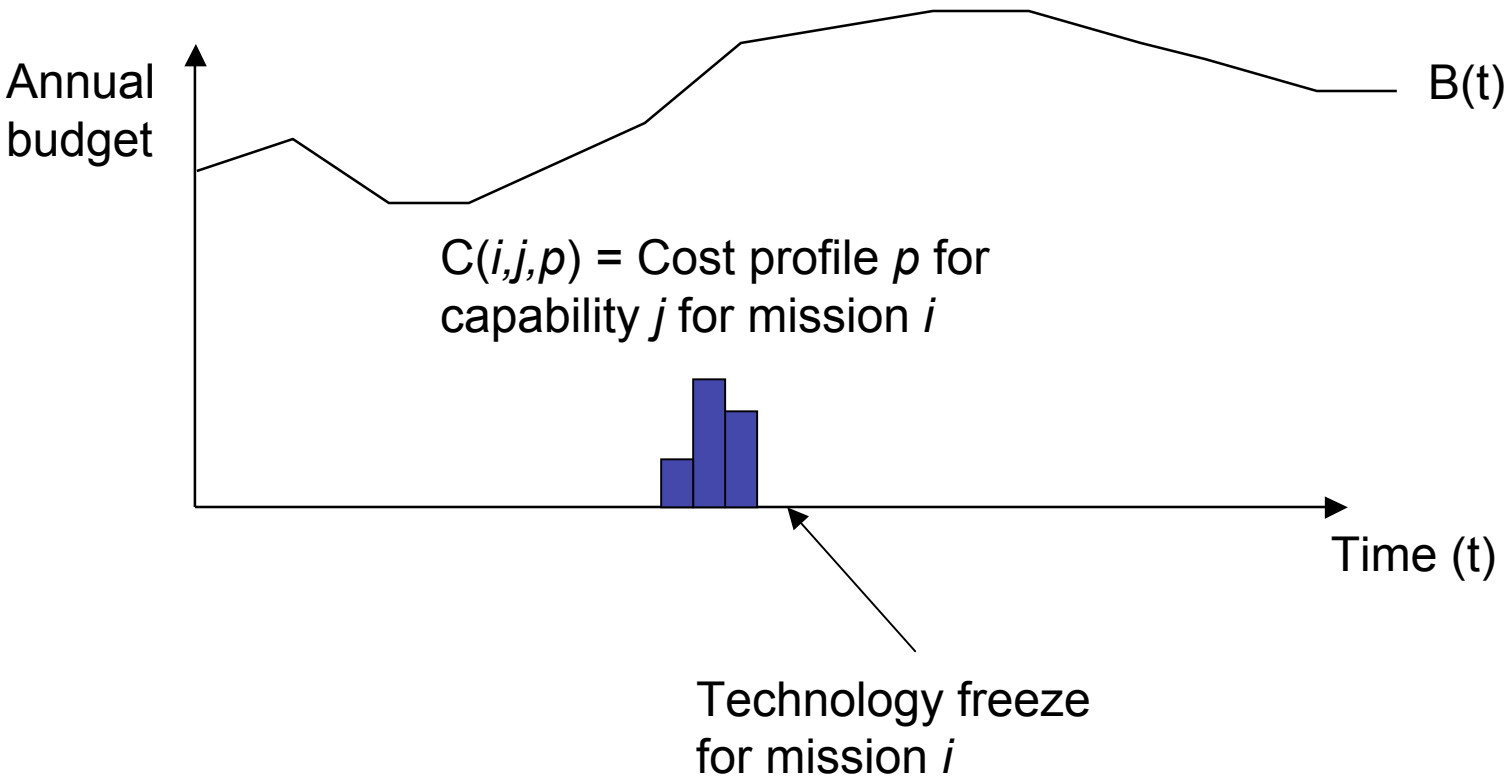
Autonomous precision landing and GN&C (Lunar & Mars)	0.0%
EVA Suit (surface including portable life suppport system)	0.0%
Habitability systems (waste management, hygiene)	0.0%
Surface heat rejection	0.1%
Low temperature electronics & systems (permanent shadow region ops)	0.3%
Advanced air & water recovery systems	0.5%
Advanced environmental monitoring & control	0.7%
Demonstration of polar volatile collection and seperation	0.8%
Human-System interaction (including robotics)	3.5%
In space engine and propulsion system, human rated, (CM for ISS orbital ops, lunar ascent and TE	4.0%
Lightweight structures -- pressure vessel, insulation (vehicle)	14.3%
Long-term, cryogenic, storage, management and transfer (for lunar surface module)	16.5%
Surface mobility	22.4%
Tool Development for Architecture/Mission/Technology Analysis/Design, Modeling & Simulation	39.3%
Demostration of regolith excavation & handling for resource processing	42.0%
Radiation hardened/tolerant electronics & processors	44.5%
Detachable, human-rated, ablative environmentally compliant TPS - ISS and lunar sortie.	46.2%
Demonstration of oxygen production from regolith	50.5%
Surface handling, transportation, and operations equipment (Lunar or Mars)	50.9%
Technology Investment Portfolio Assessment & Systems Engineering and Integration	63.3%
Atmospheric management - CMRS	74.9%
Detector and instrument technology (Mars precursor measurements)	75.9%
Integrated System Health Management (CLV, LAS, EDS, CEV, Lunar ascent/descent, habitat)	86.9%
Spacecraft autonomy (vehicles & habitat)	87.5%
Fuel Cells (surface systems)	88.2%

