Abstract

An integrated approach that simultaneously models value and cost uncertainties to better identify value and risks

System engineers often use value modeling to capture a composite perspective of multiple stakeholders with conflicting objectives to help understand trade-offs among several design alternatives. Uncertainties are inherent in many forms during a system's life-cycle and must be considered during any design decision. These uncertainties include stakeholder concerns, technological maturity, adversary and competition actions, scenarios, costs, schedules, and many more. Uncertainty and risk analysis are often performed after analyzing a value model. As a result, our decisions become biased toward deterministic solutions that we select before understanding their risks. To eliminate this cognitive bias, we propose an approach that integrates uncertainty modeling with value modeling in order to help understand value and risk while we analyze alternatives. By assigning probability distributions to uncertain independent variables and cost components, we can perform Monte Carlo simulations to propagate these uncertainties through the value and cost models and examine cumulative distribution functions in order to identify dominant solutions. We can then use tornado diagrams to identify which value measures and cost components explain the majority of the alternatives' value and cost variations. Integrating both value measure and cost uncertainties simultaneously will better facilitate value and risk identification to help system engineers perform trade-off analysis during design decisions throughout the life-cycle.

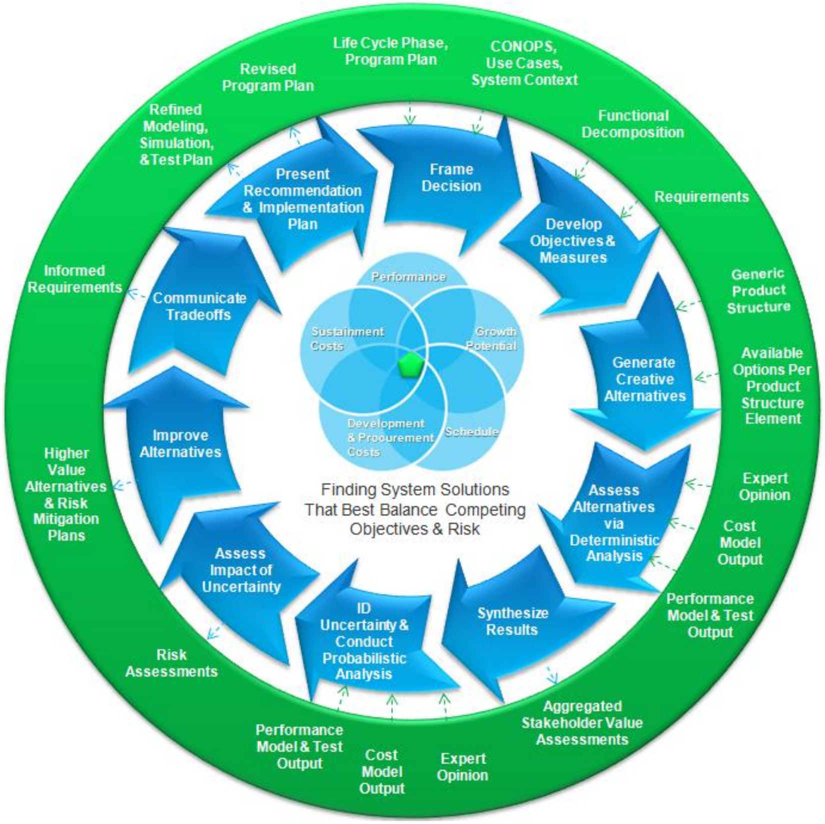
An integrated approach that simultaneously models value and cost uncertainties to better identify value and risks

Dr. Greg Parnell
University of Arkansas
LTC Alex MacCalman
United States Military Academy

Motivation for Change!

