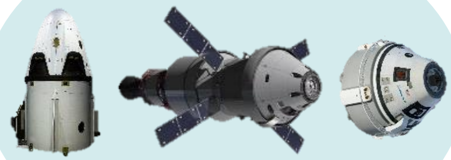
Assessing Program Level Objectives of Human Mars Missions Using Portfolio Optimization Methods

Bill O’Neill

Motivation (1): Space Architecture Development is Difficult

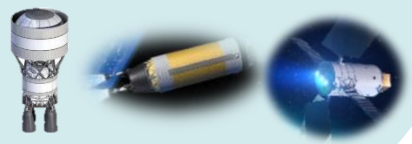
Launch Vehicles

Crew Vehicles



Space Habitats

In-Space Propulsion



Surface Support Elements

Destinations

Logistics Modules

Many choices, combinations, uncertainties…results in high complexity for decision-makers

Images courtesy NASA, Blue Origin, SpaceX

Motivation(2) -Specifics

1. Many ways to return to the Moon and Mars with countless potential system choices with different characteristics
   - System Performance
   - Technological Maturity
   - Cost/Schedule
2. Several techniques exist to measure Cost, Performance, Robustness & Schedule individually, or in pairs, but …
   - No technique exists to accommodate all 4 measures in seeking optimal portfolios of systems
   - Several techniques address architecture scheduling, but not the ***portfolio selection*** problem

<u>**Goal:**</u> Develop, demonstrate a methodology that could generate and explain 'good' architecture choices – make decision-makers smarter in their choices

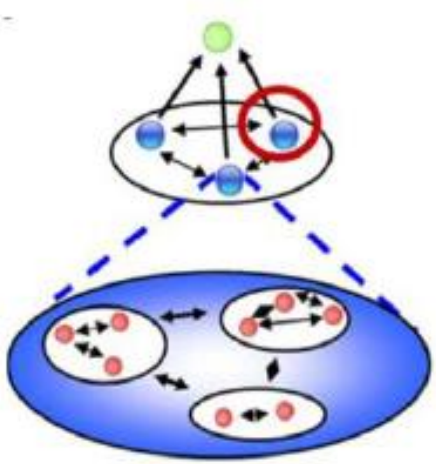
What is Programmatic Portfolio Optimization?

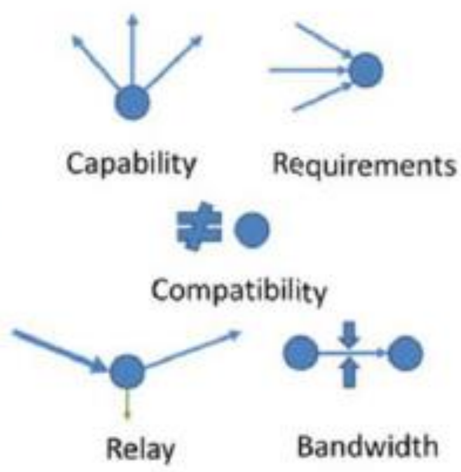
<u>Programmatic</u>– Addresses architecture cost, performance, schedule and robustness

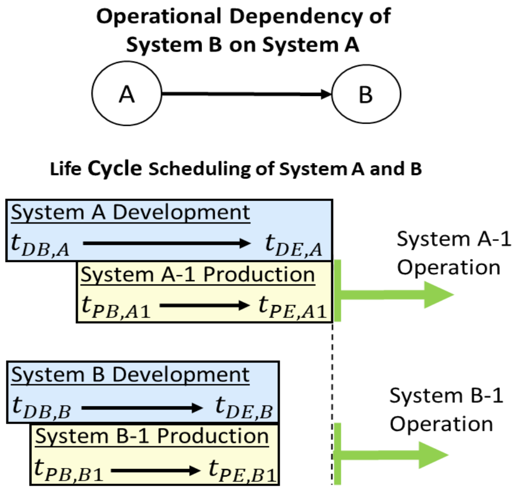
<u>Portfolio</u> – Selection of systems from a candidate library

<u>Optimization</u> – Best selection of systems to meet some criteria and given constraints

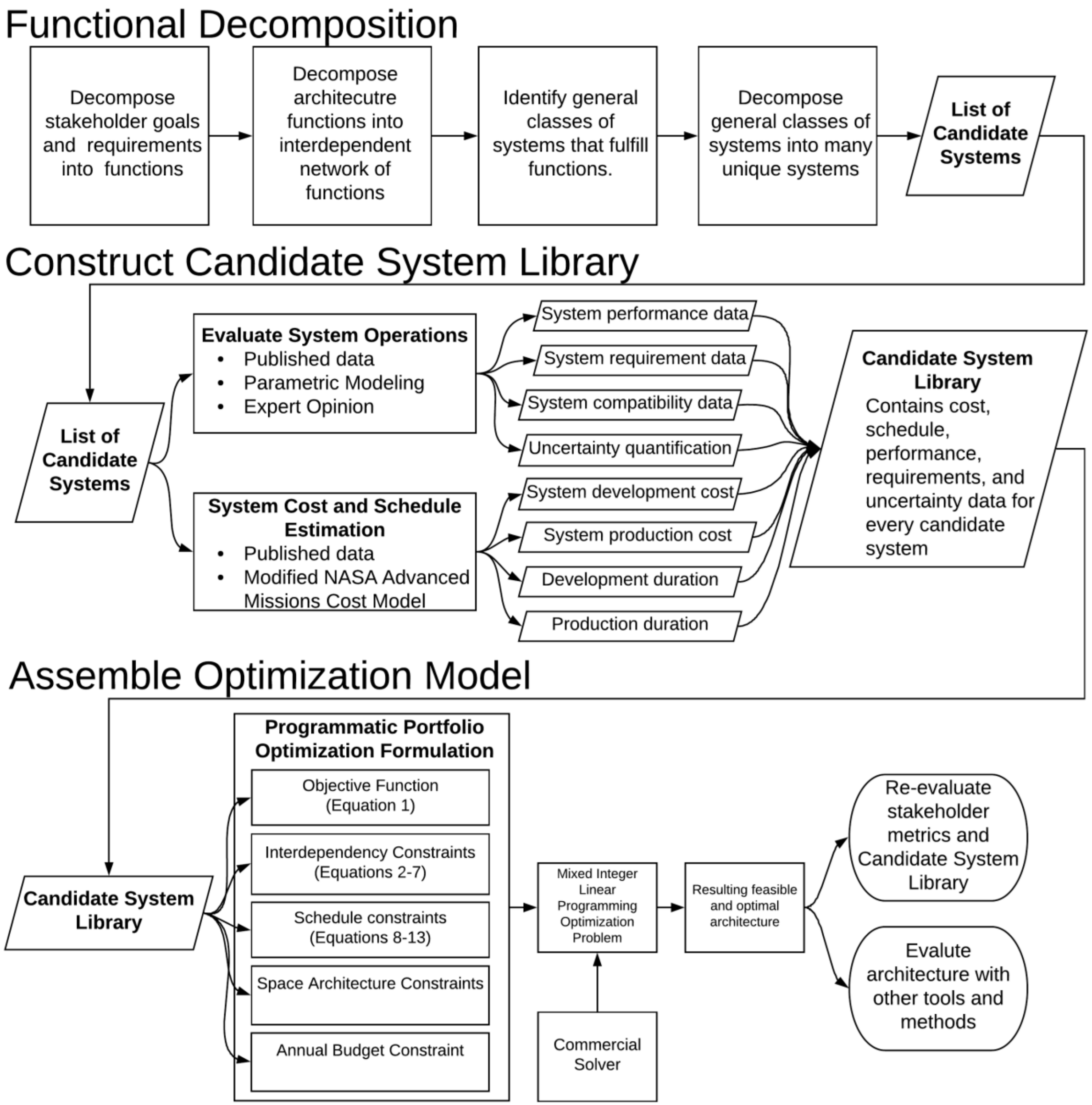
Selection of "best" systems and how they interact with each other to satisfy stakeholder objectives in terms of cost, schedule, robustness and performance







Methodology Overview



Modeled after Three-Phase System of Systems method:

- Definition
- Abstraction
- Implementation

RPO - Mixed Integer Linear/Quadratic Programming Problem

Variables

A_i^B: *Vector of system selection (Binary Decision Vector)*

x_{cij}: *Transfer of capability betwen systems (Real Value Decision matrix)*

x_{cij_bin}: *Connectivity between systems (Binary Decision matrix)*

S_{ci}: *Vector of system capabilities (Matrix of Constants)*

S_{ri}: *Vector of system requirements (Matrix of Constants)*

Connectivity Constraints

$$\sum_j x_{cij} \leq A_i^B S_{ci}$$ Finite Node Capability

$$\sum_i x_{cij} \geq A_i^B S_{rj}$$ Node Requirements

$$\sum_j x_{cij\_bin} \leq Limit_i$$ Finite number of connections

Supporting Constraints

$$X_{cij} - M * X_{cij\_bin} \leq 0$$

$$X_{cij} - X_{cij_{bin}} \geq 0$$

Details of specific objective/constraint modeling in Backups

Example Objective Function

$$\max\left(\sum_i \frac{(S_{ci} \cdot A_i^B)}{C_{Capability}} - \sum_i \frac{(C_i \cdot A_i^B)}{C_{Cost}}\right)$$

Capability — Cost

$C_{Capability}, C_{Cost}$: *Normalizing constants*

C_i: *Unit cost vector*

Scheduling Constraints(Dev, Production, Operation)

National Aeronautics and Space Administration | Johnson Space Center | Engineering Directorate | Project Management and Systems Engineering Division

