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Paper #132

# Applying Model-Based Systems Engineering Methods to a Novel Shared Systems Simulation Methodology

# Authors



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# Agenda

- ▶ Shift to Model-Based Systems Engineering
- ▶ Problem Statement
- ▶ Model-Based Architecture Development
- ▶ Shared Systems Simulation Coupling
- ▶ Architecture Trade Study Example
- ▶ Interface and Complexity Challenges



# Traditional Systems Engineering

- ▶ Document-centric
- ▶ Isolated, disjointed views
- ▶ Ineffective for cross-functional collaboration



Slide adapted from M. Vinarcik, 2022

*Supercruise: Model-Based Systems Engineering and Digital Engineering in 2022* <sup>[1]</sup>





# Traditional Systems Engineering

- ▶ Document-centric
- ▶ Isolated, disjointed views
- ▶ Ineffective for cross-functional collaboration
- ▶ Integrated system models viewed as **secondary and descriptive only.**  
(Weilkiens, et al. 2016) [2]



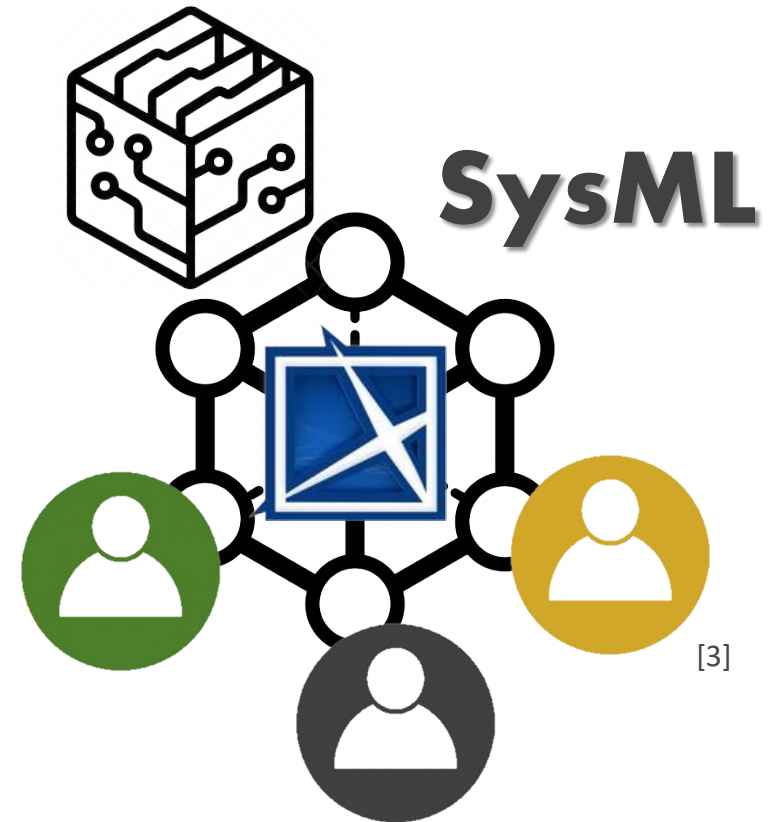
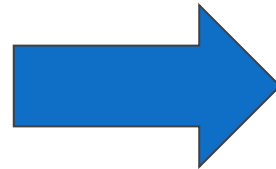
Slide adapted from M. Vinarcik, 2022

*Supercruise: Model-Based Systems Engineering and Digital Engineering in 2022* [1]

# The Shift to Model-Based Systems Engineering



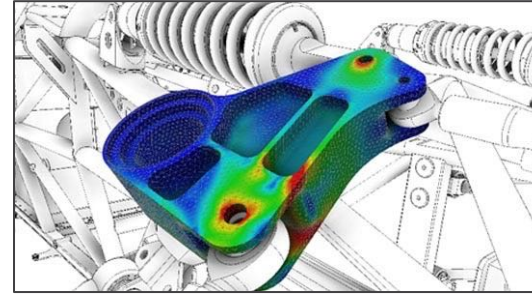
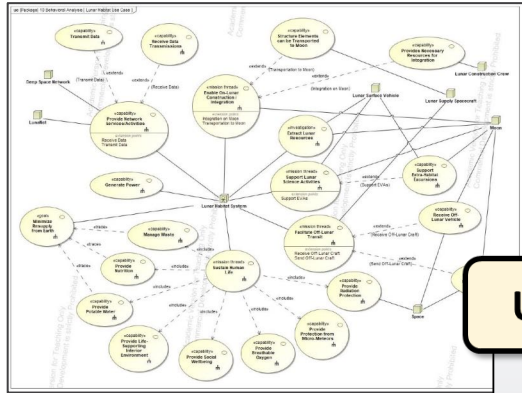
**Document Based**



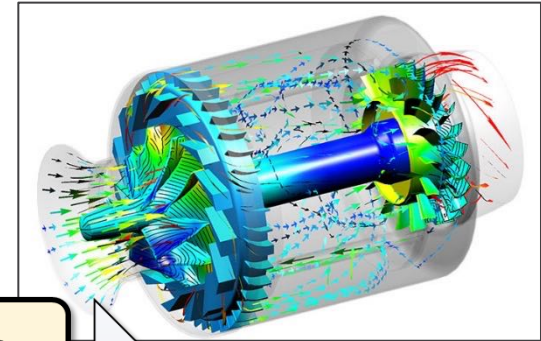
**Shared Common Model**



# Up-Front Architecting → Detailed Systems Engineering



[4]



[5]

Understand

Deploy

Operate

Replace

Define

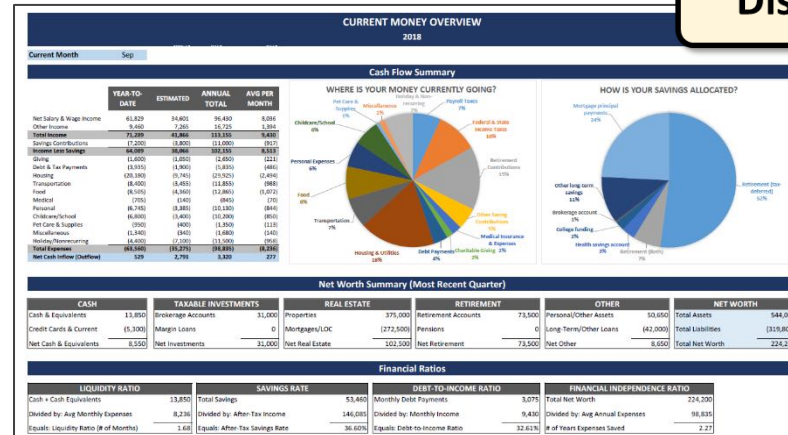
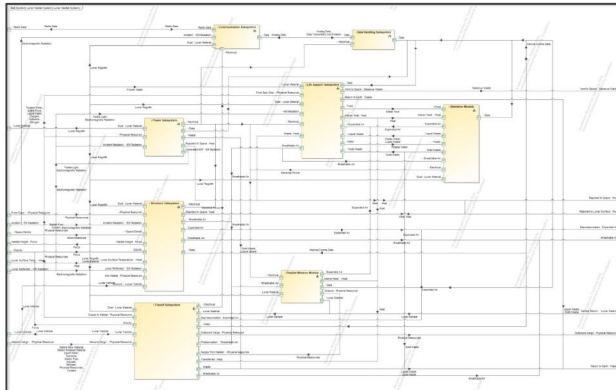
Deliver

Support

Retire

Develop

Dispose



[6]



# Executable System Models

- ▶ Descriptive system model → executable simulation
- ▼ Ineffective toolchains
- ▼ Significant descriptive model rework



# Problem Statement

- ▶ How can the rigor and precision of a model-based approach be extended from the system definition space into the **system simulation and analysis domain**?







# System of Interest

Technical  
Complexity

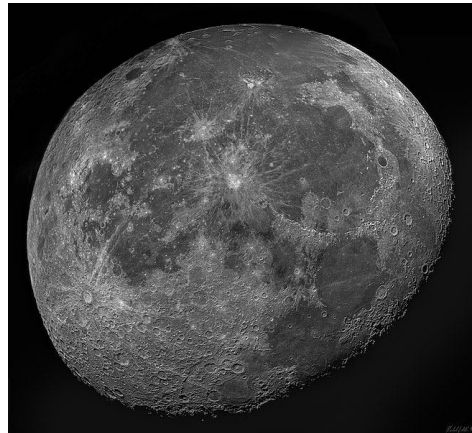
Stakeholder  
Interest

Engineering  
Novelty



“We choose to go to the moon” – John F. Kennedy

Technical  
Complexity



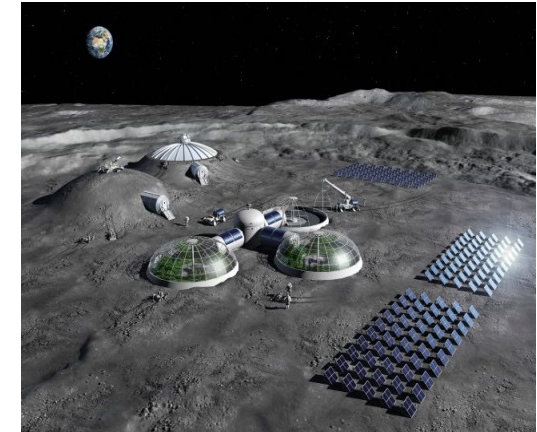
[8]

Stakeholder  
Interest



[9]

Engineering  
Novelty

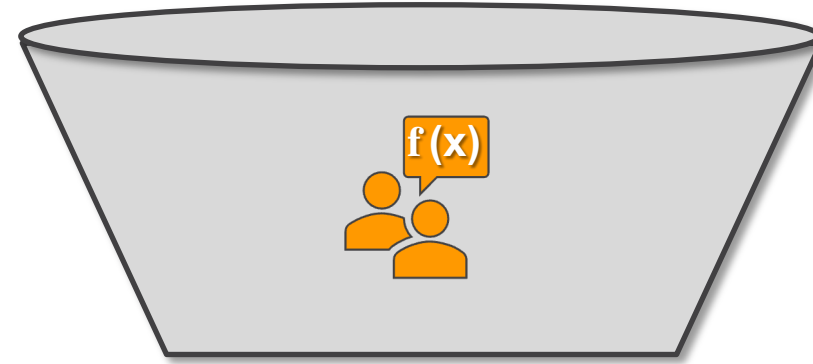


[10]

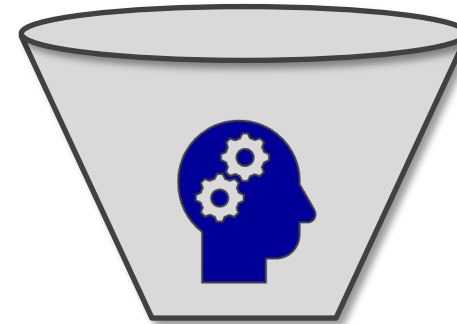
# The Three Phases of Architecture Decomposition



**Functional**



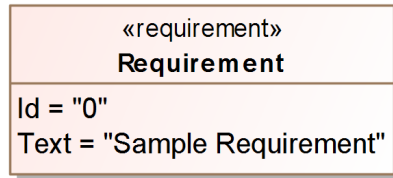
**Logical**



**Physical**



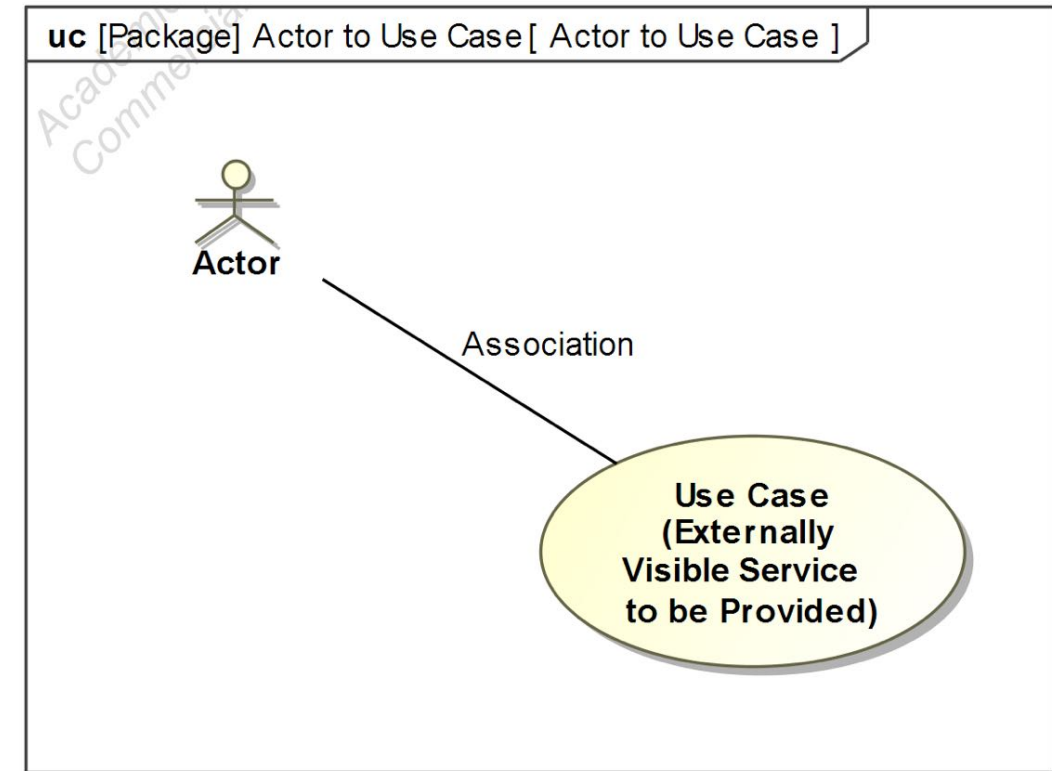
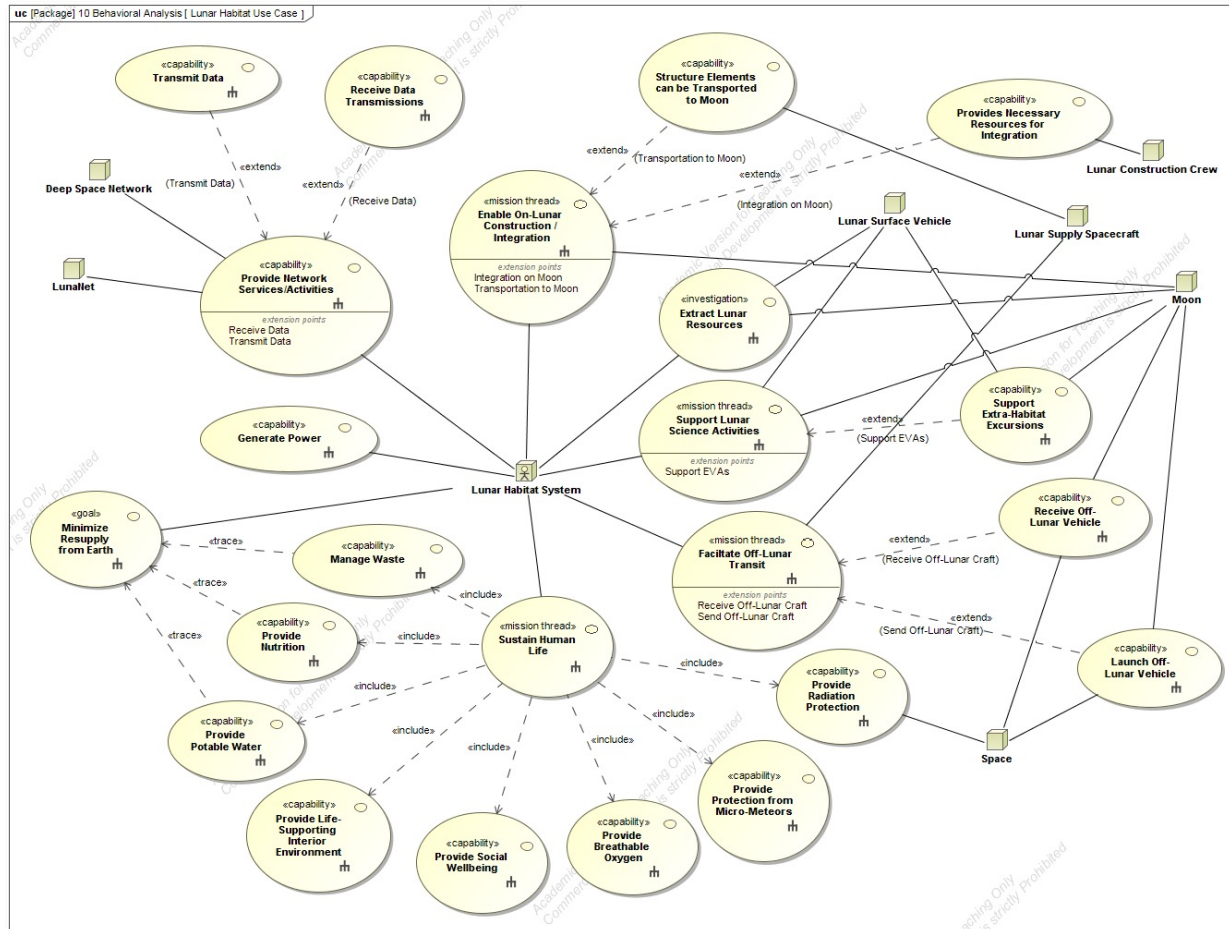
# Functional Decomposition