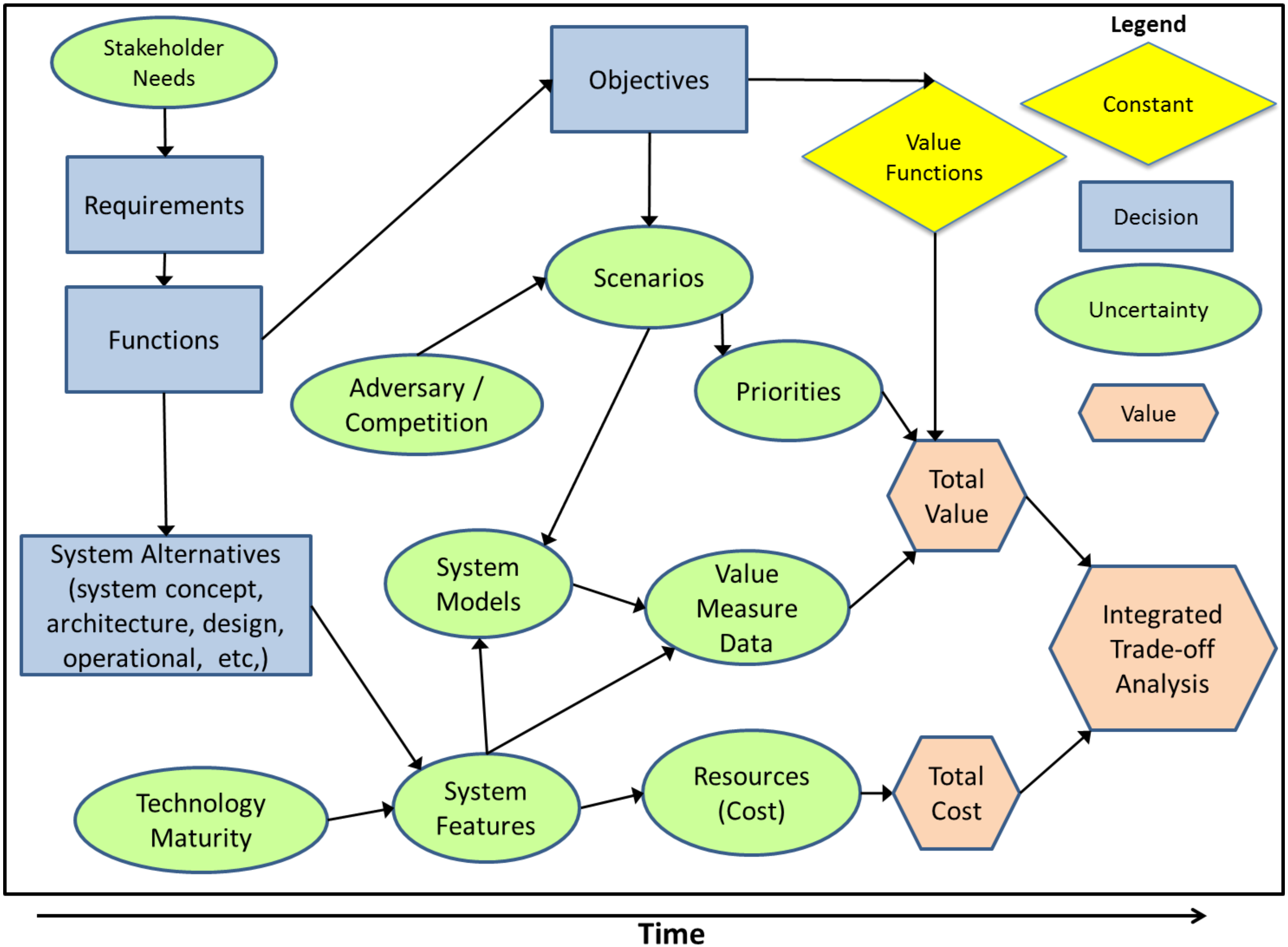
- There is a demand for guidance on trade studies from the INCOSE Corporate Advisory Board.

- Currently there is no good industry information that crosses the life cycle and aligns with INCOSE process guidance (Handbook, SEBOK, ISO/IEC 15288, DAG,CMMI).



- Actions to address need:
  - ✓ – Developed INCOSE Decision Management Process for Trade Studies.
  - ✓ – Updated INCOSE SE Handbook section 5.3 (Decision Management).
  - ✓ – Updated SEBoK section on Decision Management. http://sebokwiki.org/wiki/Decision_Management
  - – Write a Trade-off Analysis book (to publisher Jan 2016).

We can represent a systems decision using an influence diagram.

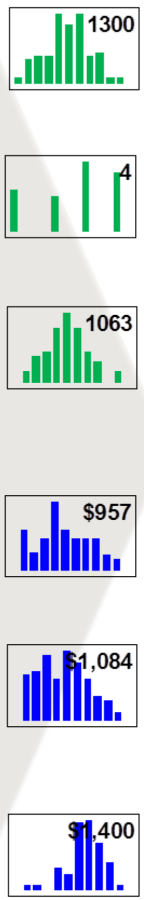


Our integrated approach propagates uncertainty through the value and cost models.

Uncertainty Modeling

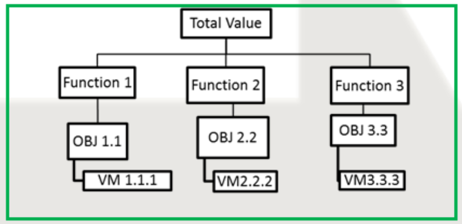
- stochastic simulations
- subject matter expert input
- Bayesian nets
- Mote Carlo Simulations
- distributions from historical data
- elicited probabilities
- estimated probabilities from data
- analogies
- cost estimating relationships
- learning curves