Variables

t_{DB}: System development beginning time (Decision Variable)

t_{DE}: System development ending time (Decision Variable)

T_D: System development duration (Constant)

t_{PB}: System production beginning time (Decision Variable)

t_{PE}: System production ending time (Decision Variable)

T_P: System production duration (Constant)

t_O: System operation time (Decision Variable)

Constraints

$$t_{DE,i} \geq t_{DB,i} + T_{D,i}$$

$$t_{PE(i)} \geq t_{DE(j)}$$

$$t_{PE(i)} \geq t_{PB(i)} + T_P$$

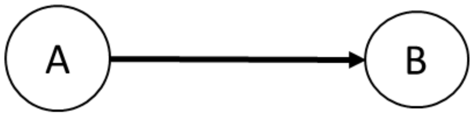
$$t_{O(i)} \geq t_{PE(i)}$$

$$t_{PB(i+1)} \geq t_{PE(i)}$$

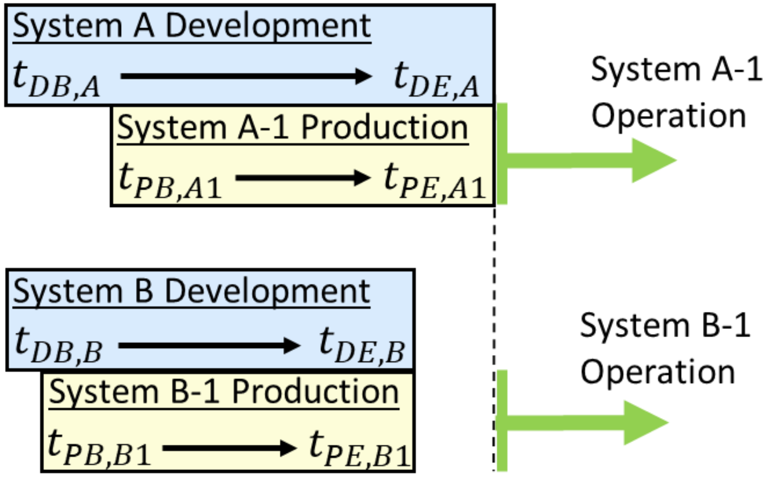
$$\left(t_O(j) - t_O(i)\right) \geq -(1 - (x_{cij,bin}\,(i,j))) * M$$

$$t_{DE,D} \leq t_{DB,i} + T_D * (0.2)$$

Operational Dependency of System B on System A



Life Cycle Scheduling of System A and B



Cost and Schedule Estimation Relationships (Modified AMCM)

- Cost Estimating Relationship(CER) and Schedule Estimating Relationship(SER) is modified form of NASA Advanced Mission Cost Model (SER)
  - AMCM updated by Rolley et al for exploration missions
  - Human Exploration SERs currently being re-evaluated by JSC
- "Best" publicly available calculation for exploration schedule estimation of human moon/mars missions
- Current optimization is modular and AMCM can be replaced

Overview of Formulation

$$D = -2.5 + TC + \left(\frac{OD}{15}\right) + \frac{RT - 80}{98 - 80} + HR + PC$$

$$DDTE_{duration} = 1.20 \times D + 5.94$$

$$Prod_{duration} = (0.11 \times D + 0.33) \times DDTE_{duration}$$

$$DDTE_{cost}^{16} = a \times Q^{b} \times W^{c} \times d^{S} \times e^{\frac{1}{IOC-1900}} \times B^{f} \times g^{D} \times inflation_{99}^{16}$$

$$Prod_{cost}^{16} = 0.20\ (\pm 0.10) \times DDTE_{cost}^{16}$$

Table 1. AMCM Variables.

Variable	Description
Q	Number of systems to produce
W	Dry mass
S	System type
IOC	Initial Operating Year
B	System Generation
D	Difficulty

Table 2. AMCM Constants.

Constant	Value
a	9.51×10^{-4}
b	0.59
c	0.66
d	80.6
e	3.81×10^{-55}
f	-0.36
g	1.57
inflation	1.43

Table 4. Variables used to calculate difficulty parameter.

Variable	Description	Possible Values
TC	Technical complexity	Low = 0 Medium = 0.5 High = 1
OD	Planned years of operation without repair	0 to 15 years
RT	Acceptable risk tolerance	Low (98% chance of mission success) = 1 Medium (90% chance of mission success) = 0.5 High (80% chance of mission success) = 0
HR	Whether system is human rated	Yes = 1 No = 0
PC	Programmatic complexity	Low = 0 Medium = 0.5 High = 1

Rolley, Robert, et al. "Life Cycle Cost Estimation of Conceptual Human Spaceflight Architectures." *AIAA SPACE and Astronautics Forum and Exposition*. 2017.

Example: Human Mars Mission Trade Study

Scenario: Human exploration mission to surface of Mars

- Compare NASA Design Reference Architecture 5 design trades

ID	Propulsion	Deployment	Capture	ISRU
A	NTR	Pre	Aero	Yes
B	Chem	Pre	Aero	Yes
C	NTR	Pre	Aero	No ISRU
D	Chem	Pre	Aero	No ISRU
E	NTR	Pre	Propulsive	No ISRU
G	NTR	All Up	Propulsive	No ISRU

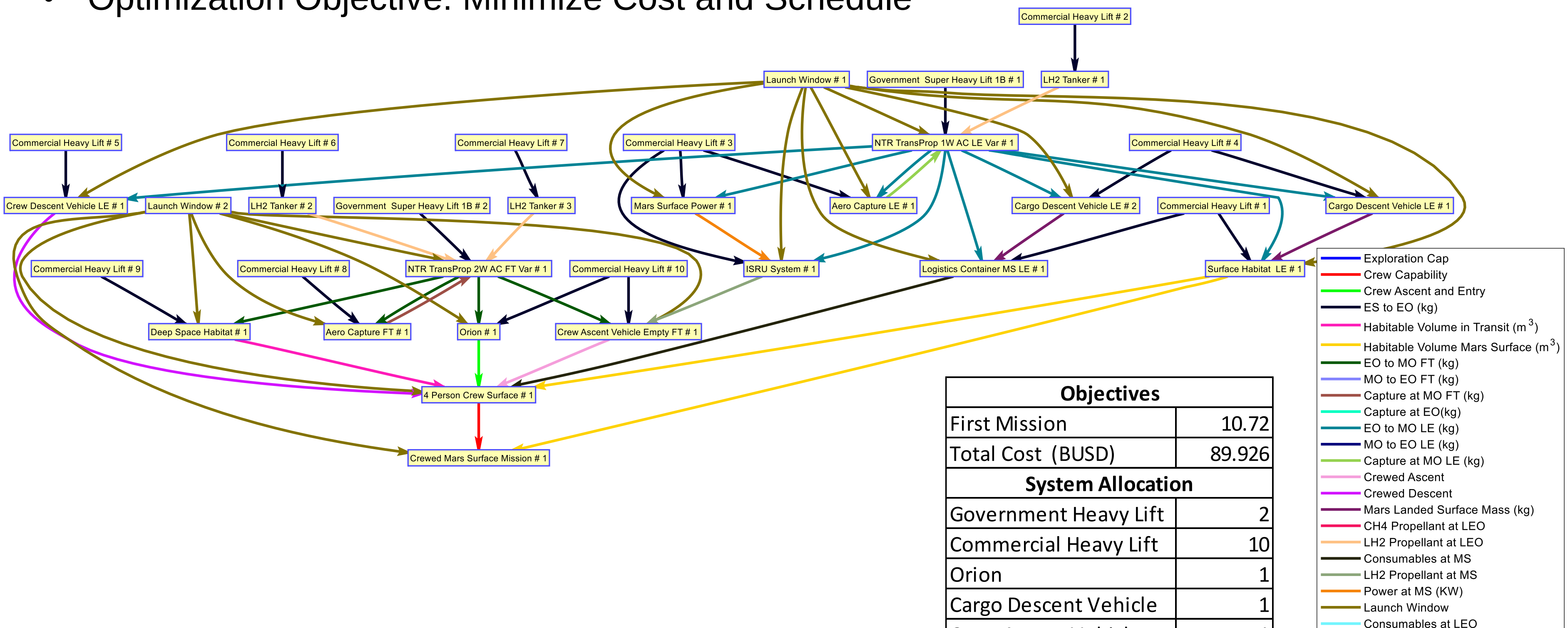
Application(3 Phase Method)

- Functional Decomposition
- Candidate System Library
  - Includes transit propulsion, transit habitat, lander elements, aerocapture, launch vehicles, crew vehicles, ascent elements, and Mars surface systems
  - Custom propulsion sizer for in space propulsion characterization
  - DRA 5 documentation for system sizing
  - Modified version of NASA's Advanced Missions Cost Model
  - Estimation of technology TRL and cost/schedule impacts through literature review
- PPO Method (RPO + Scheduling + Var Cap)
  - Investigate each DRA case individually amongst larger design space

