INCOSE International Symposium
Las Vegas, NV
June 30 - July 3, 2014

Reducing the Effort of LCC Evaluation and Optimization

IBM – Lockheed Martin

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What are we really saying

- Complex MBSE task
- **Perceived** as high upfront effort
- In reality, many building blocks are there

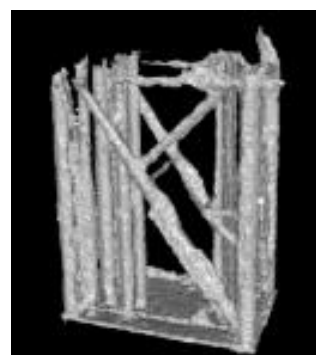
Bottom Line

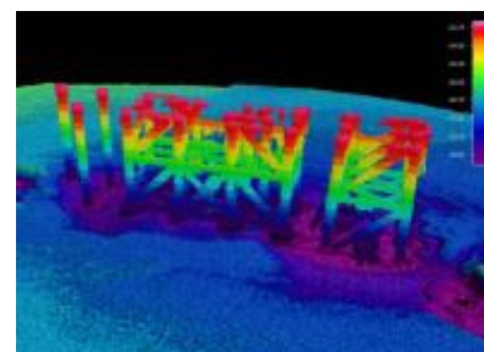
Value is within reach

Task at Hand

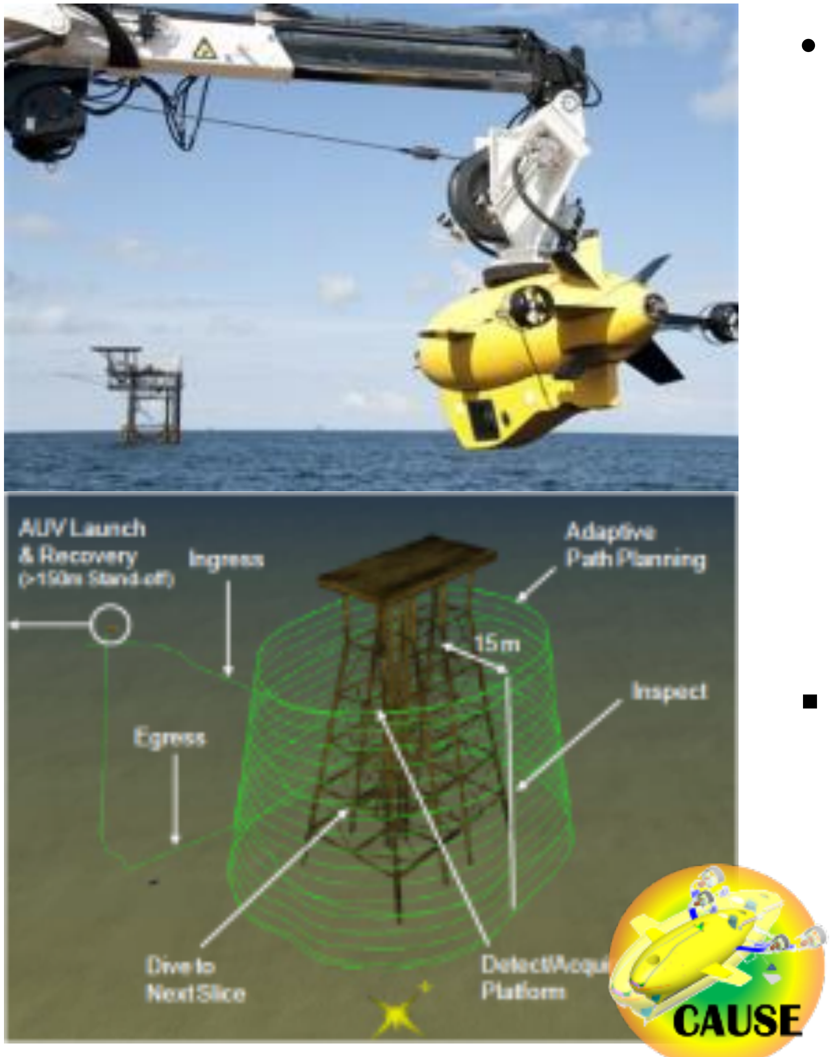
Lockheed Martin Flagship Product: Marlin® AUV

- Marlin® Autonomous Underwater Vehicle (AUV) Capabilities
  - Subsea acoustic survey using high resolution 3D sonar and integrated sensor packages
  - Autonomous real-time change detection against a reference model
  - Generation of high fidelity 3D geo-referenced models
- Marlin® Applications
  - Subsea Facility Inspection
    - Post-construction “as-built” survey
    - Baseline survey of existing structure
    - In-service inspection
    - Decommissioning survey
  - Damage Assessment
    - Post-hurricane inspection
    - Debris field mapping





Key AUV Goals



- Metrics
  - Production costs (up-front materials & fabrication)
  - Mission costs (vessel & crew for vehicle deployment & recovery)
  - Maintenance costs (planned upkeep & corrective repairs)
  - Availability (is the vehicle operational when it is needed)
  - Size (weight and volume)
- UUV designs are valuated using LM Palm Beach **CAUSE** analysis tool (**C**onceptual **A**utomated **U**UV **S**izing **E**nvironment)

Selection of vehicle architecture directly influences cost and availability metrics

Key UUV Subsystem Trades

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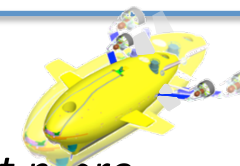
- Energy Subsystem
  - Rechargeable batteries
    - *Low cost but moderate energy*
  - Limited-use batteries
    - *High cost but high energy*
  - Future Technology Battery
    - *Rechargeable & high energy*

- Propulsion Subsystem
  - Single ducted propeller
    - *Efficient (lower energy) but single point of failure*
  - Dual unducted propellers
    - *Less efficient but redundant for higher reliability*

- Hull Shape
  - Elliptical
    - *Low drag (lower energy) but inefficient packaging*
  - Cylindrical
    - *Moderate drag & packaging*
  - Rectangular
    - *High drag but efficient packaging (shorter vehicle)*



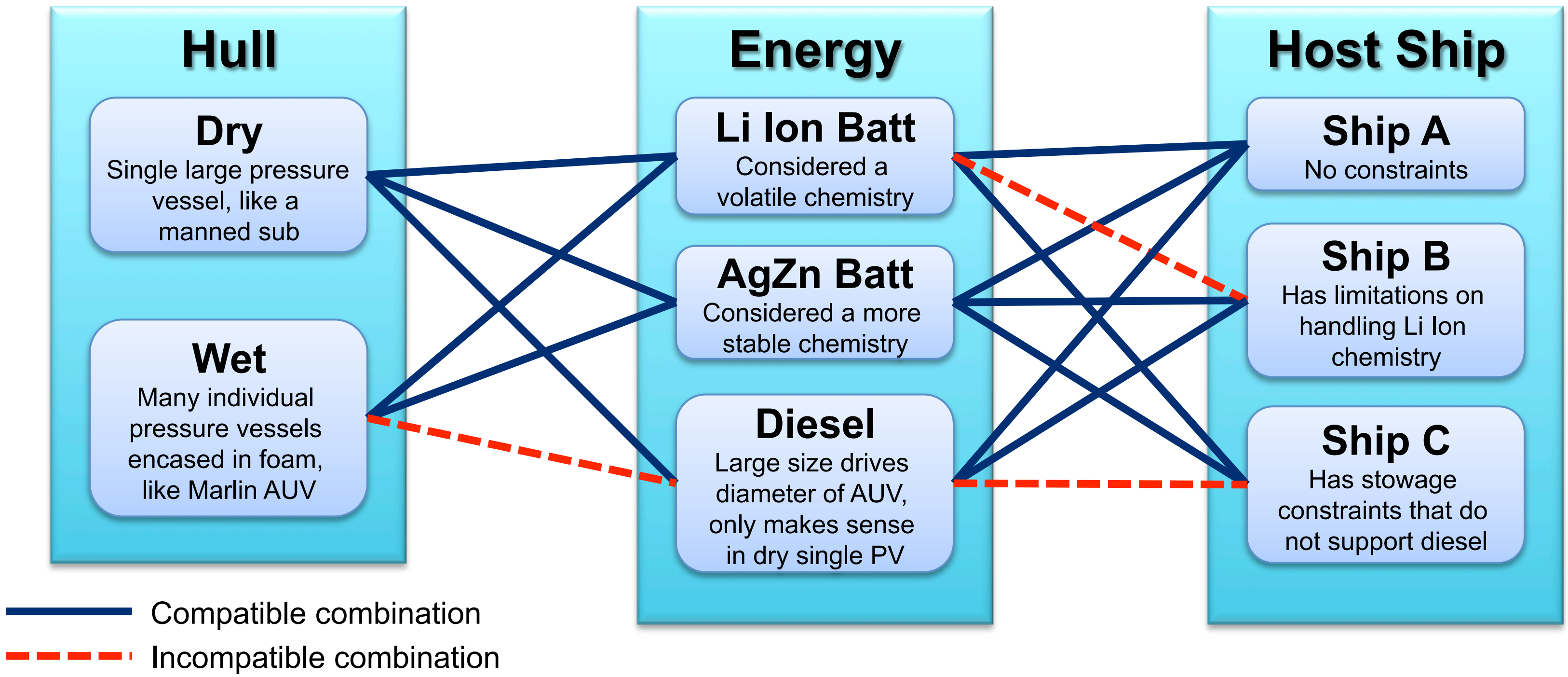
- Vehicle Packaging
  - Dense packaging
    - *Smaller vehicle but more costly to maintain*
  - High Packing Factor
    - *Larger vehicle but easier to maintain*

Vehicle design solution that yields high performance **and** affordability across the lifecycle is not easily identified- advanced analysis is necessary

Trade Constraints

- In the example UUV trades presented, all possible subsystem combinations are compatible
- Trades may at times include incompatible combinations- how are these constraints captured in the model?

