2020 Annual INCOSE international workshop
Torrance, CA, USA
January 25 - 28, 2020

Production and Logistics Modeling Challenge Team Breakout Session

Timothy Sprock[a], Leon McGinnis[b], Conrad Bock[a] , George Thiers[c]
[a] National Institute of Standards and Technology, [b] Georgia Tech, [c] MBSE Tools, Inc.

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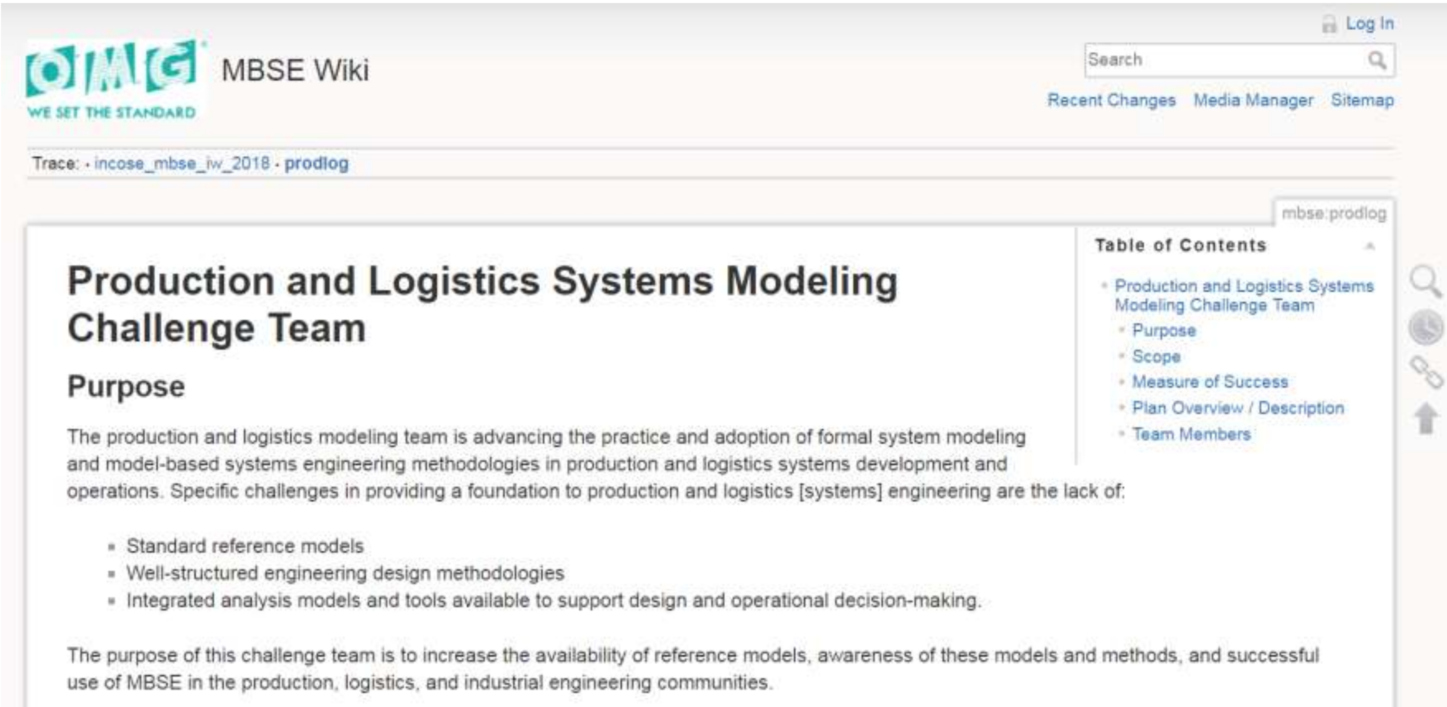
Contents

Production and Logistics Systems Modeling

- http://www.omgwiki.org/MBSE/doku.php?id=mbse:prodlog



Challenge team weekly meeting at 11 am (EST) Fridays.

The meeting information is:

To join the Meeting:
https://bluejeans.com/419553114

To join via phone :

1) Dial:
   +1.408.317.9254 (US (San Jose))
   +1.888.240.2560 (US Toll Free)
   +1.408.317.9253 (US Alternate)
   (see all numbers - http://bluejeans.com/numbers)
2) Enter Conference ID : 419553114

Summary of P&L-related Products

- Model Libraries
  - https://github.com/usnistgov/DiscreteEventLogisticsSystems
- Documentation (DRAFT)
  - Overleaf: https://v2.overleaf.com/read/hhsmnkssjwcp
  - https://doi.org/10.6028/NIST.IR.8262
- Central Fill Pharmacy Case
  - https://doi.org/10.6028/NIST.GCR.19-022
- MBISE Playbook – How to apply DELS model libraries
  - INCOSE Production and Logistics Systems Modeling Challenge Team
  - Overleaf (DRAFT): https://v2.overleaf.com/read/rsjqhqzmxtxq
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- Reference Implementation of SAI (Matlab)
  - https://github.com/usnistgov/dels-analysis-integration
    - Email timothy.sprock@nist.gov for access (need github account)

Roadmap - Identify a Case Study

- Examples of SysML diagrams and syntax
- Capture domain-specific concepts:
  - Requirements
  - Architecture
  - Product, Process, Resource, & Facility
  - How do you control your system?
  - What do you want to know about the system? (metrics)

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Production and Logistics Modeling Challenge Team Overview

Timothy Sprock[a], Leon McGinnis[b], Conrad Bock[a] , George Thiers[c]
[a] National Institute of Standards and Technology, [b] Georgia Tech, [c] MBSE Tools, Inc.

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Audience Exercise: Stand Up!

- Now, sit down if you are involved in designing/developing:
  - Aerospace systems
  - Ground-based vehicle systems
  - Naval systems
  - Communication systems
  - Medical device systems
  - Anything that is not a production or logistics system
- Who's left?

Thought Experiment

- New program: Falcon 2035
  - Program cost of \$5 x 10^9
  - Revenue is \$350 x 10^6 per unit
  - => 1428 units to breakeven
  - You have great confidence in your engineering estimates of performance

Thought Experiment

- New
  - Pro
  - Rev
  - => 1
  - You ineering
    esti

Now suppose

- Estimate of facility cost was $\$2 \times 10^9$, is actually $\$2.4 \times 10^9$
- Estimated ramp of 12, 32, 60, 60 … per year is actually 6, 12, 32, 50, 50 ….per year
- Original time to breakeven estimated as 25 years
- New time to breakeven is 30 years

Now suppose

- Estimate … , is actually $…
- Estimated … per year is actually … ear
- Original t… d as 25 years
- New time…

“How could that happen?” You say

- It has and is happening
- In part because production and logistics system design is decades behind aerospace design
- Mission of this challenge team is to change that *(not limited to aerospace!)*

Why don't we just take what we already know about MBSE and apply it to production/logistics?

Because they are different domains!

Produced systems

- Semantic standards
- Well-defined requirements
- Continuous dynamics
- Minimal internal variability
- Tight integration
- Response very predictable
- Safety factors
- Integrated analyses

Producing systems

- No semantic standards
- Ambiguous requirements
- Discrete dynamics
- Large internal variability
- Decoupling
- Response hard to predict
- Risk factors
- *Ad hoc* analyses

Because they are different domains

Produced systems

- Semantic standards
- Well-defined requirements
- Continuous
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- Response very predictabl
- Safety factors
- Integrated analyses

What we can impact (now)

Producing systems

- No semantic standards
- Ambiguous requirements
- Discrete dynamics
- Large internal variability
- Decoupling
- Response hard to predict
- Risk factors
- *Ad hoc* analyses

So how do we fulfill our mission?

- Understand key success factors for MBE/MBSE in product domain
- Adapt/adopt strategies to duplicate those success factors for production/logistics
- Demonstrate actual successes

Success Factors in Produced Systems?

- Almost 50 years of effort to “standardize” the specification of the product—culminating in the ability to exchange designs between CAD systems ***(Reference models)***
- Similar efforts to integrate engineering analyses with CAD models specifying the product ***(Analysis integration)***
- Emergence of SysML, a platform for unifying different disciplines and subsystem models ***(Enabling platform)***
- Recognition of the potential payoff ***(Value proposition)***
- Resulting commitment of resources to accomplish transformation ***(Demonstrations)***

Challenge Team Purpose

Increase the availability of reference models, awareness of these models and methods, and successful use of ***MBSE to support design of production and logistics systems***.

- Design methodology (like RFLP)
- Specify product, process, resource + behavior, control, interactions
- Feasibility and cost

What has been our focus?

- Foundation—reference model, semantics
- Application modeling—best practices
- Analysis integration/automation

In the production and logistics systems domain!

Available today:

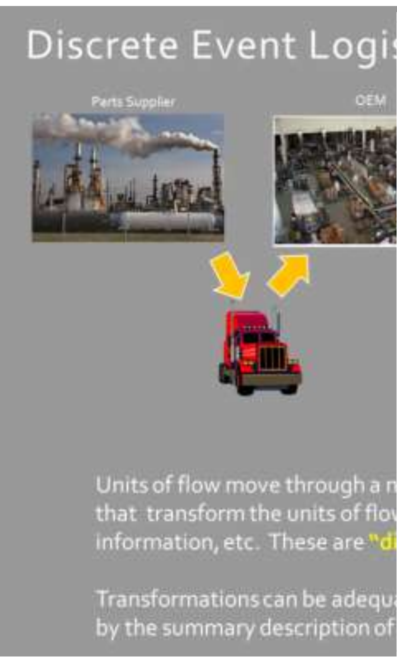
- "Foundations" document: fundamental concepts and abstractions ***(Reference model*** -> developers)
- Case: Aerospace composite production: product, process, resource (but not MH), behavior; examples of conforming analyses; 90 pp report plus MagicDraw SysML
- Case: Central Fill Pharmacy, product, process, resource (including MH), behavior, control; 75 pp report plus MagicDraw SysML

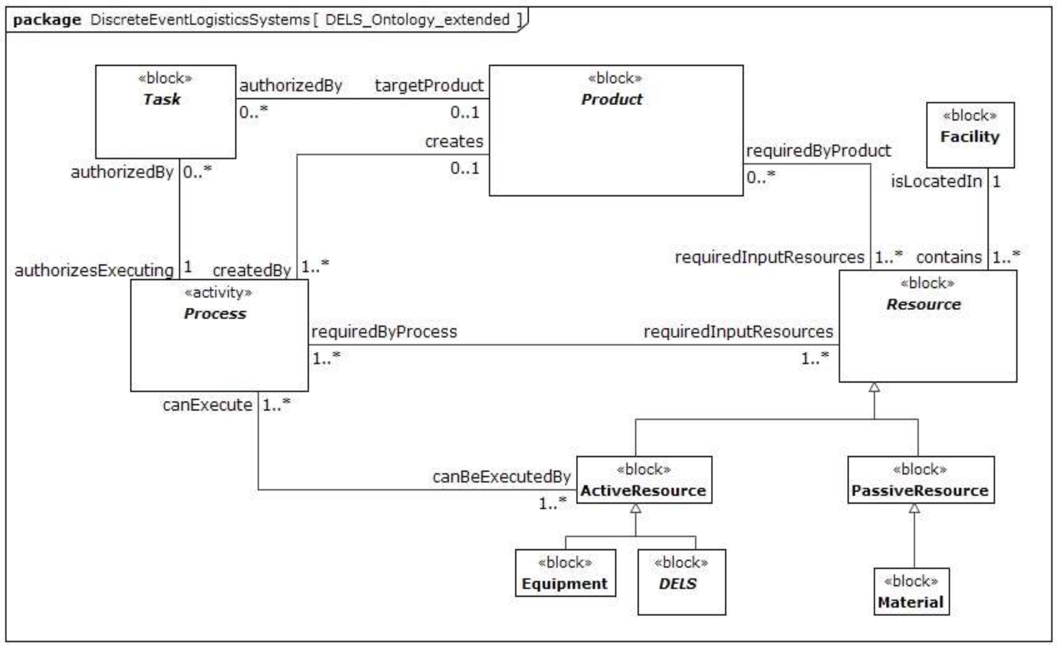
Preview the Tuesday working session

- DELS Reference Model

Preview the Tuesday working session

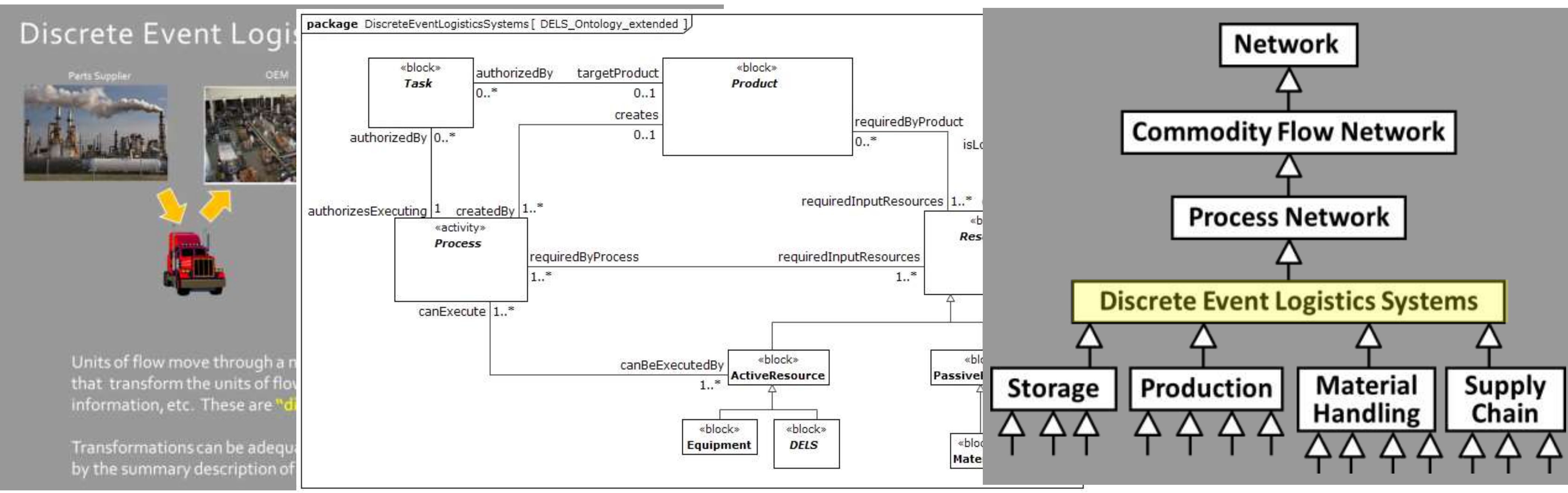
- DELS Reference Model





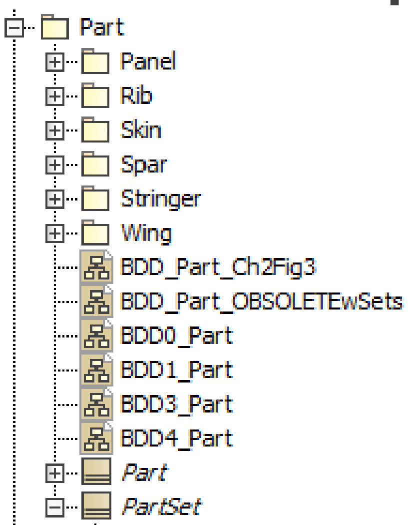
Preview the Tuesday working session

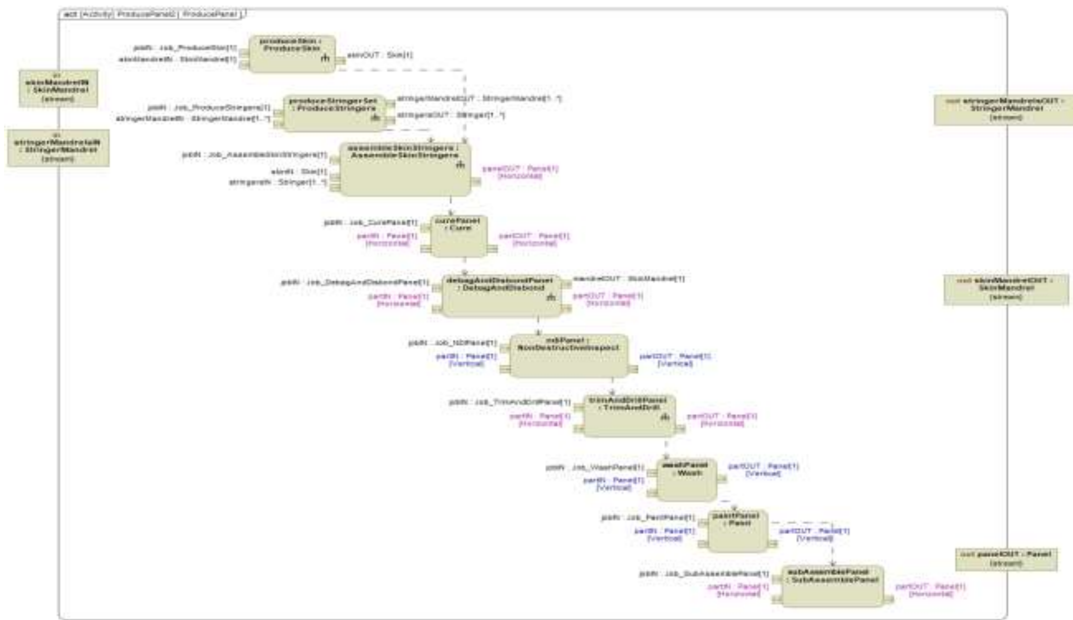
- DELS Reference Model

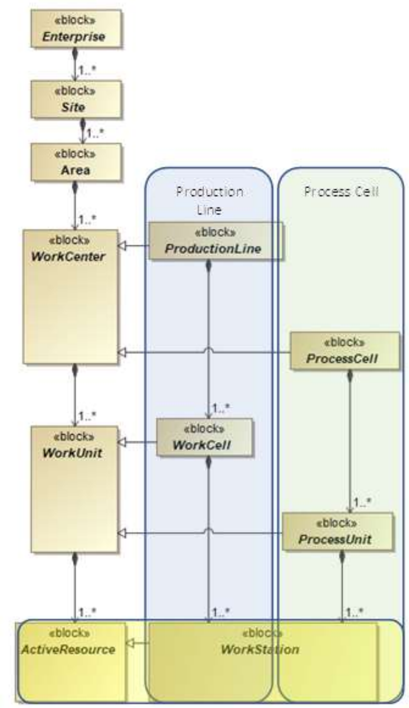


Preview the Tuesday working session

- Composite part manufacturing







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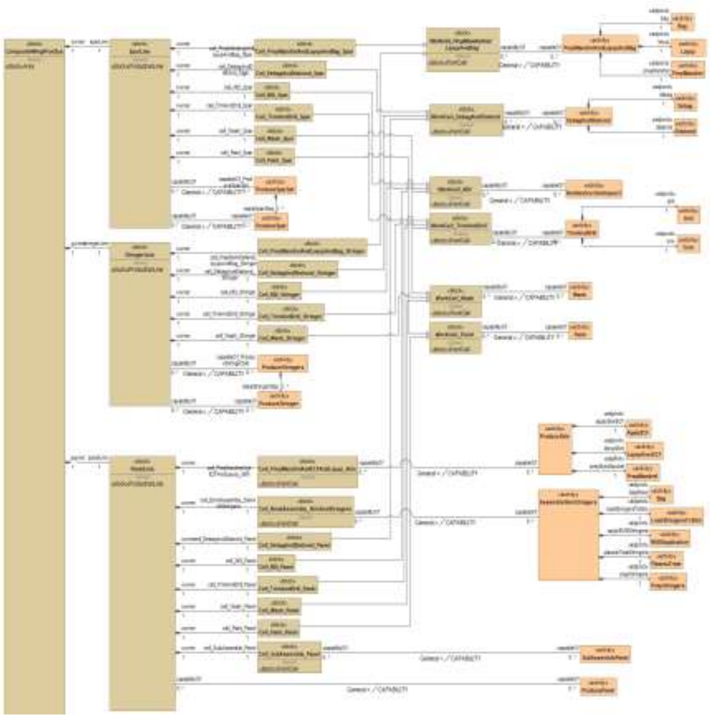

