34th Annual INCOSE international symposium

hybrid event

Dublin, Ireland
July 2 - 6, 2024

Sean Bumgarner, Graduate Student in Systems Engineering, Colorado State University
Sarah Rudder, Graduate Student in Systems Engineering, Colorado State University
Jeremy Daily, Associate Professor of Systems Engineering, Colorado State University

A Model-Based System Engineering Approach for Trucking Fleet Replacement

Agenda

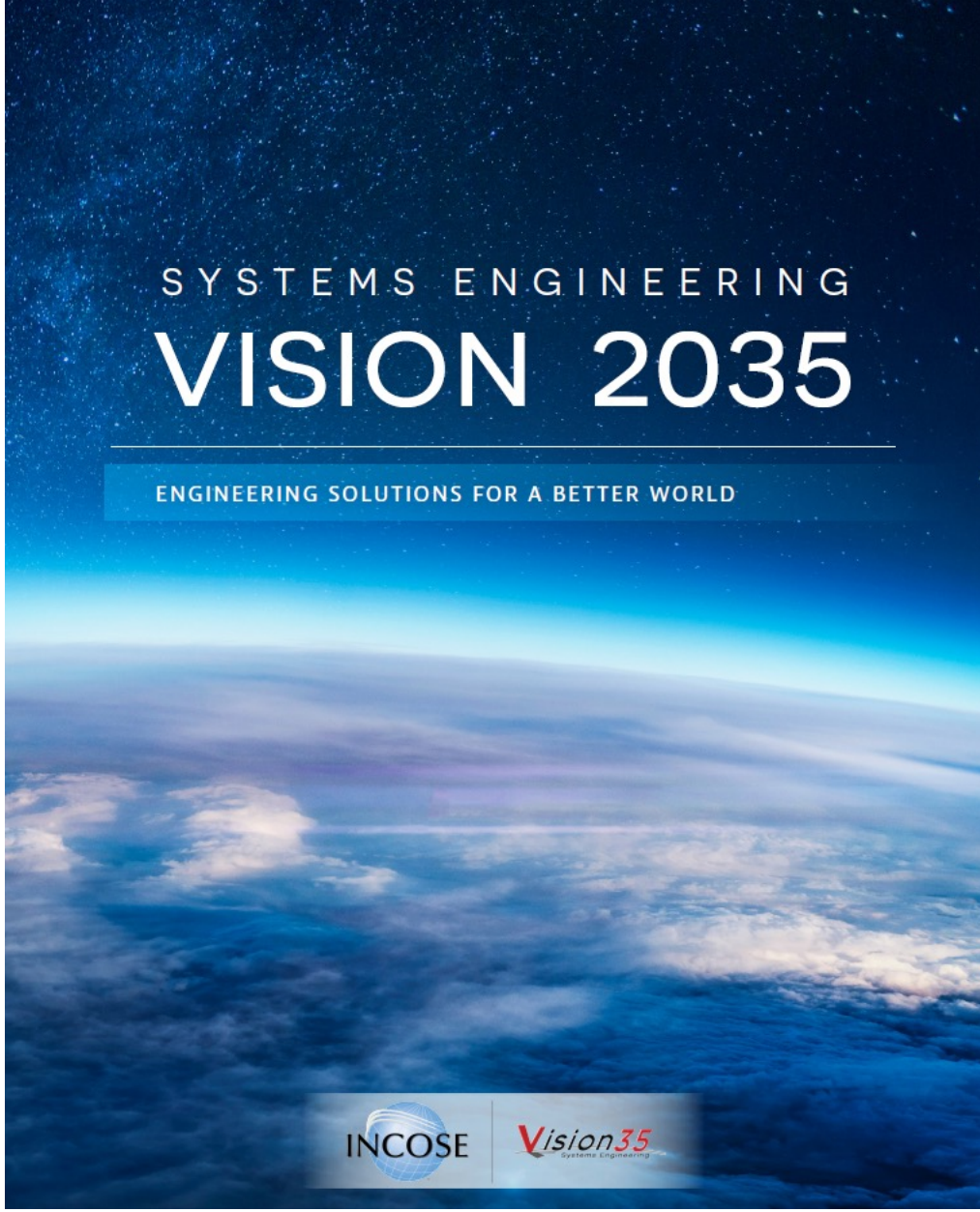
- Trucking as a system
- Truck replacement
- Challenges
- Modeling approach
- Parametrics
- Results
- Take Aways

Trucking as a System

- Engineer: “The future of systems engineering is model-based…”
- Trucker: “What is systems engineering?”

“Systems engineering will be embraced by a greater number and broader range of small and medium enterprises...”
-INCOSE Vision 2035

Trucking is one example of these new enterprises to systems engineering.



About Motor Freight Transportation (Trucking)

- “If you bought it, a truck brought it.”
- Most trucking is done by small business (10 trucks or less).
- In the USA, there are approximately 13 million trucks.
- There are around 3.5 million truck drivers in the USA
- 1.86 million companies operate at least 1 semi-truck, straight truck, or other truck.

Even CSU students drive trucks.

Types of Motor Carriers

- Major for-hire segments
  - Truckload – A trailer full of one thing
  - **Less-than-truckload** – A trailer of different things
  - Parcel/courier – Small packages (e.g. UPS, Fedex, DHL)
  - Hazardous materials – Liquid or dry chemicals and other nasty things
  - Specialized hauls – Chemicals, bridge spans, wind turbines, etc.
  - Household goods – Moving companies
  - Intermodal – Shipping to/from rail or port
- Not-for-hire
  - Private Fleets (e.g. Walmart)
  - Heavy haul (race teams, horse farms)

https://www.freightwaves.com/wp-content/uploads/2020/05/ATS_project_cargo_2.jpg

Eventually, trucks need to be replaced.

Prior Work for Fleet Replacement Model

Assumptions with age:

- Maintence cost per-mile increases
- Fuel economy deteriorates
- Resale value decreases
- Procurement cost rise

Age	Vehicle Miles Traveled	Maintenance Cost ($)	Resale Value ($)
1	[28000,48000]	0.2	28,000
2	[25900,44400]	0.24	27,000
3	[25200,43200]	0.28	26,000
4	[22400,38400]	0.32	24,000
5	[21700,37200]	0.36	21,000
6	[21000,36000]	0.4	17,000
7	[21000,36000]	0.44	16,000
8	[20300,34800]	0.48	15,000
9	[20300,34800]	0.52	15,000
10	[20300,34800]	0.56	15,000

Taghipour, S., & Salari, N. (2015). Optimal sustainable vehicle replacement model. *2015 Annual Reliability and Maintainability Symposium (RAMS)*, 1–6. https://doi.org/10.1109/RAMS.2015.7105110

Developing Constraint Limits

- Measure economy per mile-based on age
- Use trade studies to calculate CO2 impacts

Age	Costs per mile ($)			Total cost ($)
	Fuel	CO2	Total	
1	0.13	0.09	0.43	[11913,20423]
2	0.14	0.10	0.48	[12495,21421]
3	0.16	0.11	0.54	[13663,23423]
4	0.17	0.12	0.61	[13561, 23248]
5	0.19	0.13	0.67	[14608,25042]
6	0.21	0.14	0.75	[15685, 26889]
7	0.23	0.16	0.83	[17404,29836]
8	0.26	0.18	0.92	[18719,32090]
9	0.26	0.18	0.96	[19531,33482]
10	0.26	0.18	1.00	[20343,34874]

Taghipour, S., & Salari, N. (2015). Optimal sustainable vehicle replacement model. *2015 Annual Reliability and Maintainability Symposium (RAMS)*, 1–6. https://doi.org/10.1109/RAMS.2015.7105110