Example Trade "Swimlane" Chart:



*There are no constraints between Hull & Host Ship options

Challenge

- Costs are the main driver for projects' defaults
- Lockheed Martin must maximize the value of solutions to our customers by satisfying their true needs at minimal cost over the lifecycle
  - Thorough assessment of the needs of the customer
  - Thorough accounting of the cost to develop, use, and retire a product
- Enabling early in the design cycle to understand the full impact of engineering decisions on a solution's ability to meet performance and cost thresholds will position Lockheed Martin to ultimately provide maximum value to the customer

Consideration of Design Impacts on Cost Must Extend Beyond Material Cost to Fully Determine System Affordability

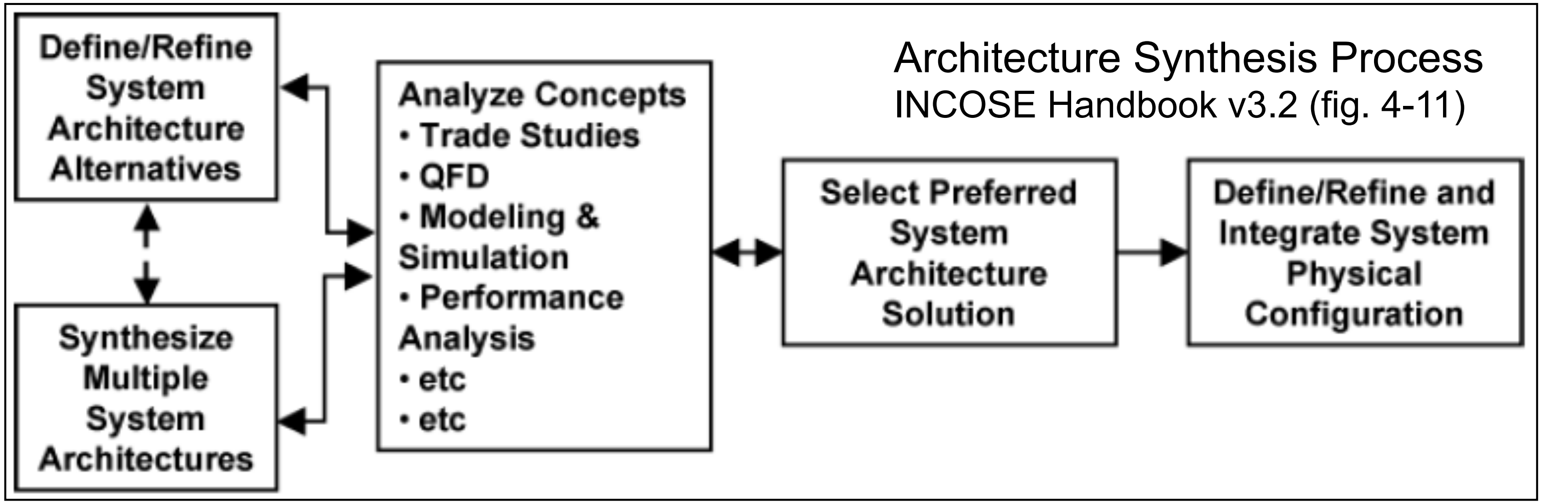
Research Goal

- Create an optimal UUV architecture to maximize overall business value
  - Holistic Architecture (design, manufacturing, operations, etc.)
  - Trade study – final decision by the engineer
  - Demonstrate ROI

Building Blocks

Architectural Design - Definition

- **Dictionary**: Concept that focuses on the components or elements of a structure or system and unifies them into a coherent and functional whole, according to a particular approach in achieving the objective(s) under the given constraints or limitations.
- **Actually means**: Understanding the existing and envisioned building blocks, selecting which ones to use and arranging them in a way that satisfies the requirements, while mapping the system functions to the architecture elements.



Architecture Synthesis Process
INCOSE Handbook v3.2 (fig. 4-11)

Parametric Optimization vs. Architecture Optimization

Parametric Optimization

- Investigate the behavior and properties of a given system with parameters as the decision variables
- Numerical optimization
- Focus on input and output analysis – collection of black boxes in sequence

Simple Example:

Architecture Optimization

- Focus on finding the optimal structure with topology and components as decision variables
- Considering architectural, physical and technological constrains
- Considering variety of optimization goals (both parametric and complex)

Simple Example:

- **Some names:**
  - **Phoenix Integration ModelCenter®**
  - **Esteco ModeFrontier®**
  - **Dassault iSight**
  - **PACE SysArc**

Complementary solutions

Architecture Optimization Workbench Purpose: Accelerate Smarter Architectural Decisions

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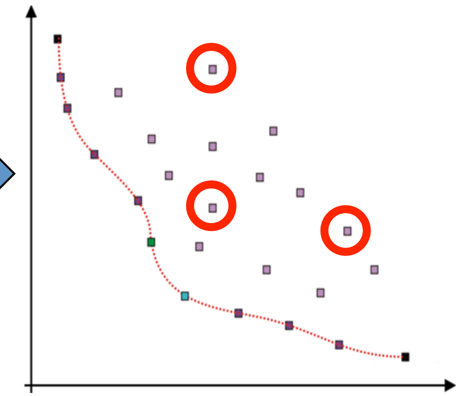
NOW

Definition of design alternatives

Analysis

Review

- Manual process
  - Mostly based on individual undocumented experience
  - Lots of reuse of previous designs
  - No assurance for solution optimality
  - Each additional design – linear effort
- No formal capture of designs
  - Modeling for specific analysis types



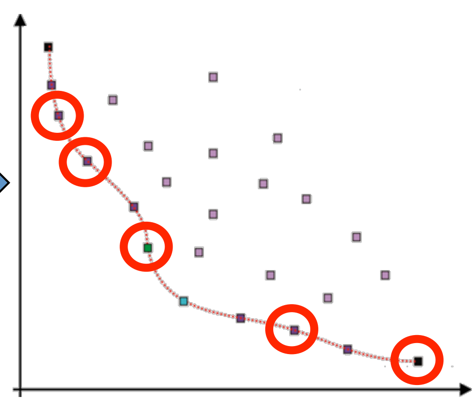
time

With AOW

Architectural template definition

Review

Automated Design Space Exploration



- Faster design
- Smarter designs
- Transparency, traceability
- Knowledge capture and reuse
- Optimization Capabilities in the hands of Architects

Architecture Optimization Workbench Concept

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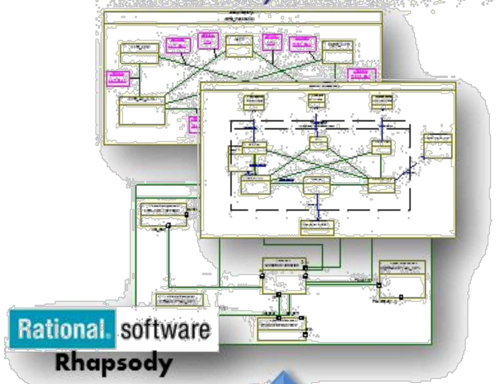
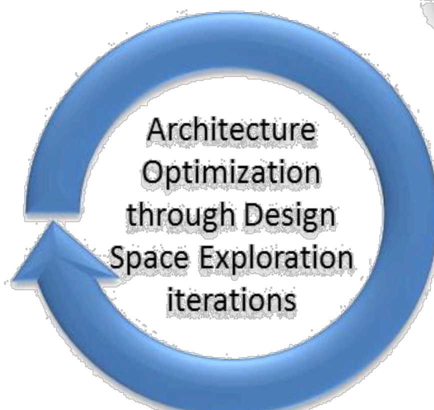
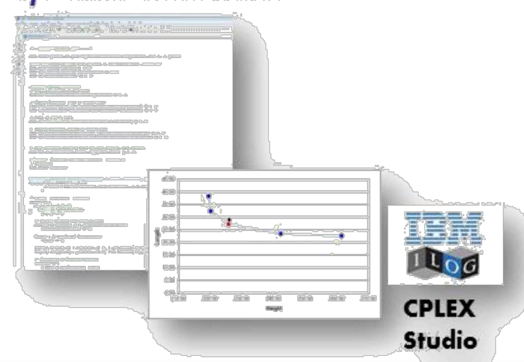
1. Describe system through different SysML views, including design alternatives, constraints and goals



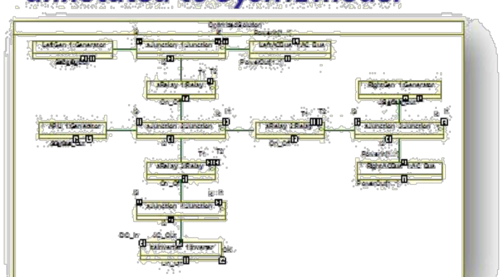
2. Derived Data Schema for Input and output structures



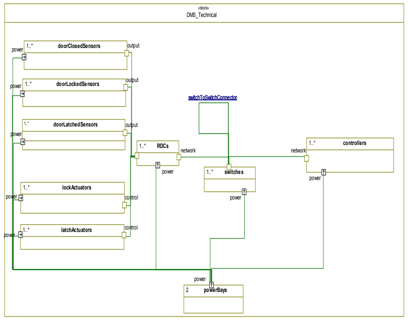
3. Automatic translation(via an interchange format) into Optimization solver

