An Analysis of Low Earth Orbit Launch Capabilities

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- Objectives and scope
- Technical approach
- Model / Architecture
- Results
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Private Sector

- Billionaire Investors:
    - Jeff Bezos (Blue Origin)
    - Paul Allen (Stratolaunch Systems)
    - Sir Richard Branson (Virgin Galactic)
    - Elon Musk (SpaceX)
    - Larry Page and Eric Schmidt (Planetary Resources Inc.)
- **Total Net Worth: ~$64 Billion**

"Planetary Resources' high-profile investors are in good company, for private spaceflight ventures have attracted the attention of some of the world's richest people in the last decade or so. And some of these folks aren't just money men, advisers or paying customers they're running the show" -Mike Wall (Apr 25, 2012)

Source: http://www.space.com/15419-asteroid-mining-billionaires-private-spaceflight.html

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Political Climate

Presidential Policy:

- In 2010 President Obama set goal of asteroid exploration in 2025
- Transient goals reflect shortcomings of space exploration based solely on government agendas
- Shuttle Program Cancelled

Government Agencies with a focus on long-term interstellar travel:

- Defense Advanced Research Projects Agency (DARPA) 100 Year Starship Program

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Technical Advances

International Space Station (ISS) Baseline:

- Costs of the ISS were astronomical due to phased construction, a more holistic approach will provide significant savings in construction costs
- Lessons learned from the ISS can help in construction of this base and future permanent LEO habitations
- Better technologies, specifically launch capabilities will result in cheaper launch costs

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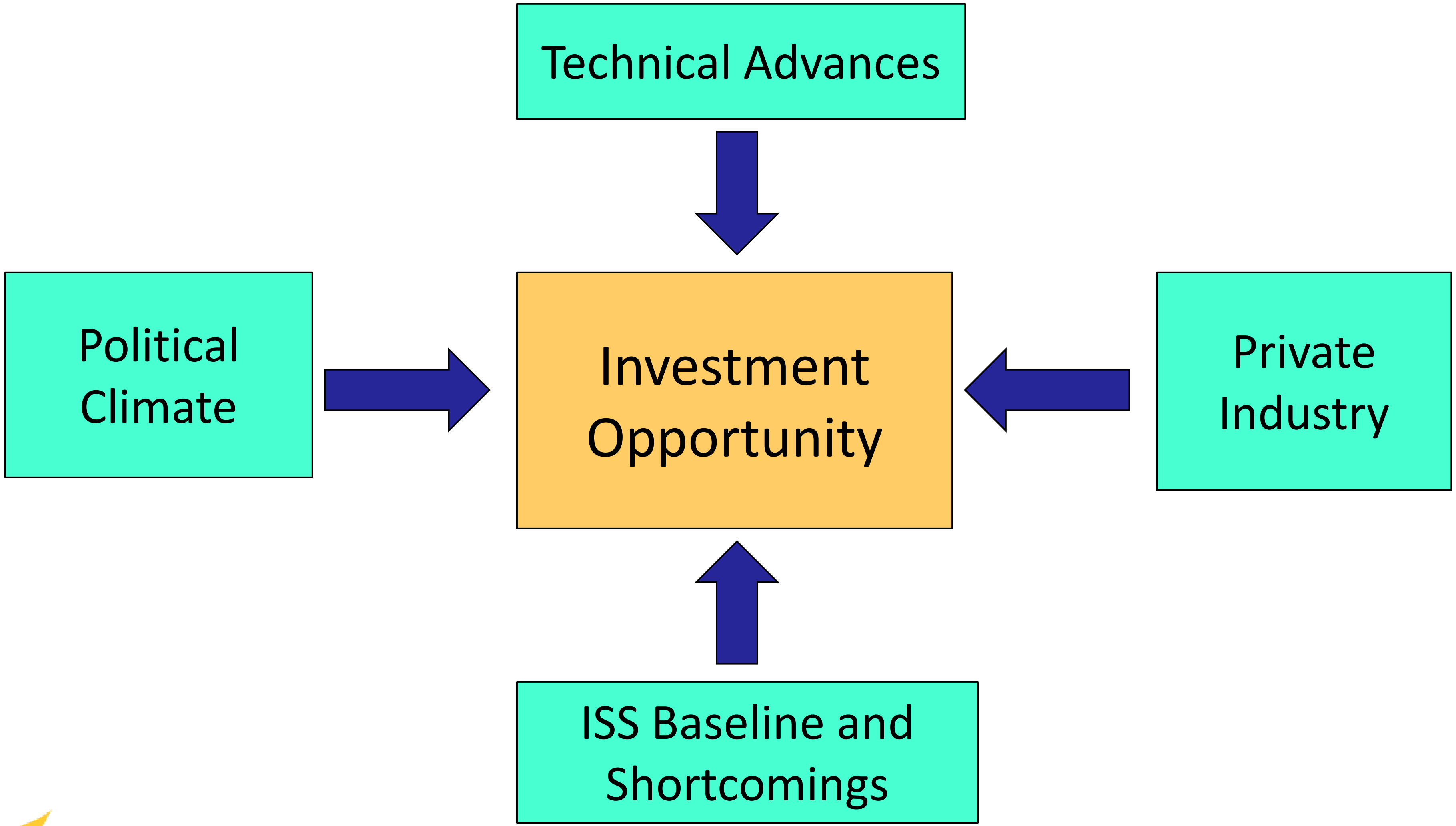
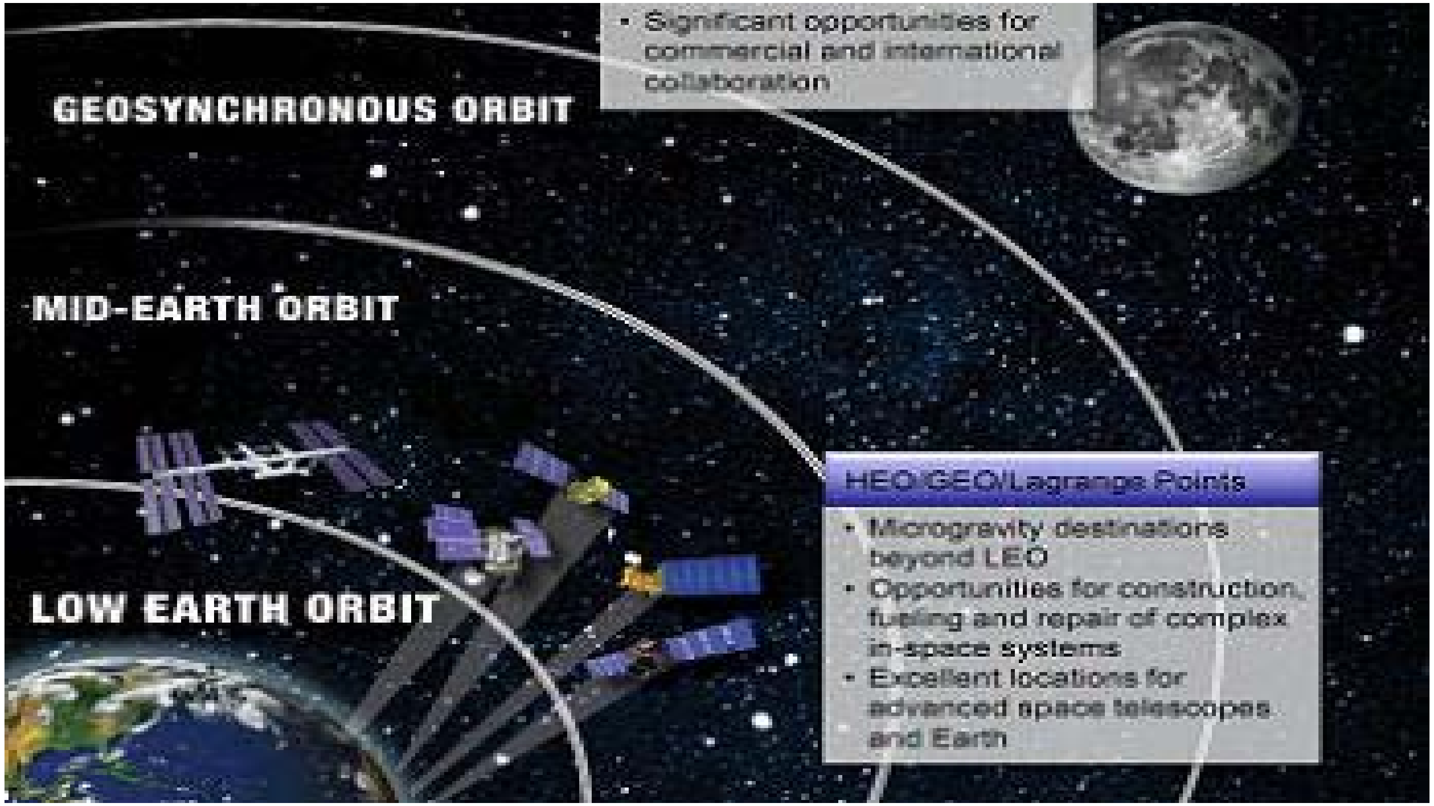
An Opportunity