Inputs

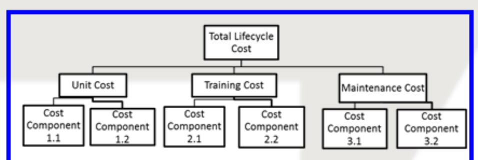


Value and Cost Modeling

Value Model

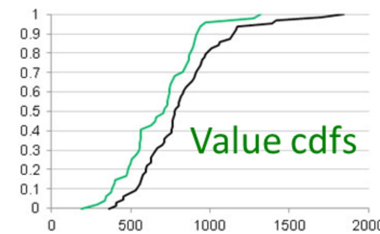


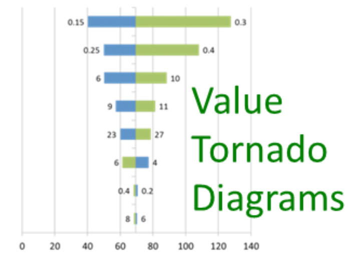
Lifecycle Cost Model

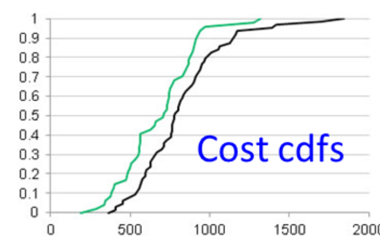


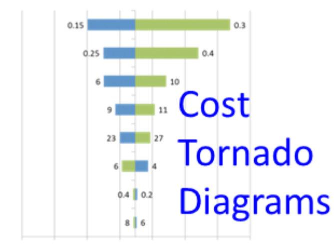
Outputs

Integrated Tradeoff Analysis





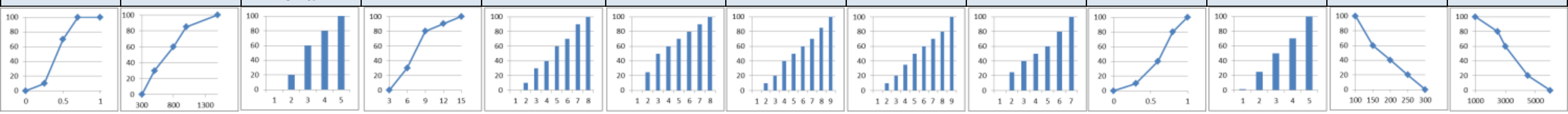




The functional hierarchy defines the value tradespace using functions, objectives, and value measures.

Value Hierarchy Legend: Function Objective Value Measure

Squad achieves overmatch against enemies in complex environments												
Command and control the Squad					Maneuver the Squad	Protect the Squad			Achieve Mission Effects		Sustain the Squad	
Maintain situational		Maintain networked communications										
Incr. beyond line of sight awareness	Incr. line of sight range	Max. range	Max. bandwidth	Provide secured connectivity	Incr.soldier mobility	Protect against kinetic threats	Protect against chemical, biological, radiological, nuclear threats		Maximize kinetic effects	Min. lateral damage	Max.power efficiency	Min. logistical footprint
Beyond LOS	Detection Distance	Commo Range Various Terrain	Bandwidth	Secured Connectivity	Weighted Mobility	Kinetic Protection	Chem Bio Protection	Nuclear Radio Protection	Lethality	Lethal Mitigation	Power	Logistical Impact

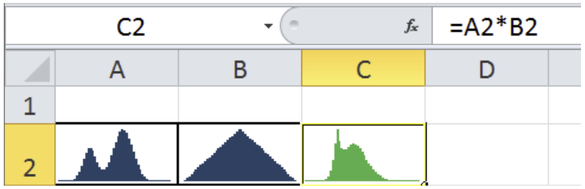


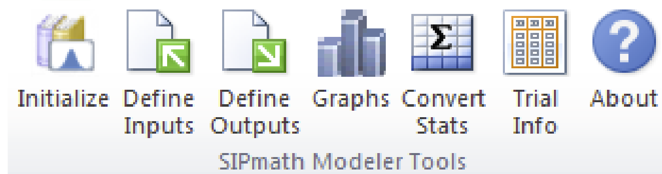
- The functional value hierarchy represents the composite perspective of multiple stakeholders and conflicting objectives and is used to assess alternatives.
- There are five major functions (one with two sub-functions) the system must perform.
- Functions have one or more objectives that define what we are trying to achieve with respect to each function.
- Each objective has one or more value measures that defines how well an alternative achieves the objective.
- Value functions for each value measure express the returns to scale between the walk away point and the ideal and are either continuous or discrete, constructed scales.

Alternatives are defined by the type of subsystems and the system features that characterize them.

		Baseline	Sustainable	Attack	LongRange	Survivable	Defendable	Performance
								
Subsystem	System Feature	Design Choice	Design Choice	Design Choice	Design Choice	Design Choice	Design Choice	Design Choice
Heads Up Display	Mount Type	NA	Helmet	Goggle	Helmet	Goggle	Integrated	Integrated
	Display Type	NA	2D Small	3D Small	2D Large	3D Medium	2D Medium	3D Large
Lenses	Magnification	0X	0.5X	1X	3X	1X	2X	4X
	Field of View	50 deg	60 deg	80 deg	60 deg	90 deg	100 deg	150 deg
	Range	300 m	900 m	800 m	1300 m	1000 m	1100 m	1400 m
Radio	LOS Range	1000 m	1200 m	1500 m	800 m	1400 m	1300 m	1600 m
	Bandwidth	5 mbps	10 mbps	9 mbps	13 mbps	12 mbps	6 mbbs	12 mbps
	Security	Freq Hop	Freq Hop	TK400	TK650	KLM40	PX33	FH98
	Operating Time	12 hrs	14 hrs	10 hrs	24 hrs	16 hrs	10 hrs	18 hrs
	Power Source	5 watts	10 watts	40 watts	30 watts	38 watts	20 watts	25 watts
Rifle	Rate of Fire	700 rpm	700 rpm	1300 rpm	600 rpm	1100 rpm	800 rpm	1500 rpm
	Max Range	500 m	600 mm	700 mm	1200 mm	800 mm		1500 m
	Ammo Type	5.56 mm	7.62 mm	12.7 mm	6.5 mm	10 mm	8 mm	12.7 mm
	Ammo Capacity	30 rds	50 rds	150 rds	50 rds	200 rds	300 rds	500 rds
	Muzzle Velocity	880 m/s	1000 m/s	1500 m/s	900 m/s			1500 m/s
Exoskeleton	Max Speed	4 mph	4 mph	5 mph	5 mph	5.5 mph	6 mph	8 mph
	Power Source	NA	BA90	BA75	Tablet	BA550	Integrated	Integrated
	Frame Size	NA	Small	Medium	Medium	Medium	Large	Large
Body Armor	Protection Level	Type III	Type III	Type III	Type IV	Type III	Type V	Type V
	Coverage Area	Vital Only	Vital & Extreme	Full	Full	Full	Full	Full
	Thickness	2 in	1 in	2.5 in	3 in	2.5 in	3 in	3.5 in
	2.5 in	Kevlar	Kevlar	MX500	P4	LM900	Kevlar III	Telex
	Flexibility	Hard	Soft	Medium	Hard	Hard	Soft	Medium
UAV	Model	NA	Cardinal	Buzzard	Crow	Pigeon	Robin	Dove
Robot Type	Transport System	NA	Track	Track	Quad	Track	Mixed	Quad
	Max Speed	NA	2 mph	2.3 mph	4 mph	2.7 mph	5 mph	8 mph
	Operating Time	NA	24 hrs	8 hrs	20 hrs	5.5 hrs	10 hrs	18 hrs
	Range	NA	600 m	500 m	700 m	300 m	700 m	1000 m
Robot Sensor	Magnification	NA	1X	2X	1.5X	3X	2.5X	2X
	Field of View	NA	50 deg	360 deg	180 deg	80 deg	100 deg	75 deg
	Range	NA	300 m	400 m	200 m	500 m	4050 m	500 m

