SYSTEMS ENGINEERING RESEARCH CENTER

SERC DOCTORAL STUDENT FORUM 2024 | NOVEMBER 13, 2024

Impact of Technical Measure Omission

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Introduction: Casey Eaton

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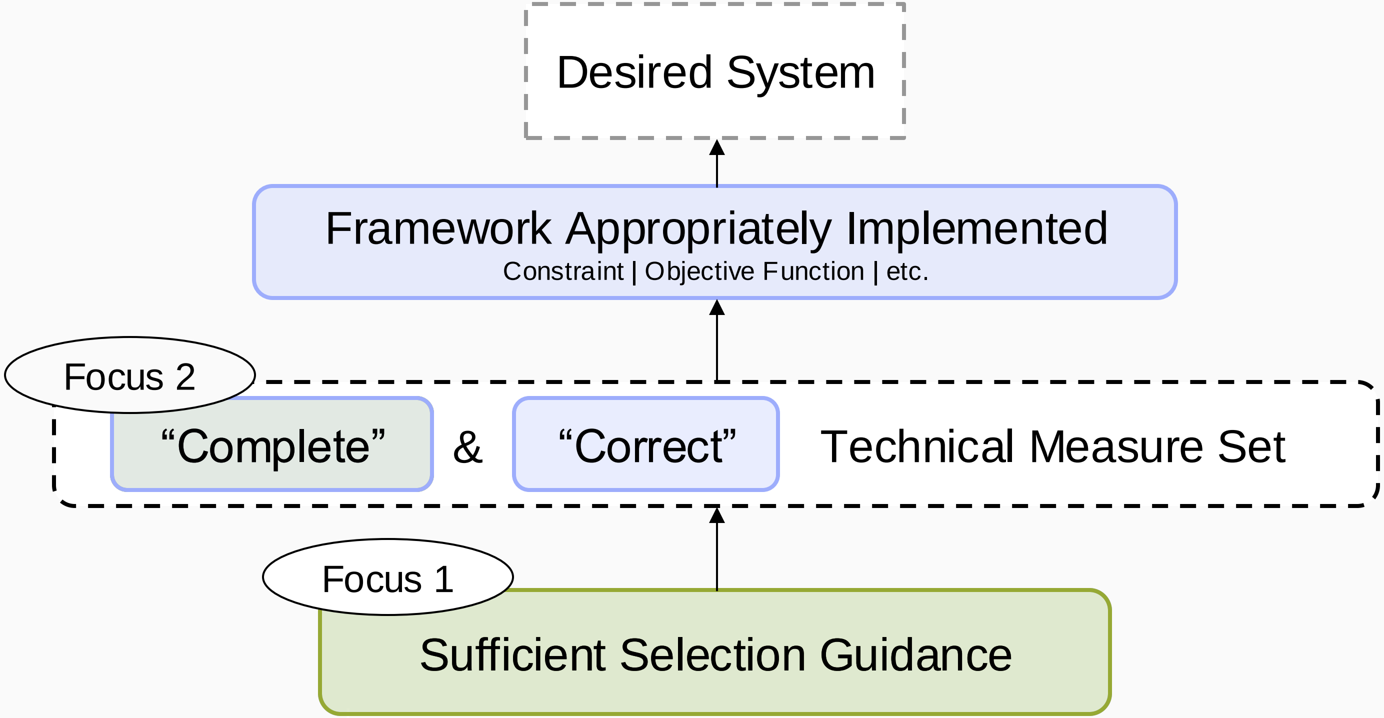
NASA Systems Engineering Consortium *(2020-2023)*

Technical Measures

A set of measures that assesses a system (e.g. mass, distance, cost) [1]

- Basis for decision making [2-6]
- Provide justification for decisions made
- Different types depending purpose & organizations (MOEs, TPMs, etc.) [1] [4] [7-8]

Idealized Use of Technical Measures



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SYSTEMS ENGINEERING RESEARCH CENTER

Focus 1

Selection of Technical Measures in Large-Scale Complex Engineered Systems Design

Casey Eaton[1], Bryan Mesmer[1], Susan Ferreira[2]

[1] The University of Alabama in Huntsville
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NASA Grant Number: NNM11AA01A 14.1
NASA Cooperative Agreement: 80NSSC20M0044

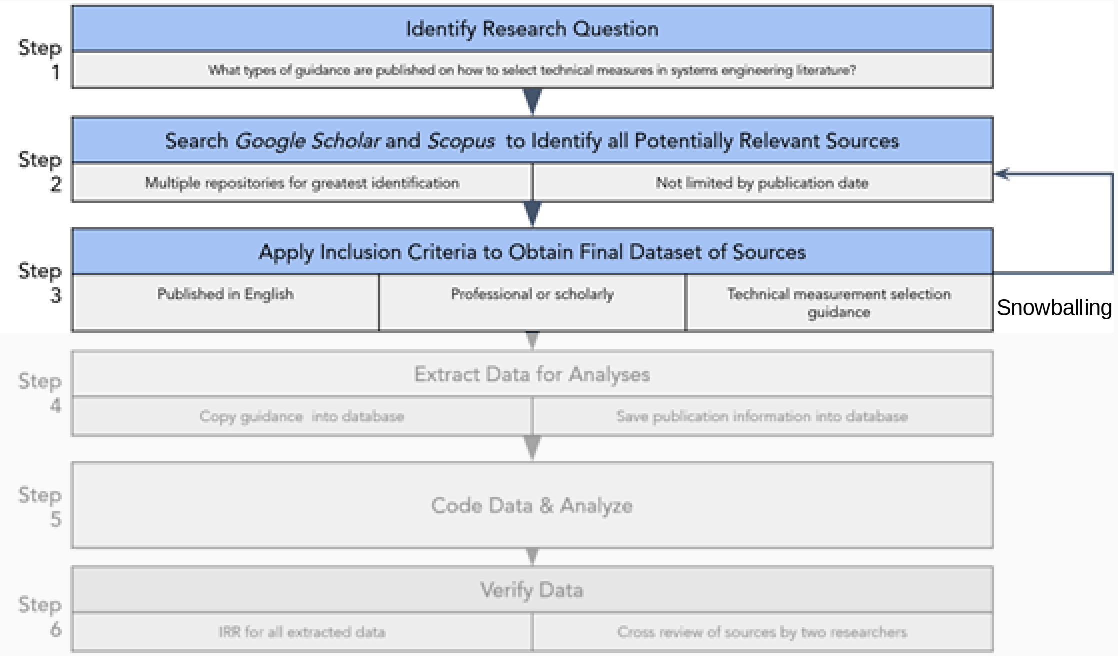
Research Gap: Sufficient guidance?

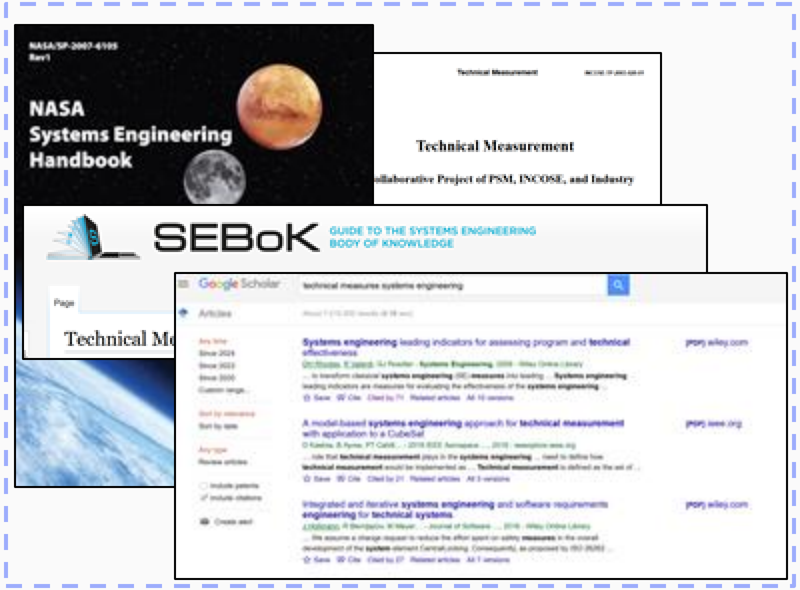
What we know about technical measures & selection guidance:

- Selected through heuristics and experience as acknowledged by [9-12]
- Varied guidance available for practitioners [13]
- No synthesis assessing current guidance [13]

RQ: Is selection guidance sufficient for practitioners to select a technical measure set that results in the desired system?