, and

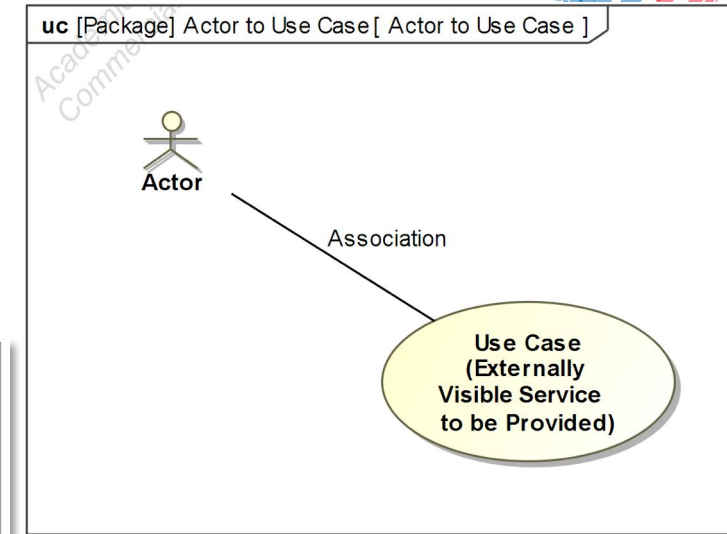
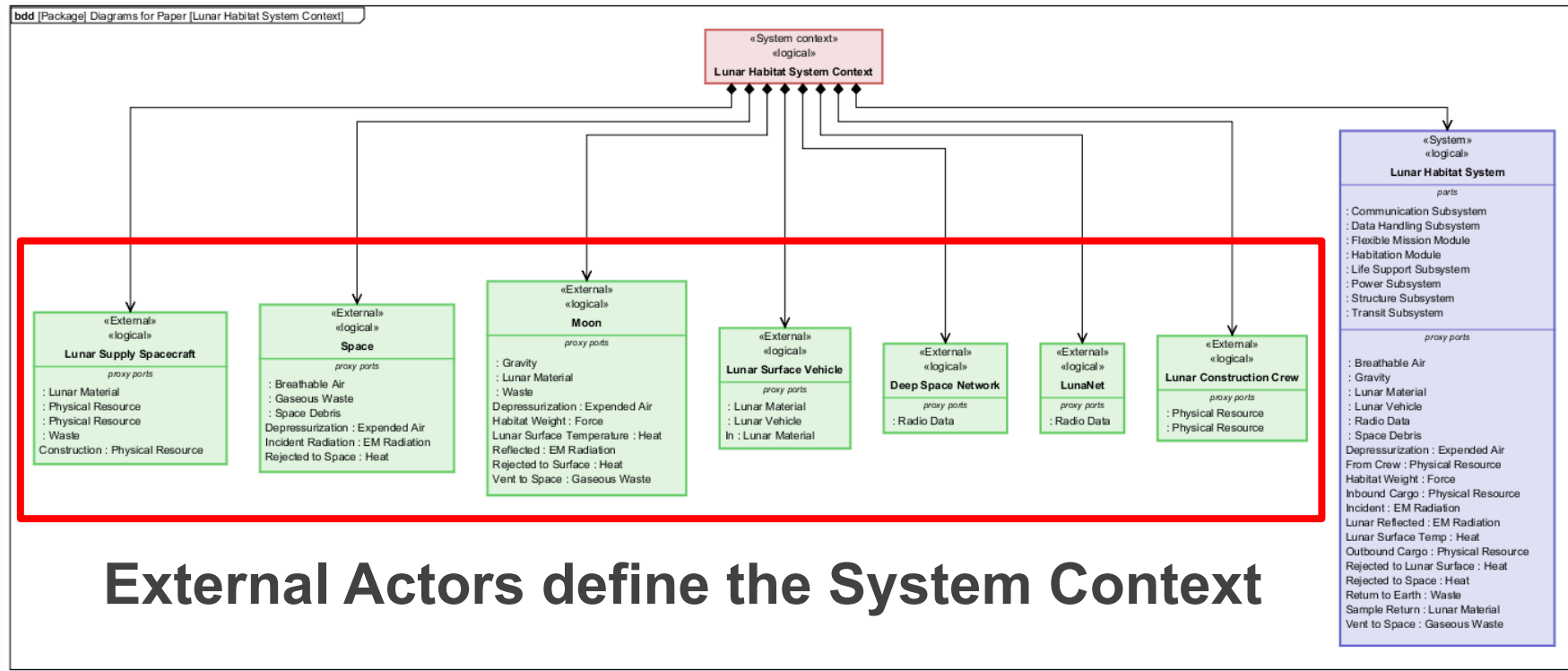
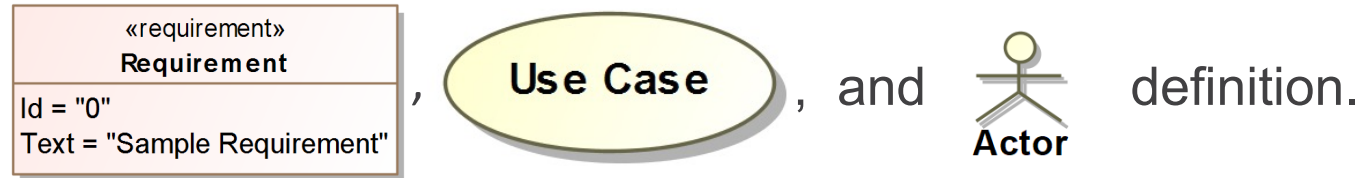


definition.