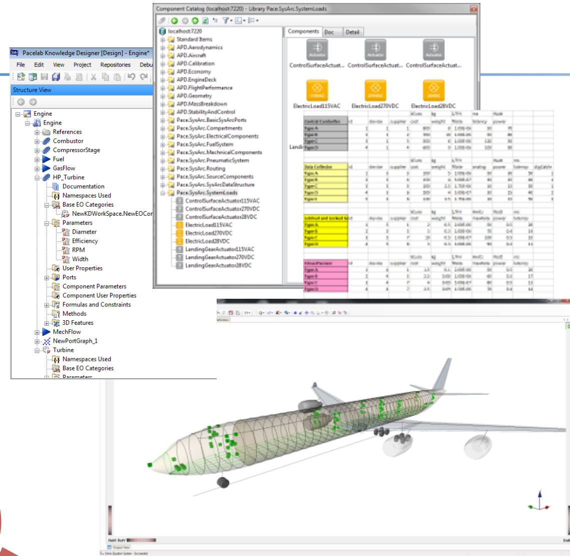


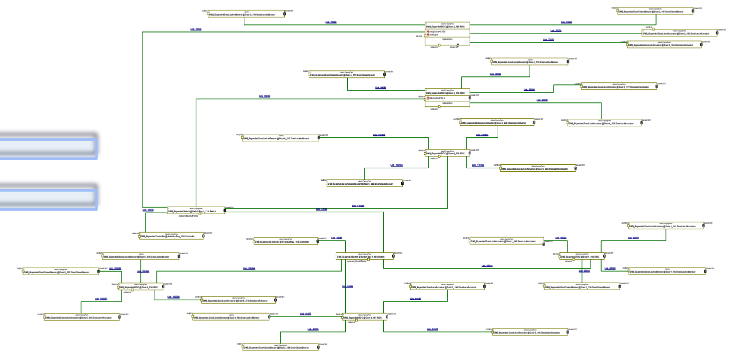
4. Optimized architecture back annotated to SysML model



Concise Modeling







Lots of elements

Large architecture models

Time consuming

Error Prone

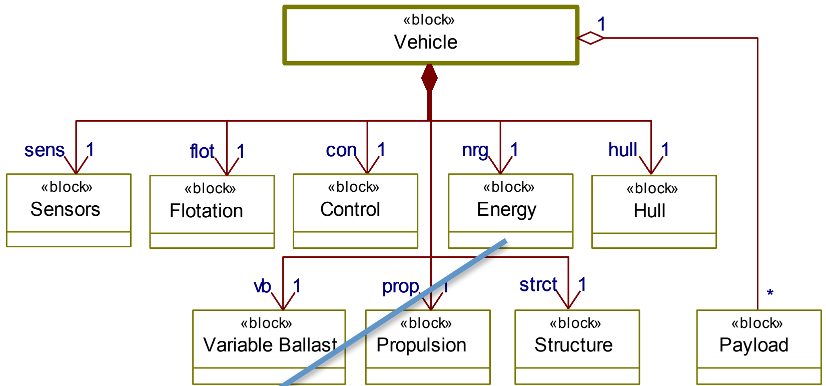
SysML for composition rules

Concise Modeling

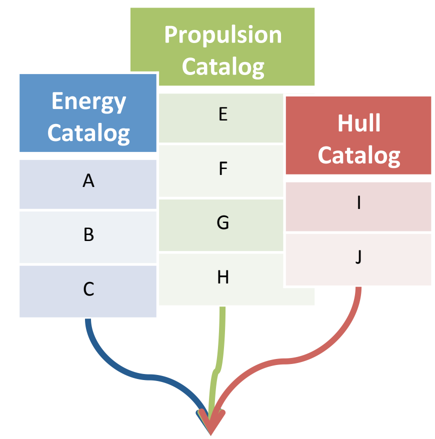
Tabular Instantiation

Days to Hours

Concise Modeling Example



A unique combination of physical options is a candidate physical architecture.



Unique Candidate Physical Architecture:
B – H – I

Energy Catalog

int	float	float	float	float	float
id	IN_SUB_propulsor_type	IN_SUB_propulsor_ducted	IN_VEH_propulsors_num	IN_SUB_propulsor_redundancy	MaintenanceFreq
13500000	1	0	1	0	35
13500001	1	1	1	0	35
13500002	2	1	1	0	35
13500003	1	0	2	0	35
13500004	1	1	2	0	35
13500005	2	1	2	0	35
13500006	1	0	2	1	35
13500007	1	1	2	1	35
13500008	2	1	2	1	35

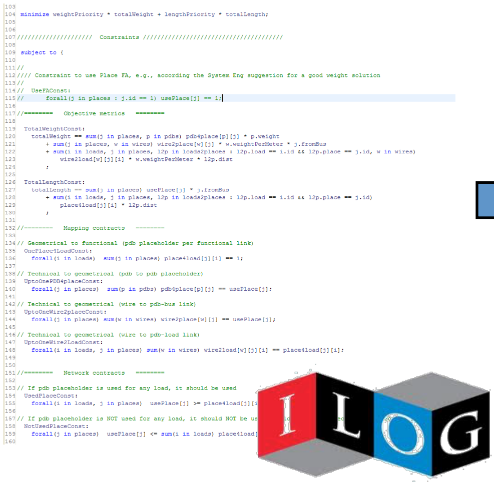
Propulsion Catalog

int	int	int	int	float	float	float
id	energy_type	IN_ENERGY_specificE	energy_fuel_cell_type	MissionCost	MaintenanceFreq	MaintenancePlanCost
3500000	1	68	1	0	18	600
3500000	1	39	1	0	18	1000
3500000	1	62	1	0	18	400
3500000	1	69	1	0	18	800
3500000	2	68	1	0	18	1200
3500000	2	68	2	0	18	800
3500000	2	68	3	0	18	800
3500000	2	68	4	0	18	1000

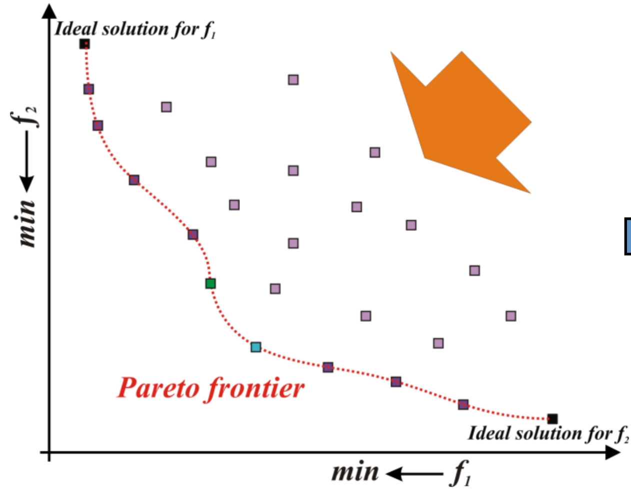
**NOTE: Numerical values are fictional, not actual, and intended only to demonstrate the functionality of FAME.*

Multi Objective Optimization

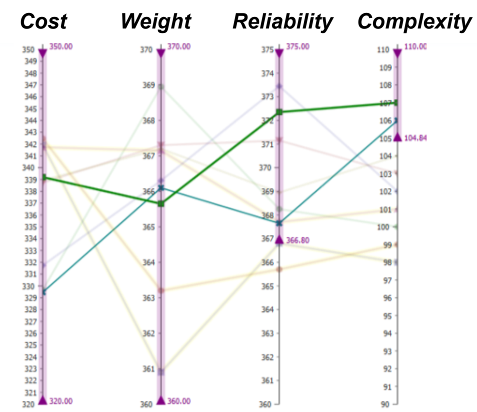
Optimization Problem Formulation (CPLEX)