Calculating Constraints

	Remaining Year				
Age	10	9	8	7	6
1	M*	M	M	M	M
2		17,902	M	21,214	19,819
3			20,274	19,773	18,062
4				18,310	16,825
5					15,958

- M indicates the truck should always be repaired
- Repairs with values, should only be repaired if cost is under the limit

	Remaining Year				
Age	5	4	3	2	1
1	M	M	M	M	M
2	21,246	M	M	M	M
3	18,068	22,322	M	M	M
4	15,705	19,238	M	M	M
5	14,687	17,111	23,388	M	M
6	17,408	18,199	23,270	M	M
7		17,687	21,443	M	M
8			20,685	30,830	M
9				29,728	M
10					M

Taghipour, S., & Salari, N. (2015). Optimal sustainable vehicle replacement model. *2015 Annual Reliability and Maintainability Symposium (RAMS)*, 1–6. https://doi.org/10.1109/RAMS.2015.7105110

Case Study Modelling

- Cost models that do not take emissions into account recommend more repair.
- Transform the document-based approach to a model.
- Goal: application to an arbitrary fleet.

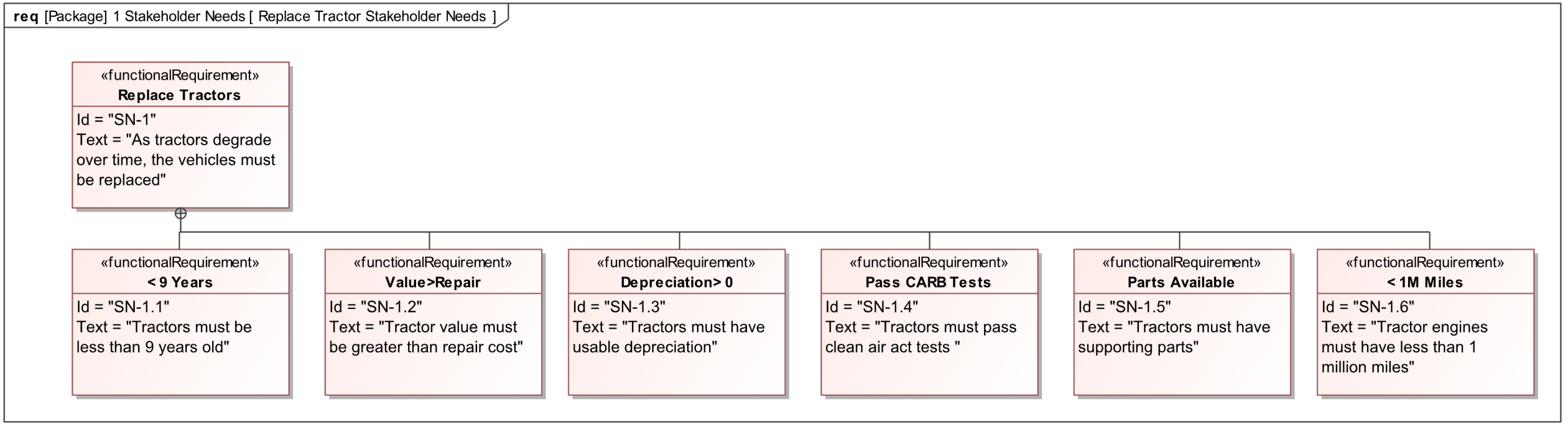
https://www.quora.com/What-causes-white-smoke-from-my-diesel-truck-when-cold

Tool: Catia Magic Systems of Systems Architect
Language: SysML

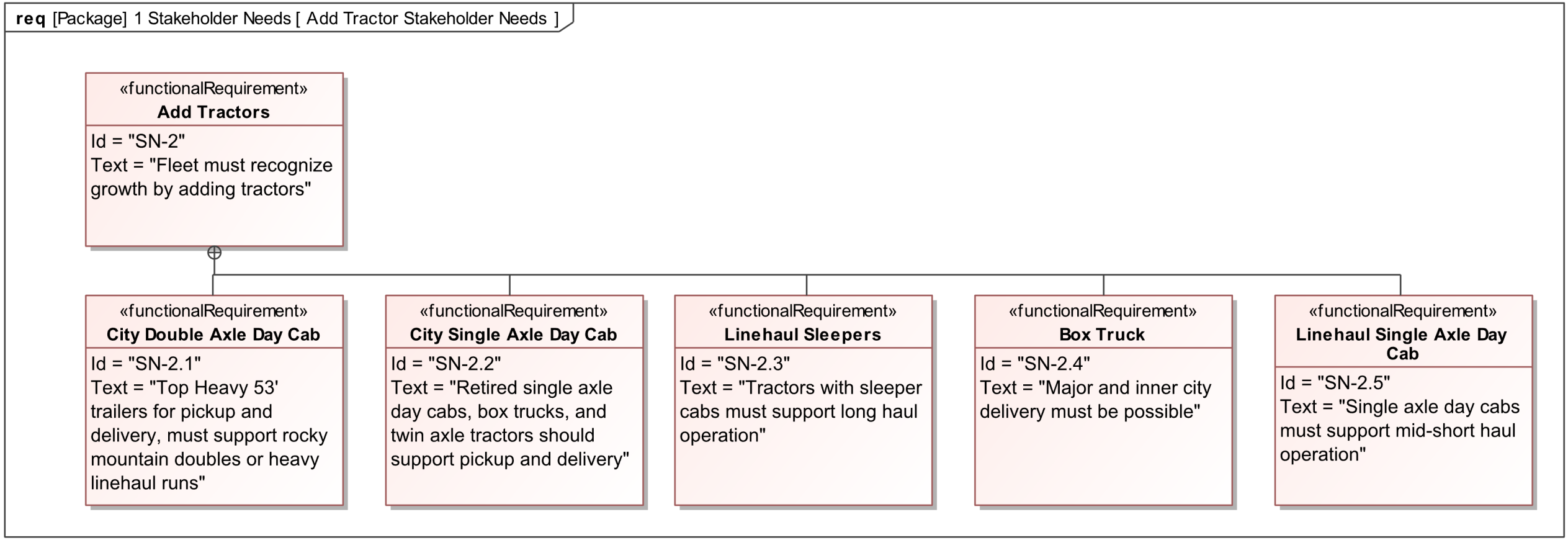
Modeling Approach

		PILLAR			
		REQUIREMENTS	BEHAVIOR	STRUCTURE	PARAMETERS
DOMAIN	PROBLEM (BLACK BOX)	B1-W1 Stakeholder Needs Stakeholder Needs	B2 Use Cases Use Cases	B3 System Context System Context	B4 Measurements of Effectiveness Measurements of Effectiveness
	PROBLEM (WHITE BOX)		W2 Functional Analysis Functional Analysis	W3 Logical Subsystem Communication Logical Subsystems Communication	W4 Measurements of Effectiveness –
	SOLUTION	S1 System Requirements	S2 System Behavior System Behavior	S3 System Structure System Structure	S4 System Parameters System Parameters
		SS1 Subsystem Requirements –	SS2 Subsystem Behavior Subsystem Behavior	SS3 Subsystem Structure Subsystem Structure	SS4 Subsystem Parameters –
	IMPLEMENTATION	I1 Physical Requirements –	Software, Electrical, Mechanical		