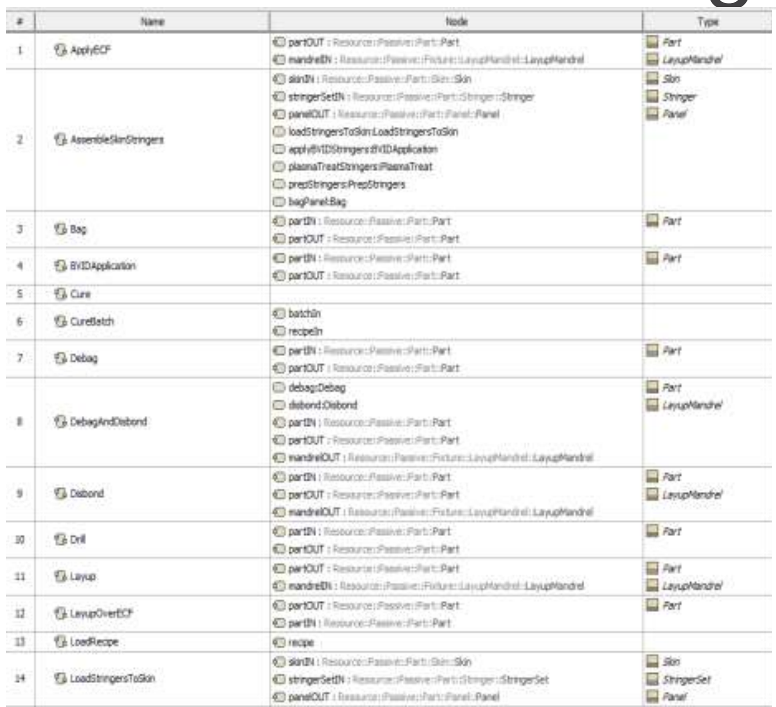

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2	AssembleSkinStringers	skinIN : Resource::Passive::Part::Skin::Skin stringerSetIN : Resource::Passive::Part::Stringer::Stringer panelOUT : Resource::Passive::Part::Panel::Panel loadStringersToSkin:LoadStringersToSkin applyBVIDStringers:BVIDApplication plasmaTreatStringers:PlasmaTreat prepStringers:PrepStringers bagPanel:Bag	Skin Stringer Panel
3	Bag	partIN : Resource::Passive::Part::Part partOUT : Resource::Passive::Part::Part	Part
4	BVIDApplication	partIN : Resource::Passive::Part::Part partOUT : Resource::Passive::Part::Part	Part
5	Cure		
6	CureBatch	batchIn recipeIn	
7	Debag	partIN : Resource::Passive::Part::Part partOUT : Resource::Passive::Part::Part	Part
8	DebagAndDisbond	debag:Debag disbond:Disbond partIN : Resource::Passive::Part::Part partOUT : Resource::Passive::Part::Part mandrelOUT : Resource::Passive::Fixture::LayupMandrel::LayupMandrel	Part LayupMandrel
9	Disbond	partIN : Resource::Passive::Part::Part partOUT : Resource::Passive::Part::Part mandrelOUT : Resource::Passive::Fixture::LayupMandrel::LayupMandrel	Part LayupMandrel
10	Drill	partIN : Resource::Passive::Part::Part partOUT : Resource::Passive::Part::Part	Part
11	Layup	partOUT : Resource::Passive::Part::Part mandrelIN : Resource::Passive::Fixture::LayupMandrel::LayupMandrel	Part LayupMandrel
12	LayupOverECF	partOUT : Resource::Passive::Part::Part partIN : Resource::Passive::Part::Part	Part
13	LoadRecipe	recipe	
14	LoadStringersToSkin	skinIN : Resource::Passive::Part::Skin::Skin stringerSetIN : Resource::Passive::Part::Stringer::StringerSet panelOUT : Resource::Passive::Part::Panel::Panel	Skin StringerSet Panel

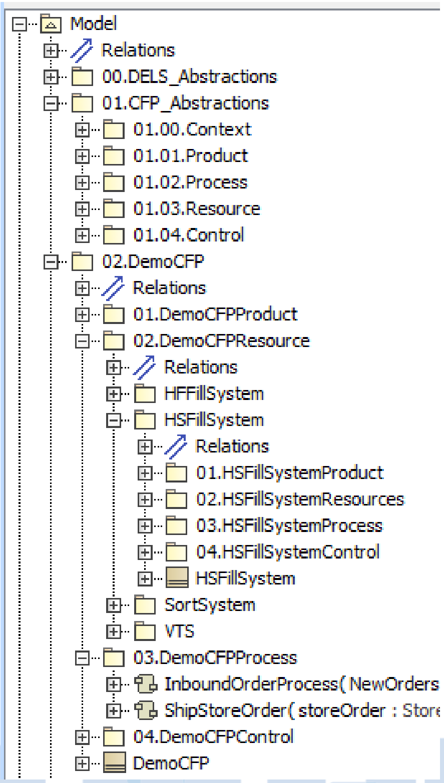
	Part Type	WP	SS	LS	S
Req'd TH		0.067	0.100	0.067	0.0
Iteration 1	Mandrels	1	6	4	
	TH	0.043	0.114	0.074	0.
Iteration 2	Mandrels	2	6	4	
	TH	0.059	0.100	0.064	0.0
Iteration 3	Mandrels	3	6	5	
	TH	0.070	0.090	0.071	0.0
Iteration 4	Mandrels	3	7	5	
	TH	0.063	0.097	0.066	0.0
Iteration 5	Mandrels	4	8	6	
	TH	0.068	0.098	0.070	0.
Iteration 6	Mandrels	4	9	6	
	TH	0.063	0.103	0.066	0.
Iteration 7	Mandrels	5	9	7	
	TH	0.069	0.095	0.070	0.0
Iteration 8	Mandrels	5	10	7	
	TH	0.064	0.099	0.067	0.

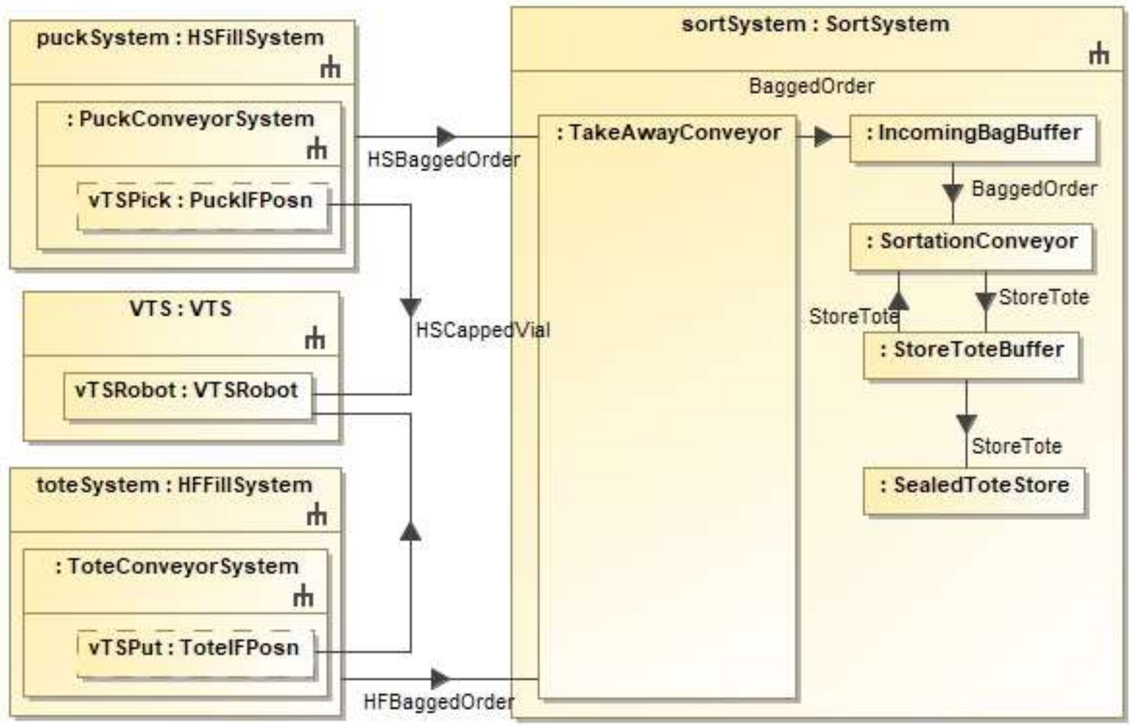
Preview the Tuesday working session

- Central-fill pharmacy case and model

Preview the Tuesday working session

- Central-fill pharmacy case and model





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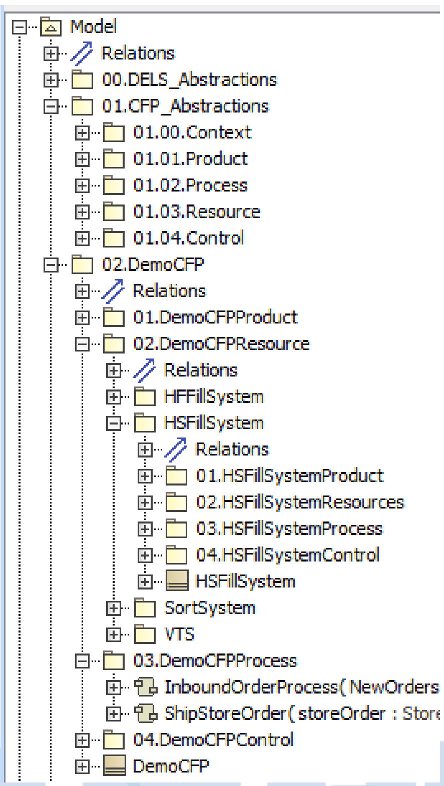
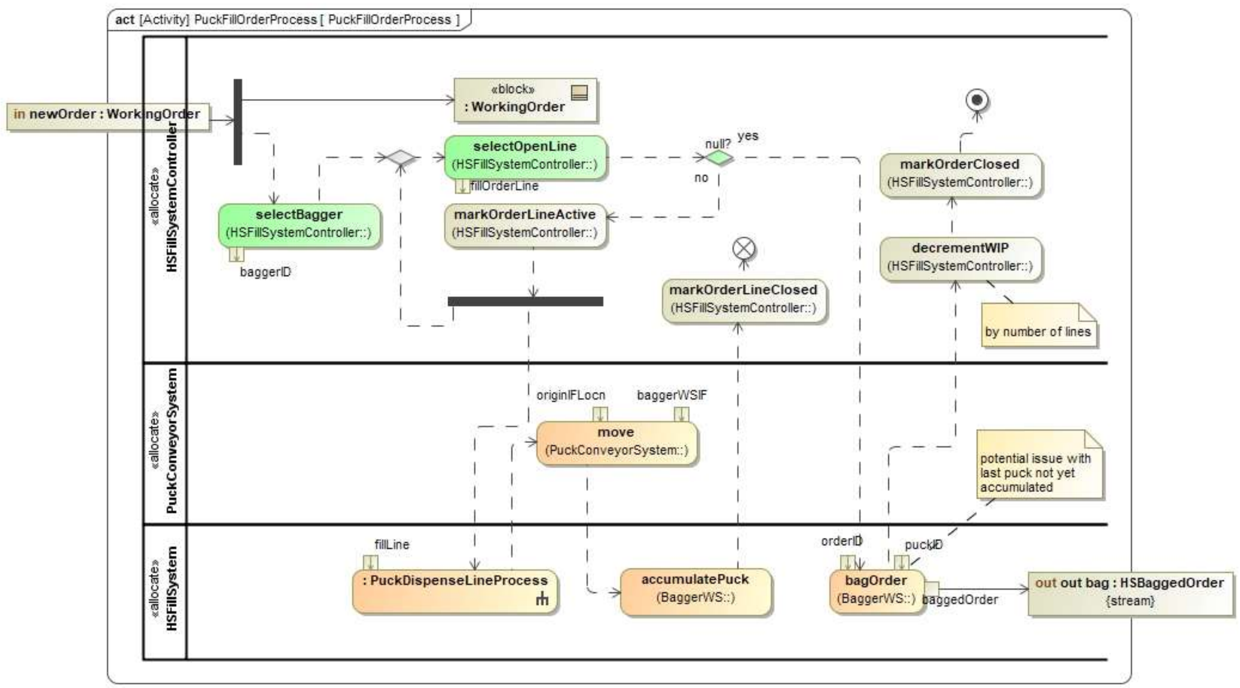


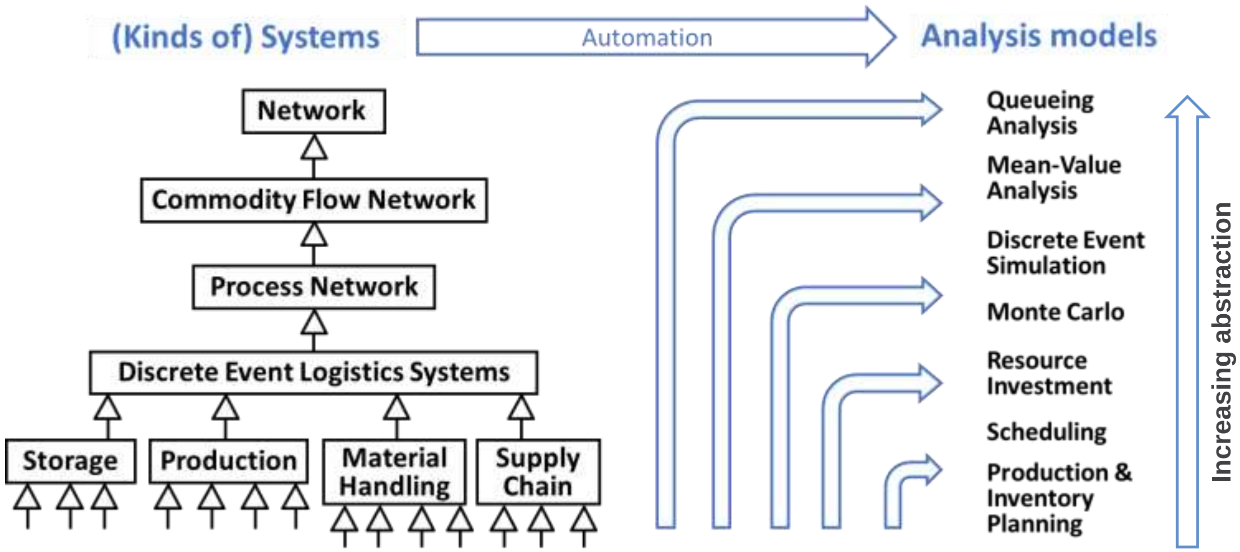


In process:

- “Playbook”: guidelines for creating production system models, using SysML, conforming to “foundations” document
- Analysis integration: automating access to network-centric OR models for answering key questions about performance
- Additional case studies: semiconductor manufacturing, distribution systems

Preview the Tuesday working session

- Analysis integration (George Thiers, MBSE Tools, Inc)



Preview the Tuesday working session

- Additional topics for discussion
  - MBSE impact on managing engineering data to manufacturing (Eugenio Rios, Collins Aero)
  - MBSE and new supply chain paradigms—case of additive manufacturing (Bill Bihlman, Purdue)
  - ***Your*** topic

Go forward plan:

- Define a neutral scenario
- Establish collaboration platform
- Build out alternative production/supply chain scenarios with associated system models and integrated analyses

Acknowledgements

- NIST
- Collins Aerospace
- McKesson High Value Solutions
- Boeing
- Physical Internet Center, GaTech.
- MBSETools, Inc.