Mission Technology Development Timeline



Timeline for mission i

Portfolio Timeline



Temporal Portfolio Investment

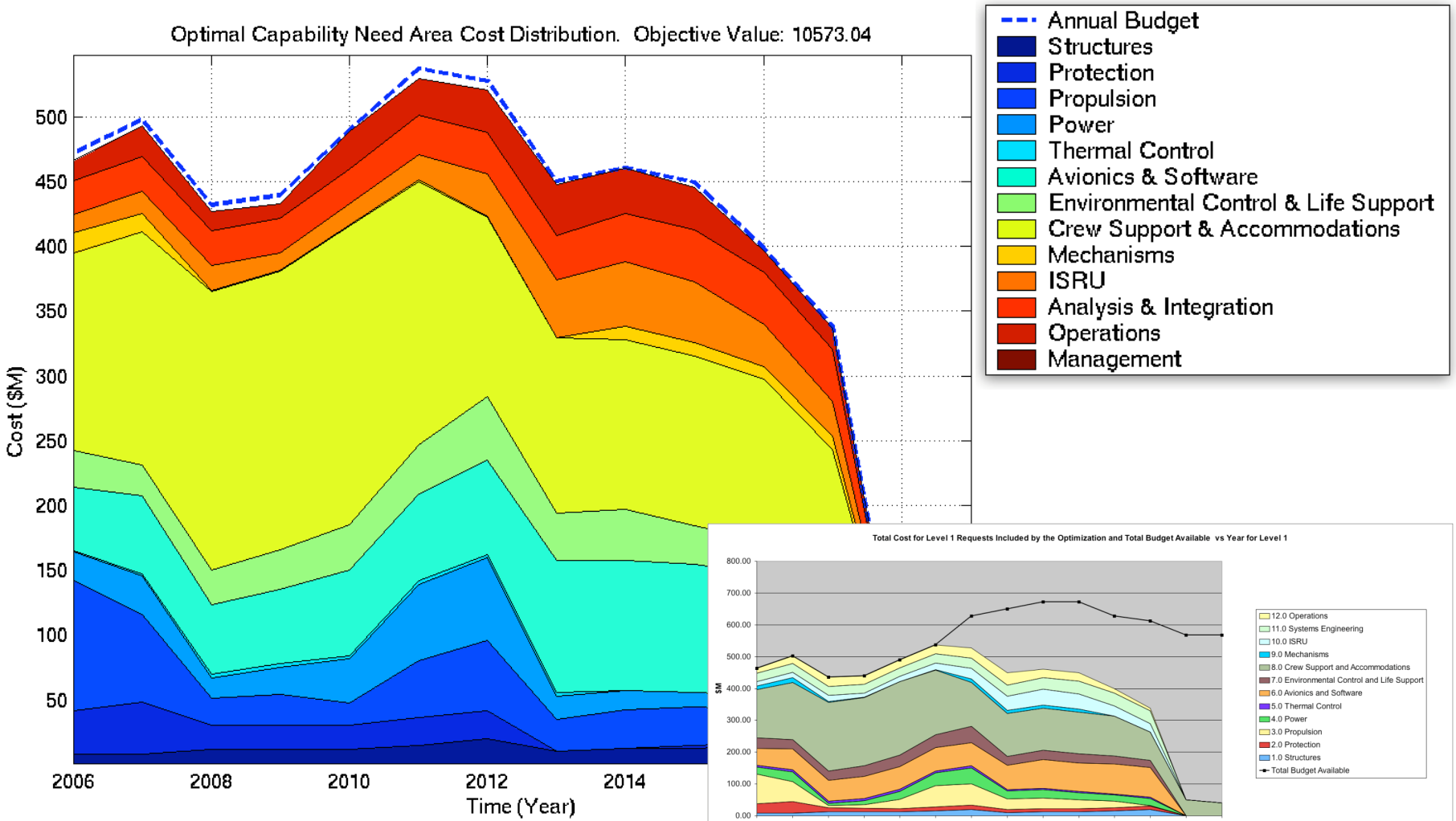
- **The case under consideration is the portfolio investment of independent missions (no dependencies).**
- **Funding profile for individual technology developments is constrained within mission timeline.**
- **Cost profiles for capabilities are complete, I.e. need to fully fund capability.**
- **The optimization problem:**