Need to Replace Tractors

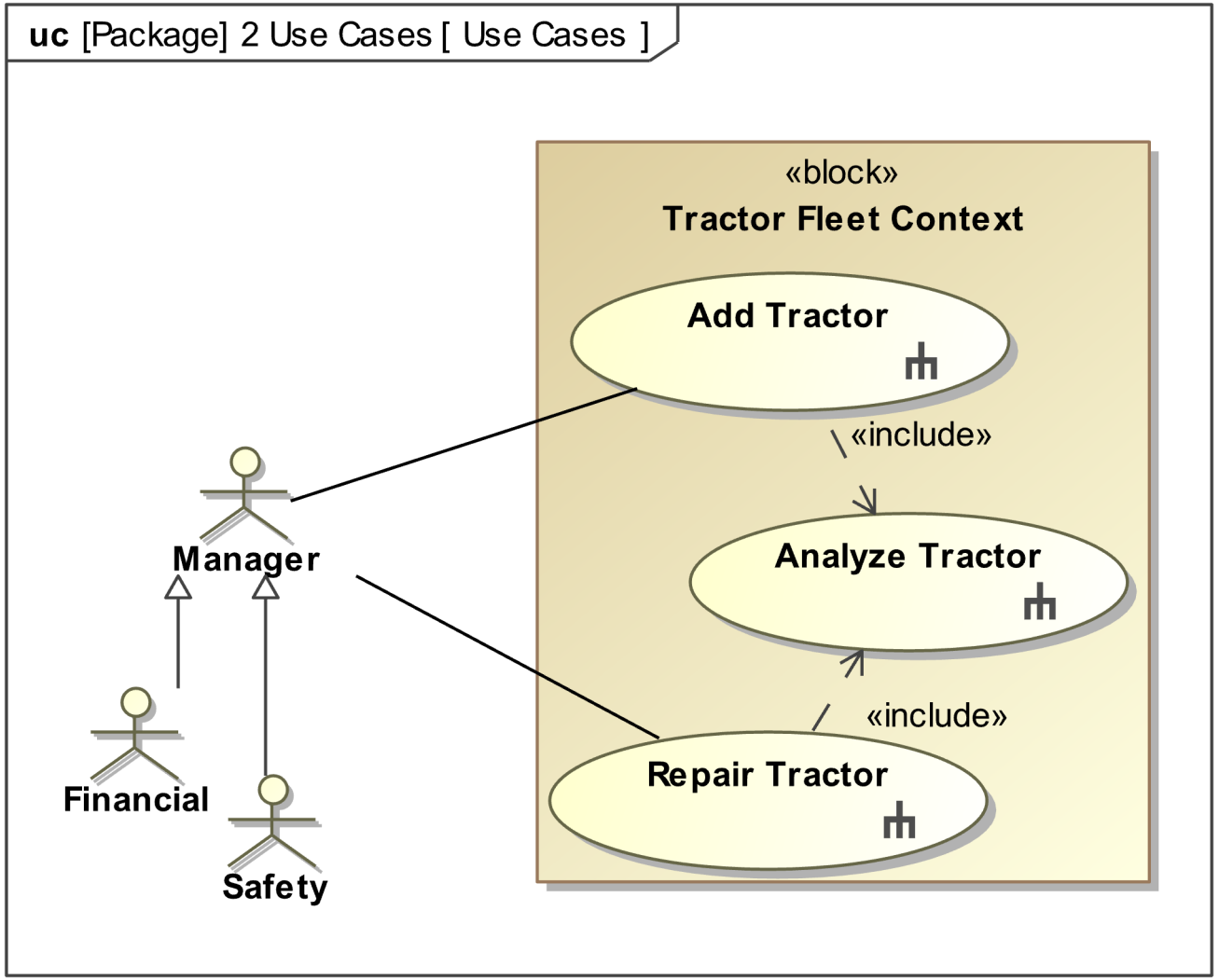


Need to Add Tractors

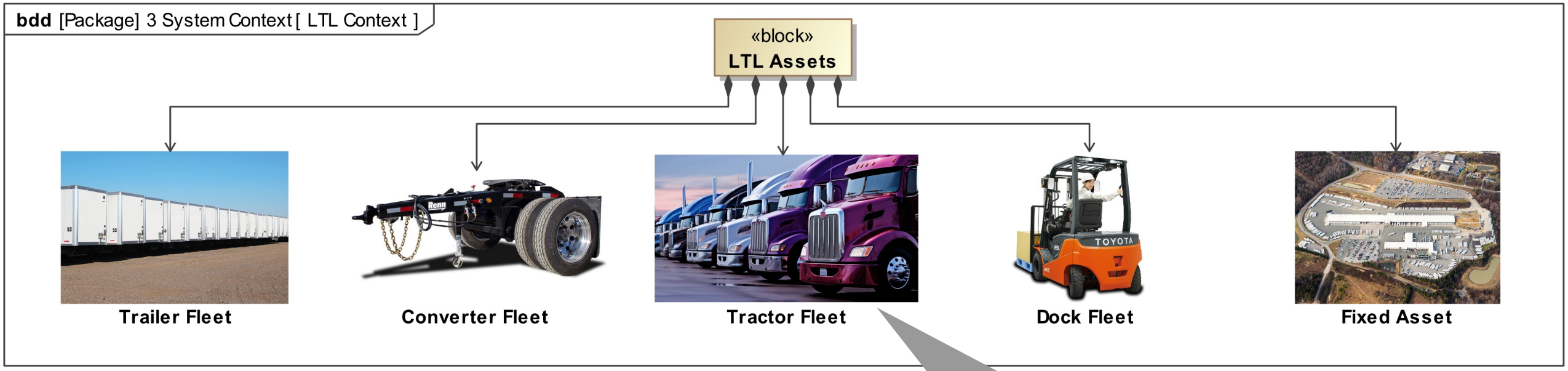


System Use Cases

- The manager is associated with the tractor fleet base use cases of *Add Tractor* and *Repair Tractor*