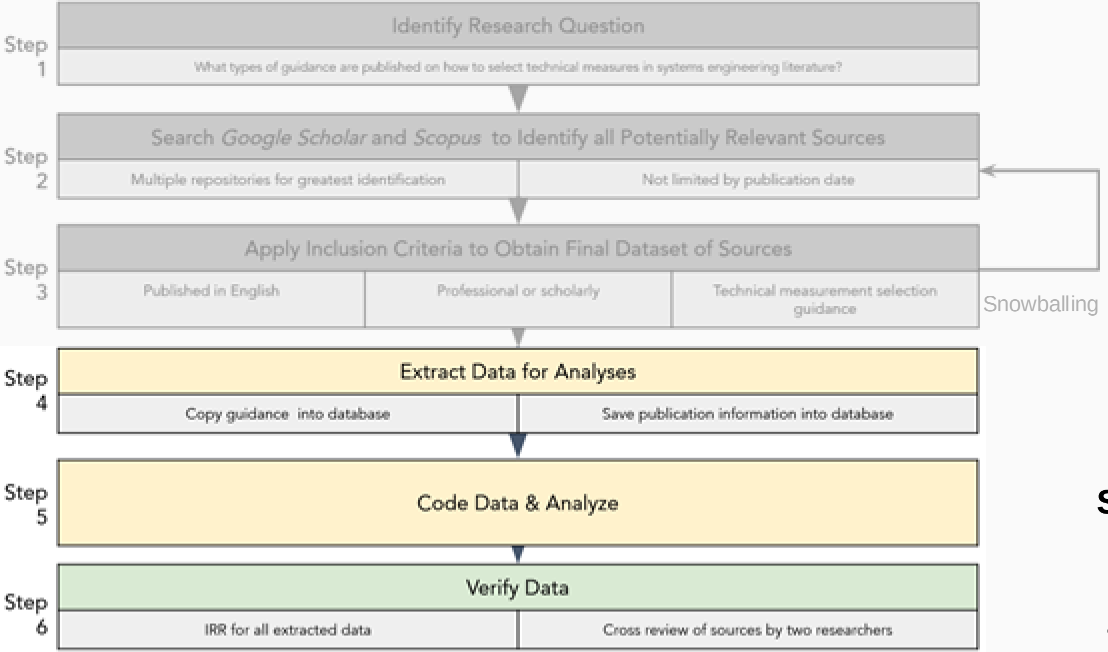
Research Methods: Systematic Literature Review [14]

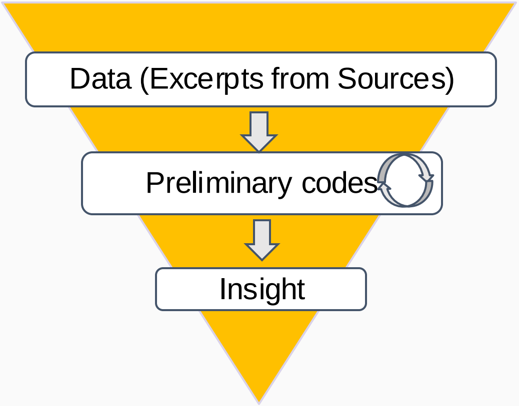




Organizational and Research Guidance

Research Methods: Inductive Content Analysis [15-16]





Step 5:

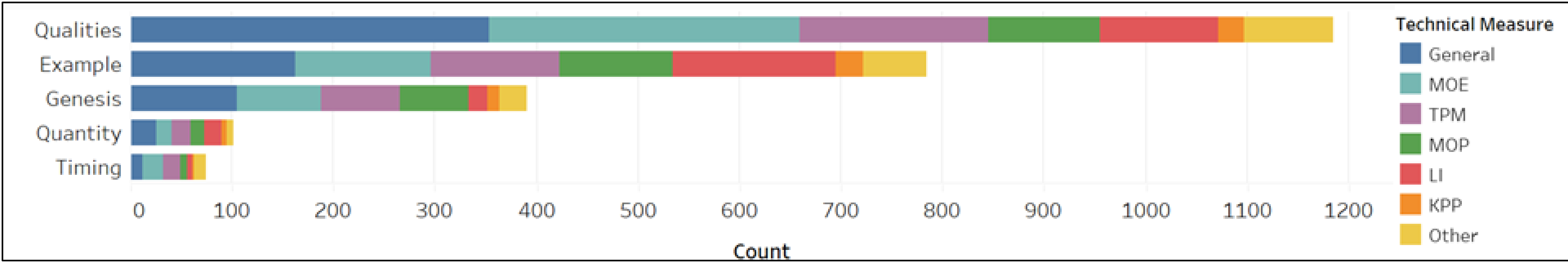
Guidance statement 1
(Timing)

"Technical measures should be **selected early** and **relevant to the system**."

Guidance statement 2
(Qualities)

Findings: Guidance Largely Consists of *Qualities* and *Examples*

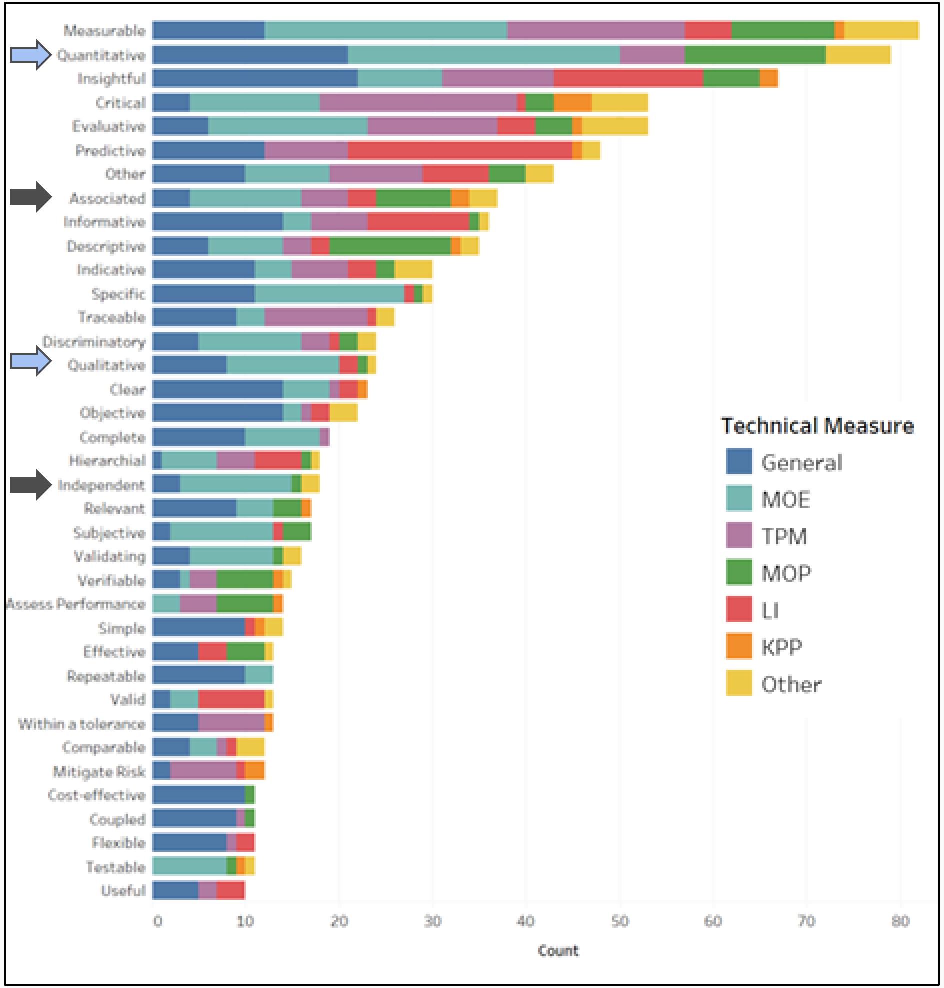
89 Sources; 2,535 Guidance Statements



Findings: *Qualities* guidance may be contradicting or non-restricting.