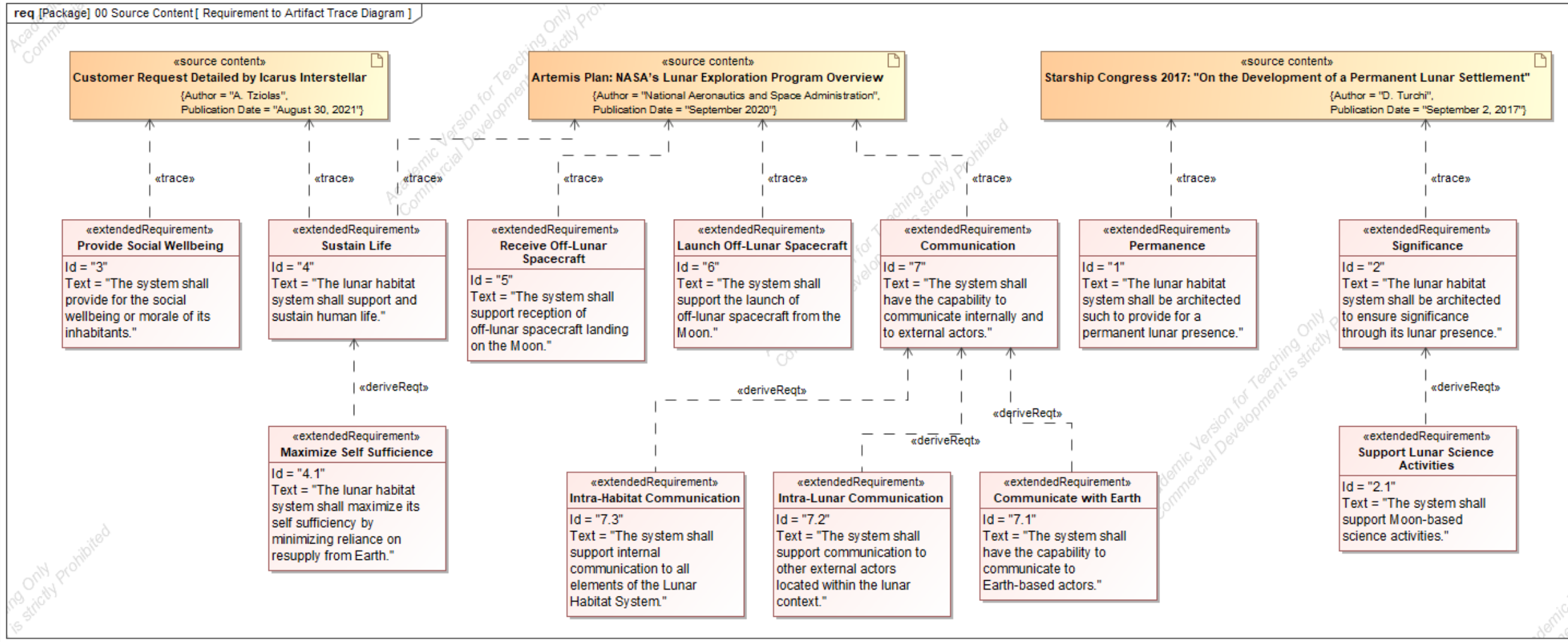




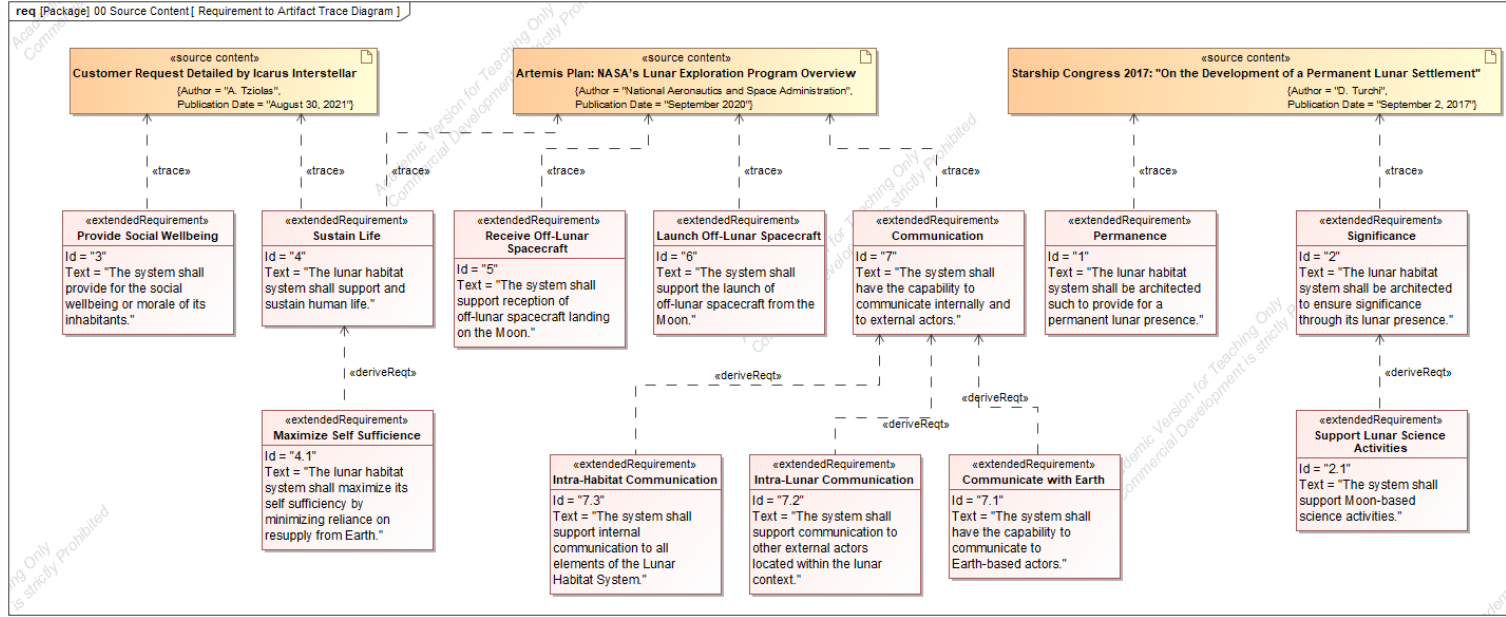
# Functional Decomposition



# Functional Decomposition



# Functional Decomposition



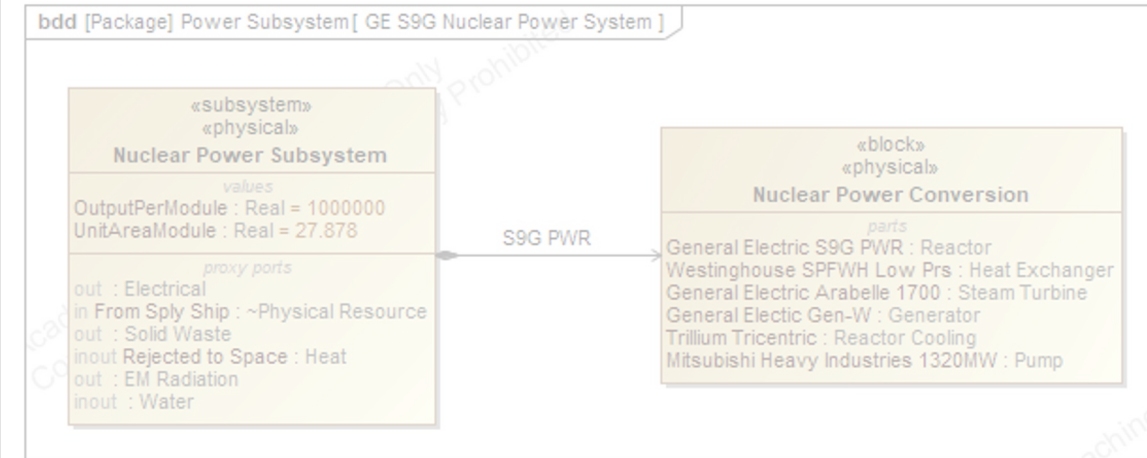
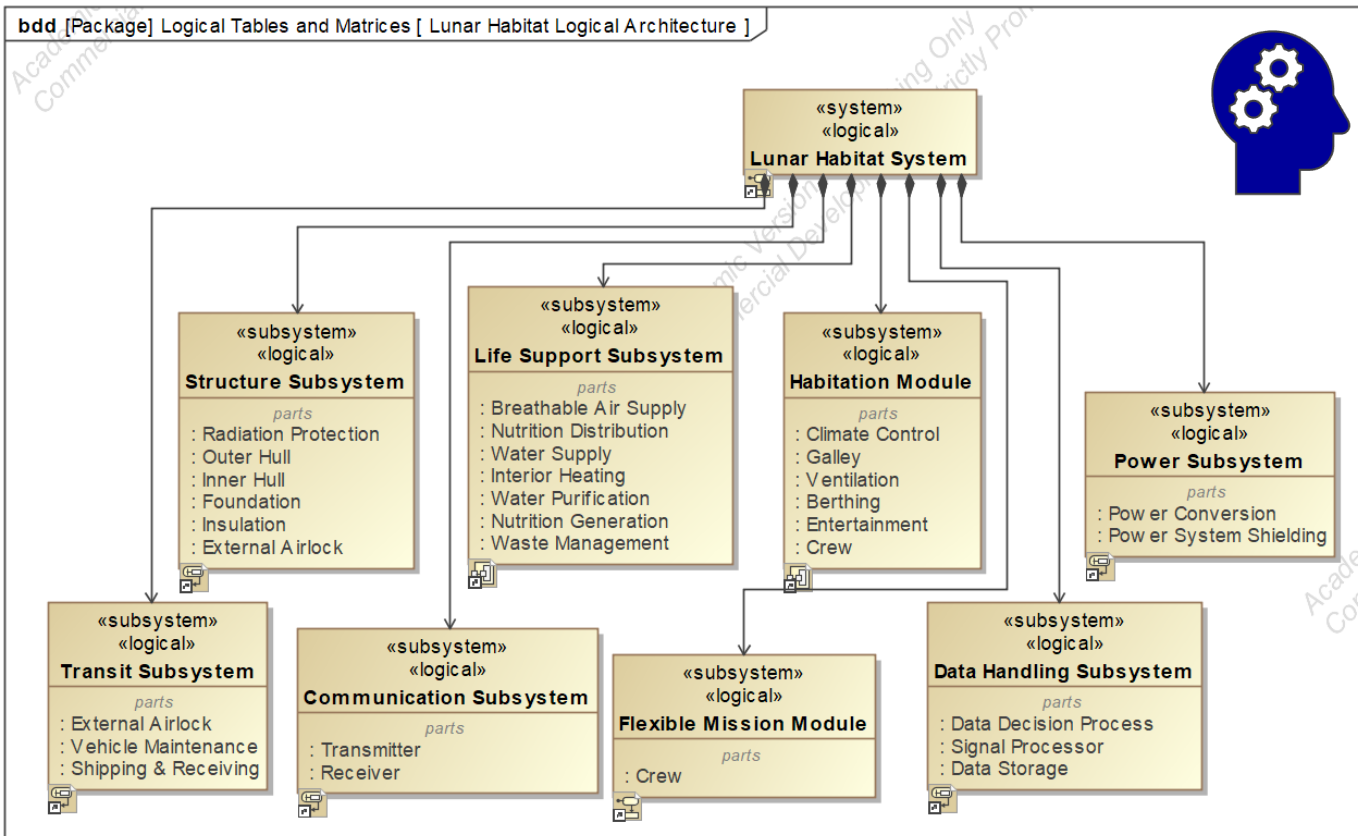
Legend

	1 Permanence	2 Significance	2.1 Support Lunar Science Activities	3 Provide Social Wellbeing	Sustain Life	Maximize Self Sufficiency	Receive Off-Lunar Spacecraft	Launch Off-Lunar Spacecraft	7 Communication	7.1 Communicate with Earth	7.2 Intra-Lunar Communication	7.3 Intra-Habitat Communication
Enable On-Lunar Construction / Integration												
Extract Lunar Resources												
Facilitate Off-Lunar Transit												
Generate Power												
Launch Off-Lunar Vehicle												
Manage Waste												
Minimize Resupply from Earth												
Provide Breathable Oxygen												
Provide Life-Supporting Interior Environment												
Provide Network Services/Activities												
Provide Nutrition												
Provide Potable Water												
Provide Protection from Micro-Meteors												
Provide Radiation Protection												
Provide Social Wellbeing												
Provides Necessary Resources for Integration												
Receive Data Transmissions												
Receive Off-Lunar Vehicle												
Structure Elements can be Transported to Moon												
Support Extra-Habitat Excursions												
Support Lunar Science Activities												
Sustain Human Life												
Transmit Data												

# Logical and Physical Decompositions



Logical Architecture: generic representation of system elements, defined in terms of functions they provide





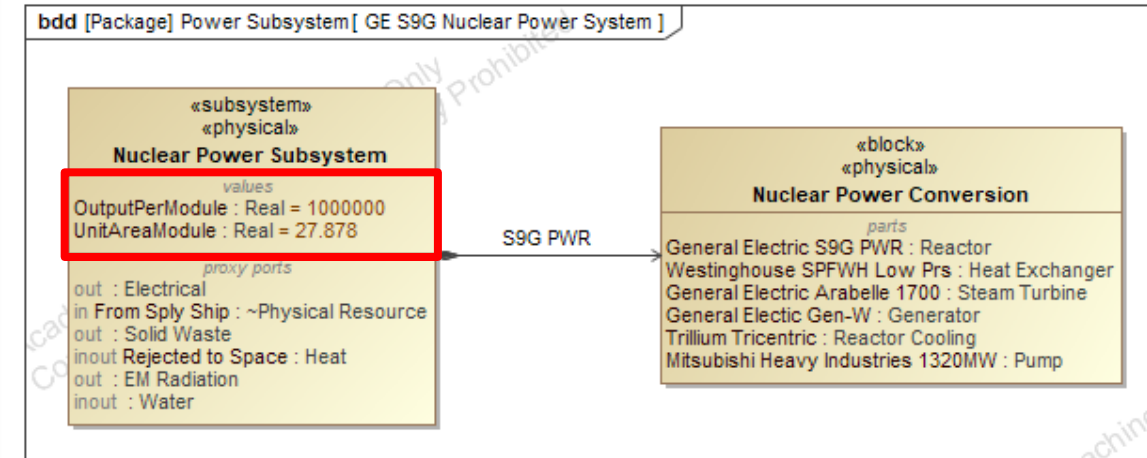
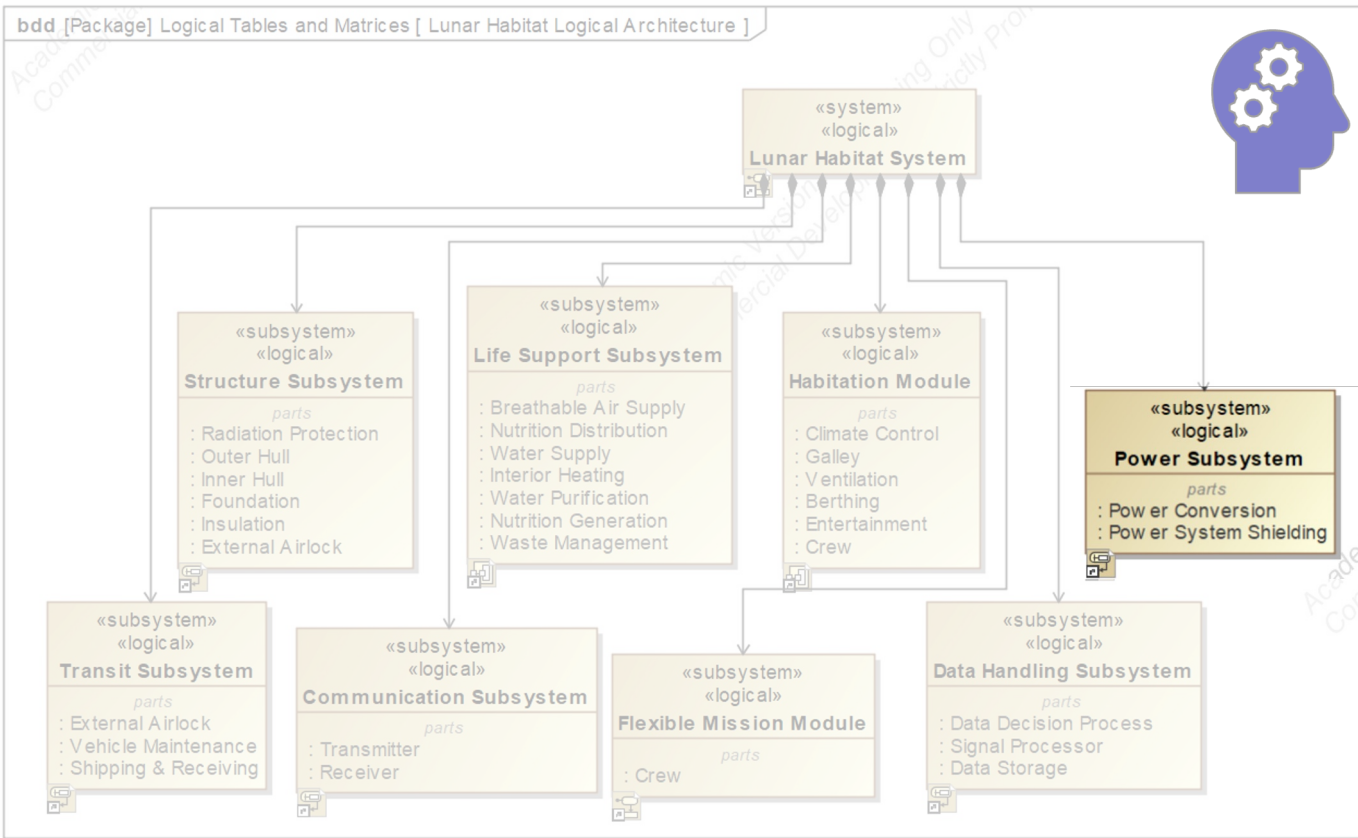
# Logical and Physical Decompositions



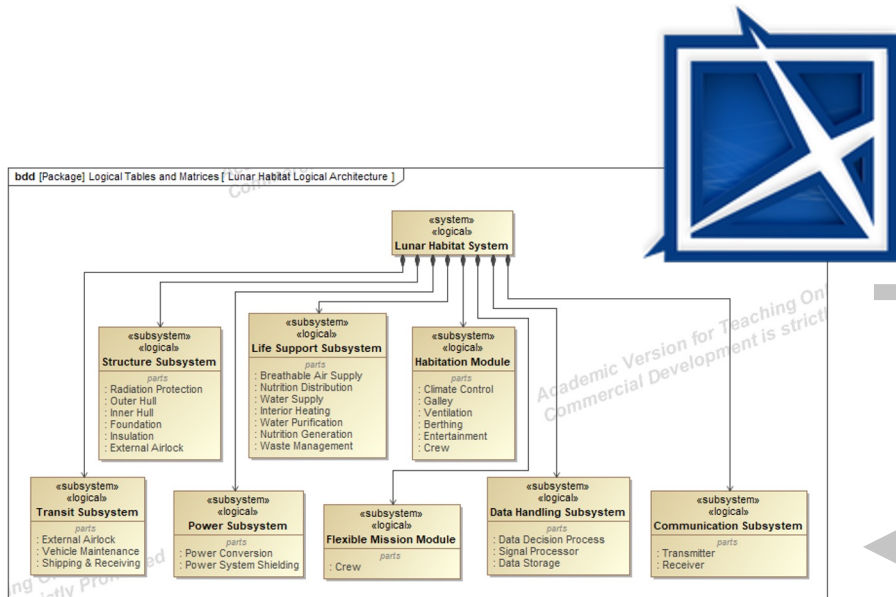
Logical Architecture: generic representation of system elements, defined in terms of functions they provide



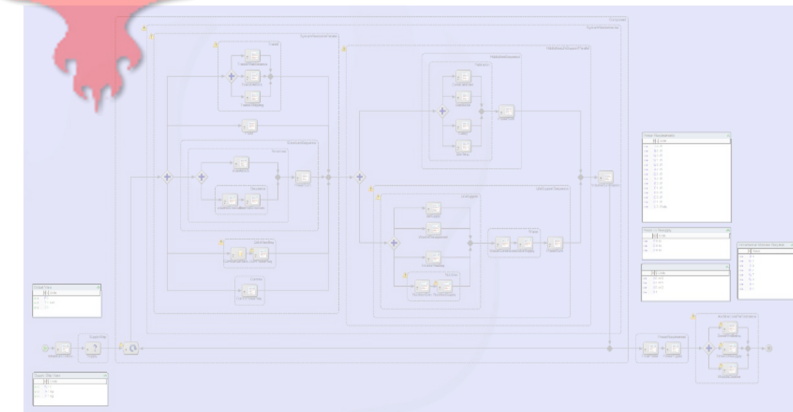
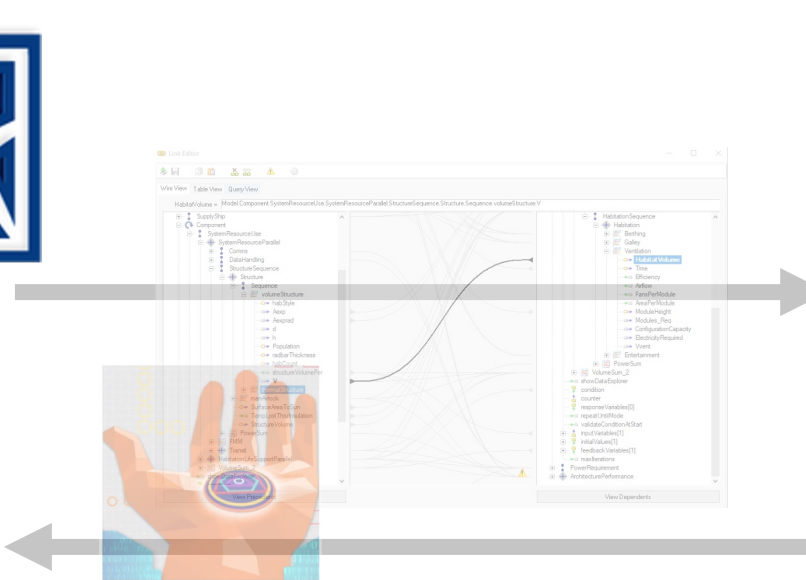
Physical Architecture: unique, specific instantiations of system elements