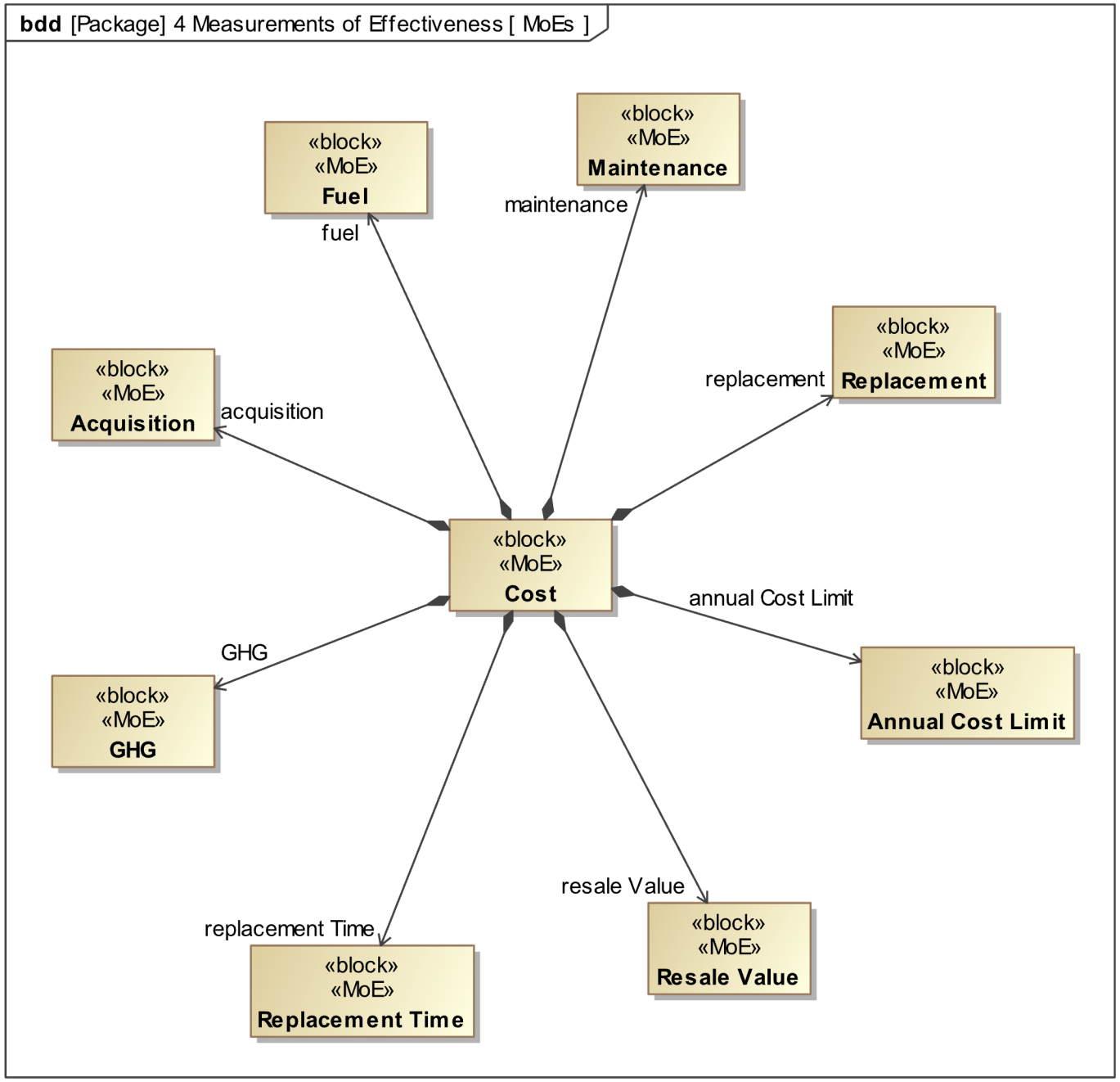


Context based on Less-than-truckload (LTL) Assets



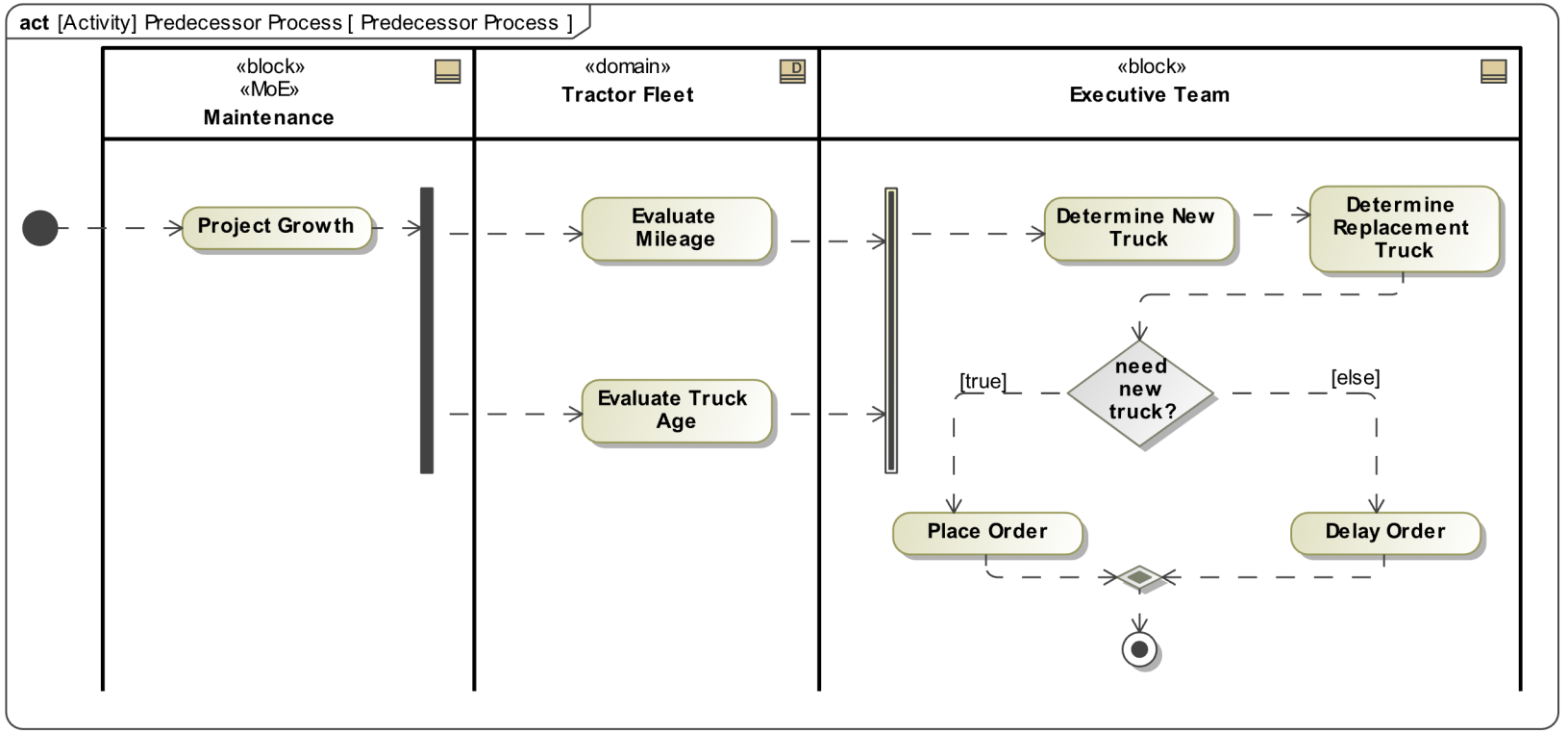
Measures of Effectiveness (MoE)

