SAND2022-4152C

Sandia National Laboratories

Exceptional service in the national interest

Methodology for the Creation of Concurrent Technology and Mission Scheduling for Space Exploration Architectures

Andrew D. Sanders

asande@sandia.gov

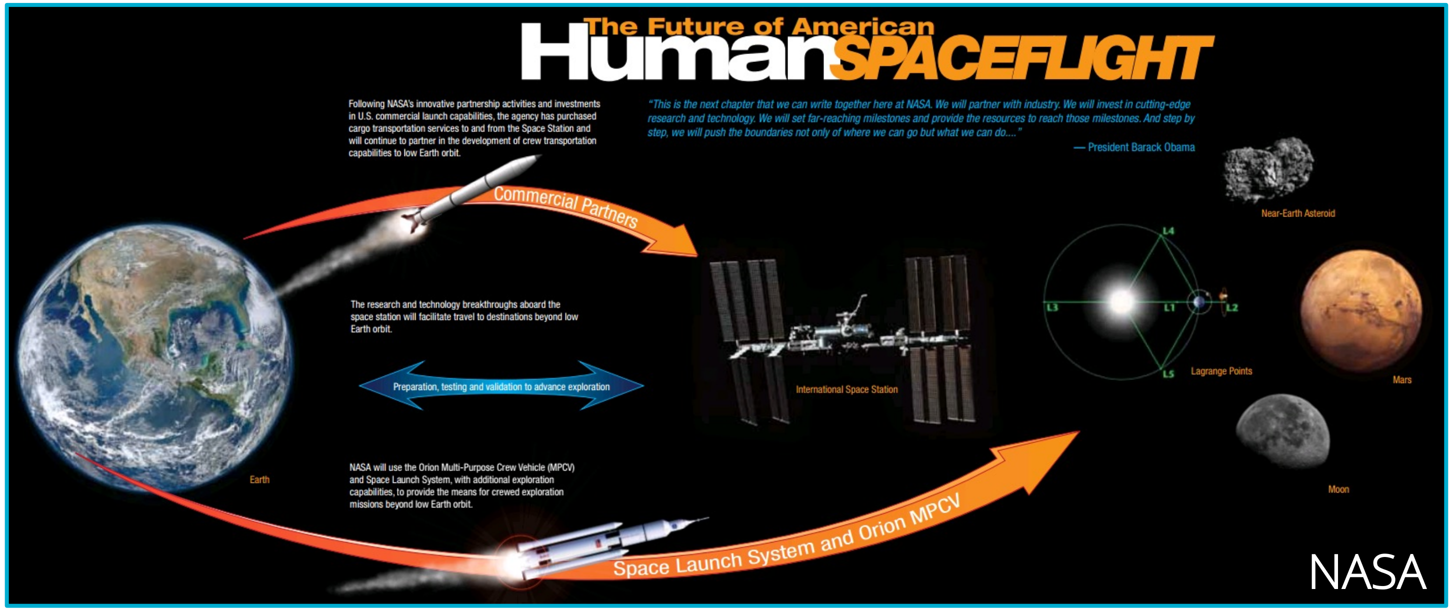
AIAA Defense Forum, April 2022

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. ...ation under contract DE-NA0003525.

Background and Motivation

- Goal: Present a methodology that may be relevant to planning out future defense programs and technology maturation schedules / priorities
- Work was completed in 2014 as part of my graduate research, however is relevant today
- Used an unclassified example of a notional human mission to Mars to demonstrate methodology and provide technology set
- Considers different metrics for prioritization to examine results



Primer: General Description of Methodology

- A methodology was desired to identify, prioritize, and schedule technology development to enable a future mission set while:
  - Accounting for a concurrent capability evolution
  - Accounting for mission constraints and allowing for flexible scheduling.

- Uses a petri-net type resource tracking as the control logic for mission planning

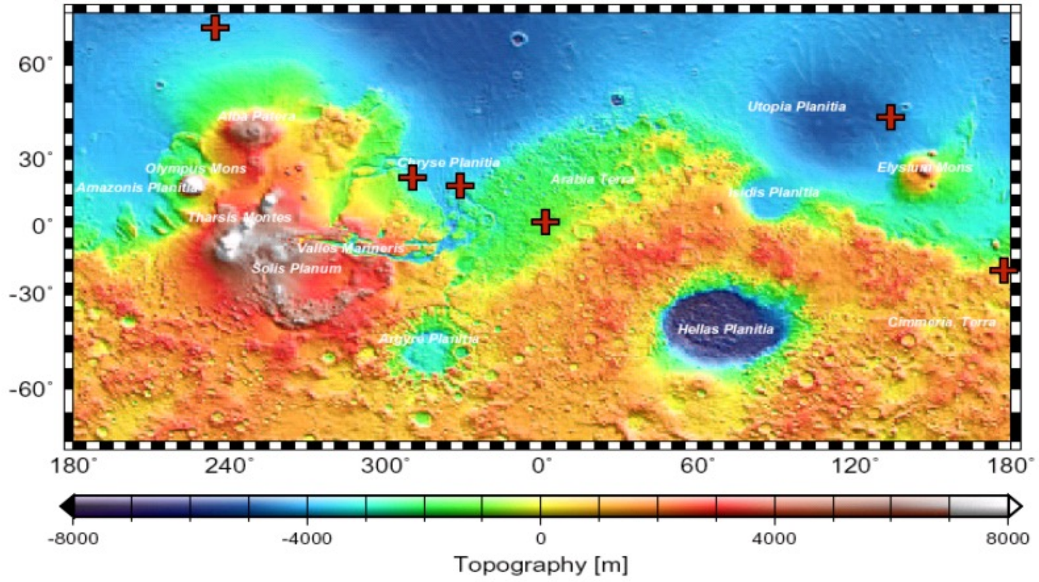
- Combination of Monte Carlo and Genetic Algorithm to generate cases

- Uses “k-factor” to represent technology impacts on key areas based on predicted performance
  - Allows for simplified comparison and analysis

- Future work could:
  - Implement cost/schedule uncertainties and sensitivity studies
  - Broaden scope to include more technology categories

Technology of Interest: Entry, Descent, and Landing (EDL)