DRA 5 Case A – NASA's Final Recommendation

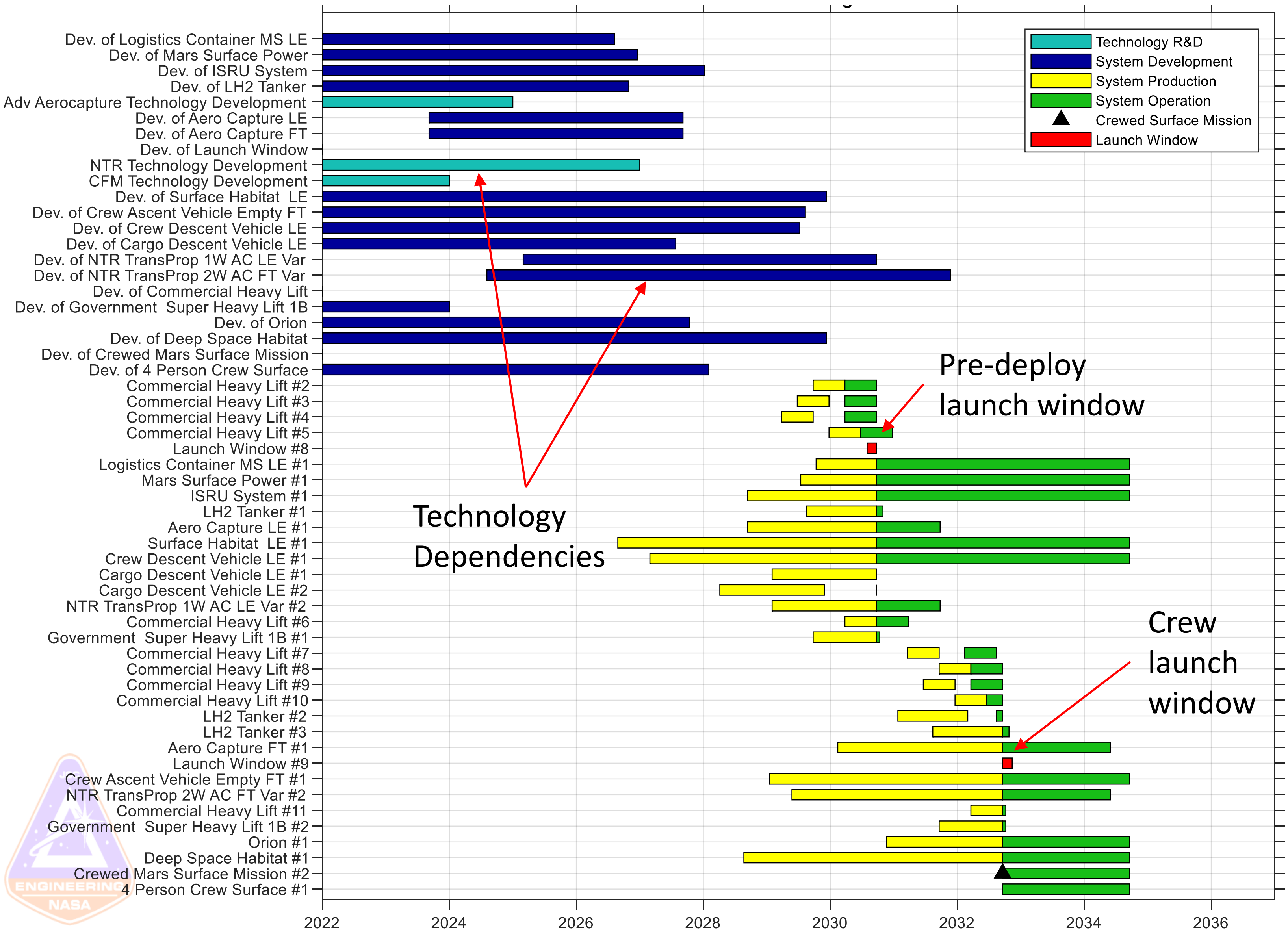
For demonstrative purposes

- Constrain to Case A: NTR, Pre-deploy cargo, ISRU,Aerocapture
- Optimization Objective: Minimize Cost and Schedule



Objectives	
First Mission	10.72
Total Cost (BUSD)	89.926
System Allocation	
Government Heavy Lift	2
Commercial Heavy Lift	10
Orion	1
Cargo Descent Vehicle	1
Crew Ascent Vehicle	1
Crew Descent Vehicle	1
NTR Propulsion Stage	2
ISRU System	1
LJH2 Tanker	3
Logistics Container	1
Mars Surface Habitat	1
Aerocapture Systems	2

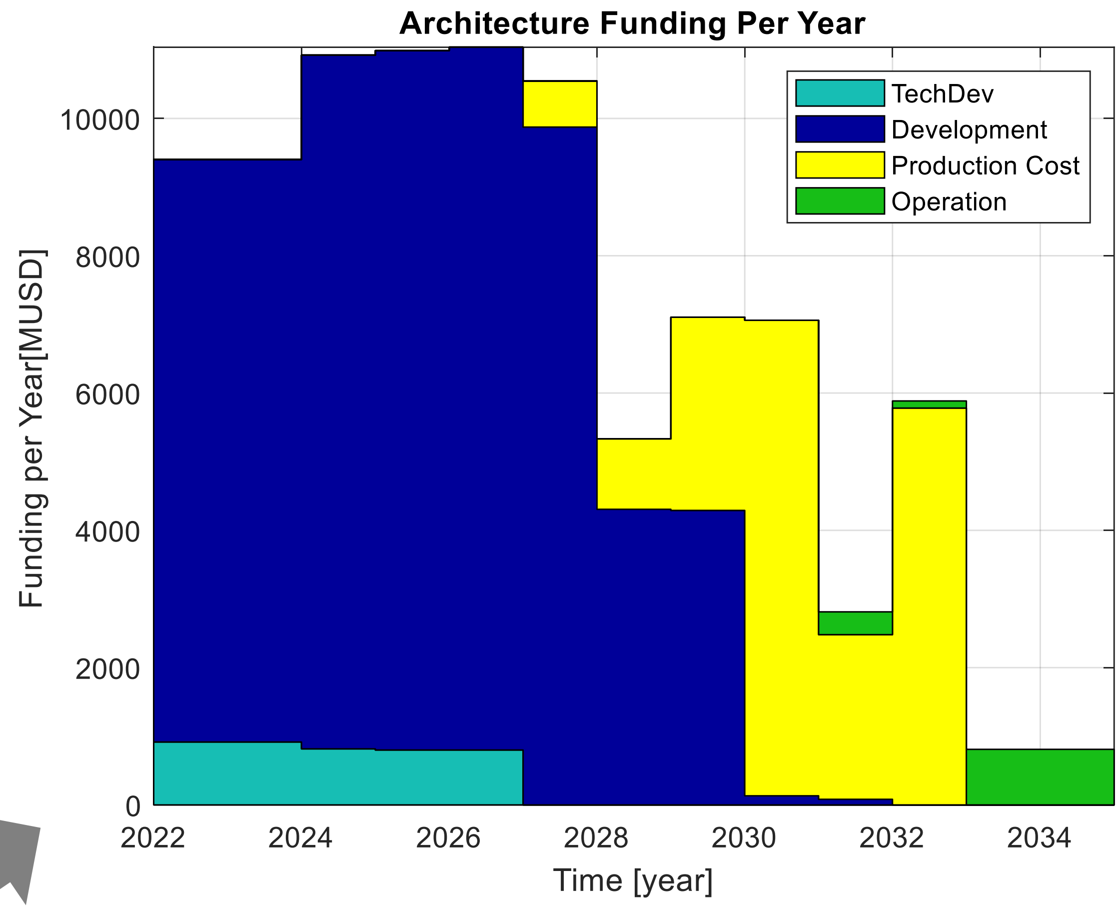
DRA 5 Case A Scheduling

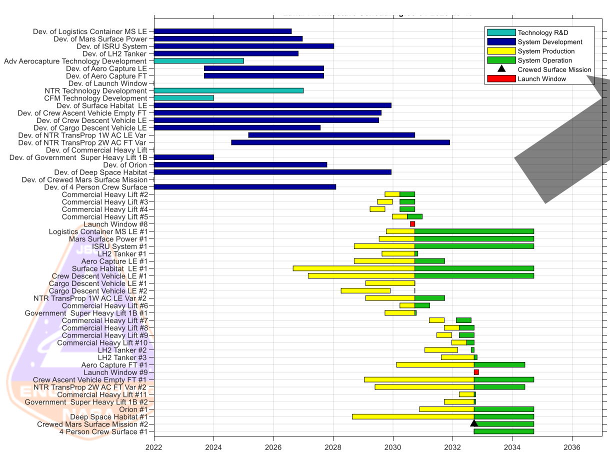


Annual Funding Visualization

Notes:

- Large initial development budget followed by production and operation
- Production costs tightly associated with launch windows
- “Large” annual budget for single program
- Doesn’t account for Moon2Mars efforts