Summary: DELS-related Products

- Model Libraries
  - https://github.com/usnistgov/DiscreteEventLogisticsSystems
- Documentation (DRAFT)
  - Overleaf: https://v2.overleaf.com/read/hhsmnkssjwcp
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Challenge team:
http://www.omgwiki.org/MBSE/doku.php?id=mbse:prodlog

Tuesday @ 10:00 am in Bungalow

timothy.sprock@nist.gov
leon.mcginnis@gatech.edu
conrad.bock@nist.gov
george.thiers@mbsetools.com
Gregory.Pollari@collins.com
eugenio.rios@collins.com

Quick overview of DELS reference model
Intro to system models for composites manufacturing, central fill pharmacy
Focused discussion: focusing on key needs, identifying the players
Next steps

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Agenda

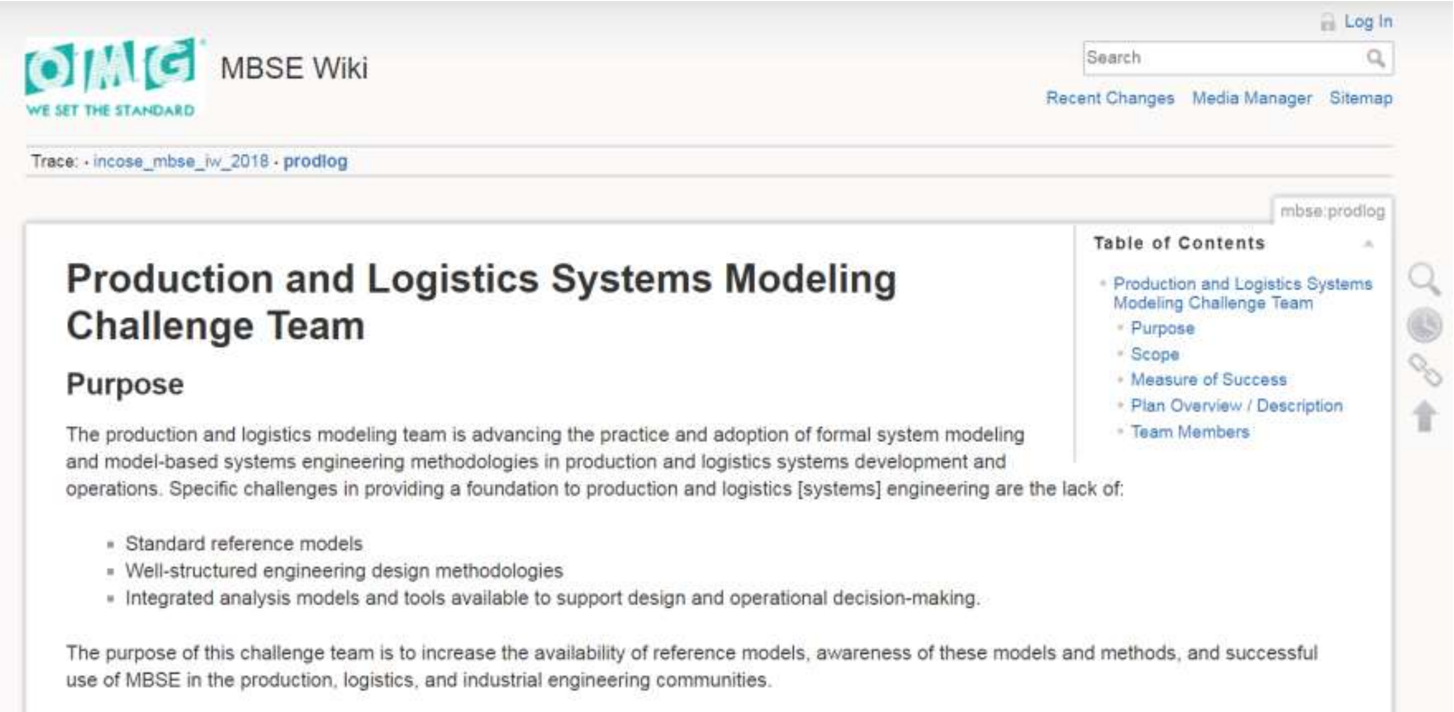
- Introductions: who's here?
- Review purpose, mission statement
- Case Studies
  - Aero composite part fab and assembly – Leon McGinnis, Georgia Tech
  - Central Fill Pharmacy Models – Leon McGinnis, Georgia Tech
- Foundations Document
  - Theory of DELS Specification: foundations document
- Other Updates
  - Analysis integration automation – George Thiers, MBSE Tools
  - Application at Collins Aerospace – Eugenio Rios, Collins Aerospace
  - Additive Manufacturing Supply Chain – Bill Bihlman, Purdue
- Roadmap:
  - Objectives
  - Identify unifying neutral case study
    - Model-based Industrial and Systems Engineering Playbook: on hold
  - Establish collaboration platform
  - Grow number of liaisons

Introductions

- Name, company
- Motivation to attend
- What would you like to get out of this meeting?
- Please add name & email to sheet

Production and Logistics Systems Modeling Charter

- http://www.omgwiki.org/MBSE/doku.php?id=mbse:prodlog



Production and Logistics Systems Modeling Challenge Team

Increase the availability of reference models, awareness of these models and methods, and successful use of MBSE in the production, logistics, and industrial engineering communities.

Specific challenges in providing a foundation to production and logistics [systems] engineering are the lack of:

- Standard reference models
- Well-structured engineering design methodologies
- Integrated analysis models and tools available to support design and operational decision-making.

http://www.omgwiki.org/MBSE/doku.php?id=mbse:prodlog

Currently Active Contributors

- Tim Sprock, NIST: lead on “theory”; contributing everywhere
- Conrad Bock, NIST: technical guru
- George Thiers, MBSE Tools, Inc: lead on analysis integration
- Leon McGinnis, Georgia Tech: lead on “cases”
- Greg Pollari, Eugenio Rios, Collins Aerospace: contributing case study, industry perspective

Roadmap (post-lunch discussion)

- Identify neutral (product) case study
  - Potentials: smart car; electronic ass'y;
- Structured approach to description (of prod'n system)
- Collaboration platform (OpenMBEE?)
- Target users: (teaching, on-boarding/training)

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Contact Us:

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An initial investigation of MBSE for:

Central Fill Pharmacy

Leon McGinnis
Georgia Tech, School of Industrial and Systems Engineering
leon.mcginnis@gatech.edu

Central Fill Pharmacy, ver 1.0

Formalizing ISA-95 Level 3 Control with Smart Manufacturing System Models

Prepared for
Allison Barnard Feeney
Conrad Bock
U.S. Department of Commerce
Engineering Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899-8260

By
Leon F. McGinnis
The Georgia Institute of Technology
School of Industrial and Systems Engineering

September 2019

Report—current version—is 75 pages, with 72 illustrations. The companion SysML model has 72 diagrams, 88 activities and 151 blocks.

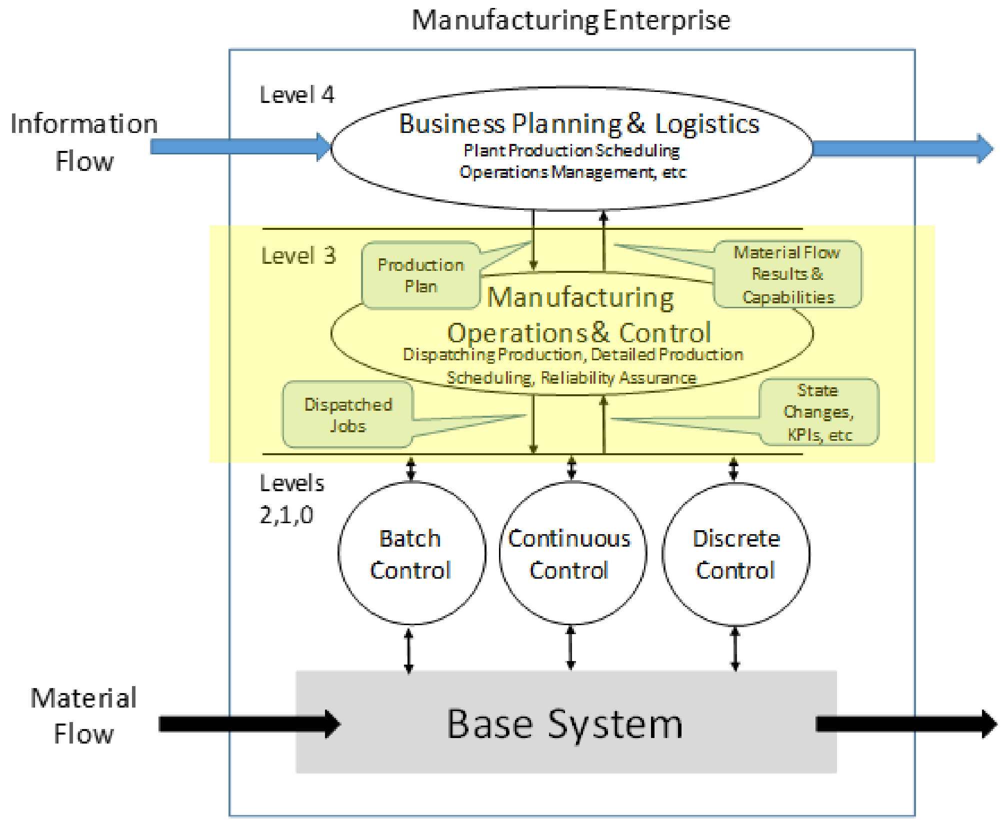
Report and companion SysML model available upon request.

Fundamental Motivation

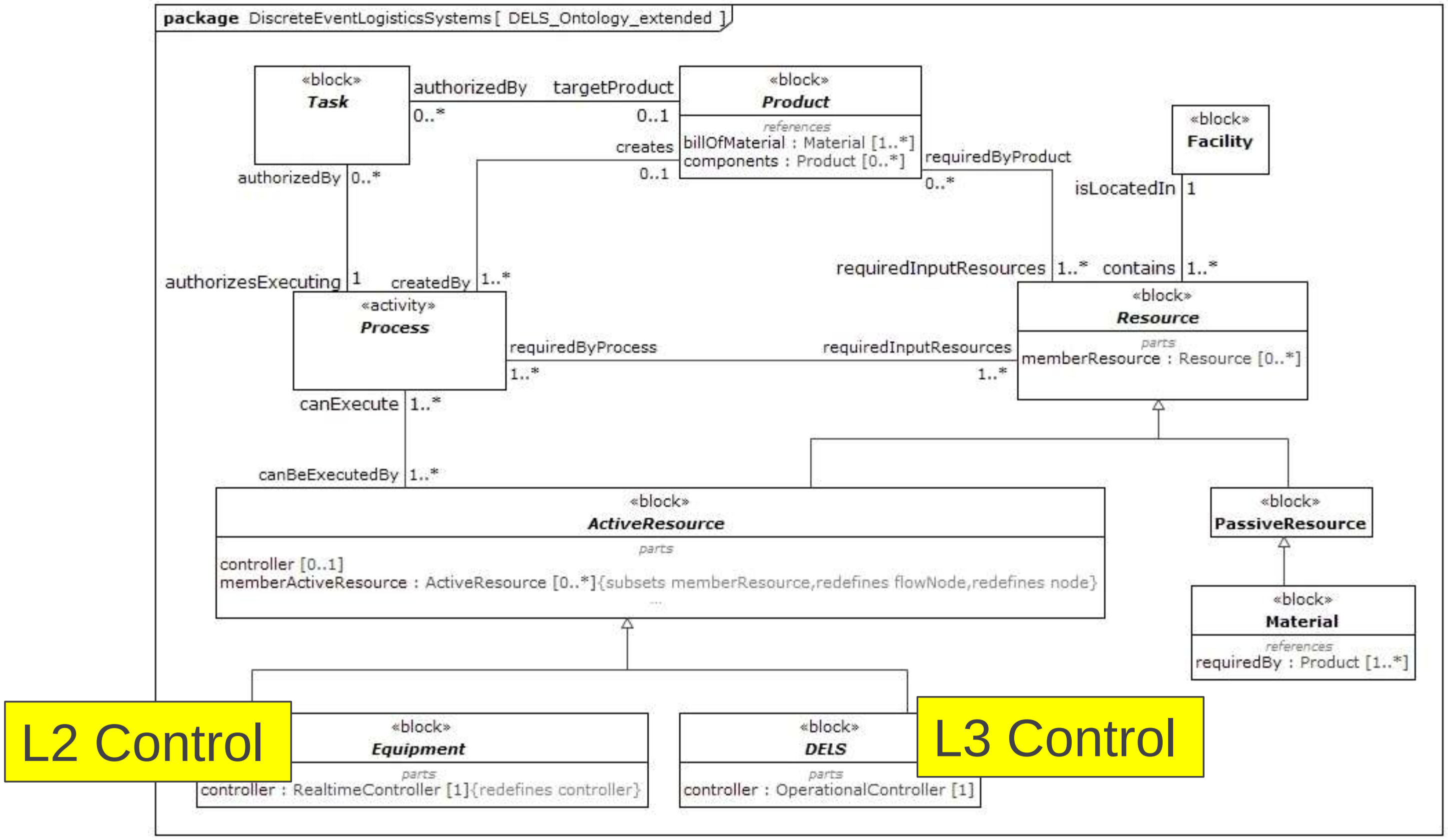
Integrate existing standards for operational control (ISA-95) and DELS framework to support designing and testing operational controllers.

Use central fill pharmacy—a highly automated system—as the testbed for demonstrating concepts.

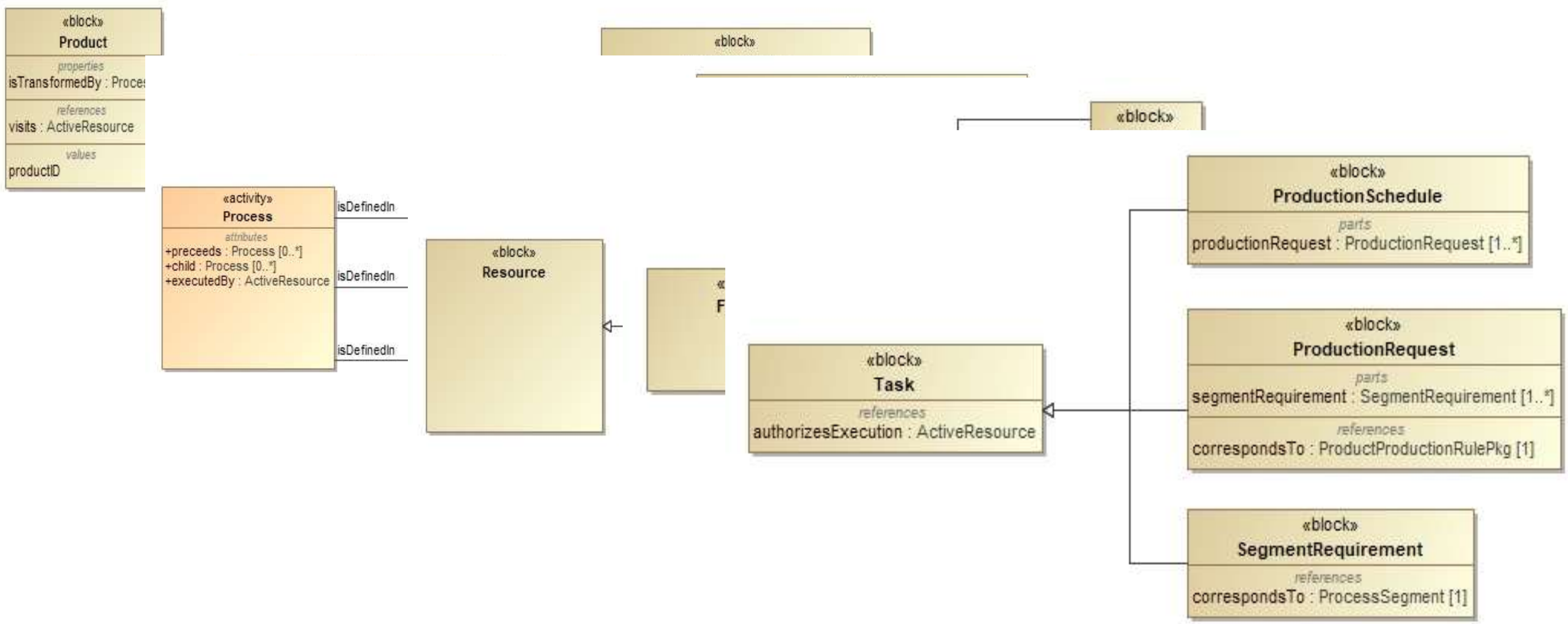
ISA-95 Control Model



DELS Framework



DELS/ISA-95 Correspondences



L3 Controller Requirements

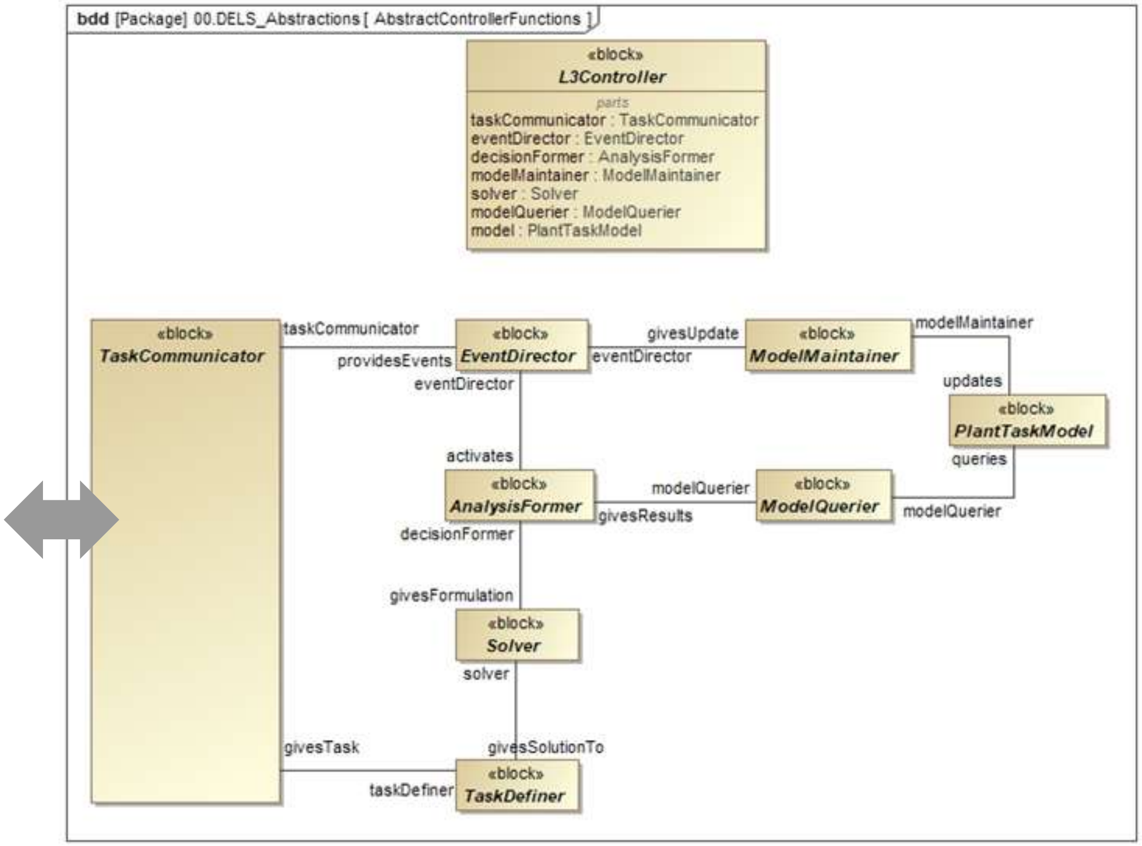
- Manage completion of accepted or assigned tasks
  - Assign, sequence and monitor process execution by owned or referenced resources
  - Capture, interpret and respond to relevant events
  - Goal-appropriate decisions