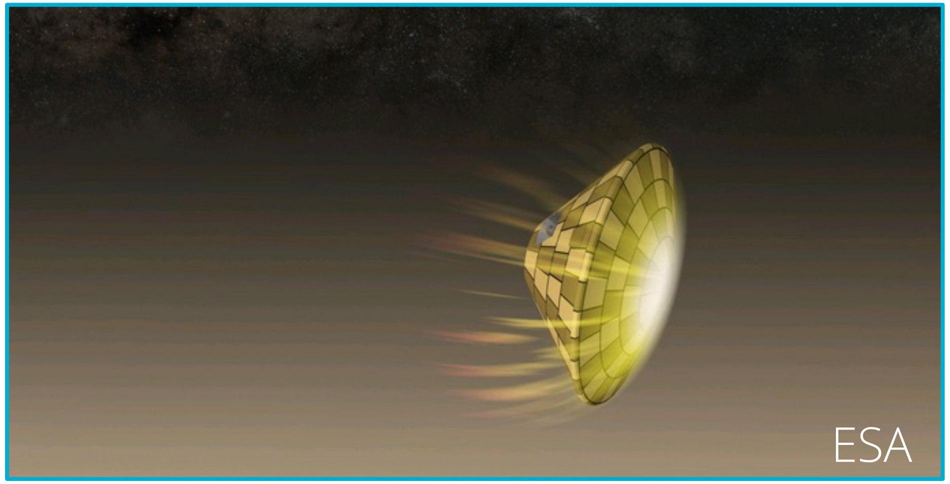
- EDL is the emergent system behavior of bringing a vehicle from approach conditions to contact with the surface of a body [7]
- EDL is one of the most critical and difficult mission phases
- Key Metrics for EDL [10]
  - Delivery/Performance Reliability
  - Cost
  - Delivered Mass
  - Landing Site Access
  - Landing Precision



Test Case: Overall Mission

- The relatively thin Martian atmosphere coupled with substantial Martian gravity creates an extremely difficult EDL environment
- To date, the largest landed mass is ~1t (MSL)
- The limit of current (Viking era) EDL technologies for Mars is ~1.5t
- Current mission architectures for manned missions to the Martian surface require landed masses of up to 40-60t
- The hostile EDL environment requires high performance technologies for specific mass and payload classes
- A method is needed to generate / validate technology development plans to enable future missions

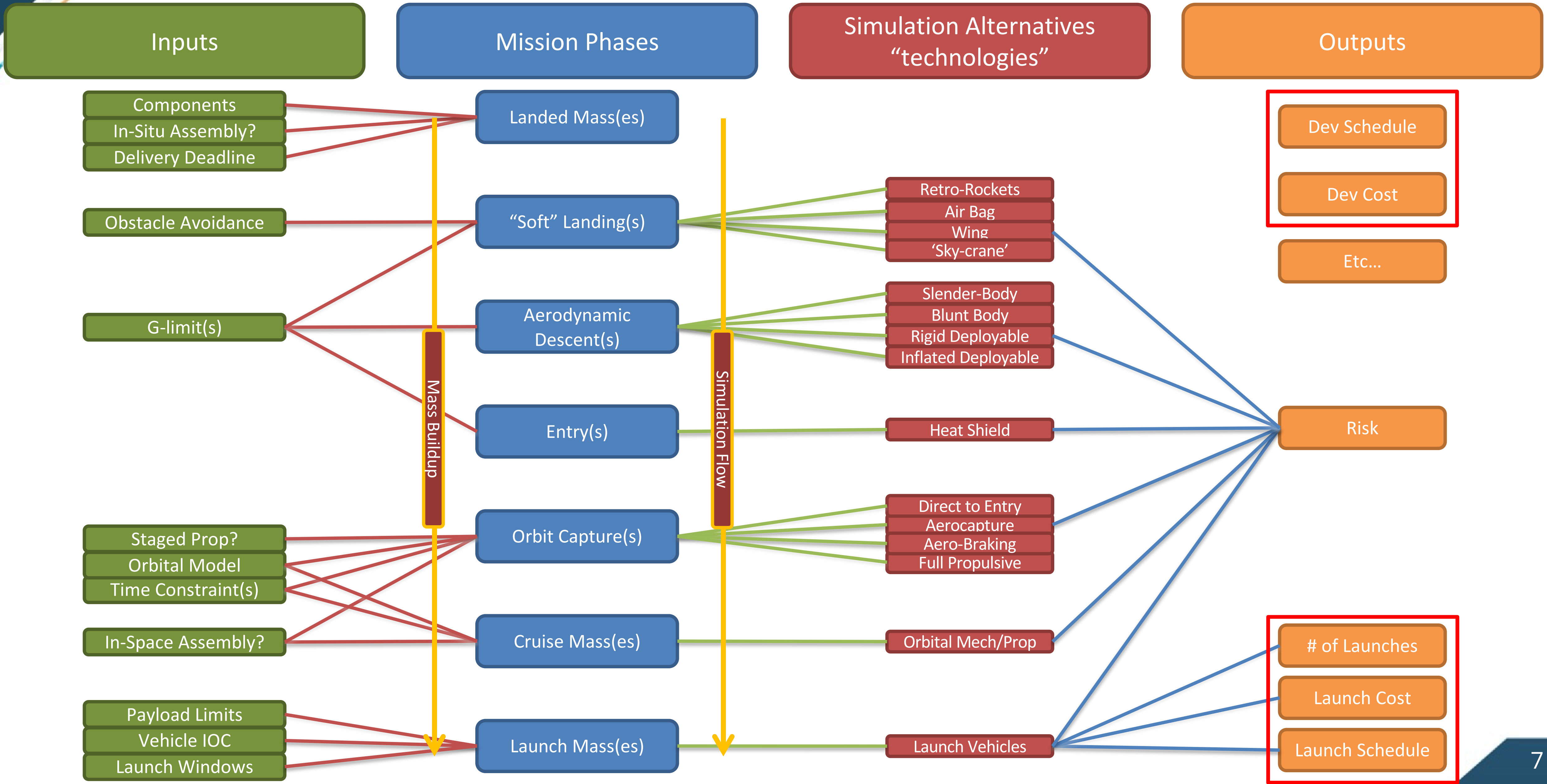
- RASC-AL Mars Colony Architecture Study [8]
  - 40 year timespan starting in 2014
  - Flat NASA budget of $16B per year
  - Establish a 25 person self-sufficient colony by year 40
  - 4 up 4 down crew rotation every other year



Simulation Method

- A parametric environment was generated to allow the designer to compare long term mission architectures by a landed mass / timetable point of view
- This allows for an informed decision to be made in the creation or refinement of a technology development plan for EDL
- The environment was coded in MATLAB and is designed to work with and support existing tools
- A genetic algorithm was used to generate alternative timeline and launch combinations