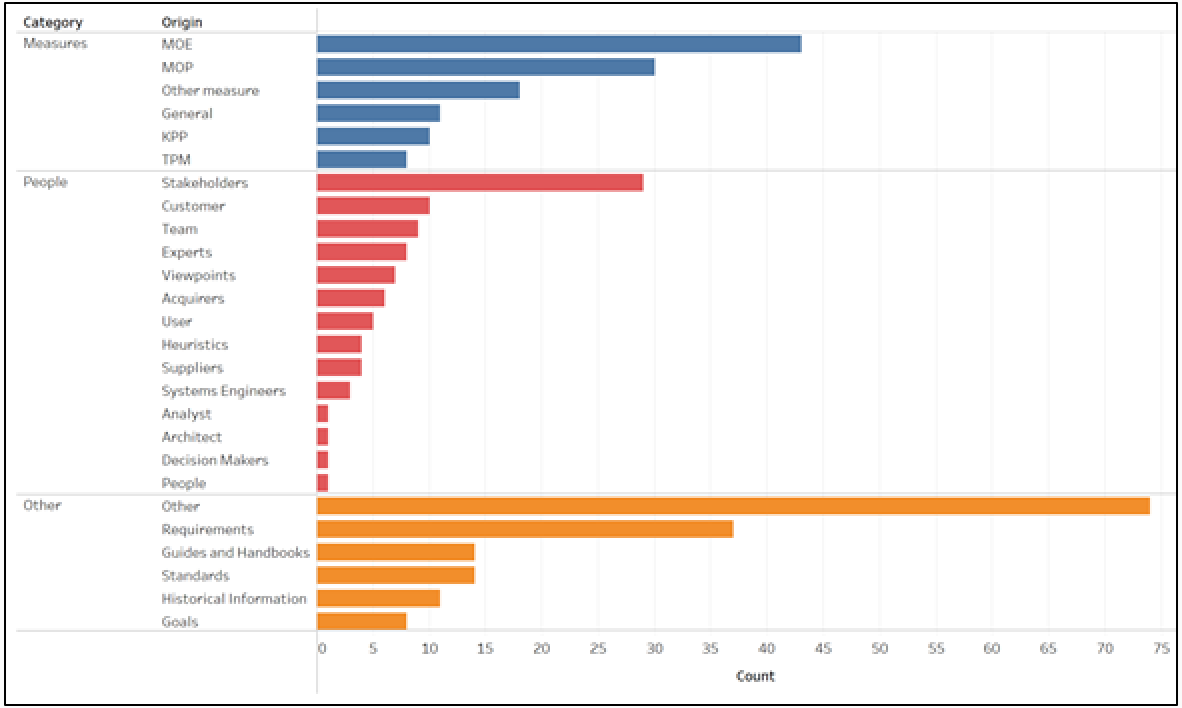
Explains <u>which</u> qualities but not <u>how</u> to achieve them.

Not specified when guidance applies.

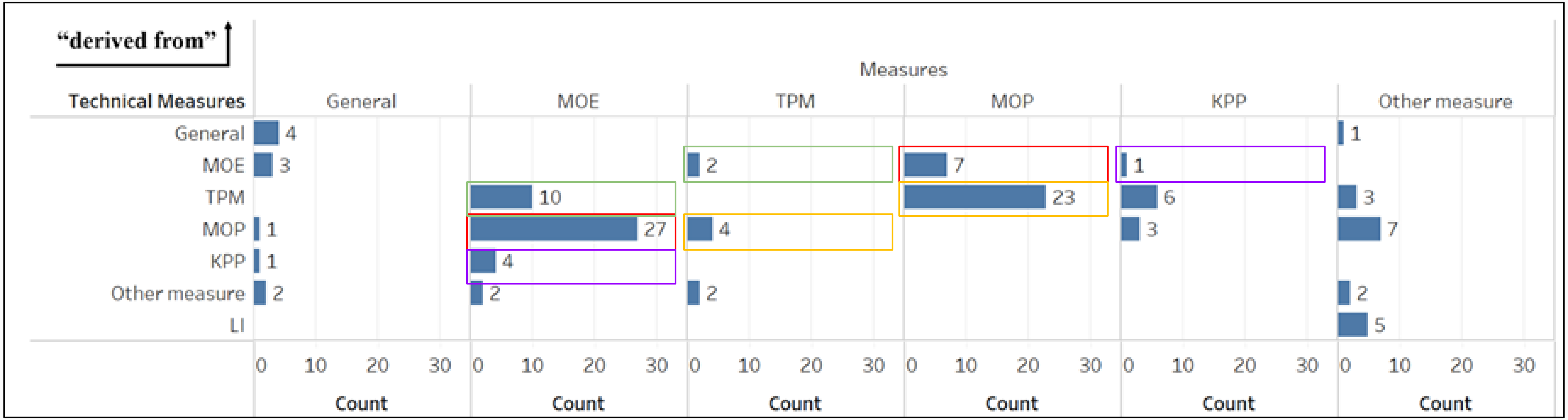


Findings: Multiple origins identified in *Genesis* guidance

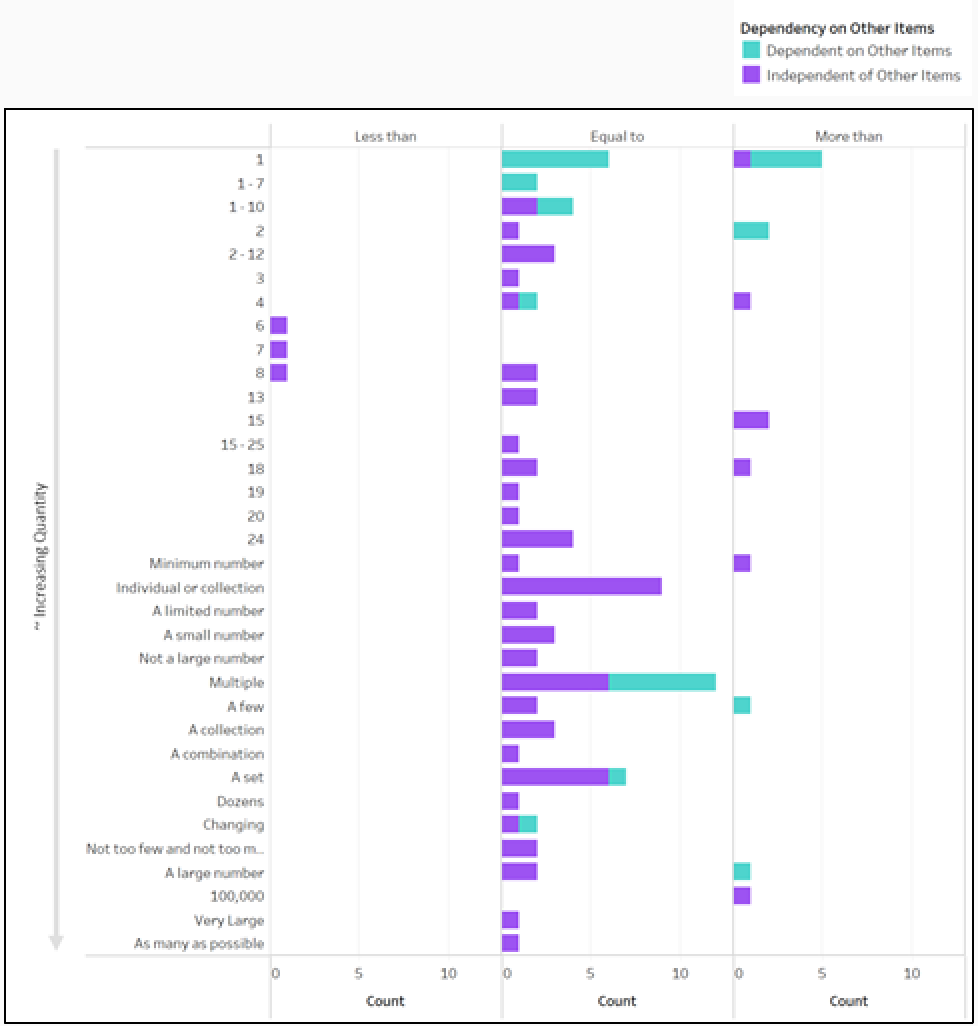
Little guidance on <u>how</u> to derive measures. No guidance on deconfliction.



Findings: Derivation process is inconsistent



Findings: *Quantity* guidance is inconsistent but **does not explain under what conditions it is applicable.**



What does Focus 1 research tell us?

Selection guidance contradicts and lacks underlying evidence & specificity on when guidance applies.