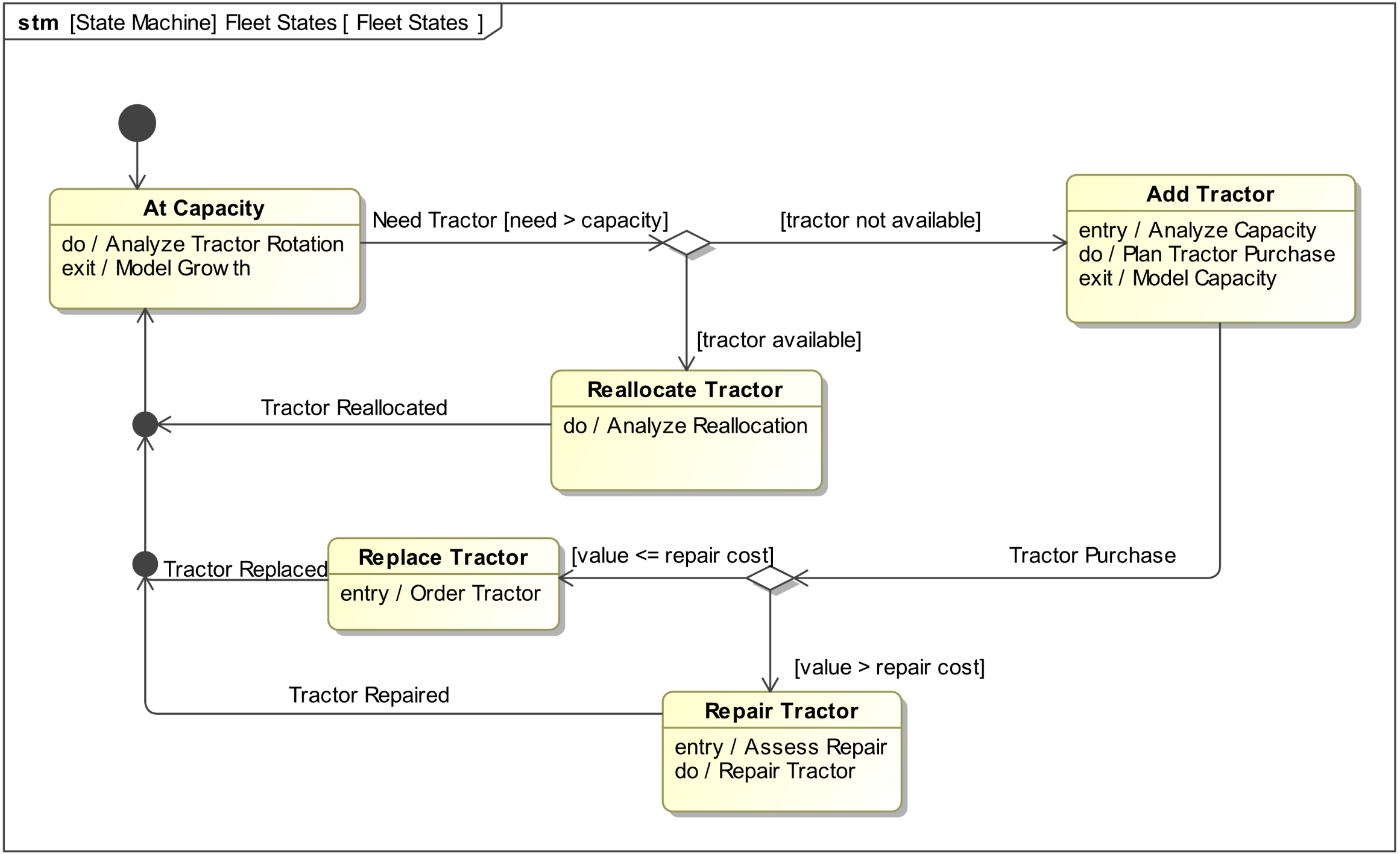
- Cost models are the primary driver for decisions



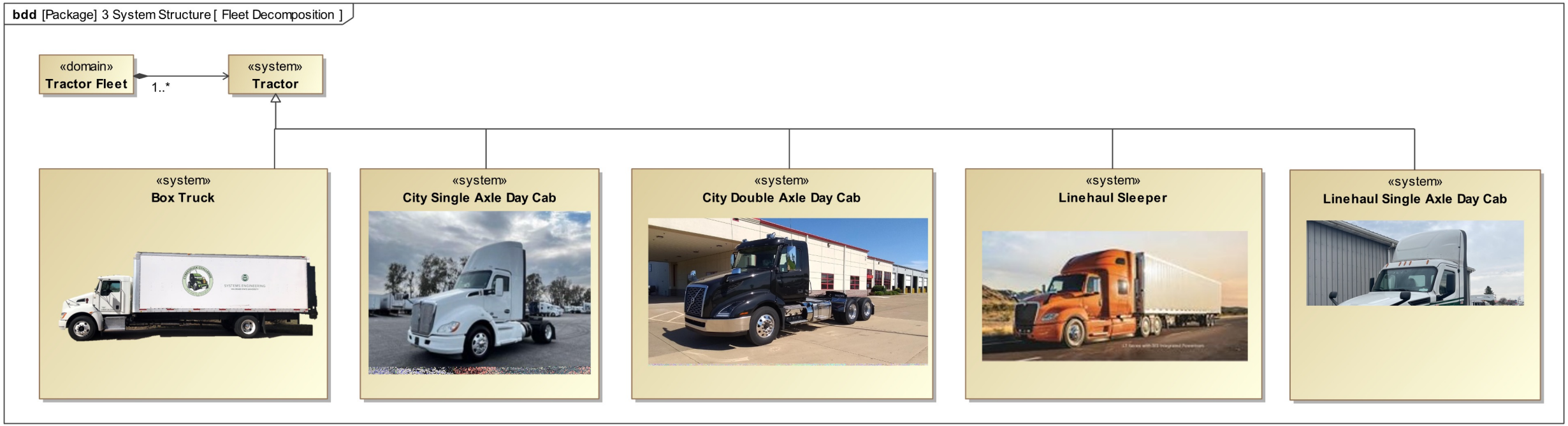
Predecessor System Activities

- Activities
  - Project Growth
  - Replace old
    - High mileage
    - Age




stm [State Machine] Fleet States [Fleet States]
At Capacity
do / Analyze Tractor Rotation
exit / Model Grow th
Need Tractor [need > capacity]
[tractor not available]
Add Tractor
entry / Analyze Capacity
do / Plan Tractor Purchase
exit / Model Capacity
[tractor available]
Reallocate Tractor
do / Analyze Reallocation
Tractor Reallocated
Tractor Replaced
Replace Tractor
entry / Order Tractor
[value <= repair cost]
Tractor Purchase
[value > repair cost]
Tractor Repaired
Repair Tractor
entry / Assess Repair
do / Repair Tractor