Calculation of Efficient Frontier

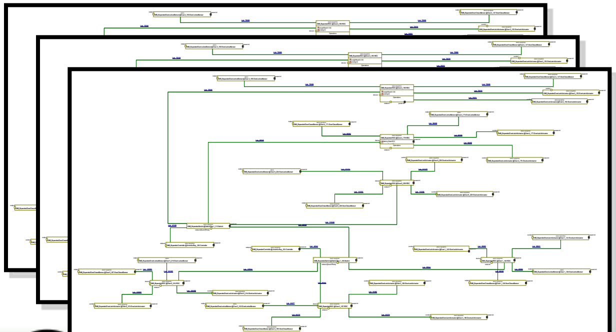


Multi Objective visualization



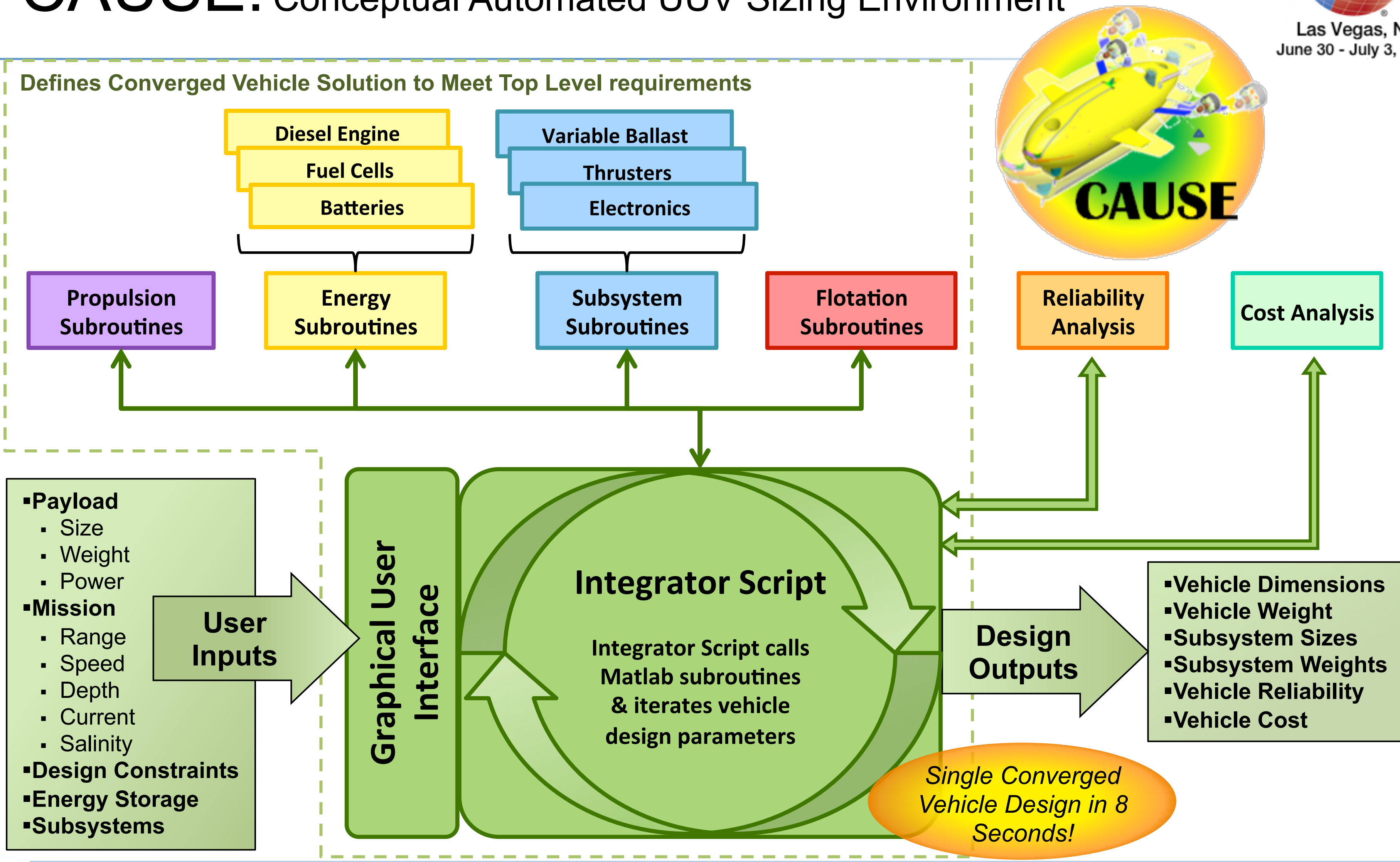
Selection of desired frontier

Architectures on efficient frontier



Next iteration

CAUSE: Conceptual Automated UUV Sizing Environment



CAUSE rapidly evaluates a unique vehicle architecture and defines the overall vehicle size, material cost, and reliability- broader analysis is still necessary

Stitching things together

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FAME
Framework for Affordability Modeling & Evaluation

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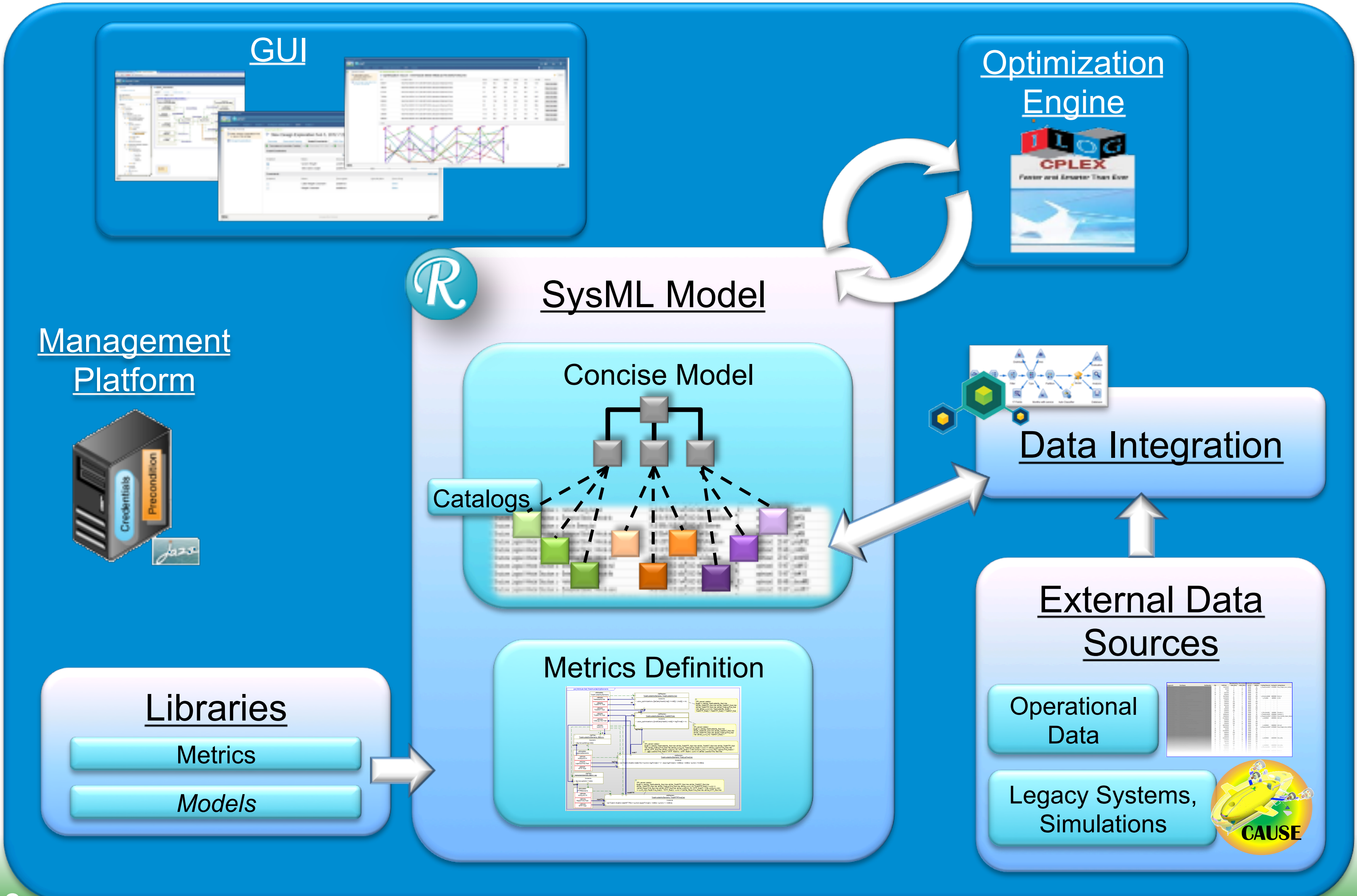
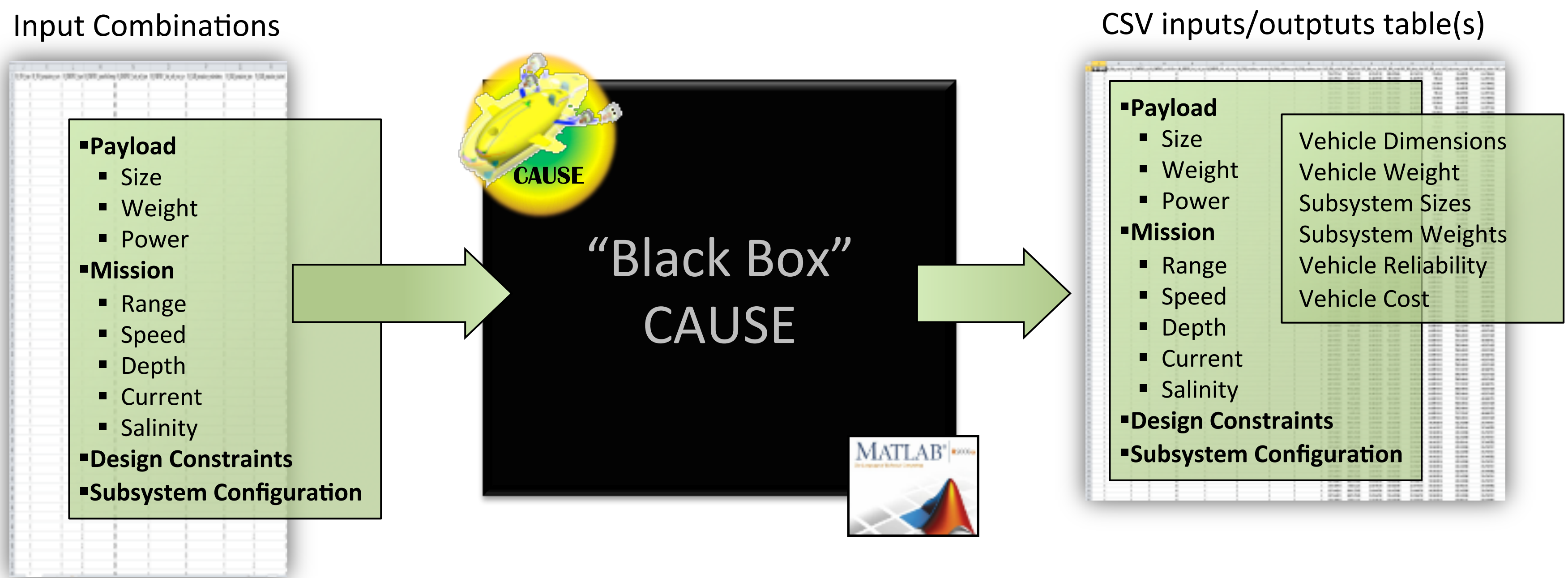