$$BF = \sum_{i=1,N_{missions}} W_i \sum_{j=1,M_{needs}} Y_{i,j} * P_{i,j} \sum_{k=1,R} FOM_{i,j,k}$$

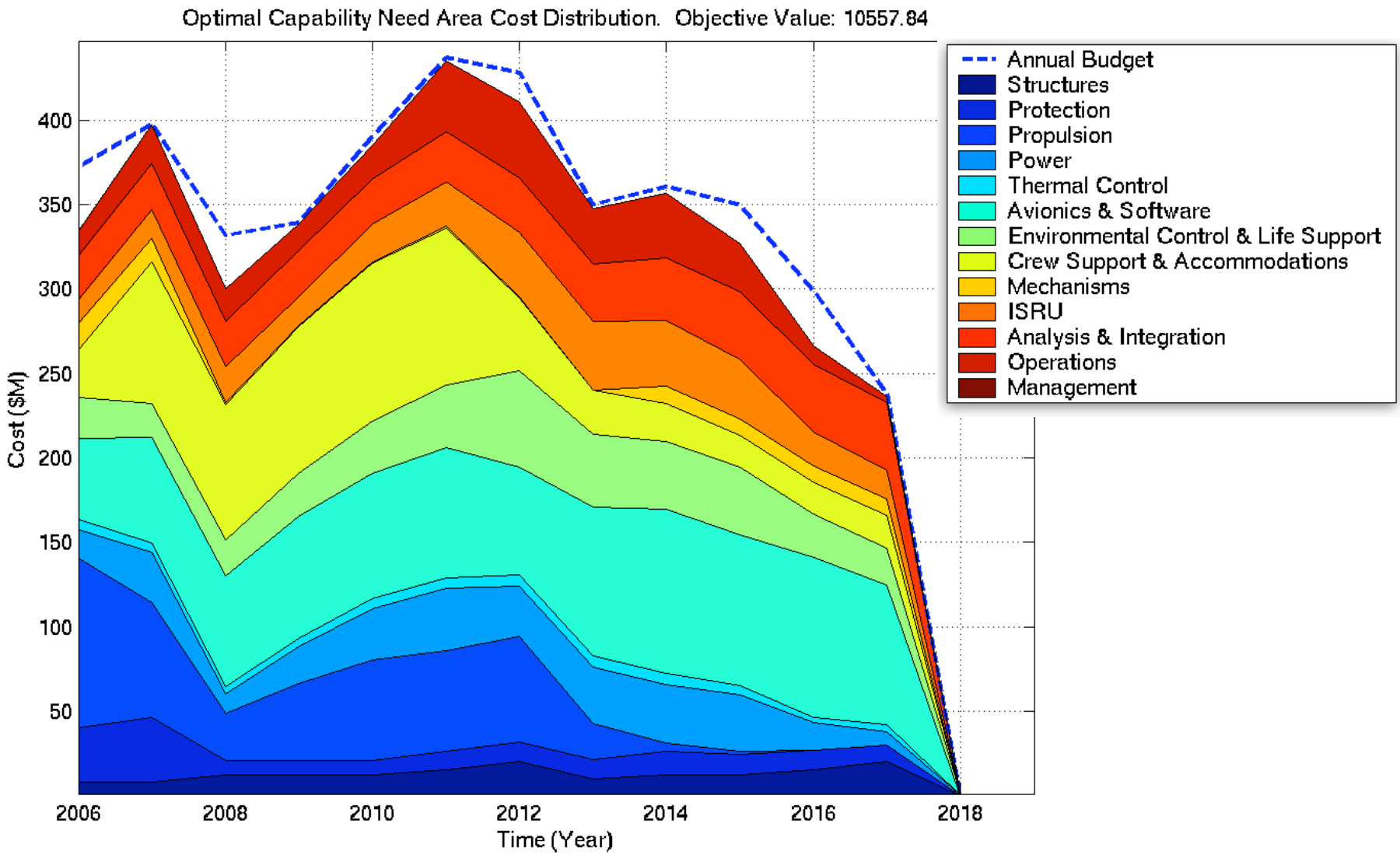
  - $Y_{i,j}$ = 1 if and only if capability j for mission i is funded.
  - $X_{i,j,p}$ = 1 if and only if profile p of capability j for mission i is funded.
  - $Y_{i,j} = \{0,1\}$ and $X_{i,j,p} = \{0,1\}$
  - Find $Y_{i,j}$ and $X_{i,j,p}$ such that it maximizes BF
  - Subject to annual cost constraints $\Sigma_i \Sigma_j \Sigma_p X_{i,j,p} * C^{(t)}_{i,j,p} \leq B^{(t)}$ for all t
  - Subject to the mission constraints $\Sigma_p X_{i,j,p} = 1$ if $Y_{i,j} = 1$ (only a *single* cost profile is selected for funded capabilities)
  - Subject to the mission constraints $\Sigma_p X_{i,j,p} = 0$ if $Y_{i,j} = 0$ (no cost profiles are selected for non-funded capabilities)
  - Where p = 1, P (P number of cost profiles)
  - Where t = 2006, 2006+T (T number of years in portfolio)