L3 Controller Functions

- Maintain or access task and resource state
- Produce appropriate task management decisions

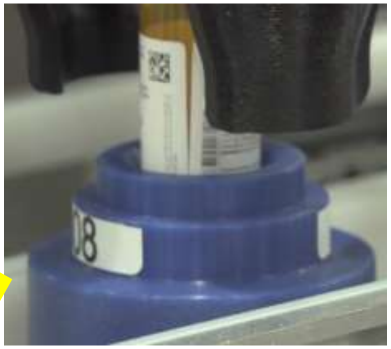
L3 Controller Logical Architecture

Interface to controlling and controlled resources



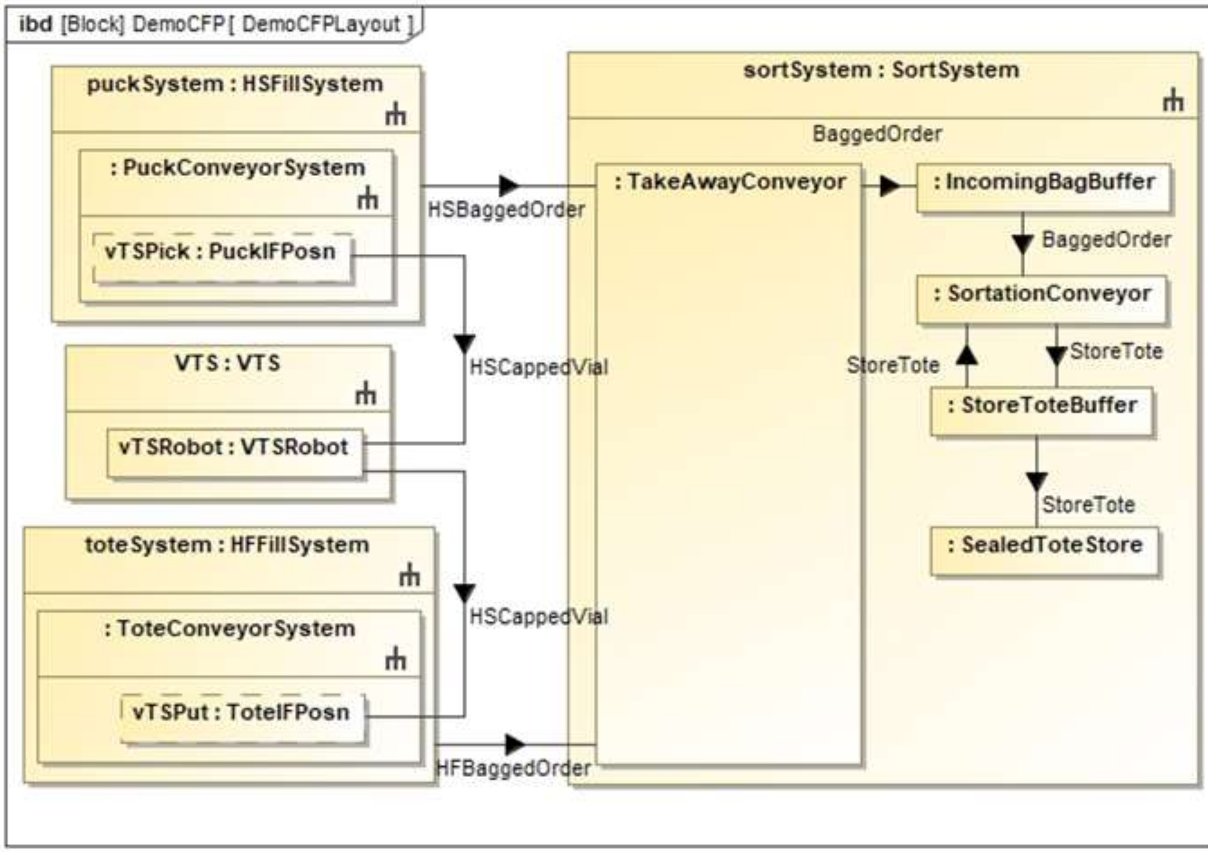
- Control decisions are based on the state of accepted tasks and active resources in the controlled domain
- Control decisions are triggered by events.

Central Fill Pharmacy



Central Fill Pharmacy

Demo CFP



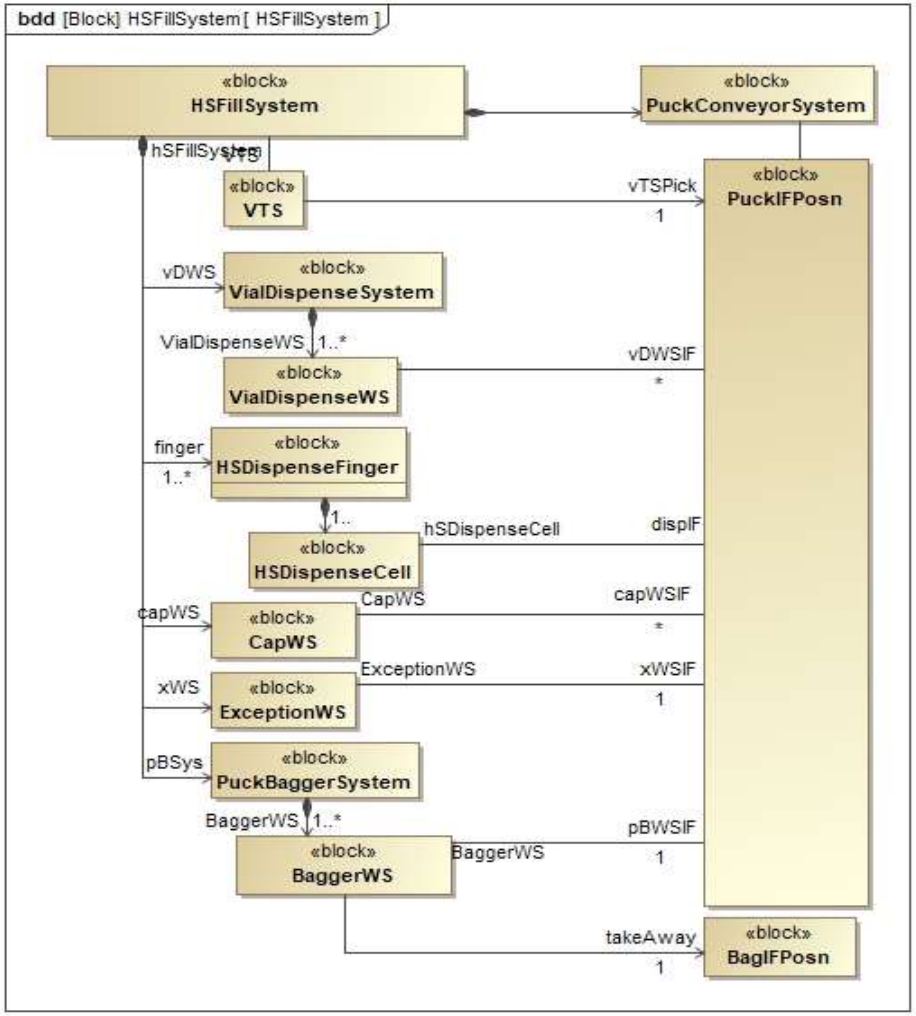
Four subsystems:

- Puck-based fill
- Tote-based Fill
- Vial Transfer
- Order sort to store

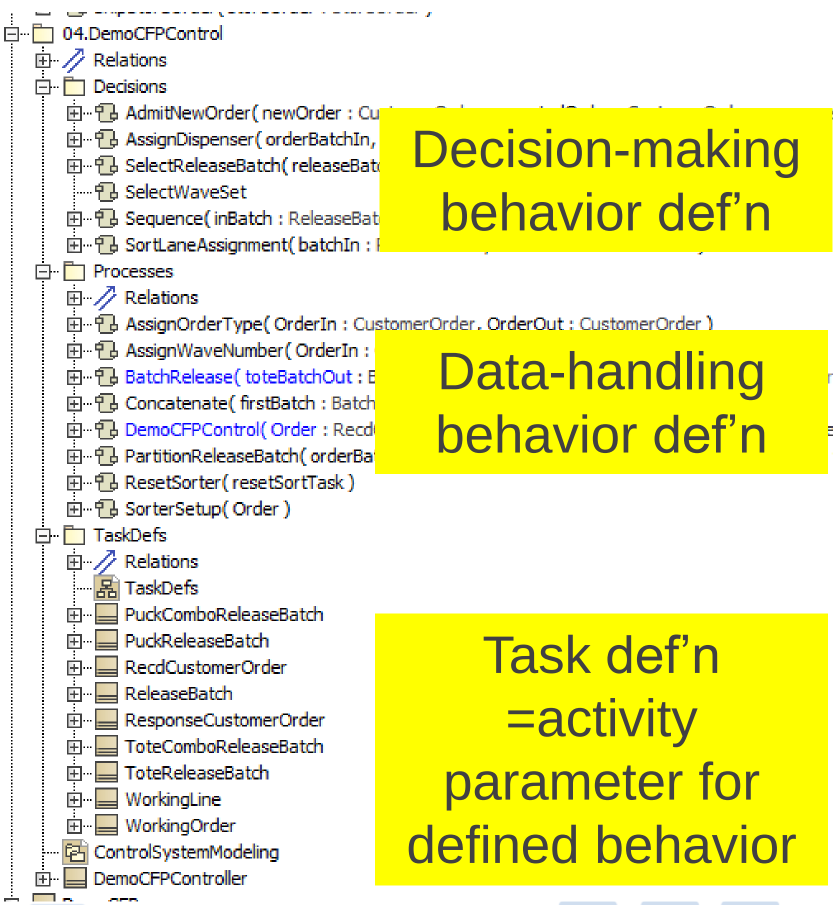
Approx 200 stores, 30,000 scripts/day

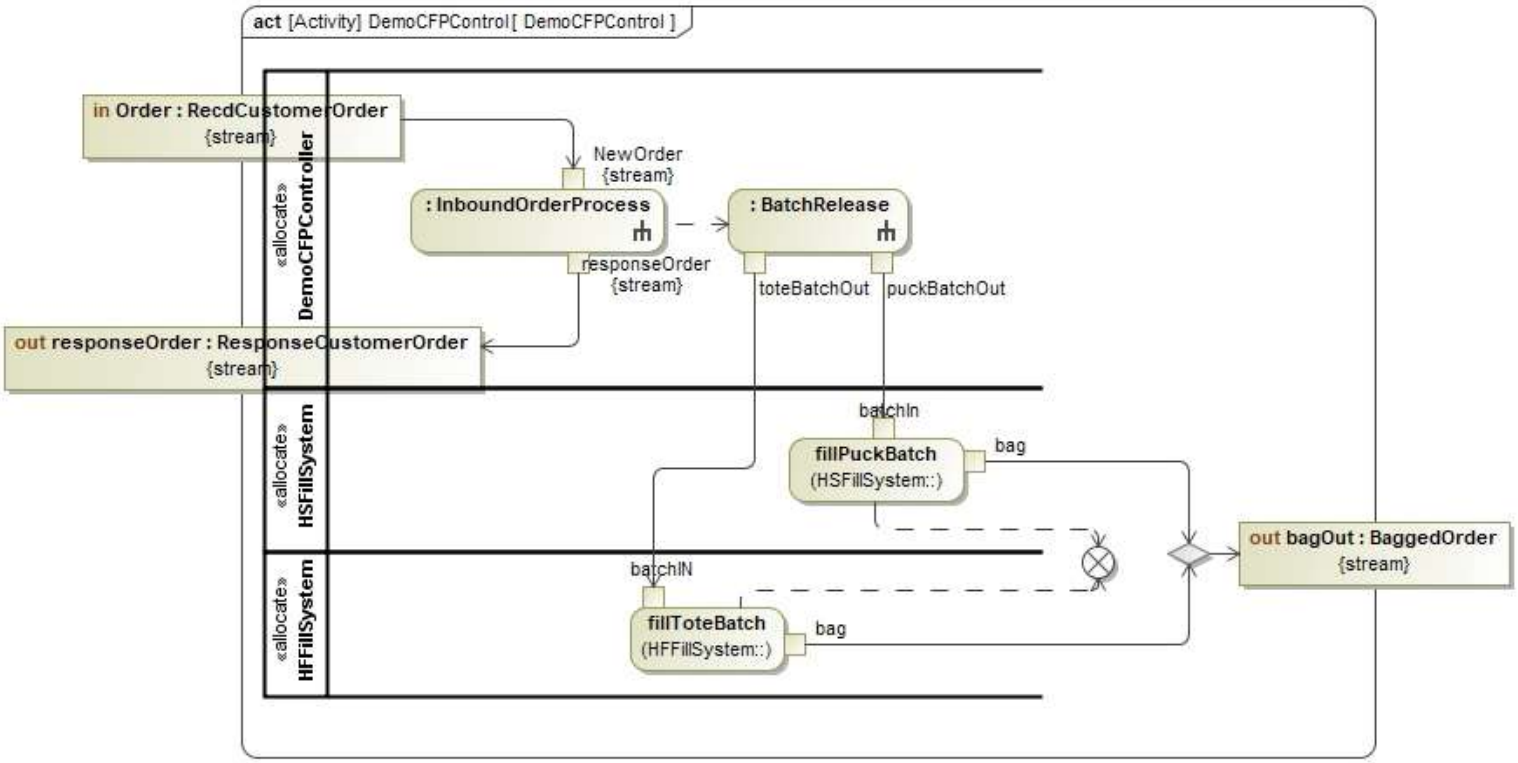
Interface Positions

Conveyor interfaces with a fulfillment resource at a specific position on the conveyor. These positions must be uniquely identified so the controller can task the conveyor to make specific moves. The appearance of a carrier in the interface position also may be a trigger for the fulfillment resources to act.

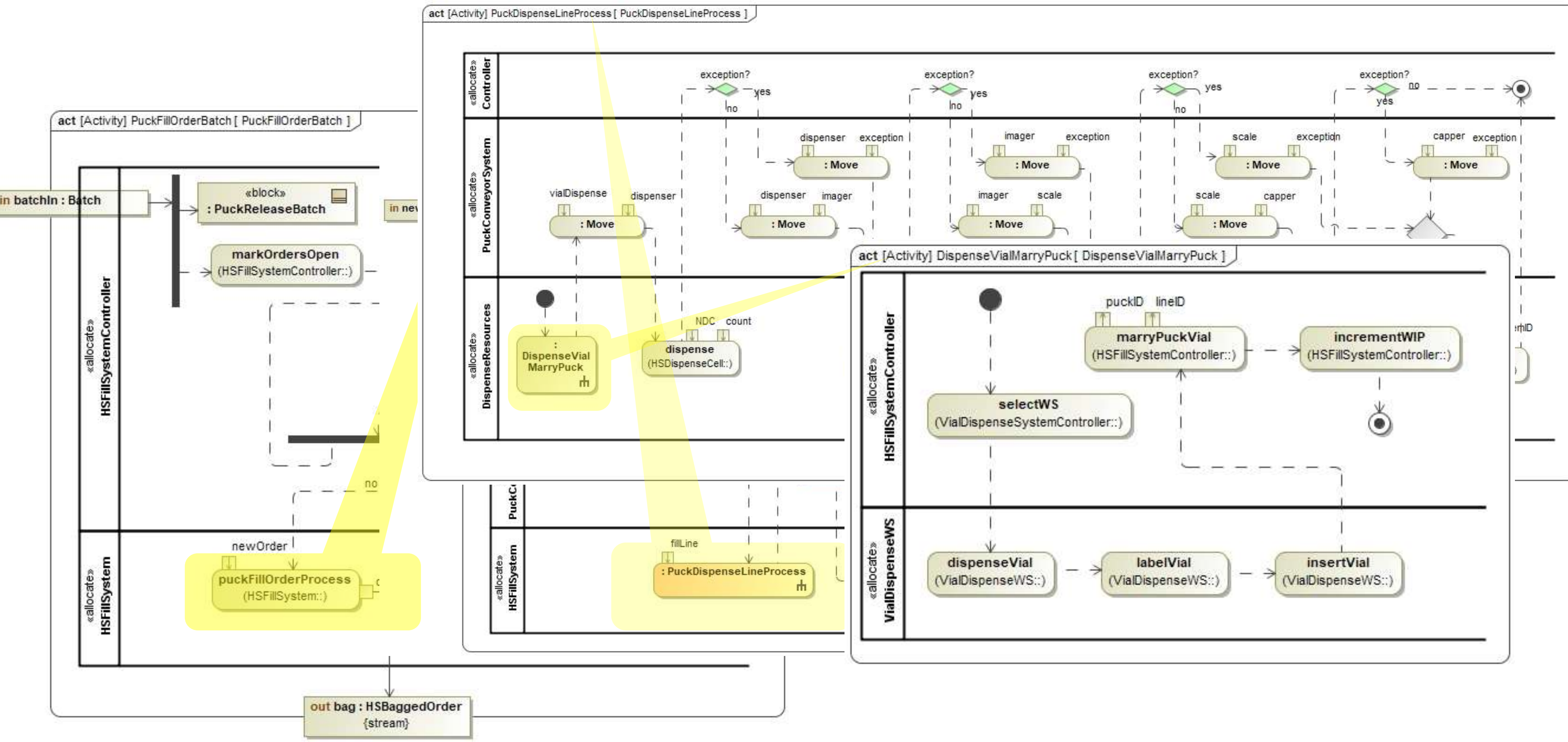


Controller Structure and Behavior





Swimlanes for controller (behavior) and controlled resources (invokable process capabilities).