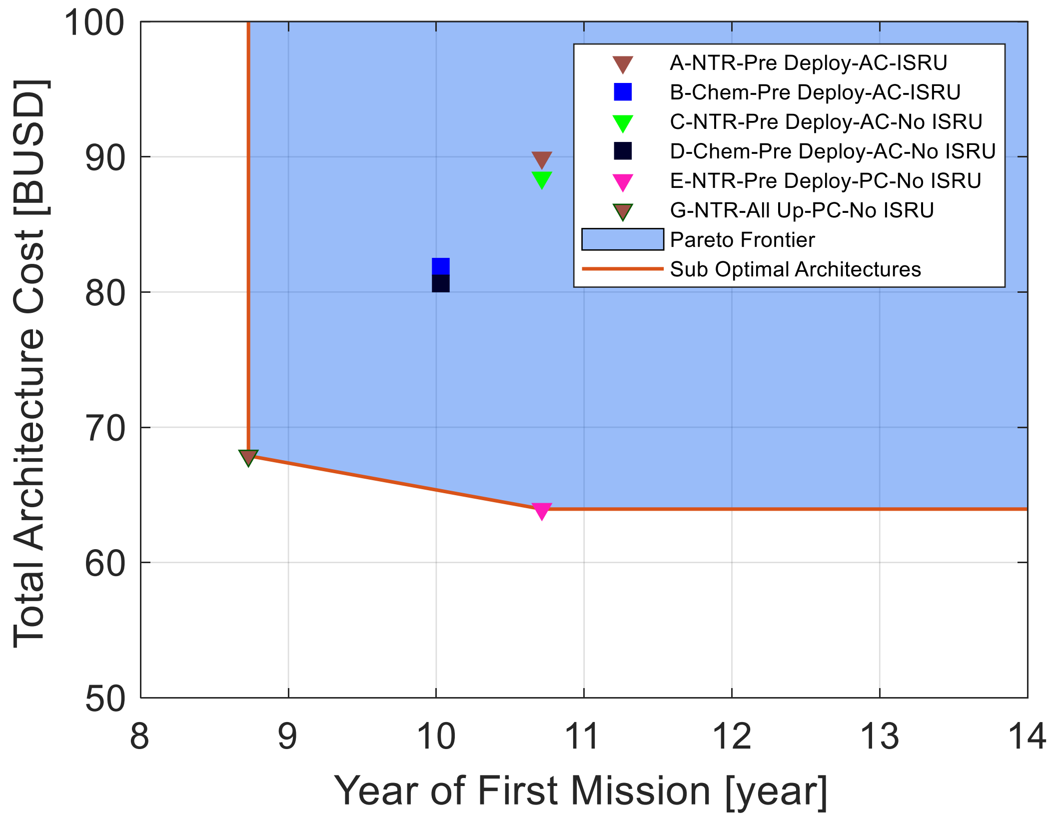




Comparison of NASA DRA recommended Cases (Single Mission)

Pareto frontier of Cost vs Schedule

- Assumes total architecture cost of single mission
- Case E – NTR Propulsive capture Pre deploy without ISRU was min cost option
- Case G – NTR Propulsive capture All up was min schedule
- Benefits of investment in ISRU and aerocapture not realized in single mission architecture



ISRU – In Situ Resource Utilization(local propellant production)
NTR – Nuclear Thermal Rocket
AC- Aero capture at Mars orbit
PC – Propulsive capture at Mars Orbit

Other Trades Not Covered Here

- Annual Budget limit vs Schedule
  - Impact of restricted budget on schedule deadlines
- Annual Budget limit vs Performance
  - Impact of restricted budget on performance capabilities within time period
- Performance vs Cost
- Robustness/Uncertainty and Stakeholder Risk Aversion Factor
  - Uncertainty in Cost components
  - Uncertainty in schedule components
  - Operational uncertainty and robustness
- Multi Domain Analysis(Moon2Mars)
  - Stakeholder utility study for various time periods and decisionmaking impacts between them

Demonstrated Example is intentionally brief to demonstrate capabilities

- Real example would have expanded Candidate System Library with additional system and technology options

Closing Thoughts

Advancements on Status Quo(RPO)

- Scheduling enhancement and variable capability enhancement beneficial to application of portfolio methods to space system architectures
- Multi Domain enhancement problematic in application to large multi-decade, multi-destination space exploration planning

Future Work

- Improve constraint efficiency to enable multi domain application (Moon 2 Mars)
- Apply methods to space scenarios with support of technical experts (Planned 2023)
  - Improved cost and schedule estimation
  - Improved system sizing
- Investigate alternate mission operation concepts
  - Low Lunar Orbit staging ground/Moon2Mars
- Solver license and compute server

Questions

Reflections on Adoption in Practice

Tested Applications

- Purdue-MSFC SoS project
- Early pathfinding analysis for lunar lander elements(JSC)

Future real-world applications

- JSC Forge (JSC Concurrent engineering team analogous to Team-X)
  - Range of human space exploration design studies
- DIECAST

Challenges

- System sizing
  - Current: Beyond LEO Architecture Sizing Tool
  - Literature and custom propulsion sizer
  - Better: NASA system sizing tools/library
- Cost/Schedule estimation
  - Current: modified NASA Advanced Mission Cost Model
  - Better:
    - Systems: Project Cost Estimating Capability(PCEC), NASA Air Force Cost Model(NAFCOM), Once NASA Cost Engineering(ONCE) database
    - Technologies: Technology Cost and Schedule Estimation (TCASE) tool/database
- Application to other fields may only require slight tweaking to constraints

Multi-Domain/Stepping-stones Difficulties

Difficulties

- Several Big-M constraints
- Problem size is quadratic with number of systems
- Can reasonably produce results for architectures of 2-3 missions(40+systems)
- Solver "bogs" down with large problems and requires weeks of computation

Attempted Improvements

- Reformulation of the problem
- Additional processors
- Solver tuning/parameters
- General Constraints (Implies in Yalmip)

Recommendation

- Status quo of commercial solvers not sufficient for such a large problem
- May require custom solver or improvements to commercial solvers

Publications

Conference Papers

- IAC 2016 "Design and Integration of Modular Deep Space Habitat Using a Robust Optimization Framework"
- IAC 2018"Enhanced Robust Portfolio Optimization for cost, performance risk and schedule analysis of a Lunar mission"
- IAC 2019"Assessment of Lunar Lander Architectures in terms of Programmatic Stakeholder Objectives"
- AIAA SPACE 2018"Assessing Cost, Performance and Risk of Human Lunar
- Exploration Missions Using Robust Portfolio Optimization"

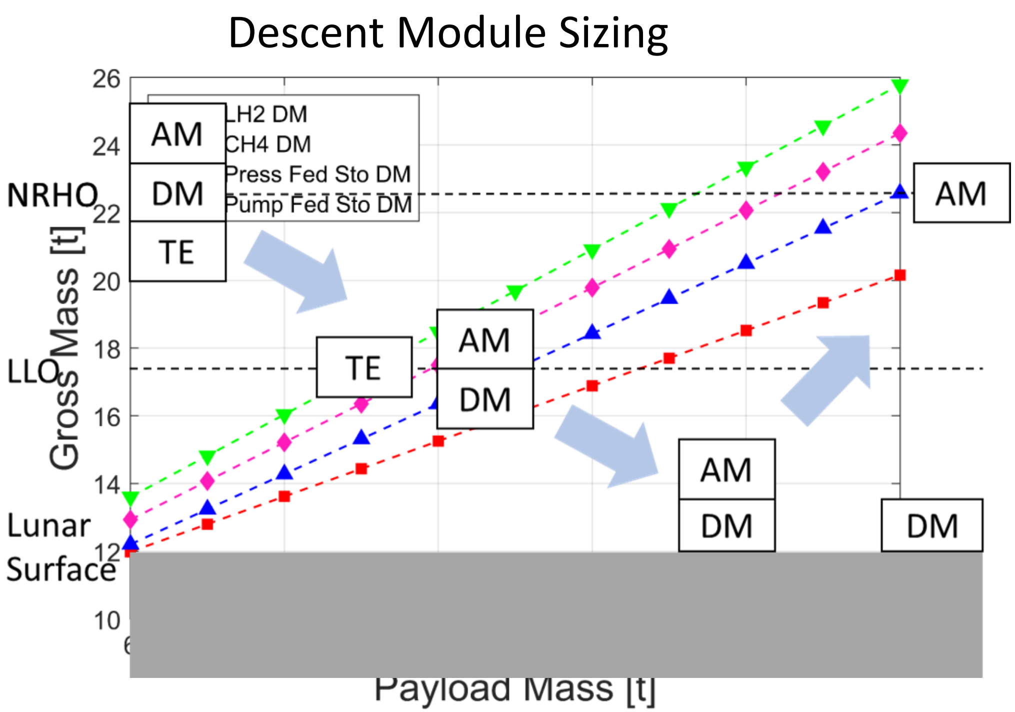
Journals

- Accepted-Assessing Program Level Objectives of Space Exploration Architectures Using Portfolio Optimization Methods – AIAA Journal of Spacecraft and Rockets
- Planned-
  - Lunar surface operations -Acta Astronautica
  - Moon to Mars Study - AIAA Journal of Spacecraft and Rockets or similar journal

Backup/Conclusion

Variable Capability Constraints

- Previous versions of RPO required fixed capabilities and requirements
- New Concept: Optimization determines select system Capabilities and Requirements given known parametric relationship



New Variables and Constants

$\boldsymbol{Var_C}$: ***Variable Cap.***

$\boldsymbol{Var_R}$: ***Variable Req***

m_{Req}: *Cap-Req relation slope*

b_{Req}: *Cap−Req relation intercept*

New Constraints

$$Var_C(i) \geq \sum_j X_{cij}$$

$$Var_R \geq Var_C * m_{Req} + A_i^B * b_{Req}$$

$$\sum_i X_{cij} \geq Var_R(i,n)$$

Robustness - Operational

Application

- Operational uncertainty of in-space propulsion system and launch vehicle performance and resulting impact on dependent system