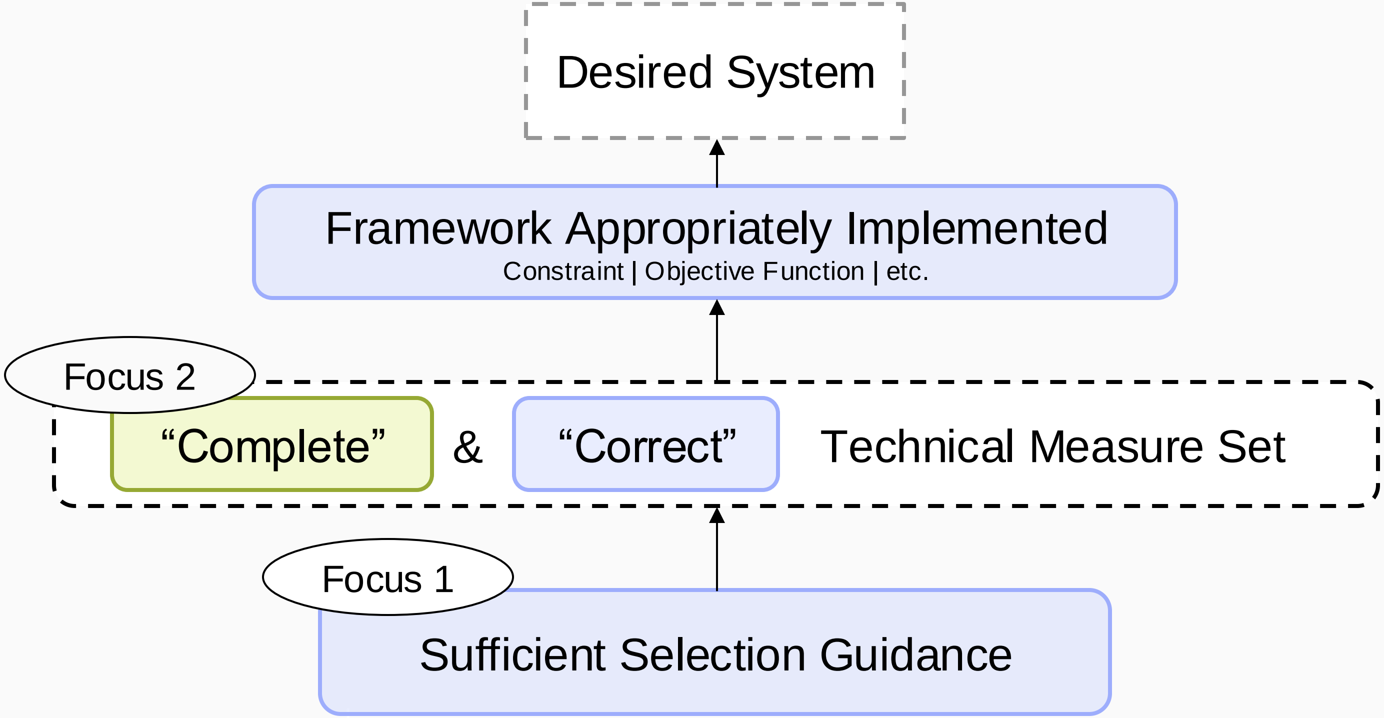
⬇

Current selection guidance may not be sufficient.

⬇

We cannot assume technical measure sets are “complete” or “correct”.

Idealized Use of Technical Measures



Focus 2

Impact of Technical Measure Omission in System Concept Selection

Casey Eaton[1], Bryan Mesmer[1],

[1] The University of Alabama in Huntsville

NASA Grant Number: NNM11AA01A 14.1
NASA Cooperative Agreement: 80NSSC20M0044

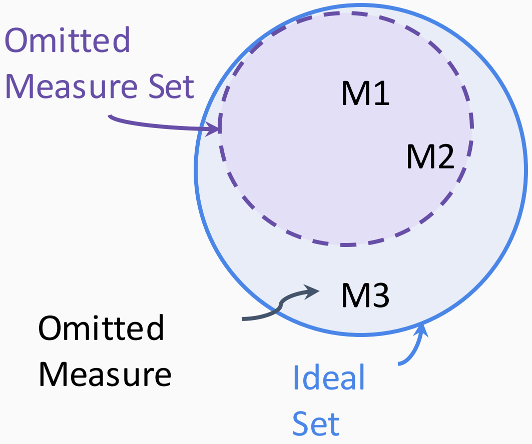
Research Gap: Impacts of Sets of Technical Measures

Theoretical impacts when using individual measures are easier to understand.

- e.g. switch from maximizing payload capacity to minimizing mass

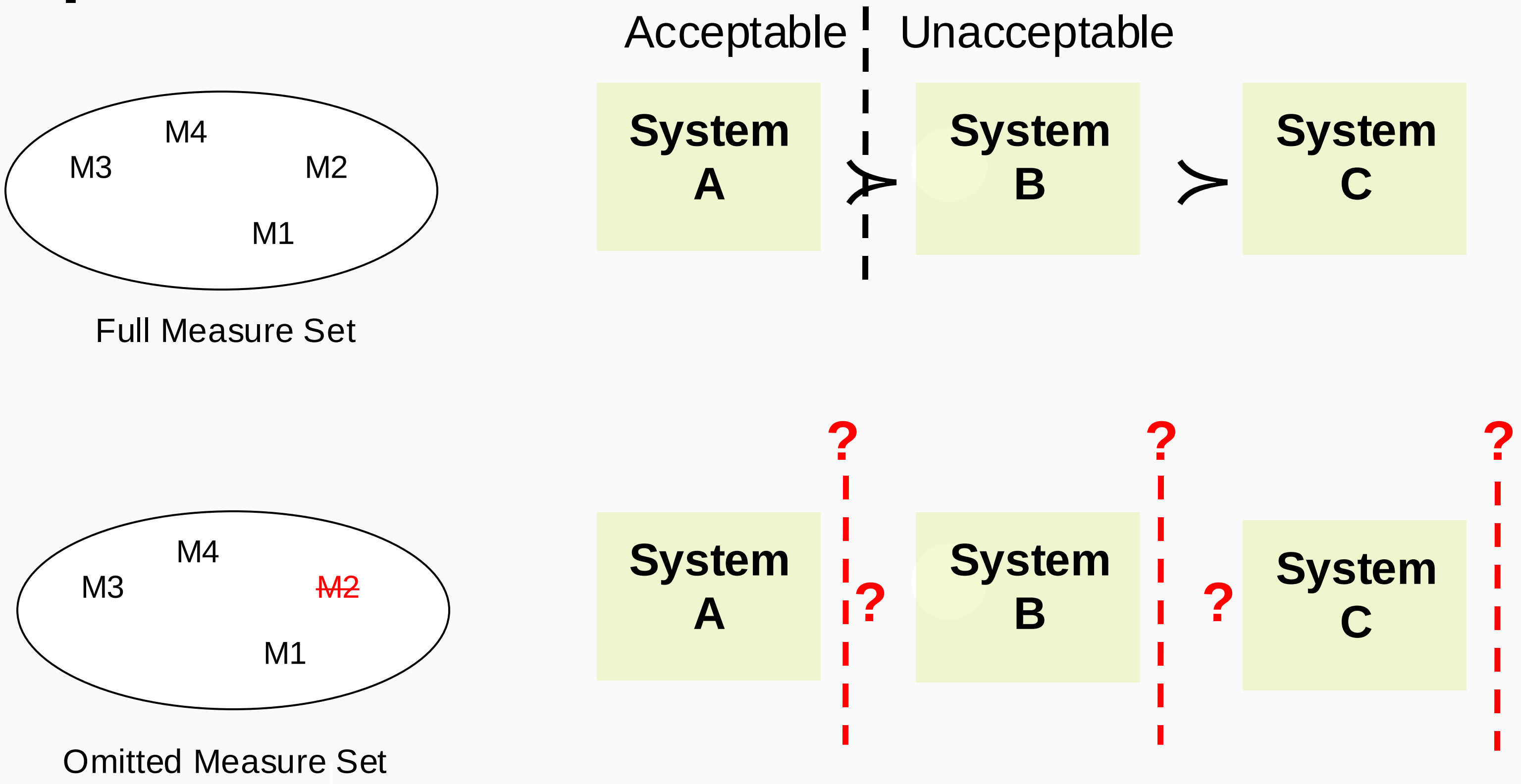
Real world impacts of a measure in a set on a decision may be less clear.

- e.g. adding or removing a new measure to/from a set of 20 measures.
- Cannot rely on having a “complete” set from guidance



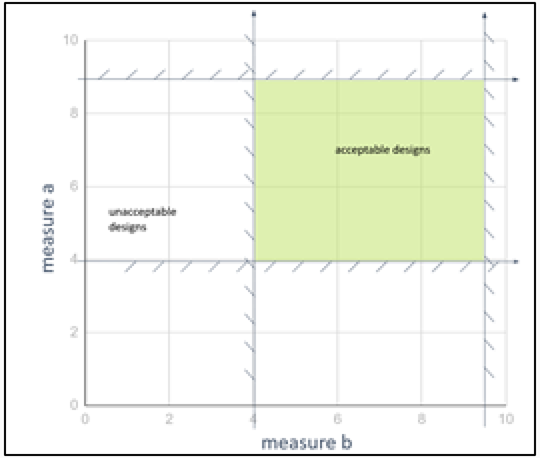
RQ: If you are missing technical measures, does it actually matter in real-world situations?