The SIPmath™ Modeler Tool facilitates Monte Carlo simulations to propagate uncertainties.



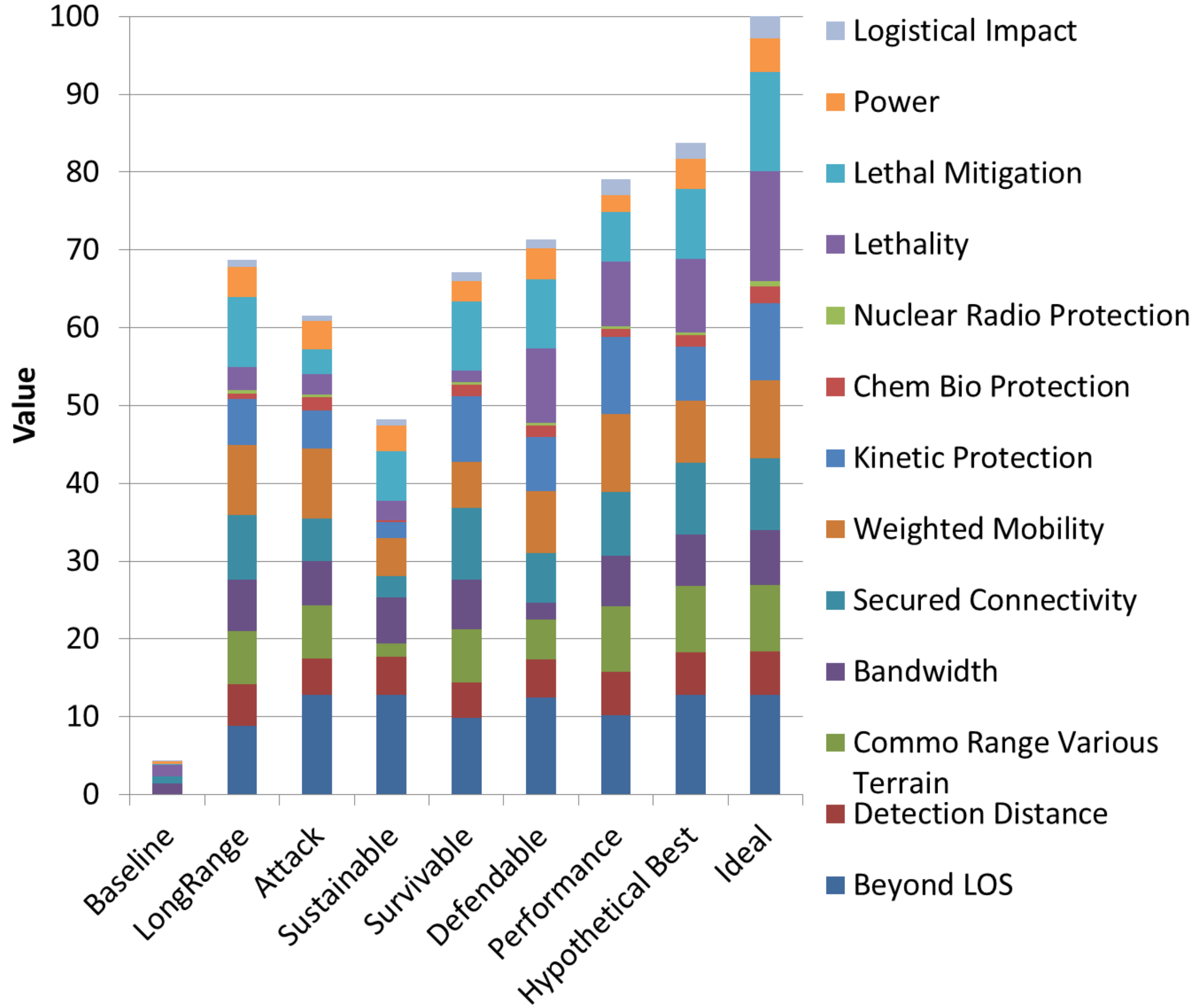


- Probability Management offers a free Monte Carlo simulation tool to help the wider community manage risk. http://probabilitymanagement.org/
- Tool facilitates arithmetic of uncertainty and allows user to change inputs without having to rerun the Monte Carlo simulation.
- Each alternative has uncertain value measure input driven by the system feature technological maturity.
- All output are dynamically updated after each input change.