act [Activity] PuckFillOrderBatch [PuckFillOrderBatch]
in batchIn : Batch
«block»
: PuckReleaseBatch
markOrdersOpen
(HSFillSystemController::)
«allocate»
HSFillSystemController
«allocate»
HSFillSystem
newOrder
no
puckFillOrderProcess
(HSFillSystem::)
out bag : HSBaggedOrder
{stream}
act [Activity] PuckDispenseLineProcess [PuckDispenseLineProcess]
«allocate»
Controller
«allocate»
PuckConveyorSystem
«allocate»
DispenseResources
exception?
yes
no
vialDispense
dispenser
imager
scale
capper
exception
: Move
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incrementWIP
(HSFillSystemController::)
selectWS
(VialDispenseSystemController::)
dispenseVial
(VialDispenseWS::)
labelVial
(VialDispenseWS::)
insertVial
(VialDispenseWS::)

Opportunities

- Further elaboration/refinement of this specific model
- Identifying “good practices” for modeling L3 controllers and systems
- Further standardization of controller components
- Integration with discrete event simulation*

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An initial investigation of MBSE for:

Composite Wing Production

Leon McGinnis
Georgia Tech, School of Industrial and Systems Engineering
leon.mcginnis@gatech.edu

Composite Wing Production, ver 1.0

Model-Based Systems Engineering
Applied to a Hypothetical
Composite Wing Production System

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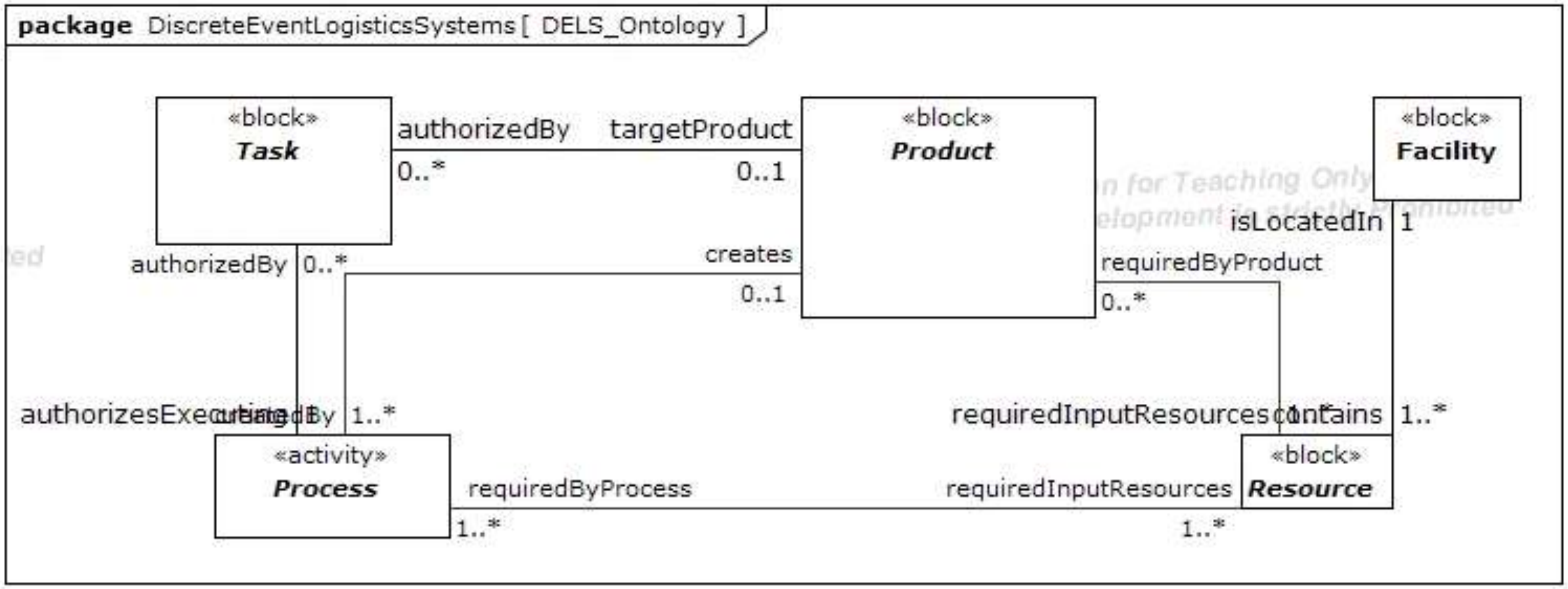
Document Version: 1.0
Tool Version: MagicDraw 18.5 sp3
Modeling Language Version: SysML 1.4, UML 2.5

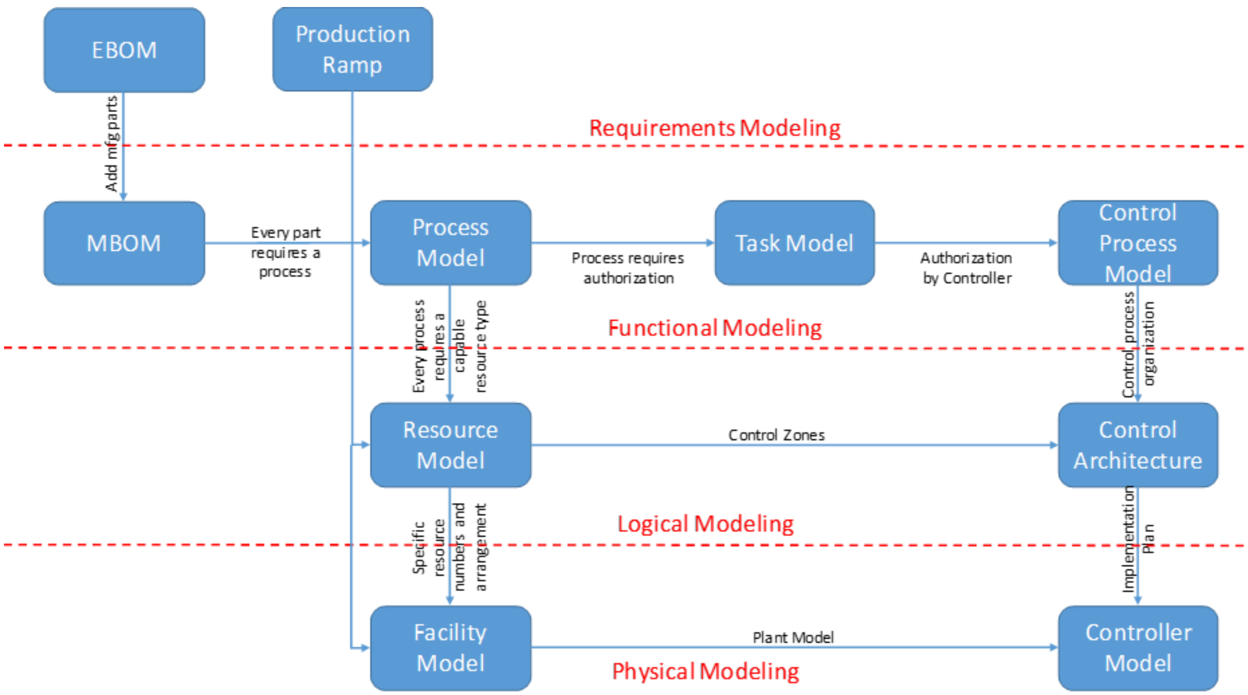
Report—current version—is 90 pages, with 74 illustrations. The companion SysML model has 5 tables, 64 diagrams,36 activities and 215 blocks.

Companion SysML, Simio and QN models available upon request.

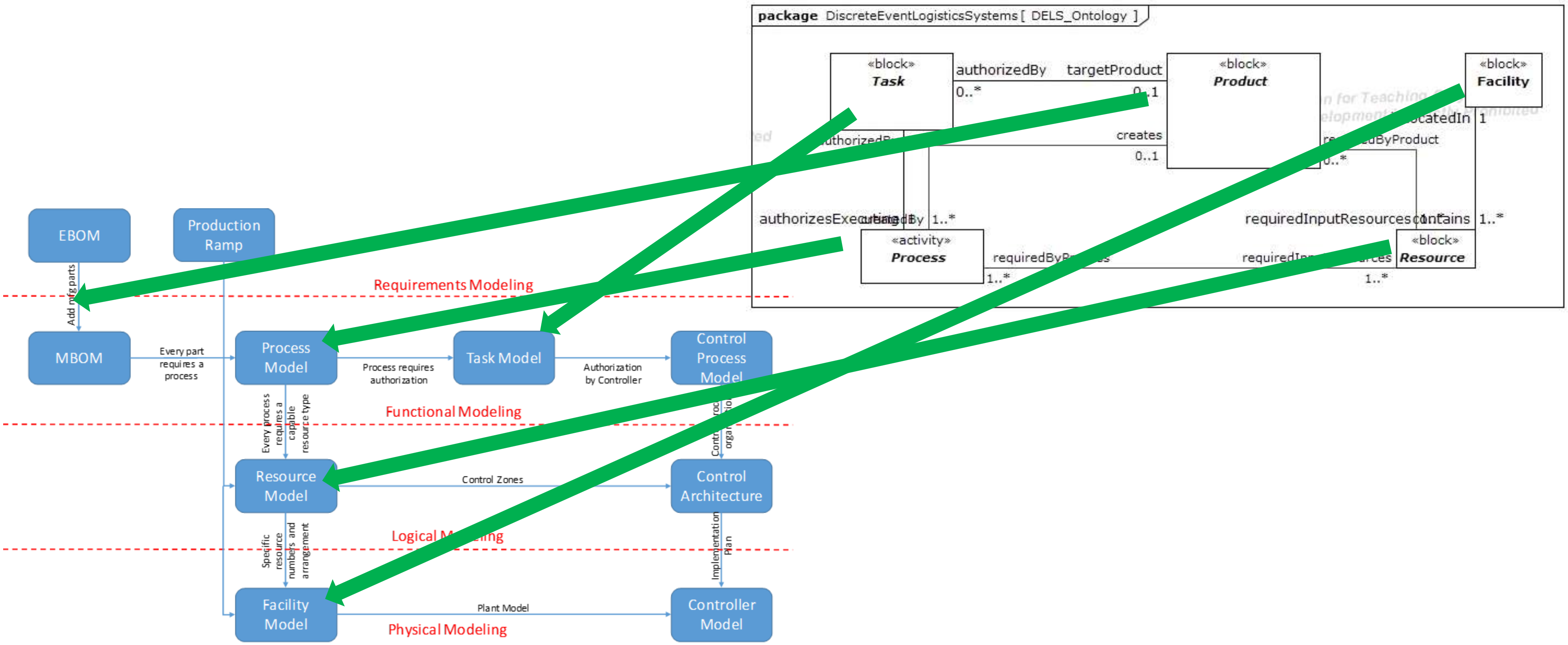
DELS Framework



Integrating DELS Ontology & RFLP

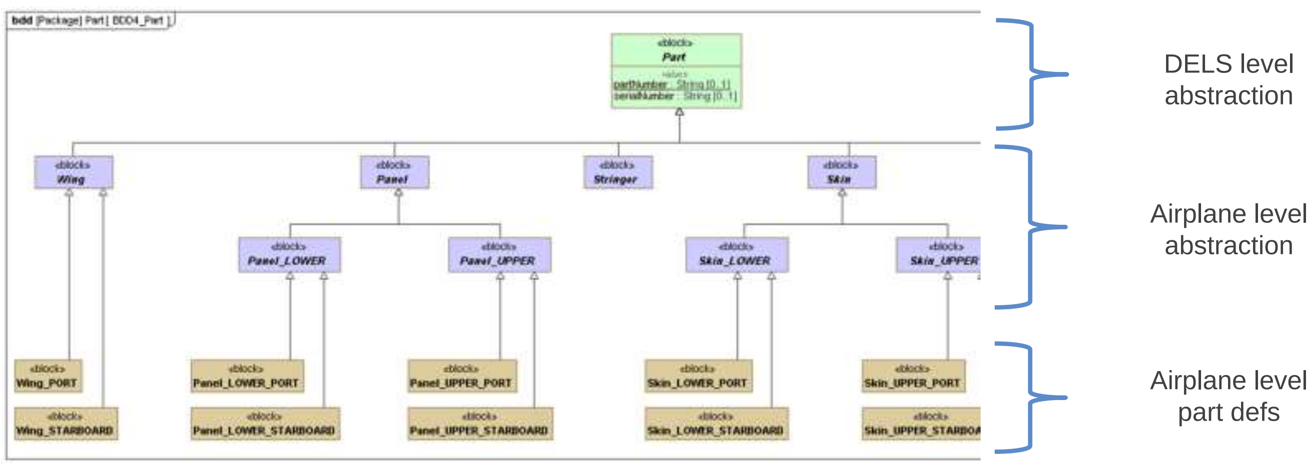


DELS + RFLP Integration

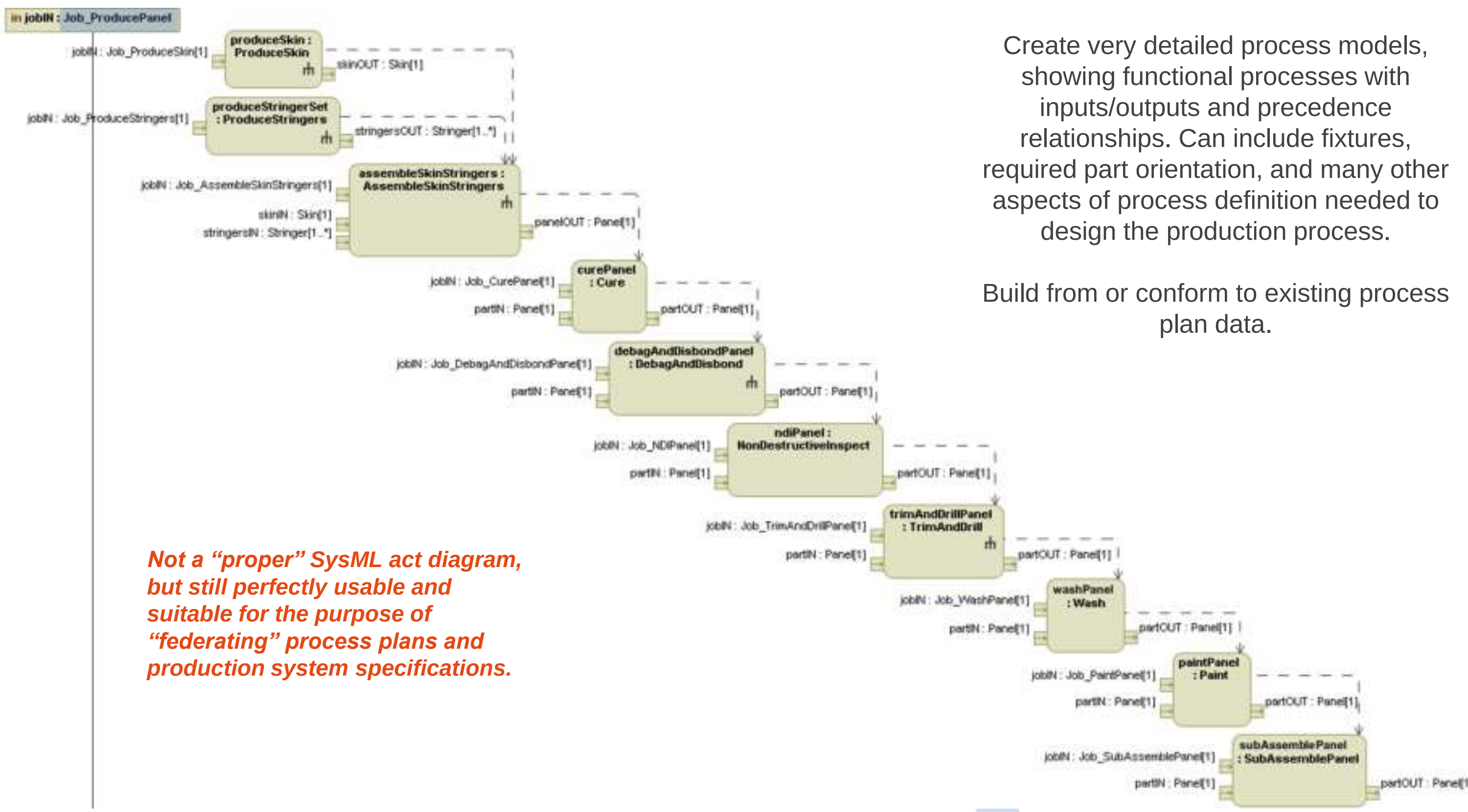


Product Modeling

Building reusable ***production-oriented*** product taxonomy/abstractions



Process Modeling

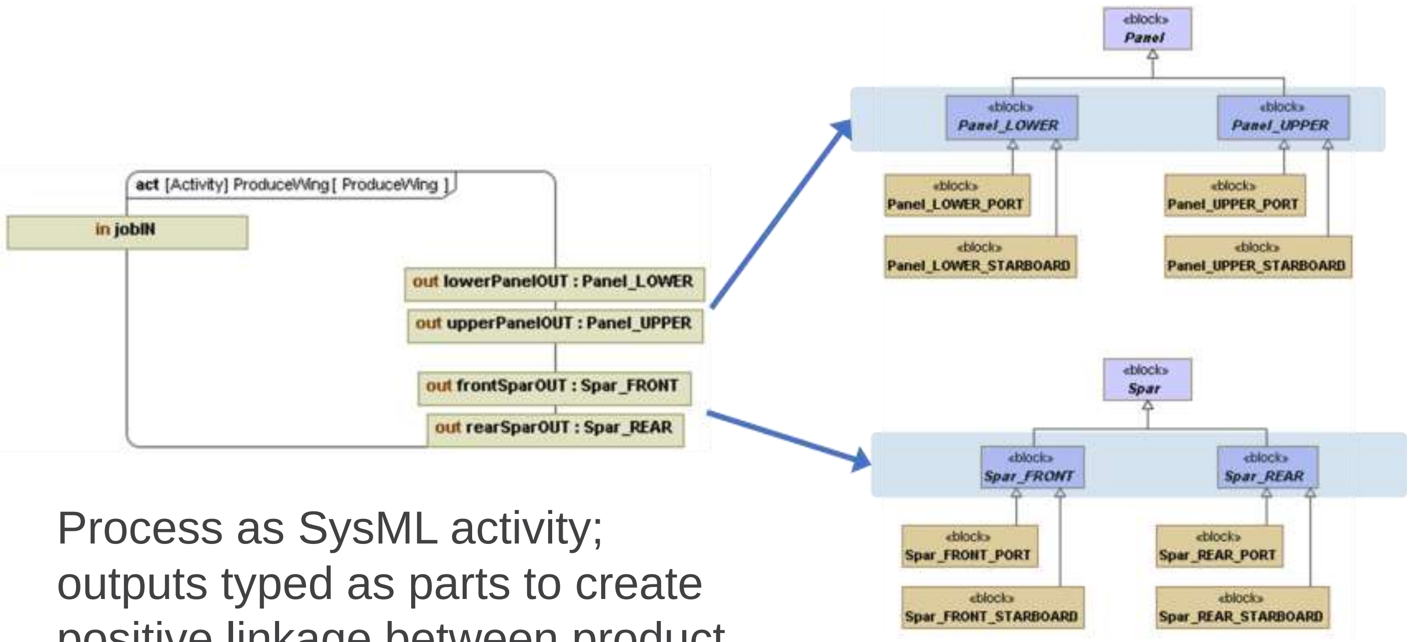


Not a "proper" SysML act diagram, but still perfectly usable and suitable for the purpose of "federating" process plans and production system specifications.