Simulation Flow Chart

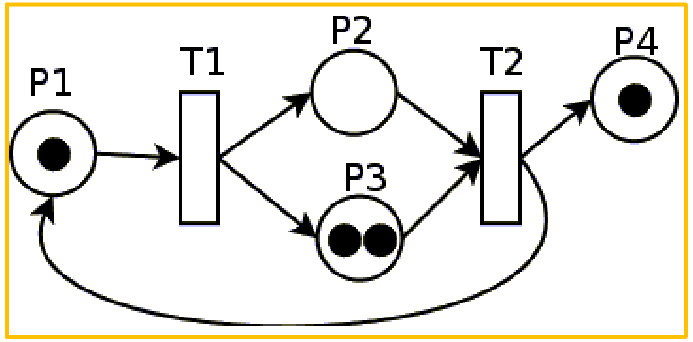


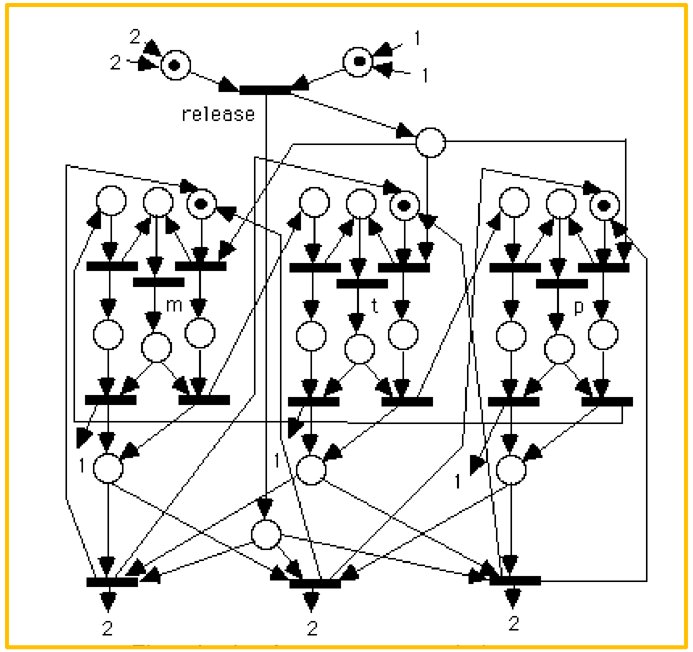
- A Petri Net methodology was used to track mission order dependencies

- Petri Nets are a graphical method of tracking states and transitions that can be used to model discrete events

- Three components of Petri Net
  - States (Circles)
  - Tokens (Dots)
  - Transitions (Rectangles)

- Easily scalable





Test Case: Tool Inputs

Launch Windows / Logistics / Fixed Values / Limits

- General Schedule of Earth-to-Mars Launch Windows
- Orbital Parameters
- Overall Funding Schedule

Landed Masses and Requirements

- Arrival Deadline
- Delivered / Used Goods
- Prerequisites
- Mass
- Acceleration Limits
- Transit Time Constraints
- In Space / In Situ Assembly Capabilities

Launch Capabilities, Windows, and Restrictions

- Vehicle
- Crew Certification
- Maximum Mass Deployment to LEO
- Launch Cost
- Operational Timeline
- Max Number of Launches per Year / Window

EDL Technology Alternatives and Development Parameters

- Development Duration
- Development Cost
- Flight Stage(s) affected
- Mass / Performance k-factors
- Mass Relation Equations

Tool Outputs

Monte Carlo simulation results in the creation of *n* unique launch/technology schedules

- *n* is a function of the number of user specified unique payload orders to be generated
- The output for each simulation case is broken down into two components

Mission Launch Schedule

- Earth to LEO Launch Schedule
- LEO to Mars Transit Schedule
- Mission Breakdown by EDL Phase
- Overall Launch Cost Estimate

EDL Technology Development Schedule

- List of Required Technologies for Mission Set
- Technology Development Schedule
- Funding Schedule / Overall Cost Estimate

Tool Mechanics

- Each case consists of a unique launch order
- For each mission a mass buildup with current technology is generated
- This mass is compared against available launch systems
- Monte Carlo decision making
  - If no viable launch available:
    - Delay launch
    - Develop technology
  - If viable launch available
    - Select lowest cost vehicle
    - Delay launch
    - Develop technology
  - Repeat until payload manifest is satisfied

Test Case: Overview

- In order to validate the methodology and tool developed, a test case was constructed
- The test case is broken into four sections corresponding to the tool inputs:
  - Landed Masses
  - Launch Vehicles
  - Launch Windows (every 26 months for direct)
  - Technology Programs
- The test case showcases the full functionality of the tool

Test Case: Landed Masses

- Notional mission set represents a long term Mars colony architecture
- 20 total landed masses of 9 unique types
- Each mass defined by 12 metrics
- Four Petri Net values used
  - Food (human life support)
  - Supplies
  - Infrastructure
  - Return

Payload	# of	Direct to Mars	Delivered				Prerequisite				Mass (MT)	In Space Assembly	In Situ Assembly
			F	S	I	R	F	S	I	R			
Nav Beacon	3	N	0	0	1	0	0	0	0	0	0.5	0	0
Habitat + Crew	3	Y	-4	-2	-1	-1	5	5	7	1	40	0	0
Supply Depot	2	N	0	5	0	0	0	0	1	0	30	0.5	0.5
Food Depot	2	N	5	0	0	0	0	0	1	0	30	0.5	0.5
Green House	1	Y	5	-2	0	0	0	2	3	0	20	0.5	0.5
Rover	2	N	0	-1	0	0	0	0	3	1	5	0	0
Return Vehicle	3	N	0	0	0	1	0	0	3	0	50	0	0
Power Plant	2	N	0	0	2	0	0	0	3	0	35	0.5	0
Fuel Plant	2	N	0	0	3	0	0	0	3	0	45	0.5	0