Comparison to Base Case

- Optimization resulted in no changes to funding from base case
- Data is over constrained



$100M Below Annual Budget



Least Robust Capability Needs

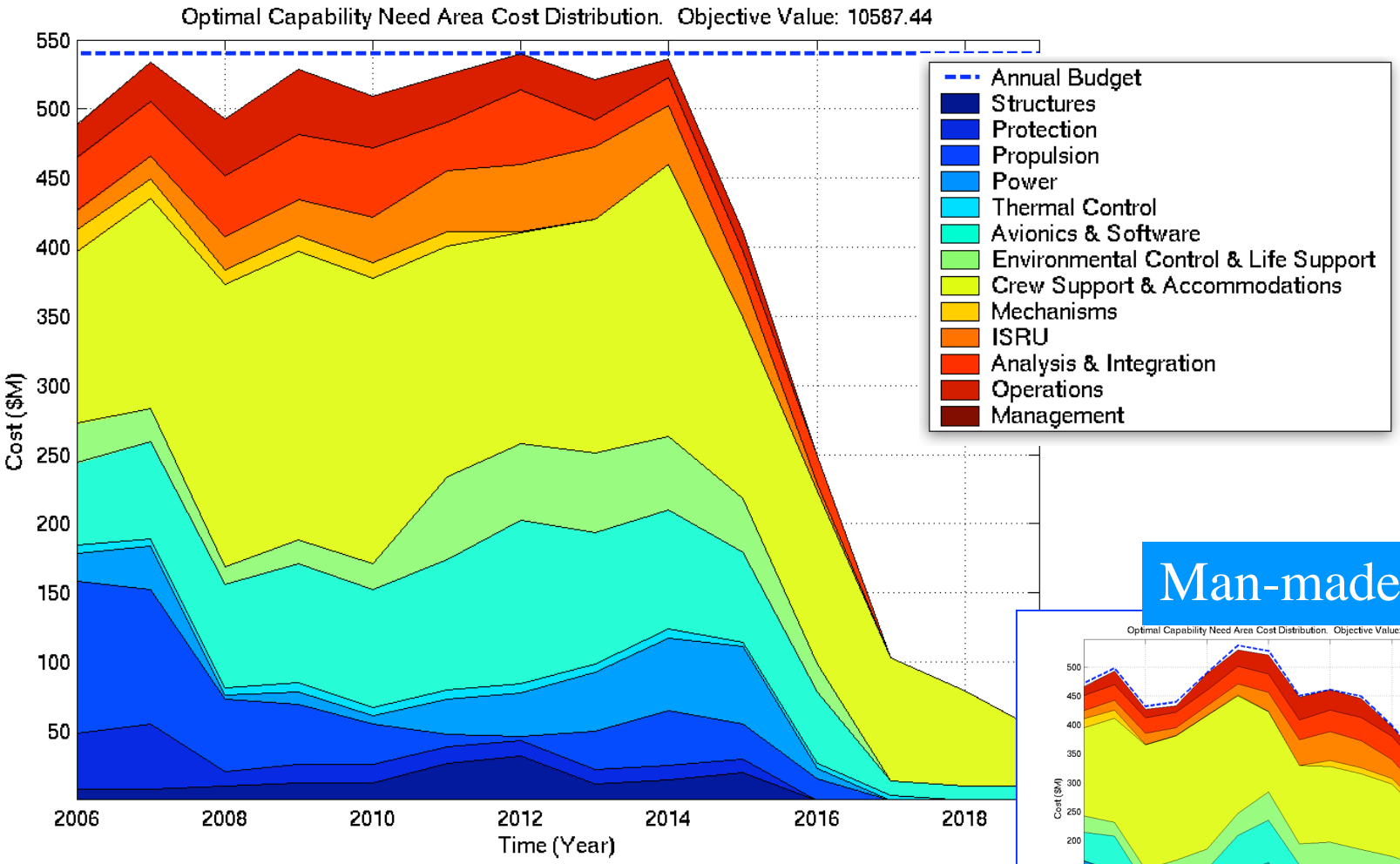
- **Perform optimization with parameter sweep for given budget levels -$250M to +$100M**

Percentage Selected	Mission	Capability	Capability Name
23.81%	Lunar Outpost	8e	Crew healthcare systems (medical tools and techniques, countermeasures, exposure limits)
66.67%	Lunar Outpost	7c	Advanced air and water recovery systems
71.43%	Lunar Outpost	8f	Habitability systems (waste management, hygiene)
71.43%	Lunar Outpost	10h	In-situ production of electrical power generation (lunar outpost solar array fabrication)