Create very detailed process models, showing functional processes with inputs/outputs and precedence relationships. Can include fixtures, required part orientation, and many other aspects of process definition needed to design the production process.

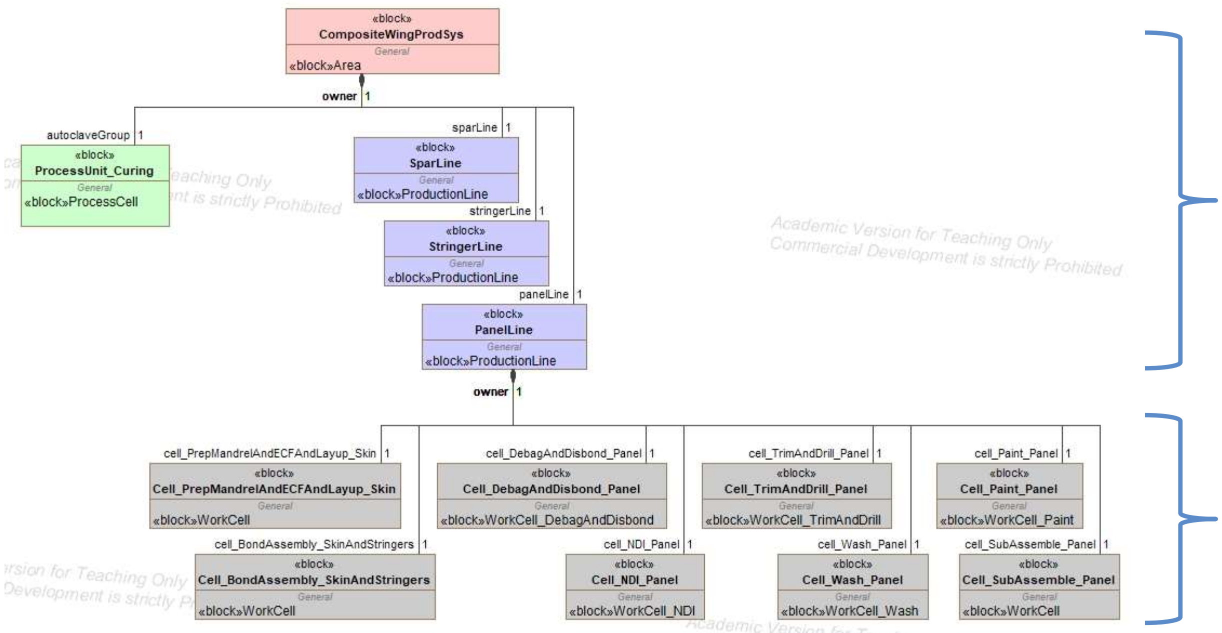
Build from or conform to existing process plan data.

Process-Product Model Integration



Process as SysML activity; outputs typed as parts to create positive linkage between product and process models.

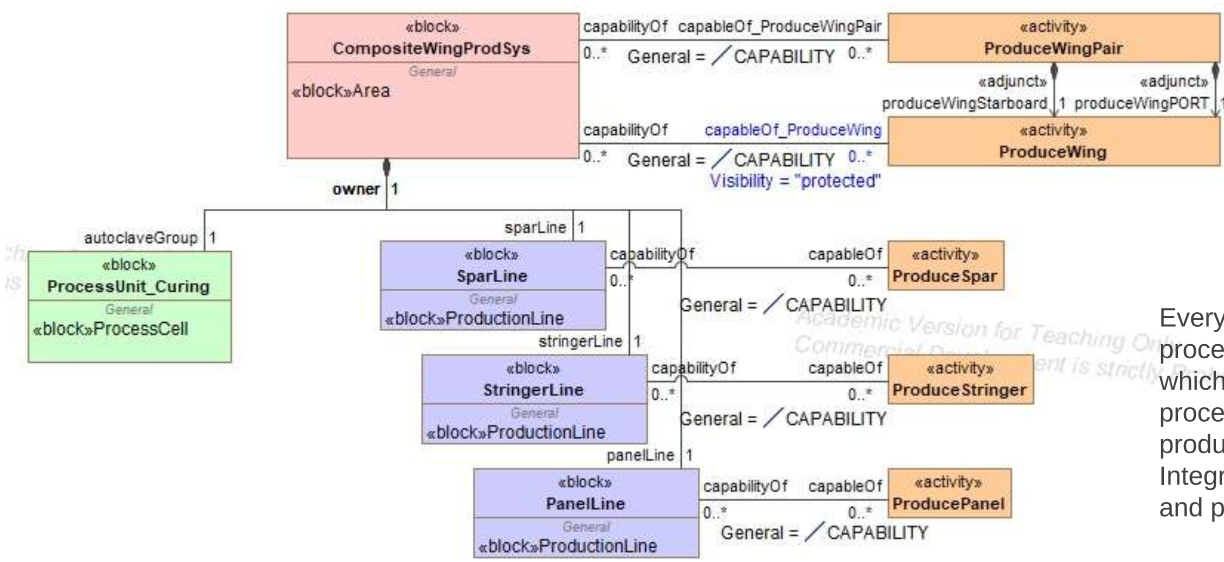
Resource Modeling



Organization of resources

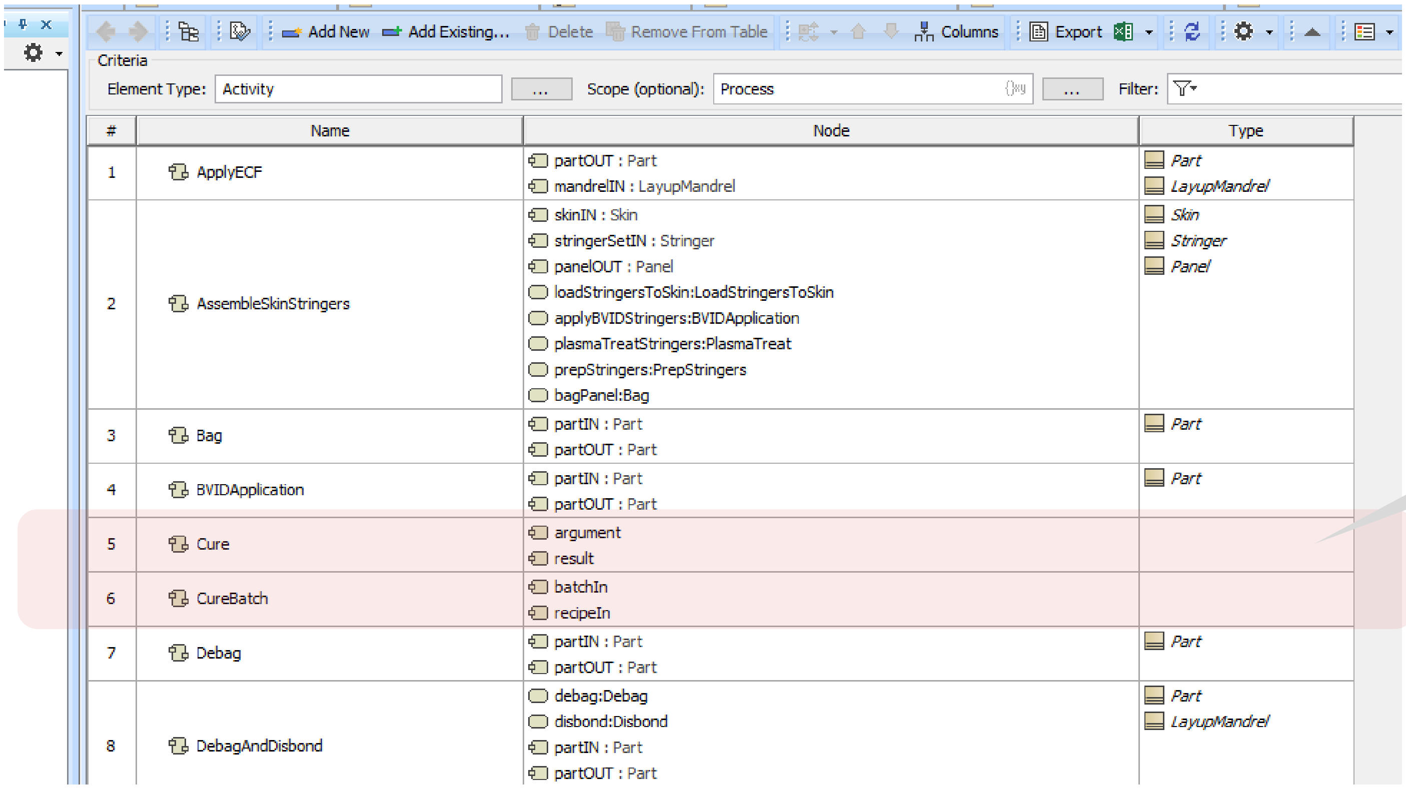
Cell-level resource definition; can refine further as needed, to identify specific equipment, trades, etc.

Resource-Process Model Integration



Every resource has process ***capabilities*** which correspond to the processes required to produce the products. Integrating the resource and process models.

Model Verification



#	Name	Node	Type
1	ApplyECF	partOUT : Part mandrelIN : LayupMandrel	*Part* *LayupMandrel*
2	AssembleSkinStringers	skinIN : Skin stringerSetIN : Stringer panelOUT : Panel loadStringersToSkin:LoadStringersToSkin applyBVIDStringers:BVIDApplication plasmaTreatStringers:PlasmaTreat prepStringers:PrepStringers bagPanel:Bag	*Skin* *Stringer* *Panel*
3	Bag	partIN : Part partOUT : Part	*Part*
4	BVIDApplication	partIN : Part partOUT : Part	*Part*
5	Cure	argument result	
6	CureBatch	batchIn recipeIn	
7	Debag	partIN : Part partOUT : Part	*Part*
8	DebagAndDisbond	debag:Debag disbond:Disbond partIN : Part partOUT : Part	*Part* *LayupMandrel*

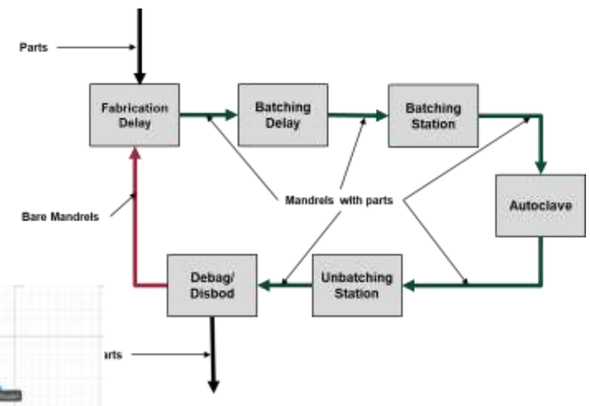
Are the parameters for every defined process properly typed?

Processes missing parameter types

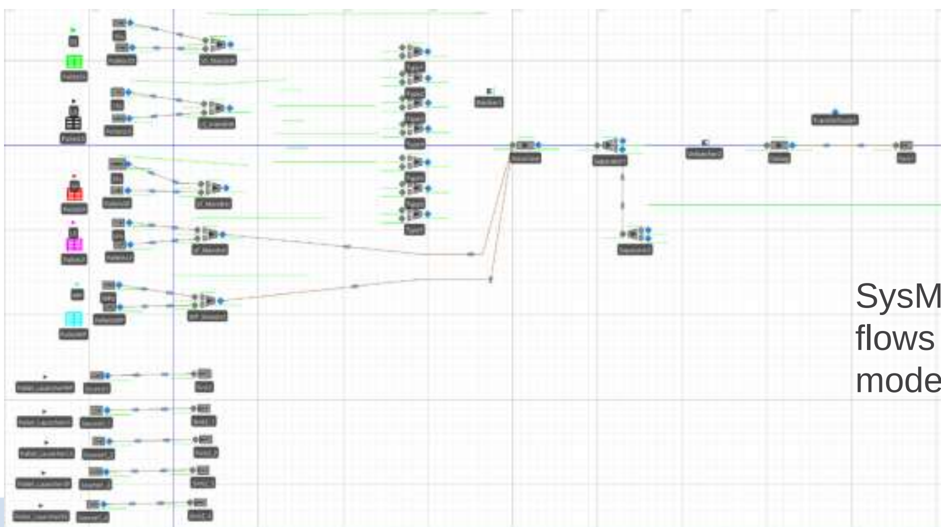
Analysis Model Integration

For the current resource portfolio and production requirements, how many mandrels are needed for each part type?

Closed Queuing Network



Simio Simulation Model



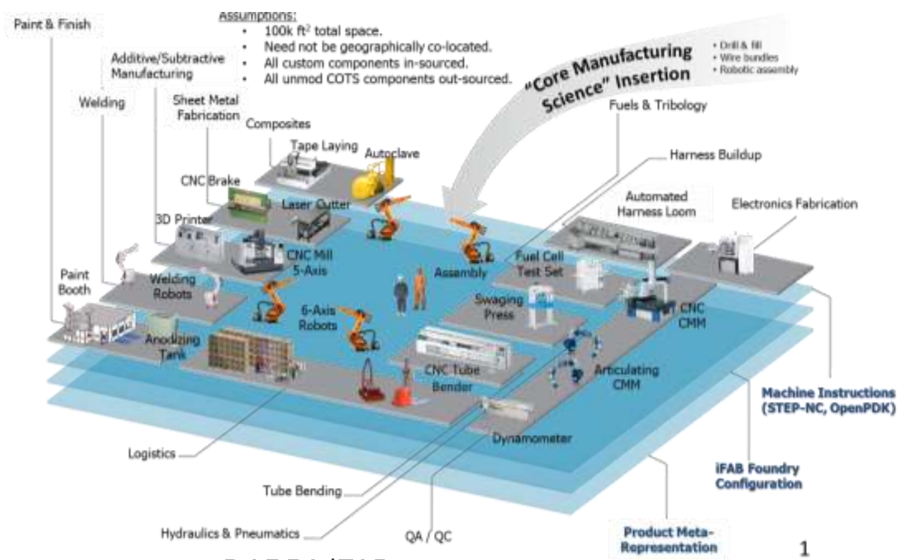
SysML model defines objects and flows needed to populate analysis models.

Opportunities

- Playbook
  - Feedback from production system modelers
  - Identify highest value areas to add or refine (we think it is material handling, then control)
- Decision-support framework
  - Need better understanding of production system development processes and opportunities to support decision makers
  - Decision support analysis automation (model validation, static analysis, simulation)
  - Problem of the infeasible initial condition—how to “calibrate” analysis models to reflect unspecified (unknown?) constraints
- Control modeling, especially contingency management
  - Requires more in-depth understanding of contemporary practices and systems
  - Fundamental problem, not well-understood or –solved in general

Digital Twin, Industrie 4.0, Smart Factory, …..

Getting to full maturity is hard!



DARPA iFAB Foundry

Control of individual processes is pretty mature.

Synchronization of processes, i.e., logistics, ***is not mature***:

- Predictability of manual processes
- Unpredictable interruptions
- Cascading impacts
- Queuing effects
- Plan/schedule changes

You can't create an effective "digital twin" unless you have the (formal) language to capture the main effects of uncertainty, interruptions and queuing, ***and*** how the control system deals with these effects.

2020
Annual INCOSE
international workshop
Torrance, CA, USA
January 25 - 28, 2020

Overview of DELS: Modeling the Foundation of Production and Logistics Systems

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www.incose.org/IW2020

Outline

- What are Discrete Event Logistics Systems (DELS)?
- DELS-related Products
  - SysML Model Libraries
  - Documentation (DRAFT)
  - Reference Implementation of SAI (Matlab)

What are DELS?

Discrete event logistics systems (DELS) transform discrete flows through a network of interconnected subsystems.

- ➢ These systems share a common abstraction, i.e. *products* flowing through *processes* being executed by *resources* configured in a *facility* (PPRF).

Examples include:

- Supply chains
- Manufacturing systems
- Transportation
- Material handling systems
- Storage systems
- Humanitarian logistics
- Healthcare logistics
- Sustainment Logistics
- Reverse and Remanufacturing Logistics
- And many more …

- ➢ Fundamentally, these systems are very similar, and often DELS are actually composed of other DELS.
- ➢ This similarity (and integration) produces a common set of analysis approaches that are applicable across the many systems in the DELS domain.