Formulation

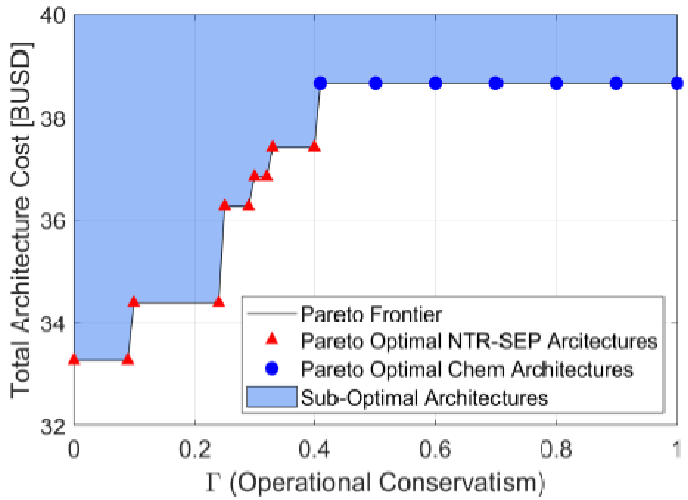
$$CX \leq b$$

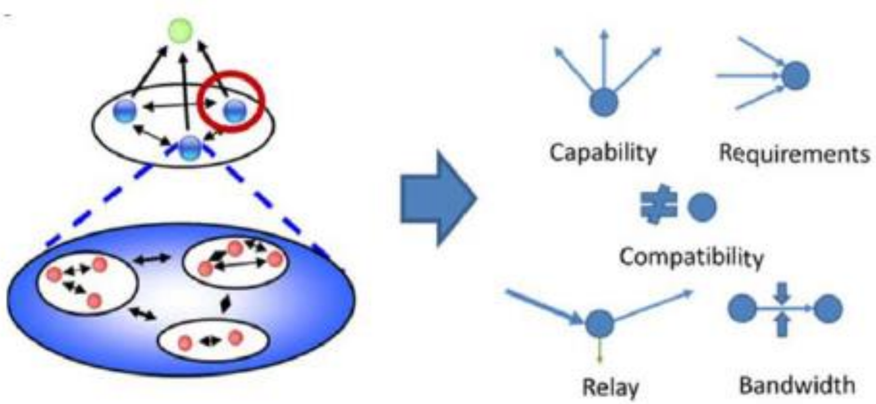
$$\sum_j C_{ij}X_j + z_i\Gamma_i + \sum_{i \in J_i} p_{ij} \leq b_i$$

$$z_i + p_{ij} \geq \hat{C}_{ij} y_i$$

$$-y_i \leq x_j \leq y_i$$

$$z_i\,, p_{ij}\,, y_i \geq 0$$





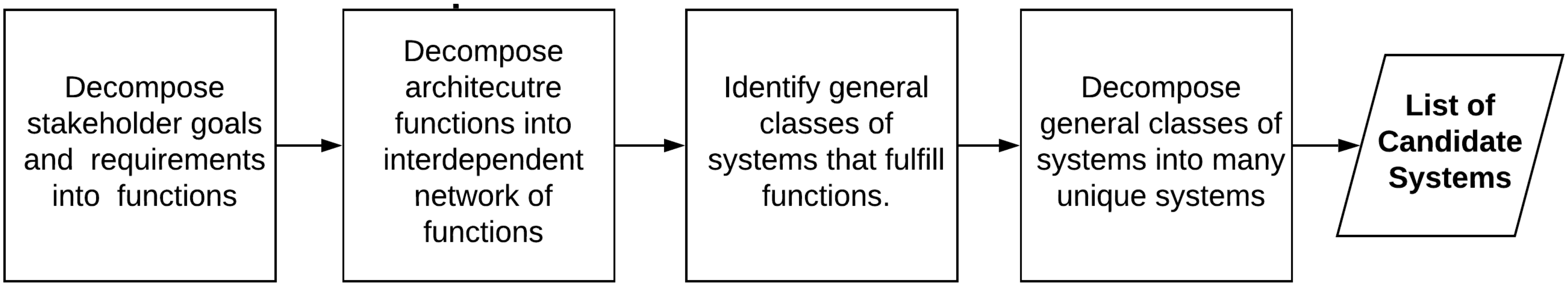
Literature Review and Identified Gaps

- The bottom up approach that is prevalent in most architecture studies limits effective comparison of multiple systems and technologies when combined into an architecture
- Many technology assessment methods exist but either A) correlate a benefit with a stakeholder value or B) assess how immediately related systems are impacted and do not assess combinations of technologies at the architecture level or how these technologies affect future decisions
- The current version of Robust Portfolio Optimization lacks the ability to assess system lifecycle phases and requires systems with fixed values prior to optimization. Both of these deficiencies preclude the ability to solve the first two literature gaps.

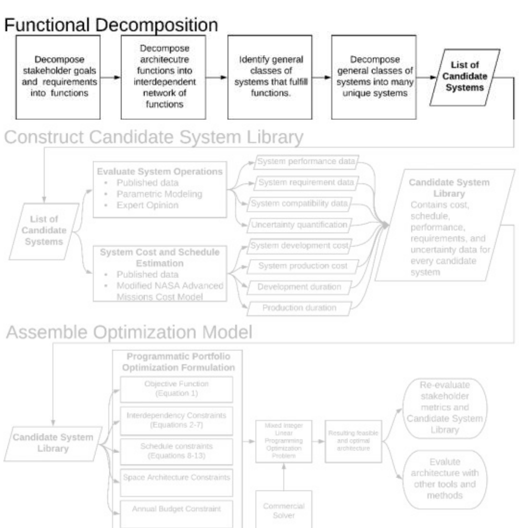
An enhanced version of RPO (formulation and solution techniques) is proposed to:

1. ***Account for lifecycle phase scheduling within optimization to assess how complexity and technical maturity of system options impact overall architecture schedule***
2. ***Include system sizing within the optimization to improve optimality of system selection and practicality of usage***
3. ***Account for system selection over multiple time periods to assess impact of technologies on system selection***

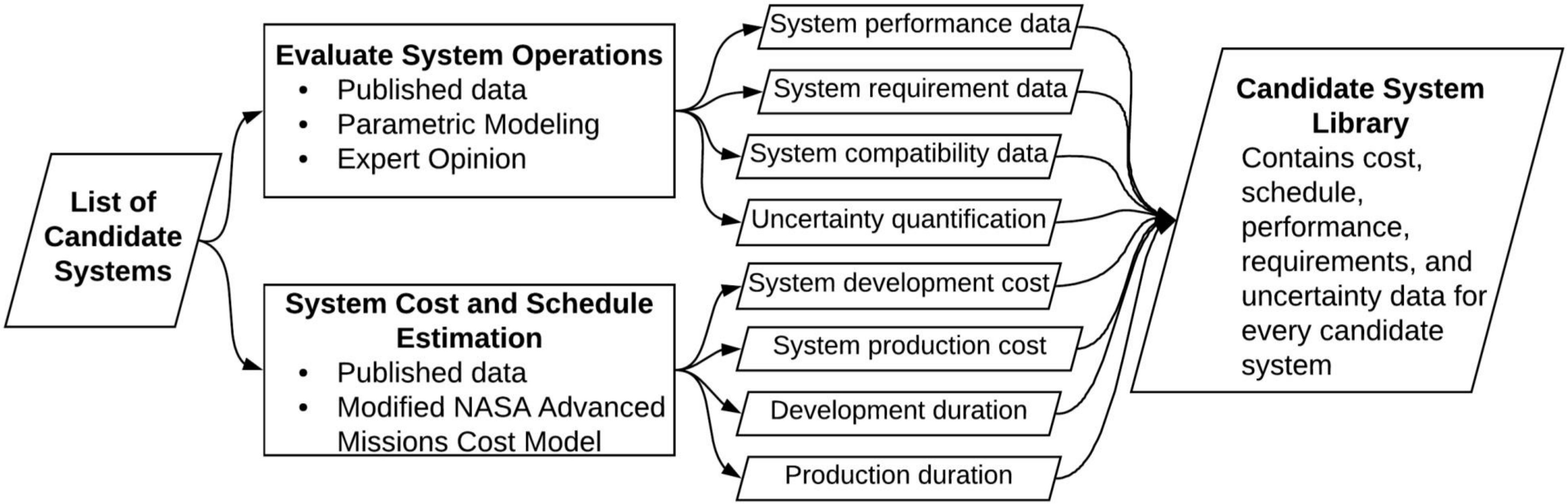
1. Functional Decomposition



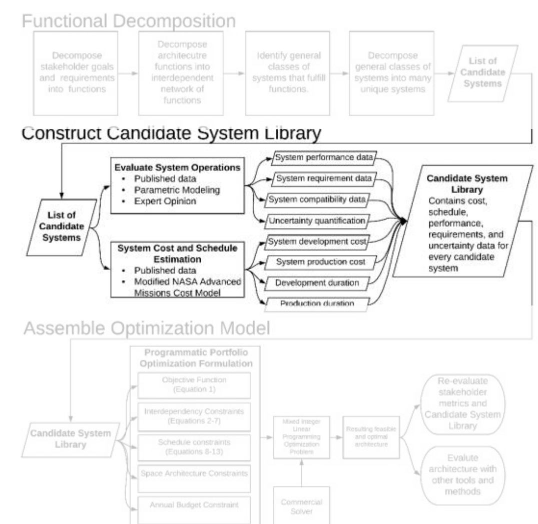
- Two goals:
  - Identify architecture functions
  - Identify candidate systems to further examine
- Efficiency in this phase is supported by MBSE practices