Integration of Legacy Analyses

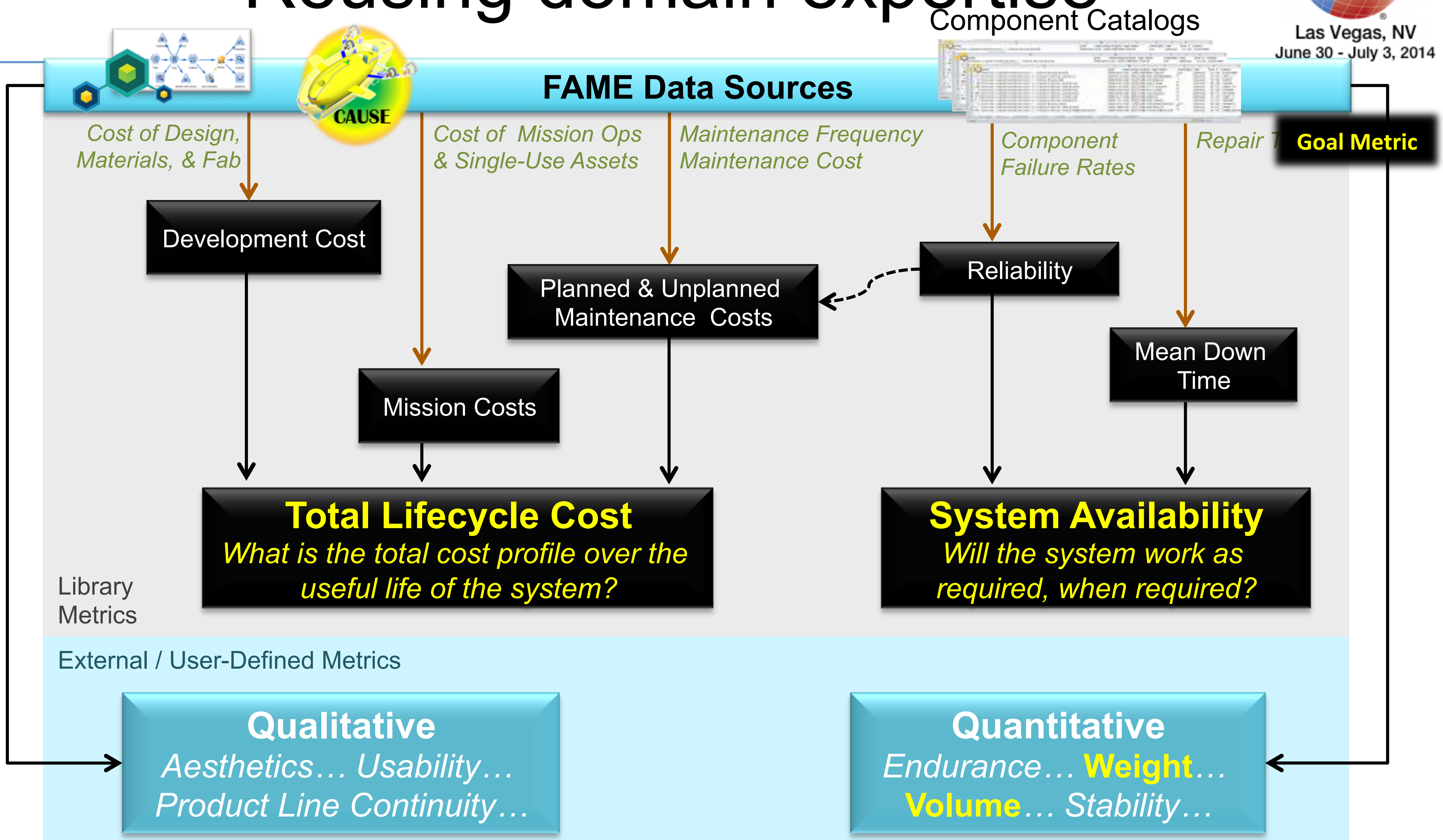
- CAUSE as a Black Box model
- Simulation based, or
- CAUSE inputs & outputs are captured as an approximation model connected to the UUV Concise Model



Black Box approach key points

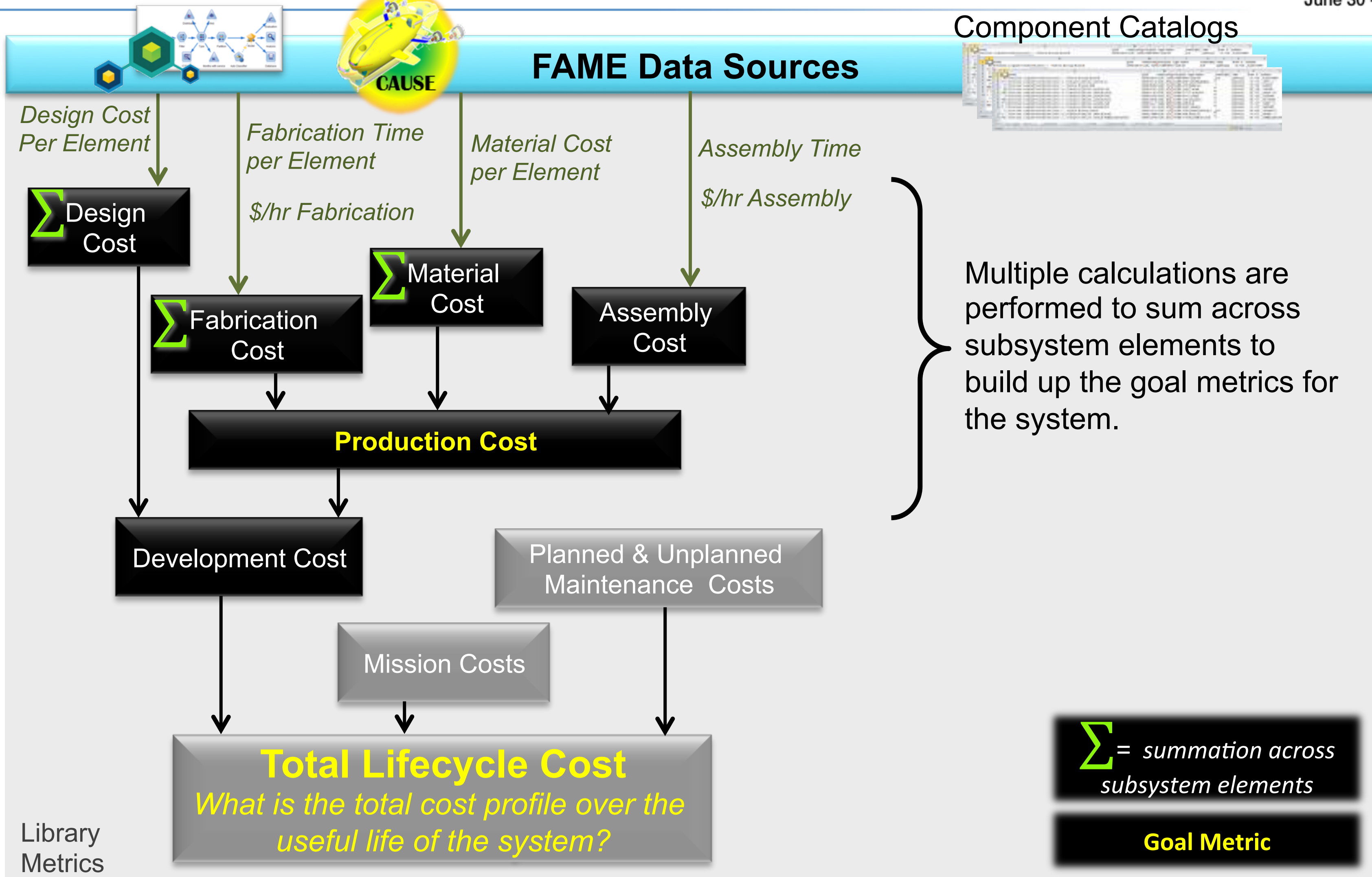
- Simple
- Modular
- Separation of concerns
- Preserves IP and ITAR
- Actually works