Research Methods: Model Omission Impacts in Concept Selection

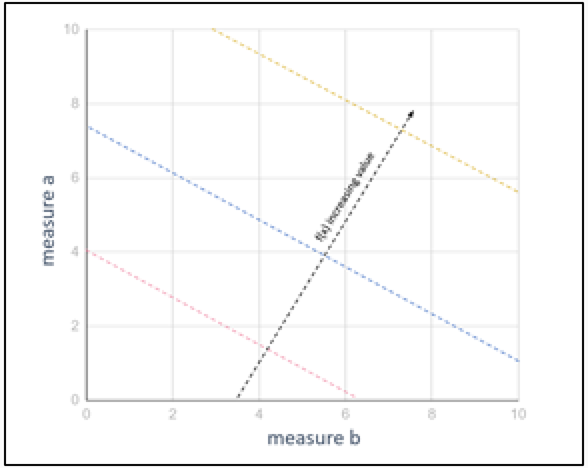


Research Methods: Two Common Frameworks [17-19]

Requirements-based: Constraint Framework



Optimization-based: Objective Function Framework



Methodology Overview

0. Select Case Study System
1. Extract Technical Measure Set for System
2. Formalize Thresholds and Goals
3. Identify Sample Systems
4. Apply Frameworks with TM Sets
5. Assess Omission Impacts

Research Methods: Modeling Impact of Measure Omissions

1. Extract Technical Measure Set for HLS

National Aeronautics and Space Administration

HLS-PLAN-008-ANX-03
REVISION A
RELEASE DATE: JULY 25, 2022

HUMAN LANDING SYSTEM (HLS) PROGRAM
TECHNICAL PERFORMANCE MEASURES (TPM)
PLAN
ANNEX 03 – SUSTAINED PHASE PROVIDER
REQUESTED TPMs

2. Formalize Thresholds and Goals

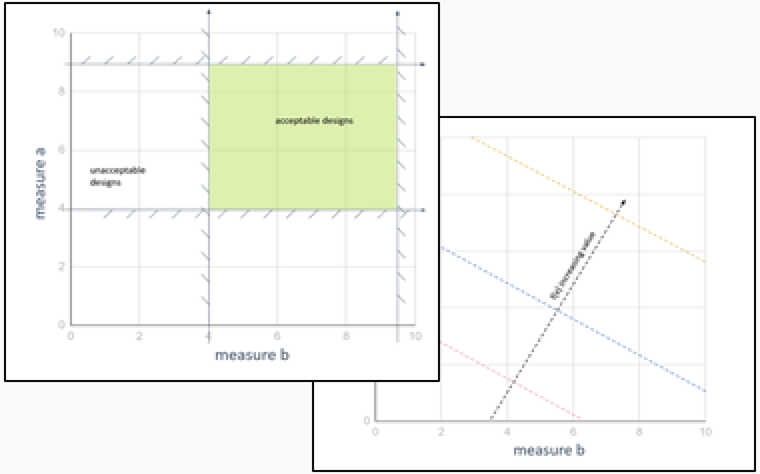
1	Notes	TPM #	TPM Title	Units	Connected to	Appears in Eq	Value (current)	Threshold (current)	Goal (current)
2	Comm	3.3A	Communication Link Margin – Downlink (for each band)	dB	n/a	g2(x)		3.00	6.00
3	Comm	3.29A	Lunar Surface Communication Range (UHF)	km	n/a	g3(x)		2.00	40.00
4	Duration	3.14A	Duration Between First Launch and LOCR Completion – Maximum	days	n/a	g4(x)		10.00	None
5	Duration	3.51	Uncrewed Lunar Orbit Operations Duration	days	n/a	g5(x)		90.00	None
6	Duration	3.46	Surface Mission Duration – Maximum	days	3.28, 3.45	g6(x)		6.50	None
7	Duration	3.28B	Lunar Darkness Survival Duration (total duration)	hours	3.45, 3.46	g7(x)		150.00	192.00
8	Duration	3.45	Surface EVA Duration per EVA	hrs	3.28, 3.46	g8(x)		9.00	None
9	System	3.56	Vehicle Reliability	-	n/a	g9(x)		0.975	None
10	System	3.34	MMOD Probability of No Penetration	-	n/a	g10(x)		0.99904	None
11	Landing	3.24	Landing Accuracy	m	n/a	g11(x)		<50	None
12	Landing	3.27	Leveling Capability	degrees	3.48, 3.44	g12(x)		2.00	5.00
13	Landing	3.44	Slope Tolerance Maximum (landing)	degrees	3.48, 3.27	g13(x)		10.00	None
14	Landing	3.48	Surface Operations Vertical Orientation (landing after leveling)	degrees	3.27, 3.44	g14(x)		8.00	5.00
15	Prop	x.1	Specific Impulse (for each module if applicable)	s	x.2	g15(x)		300.00	380.00

3. Identify Sample Systems

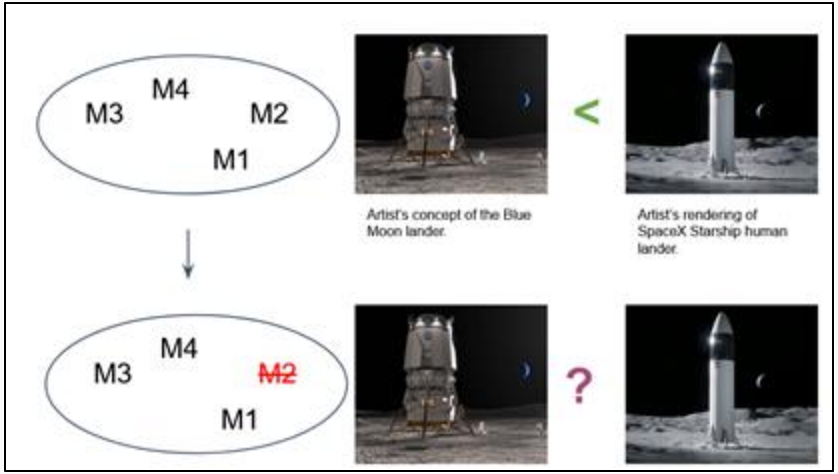
			System Alternatives			Prior HLS		Uncrewed Similar Systems									
Type	Tech Measure	Units	Blue Moon (Blue Origin)	SpaceX Starship	Dynetics ALPACA HLS	Altair (Constellation)	LM-1 (Apollo 5) (descent)	Viking 1 (non-crew)	Pathfinder (non-crew)	Mars Polar Lander (non-crew)	Phoenix (non-crew)	Mars Science Laboratory EDL (non-crew)	Mighty Eagle (non-crew prototype) (RLL)	NASA Morpheus (non-crew)	Insight Lander (non-crew)	Mars 2020 EDL (non-crew)
Comm	Communication Link Margin – Downlink (f	dB	3	3	3	3	3	3	3	3	3	3	3	3	3	[illegible]
Duration	Uncrewed Lunar Orbit Operations Duratio	days	49.75	49.75	49.75	14	3	49.75	49.75	90	90	49.75	49.75	49.75	49.75	49.[illegible]
Duration	Surface Mission Duration – Maximum	days	30	7	14	7	3	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12[illegible]
Duration	Lunar Darkness Survival Duration (total du	hours	192	3816	3816	7440	3816	3816	3816	3816	3816	3816	3816	3816	3816	38[illegible]
Reliability	Vehicle Reliability	-	0.98	0.5	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.[illegible]
Landing	Landing Accuracy	km	0.1	0.2	0.05	1	3.6	280	201	200	100	20	20	0.02	130	[illegible]
Landing	Slope Tolerance Maximum	degrees	12.33333333	12.33333333	10	12.33333333	12	12.33333333	12.33333333	12.33333333	12.33333333	15	12.33333333	12.33333333	12.33333333	12.333333[illegible]
Prop	Specific Impulse (for each module if applic	s	453	327	300	450	311	180	230	228	212	204	302	321	235	2[illegible]
Prop	Thrust of Main Propulsion System	N (lbf)	44,482.22	3,310,000	28,000	16,600	6,900.00	8006.796	22064.96	1064	3516	3603	3100	24000	1,320	249[illegible]
Prop/Mass	T/M Ratio	N/kg	0.99	2.55	0.36	0.41	0.96	12.11	24.79	3.07	5.25	1.50	9.60	6.00	3.11	5.[illegible]
Mass	PMF		0.424	0.857	0.300	0.342	0.632	0.080	0.240	0.181	0.478	0.162	0.359	0.725	0.158	0.0[illegible]
Mass	Usable Propellant Mass at Earth Launch (t	kg	11753	1,200,000	40000	24859	8087	85	214	64	320	390	116	2900	67	3[illegible]
Mass	HLS Cargo Mass Capability – Earth to NRH	kg	14,968.55	150,000	12,000	14,500	10334	661	895	354	679	2401	323	4000	425	4[illegible]

Research Methods: Modeling Impact of Measure Omissions

4. Apply Frameworks with TM Sets



5. Assess Omission Impacts



NASA HLS Expected Model Selection [20]

Constraint Framework: Starship & Blue Moon Acceptable. ALPACA Unacceptable.