Fleet Composition Structure

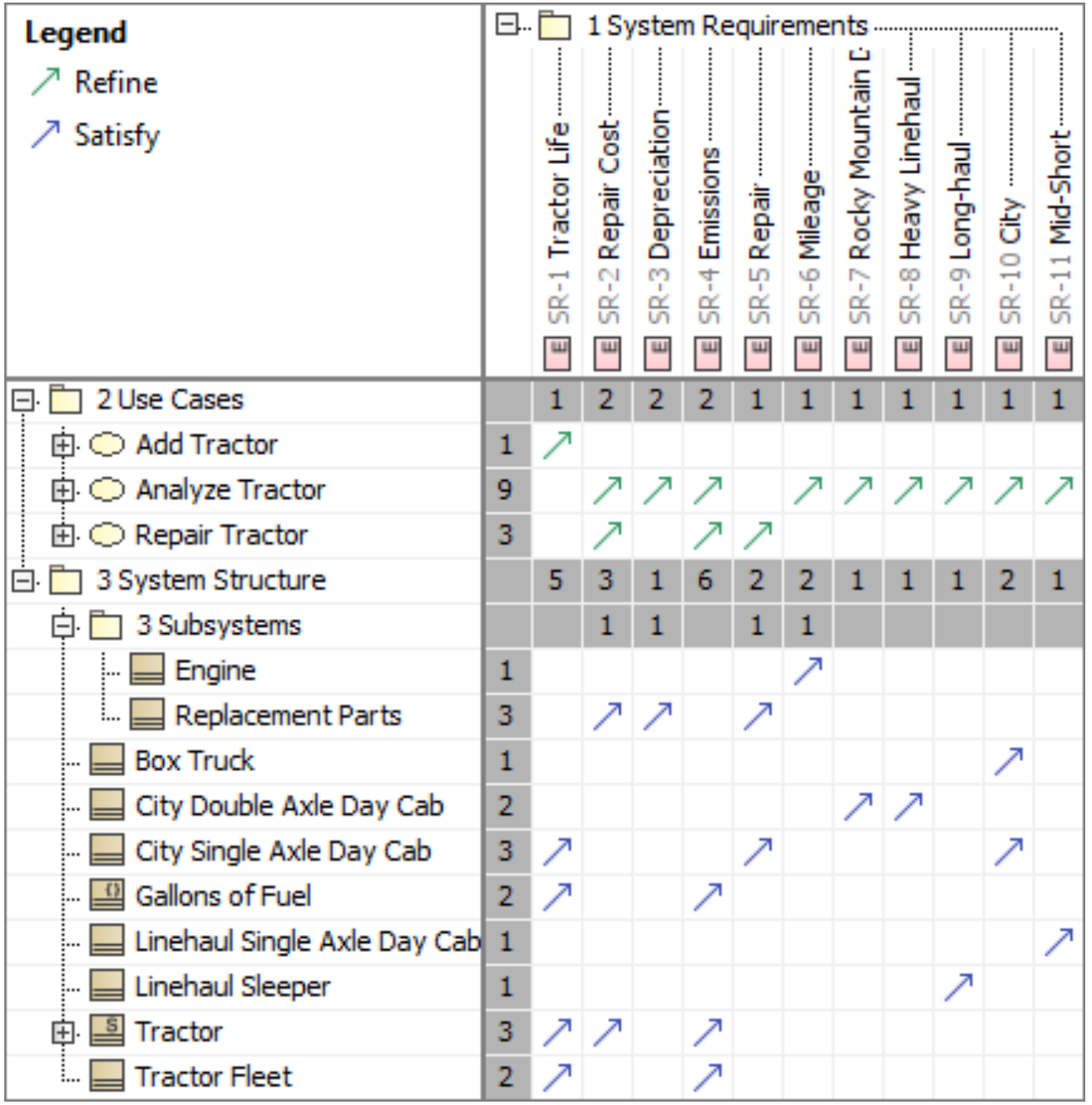


Fleet Composition Requirements

#	Name	Text	Verify Method	△ Satisfied By
1	SR-10 City	The tractor fleet shall support major and inner city pickup and delivery.	Demonstration	Box Truck City Single Axle Day Cab
2	SR-7 Rocky Mountain Doubles	The tractor fleet shall support pickup and delivery for rocky mountain doubles runs.	Demonstration	City Double Axle Day Cab
3	SR-8 Heavy Linehaul	The tractor fleet shall support pickup and delivery for heavy linehaul runs.	Demonstration	City Double Axle Day Cab
4	SR-6 Mileage	Tractors shall have less than 1000000 vehicle miles traveled.	Inspection	Engine VMT : 2 Solution Domain::4 System Parameters::Vehicle Miles T
5	SR-11 Mid-Short	The tractor fleet shall support mid-short haul operations.	Demonstration	Linehaul Single Axle Day Cab
6	SR-9 Long-haul	The tractor fleet shall support long-haul operations.	Demonstration	Linehaul Sleeper
7	SR-3 Depreciation	Tractors shall have usable depreciation.	Analysis	Replacement Parts
8	SR-5 Repair	Tractor replacement parts shall be available.	Inspection	Replacement Parts City Single Axle Day Cab
9	SR-2 Repair Cost	Total cost shall be less than 120000.	Analysis	Replacement Parts Tractor CT : 2 Solution Domain::4 System Parameters::Total Cost [*]
10	SR-1 Tractor Life	Tractors shall be less than 9 years old.	Inspection	Tractor Fleet Tractor City Single Axle Day Cab Age : 2 Solution Domain::4 System Parameters::Truck Age
11	SR-4 Emissions	Tractors shall pass all administered Clean Air Act (CAA) tests.	Test	Tractor Tractor Fleet CE : 2 Solution Domain::4 System Parameters::Emission Cost EDC : 2 Solution Domain::4 System Parameters::Environmental EF : 2 Solution Domain::4 System Parameters::Emission Factor