Concurrent Technology: Launch Vehicles *SLS timeline did not age well

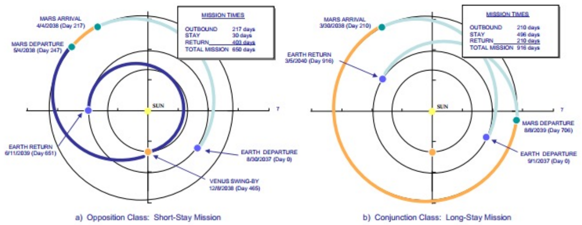
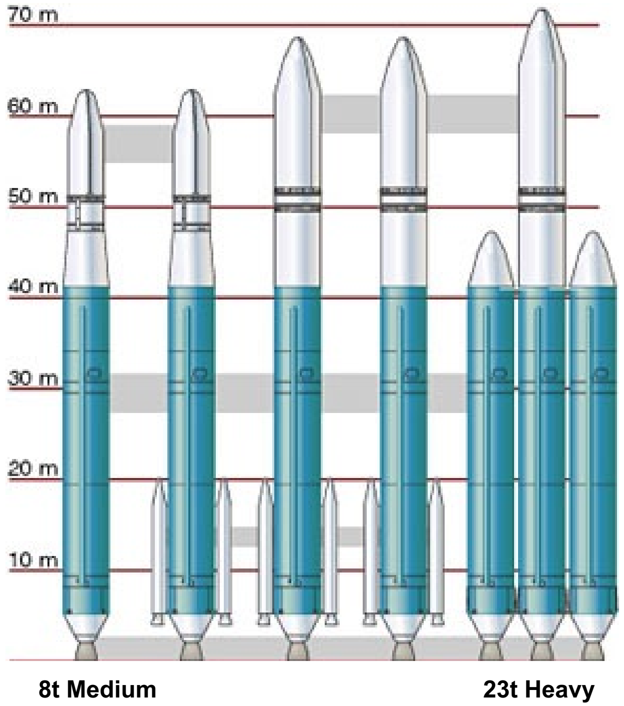
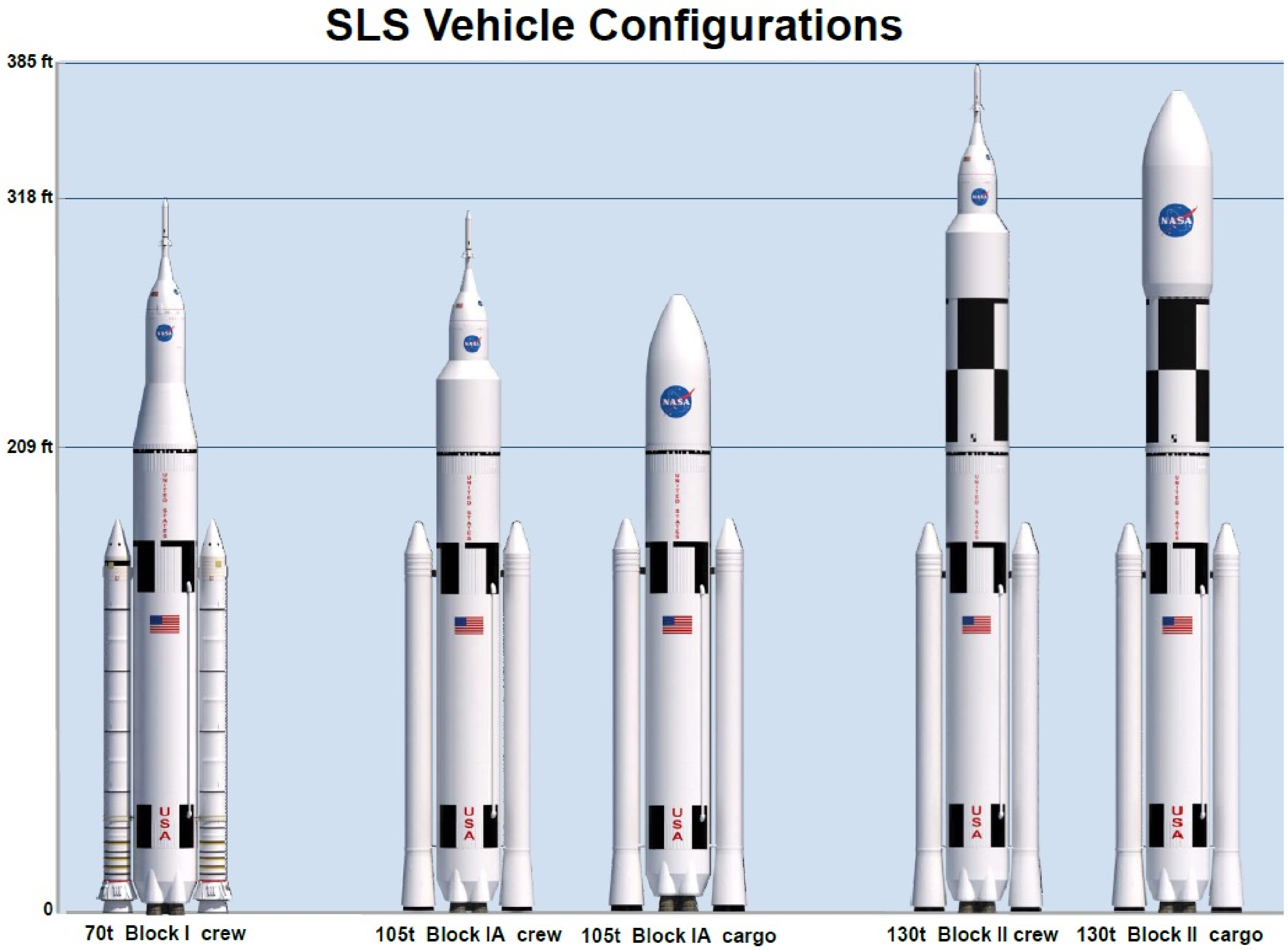


Figure 6-2. Comparison of (a) Opposition-class and (b) Conjunction-class mission profiles.





Increasing Launch Mass Capability

Test Case: Launch Vehicle Availability

Vehicle	Variant	Crew Certified?	Mass to LEO	Base Launch Cost ($M)	Year Active	Max Launchers per Year
Delta IV	Medium	N	9	170	2014	5
Delta IV	Heavy	N	28	375	2014	5
SLS	Block 1 Crew	Y	70	520	2018	3
SLS	Block 1A Cargo	N	105	500	2021	2
SLS	Block 1A Crew	Y	105	520	2022	2
SLS	Block 2 Cargo	N	130	600	2032	2
SLS	Block 2 Crew	Y	130	620	2033	2

Test Case: Technologies Modelled

- 14 Technologies Considered
- Technology areas rather than specific programs modeled
- These areas are taken from a NASA technology tree for EDL
- Development time and cost randomized within common ranges
  - Actual information not available
  - Still allows for tool validation

Technology	Dev Time	Dev $M	k_entrymass	k_descentmass	k_landmass	k_cruise
Rigid TPS	45	24.489	-0.067	-	-	-
Flex TPS	28	21.7307	-0.033	-	-	-
Rigid Decelerator	46	19.5044	-0.067	-	-	-
Deployable Decelerator	23	19.9671	-0.120	-	-	-
Monitoring / Modeling	39	21.2439	-0.018	-	-	-
Attached Deployable	27	25.6452	-	-0.067	-	-
Trailing Deployable	37	21.1496	-	-0.067	-	-
Descent Retropropulsion	23	18.1514	-	-0.090	-	-
Descent GN&C / Modeling	41	22.2186	-	-0.018	-	-
Touchdown Systems	47	24.0245	-	-	-0.010	-
Egress and Deployment	38	23.735	-	-	-0.010	-
Landing Propulsion	25	17.7701	-	-	-0.010	-
Landing GN&C / Modeling	38	15.5842	-	-	-0.018	-
Dual Pulse TPS	36	29.4472	-	-	-	-0.120