76.19%	Lunar Outpost	5b	Surface heat rejection
80.95%	Lunar Outpost	6l	Low temperature electronics and systems (permanent shadow region ops)
85.71%	Lunar Outpost	2a	Detachable, human-rated, ablative environmentally compliant TPS (ISS Mission TPS)
85.71%	Lunar Outpost	4f	Surface solar power (high efficiency arrays, and deployment strategy)
85.71%	Lunar Outpost	6d	Integrated System Health Management

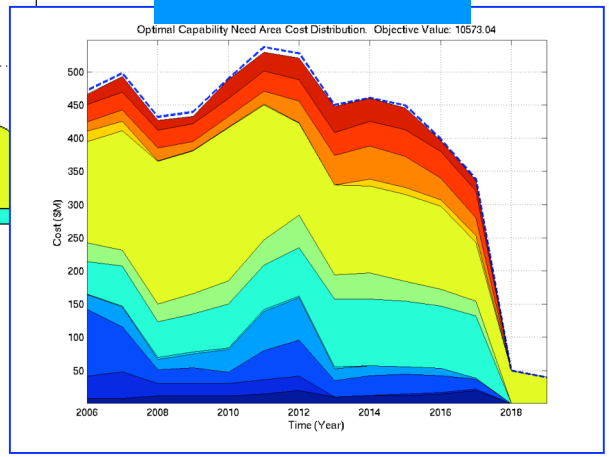
Find Better Annual Budgets

- Give temporal optimization an annual budget cap
- Get best solution that includes all capability needs with smallest annual budget
- Get robustness of capability needs