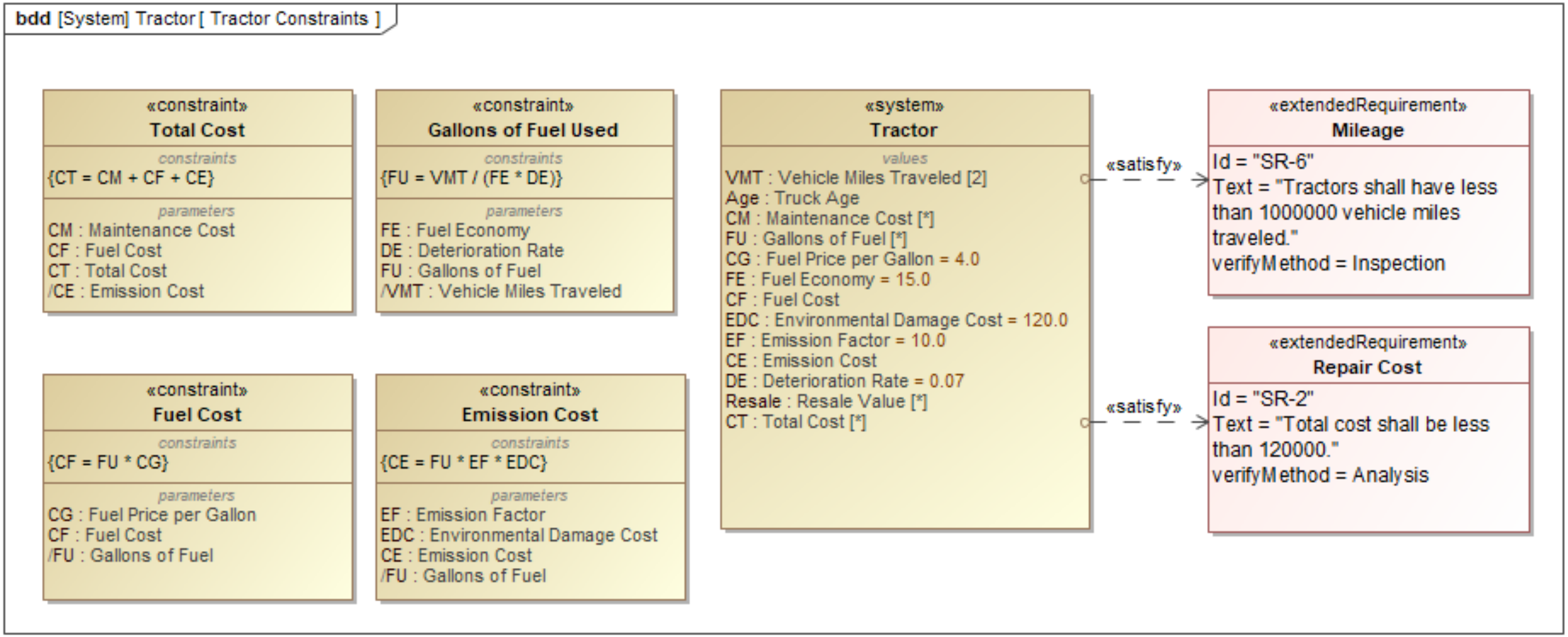
Requirements Traceability

- Demonstrate relationships in model entities

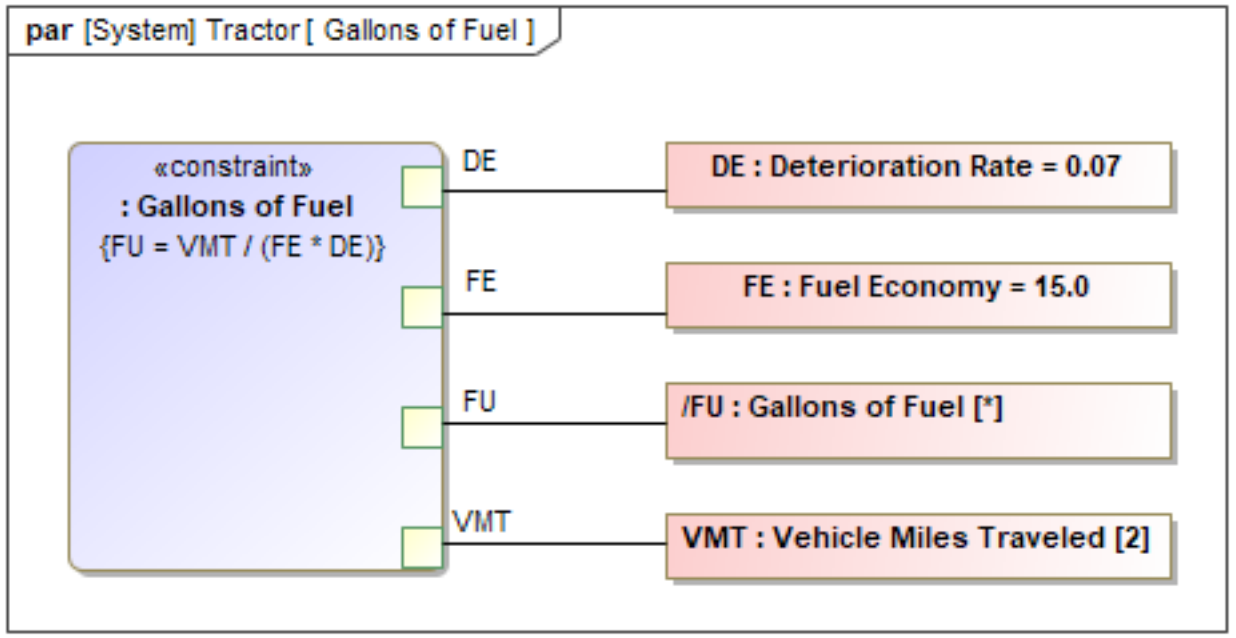


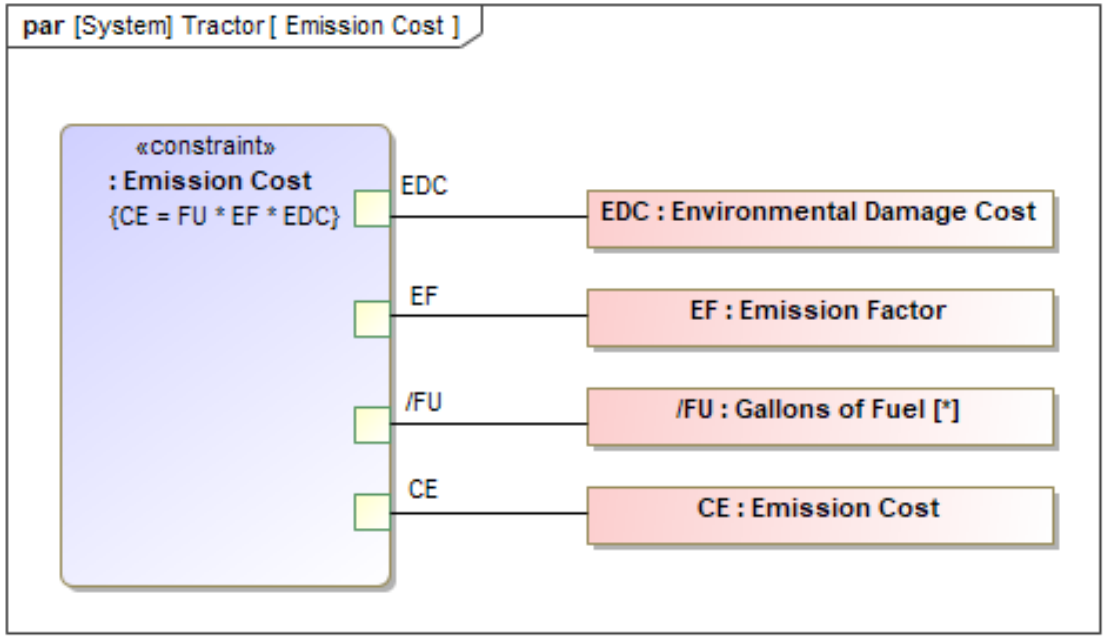
Parametrics

System Constraint Blocks

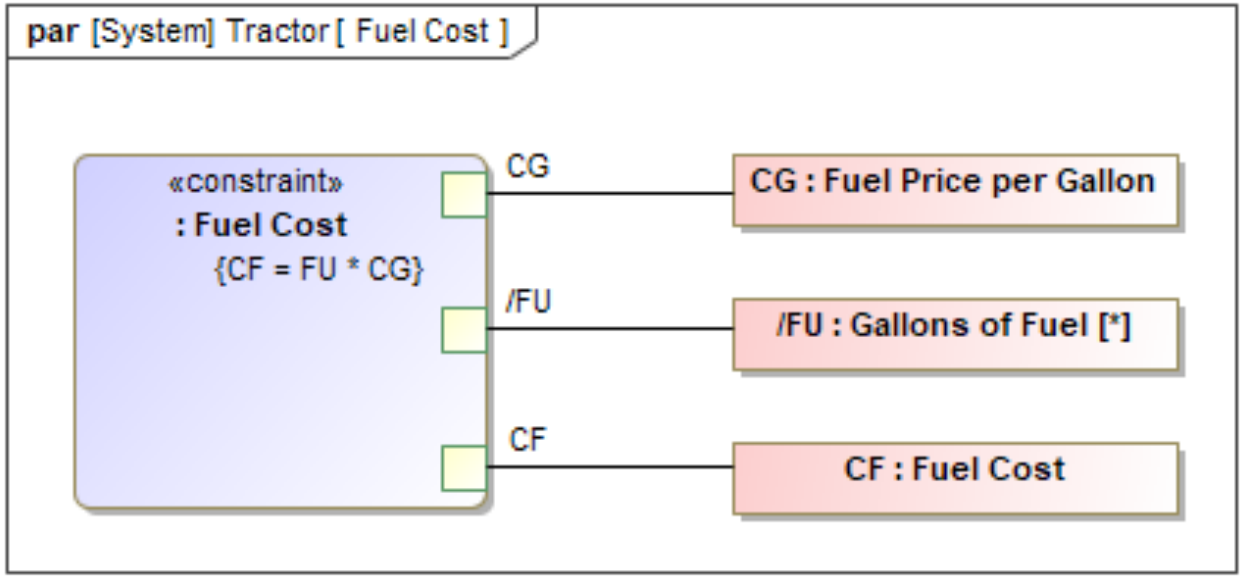


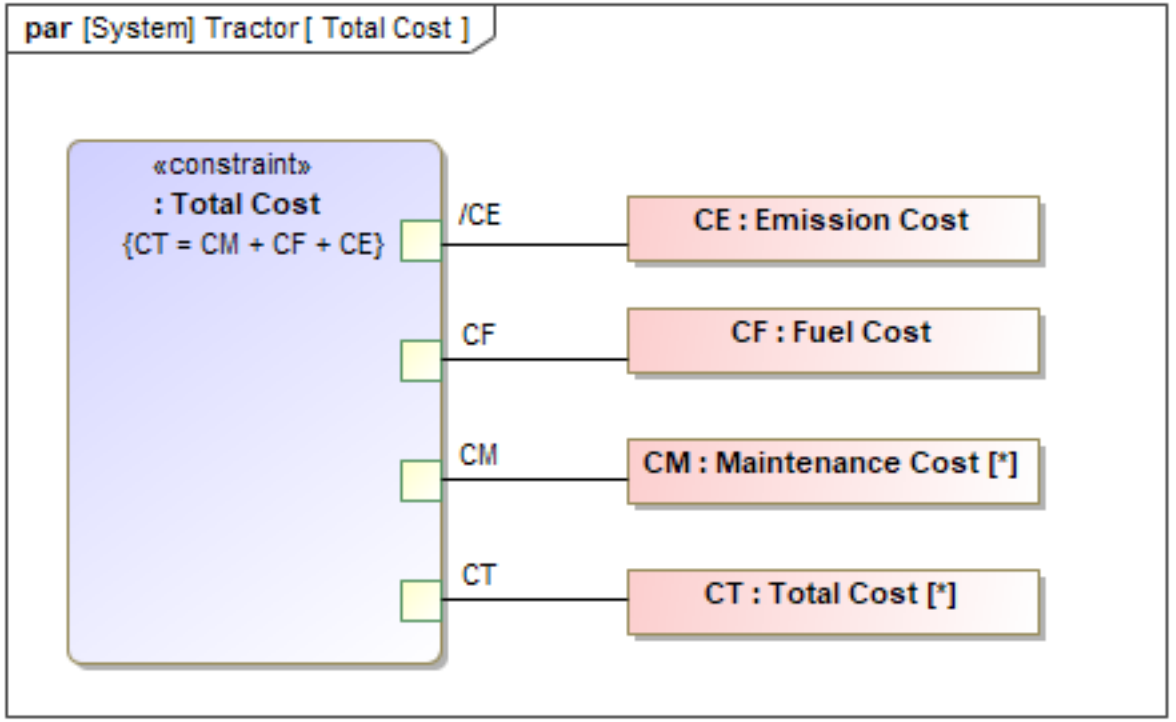
Parametric System of Equations (1/2)