Objective Function Framework: Starship ≻ Blue Moon ≻ ALPACA

Acceptable Systems | Unacceptable Systems

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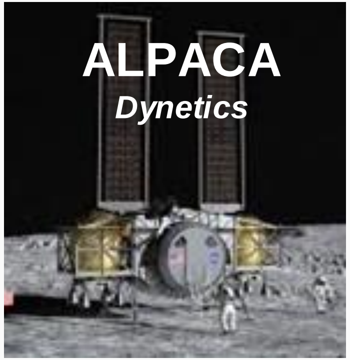


Constraint Framework Overview

Constraint satisfaction problem formed from thresholds.

Example Constraints

Landing Accuracy:

$g_{11}(x) = LA - 50 \le 0\ km$

Slope Tolerance

$g_{13}(x) = -ST + 10 \le 0\ degrees$

$0 \le LA\ km$

$0 \le ST \le 180\ degrees$

Strict (1) and (2) Penalty Interpretation

$$P = m_1 \cdot m_2 \cdot ...\ m_n \quad (1)$$

$$\min P(\bar{m}) = \sum_{k=1}^{l} (h_k(\bar{m}))^2 + \sum_{j=1}^{p} max(0, g_j(\bar{m}))^2 \quad (2)$$

Complete Measure Set Violations

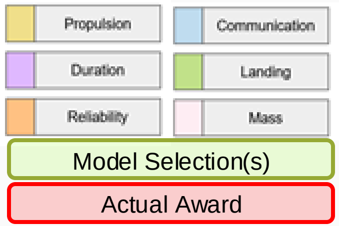
Propulsion | Communication | Duration | Landing | Reliability | Mass

Model Selection(s)

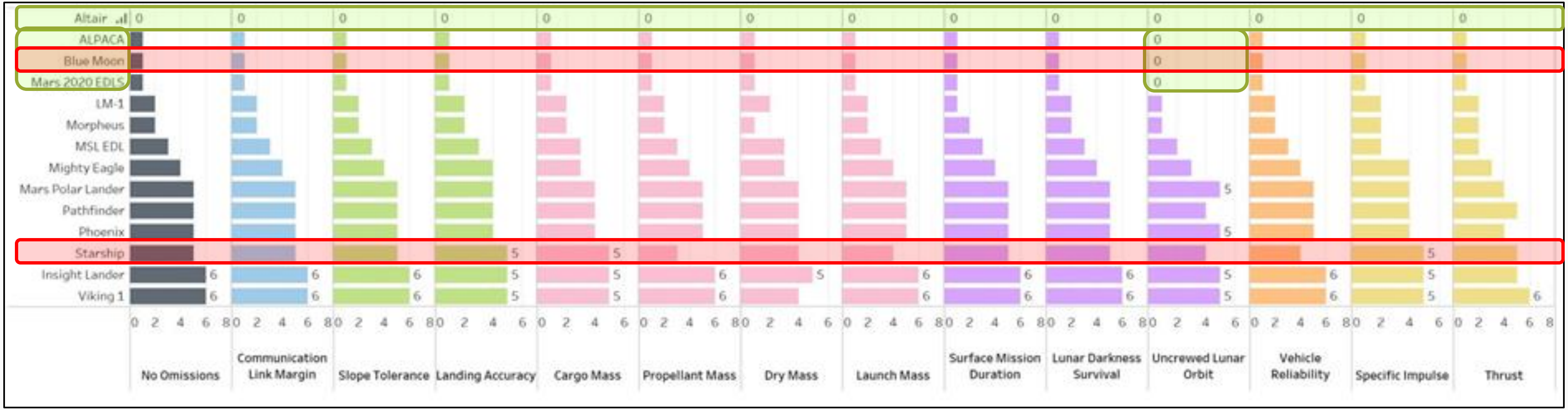
Actual Award

System	Constraint														Violated Constraints
	g1(x)	g2(x)	g3(x)	g4(x)	g5(x)	g6(x)	g7(x)	g14(x)	g8(x)	g9(x)	g10(x)	g11(x)	g12(x)	g13(x)	
	CLM	LA	ST	CMC	UPM	DM	LMA	CMC, UPM, LMA	ULD	SMD	KDD	VR	ISP	TP	
Altair	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	0
ALPACA	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	1
Blue Moon	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	1
Mars 2020 EDLS	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	1
LM-1	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Violated	Satisfied	Satisfied	Satisfied	Satisfied	2
Morpheus	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	2
MSL EDL	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Violated	Violated	3
Mighty Eagle	Satisfied	Satisfied	Satisfied	Violated	Satisfied	Violated	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Satisfied	Violated	4
Mars Polar Lander	Satisfied	Violated	Satisfied	Violated	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Violated	5
Pathfinder	Satisfied	Violated	Satisfied	Violated	Satisfied	Violated	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Violated	Satisfied	5
Phoenix	Satisfied	Violated	Satisfied	Violated	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Violated	5
Starship	Satisfied	Satisfied	Satisfied	Satisfied	Violated	Satisfied	Violated	Violated	Violated	Satisfied	Satisfied	Violated	Satisfied	Satisfied	5
Insight Lander	Satisfied	Violated	Satisfied	Violated	Satisfied	Violated	Satisfied	Satisfied	Violated	Satisfied	Satisfied	Satisfied	Violated	Violated	6
Viking 1	Satisfied	Violated	Satisfied	Violated	Satisfied	Violated	Satisfied	Violated	Violated	Satisfied	Satisfied	Satisfied	Violated	Satisfied	6