Low Earth Orbit

Low Earth orbit is defined as the distance between 180km and 2,000km above the earths surface.



Stakeholders

U.S. Government:

-FAA
-NASA
-DARPA (and other R&D Facilities)

Private Sector:

-Potential Investors
-Companies involved in launch capabilities (i.e. SpaceX)
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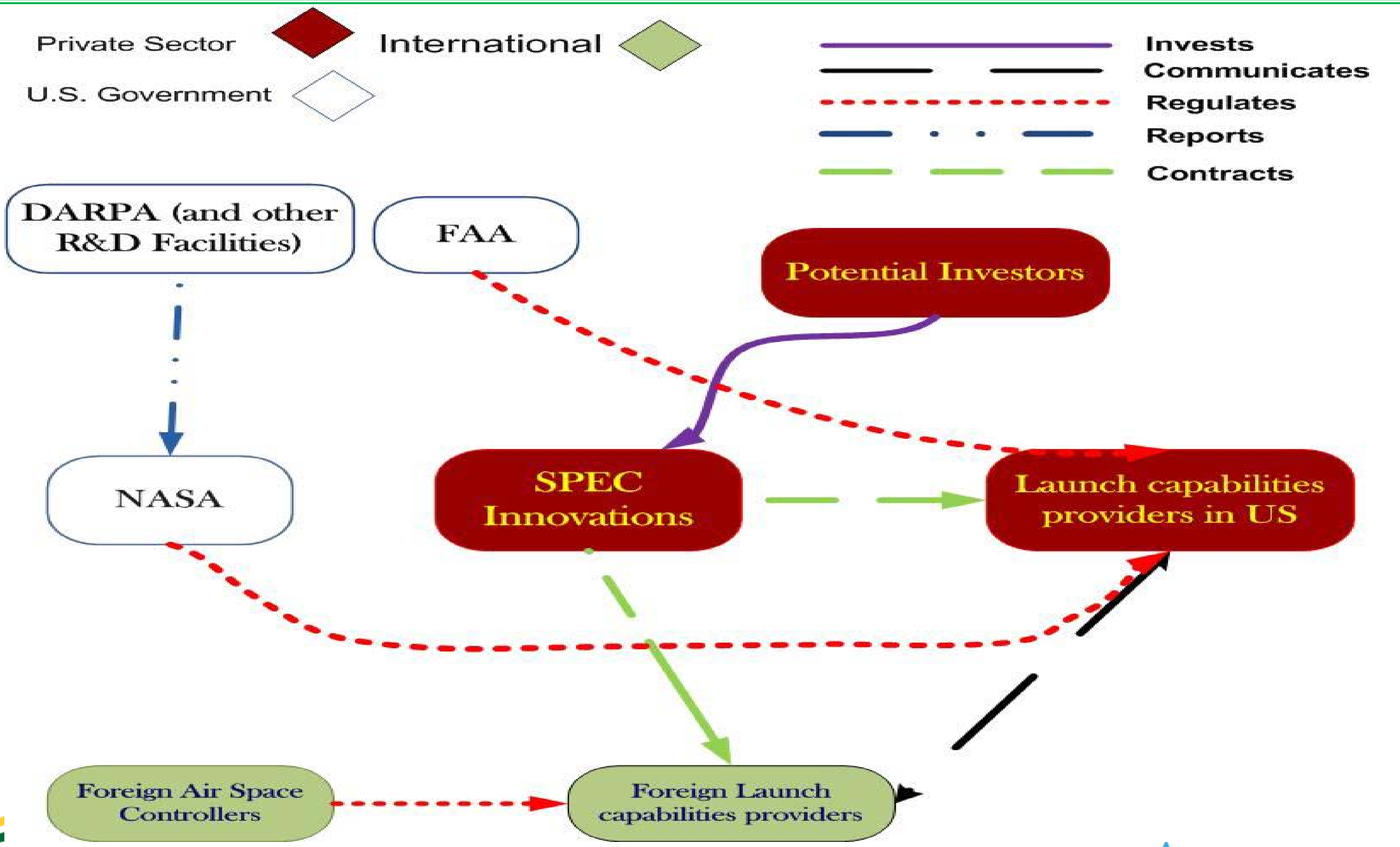
Foreign Governments:

-Foreign Air Space Controllers
-Foreign Government Launch Agencies

Notional Stakeholder Interactions



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Scope

- Constraints on NASA's Technology Readiness Levels (TRLs) and rocket diameter will eliminate many launch capabilities
- Feasibility determined by NASA’s Technology Readiness Levels.
- Environmental/docking constraints in LEO are not considered
- Avoided complex cost analysis. Assumed capability providers estimates to be accurate

Problem Statement

- Investigate lower cost, higher performance Launch Capabilities for transporting mass into low earth orbit given the following constraints:
  - Within the next ten years
  - Lift 1000 metric tons into orbit
  - At least 200 km above the earth's surface
  - During a period no longer than 2.5 years
  - Minimize cost/pound
  - With no more than 30 launches.

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Assumptions

- Turnaround times are meant to represent an average between all chosen launch methods

- Limitations on number of launches based upon turnaround time (900 days / turnaround time [days])

- Astronauts will work in groups of 6.
    - They are to be replaced every 6 months.
    - Each manned launch has a capacity of 3 passengers
    - Minimum of 10 launches to have 6 astronauts continuously working

Technical Approach

Perform analysis of current and predicted capabilities to determine which best meet(s) cost / performance / feasibility needs for building a permanent commercial space structure in LEO.

- Use available launch capabilities in order to create models demonstrating cost minimization according to various turnaround times
- Include trip minimization models where cost is excluded
- Perform “What-if” scenarios relevant to optimization
- Analyze optimal launch capabilities to provide a cost range at which they remain optimal
- Provide recommendations based on comparisons

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Methodology

- Use NASA’s Technology Readiness Levels (TRLs) in order to identify launch methods that are feasible to analyze (within 5-10 year timeframe)

- Compare costs, number of launches, timeframe adherence, overall capabilities of competing technologies

- Provide a detailed analysis of chosen launch capability(s)

Phase	TRL	Maturity Level
System test, launch, and operations	9	System verified by successful mission
	8	System flight-qualified through test
Technology demonstration	7	System prototype demonstrated in space environment
System/subsystem development	6	System demonstrated in relevant environment (ground or space)
Technology development	5	Component and/or breadboard validation in a relevant environment
	4	Components validated in laboratory
Feasibility verification	3	Analytical and experimental critical function, characteristic proof-of-concept
	2	Technology concept and application formulated
Basic technology research	1	Basic principles observed and reported