Parametric System of Equations (2/2)





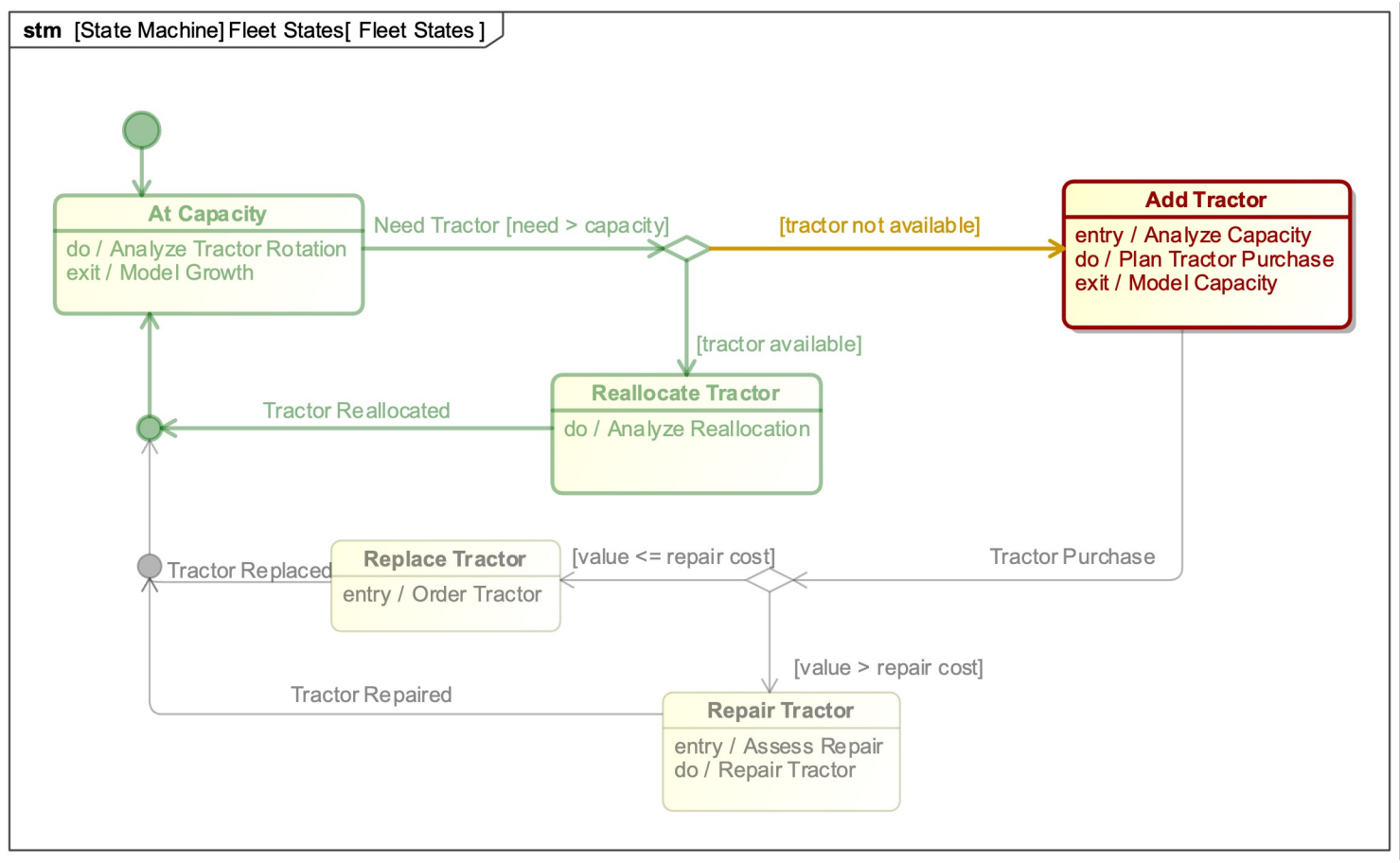
Parametric Results on an LTL Fleet

#	Age : Truck Age	VMT : Vehicle Miles Traveled	CM : Maintenance Cost	Resale : Resale Value	FU : Gallons of Fuel	CF : Fuel Cost	EDC : Environmental Damage Cost	EF : Emission Factor	CE : Emission Cost	CT : Total Cost	
1	1	75849 200535	0.2	1000000	72237.1429 190985.7143	288948.5714	120	10	8.6685E7	8.6974E7	
2	2	186944 845373	0.24	70000	178041.9048 805117.1429	712167.619	120	10	2.1365E8	2.1436E8	
3	3	357047 666066	0.28	60000	340044.7619 634348.5714	1360179.0476	120	10	4.0805E8	4.0941E8	
4	4	101508 223724	0.32	50000	96674.2857 213070.4762	386697.1429	120	10	1.1601E8	1.164E8	
5	5	641577 1116664	0.36	40000	611025.7143 1063489.5238	2444102.8571	120	10	7.3323E8	7.3567E8	
6	6	721967 1150144	0.4	30000	687587.619 1095375.2381	2750350.4762	120	10	8.2511E8	8.2786E8	
7	7	668806 1345439	0.44	20000	636958.0952 1281370.4762	2547832.381	120	10	7.6435E8	7.669E8	
8	8	764350 1204082	0.48	6000	727952.381 1146744.7619	2911809.5238	120	10	8.7354E8	8.7645E8	
9	9	859893 1233222	0.52	4800	818945.7143 1174497.1429	3275782.8571	120	10	9.8273E8	9.8601E8	
10	10	955437 1260914	0.56	4800	909940 1200870.4762	3639760	120	10	1.0919E9	1.0956E9	

- For our generalized example fleet, loosely based on an LTL fleet type behavior.
- If a truck projects to operate out of the cost control from a repair or an environmental factor limit, the truck will be replaced.

MBSE Takeaways

- System model successfully demonstrates optimal sustainable vehicle replacement based on time and cost.
- SysML diagram views are understandable and relatable to the fleet maintenance stakeholders.
- Input data for these decisions can be easily adjusted to address future changes and assumptions.



Conclusions and Future Work

- Trucking is a multi-billion dollar industry with little exposure to systems engineering
  - MBSE has potential for showing operational benefit
  - Examples, like tractor replacement, show value to the trucking companies.
- Challenges remain
  - Education
  - Ease of use
  - Utilization