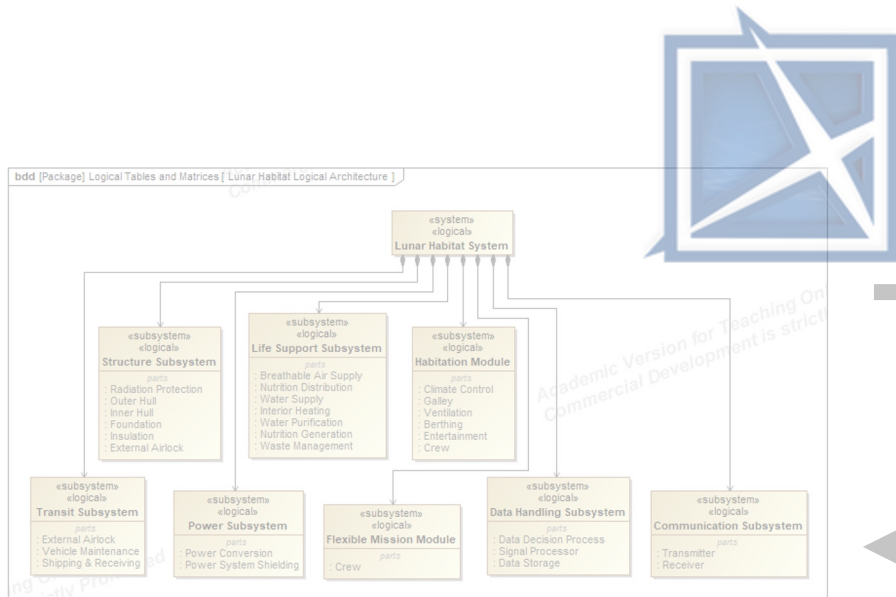




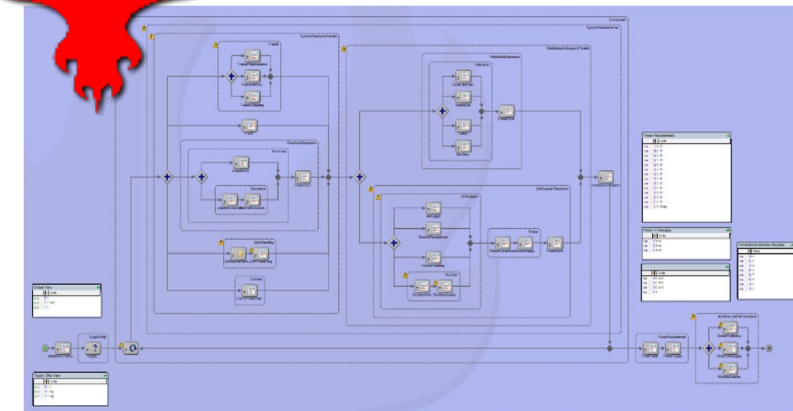
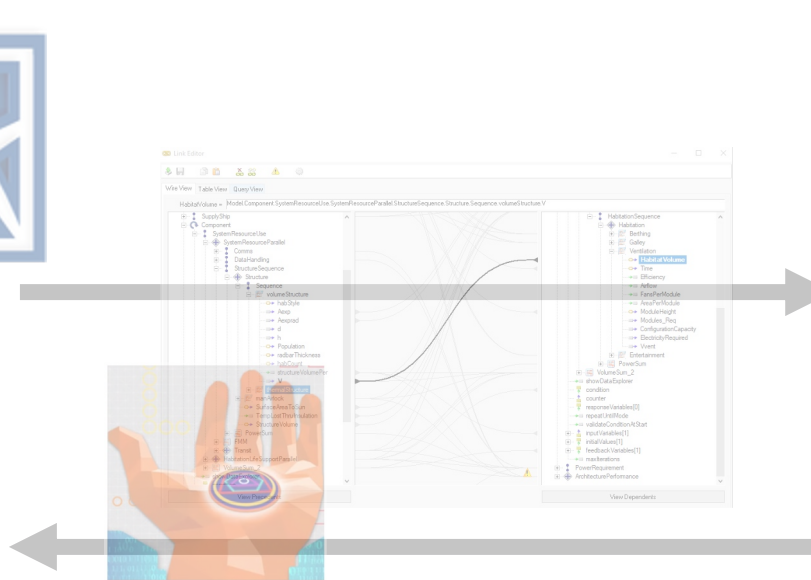
## Model-Based Architecture



## Systems Simulation



Model-Based Architecture



Systems Simulation

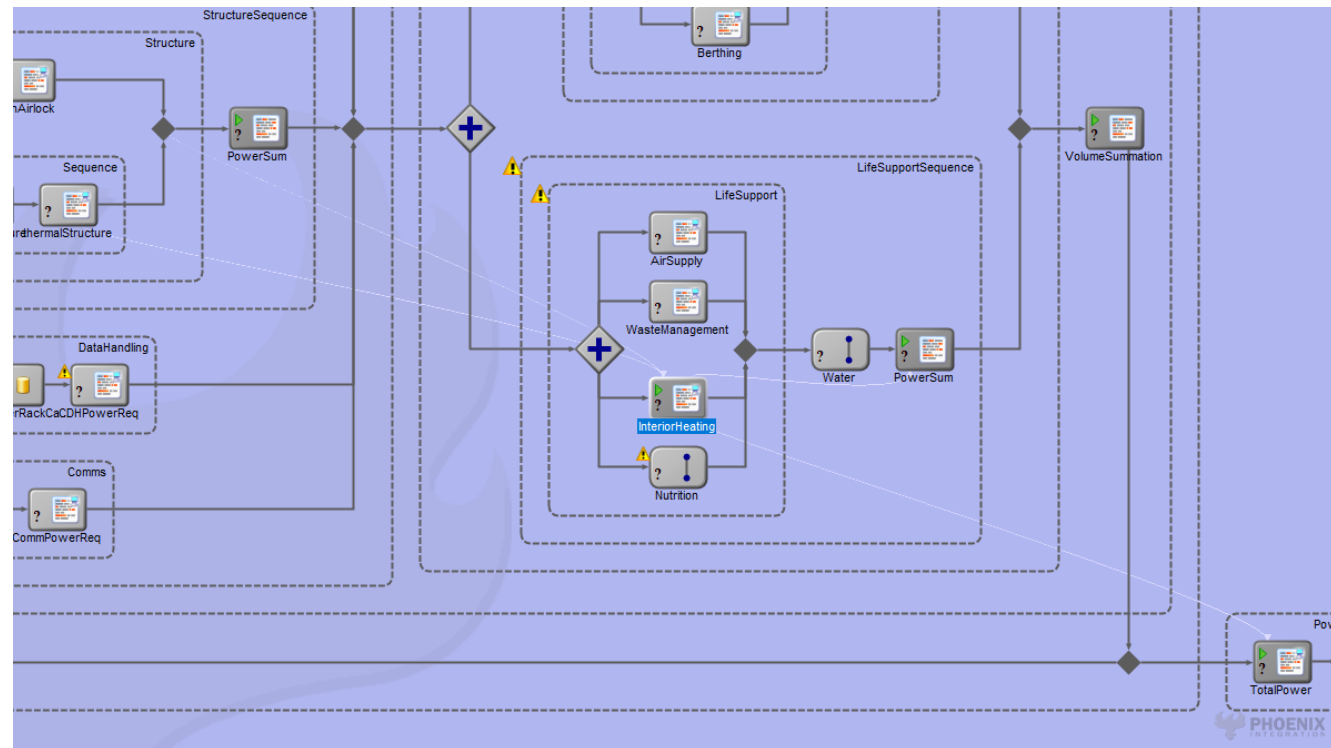


# Shared Systems Simulation Development

- ▶ Defined system behaviors using detailed system simulations
- ▶ Sequenced and integrated simulation elements via a simulation workflow

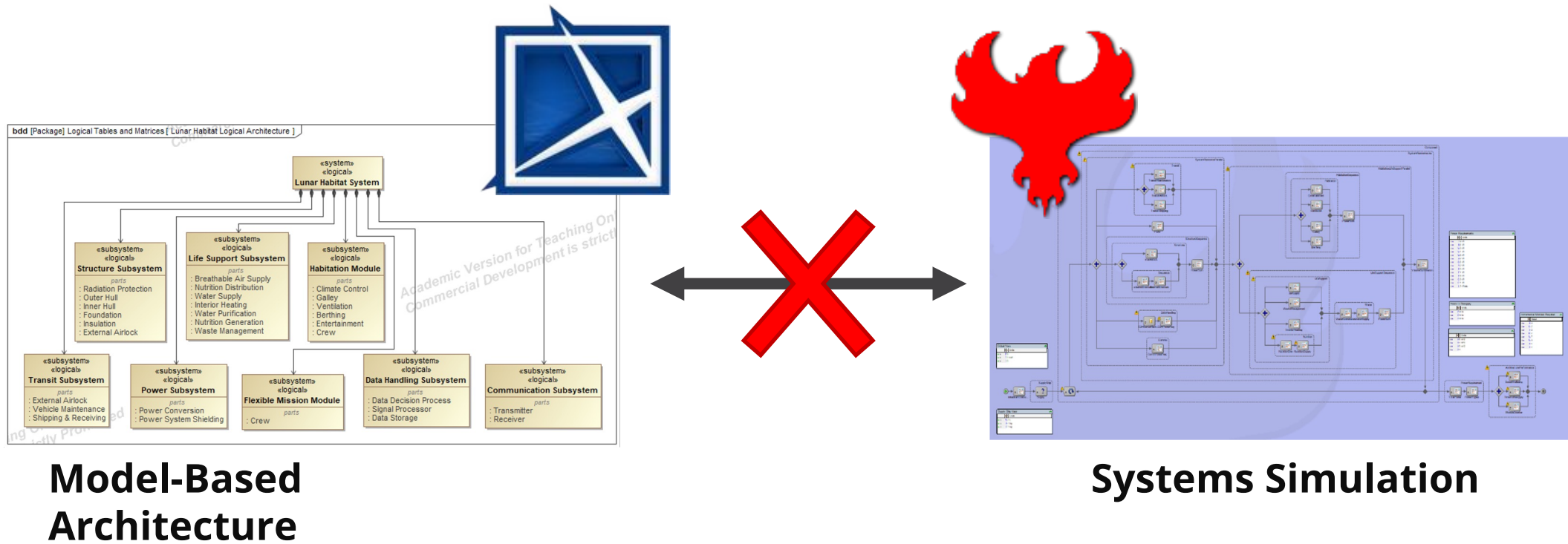


[6]

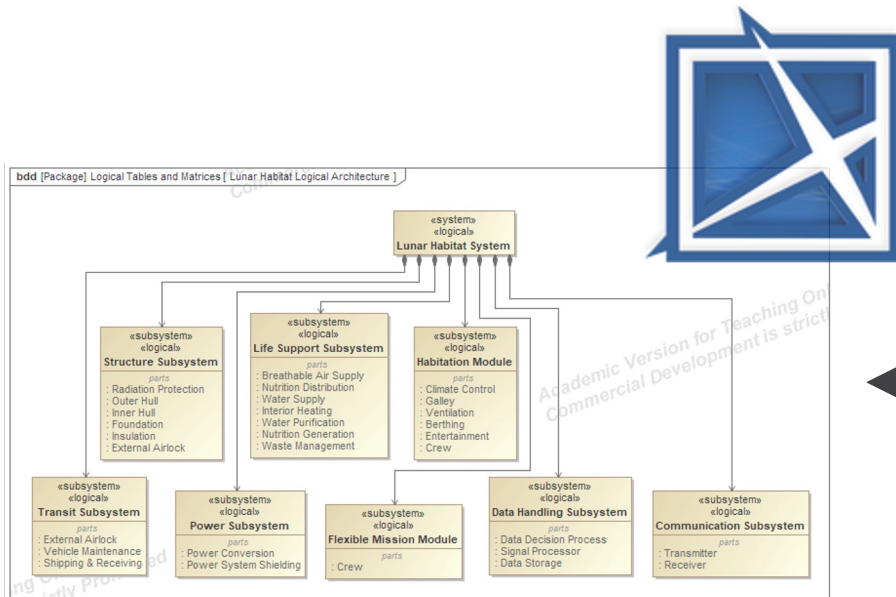




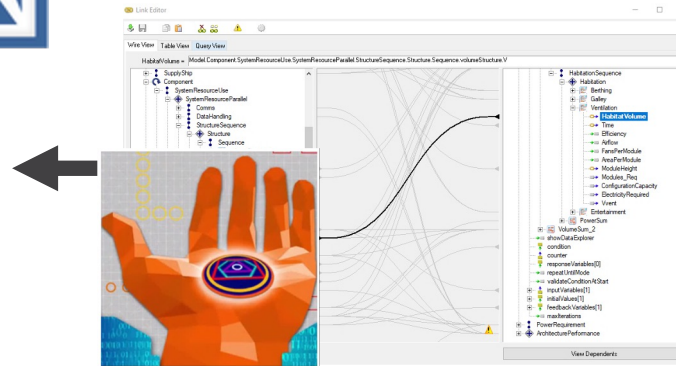
# Shared Systems Simulation Coupling



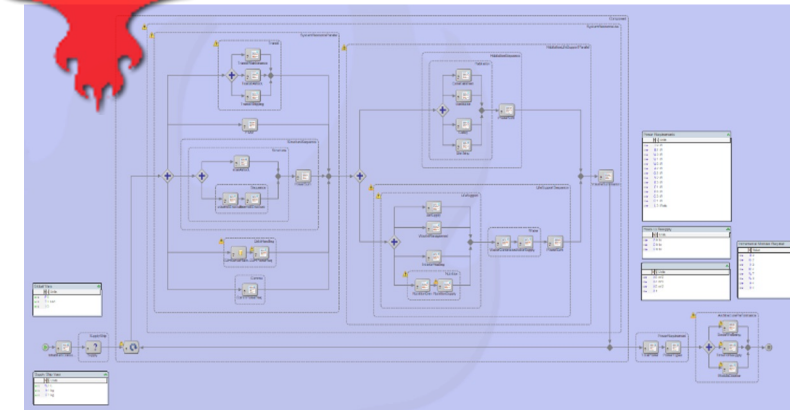
# Shared Systems Simulation Coupling



Model-Based  
Architecture



MBSE Connector  
Interface



Systems Simulation

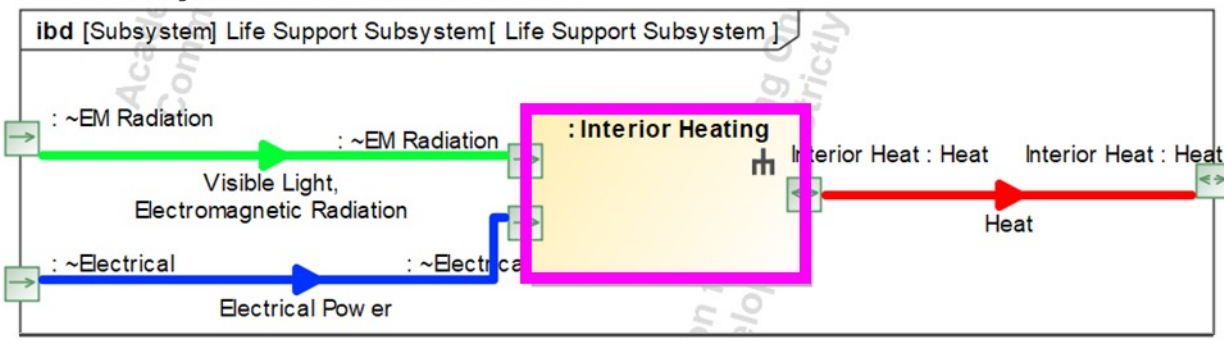




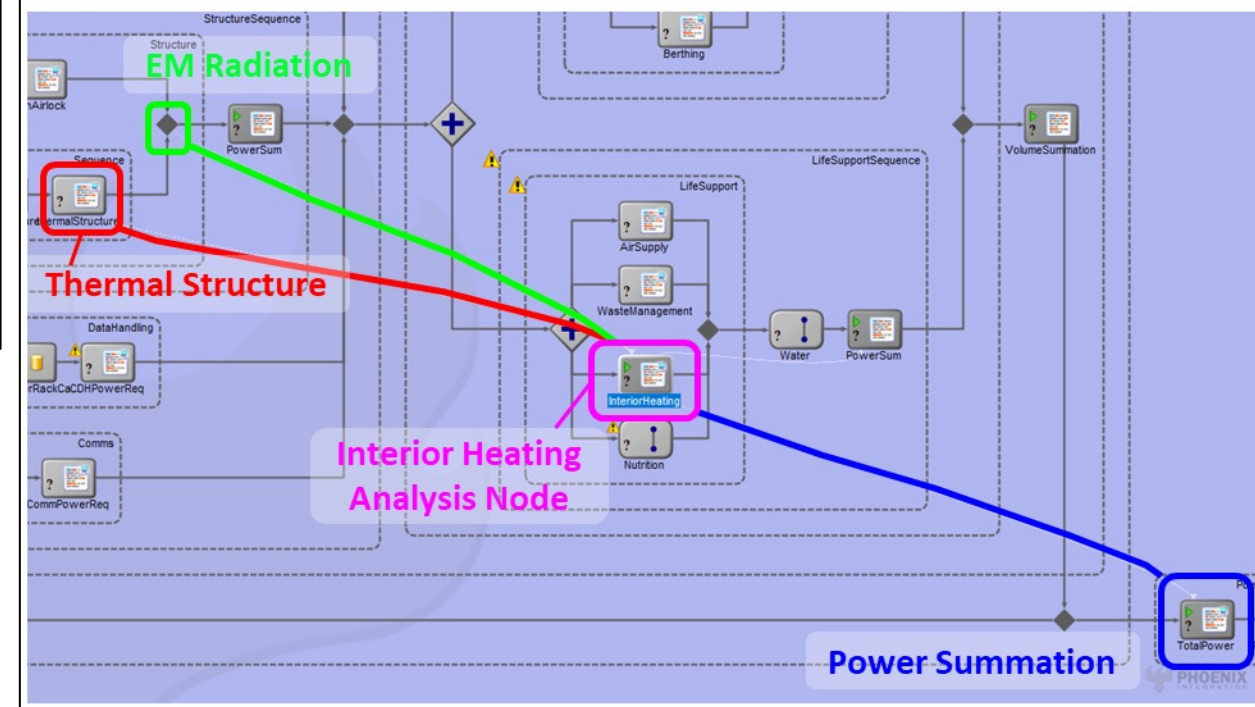
# Shared Systems Simulation Coupling

- Coupled the simulation to the model-based architecture

## MSBE System Architecture



## ModelCenter Simulation Workflow



## Manage Projects:

- Create New Project
- Open Project

## Recent Projects:

- 21F\_L...Habitat Thesis/trunk
- 21F\_L...tat Thesis/trunk#136
- 21F\_L...tat Thesis/trunk#137
- 21F\_L...tat Thesis/trunk#138