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Launch Capabilities

Capability	Cost per launch ($ ' million)	Mass to LEO(' 000 kg)	Company	TRL	Type
Falcon Heavy	**128**	**53**	**Space X**	**7**	**Mixed**
Ariane 5ECB	**165**	**21**	**EADS Astrium**	**8**	**Cargo**
Chinese Long March5	110	25	CALT	7	Cargo
Chinese Long March3B	105	21.6	CALT	9	Cargo
Proton launch Vehicle	**95**	**44.2**	**Krunichev**	**9**	**Cargo**
Space Launch System SLS	**270**	**70**	**Allianttech system/ Boeing**	**7**	**Cargo**
Delta IV heavy	**271**	**25.8**	**United Launch Alliance**	**9**	**Cargo**
H-IIB Launch Vehicle	**165**	**19**	**Mitsubishi Heavy Industry**	**9**	**Cargo**
Ariane 5ECA	**165**	**21**	**EADS Astrium**	**9**	**Cargo**
Ariane 5ES	**165**	**21**	**EADS Astrium**	**9**	**Cargo**
Antares	45	5	Orbital Sciences	7	Cargo
PSLV-HP	17.5	3.7	ISRO	9	Cargo
GSLV- MkIII	54	10	ISRO	7	Cargo
Atlas V 541	180	15.3	United Launch Alliance	8	Cargo
Atlas V 531	170	17.1	United Launch Alliance	8	Cargo
Zenit-2M	61	13.9	Yuzhnoye Design Bureau	9	Mixed
PSLV-XL	36	3.8	ISRO	9	Cargo
Chinese Long March 4C	35	4.2	CALT	9	Cargo
Chinese Long March 4B	42	4.2	CALT	9	Cargo
Soyuz-U	48	6.7	TsSKB-Progress	9	Mixed
Dnepr-1	13	4.5	Yuzhnoye Design Bureau	9	Cargo
soyuz-2	40	7.8	TsSKB-Progress	9	Cargo
Soyuz- FG	45	7.1	TsSKB-Progress	9	Mixed

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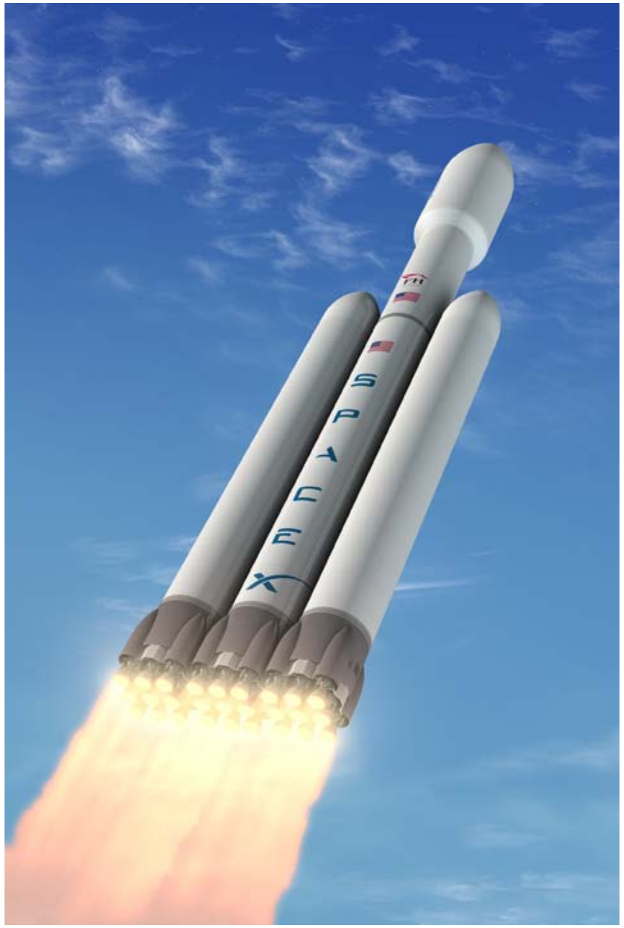
Heavy Lift Launch Systems

(1 of 2)



Falcon Heavy

Space Launch System

Proton

Heavy Lift Launch Systems

(2 of 2)

Soyuz

Zenit

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Variables in Model

- Diameter of Rocket (5m)
- Launch Cost (<$10 Billion)
- Number of Launches (20-30)
- TRL Level (>7)

Model Formulation

$$\min \sum_{i}^{j} C_i X_i + \sum_{k}^{l} C_k Y_k$$

such that:

$$\sum_{i}^{j} S_i X_i, \sum_{k}^{l} S_k Y_k \leq t \ \ (\text{time constraint})$$

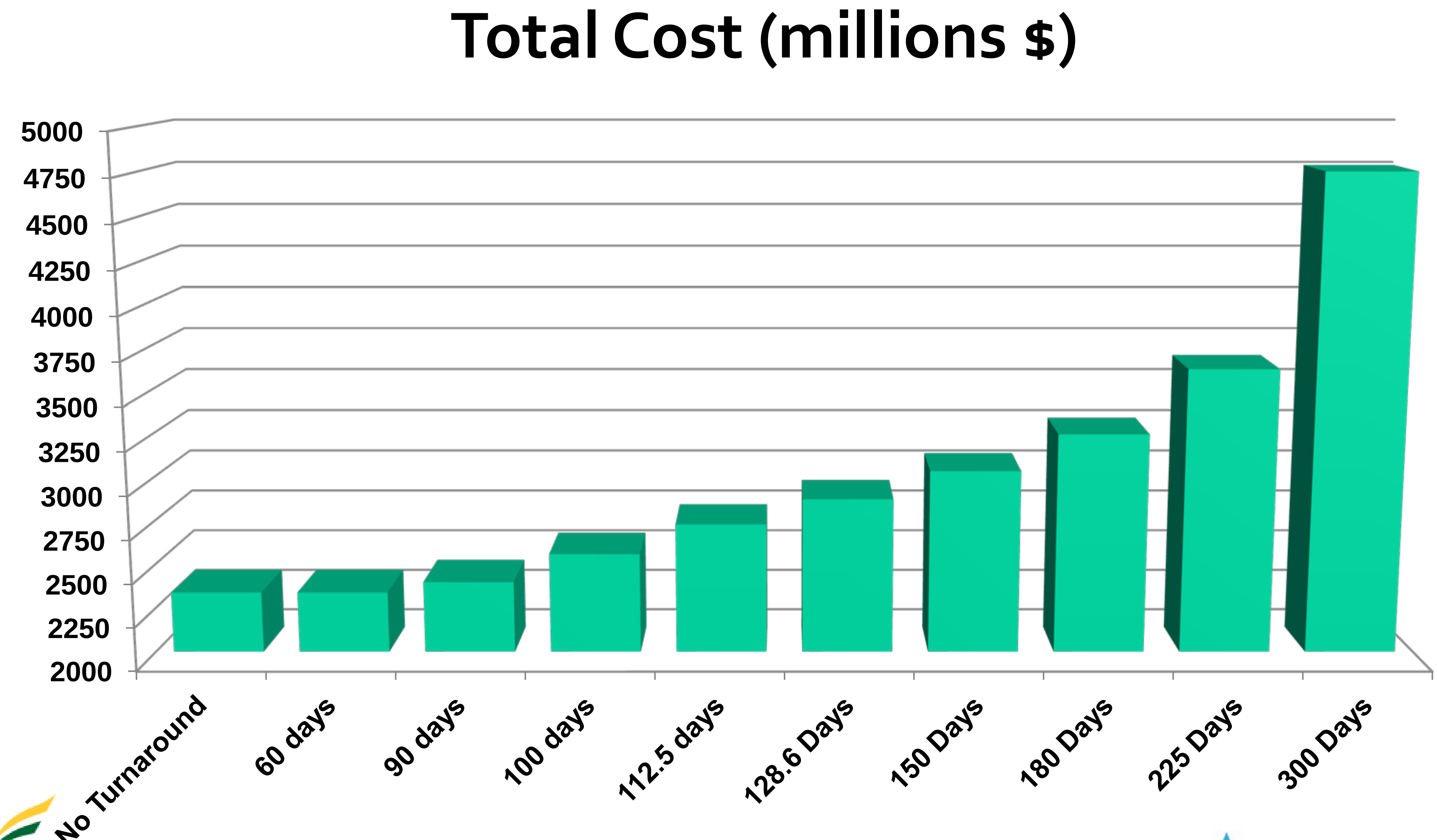
$$\sum_{i}^{j} W_i Y_i + \sum_{k}^{l} W_k Y_k \geq 1000 \ (\text{weight constraint})$$

$$\sum_{k}^{l} Y_k \ \geq 10 \ (\text{personnel constraint})$$

$$X_i, Y_k \in \mathbb{Z}$$

X_i = cargo launch of type i
Y_k = mixed launch of type k
C_i = cost per launch of type i
C_k = cost per launch of type k
S_i = Setup time per launch of type i
S_k = Setup time per launch of type k
W_i = Mass transported per launch of type i
W_k = Mass transported per launch of type k
t = turnaround time between launches