Outline

- What are Discrete Event Logistics Systems (DELS)?
- **DELS-related Products**
  - SysML Model Libraries
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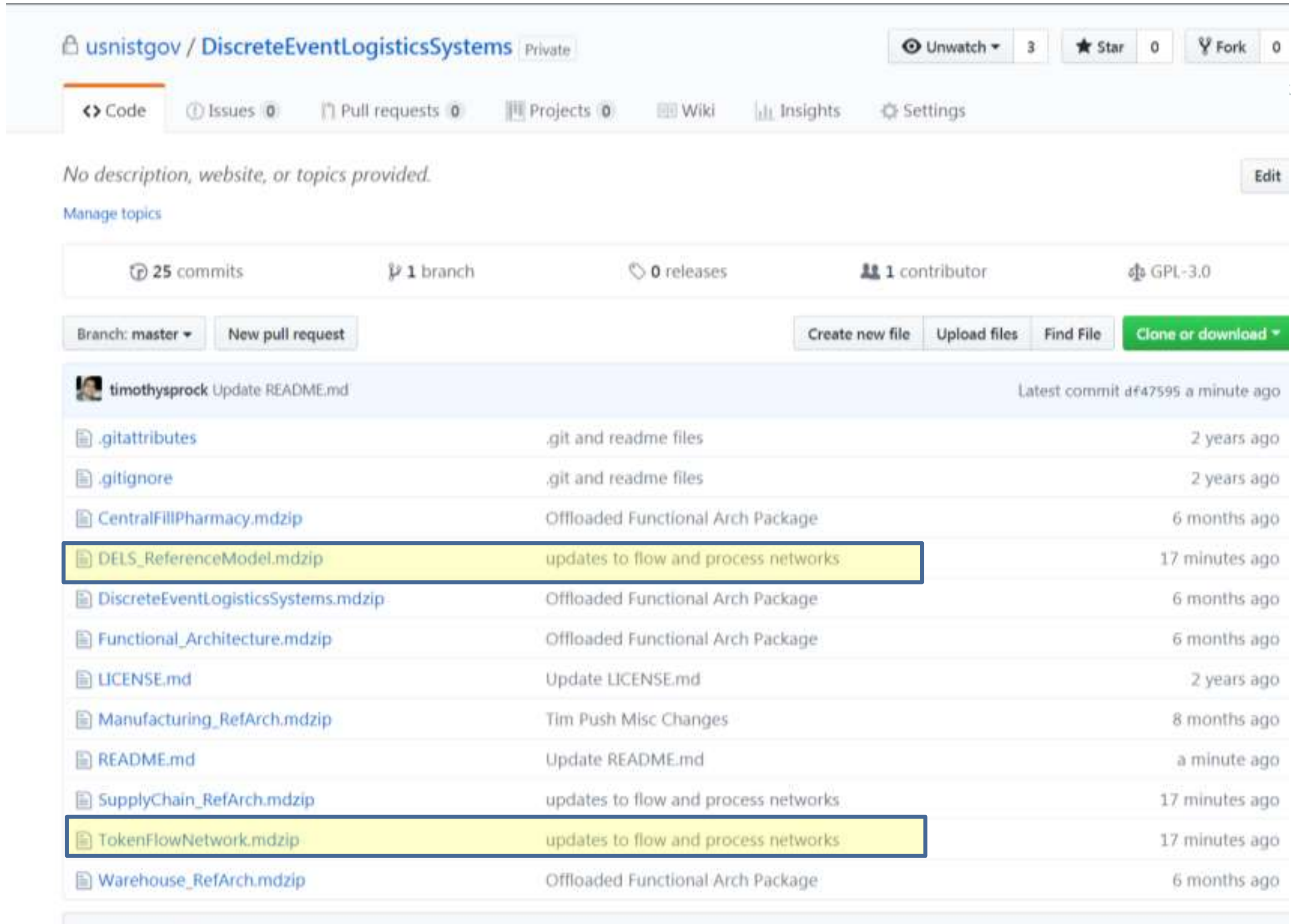
SysML Model Libraries

Two libraries focused on today:

- Network Abstractions
- DELS Abstractions

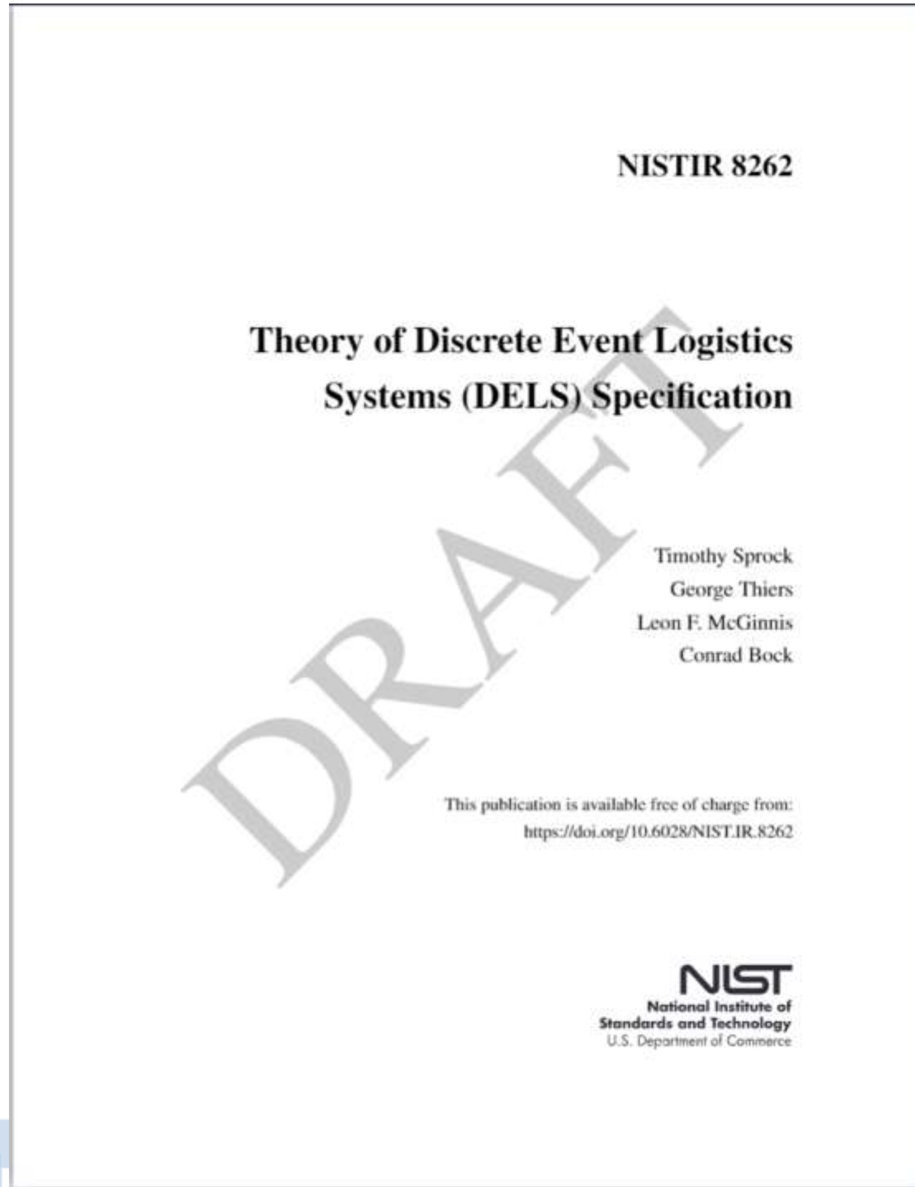


https://github.com/usnistgov/DiscreteEventLogisticsSystems

DELS Model Libraries Documentation

Documentation (Draft):
https://v2.overleaf.com/read/hhsmnkssjwcp

Future Location:
https://doi.org/10.6028/NIST.IR.8262


NISTIR 8262

Theory of Discrete Event Logistics Systems (DELS) Specification

DRAFT

Timothy Sprock
George Thiers
Leon F. McGinnis
Conrad Bock

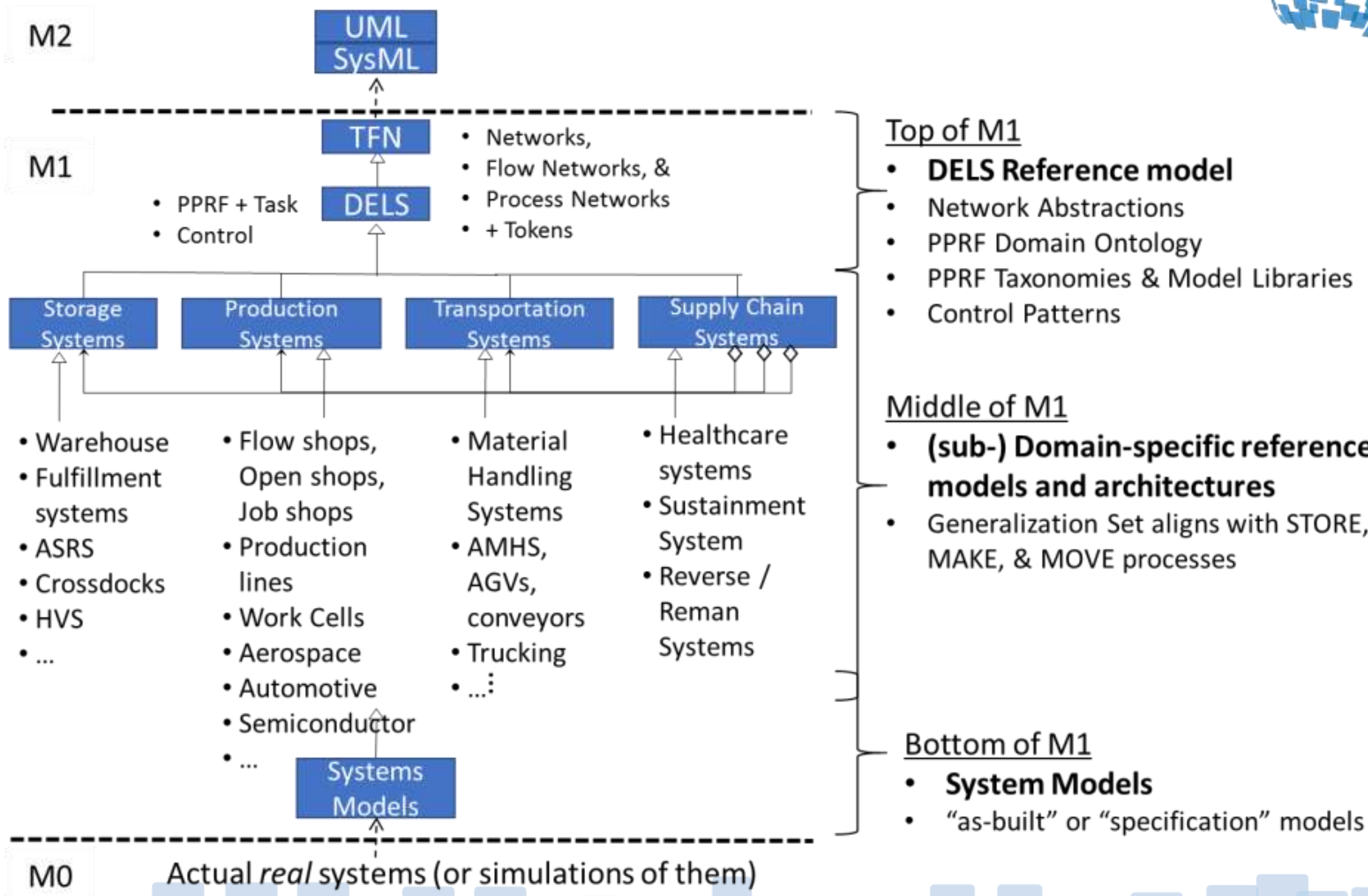
This publication is available free of charge from:
https://doi.org/10.6028/NIST.IR.8262

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

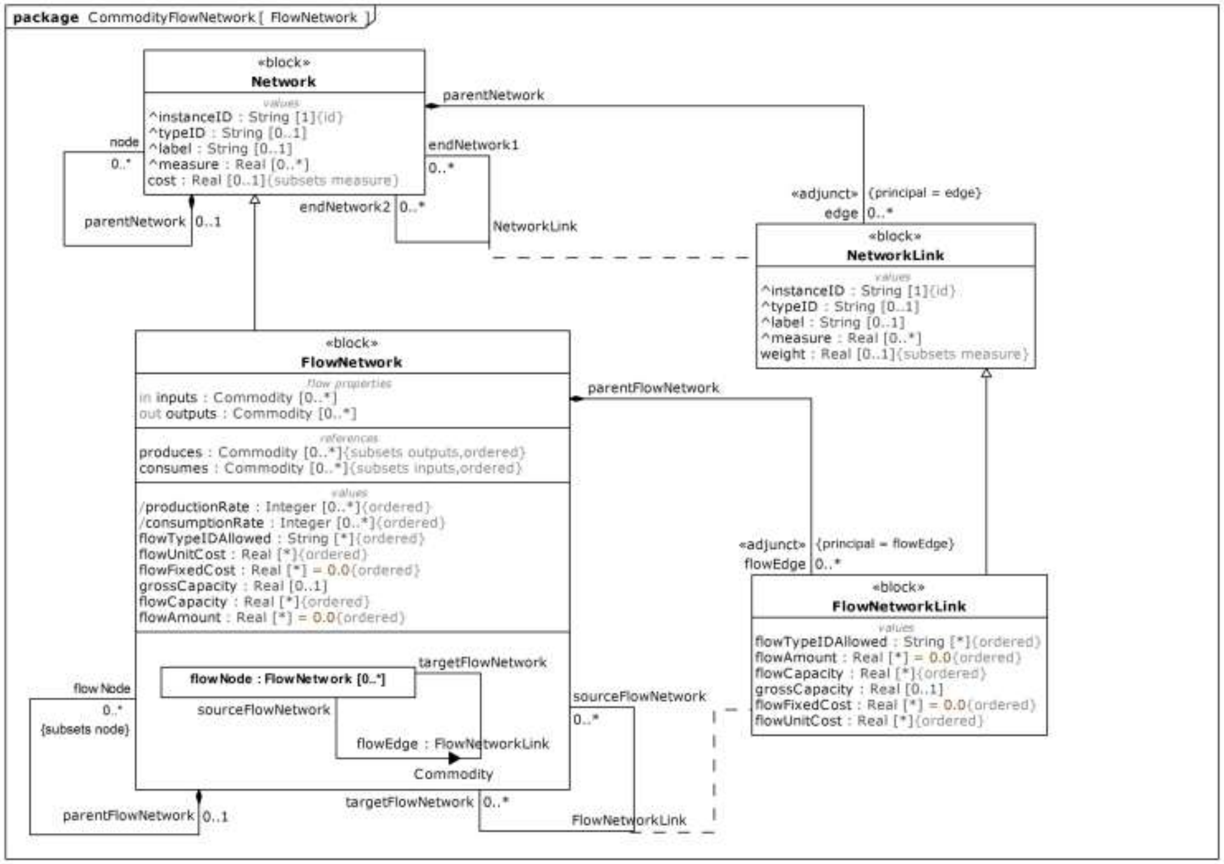
Theory of Discrete Event Logistics Systems (DELS) Specification

1. Introduction
2. Modeling Framework
3. Network Abstractions
   3.1 Basic Networks
   3.2 Flow Networks
   3.3 Process Networks
4. Discrete Event Logistics Systems
   4.1 Resource
   4.2 Process
   4.3 Product
   4.4 Facility
   4.5 Task
   4.6 Interfaces
5. DELS Operational Control
   5.1 Patterns for Modeling Operational Control
   5.2 DELS Controller
6. Extended DELS Definition
7. Specializing DELS
8. Composing Specialized DELS

Framework: DELS Reusable Model Libraries

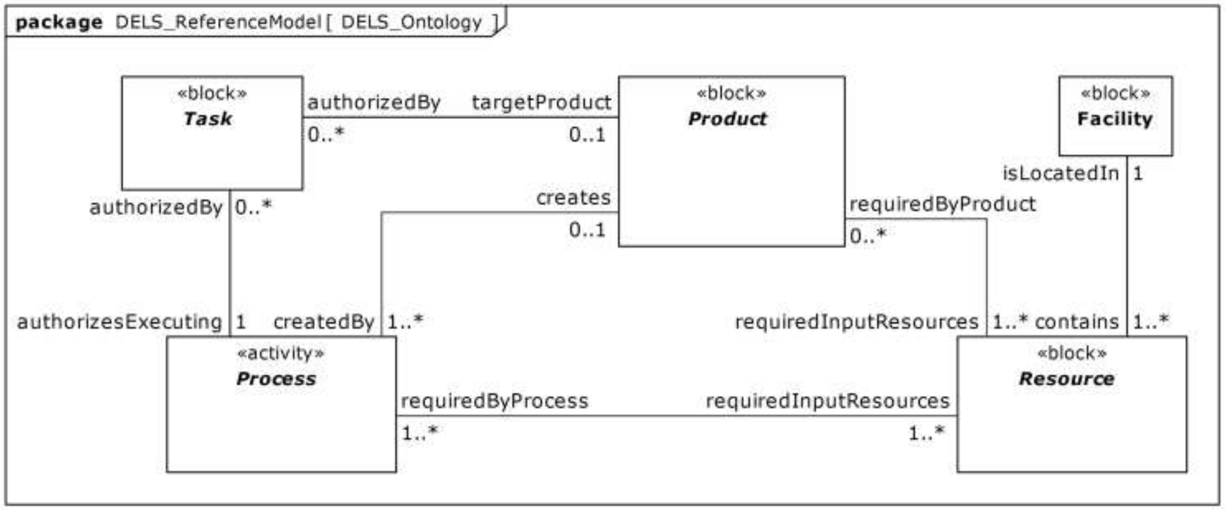


Network Models – Basic, Flow, & Process



- Reusable abstractions that closely align with the foundation of many analysis models
- Flow Networks → Multi-commodity flow network optimization
- Flow Networks → Foundation of discrete event simulation
- Process Networks → Queueing Network Analyses
- Process Networks → Foundation of Process Interaction discrete event simulation
- Create system models that are specialized from these abstractions
  - Automate the generation of analysis models