## No Magic News

- Release of 19.0 SP3
- Release of 19.0 SP2
- Release of Cameo Inter-Op 19.0 SP1 and Cameo Workbench 19.0 SP1
- Release of Cameo Inter-Op 19.0 LTR and Cameo Workbench 19.0 LTR
- Release of 19.0 SP1



What's New



Resources



Samples

# Video: Architecture to Simulation Mapping



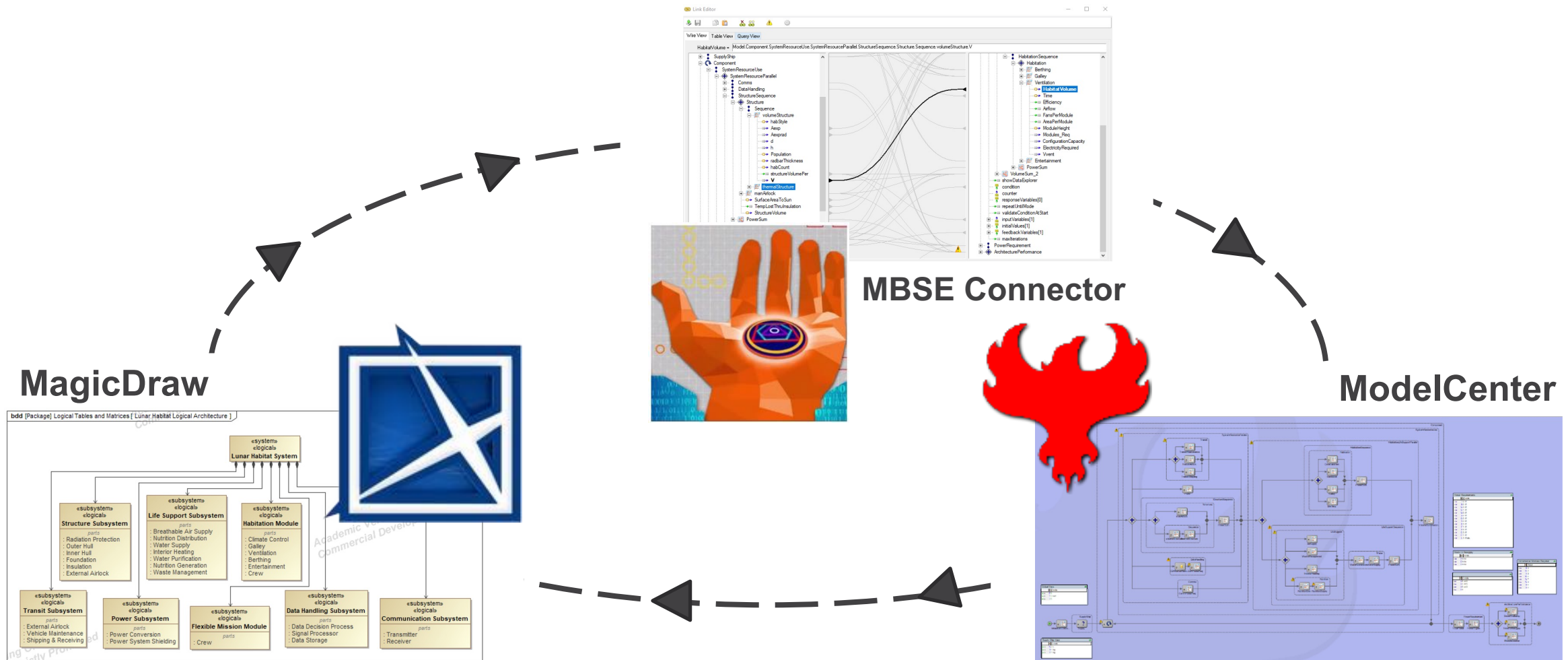
Updates are available

New service pack version 19.0 SP3 is

[Details](#)



# Shared Systems Simulation Coupling





# Agenda

- ✓ Shift to Model-Based Systems Engineering
- ✓ Problem Statement
- ✓ Model-Based Architecture Development
- ✓ Shared Systems Simulation Coupling
  - ▶ Architecture Trade Study Example
  - ▶ Interface and Complexity Challenges



# Agenda

- ✓ Shift to Model-Based Systems Engineering
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- ✓ Shared Systems Simulation Coupling
- ▶ **Architecture Trade Study Example**
- ▶ Interface and Complexity Challenges

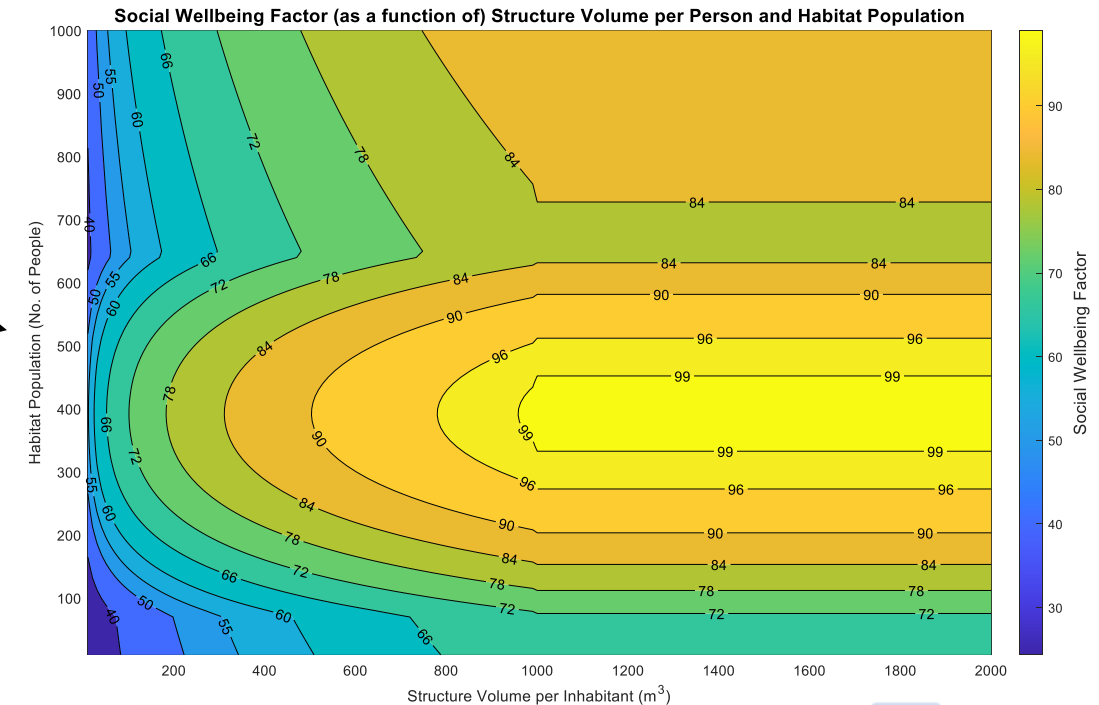




# Architecture Trade Studies

- Coupled system simulation enabled trade studies to characterize system behavior and guide decision-making

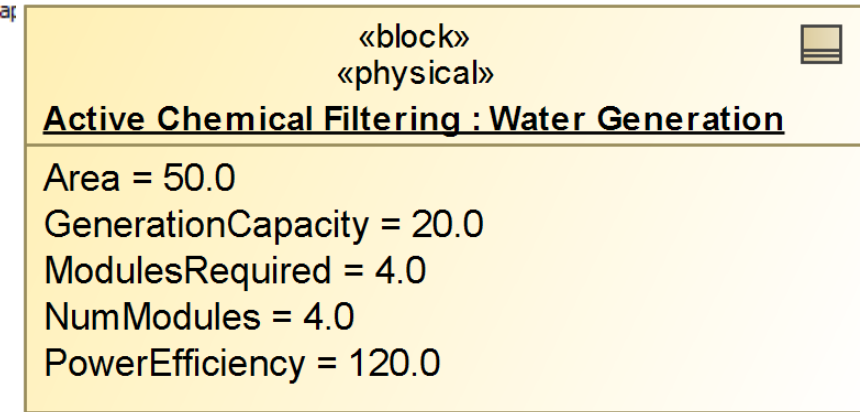
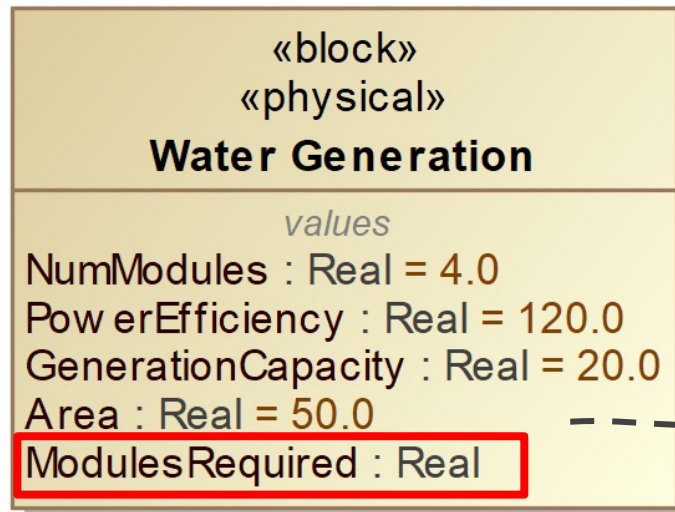
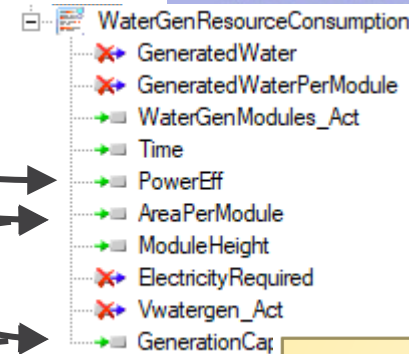
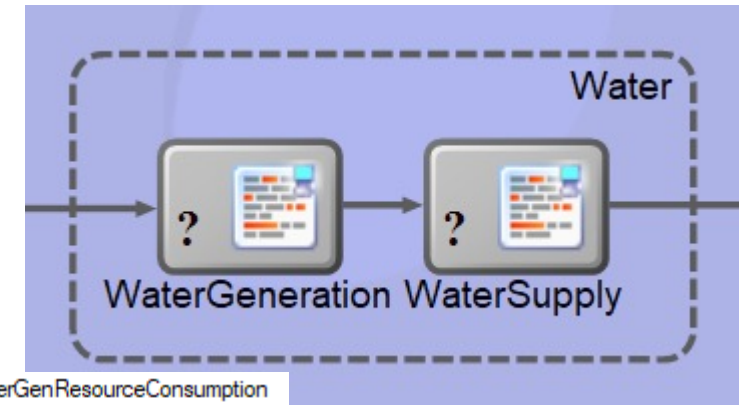
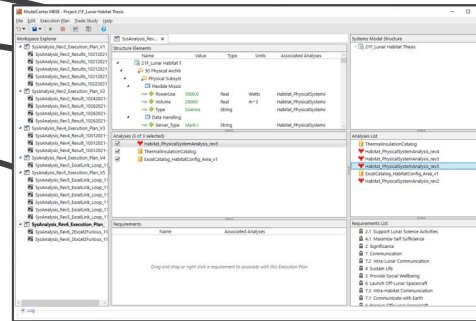
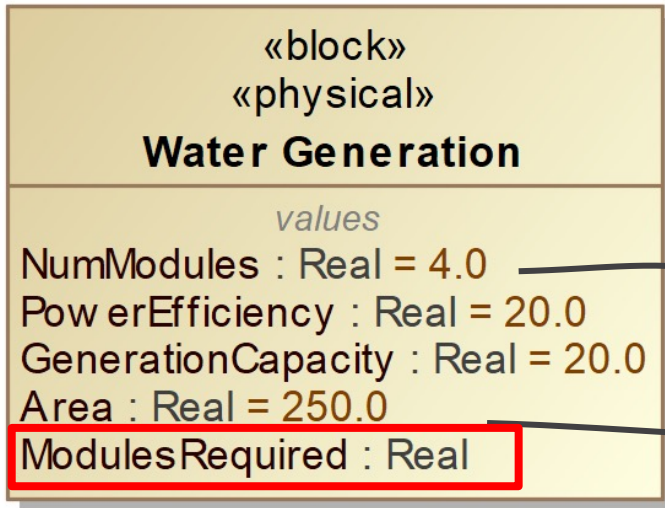
Table - Trade Study 1 - Data Explorer																
File Chart Help																
Add View Finders Plug-Ins																
Legend																
	input					valid output					invalid output					
	1	2	3	4	5	6	7	8	9	10	11	12	13			
MANUAL SCROLL																
design variable(Model Component SystemResourceUse SystemResourceUse)	2000	1783.33	1566.67	2000	1783.33	1566.67	1250	1133.33	916.667	700	483.333	266.667	50	2000	1783.33	1566.67
design variable(Model Component Population)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
response(Model ArchitecturePerformance SocialWellbeing Wellbeing)	1.04146	1.04146	1.04146	1.04146	1.04146	1.04146	1.04146	1.04146	1.04146	1.00704	0.97378	0.92532	0.8191	0.94968	0.94968	0.94968
response(Model ArchitecturePerformance SocialWellbeing Wellbeing)	0.20829	0.20829	0.20829	0.20829	0.20829	0.20829	0.20829	0.20829	0.20829	0.20411	0.19478	0.18666	0.16322	0.18874	0.18874	0.18874
Model habStyle	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder
Model Population	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Model Time	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
Model Illuminated	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Model habCount	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Model radBasThickness	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Model intThickness	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Model ModuleHeight	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Model InhabitantConsumption Population	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Model InhabitantConsumption OxygenPerHour	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7	24492.7
Model InhabitantConsumption WaterPerHour	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333	458.333
Model InhabitantConsumption FoodPerHour	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5
Model SupplyShip WaterPerSupply	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000
Model SupplyShip AirPerSupply	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Model SupplyShip FoodPerSupply	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750	750
Model Component showRelatedSphere	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
Model Component condition	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Model Component counter																
Model Component responseVariables	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true	true
Model Component repeatInitMode	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false	false
Model Component validateConditionAtStart	2000	1783.3333	1566.6666	2000	1783.3333	1566.6666	1250	1133.3333	916.6666	700	483.3333	266.6666	50	2000	1783.3333	1566.6666
Model Component inputVariables	2000	1783.33	1566.67	2000	1783.33	1566.67	1250	1133.33	916.667	700	483.333	266.667	50	2000	1783.33	1566.67
Model Component initialValues																
Model Component feedbackVariables	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215
Model Component feedbackVariables[0]	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215	215
Model Component modifications	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Model Component SystemResourceUse SystemResourceUseParallel...	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Model Component SystemResourceUse SystemResourceUseParallel...	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350	350
Model Component SystemResourceUse SystemResourceUseParallel...	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1
Model Component SystemResourceUse SystemResourceUseParallel...	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36
Model Component SystemResourceUse SystemResourceUseParallel...	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Model Component SystemResourceUse SystemResourceUseParallel...	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Model Component SystemResourceUse SystemResourceUseParallel...	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100
Model Component SystemResourceUse SystemResourceUseParallel...	0.29733	0.29733	0.29733	0.29733	0.29733	0.29733	0.29733	0.29733	0.29733	0.29733	0.29733	0.29733	0.29733	0.1699	0.1699	0.1699
Model Component SystemResourceUse SystemResourceUseParallel...	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36
Model Component SystemResourceUse SystemResourceUseParallel...	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36
Model Component SystemResourceUse SystemResourceUseParallel...	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Model Component SystemResourceUse SystemResourceUseParallel...	75443.1	69140.6	62707.9	75443.1	69140.6	62707.9	56124.4	49351.8	42332.5	34972.2	27993.3	18277.5	6604.99	48289.7	44441.6	40501.4
Model Component SystemResourceUse SystemResourceUseParallel...	2.10014e+06	1.79347e+06	1.56681e+06	2.10014e+06	1.79347e+06	1.56681e+06	1.35014e+06	1.12347e+06	916808	700141	463475	266408	50141.4	1.10011e+06	967946	861793
Model Component SystemResourceUse SystemResourceUseParallel...	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder	cylinder
Model Component SystemResourceUse SystemResourceUseParallel...	75443.1	69140.6	62707.9	75443.1	69140.6	62707.9	56124.4	49351.8	42332.5	34972.2	27993.3	18277.5	6604.99	48289.7	44441.6	40501.4
Model Component SystemResourceUse SystemResourceUseParallel...	79591.9	73125.4	66524.8	79591.9	73125.4	66524.8	59761.2	52793.5	45593.3	37966.6	29794.3	20619.3	8360.29	51699.8	47734.5	43663.7
Model Component SystemResourceUse SystemResourceUseParallel...	112.838	106.551	98.8695	112.838	106.551	98.8695	82.7058	64.8413	56.2916	46.7956	36.4707	41.2028	17.8412	63.6828	79.0201	74.0644
Model Component SystemResourceUse SystemResourceUseParallel...	16.419	15.2794	14.0342	16.419	15.2794	14.0342	12.8476	10.6113	8.92662	7.1959	5.33779	27.7263	8.5062	41.8414	29.5101	27.0222
Model Component SystemResourceUse SystemResourceUseParallel...	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Model Component SystemResourceUse SystemResourceUseParallel...	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Model Component SystemResourceUse SystemResourceUseParallel...	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Model Component SystemResourceUse SystemResourceUseParallel...	2000	1783.33	1566.67	2000	1783.33	1566.67	1250	1133.33	916.667	700	483.333	266.667	50	2000	1783.33	1566.67
Model Component SystemResourceUse SystemResourceUseParallel...	2e-06	1.78333e-06	1.56667e-06	2e-06	1.78333e-06	1.56667e-06	1.35e-06	1.13333e-06	916667	700000	483333	266667	50000	1.1e-06	868833	861667
Model Component SystemResourceUse SystemResourceUseParallel...	75443.1	69140.6	62707.9	75443.1	69140.6	62707.9	56124.4	49351.8	42332.5	34972.2	27993.3	18277.5	6604.99	48289.7	44441.6	40501.4
Model Component SystemResourceUse SystemResourceUseParallel...	79591.9	73125.4	66524.8	79591.9	73125.4	66524.8	59761.2	52793.5	45593.3	37966.6	29794.3	20619.3	8360.29	51699.8	47734.5	43663.7