Alternatives	Beyond LOS	Detection Distance	Commo Range Various Terrain	Bandwidth	Secured Connectivity	Weighted Mobility	Kinetic Protection	Chem Bio Protection	Nuclear Radio Protection	Lethality	Lethal Mitigation	Power	Logistical Impact
Baseline	0	300	1	5	2	1	1	1	1	1	1	280	5500
LongRange	0.50	1300	4	13	7	7	6	4	4	0.41	4	110	4042
Attack	0.80	983	4	9	5	7	5	8	3	0.39	2	120	4298
Sustainable	0.84	1063	2	10	3	3	3	2	1	0.38	3	130	4213
Survivable	0.55	957	4	12	8	4	8	7	4	0.30	4	150	3695
Defendable	0.68	1084	3	6	6	5	7	7	3	0.74	4	110	3704
Performance	0.57	1400	5	12	7	8	9	5	4	0.69	3	171	2728

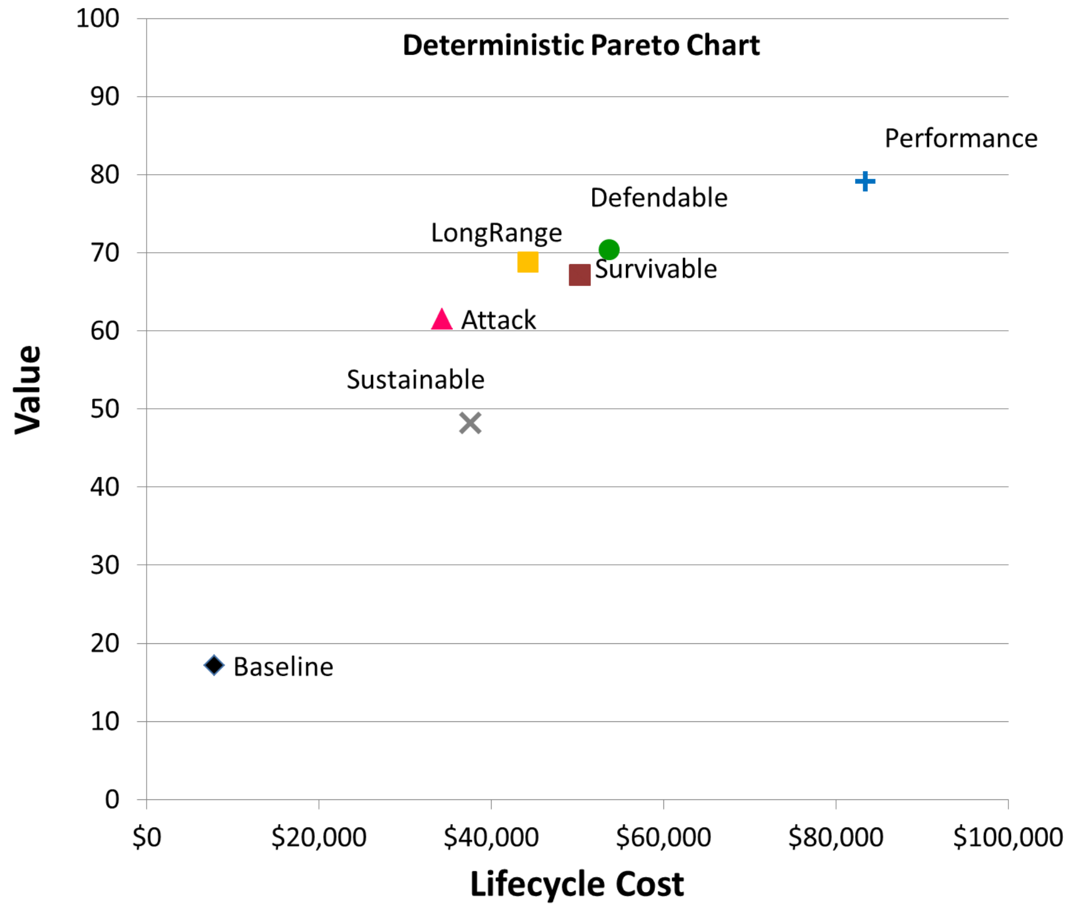
The deterministic Value Component Chart displays the sources of value.

- The value component chart reveals each alternatives value score for each value measure.
- The *Hypothetical Best* is the maximum value score achieved for each value measure among the set of alternatives.
- Identifies the value gap not achieved among the set of alternatives.
- Does not consider the uncertainties.



Deterministic Pareto charts identify the non-dominated set of alternatives.