$540M Annual Budget Cap

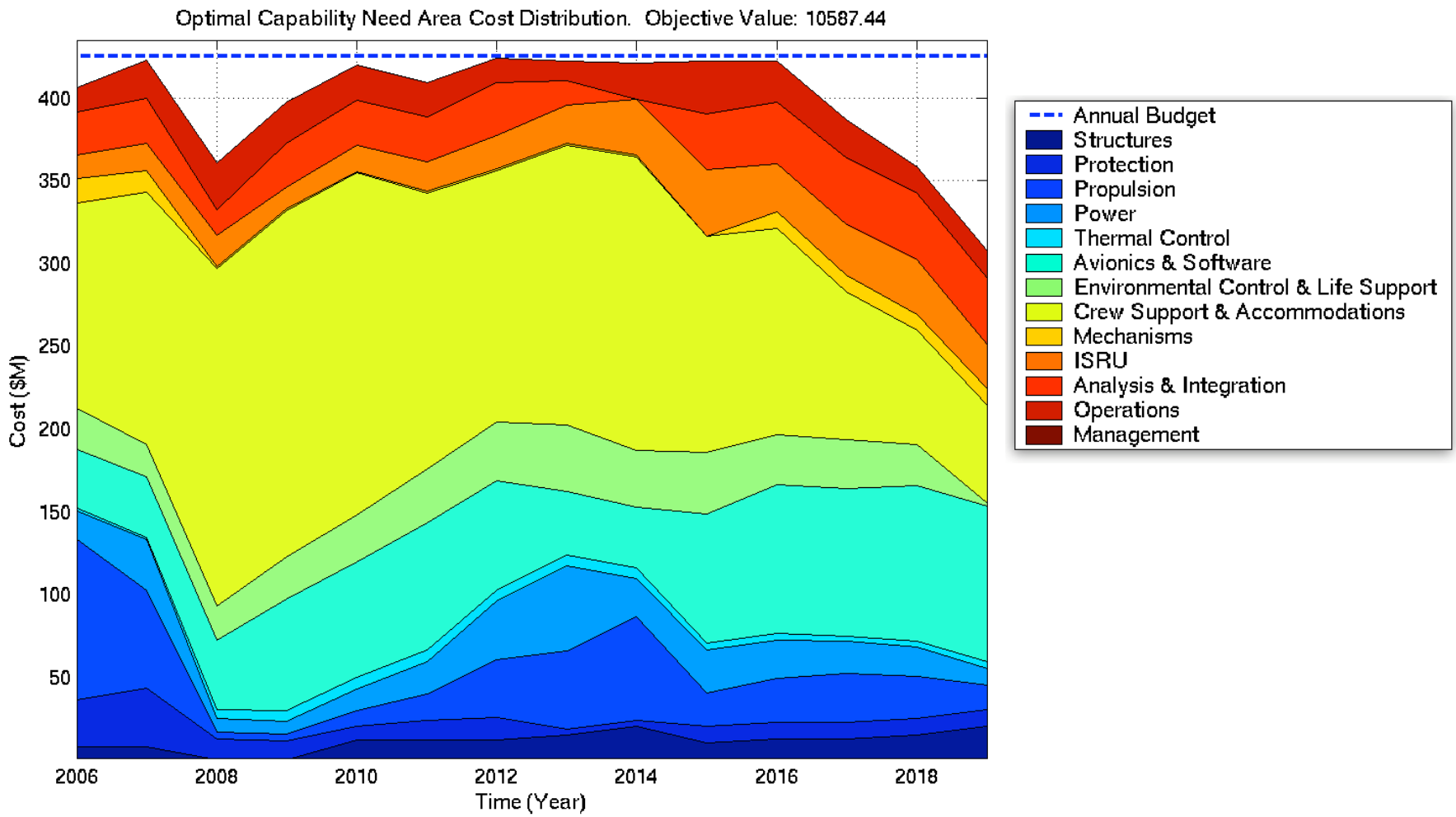


Man-made



Optimal Annual Budget Cap

- **$425M annual budget cap**



Conclusions

- **START approach demonstrated for ESAS Capability Needs Prioritization**
- **Sensitivity of budget allocations are shown for:**
  - Cost uncertainties
  - Reduced available budget levels
  - Changes in mission importance weighting
- **Temporal optimization demonstrates alternative budget profiles**