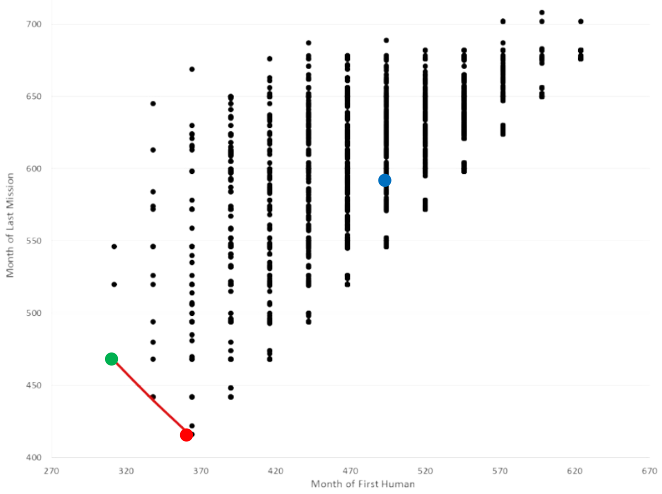
$$k_{eff} = k_{eff-1} * (1 + k_{selected})$$

$$m_{cruise} = k_{cruisemass} * (1.1) * m_{entry} e^{\left(\frac{\Delta V * m_{entry}}{g_{earth} ISP}\right)}$$

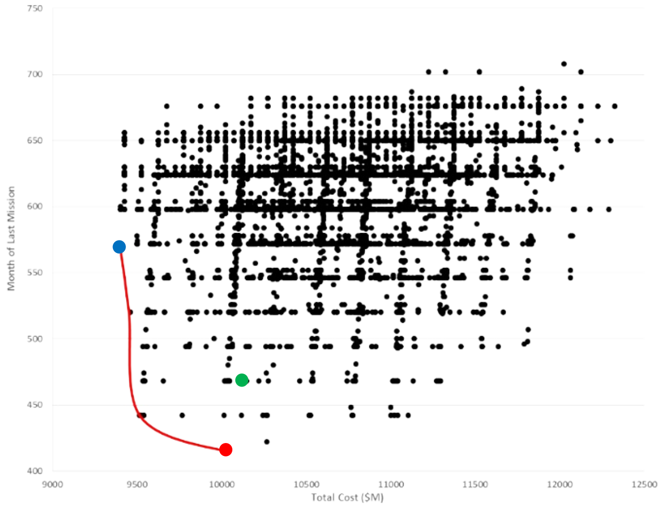
Test Case: Results

1,300 unique mission architectures generate

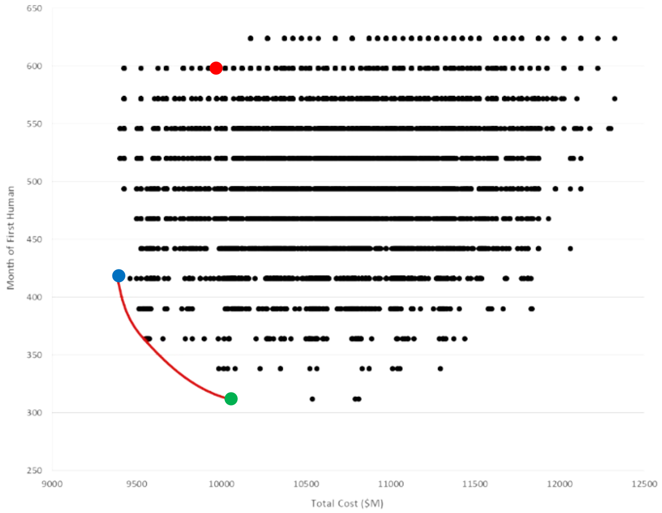
Pareto Optimal Points for 3 Conflicting MOI					
Mission Preference	Total Cost ($M FY2014)	Timeline (Months)	First Manned Mission (Month)	Number of Missions	Number of Technologies
Low Cost ● (blue)	9,401	598	516	20	13
Short Timeline ● (red)	10,017	416	364	21	9
Early Manned Mission ● (green)	10,046	468	312	21	10



Scatterplot of month of first human mission versus the total mission timeline.



Scatterplot of total mission cost versus the month of final mission launch.



Scatterplot of total mission cost versus the month of the first manned mission to Mars.

Test Case: Result, Minimum Cost

Mission Preference	Total Cost ($M FY2014)	Timeline (Months)	First Manned Mission (Month)	Number of Missions	Number of Technologies
Low Cost	9,401	598	516	20	13

Seven technologies occur in all three mission sets:

- Attached deployable
- Trailing deployable
- Rigid decelerators
- Dual pulse TPS
- Descent retropropulsion
- Flexible TPS
- Deployable decelerators

Mission	Vehicle	Payload	Mass (MT)	Month
1	Delta IV Medium	Nav Beacon	2.29	0
2	Delta IV Medium	Nav Beacon	2.29	2
3	Delta IV Medium	Nav Beacon	2.29	4
4	SLS Block 2 Cargo	Return Vehicle	116.90	371
5	SLS Block 1A Cargo	Fuel Plant	104.85	377
6	SLS Block 2 Cargo	Return Vehicle	116.90	383
7	SLS Block 1A Cargo	Power Plant	80.98	389
8	SLS Block 1A Cargo	Supply Depot	69.17	395
9	Delta IV Heavy	Rover	11.33	395
10	SLS Block 1A Cargo	Food Depot	69.17	401
11	SLS Block 1A Cargo	Supply Depot	69.17	407
12	SLS Block 1A Crew	Habitat + Crew	92.87	416
13	SLS Block 1A Cargo	Food Depot	67.21	510
14	SLS Block 2 Cargo	Return Vehicle	113.54	516
15	SLS Block 1A Cargo	Fuel Plant	101.84	522
16	SLS Block 1A Cargo	Power Plant	78.67	528
17	SLS Block 1A Cargo	Green House	44.50	546
18	SLS Block 1A Crew	Habitat + Crew	90.22	572
19	SLS Block 1A Crew	Habitat + Crew	90.22	598
20	Delta IV Heavy	Rover	11.01	598

Program	Technology	Dev Month	Dev Time (Months)	Dev Cost ($M)
1	Attached Deployable	4	27	25.6452
2	Rigid TPS	31	45	24.489
3	Trailing Deployable	76	37	21.1496
4	Rigid Decelerator	113	46	19.5044
5	Dual Pulse TPS	159	36	29.4472
6	Landing GN&C / Modeling	195	38	15.5842
7	Landing Propulsion	233	25	17.7701
8	Descent Retropropulsion	258	23	18.1514
9	Flex TPS	281	28	21.7307
10	Monitoring / Modeling	309	39	21.2439
11	Deployable Decelerator	348	23	19.9671
12	Descent GN&C / Modeling	416	41	22.2186
13	Touchdown Systems	457	47	24.0245