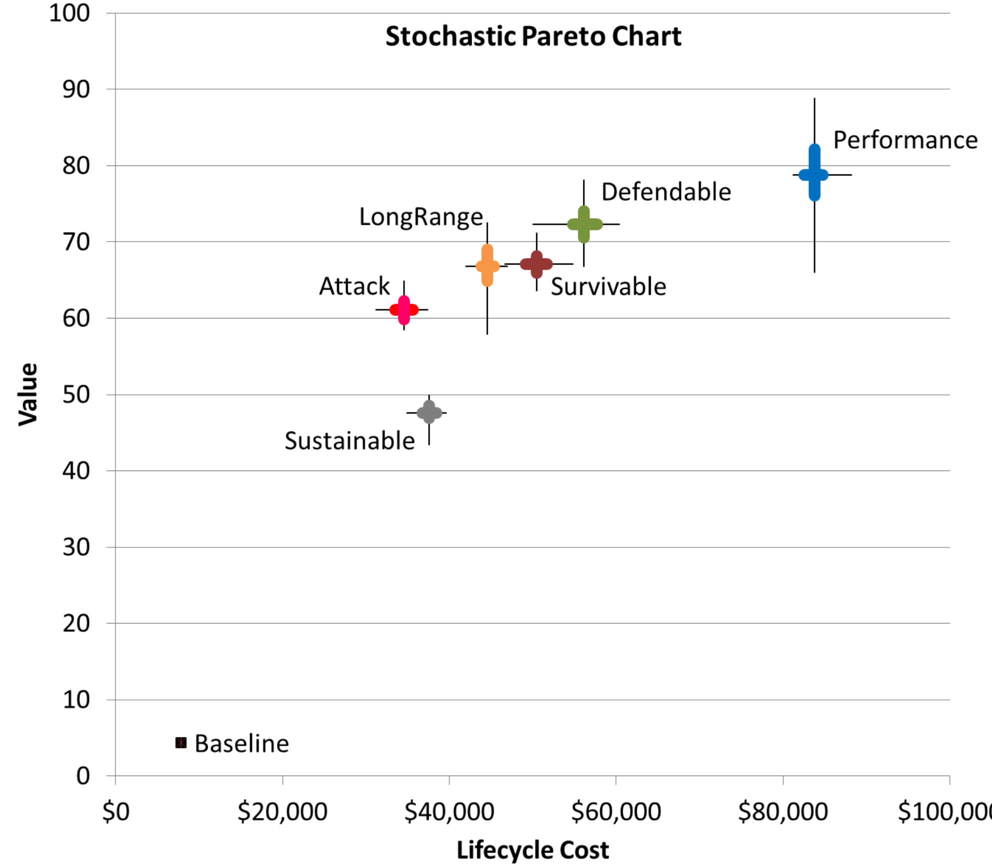
- Pareto charts bias decision makers to pick the affordable alternative with the highest value in the non-dominated set of alternatives.
- The *Sustainable* and *Survivable* alternatives are deterministically dominated and therefore not considered.
- The majority of value trade-off studies are deterministic without considering the risk associated with each alternative.



- Eliminating deterministically dominated alternatives without considering risk may lead to the wrong decision.

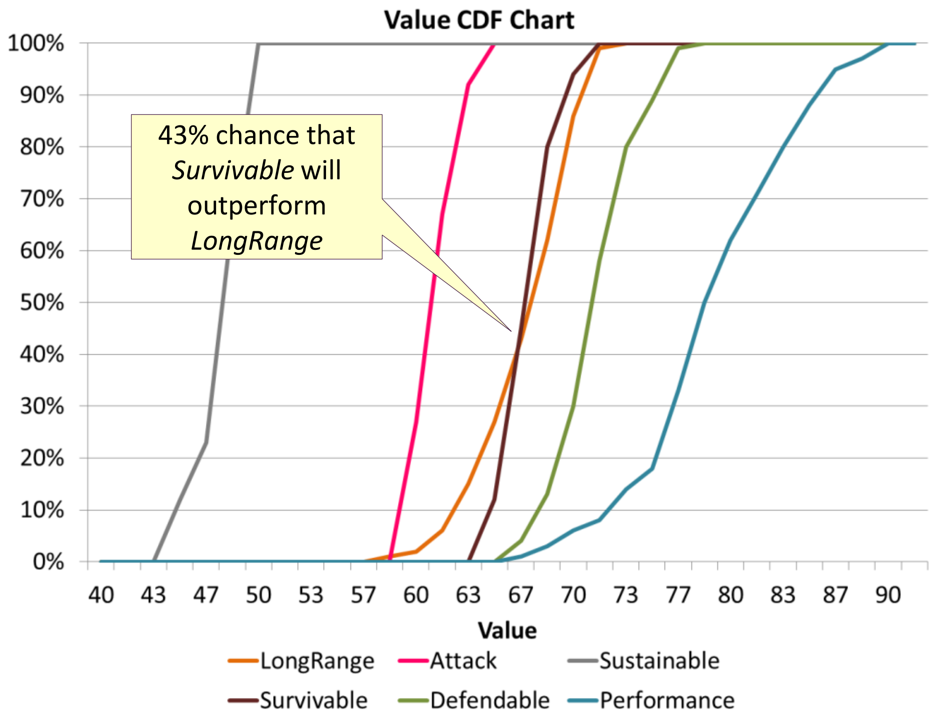
Stochastic Pareto charts captures the uncertainties with respect to value and cost.