Omission Impacts in a Strict Constraint Framework

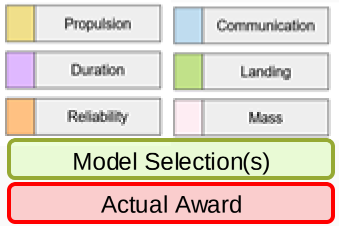


Number of Violated Constraints



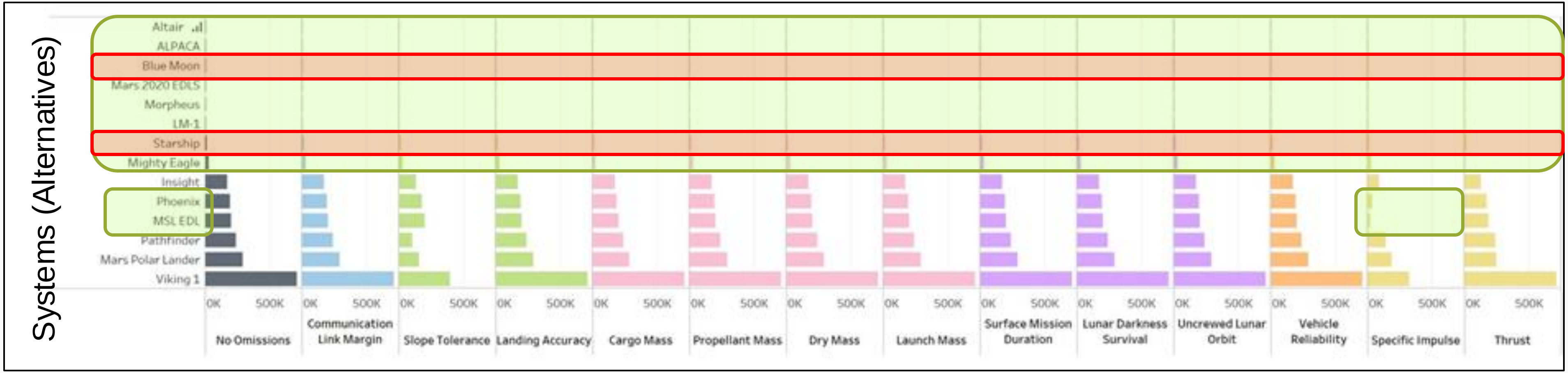
Measure Omitted

Omission Impacts in a Penalty Constraint Framework Example



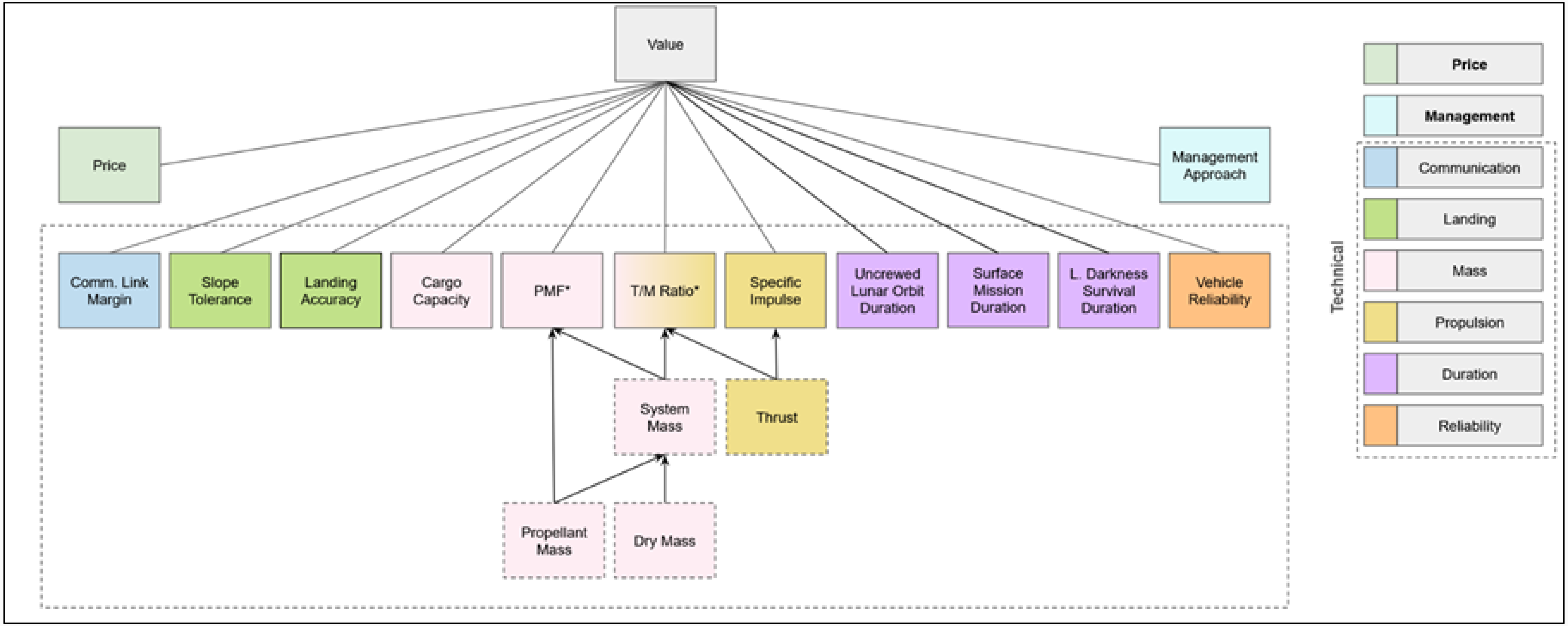
$$P = \sum_{j=1}^{P} max(0, g_j(\bar{m}) * w_j)$$

Count Shows Penalty for Violated Constraints ($)



Measure Omitted

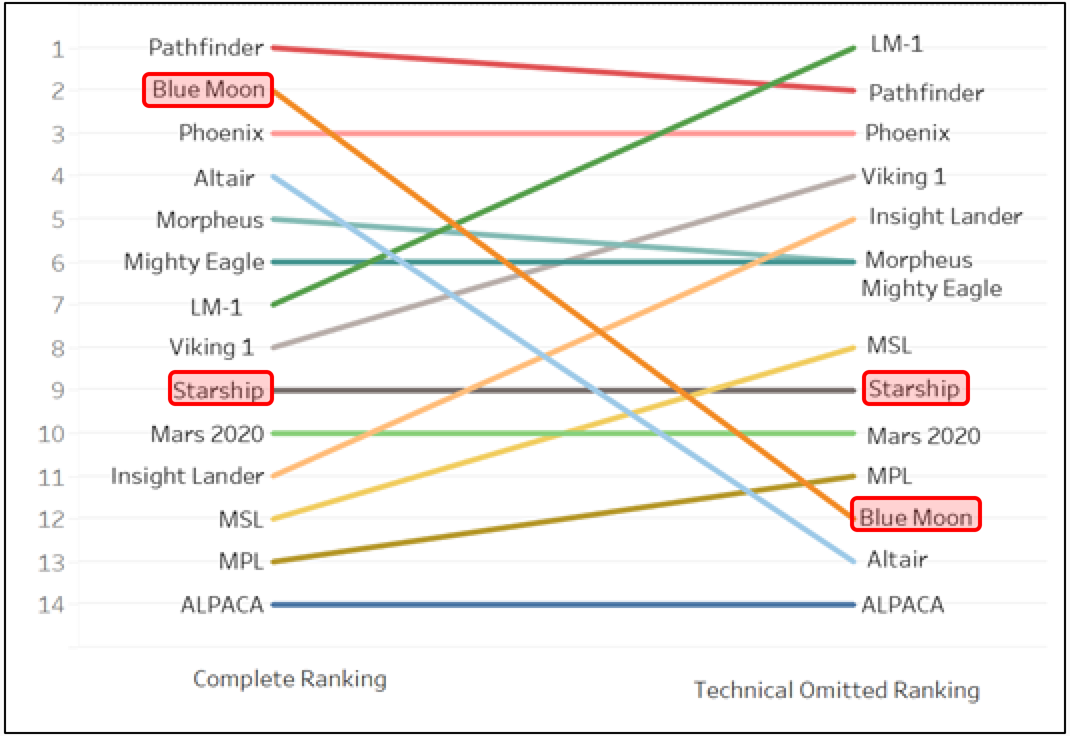
Objective Function Framework Overview

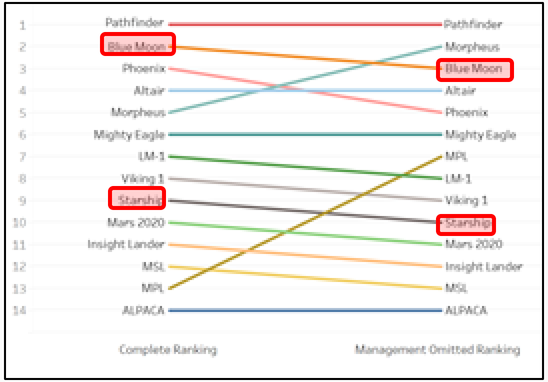


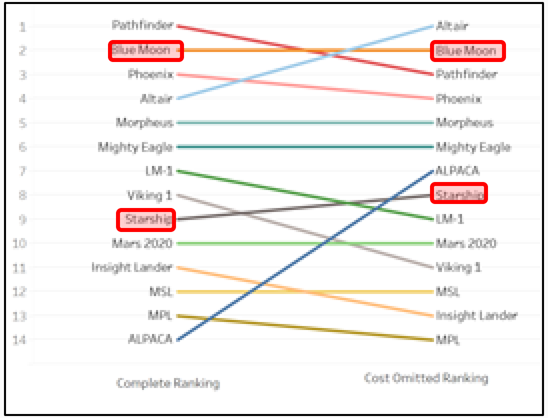
$$V = P + 300 * M + 150 * CLM + 20 * ULD + 120 * SMD + 0.5 * LDD + 40000 * VR - 6 * LA \; 35 * ST + 400 * TM + 2500 * PMF + 0.006 * CMC \quad (3)$$