Turnaround Time Results



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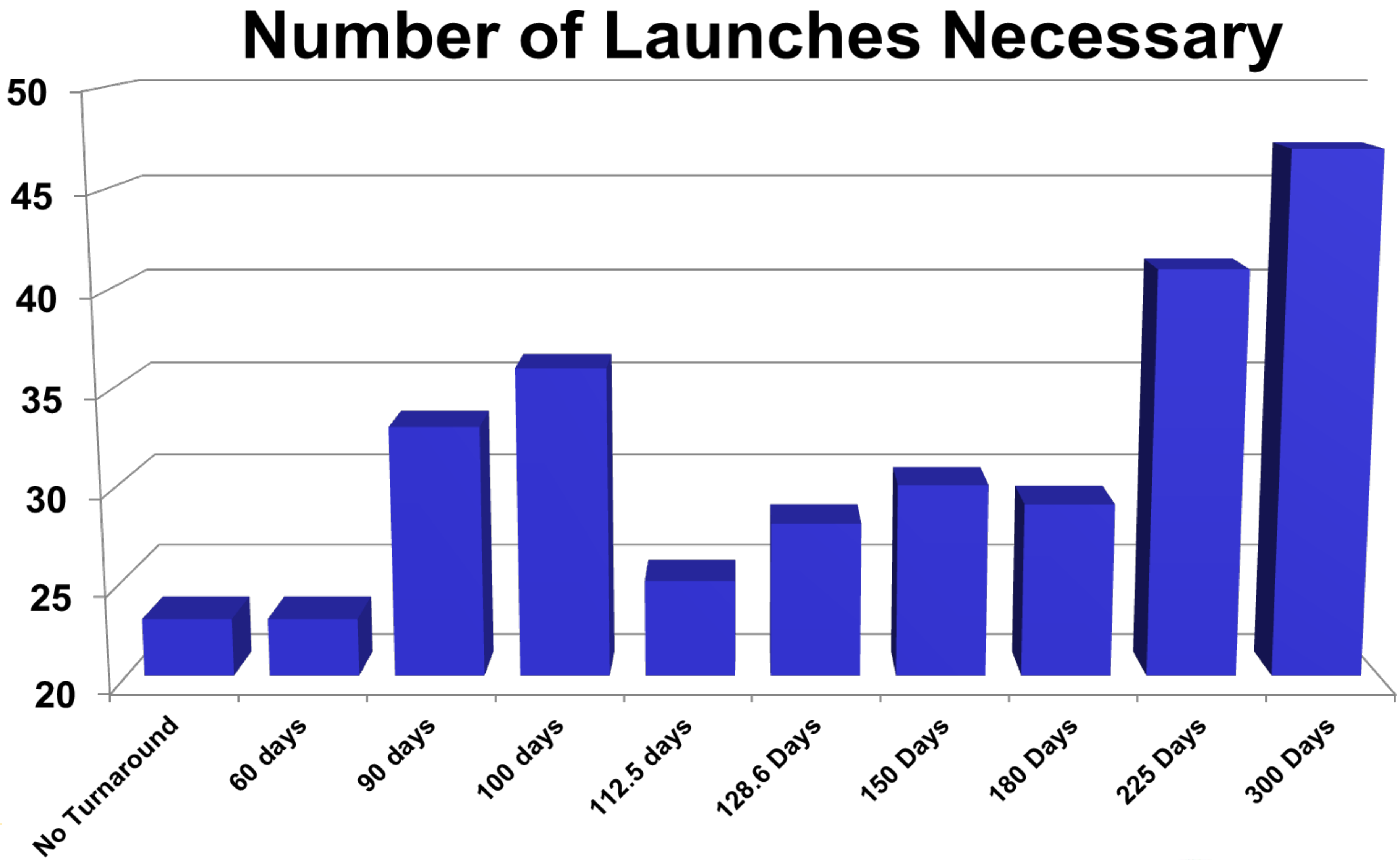
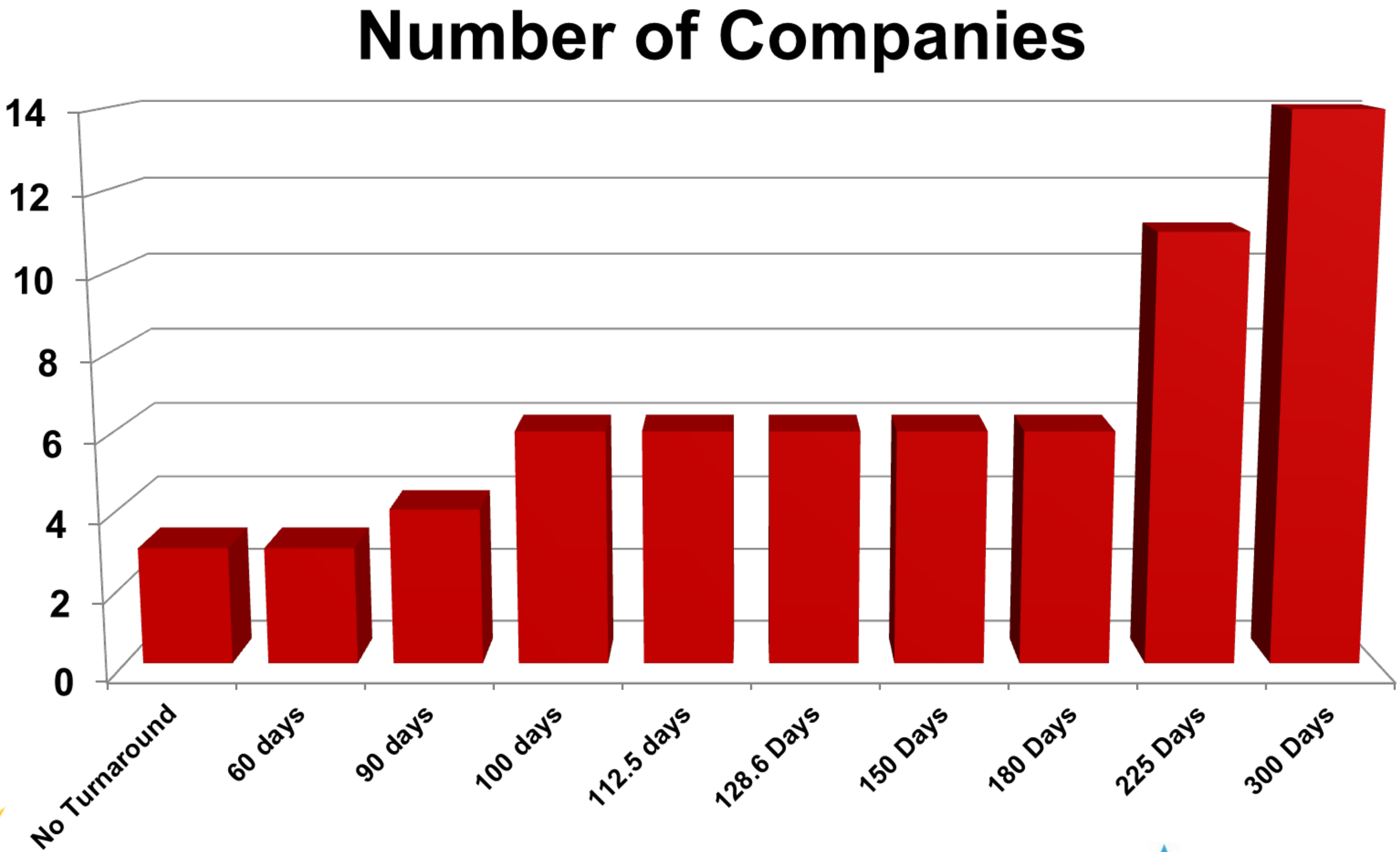
Turnaround Time Results