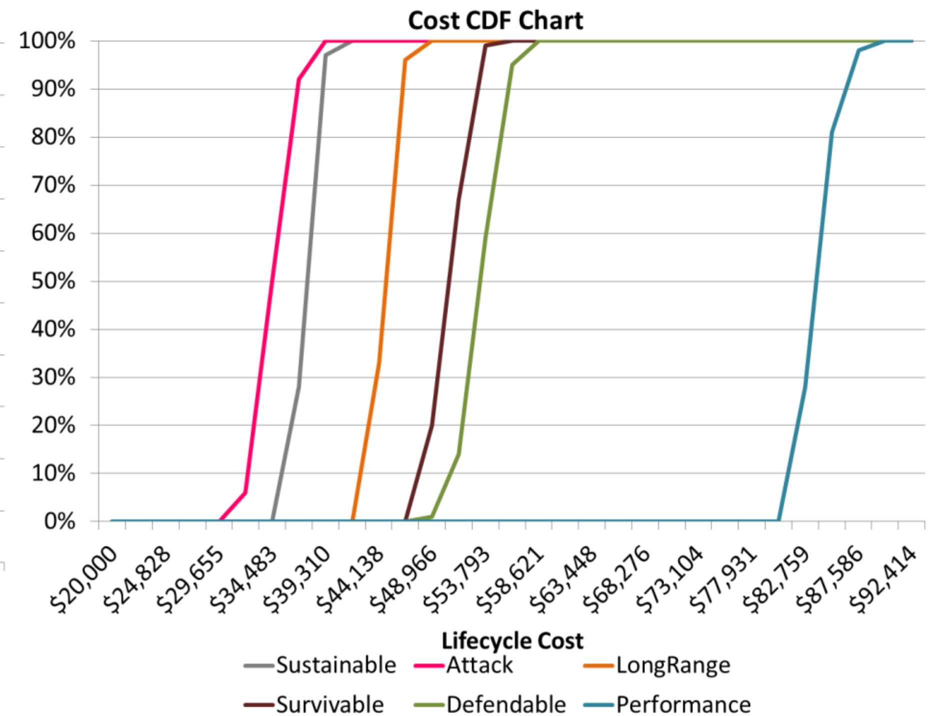
- Stochastic Pareto charts consider the alternative uncertainty in value and cost.
- We consider dominance and affordability.
- If *Performance* or *Defendable* are affordable we then focus on understanding what drives their uncertainty to mitigate risk.
- If *Defendable* is not affordable, we then consider either *LongRange* or *Survivable*.



- *LongRange* has a higher risk in value compared with *Survivable*.
  — See cumulative distributions (next chart).
- We may want to accept a higher cost by choosing *Survivable* or *Defendable* to mitigate the risk associated with *LongRange*.

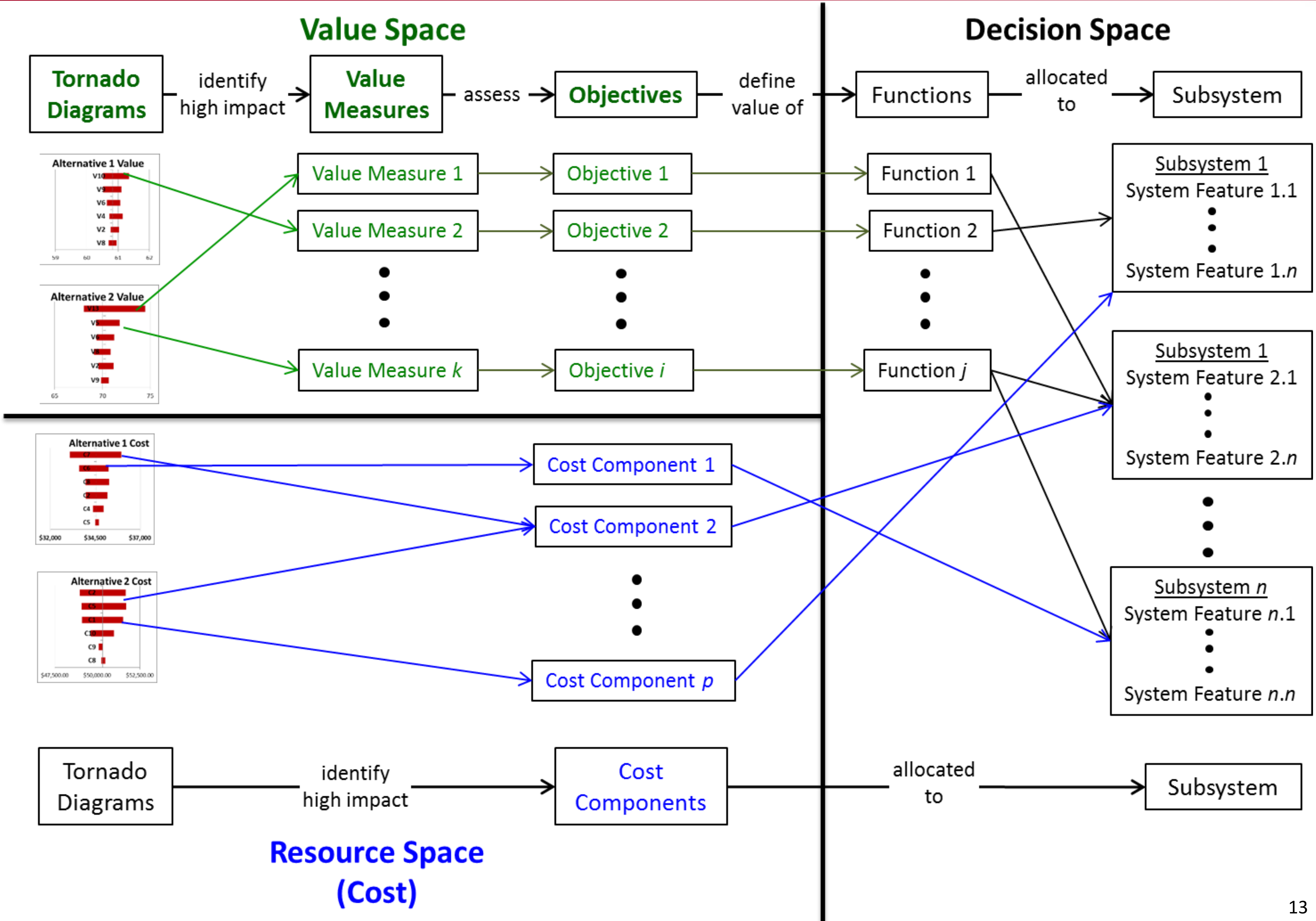
Cumulative distribution function charts identify stochastic dominance and risk profiles.