Actual Awards

Omitting High-Level Measures Changes Selection



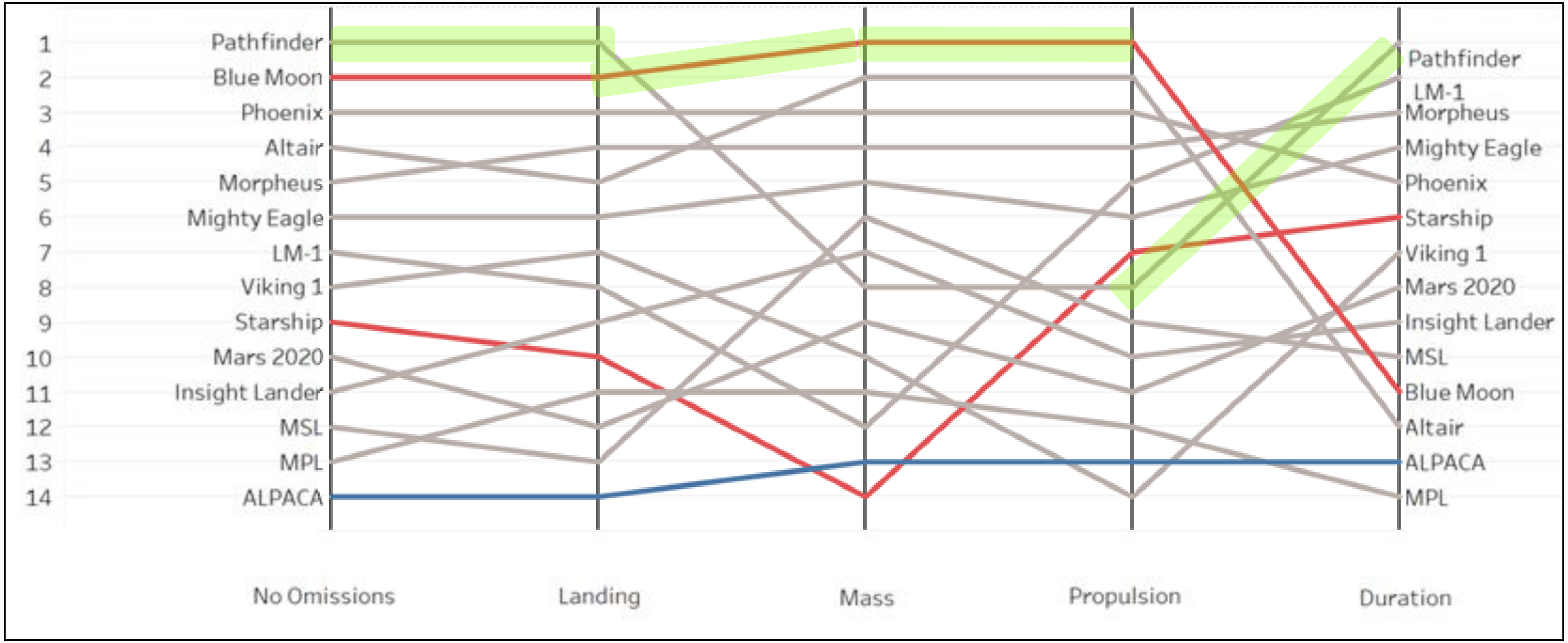




Model Selection

Actual Awards

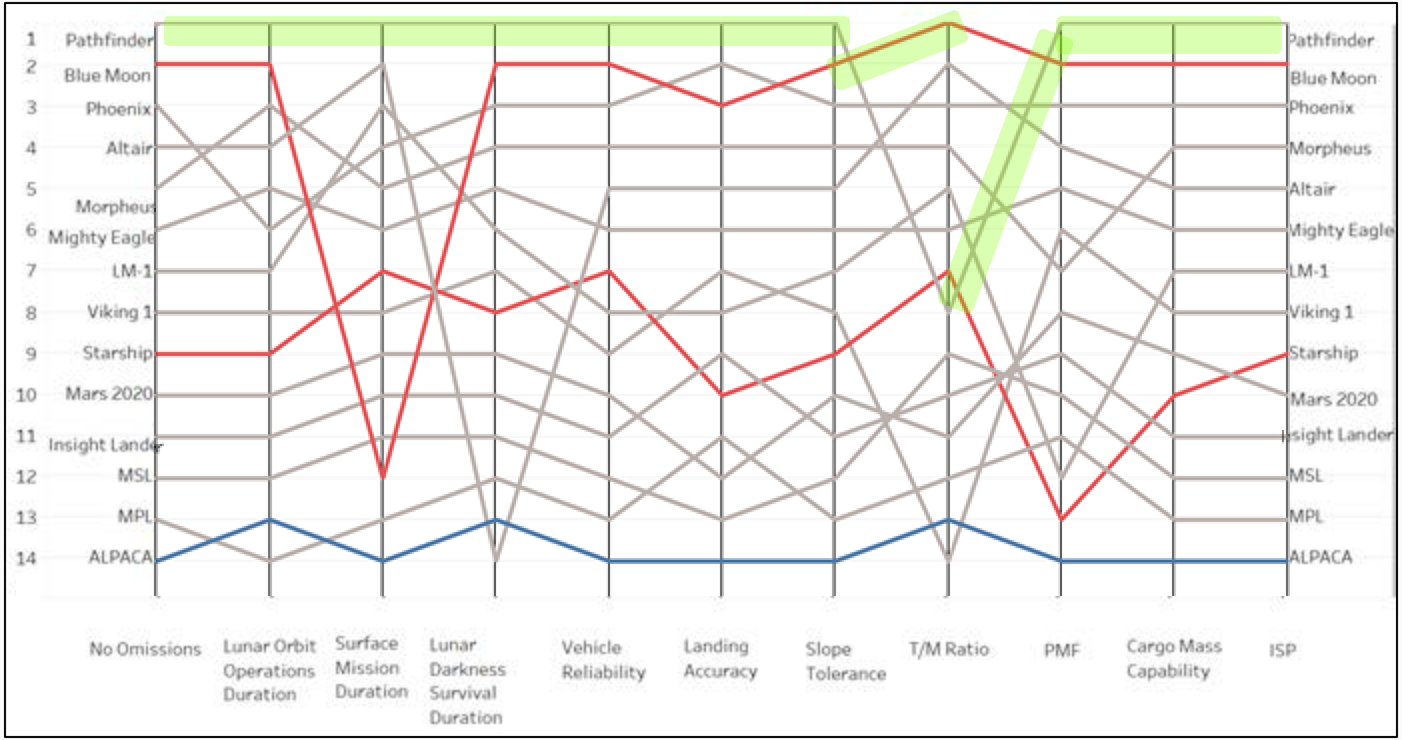
Omitting Measure Categories Changes Selection



Model Selection

Actual Awards

Omitting Individual Measures Changes Selection



Model Selection vs Actual Awards: Technical Measure Challenges in the Real World

1. Why did two systems that violated constraints win the actual awards?

- Not using a strict constraint framework.
    - Less control over decision with transparent method.
    - Expert judgement may be able to reflect preferences better than measurement-based frameworks.
- Discrepancies in publically available data.

2. Why did actual award bids not maintain ranking consistency?

- Different weighting or formation than used in our objective function.
    - e.g. high prioritization of cargo mass over reliability
- Unstated technical measures.
    - Non-technical aspects that influence decision

Next Steps for Focus 2

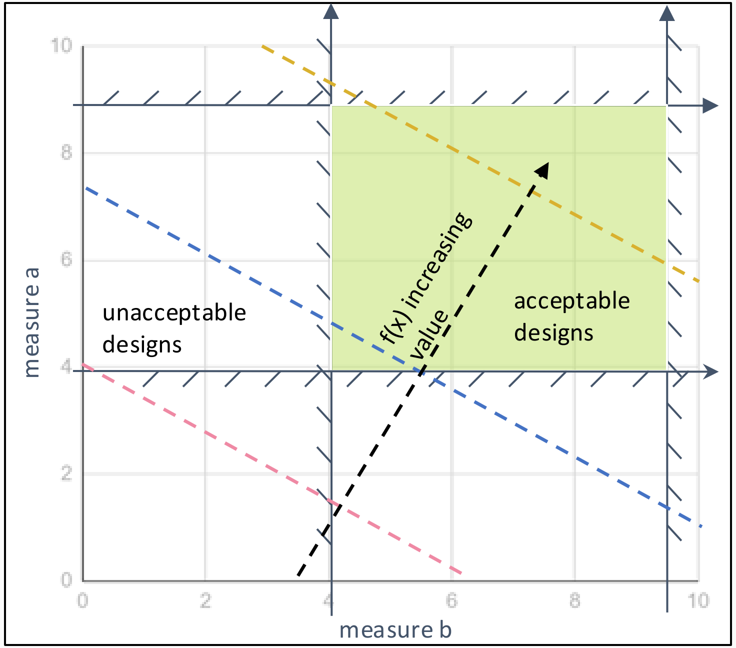
1. Transition to simulating systems

- Tests bounds of scenarios

2. Combine frameworks

3. Add uncertainty to measures

- Thresholds (constraint framework)
- Weighting (objective function framework)



What does Focus 2 research tell us?

Incomplete technical measure sets can theoretically impact design decisions.

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Case study suggests impacts can occur in real world systems.

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Impacts depend on framework; constraints appear more robust.

Why does this dissertation matter for the Systems Engineering community?

Focus 1: Observed lack of sufficient guidance

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Focus 2: Practical impact potential for omissions

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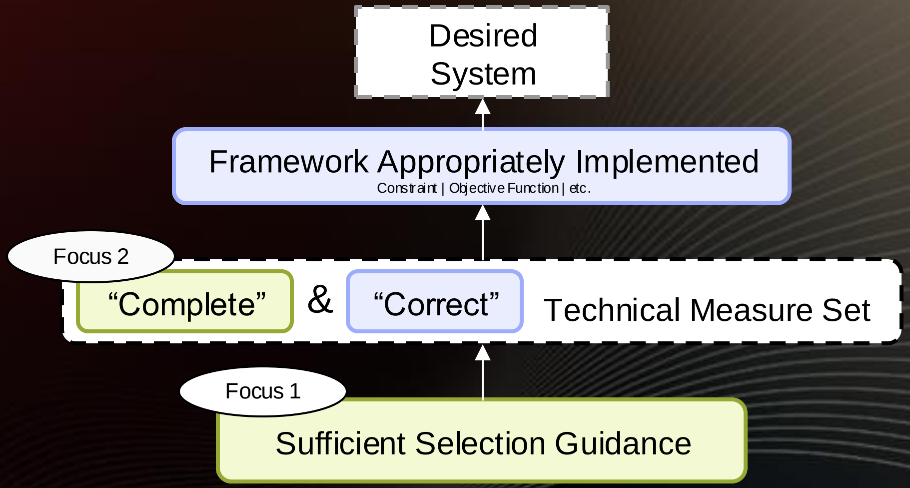
Systems Engineering frameworks should account for technical measure sets being imperfect AND develop better selection methods.



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