Turnaround Time Results



Optimal Solutions

	Capability	Cost per launch	Mass to LEO	Company	TRL	Type	diameter (m)	# Trips	Total # of Trips
Unbiased Results	Falcon Heavy	128,000,000	53,000	Space X	7	Mixed	5.2	10	23
	Proton Launch Vehicle	95,000,000	44,200	Krunichev	9	Cargo	7.4	11	
	Dnepr-1	13,000,000	4,500	Yuzhnoye Design Bureau	9	Cargo	3	2	
							Total Cost		$2,351,000,000

	Capability	Cost per launch	Mass to LEO	Company	TRL	Type	diameter (m)	# Trips	Total # of Trips
Spec-cific Results	Falcon Heavy	128,000,000	53,000	Space X	7	Mixed	5.2	8	23
	Proton Launch Vehicle	95,000,000	44,200	Krunichev	9	Cargo	7.4	13	
	Zenit-2M	61,000,000	13,900	Yuzhnoye Design Bureau	9	Mixed	3.9	2	
							Total Cost		$2,381,000,000

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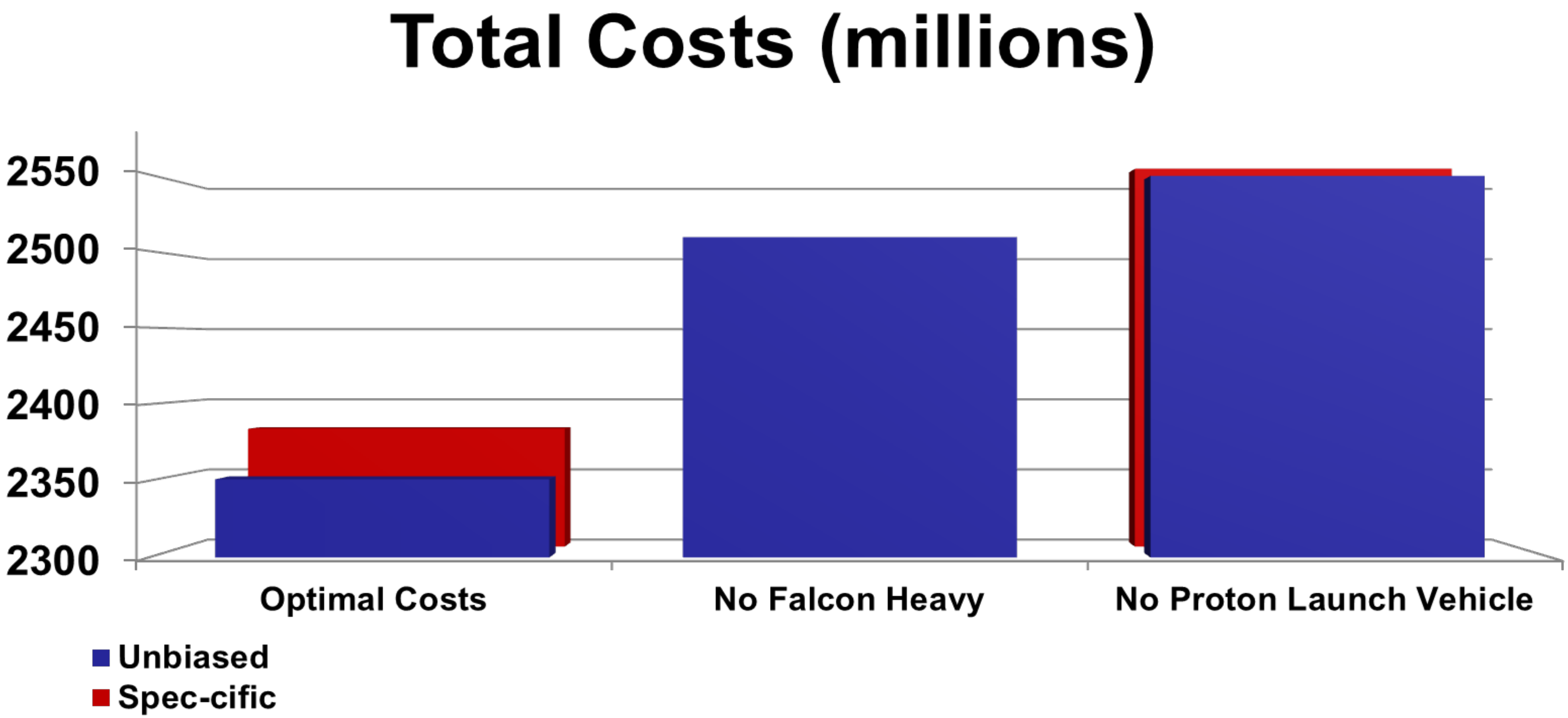
Unbiased vs. Spec-cific



	Optimal Costs	No Falcon Heavy	No Proton Launch Vehicle
Unbiased	2351	2509	2549
Spec-cific	2381	2509	2560

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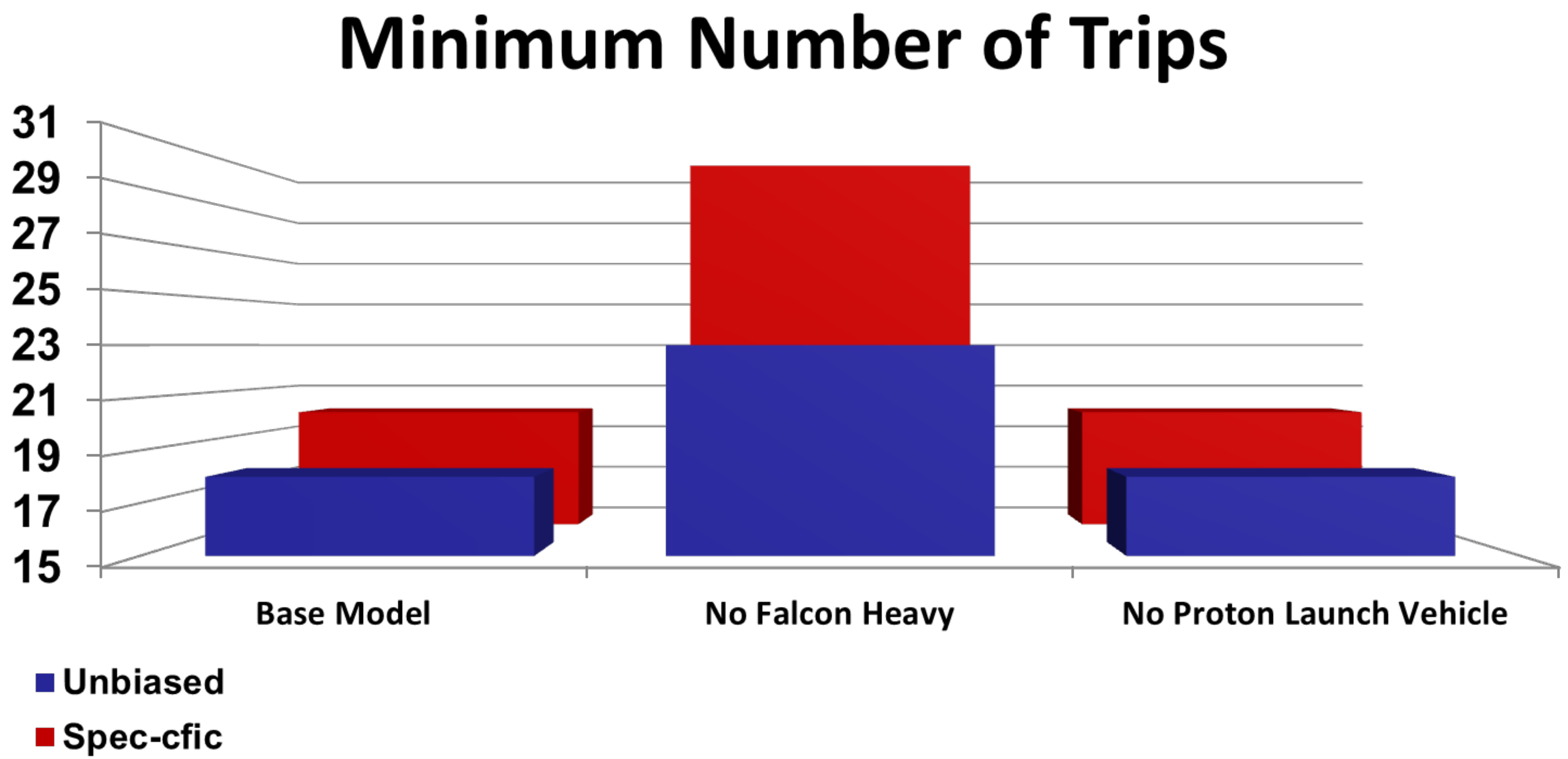
Unbiased vs. Spec-cific