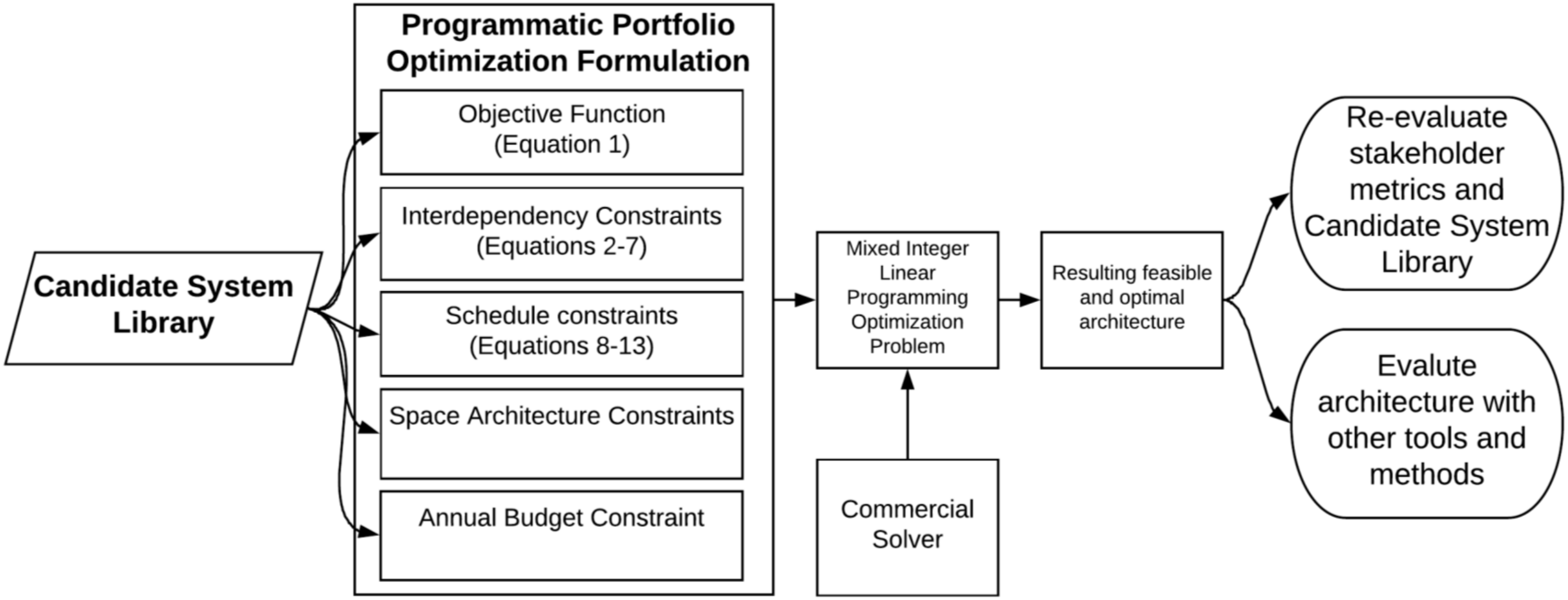
2. Candidate System Library (CSL)



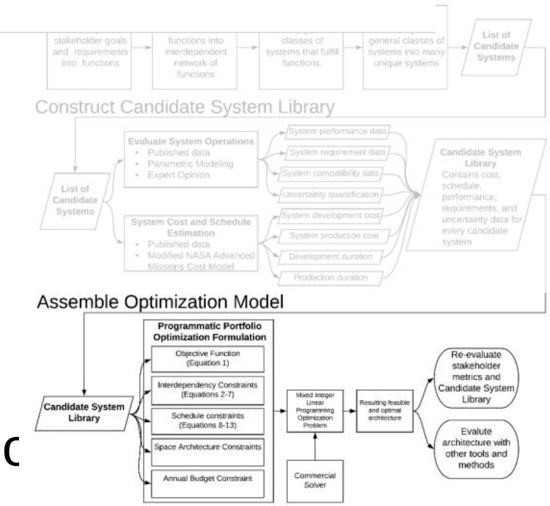
- Many methods to determine system attributes
- CSL assembly improved via team effort
- Can specify sets of systems for specific investigation(example: NASA DRA5)



3. Formulate Portfolio Optimization Problem



- Practitioner assembles optimization problem through selection of constraints and specification of objective function to form Mixed Integer Linear Programming Problem(MILP)
- Gurobi or CPLEX used to solve MILP
- May require iteration of CSL inputs, objective function, c requirements



Multi Domain Enhancement

Goal: Enforce certain stakeholder valued systems to specific time domains

- Accomplished through scheduling constraints

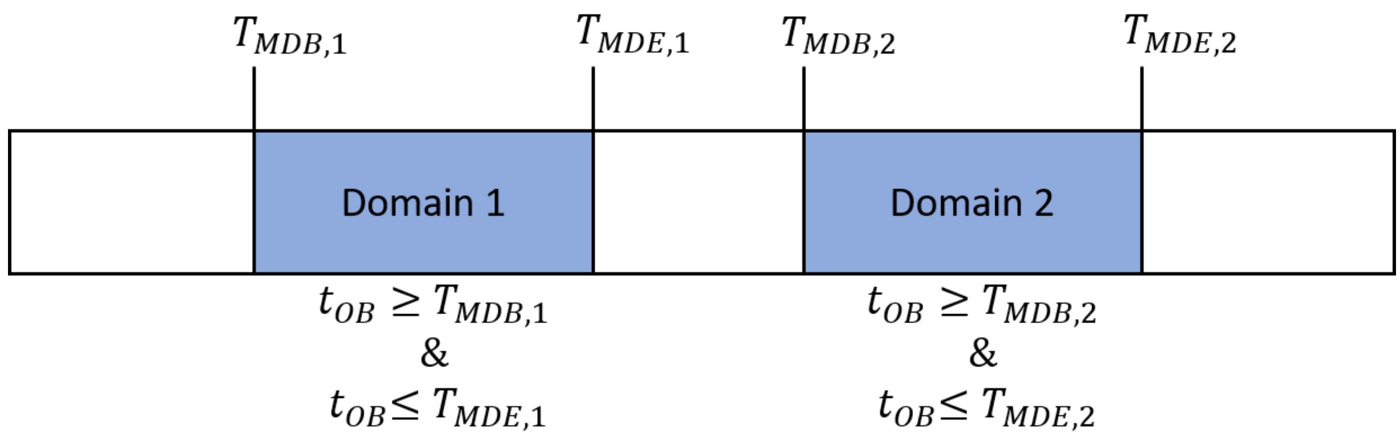
Constants

$T_{MDB,d}$: Start of valued time domain

$T_{MDE,d}$: End of valued time domain

Constraints

$$T_{MDB,d} \leq t_{OB,i} \leq T_{MDE,d}$$



Notes on Solving Mixed Integer Programming Problems

Primary Method: Branch and Cut method via MIP Solvers

- Many free solvers available
- Best performance with commercial solvers (Gurobi, CPLEX)
  - Better strategies for pre-solve, branching, and cut generation

Efficient tuning for RPO/PPO problems

- Pseudo cost branching
- Moderate cut generation

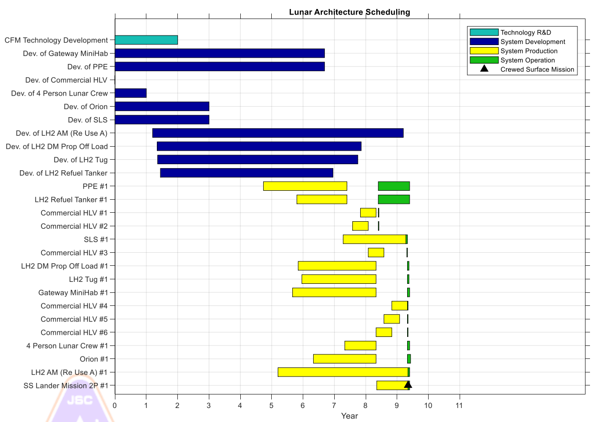
Typical Solve times:

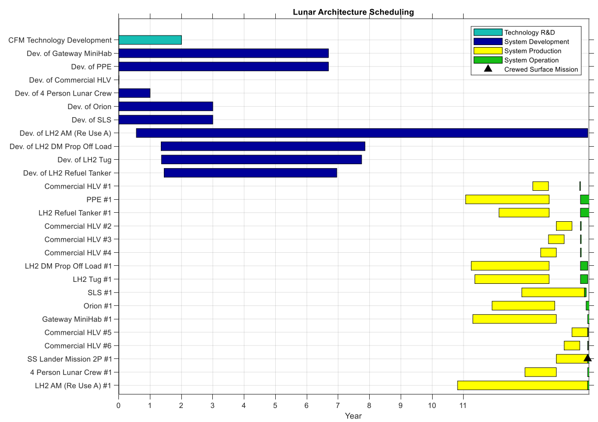
- Single lunar or Mars mission with fixed capability : ~10 sec
- Single lunar or Mars Mission with variable capability ~60 sec
- Three Mars missions with variable capability 1-2 hours
- Five Lunar missions with variable capability ~12 hours
- Multi Domain (~10 missions) : days to unsolvable

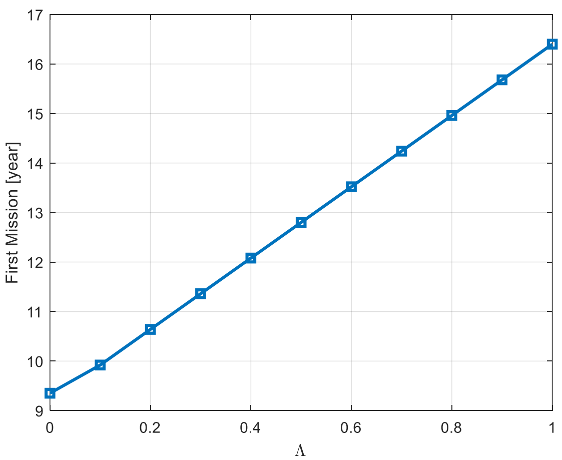
Scheduling Uncertainty

Methods to examine scheduling uncertainty

1. Within optimization, account for uncertainty with a stakeholder risk factor: $Dev\ Time' = \lambda * \mu + Dev\ Time$
2. Post Process assessment of architecture scheduling with System Developmental Dependency Analysis