Reusing domain expertise



Balancing top level metrics = maximizing value to achieve affordability

Affordability Computation



Metrics Library Concept

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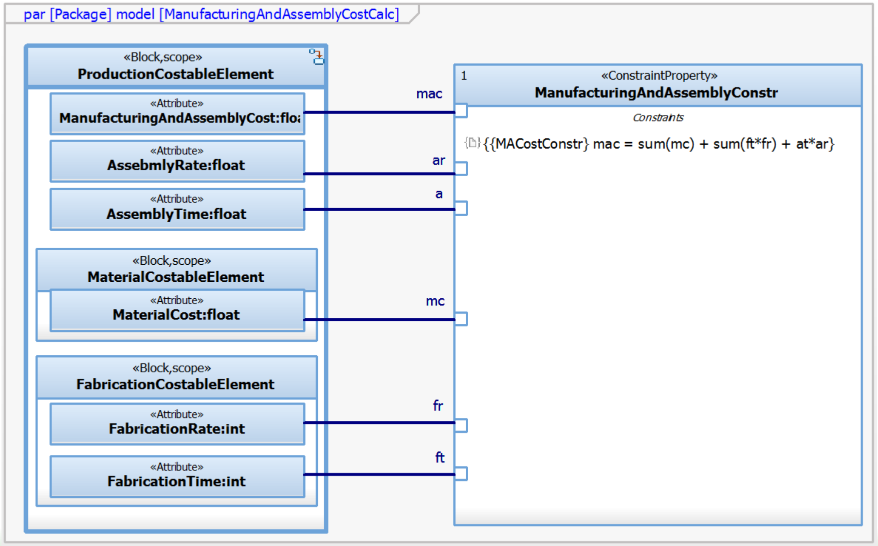
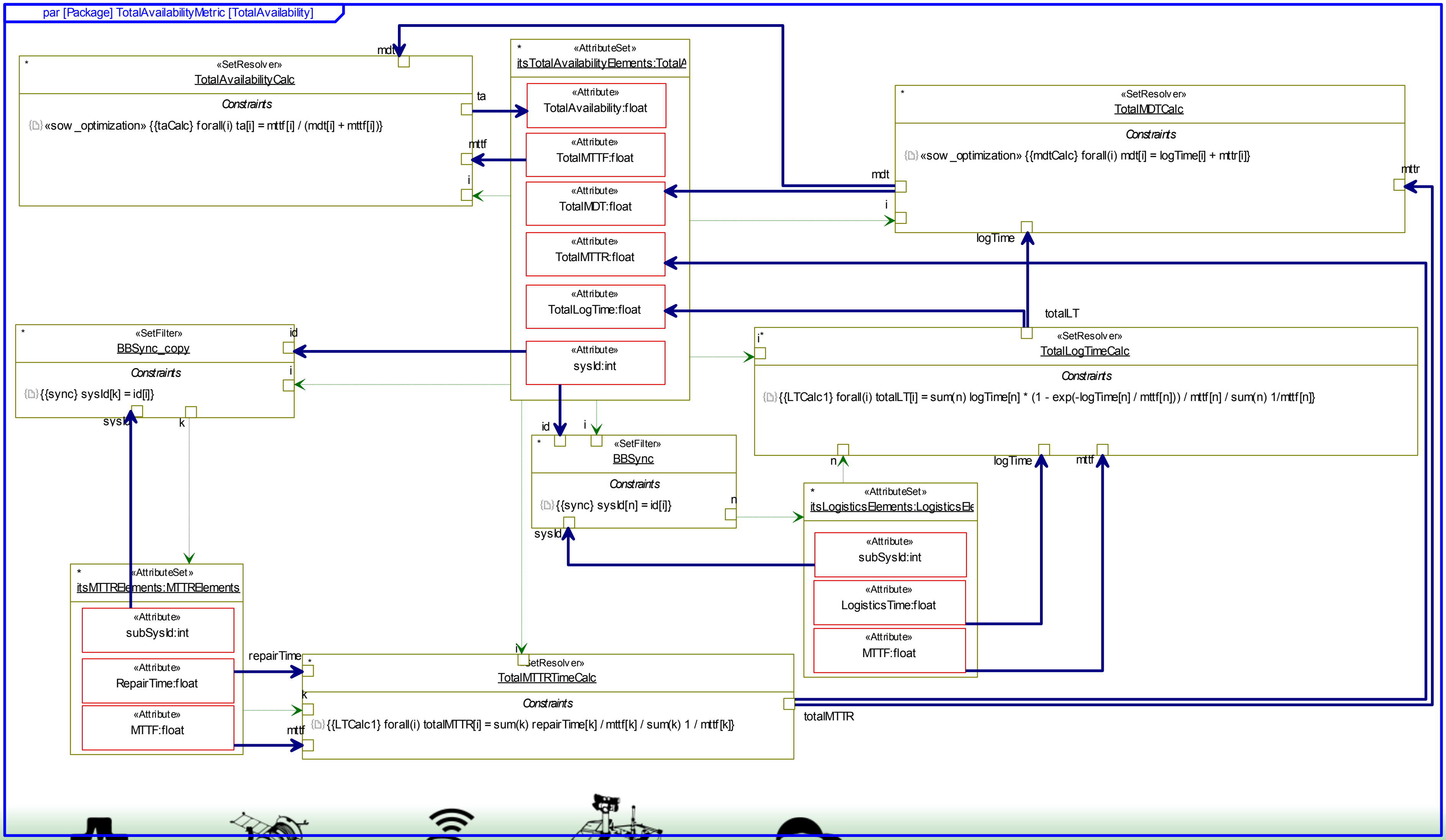
- Parametric Diagram notation captures the attributes and formulas that define Goal Metrics for the optimization
- Blocks define sets of attributes required of architecture elements to support computing the given metrics
  - Block elements are **classification-by-property blocks** (expressed by the *scope* stereotype)
  - Architecture elements can inherit attribute sets
    - “Vehicle” block, when generalized from *ProductionCostableElement,* inherits *ManufacturingAndAssemblyCost, AssemblyTime,* and *AssemblyRate* attributes

$$Cost_{Mfg\&Assy} = \sum_{Mat\_Cost\_Elmts} Cost_{Mat} + Rate_{Labor} \cdot \sum_{Fab\_Cost\_Elmts} Time_{Fab} + Rate_{Labor} \cdot Time_{Assy}$$

Common Library Metrics Are Independent of a Particular Design or Domain Model



System Availability Metric



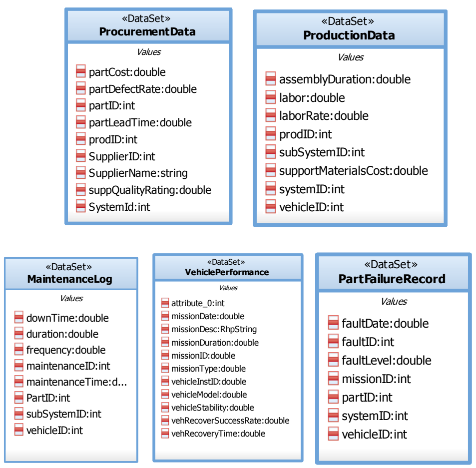
Reuse is Key

- Metrics Library supports quantification of key trade criteria that are common to many products & domains
  - Provides a baseline metric set to directly reuse or modify / expand
- Classification-by-property blocks enable quick implementation for existing structural elements to generalize & inherit the necessary attribute sets
  - Updates to attribute set block automatically flow to structural elements
  - Matching exercise clarifies any discrepancies in nomenclature when applying metrics to existing models

Operational Data Integration

- Operational data provides the opportunity to enhance trade assessments with real measured cost and performance values for trade options
- Operational data is often in a format that does not readily support direct processing in trade metrics
- Challenge: how to integrate Operational Data with Data for Optimization?

Operational data



- Large data set
- Different structure / sources/ formats

How to fill the Manufacturing Labor Time attribute with measured Operational Data?

Catalog data

Energy

subSystemID	Cost	Labor Cost
1001	100	
1002	200	
1003	50	
1004	400	
1005	20	

Propulsion

subSystemID	Cost	Labor Cost
2001	80	
2002	70	
2003	78	
2004	50	
2005	70	

- Catalog data – small data set
- Input for the Optimization Engine

Operational Data Integration

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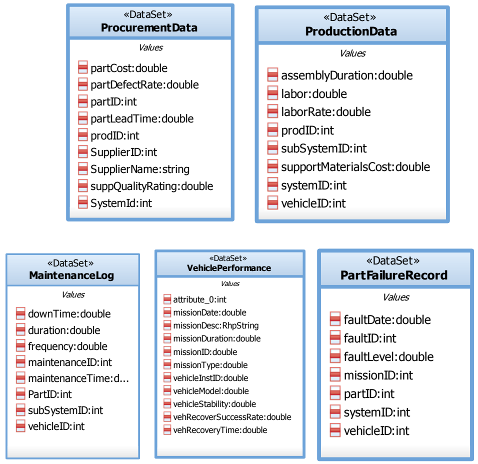
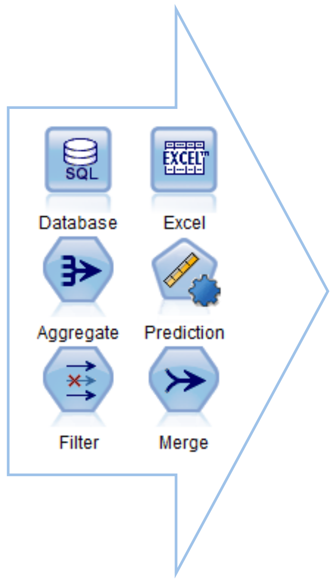
Operational data



- Large data set
- Different structure / sources/ formats



Catalog data

Energy

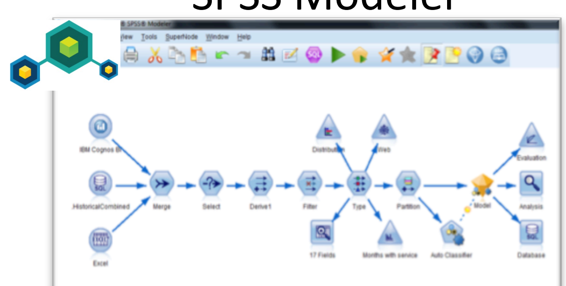
subSystemID	Cost	Labor Cost
1001	100	25
1002	200	30
1003	50	28
1004	400	17
1005	20	33

Propulsion

subSystemID	Cost	Labor Cost
2001	80	14
2002	70	15
2003	78	13.5
2004	50	17
2005	70	12

- Catalog data – small data set
- Input for the Optimization Engine

SPSS Modeler



Operational Data Integration

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Catalog ID

IDs to correlate with Cause data

Catalog data for Propulsion

id	IN_SUB_propulsc	IN_SUB_propulsor_ductec	IN_SUB_propulsor_redu	IN_SUB_propulsor_r	MaintenanceFr	MaintenancePlanCo	MaintenanceUnPlanCc	LogisticsTime	NumOfSpares	RepairTime	name
16100000	1	1	0	1	35	4000	6000	6000	1	24	Single_Duct_NoRed
16100001	1	0	1	2	35	6000	6000	4000	2	18	Double_Open_Redun