	Base Model	No Falcon Heavy	No Proton Launch Vehicle
Unbiased	18	23	18
Spec-cfic	20	31	20

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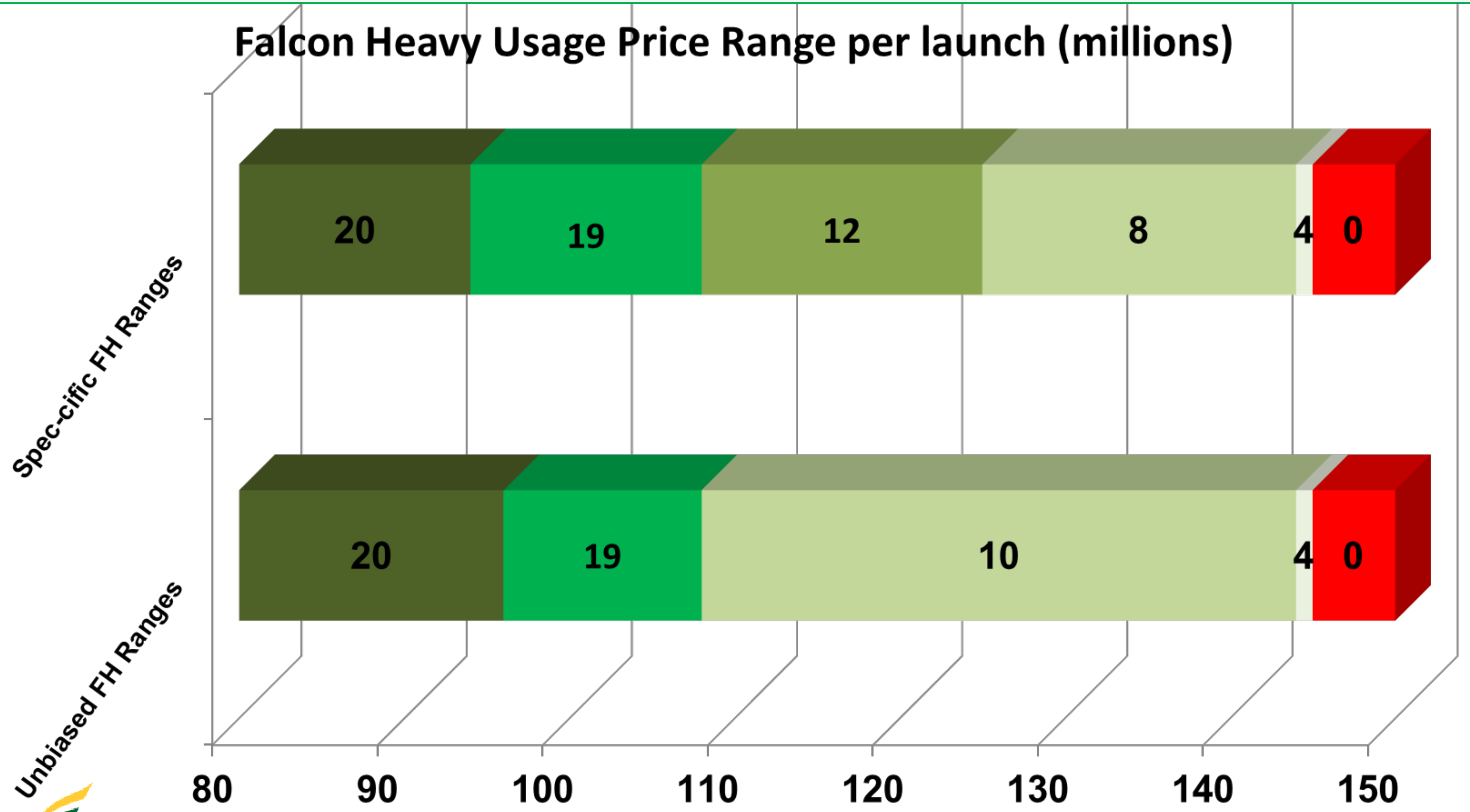
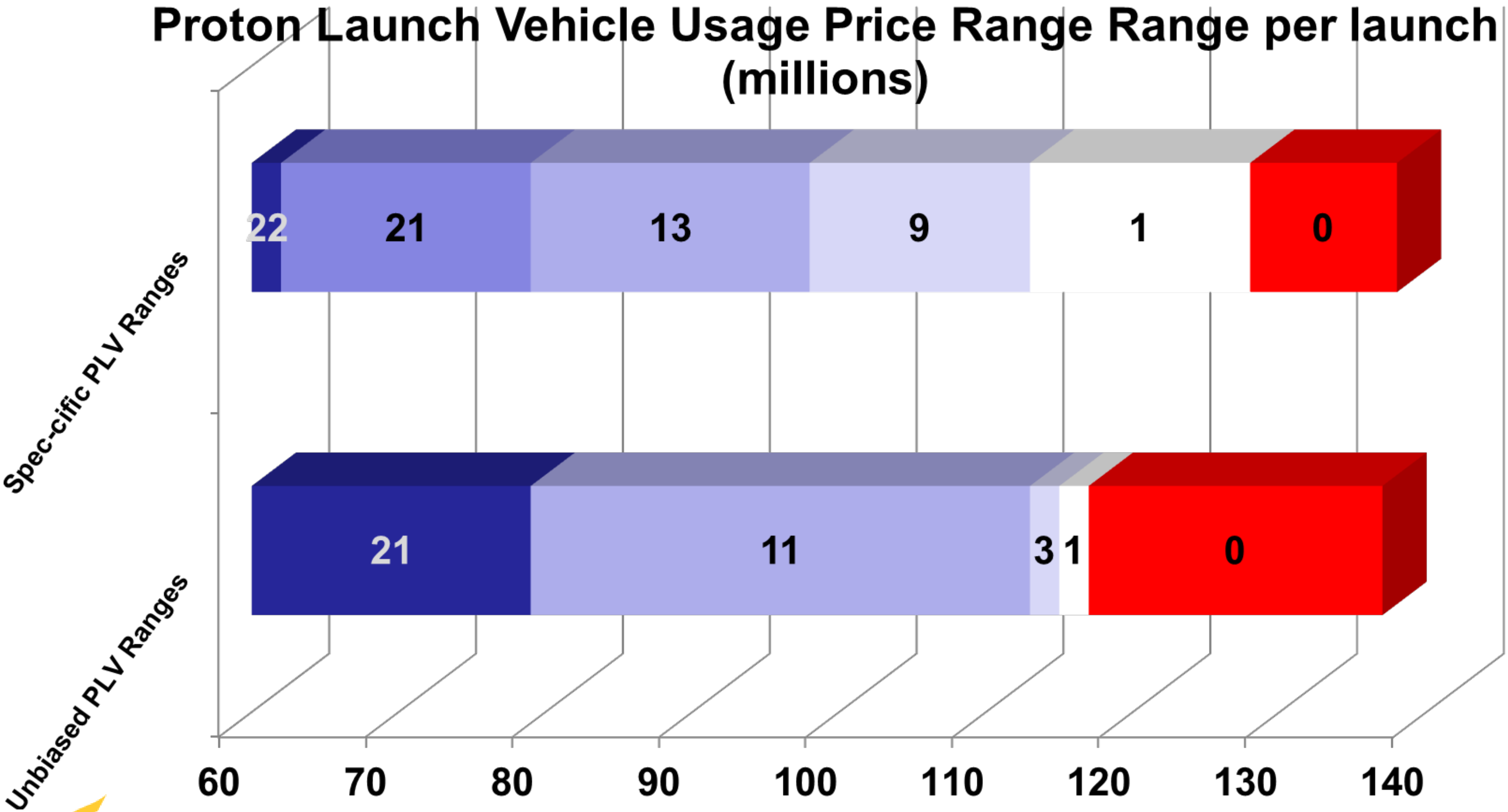
Unbiased vs. Spec-cific