Test Case: Result, Shortest Timeline

Mission Preference	Total Cost ($M FY2014)	Timeline (Months)	First Manned Mission (Month)	Number of Missions	Number of Technologies
Short Timeline	10,017	416	364	21	9

Mission	Vehicle	Payload	Mass (MT)	Month
1	Delta IV Medium	Nav Beacon	2.02	118
2	Delta IV Medium	Nav Beacon	2.02	120
3	SLS Block 1A Cargo	Partial Supply Depot	61.73	120
4	SLS Block 1A Cargo	Partial Supply Depot	61.73	126
5	Delta IV Medium	Nav Beacon	2.02	126
6	SLS Block 1A Cargo	Food Depot	87.87	208
7	SLS Block 1A Cargo	Power Plant	102.97	214
8	SLS Block 1A Cargo	Supply Depot	87.87	220
9	SLS Block 1A Cargo	Green House	58.07	234
10	SLS Block 2 Cargo	Fuel Plant	124.31	286
11	SLS Block 2 Cargo	Return Vehicle	129.06	329
12	Delta IV Heavy	Rover	12.47	329
13	SLS Block 2 Cargo	Fuel Plant	115.71	335
14	SLS Block 1A Crew	Habitat + Crew	102.46	364
15	SLS Block 1A Cargo	Power Plant	89.31	370
16	SLS Block 2 Cargo	Return Vehicle	129.06	376
17	SLS Block 1A Crew	Habitat + Crew	102.46	390
18	SLS Block 1A Cargo	Food Depot	76.26	396
19	SLS Block 2 Cargo	Return Vehicle	129.06	402
20	SLS Block 1A Crew	Habitat + Crew	102.46	416
21	Delta IV Heavy	Rover	12.47	416

Seven technologies occur in all three mission sets:

- Attached deployable
- Trailing deployable
- Rigid decelerators
- Dual pulse TPS
- Descent retropropulsion
- Flexible TPS
- Deployable decelerators

Program	Technology	Dev Month	Dev Time (Months)	Dev Cost ($M)
1	Flex TPS	0	28	21.7307
2	Attached Deployable	28	27	25.6452
3	Egress and Deployment	55	38	23.735
4	Landing Propulsion	93	25	17.7701
5	Dual Pulse TPS	126	36	29.4472
6	Deployable Decelerator	162	23	19.9671
7	Descent Retropropulsion	185	23	18.1514
8	Rigid Decelerator	234	46	19.5044
9	Trailing Deployable	286	37	21.1496

Test Case: Result, Earliest Manned Flight

Mission Preference	Total Cost ($M FY2014)	Timeline (Months)	First Manned Mission (Month)	Number of Missions	Number of Technologies
Early Manned Mission	10,046	468	312	21	10

Mission	Vehicle	Payload	Mass (MT)	Month
1	Delta IV Medium	Nav Beacon	2.29	0
2	SLS Block 1A Cargo	Food Depot	83.56	201
3	Delta IV Medium	Nav Beacon	1.36	201
4	Delta IV Medium	Nav Beacon	1.27	230
5	SLS Block 2 Cargo	Return Vehicle	129.32	271
6	SLS Block 2 Cargo	Return Vehicle	129.32	277
7	SLS Block 2 Cargo	Fuel Plant	115.94	283
8	SLS Block 1A Cargo	Power Plant	89.49	289
9	SLS Block 2 Cargo	Return Vehicle	129.32	295
10	SLS Block 1A Cargo	Supply Depot	76.41	301
11	SLS Block 1A Crew	Habitat + Crew	102.66	312
12	SLS Block 1A Cargo	Partial Supply Depot	37.77	318
13	SLS Block 1A Cargo	Partial Supply Depot	37.77	324
14	SLS Block 1A Cargo	Power Plant	89.49	330
15	SLS Block 2 Cargo	Fuel Plant	115.94	336
16	Delta IV Heavy	Rover	12.49	336
17	SLS Block 1A Cargo	Food Depot	76.41	342
18	SLS Block 1A Cargo	Green House	47.12	390
19	SLS Block 1A Crew	Habitat + Crew	94.62	442
20	SLS Block 1A Crew	Habitat + Crew	94.62	468
21	Delta IV Heavy	Rover	11.54	468

Seven technologies occur in all three mission sets:

- Attached deployable
- Trailing deployable
- Rigid decelerators
- Dual pulse TPS
- Descent retropropulsion
- Flexible TPS
- Deployable decelerators

Program	Technology	Dev Month	Dev Time (Months)	Dev Cost ($M)
1	Rigid Decelerator	0	46	19.5044
2	Rigid TPS	46	45	24.489
3	Flex TPS	91	28	21.7307
4	Descent Retropropulsion	119	23	18.1514
5	Deployable Decelerator	142	23	19.9671
6	Dual Pulse TPS	165	36	29.4472
7	Attached Deployable	201	27	25.6452
8	Descent GN&C / Modeling	230	41	22.2186
9	Trailing Deployable	342	37	21.1496
10	Egress and Deployment	390	38	23.735

Conclusion

- A first iteration conceptual level design tool for the generation of launch and development timelines was created
  - Can be adapted to other use cases and technologies
- The tool was validated against past and future concept Mars lander missions
- The tool was applied to a 20 payload notional mission architecture as a proof of concept
- Output plots were analyzed to showcase utility to decisions makers
- Example showed that seven key technologies were common across the three prioritization options.

Q&A / Discussion

Thank You

References

[1] "Human Exploration of Mars Design Reference Architecture 5.0." July 2009

[2] Braun, R.D. and Manning, R.M. "Mars Entry, Descent and Landing Challenges," Journal of Spacecraft and Rockets, Vol. 44, No. 2, pp. 310–323, Mar-Apr, 2007.

[3] "Space Launch System," http://www.nasa.gov/sls

[4] Khan, Zahra. "Entry, Descent and Landing Vehicle Design Space Exploration for Crewed Mars Missions," MIT Masters Thesis, 2008.

[5] Collett, Kelly. "Qualitative Architecture Space Exploration," AE 8900 Special Topics Report, Georgia Institute of Technology, 2014.

[6] Engelund, W. C. et al. "Entry, Descent, and Landing Architecture and Technology Challenges for Human Exploration of Mars," Journal of Cosmology, Vol 12, Oct-Nov, 2010

[7] "Space Technology Roadmaps," NASA, 2012, http://www.nasa.gov/sites/default/files/501326main_TA09-ID_rev5_NRC_wTASR.pdf

[8] 2015 RASC-AL Themes: http://nia-cms.nianet.org/RASCAL/index.aspx

[9] 2015 RASC-AL Supporting Documents: http://nia-cms.nianet.org/RASCAL/Program-Info/Resources.aspx

[10] Braun, Robert. Planetary Entry, Descent, and Landing. Graduate level course, Georgia Institute of Technology, Atlanta, GA, Fall, 2014.