# Design Configuration #1: Passive Filtration



## MBSE Connector

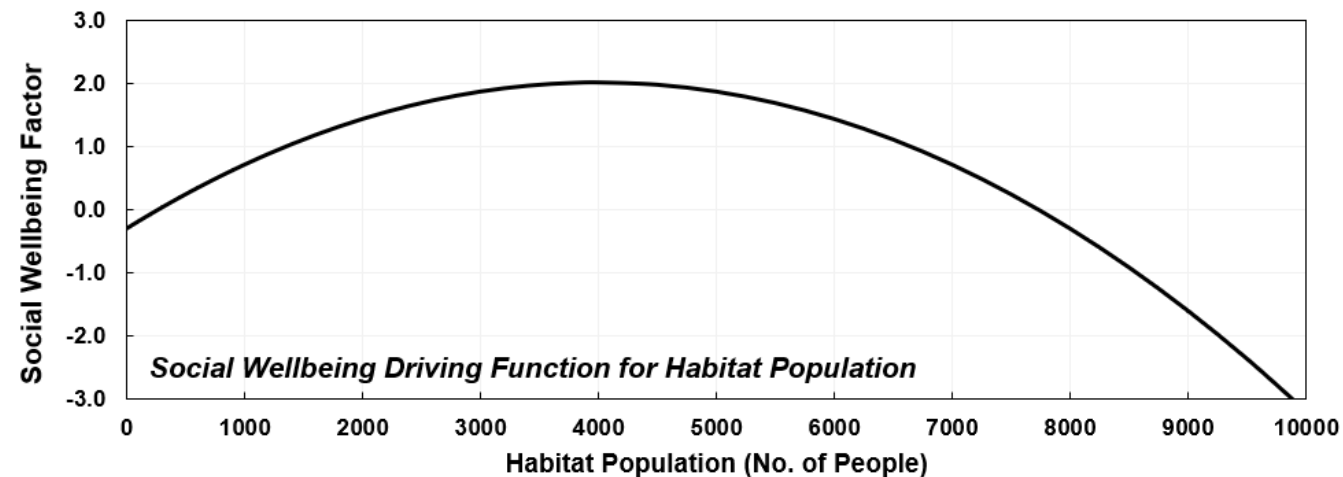
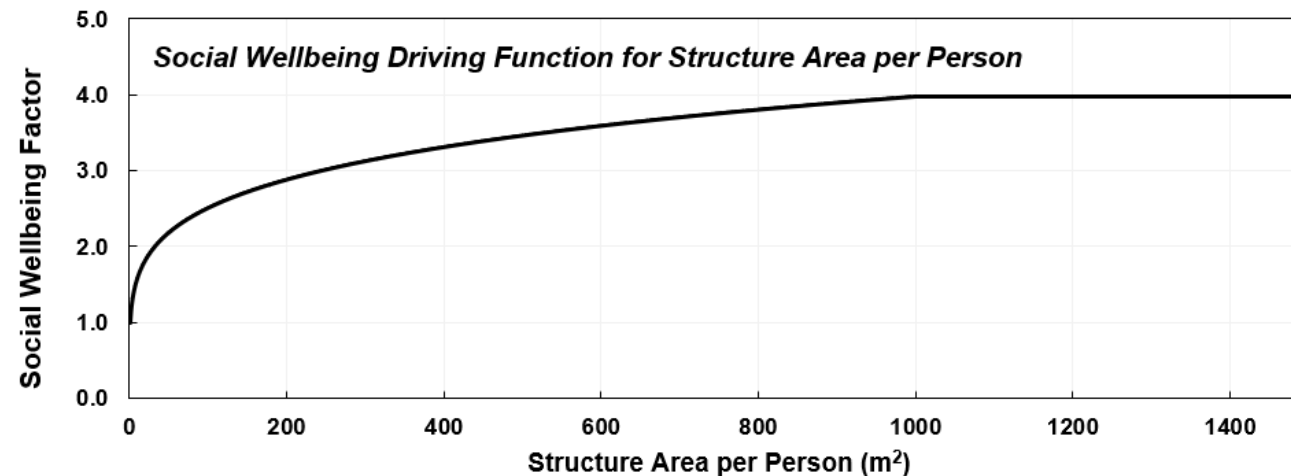


# Design Configuration #2: Active Chemical Filtering



# Example Trade Study: Social Wellbeing

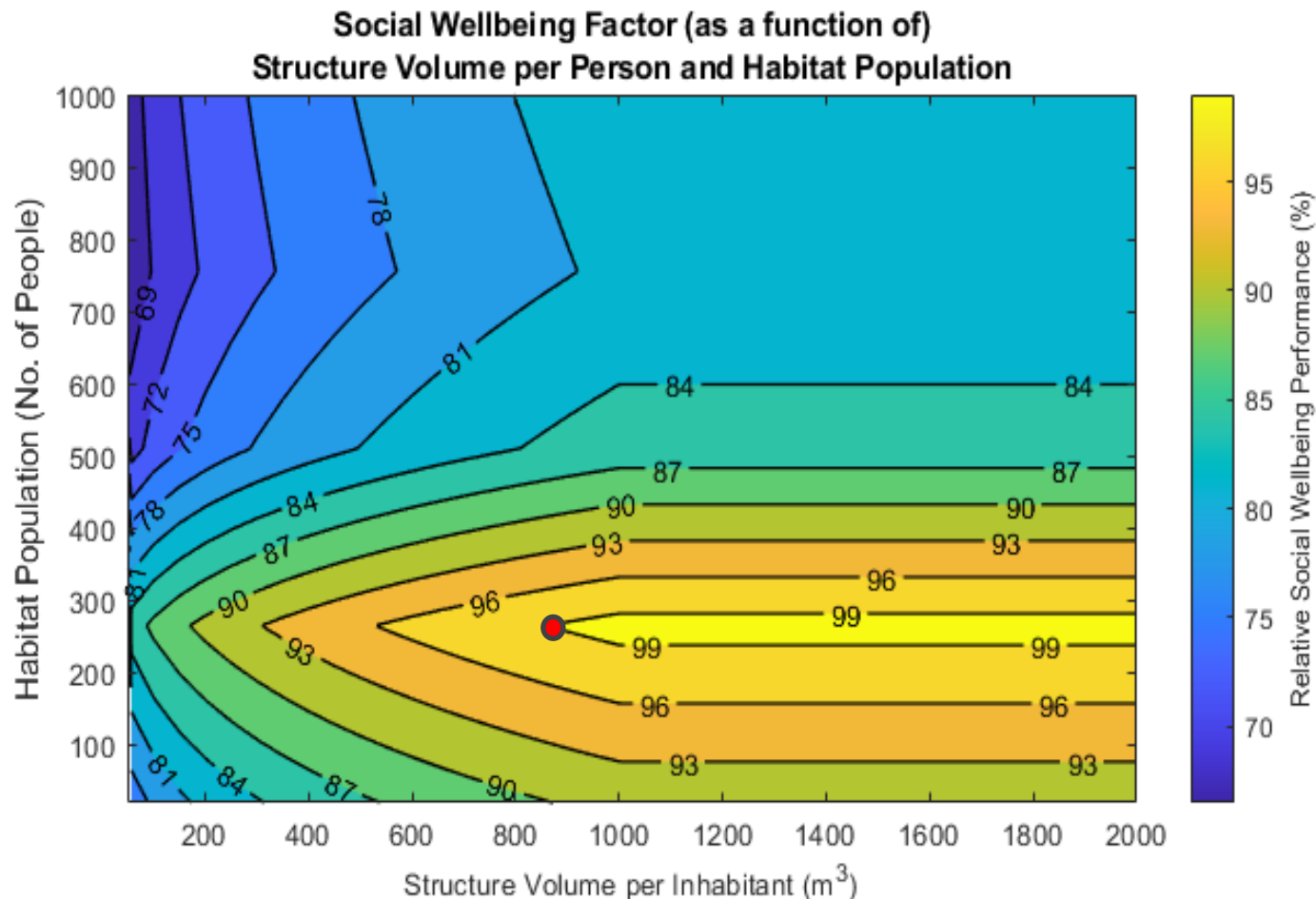
- ▶ Social considerations = sustained architecture success
- ▶ *Social Wellbeing Factor* enables qualitative analysis in the shared system model





# Example Trade Study: Social Wellbeing

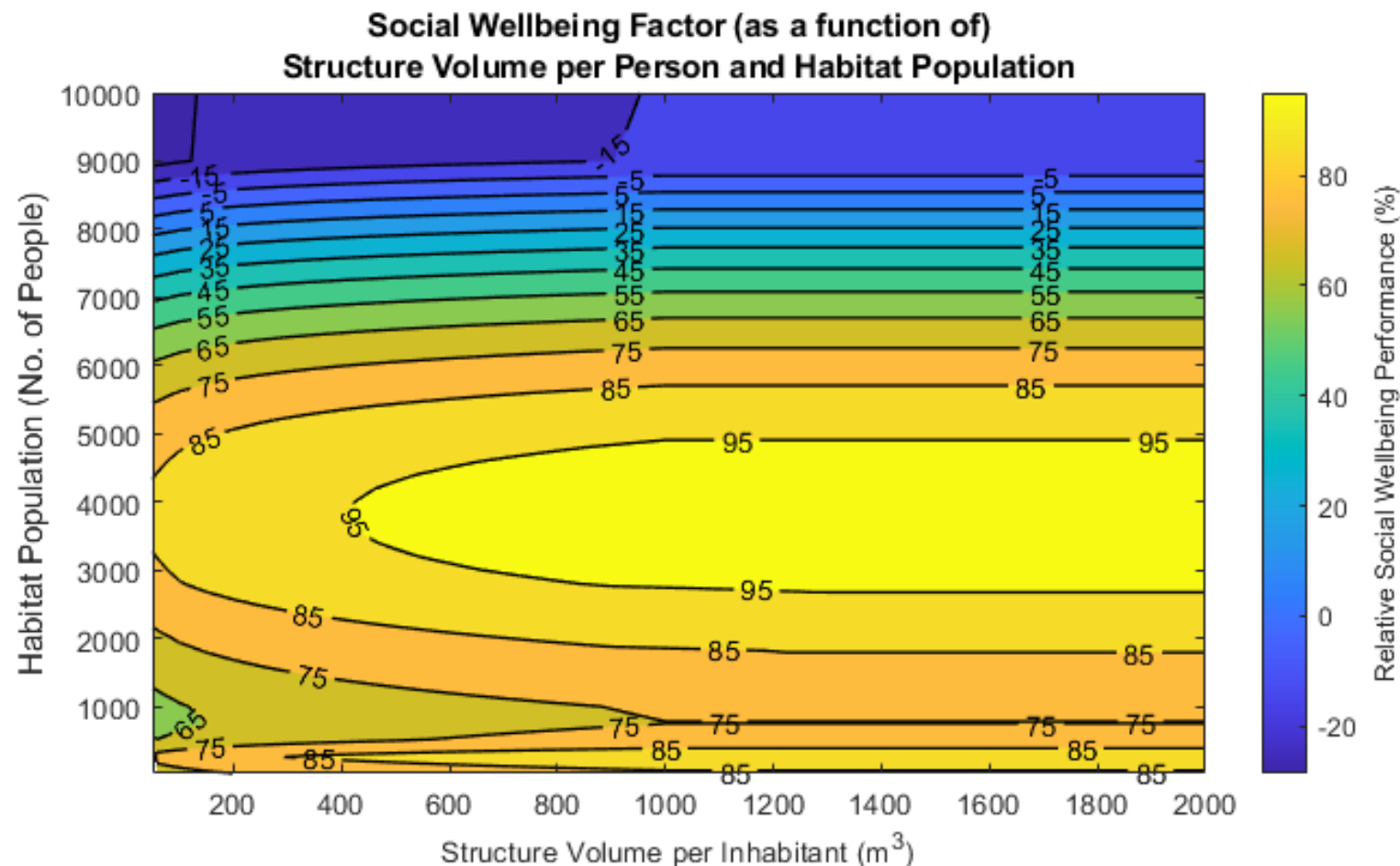
- Architecture decisions influence down-stream system response
- Identify sociological emergent behavior