CAUSE data for Propulsion

The CAUSE data ID

Input configuration

CAUSE output

Extract from the Manufacturing Operational Data

id	IN_SUB_propulsor_num	IN_SUB_propulsor_redundancy	IN_SUB_propulsor_type	IN_SUB_propulsor_ducted	OUT_propulsor_volume	OUT_Propulsor_Diameter	ConfigId	MC_mttf_effective	LaborTime	UnitCost
38000000	1	0	1	1	46623.73928	1.854019446	1	1414788.576		
38000001	1	0	1	1	25056.1019	1.507277846	2	1414788.576		
38000002	1	0	1	1	29362.26699	1.58912605	3	1414788.576		
38000003	2	1	1	0	30295.79777	2.538524122	4	1414788.576		
38000004	2	1	1	0	15009.18252	2.008299673	5	1414788.576		
38000005	2	1	1	0	17916.54636	2.130503092	6	1414788.576		
38000006	1	0	1	1	40343.11383	1.766702423	7	1414788.576		

Manufacturing data

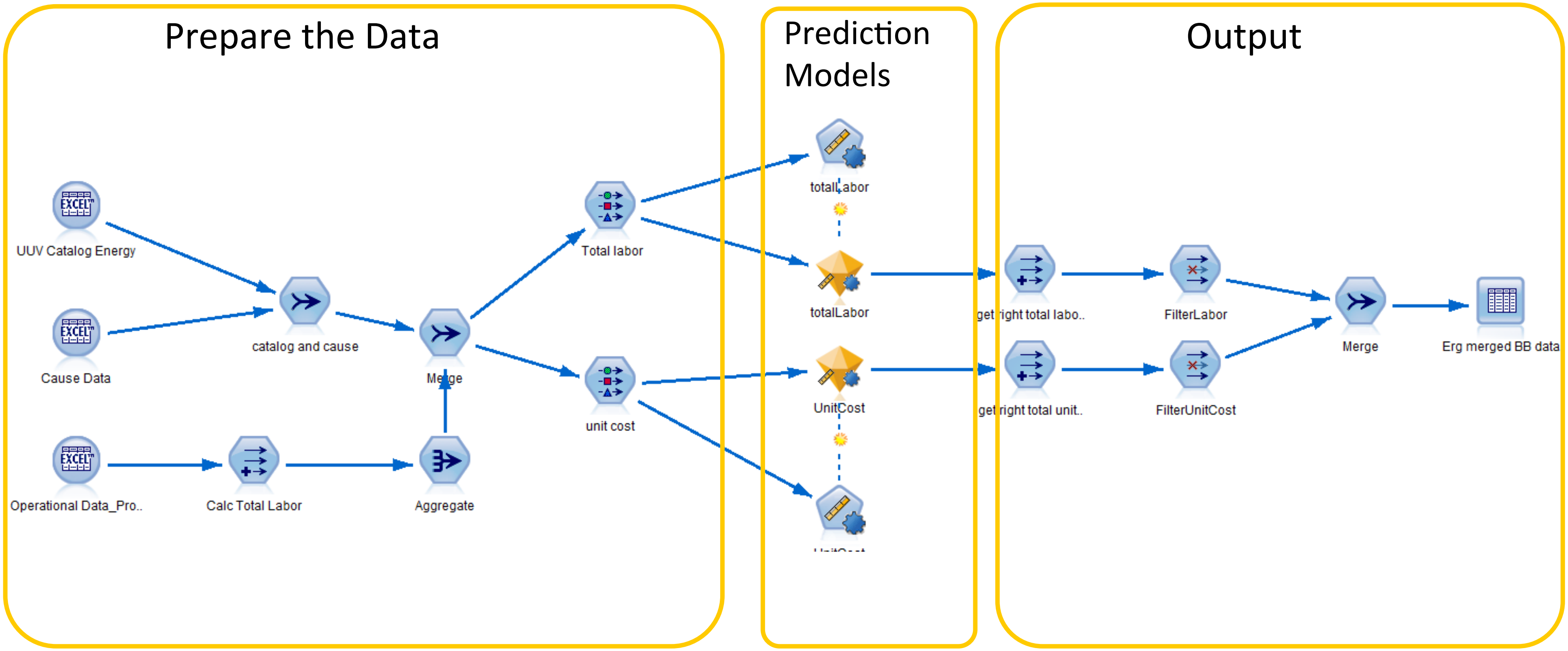
UUV production data modeled after SAP schema

Additional data input supports mapping operational data to catalog

Program ID	Part Name	PartNumber	Qty	UnitCost	Manufacturing Labor (hrs)	Procurement Labor (hrs)	RefVehVol (in^3)	RefVehkWh (kWhr)	Catalog Element	Catalog ID	Catalog Name

The SPSS Process for Energy

- Historic trends to predict future developments



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SPSS Results for Energy

ConfigId	id	name	UnitCost	totalLabor
1.000	4800000....	Engy Batt Secondary	121439....	21.818
16.000	4800000....	Engy Batt Secondary	121439....	21.818
34.000	4800000....	Engy Batt Secondary	121439....	21.818
13.000	4800000....	Engy Batt Secondary	121439....	21.818
4.000	4800000....	Engy Batt Secondary	121439....	21.818
31.000	4800000....	Engy Batt Secondary	121439....	21.818
22.000	4800000....	Engy Batt Secondary	121439....	21.818
7.000	4800000....	Engy Batt Secondary	121439....	21.818
28.000	4800000....	Engy Batt Secondary	121439....	21.818
19.000	4800000....	Engy Batt Secondary	121439....	21.818
10.000	4800000....	Engy Batt Secondary	121439....	21.818
25.000	4800000....	Engy Batt Secondary	121439	21.818
18.000	4800002....	Engy Batt FutureSec	$null$	$null$
33.000	4800002....	Engy Batt FutureSec	$null$	$null$
30.000	4800002....	Engy Batt FutureSec	$null$	$null$
27.000	4800002....	Engy Batt FutureSec	$null$	$null$
24.000	4800002....	Engy Batt FutureSec	$null$	$null$
21.000	4800002....	Engy Batt FutureSec	$null$	$null$
36.000	4800002....	Engy Batt FutureSec	$null$	$null$
15.000	4800002....	Engy Batt FutureSec	$null$	$null$
12.000	4800002....	Engy Batt FutureSec	$null$	$null$
9.000	4800002....	Engy Batt FutureSec	$null$	$null$
6.000	4800002....	Engy Batt FutureSec	$null$	$null$
3.000	4800002....	Engy Batt FutureSec	$null$	$null$
35.000	4800001....	Engy Batt Primary	337237....	23.000
11.000	4800001....	Engy Batt Primary	337237....	23.000
26.000	4800001....	Engy Batt Primary	337237....	23.000
17.000	4800001....	Engy Batt Primary	337237....	23.000
8.000	4800001....	Engy Batt Primary	337237....	23.000
29.000	4800001....	Engy Batt Primary	337237....	23.000
14.000	4800001....	Engy Batt Primary	337237....	23.000
5.000	4800001....	Engy Batt Primary	337237....	23.000
32.000	4800001....	Engy Batt Primary	337237....	23.000
23.000	4800001....	Engy Batt Primary	337237....	23.000
2.000	4800001....	Engy Batt Primary	337237....	23.000
20.000	4800001....	Engy Batt Primary	337237....	23.000

Predictions

- Regression
- Generalized Linear
- KNN Algorithm
- SVM
- C&R Tree
- CHAID
- Neural Net
- Linear

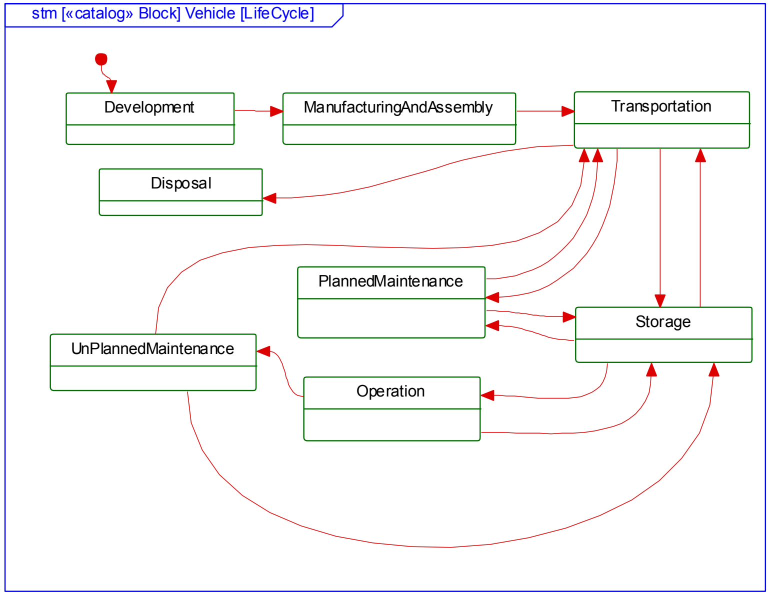
ConfigId	id	name	totalLabor	UnitCost
1.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
16.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
34.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
13.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
4.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
31.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
22.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
7.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
28.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
19.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
10.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
25.000	4800000.0...	Engy Batt Secondary	21.818	121439.636
18.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
33.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
30.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
27.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
24.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
21.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
36.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
15.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
12.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
9.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
6.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
3.000	4800002.0...	Engy Batt FutureSec	21.818	121439.636
35.000	4800001.0...	Engy Batt Primary	23.000	337237.500
11.000	4800001.0...	Engy Batt Primary	23.000	337237.500
26.000	4800001.0...	Engy Batt Primary	23.000	337237.500
17.000	4800001.0...	Engy Batt Primary	23.000	337237.500
8.000	4800001.0...	Engy Batt Primary	23.000	337237.500
29.000	4800001.0...	Engy Batt Primary	23.000	337237.500
14.000	4800001.0...	Engy Batt Primary	23.000	337237.500
5.000	4800001.0...	Engy Batt Primary	23.000	337237.500
32.000	4800001.0...	Engy Batt Primary	23.000	337237.500
23.000	4800001.0...	Engy Batt Primary	23.000	337237.500
2.000	4800001.0...	Engy Batt Primary	23.000	337237.500
20.000	4800001.0...	Engy Batt Primary	23.000	337237.500

CAUSE does not have cost prediction for Future Battery

SPSS prediction capability evaluates Future Battery Unit Cost

**NOTE: Numerical values are fictional, not actual, and intended only to demonstrate the functionality of FAME.*

Operational Models



$$Cost\downarrow Mfg\&Assy = \sum Mat\_Cost\_Elmts\uparrow ▒ (Cost\downarrow Mat\uparrow l + Rate\downarrow Labor \ldots) \sum Fab\_Cost\_Elmts\uparrow ▒ (Time\downarrow Fab + Rate\downarrow Labor \cdot Time\downarrow Ass\uparrow y)$$

- Reuse existing (recorded) business processes
- Automate the creation of metrics
- Sadly – we didn't yet have time to implement….