[11] Tentative SLS Development and Launch Schedule: http://www.nasaspaceflight.com/2011/07/preliminary-nasa-evolved-sls-vehicle-21-years-away/

[12] Sadin, S. and Povinelli, F. "The NASA Technology Push Towards Future Space Mission Systems," Acta Astronautica, Vol. 20, pages 73-77, 1989

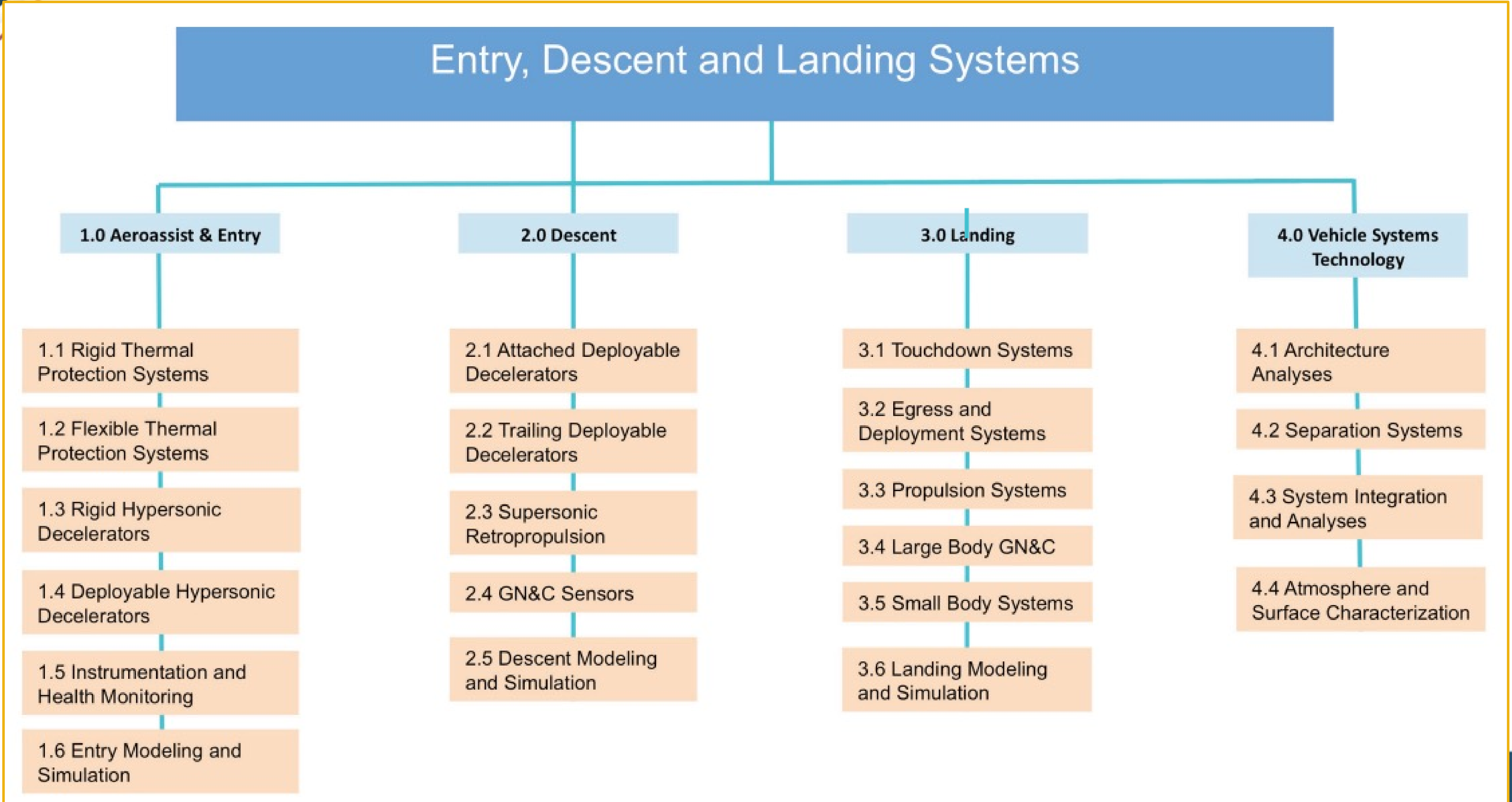
[13] Petri Nets: http://www.unc.edu/~stotts/comp723/PetriNets.pdf

[14] United Launch Alliance, "Delta IV Payload Planner's Guide," June 2013. http://www.ulalaunch.com/uploads/docs/DeltaIVPayloadPlannersGuide2007.pdf

Backup: Results

- 1,300 unique mission architectures were developed based on a notional mission set
- The simulation took 5.8 minutes to run on an Intel® Core™ i7-2600 CPU @ 3.4 GHz with 8GB of ram
- Testing showed that simulation time scales with $n^{1.2}$ where n is the number of unique architectures generated

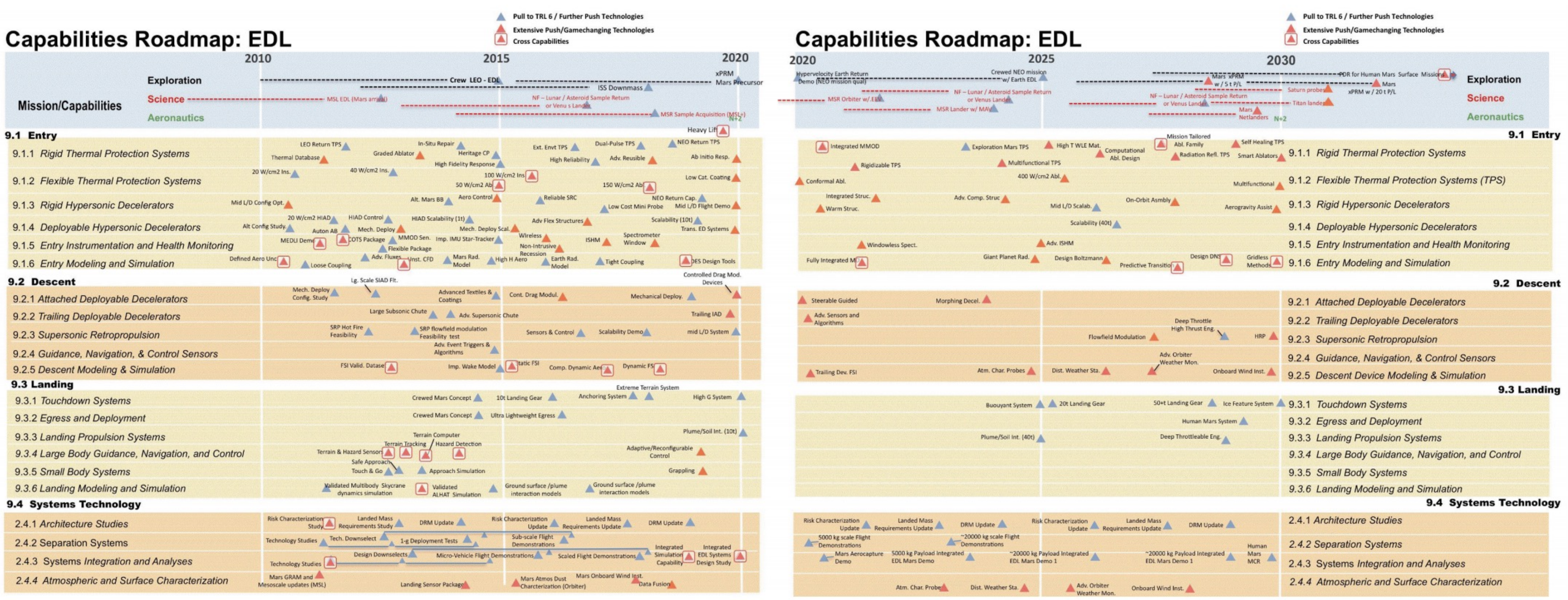
Backup: Current NASA EDL Tech Areas [7]