Unbiased vs. Spec-cific



Recommendations

- SPEC Innovations should invest in a closer examination of the Proton Launch Vehicle and the Falcon Heavy. Without these capabilities, cost and number of trips required will increase dramatically

- If the Falcon Heavy is ready in the timeframe desired for construction of the space station to begin, it can be recommended as the primary source of transport.

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Future Work

- Due to the inaccuracy of estimation in these types of problems it is recommended that the model revisit the cost and capabilities of immature technologies when more solid attributes are known

- A re-examination of the problem as a scheduling model would provide insight into effect different launch capabilities would have on the phases of platform construction

- Finally a thorough cost analysis for the entire IAA initiative, including the launch costs would give insight into the risks involved with this type of large scale space project

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Sponsor Value Added

"This is a powerful tool for commercial space"

- Dr. Steven Dam

"This work provides a solid basis for pursuing the development of a commercial space structure"

- Dr. Keith Taggart

Acknowledgements

We would like to thank our sponsors Dr. Keith Taggart and Dr. Steven Dam of SPEC Innovations as well as our Project Advisor Prof. Dr. Kathryn Laskey.

Sources

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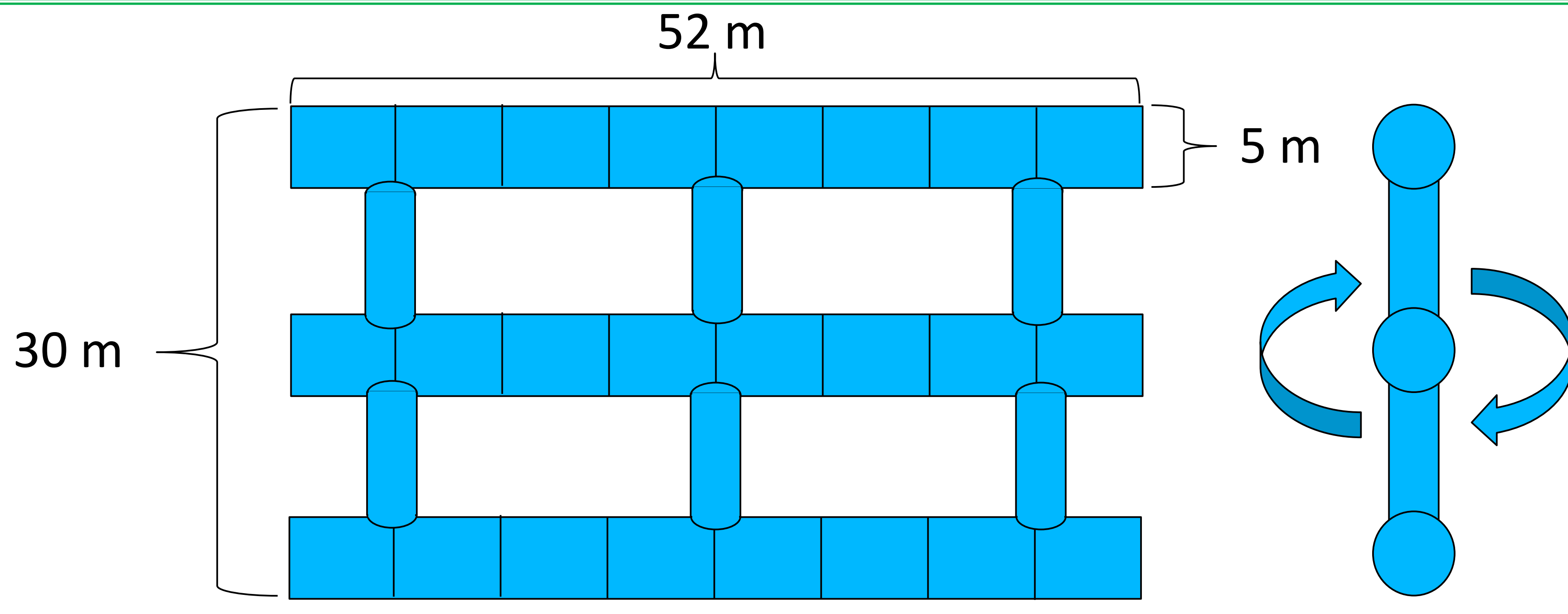
Questions?