# Example Trade Study: Social Wellbeing

- ▶ Studies can predict both present and future behavior
- ▶ Methods supports analysis of the “soft” aspects of complex socio-technical systems







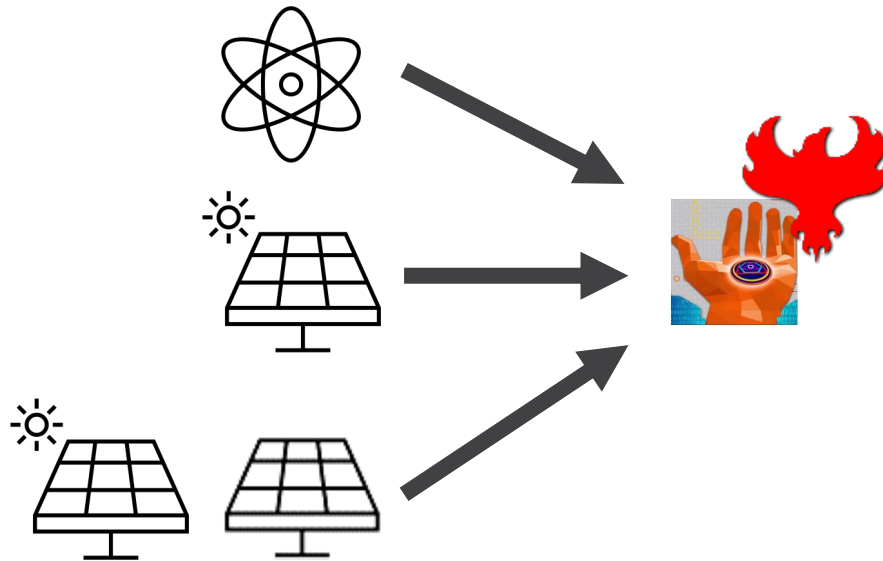
# Advantages and Successes

- ✓ Leveraged the Shared Systems Model
- ✓ Created a flexible, rigorous, robust, and efficient simulation
- ✓ Identified emergent system behaviors

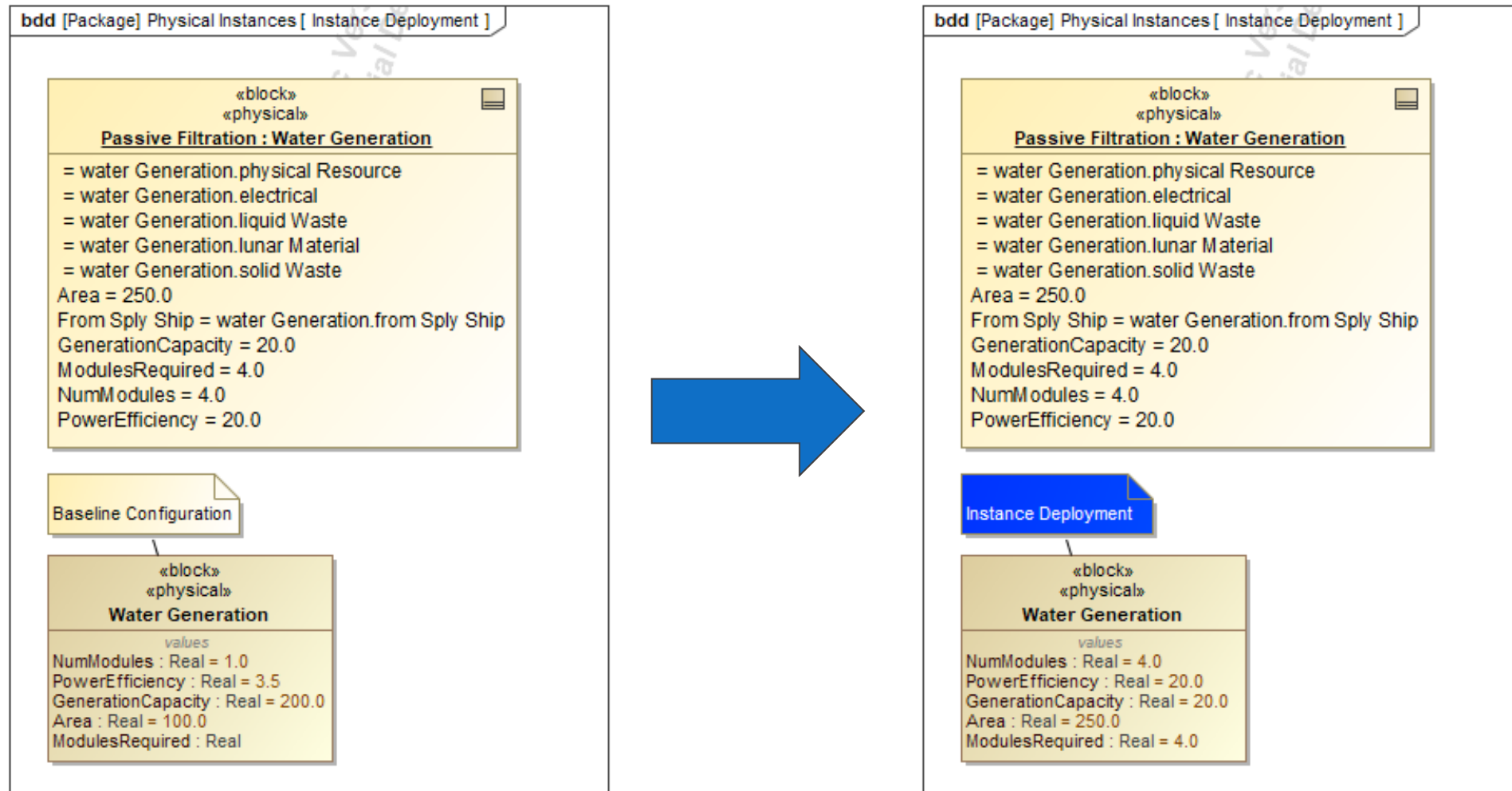


# Challenges

- ▼ System simulation DOEs require multiple physical architecture configurations



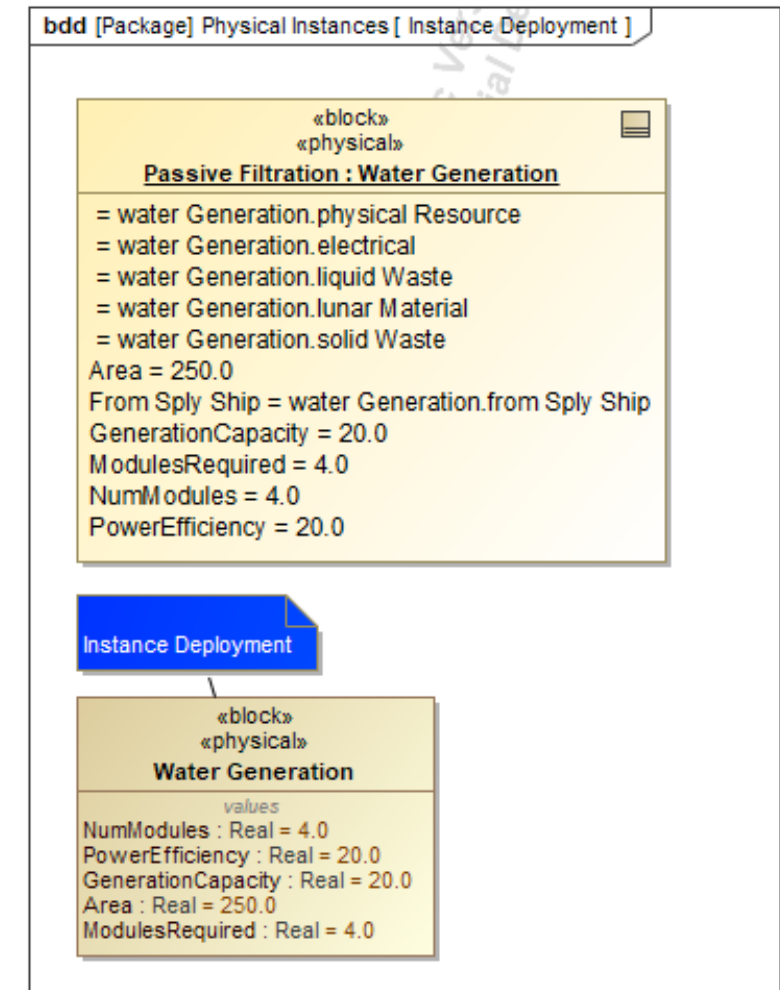
# Instance Management



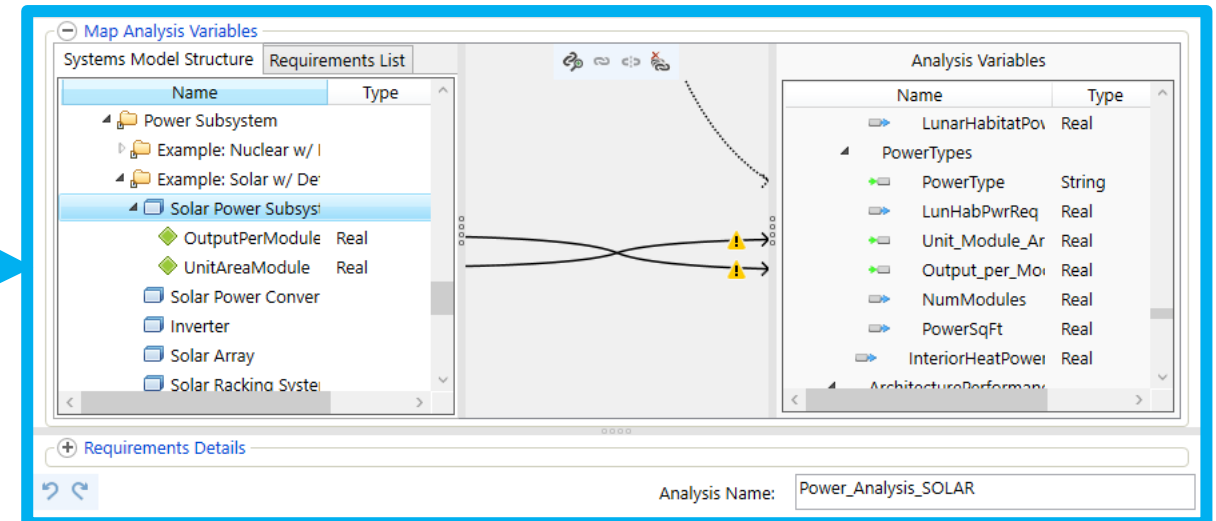
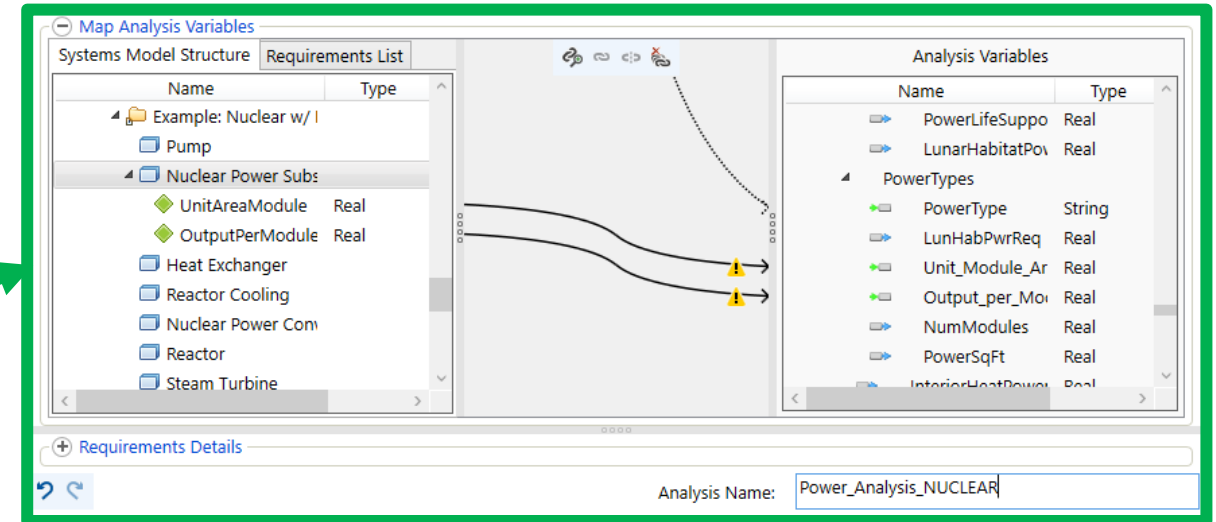
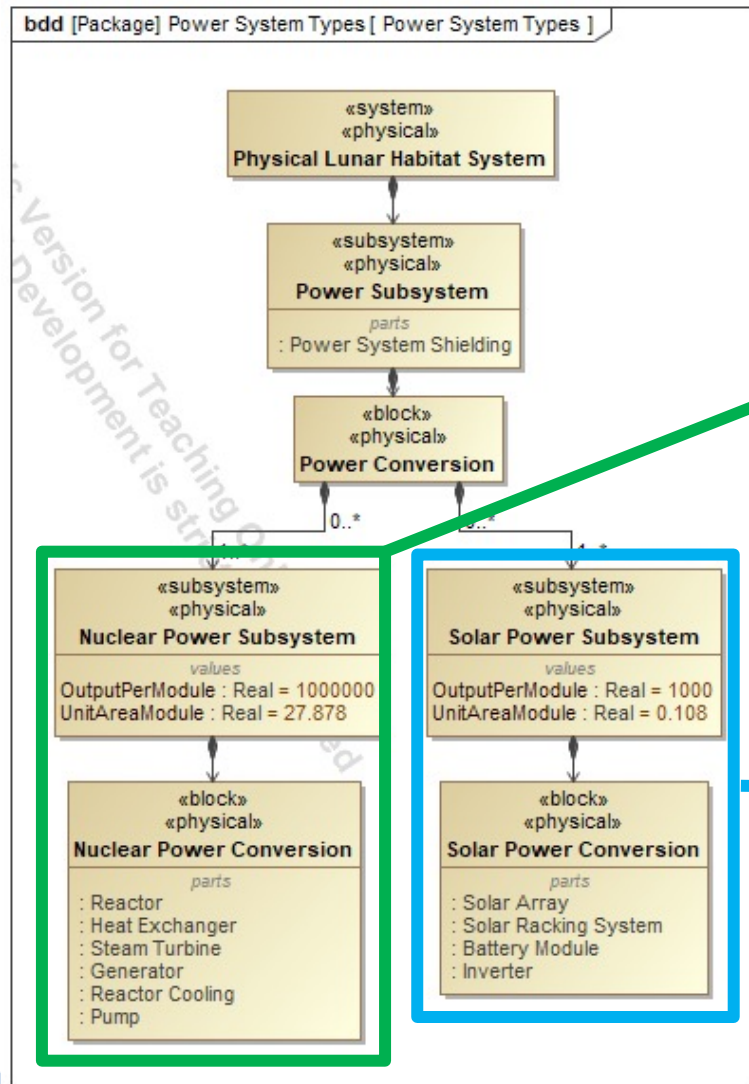


# Instance Management

- ▶ Modeler-in-the-loop intensive
- ▶ Document-centric
- ▶ Inefficient and fragile