IBM LOCKHEED MARTIN

INCOSE International Symposium
Las Vegas, NV
June 30 - July 3, 2014

Results

Design Explorations >

Apr 29, 2014, 8 results

Overview | Generated Catalog | Goals | OPL Files | **Optimization Runs**

✓ Generate and populate Catalog → ✓ Generate OPL files → ✓ Run Optimization

Num of Iterations: 8 Max duration of an Iteration [Sec]: 180 Alpha ratio [%]: 0.0001 Max Work Memory MB: 2048

100%

Total Duration: 1053 sec Iteration: 9/8 Duration: Status: end

Highest performing architecture solutions

ID	OUT_VEH_volume	OUT_VEH_weight	TotalCost	TotalProductionCost	TotalAvailability
fb2f1a2d-b022-4387-a5a0-13d47c5db698	24,379.2000	1,934.5200	44,352.4000	1,581.7600	0.9872
070db28d-17a0-4458-8923-b4f6bfa41f7e	20,802.9000	1,649.5600	64,704.1000	1,522.3200	0.9872
5f8e6812-8181-4a9b-9a91-55ace13adea4	38,715.8000	3,076.8700	44,298.8000	1,523.3700	0.9872
54dde489-d86c-4e85-bb5c-b5e25f2af0e5	24,238.2000	1,664.8900	64,334.1000	1,656.3800	0.9872
e842c55e-46bd-48e3-8717-6f641ec1a396	58,747.6000	2,716.6000	44,483.3000	1,635.5000	0.9881
18d0d83b-0090-47c0-88cc-d30fa1656736	58,914.0000	2,586.7200	44,718.1000	1,874.3400	0.9881
f5b9e4c3-2afa-4913-9f6f-6ebd6db6b59b	49,207.3000	2,274.1300	69,403.6000	1,609.1300	0.9881
a58c5614-b7f6-4760-880b-59a3dbfa8a68	49,685.8000	2,180.2700	67,867.3000	1,833.5400	0.9881

Reset

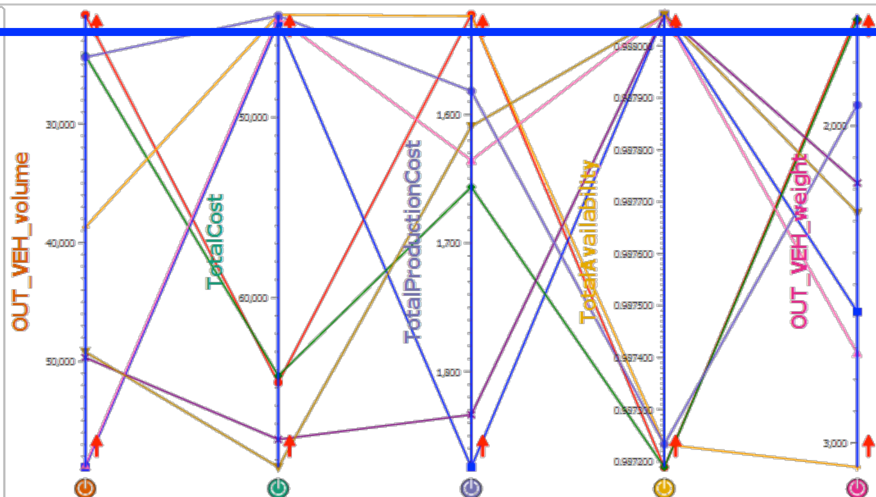
OUT_VEH_weight
1,650 - 3,077

OUT_VEH_volume
20,803 - 58,914

TotalProductionCost
1,522 - 1,874

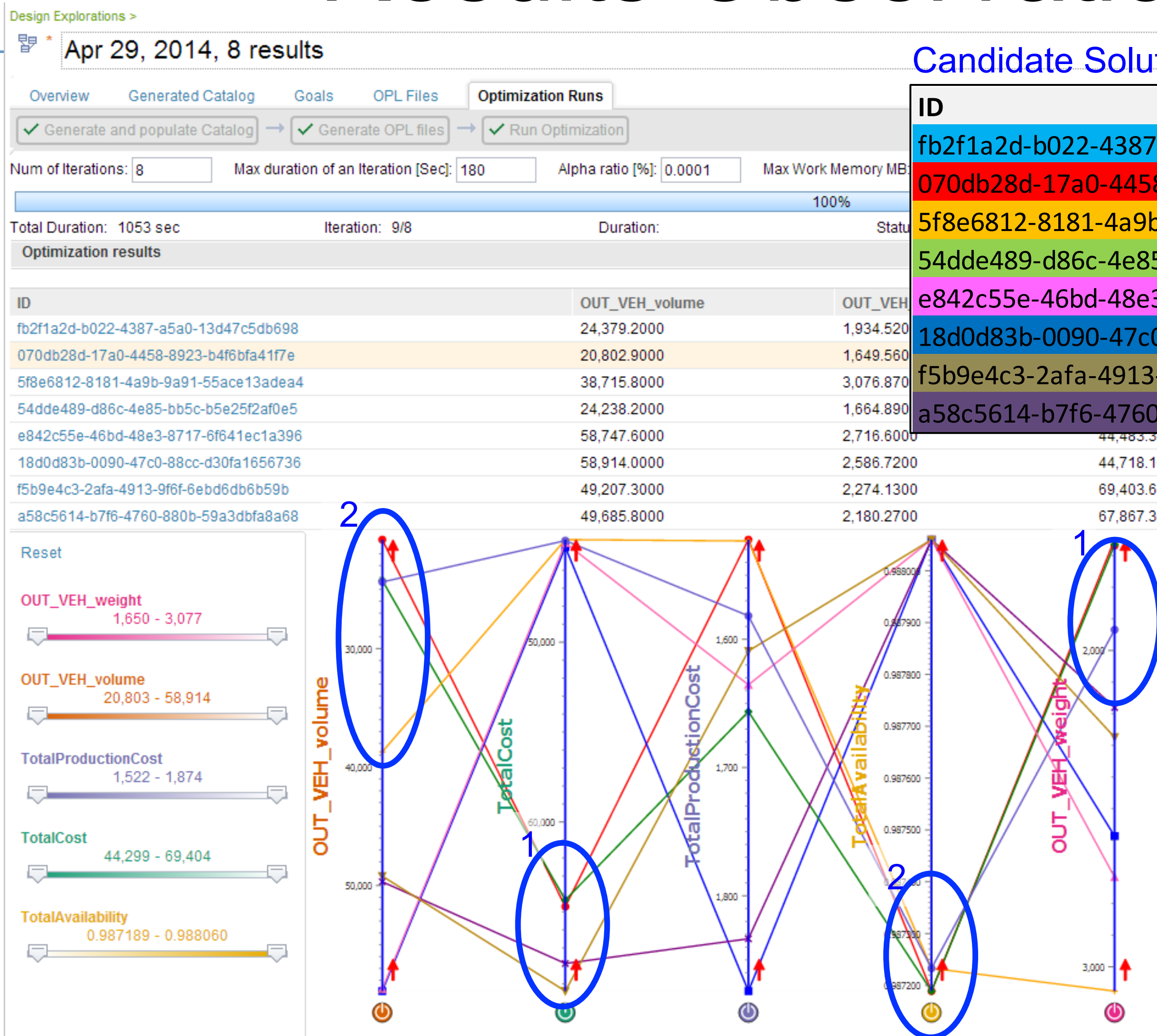
TotalCost
44,299 - 69,404

TotalAvailability
0.987189 - 0.988080



Eight optimal solutions identified

Results Observations



Candidate Solution Color Guide

ID	enrgy	prop	vhl	Hull
fb2f1a2d-b022-4387-a5a0-13d4	Future	Single Ducted	LowPF	ellip
070db28d-17a0-4458-8923-b4f	Primary	Single Ducted	LowPF	ellip
5f8e6812-8181-4a9b-9a91-55a	Secondary	Single Ducted	LowPF	ellip
54dde489-d86c-4e85-bb5c-b5e	Primary	Single Ducted	HighPF	ellip
e842c55e-46bd-48e3-8717-6f6	Future	Double Open	LowPF	ellip
18d0d83b-0090-47c0-88cc-d30	Future	Double Open	HighPF	ellip
f5b9e4c3-2afa-4913-9f6f-6ebd	Primary	Double Open	LowPF	ellip
a58c5614-b7f6-4760-880b-59a	Primary	Double Open	HighPF	ellip

1. Solutions with Primary Batteries Score the Worst in Total Cost, but the Best in Vehicle Weight
2. Solutions with Single Ducted Propellers Score the Worst in Availability, but Generally Better in Vehicle Weight & Volume
3. All Solutions Have Elliptical Hull Shape

FAME Metric Assessments Are Consistent and Valid

Summary

- Many organizations already have extensive reusable assets
- Data holds insights and fills gaps
- Reusing and planning for reuse will get you further

Thank you

Q&A