Backup

Space Station Concept



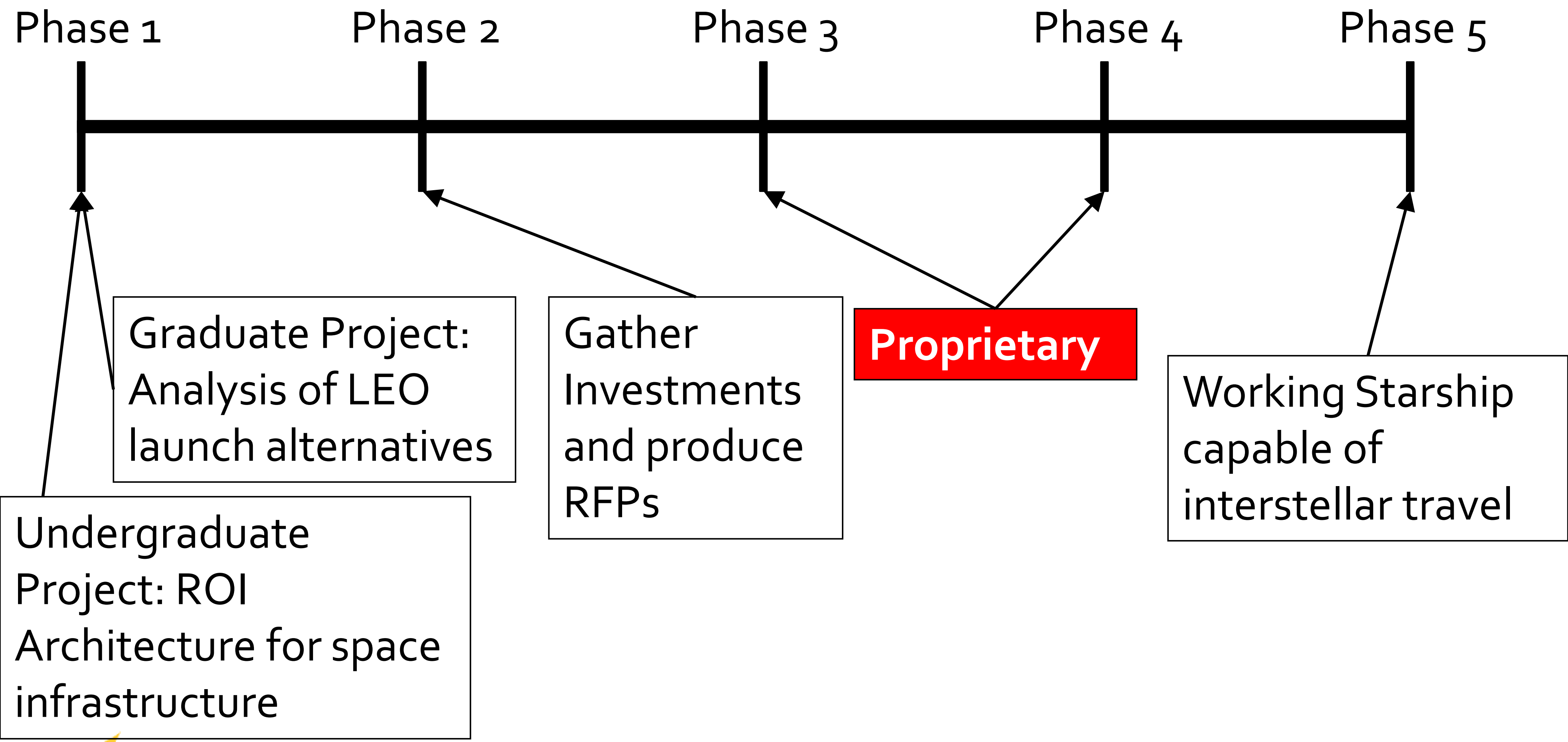
Volume = 3100 m^3

Side View

Top View

- Drawn to scale
- Genesis of 5m constraint
- 15 m radius at 3 rpm gives .15g at outer edge
- 30 m radius at 3 rpm gives .30g at outer edge

IAA Timeline



International Space Station (ISS)

- Abbreviated timeline
  - Construction begins Nov 1998
  - First full-time inhabitants arrive Nov 2000
- Key differences
  - Construction is ongoing
  - Over 100 space flights on 5 different types of vehicles

- Total Cost: $150 billion
  - 40 shuttle flights at $1.4 billion each
  - $72 billion ISS budget
  - Europe: $5 billion
  - Japan: $5 billion
  - Canada: $2 billion

Assuming 20,000 person-days from 2000-2015
Each person-day costs $7.5 million

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Swing Weight Analysis

Ranking	3	2	4	1
	Option 1	**Option 2**	**Option 3**	**Option 4**
# Launches	48	48	10	48
Cost Per Launch (Millions)	80	254	254	254
TRL	7	10	7	7
Company	Nasa	Nasa	Nasa	SpaceX

Factors	# of Launches	Cost per Launch	TRL	Company
Weights	0.1	0.2	0.3	0.4

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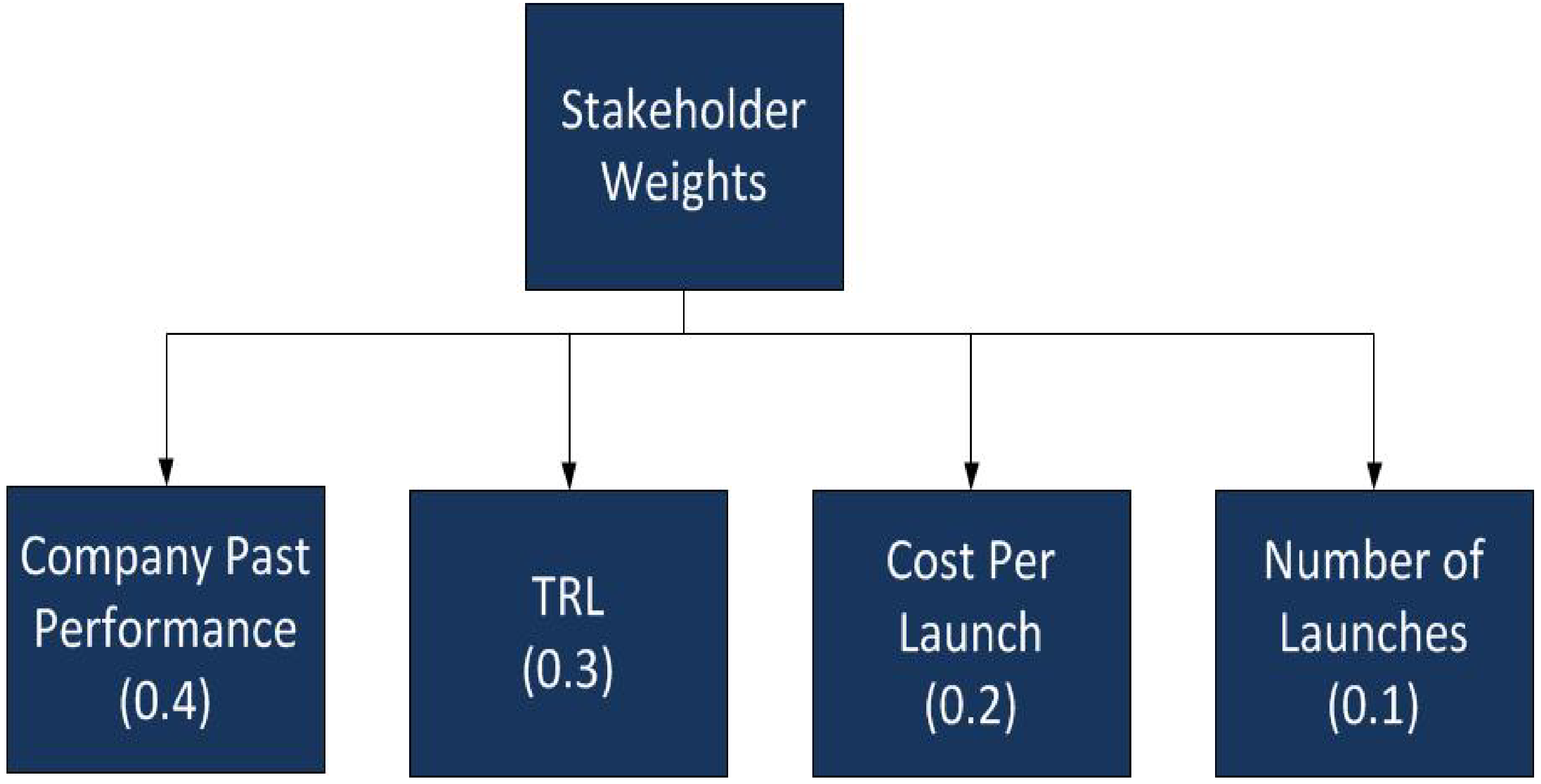
Weights



Stakeholder Weights
Company Past Performance (0.4)
TRL (0.3)
Cost Per Launch (0.2)
Number of Launches (0.1)

Company Weights

Company	Rating	Sponsor Comments
Space X:	0.9	
EADS Astrium	0.6	
Krunichev	0.8	These guys are Proton. I would rate them at 0.9 for heavy lift.
Allianttech system/ Boeing	0.2	
Boeing	0.4	
NASA	0.0	
United Launch Alliance	0.4	
Mitsubishi Heavy Industry	0.5	These guys do the H-II and the HTV supply pod to the ISS
Orbital Sciences	0.3	
ISRO	0.3	
Yuzhnoye Design Bureau	0.8	These guys are Sea Launch. I think that they are not a viable choice. I would rate them at 0.05
CALT	0.05	
TsSKB-Progress	0.8	These guys are Soyuz. Commercial marketing is handled by Starsem. I would rate them at 0.9 for human and resupply.