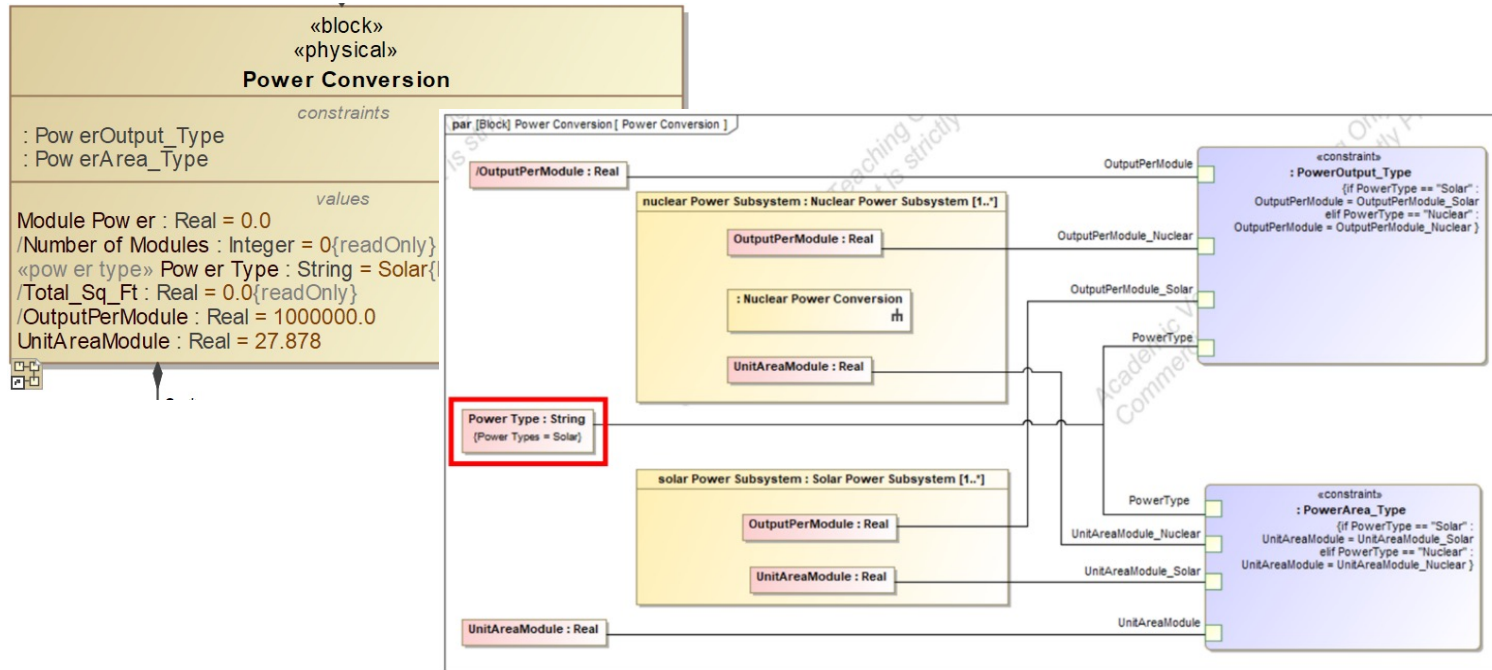


# Parallel Physical Trees





# Parametric Definition



Simulation

Simulation

Sessions x

Power Conversion [Power Conversion@179d86ec] (Ready)

Console x

00:00:00,000 : Initial solving ...  
00:00:00,000 : Initial solving completed.  
00:00:00,000 : \*\*\*\* Block Power Conversion is initialized. \*\*\*\*

Variables x

Breakpoints x

Name	Value
Power Conversion	Power Conversion@179d86ec
Module Power : Real	0.0000
/Number of Modules : Integer	0
/OutputPerModule : Real	1.0000E6
Power Type : String	Nuclear
/Total_Sq_Ft : Real	0.0000
UnitAreaModule : Real	27.8780
nuclear Power Subsystem : Nuclear Power Subsystem@72715be	Nuclear Power Subsystem@72715be
solar Power Subsystem : Solar Power Subsystem@648c1b80	Solar Power Subsystem@648c1b80
PowerOutput_Type {if Power Type == "Solar": ...	PowerOutput_Type@76289d6d
PowerArea_Type {if Power Type == "Solar": U...	PowerArea_Type@50536c03

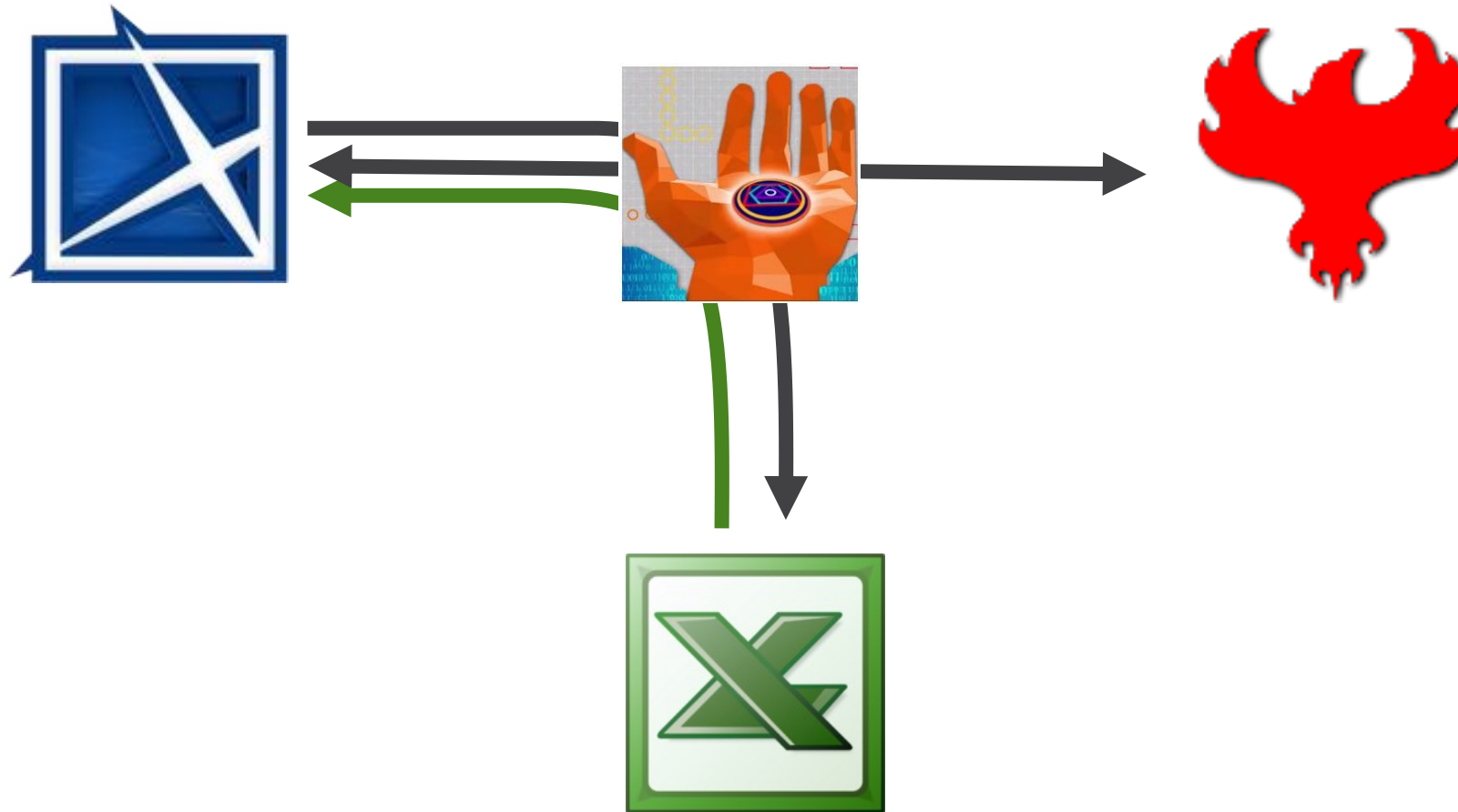
Expand Recursively  
Export Value To  
**Save To Default Value(s)**  
Show in Timeline Chart  
Go To  
Select in Containment Tree Alt+B  
Create Sequence Diagram



# Coupled Design Catalog

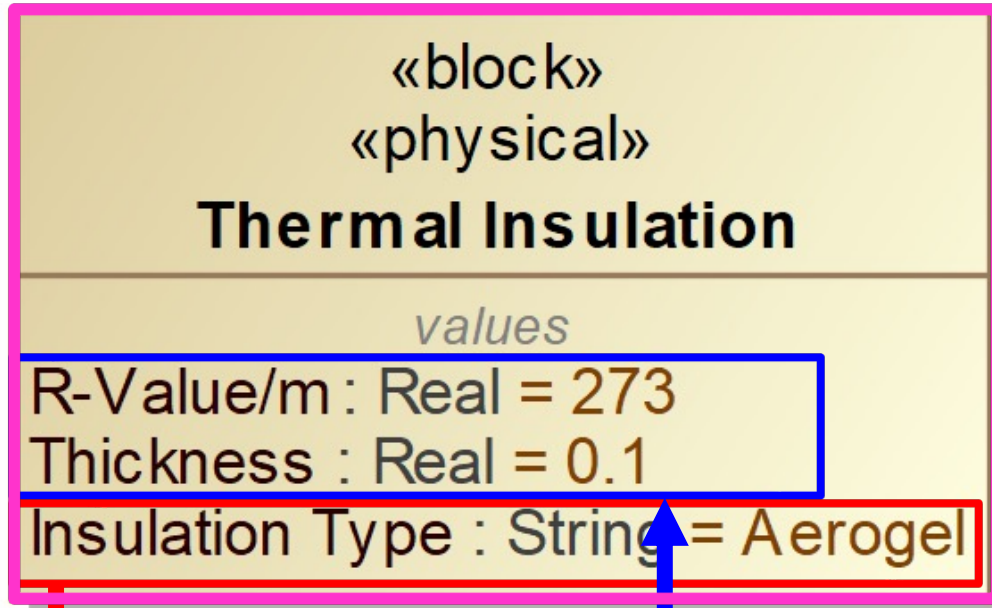
**Design Catalog:** ModelCenter Excel-based element that stores design detail in a tabular form

# Coupled Design Catalog

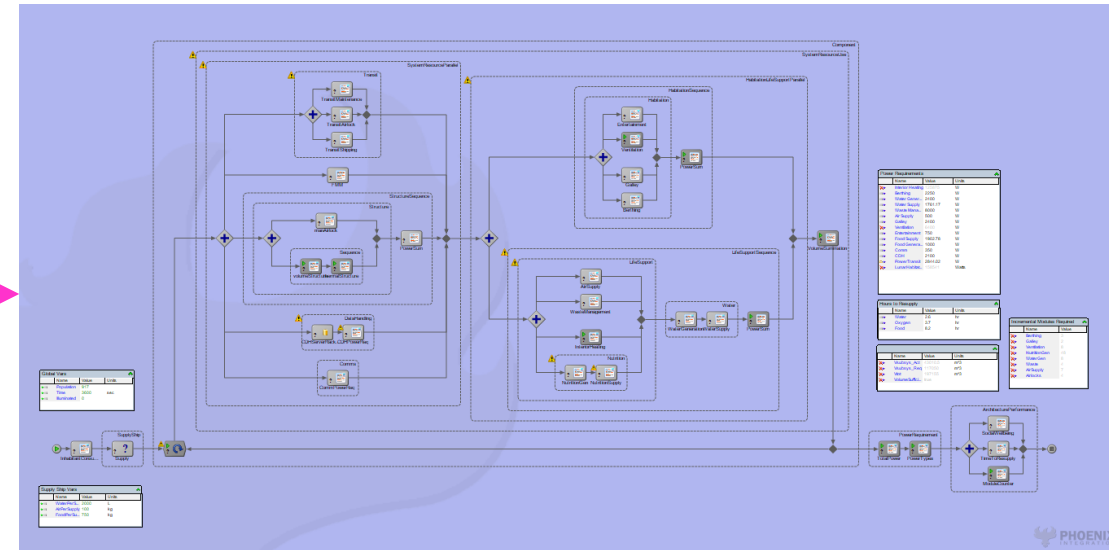




# Coupled Design Catalog



Insulation Type	R_Value	Thickness
Aerogel	273	0.1
Silica Aerogel	390	0.1
Glass Bead Aerogel	780	0.1





# Coupled Design Catalog

- ▶ No requirement of duplicate physical trees or bespoke parametric equations
- ▶ DOE support
- ▶ Architecture as authoritative source of truth
- ▶ Minimal architecture modification for executability





# Conclusions

## The Shared Systems Simulation Methodology:

- ▶ Translates MBSE rigor to the detailed engineering phase.
- ▶ Maintains the model-based architecture as the A.S.O.T.
- ▶ Supports expansive system characterization via simulations.
- ▶ Requires novel solutions to emergent issues such as multiple physical architecture configuration requirements.



# Further Reading

University of Detroit Mercy Masters Thesis:

## ***Applying Model-Based Systems Engineering (MBSE) Methods to a Novel Shared Systems Simulation Methodology*** <sup>[11]</sup>

Authors: Christopher Caron, Christopher Craft, Ashishkumar Prajapati,  
Stephen Pien, and Jeremy Ross

Advisor: Professor Michael J. Vinarcik, ESEP-Acq, FESD



# 32<sup>nd</sup> Annual **INCOSE** international symposium

hybrid event

Detroit, MI, USA  
June 25 - 30, 2022

[www.incose.org/symp2022](http://www.incose.org/symp2022)



# References

- [1] M. Vinarcik, *Supercruise: Model Based Systems Engineering and Digital Engineering in 2022*, 7 June 2022.
- [2] T. Weillkiens, J. Lamm, S. Roth, M. Walker, 2016, *Model-Based System Architecture*, 1st edn, John Wiley & Sons, Inc., Hoboken.
- [3] (Image Source) Dassault Systèmes, *MagicDraw*, DS CATIA, 2021. [Online]. Available: <https://www.3ds.com/products-services/catia/products/no-magic/magicdraw/>. [Accessed 18 October 2021].
- [4] (Image Source) Autodesk, "Simulation Overview," Autodesk Inc., 2020. [Online]. Available: <https://www.autodesk.com/solutions/simulation/overview>. [Accessed 27 March 2022].
- [5] (Image Source) Siemens, "Turbomachinery CFD Simulation Software," Siemens, 2022. [Online]. Available: <https://www.plm.automation.siemens.com/global/es/webinar/turbomachinery-cfd-simulation-software/91231>. [Accessed 27 March 2022].
- [6] (Image Source) K. Hanna, "Why Spreadsheets Are The Best Way To Handle Your Personal Finances," 24 September 2018. [Online]. Available: <https://www.makingyourmoneymatter.com/why-spreadsheets-are-the-best-way-to-handle-your-personal-finances-a-sneak-peek-at-mine/>. [Accessed 27 March 2022].
- [7] (Image Source) Phoenix Integration, "ModelCenter," Phoenix Integration | An Ansys Company, 2021. [Online]. Available: <https://www.phoenix-int.com/product/modelcenter-integrate/>. [Accessed 27 March 2022].
- [8] (Image Source) Wikipedia. Available: [https://upload.wikimedia.org/wikipedia/commons/thumb/b/bc/Gibbous\\_Moon\\_in\\_High\\_Resolution.jpg/653px-Gibbous\\_Moon\\_in\\_High\\_Resolution.jpg](https://upload.wikimedia.org/wikipedia/commons/thumb/b/bc/Gibbous_Moon_in_High_Resolution.jpg/653px-Gibbous_Moon_in_High_Resolution.jpg) [Accessed 1 December 2021].
- [9] (Image Source) Icarus Interstellar. Available: <https://www.youtube.com/channel/UCtNwXHHzshExRH3tA0v3y63w/videos>. [Accessed 1 December 2021].
- [10] (Image Source) J. Parson, "Nasa to colonise the moon with astronaut base ready for trip to Mars," 7 April 2020. [Online]. Available: <https://metro.co.uk/2020/04/07/nasa-reveals-plans-colonise-moon-astronaut-base-12519711/>. [Accessed 23 November 2021].
- [11] C. Caron, C. Craft, A. Prajapati, S. Pien, J. Ross, *Applying Model-Based Systems Engineering (MBSE) Methods to a Novel Shared Systems Simulation Methodology*, 12 December 2021.