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x_{cij_bin}: *Connectivity between systems (Binary Decision matrix)*

S_{ci}: *Vector of system capabilities (Matrix of Constants)*

S_{ri}: *Vector of system requirements (Matrix of Constants)*

Example Objective function:

$$\max \left(\sum_i \frac{\left(S_{ci} \cdot x_i^B\right)}{C_{Capability}} - \sum_i \frac{\left(C_i \cdot x_i^B\right)}{C_{Cost}} \right)$$

Capability — Cost

$C_{Capability}, C_{Cost}$: *Normalizing constants*

C_i: *Unit cost vector*

Subject to:

$$\sum_j x_{cij} \leq A_i^B S_{ci}$$ Finite Node Capability

$$\sum_i x_{cij} \geq A_j^B S_{rj}$$ Node Requirements

$$A_j^B S_{cj} + \sum_i x_{cij} - \sum_j x_{cij} - A_j^B S_{cj} = 0$$ Conservation of relay capability

$$\sum_j x_{cij\_bin} \leq Limit_i$$ Finite number of connections

Scheduling Constraints

Variables

- t_{DB}: System development beginning time (Symbolic Variable)
- t_{DE}: System development ending time (Symbolic Variable)
- T_D: System development duration (Constant)
- t_{PB}: System production beginning time (Symbolic Variable)
- t_{PE}: System production ending time (Symbolic Variable)
- T_P: System production duration (Constant)
- t_O: System operation time (Symbolic Variable)

Constraints

$$t_{DE,i} \geq t_{DB,i} + T_{D,i}$$

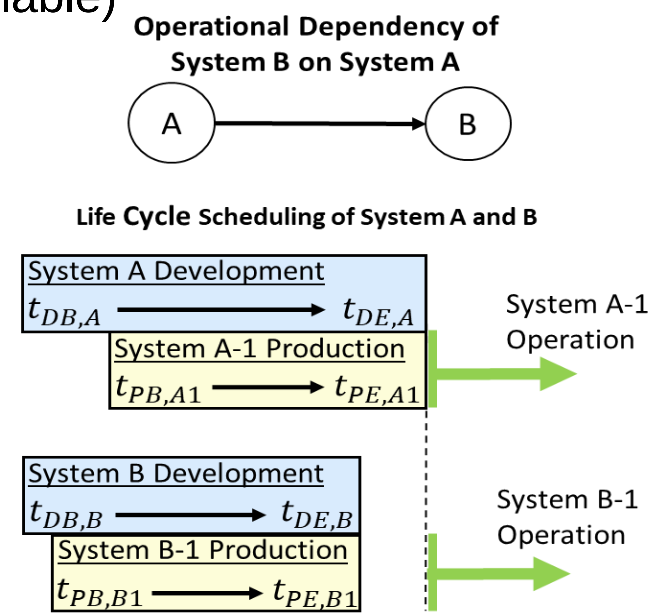
$$t_{PE(i)} \geq t_{DE(j)}$$

$$t_{PE(i)} \geq t_{PB(i)} + T_P$$

$$t_{O(i)} \geq t_{PE(i)}$$

$$t_{PB(i+1)} \geq t_{PE(i)}$$

$$\left(t_O(j) - t_O(i)\right) \geq -(1 - (x_{cij,bin}\,(i,j))) * M$$



PPO – Mathematical Basis Review

	Decision Variables	Constants	Equations
Fixed Capability Operational Constraints	A_j^B: *System selection* x_{cij}: *Transfer of capability between systems* x_{cij_bin}: *Connectivity between systems*	S_{ci}: *Sys capabilities* S_{rj}: *Sys requirements*	$\sum_j x_{cij} \le A_i^B S_{ci}$ $\sum_i x_{cij} \ge A_j^B S_{rj}$ $\sum_j x_{cij\_bin} \le Limit_i$
Variable Capability Constraints	Var_C: *Variable Cap.* Var_R: *Variable Req*	S_{ci}: *Sys capabilities* S_{rj}: *Sys requirements* m_{Req}: *Cap-Req relation slope* b_{Req}: *Cap—Req relation intercept*	$Var_C(i) \ge \sum_j X_{cij}$ $\sum_i X_{cij} \ge Var_R(i,n)$ $Var_R \ge Var_C * m_{Req} + A_i^B * b_{Req}$
Schedule Constraints	$t_{DB,j}$: *Development Begin* $t_{DE,j}$: *Development End* $t_{PB(i)}$: *Production Begin* $t_{PE(i)}$: *Production End* $t_{OB(i)}$: *Operation Begin* $t_{OE(i)}$: *Operation End*	$T_{D,j}$: *Dev. Time* $T_{P,i}$: *Prod. time* $T_{O\ Max,j}$: *Max Operational time*	$t_{DE,j} \ge t_{DB,j} + T_{D,j}$ $t_{PE(i)} \ge t_{DE(j)}$ $t_{PE(i)} \ge t_{PB(i)} + T_P$ $t_{PB(i+1)} \ge t_{PE(i)}$ $t_{OB(i)} \ge t_{PE(i)}$ $t_{OE(i)} - t_{OB(i)} \ge T_{O,max,j}$ $t_{OB(j)} - t_{OB(i)} \ge (x_{cij,bin} - 1) \cdot M$

Schedule Constraints

Schedule Constraints

Decision Variables

- $t_{DB,j}$: *Development Begin*
- $t_{DE,j}$: *Development End*
- $t_{PB(i)}$: *Production Begin*
- $t_{PE(i)}$: *Production End*
- $t_{OB(i)}$: *Operation Begin*
- $t_{OE(i)}$: *Operation End*

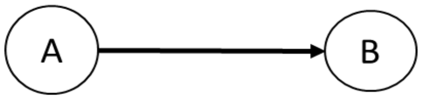
Constants

- $T_{D,j}$: *Dev. Time*
- $T_{P,i}$: *Prod. time*
- $T_{O\ Max,j}$: *Max Operational time*

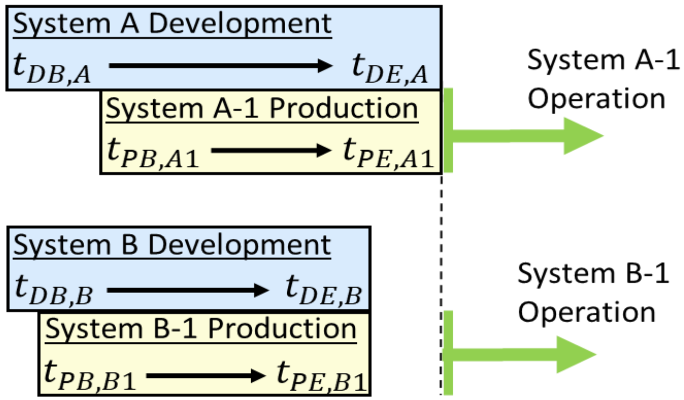
Equations

$$t_{DE,j} \geq t_{DB,j} + T_{D,j}$$
$$t_{PE(i)} \geq t_{DE(j)}$$
$$t_{PE(i)} \geq t_{PB(i)} + T_P$$
$$t_{PB(i+1)} \geq t_{PE(i)}$$
$$t_{OB(i)} \geq t_{PE(i)}$$
$$t_{OE(i)} - t_{OB(i)} \geq T_{O,max,j}$$
$$t_{OB(j)} - t_{OB(i)} \geq (X_{cij,bin} - 1) \cdot M$$

Operational Dependency of System B on System A



Life Cycle Scheduling of System A and B

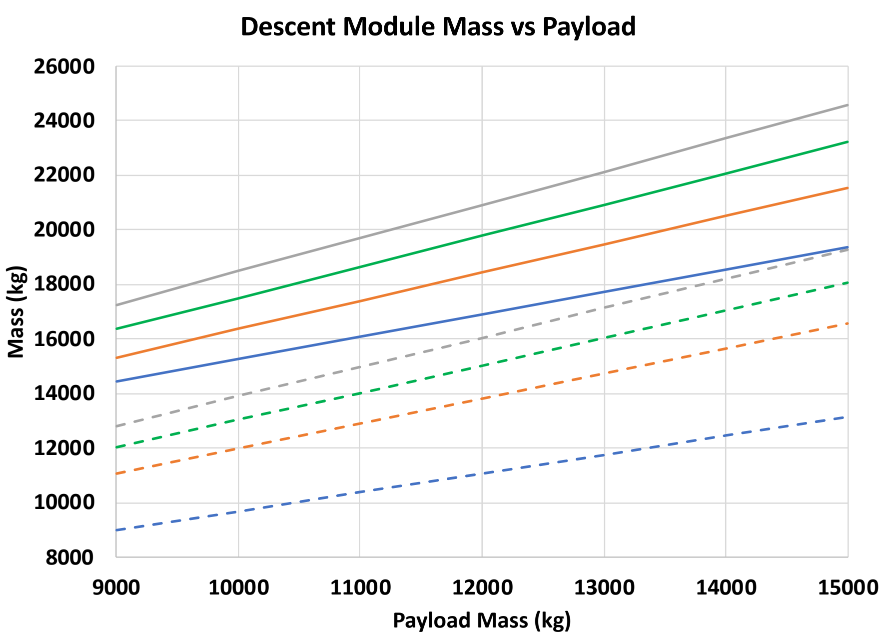


Additional Equations

$$t_{DB}, t_{DE}, t_{PB}, t_{PE}, t_{OB}, t_{OE} \geq 0$$
$$t_{DB}, t_{DE}, t_{PN}, t_{PE}, t_{OB}, t_{OE} \leq T_{End}$$
$$t_{DE(j)} \geq t_{DB(j)} + T_{D,j} * A^B_{j,dev}$$
$$t_{PE(i)} \geq t_{PB(i)} + T_{P,j} * A^B_i$$