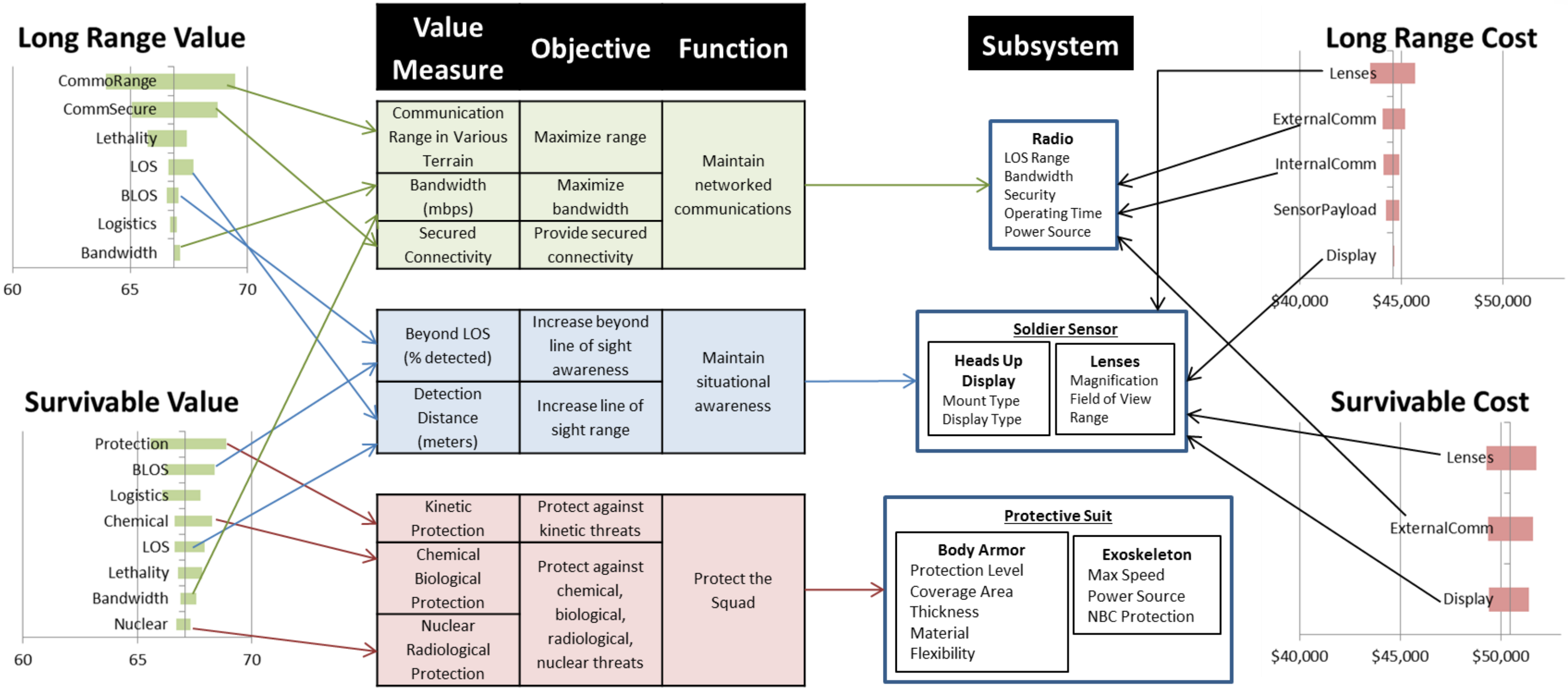


- The stepper the S-curve the less risk in the alternative.
- *Performance* and *Defendable* stochastically dominate all other alternatives with respect to value and cost.
- There is a 43% chance that *Survivable* will outperform *LongRange*.
- We can use tornado diagrams to attribute the alternative risk to specific subsystem features.

We can attribute the value, cost and risk drivers to subsystem features.



Tornado diagrams identify the highest impact value measures and cost components.



- The radio drives the majority of the risk for the *LongRange* value while soldier sensor and radio drive the majority of its cost.
- The protective suit drives the majority of the risk for the *Survivable* value while the soldier sensor and radio drives its cost.
- These insights suggest more resources should be invested to these subsystem technologies in order to mitigate risk.

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There are many other types of trade-off analysis we can perform with these models.

- Compare alternatives across scenarios.
- Evaluate concepts of operation.
- Evaluate architectures.
- Evaluate designs.
- Perform component optimization.
- Prioritize system modifications.
- Evaluate new technologies to achieve higher value.
- Evaluate alternatives to reduce risk.
- Support risk management programs.

Conclusions

- There is an industry wide need for better trade-off analysis techniques.
- Our influence diagram conveys the multiple uncertainties that we must consider in every system decision.
- Free software from Probability Management enables propagation of uncertainty through the value and cost models.
- The majority of value trade-off studies are deterministic. Cost estimation techniques already consider uncertainty.
- Our integrated approach:
  - —aligns with INCOSE Handbook and SEBoK.
  - —considers value trade-off uncertainties and simultaneously integrates them together with cost uncertainties.
  - —facilitates better value and risk identification.