Backup: Current NASA EDL Tech Areas [7]

The current development plan is constructed from expert opinion and sparse mission planning

Figure 1: *Entry, Descent, and Landing Technology Area Strategic Roadmap (TASR)*



Backup: Tool Validation

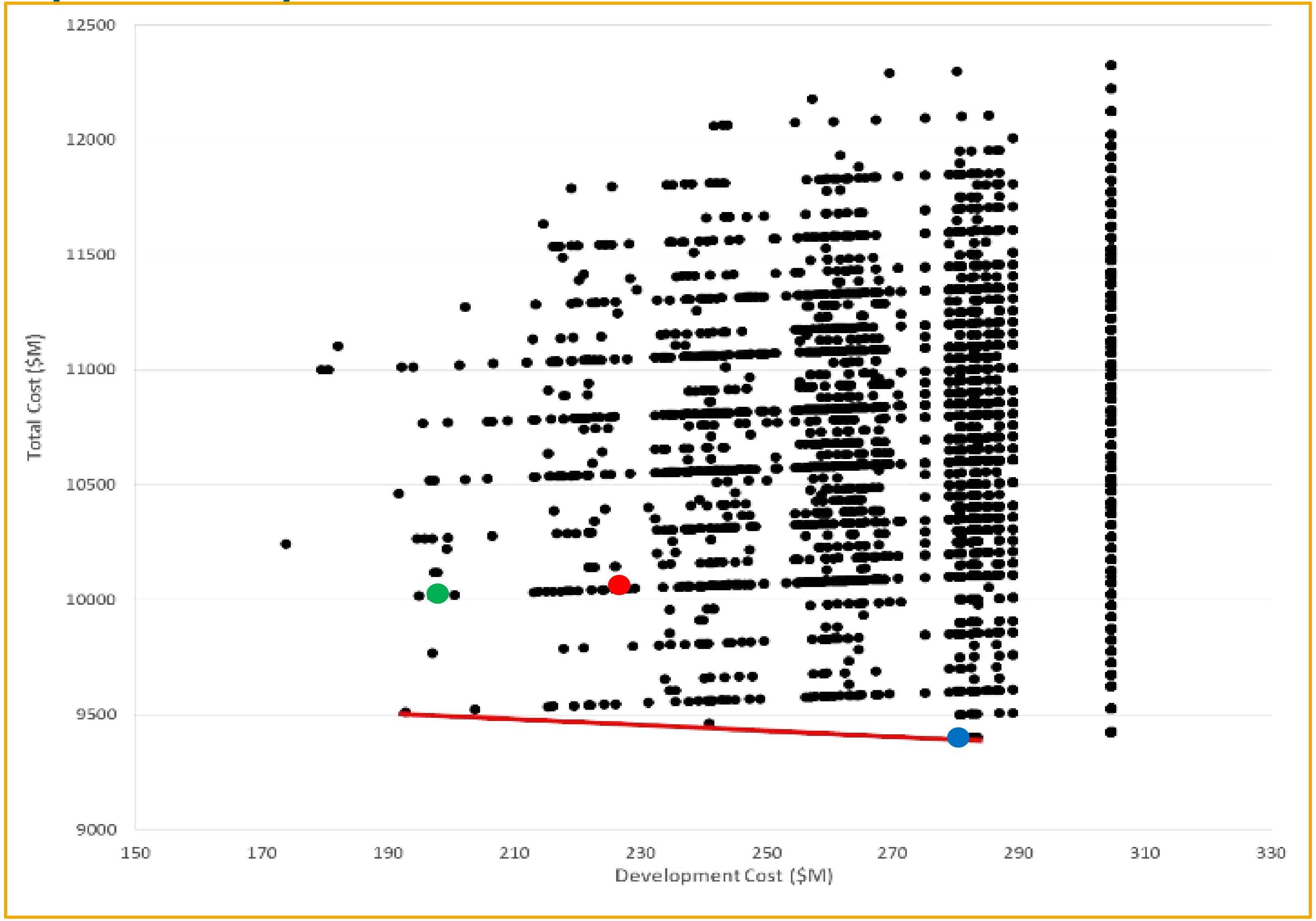
- A major segment of the simulation flow is the mass buildup from useful landed mass to total launch mass
- In order to validate the tool, a comparison was made to existing Mars EDL mass buildups
- The largest sample set for mass data is the total entry mass of the past five Mars probes
- Excluding the small MPF mission, an error of +16/-13% is seen
- Most relevant mission cases of MSL and DRA 5 habitat show an error of +2.4%

Mission	Landed Mass (MT)	Entry Mass (MT)	Modeled Entry Mass (MT)	% Difference	Assumed k-factors
Viking (1&2) [25]	0.244	0.992	1.016	2.4%	-
Mars Pathfinder [25]	0.092	0.584	0.383	-34.4%	-
MER (A&B) [25]	0.173	0.827	0.720	-12.9%	-
Phoenix [25]	0.167	0.600	0.695	15.8%	-
MSL Curiosity [25]	0.900	3.700	3.746	1.2%	-
DRA 5 Habitat [10]	40.400	109.7	109.8	2.4%	$k_{entrymass}$ = -0.08 $k_{landmass}$ = -0.27

$$k_{eff} = k_{eff-1} * (1 + k_{selected})$$

$$m_{cruise} = k_{cruisemass} * (1.1) * m_{entry} e^{\left(\frac{\Delta V * m_{entry}}{g_{earth} ISP}\right)}$$

Backup: Development Cost Vs. Total Cost



Scatterplot showing total technology development cost versus total architecture mission cost.