Variable Capability Constraints

Variable Capability Constraints	Decision Variables	Constants	Equations
	Var_C: *Variable Cap.* Var_R: *Variable Req*	S_{ci}: *Sys capabilities* S_{rj}: *Sys requirements* m_{Req}: *Cap-Req relation slope* b_{Req}: *Cap–Req relation intercept*	$Var_C(i) \geq \sum_j X_{cij}$ $\sum_i X_{cij} \geq Var_R(i,n)$ $Var_R \geq Var_C * m_{Req} + A_i^B * b_{Req}$



Additional Equations

$$UB_R * A_i^B \geq Var_R$$

$$UB_C * A_i^B \geq Var_C$$

$$Var_C \geq LB_C * A_i^B$$

$$Var_R \geq LB_R * A_i^B$$

PPO – Mathematical Basis Review

	Decision Variables	Constants	Equations
Fixed Capability Operational Constraints	A_j^B: *System selection* x_{cij}: *Transfer of capability between systems* x_{cij_bin}: *Connectivity between systems*	S_{ci}: *Sys capabilities* S_{rj}: *Sys requirements*	$\sum_j x_{cij} \le A_i^B S_{ci}$ $\sum_i x_{cij} \ge A_j^B S_{rj}$ $\sum_j x_{cij\_bin} \le Limit_i$
Variable Capability Constraints	Var_C: *Variable Cap.* Var_R: *Variable Req*	S_{ci}: *Sys capabilities* S_{rj}: *Sys requirements* m_{Req}: *Cap-Req relation slope* b_{Req}: *Cap−Req relation intercept*	$Var_C(i) \ge \sum_j X_{cij}$ $\sum_i X_{cij} \ge Var_R(i,n)$ $Var_R \ge Var_C * m_{Req} + A_i^B * b_{Req}$
Schedule Constraints	$\mathrm{t}_{\mathrm{DB},j}$: *Development Begin* $\mathrm{t}_{\mathrm{DE},j}$: *Development End* $\mathrm{t}_{\mathrm{PB(i)}}$: *Production Begin* $\mathrm{t}_{\mathrm{PE(i)}}$: *Production End* $\mathrm{t}_{\mathrm{OB(i)}}$: *Operation Begin* $\mathrm{t}_{\mathrm{OE(i)}}$: *Operation End*	$T_{D,j}$: *Dev. Time* $T_{P,i}$: *Prod. time* $T_{O\ Max,j}$: *Max Operational time*	$\mathrm{t}_{\mathrm{DE},j} \ge \mathrm{t}_{\mathrm{DB},j} + \mathrm{T}_{\mathrm{D},j}$ $\mathrm{t}_{\mathrm{PE(i)}} \ge \mathrm{t}_{\mathrm{DE(j)}}$ $\mathrm{t}_{\mathrm{PE(i)}} \ge \mathrm{t}_{\mathrm{PB(i)}} + \mathrm{T}_{\mathrm{P}}$ $\mathrm{t}_{\mathrm{PB(i+1)}} \ge \mathrm{t}_{\mathrm{PE(i)}}$ $\mathrm{t}_{\mathrm{OB(i)}} \ge \mathrm{t}_{\mathrm{PE(i)}}$ $\mathrm{t}_{\mathrm{OE(i)}} - \mathrm{t}_{\mathrm{OB(i)}} \ge \mathrm{T}_{\mathrm{O,max},j}$ $\mathrm{t}_{\mathrm{OB(j)}} - \mathrm{t}_{\mathrm{OB(i)}} \ge (\mathrm{x}_{\mathrm{cij,bin}} - 1) \cdot \mathrm{M}$

Potential Objectives

Cost based objective

$$Obj_{Cost} = A_i^B * \mathrm{C}_{Prod} + A_{Dev,j}^B * C_{Dev} + (t_{OE} - t_{OB}) * C_{Oper}$$

Capability based objective

$$Obj_{Cap} = A_i^B * S_{ci}$$

Schedule based objective

$$Obj_{Time} = t_{OB(set)}$$

C_{Oper}:Operations Cost

C_{Dev}: Development Cost

C_{Prod}: Production Cost

S_{ci}: $Sys\ capabilities$

Potential ISsues 2 – Reaches near optimal but stalls

Incumbent Bnd | Best Bnd | MIP Gap | Time

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```
 1167485 699340 33898.6084   85    34 34511.7560 33577.5902  2.71%  29.0  465s
 1182966 709901 33786.3936   59    50 34511.7560 33577.8745  2.71%  29.2  470s
 1196964 719541 34144.8083   71    32 34511.7560 33578.7560  2.70%  29.4  475s
 1210604 728642 33883.5300   88    43 34511.7560 33579.6658  2.70%  29.5  480s
 1228742 740777     cutoff  115       34511.7560 33580.3837  2.70%  29.7  485s
 1246441 752250 34177.8583   64    41 34511.7560 33581.5422  2.70%  29.9  490s
 1259888 760007 33932.0633   87    35 34511.7560 33581.6293  2.70%  30.0  495s
 1270267 766272 33874.3140   75    46 34511.7560 33582.0285  2.69%  30.2  500s
 1287899 778235 33973.9732  102    35 34511.7560 33582.8711  2.69%  30.5  506s
 1301340 787735 34021.7901  110    30 34511.7560 33583.5965  2.69%  30.6  510s
 1318912 799404 34156.8204   82    31 34511.7560 33584.6658  2.69%  30.9  516s
 1332585 808469 33788.9370   76    43 34511.7560 33585.3385  2.68%  31.1  521s
 1346220 816564 34218.8275  122    23 34511.7560 33585.8883  2.68%  31.2  525s
 1355291 822584 33728.5369   59    40 34511.7560 33586.2880  2.68%  31.4  531s
H1357717 824358                     34511.755856 33586.2880  2.68%  31.4  531s
 1363364 827906 34138.0678   99    35 34511.7559 33586.5801  2.68%  31.5  535s
 1381351 838928 34181.5757  140    28 34511.7559 33587.0448  2.68%  31.7  541s
 1390531 844988 33994.2238  107    28 34511.7559 33587.8659  2.68%  31.8  545s
 1403633 853931 34344.6962   94    42 34511.7559 33588.3899  2.68%  32.1  551s
 1413827 860342 33931.4830   79    47 34511.7559 33589.0801  2.67%  32.2  556s
 1427493 868679 34226.1129   82    31 34511.7559 33589.5801  2.67%  32.4  560s
 1439187 876800 34371.6621  156    31 34511.7559 33590.1208  2.67%  32.6  565s

[RPO_Lift]  0:MATLAB*                    "lift.ecn.purdue.edu" 00:28 18-Sep-20
```

s Engineering Division

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```
In LunarSurfaceMission_V2_b (line 734)
    diagnostics=optimize(Constraints,Objective,sdpsettings('solver','gurobi','de
bug',1,'gurobi.MIPFocus',0
    ,'gurobi.OptimalityTol',1E-3,'gurobi.MIPGap',3E-4))

>>
>>
>>
>>
>> LunarSurfaceMission_V2_b
Adding Paths
Importing Data from ../SpreadSheets/Lunar Case/CSL_LunarSurface_V3
Building constraints

 -Starting tP Constraints
 -Starting tO Constraints 10.0% 20.0% 30.0% 50.0% 60.0% 70.0% 80.0%
 Hulling ConstraintsConstraints Done

--------------------------------------------
Warning: your license will expire in 9 days
--------------------------------------------

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Optimize a model with 567917 rows, 185506 columns and 1297643 nonzeros
Variable types: 92918 continuous, 92588 integer (92588 binary)
Coefficient statistics:
  Matrix range     [2e-02, 3e+02]
  Objective range  [8e-04, 6e+03]
  Bounds range     [1e+00, 1e+00]
  RHS range        [1e-01, 3e+02]
Presolve removed 565367 rows and 184291 columns
Presolve time: 3.11s
Presolved: 2550 rows, 1215 columns, 15830 nonzeros
Variable types: 573 continuous, 642 integer (642 binary)

Root relaxation: objective 3.057882e+04, 858 iterations, 0.06 seconds

    Nodes    |    Current Node    |     Objective Bounds      |     Work
 Expl Unexpl |  Obj  Depth IntInf | Incumbent    BestBd   Gap | It/Node Time

     0     0 30578.8167    0  104          - 30578.8167      -     -    3s
     0     0 32720.2007    0  105          - 32720.2007      -     -    4s
     0     0 32720.2007    0  104          - 32720.2007      -     -    4s
     0     0 32721.5081    0  120          - 32721.5081      -     -    4s
     0     0 32721.5081    0  123          - 32721.5081      -     -    4s
     0     0 32721.5081    0  128          - 32721.5081      -     -    4s
     0     0 32721.5081    0  126          - 32721.5081      -     -    4s
     0     0 32721.5081    0  104          - 32721.5081      -     -    4s
     0     0 32721.5081    0  104          - 32721.5081      -     -    4s
     0     2 32721.5081    0  102          - 32721.5081      -     -    5s
  2975  1678 33953.2617   34   88          - 33134.4777      -  65.6   10s
  2988  1687 34192.2694   26   75          - 33134.4777      -  65.3   15s
  5997  3295 33999.7163   70   45          - 33333.5801      -  17.7   20s

[RPO_Lift] 0:MATLAB*                         "lift.ecn.purdue.edu" 00:31 18-Sep-20
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