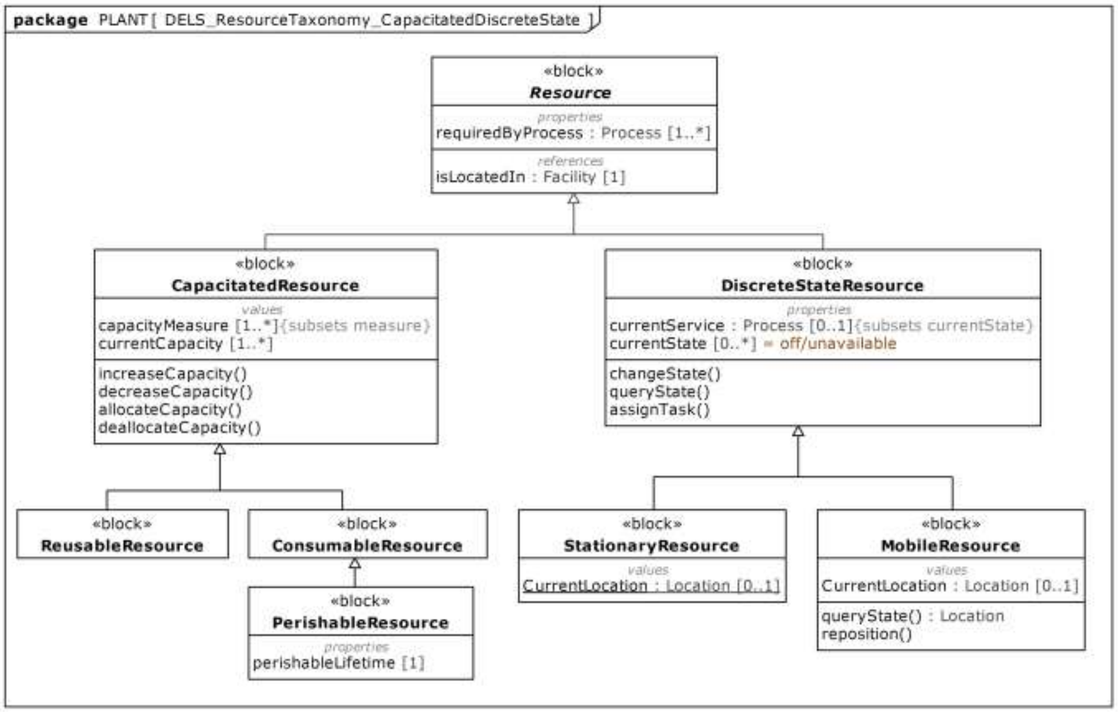
DELS Model Libraries

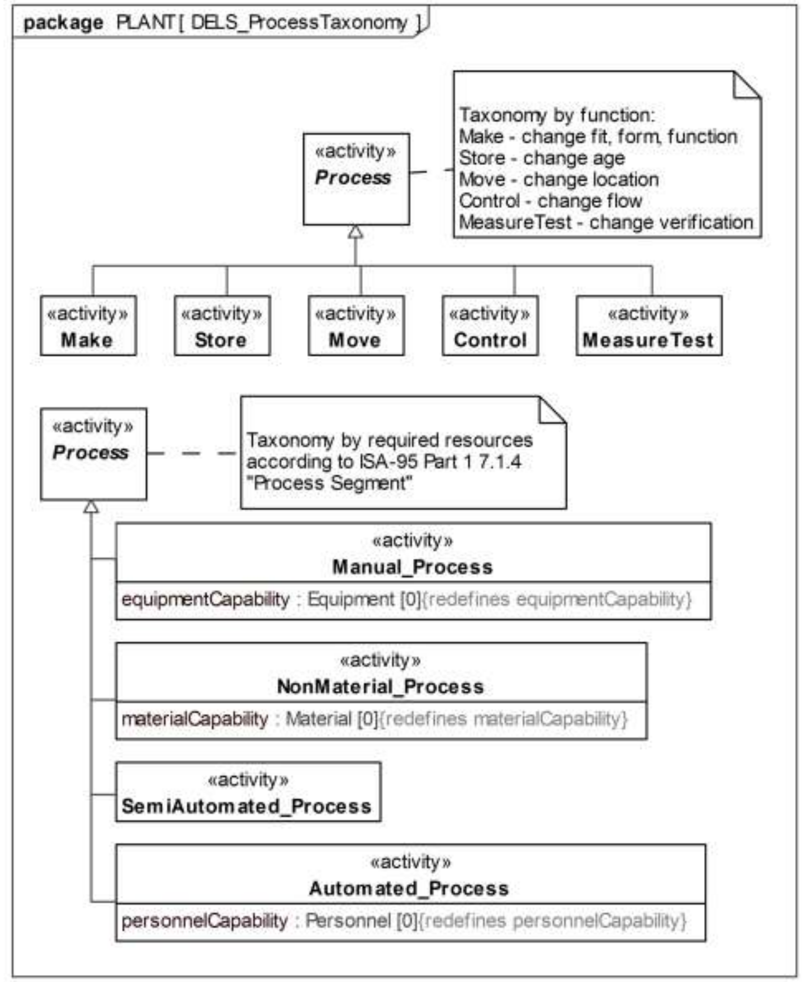


- Each element is elaborated with taxonomies and model libraries
  - Draw upon standards such as ISO MANDATE (ISO 15531), EBC (ISO 16400), MTConnect, ISA- 95 (IEC 62264), etc.
- Goals: Computational, reusable, and harmonization of definitions
- Guide specification of and/or knowledge capture from DELS

Examples – Process & Resource Taxonomy

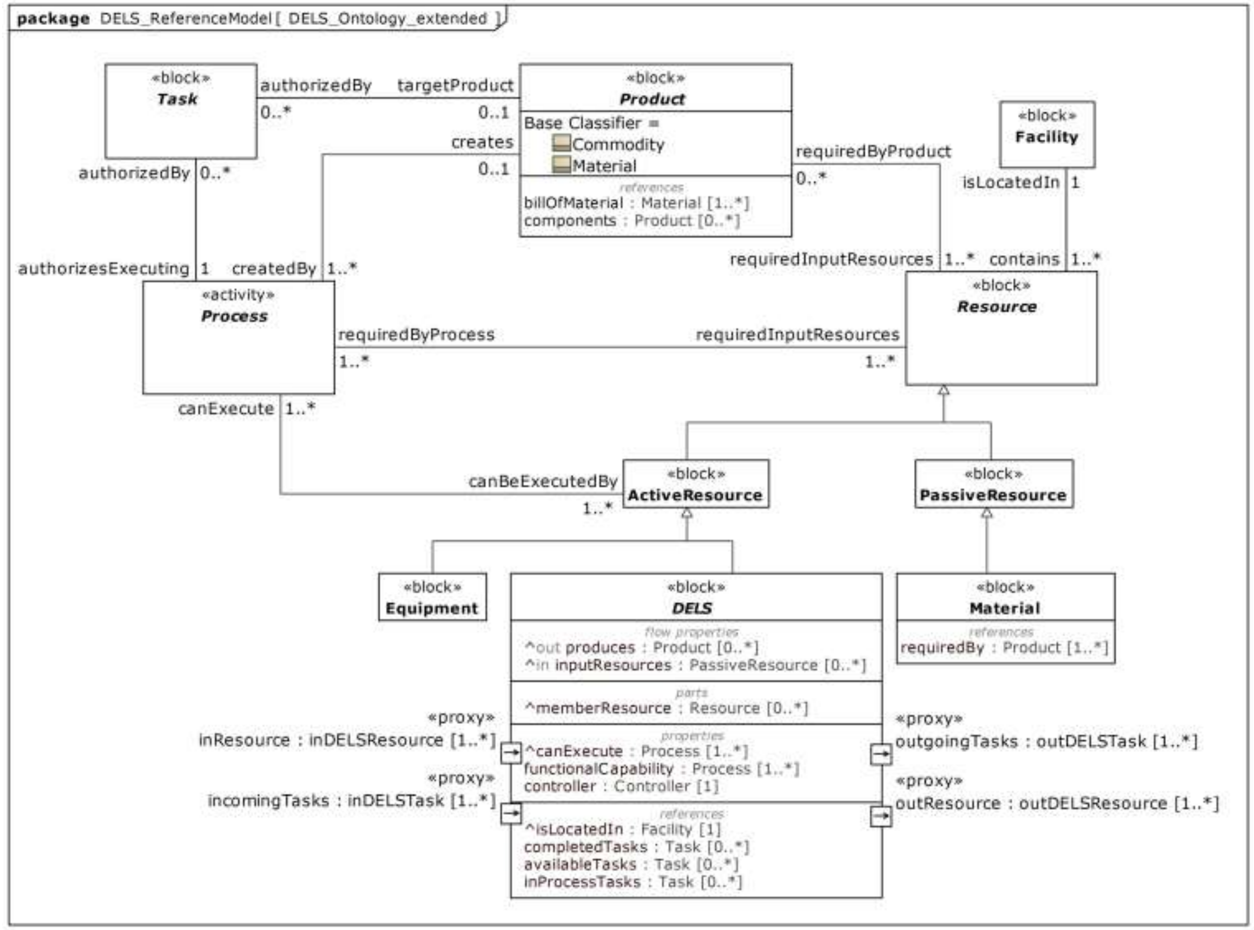
- “Upper” abstractions help map to key analysis model libraries
- Domain-specific model libraries specialize these into more concrete elements





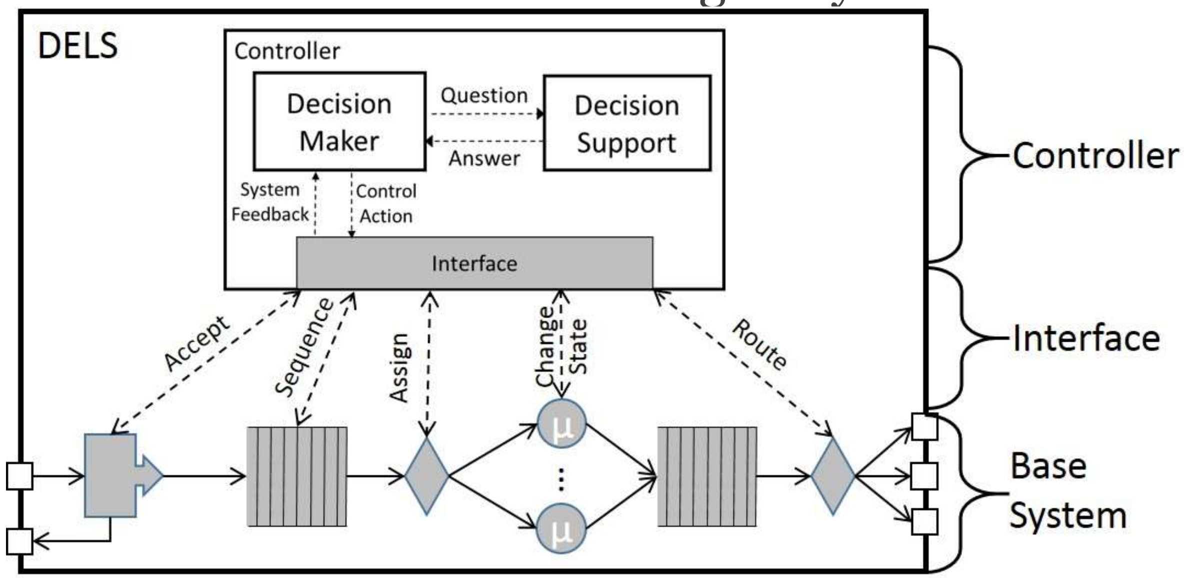
Incorporating the DELS Definition

- DELS is defined as a kind of Resource
- Allows DELS to play the role of Resource to other DELS
- Incorporates the Product, Process, Resource, Facility definition directly into the DELS definition



Operational Control Model

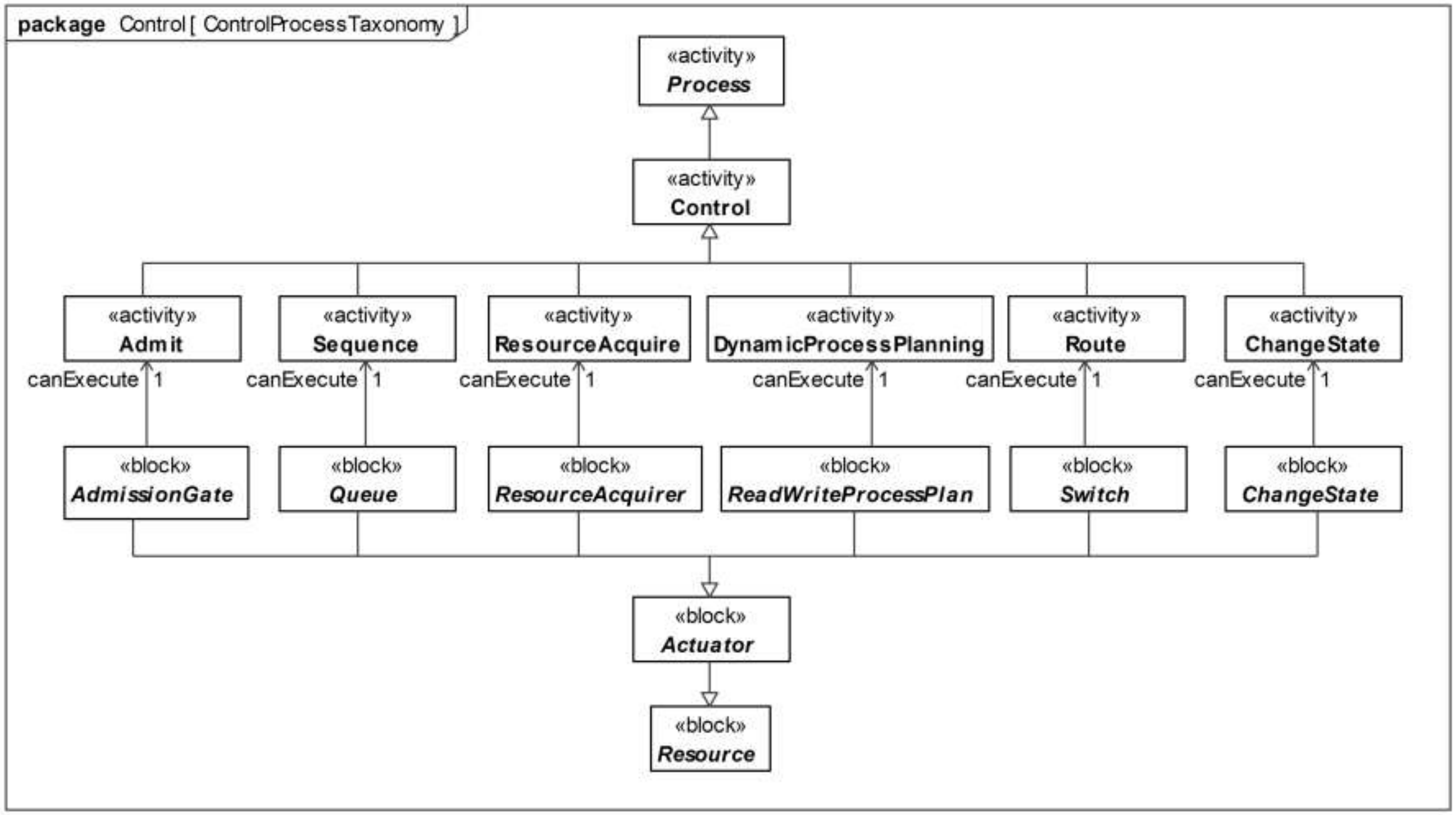
Manipulating flows of tasks and resources through a system.



- Which tasks get serviced? (Admission/Induction)
- When {sequence, time} does a task get serviced? (Sequencing/Scheduling)
- Which resource services a task? (Assignment/Scheduling)
- Where does a task go after service? (Routing/Dynamic Process Planning)
- What is the state of a resource? (task/services can it service/provide)

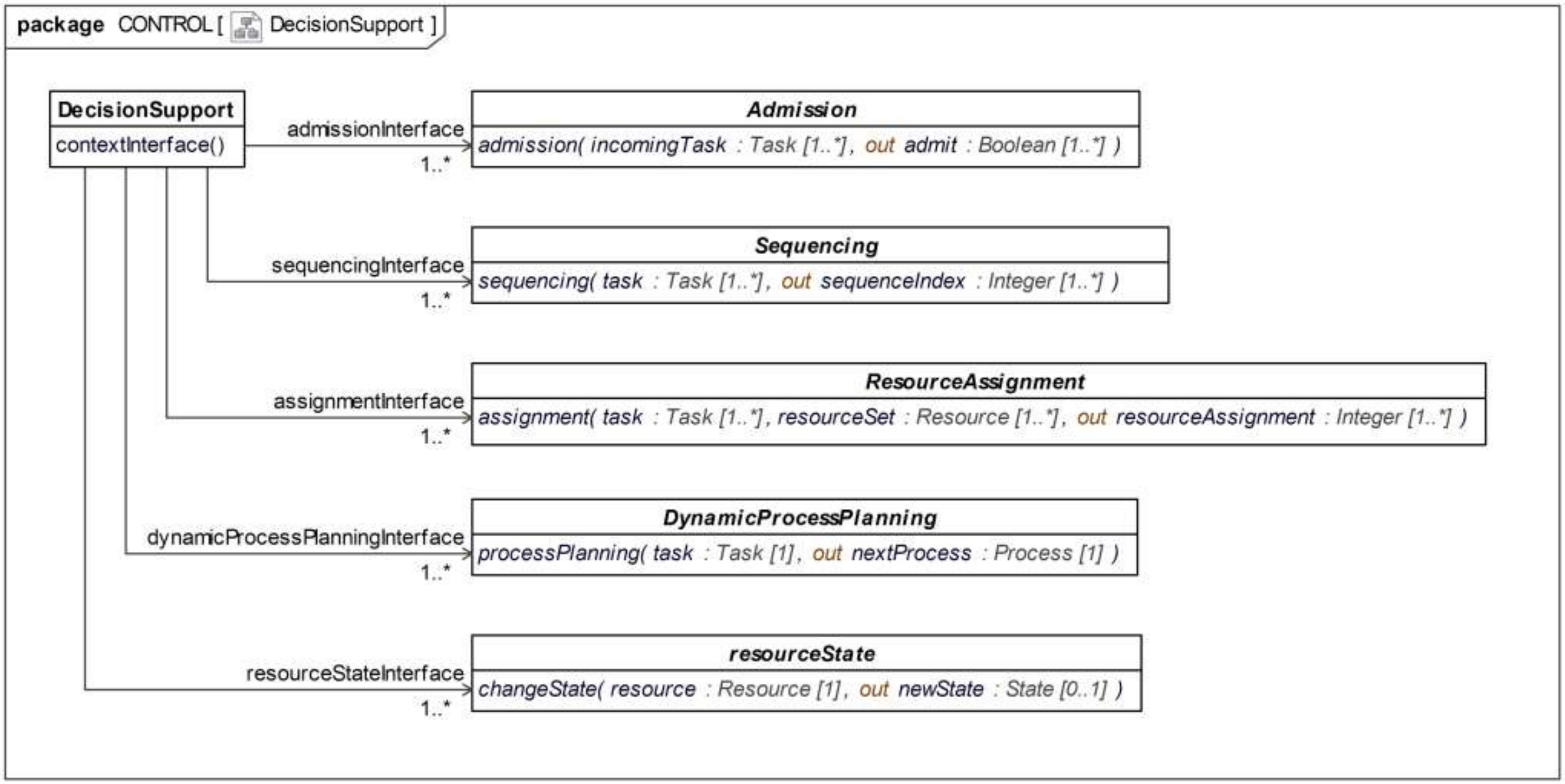
Operational Control Model Library

<u>Functional Capabilities and Resource Roles:</u> Building blocks for assembling models of system capable of implementing operational control



Standard Decision-support Interfaces

Controllers are configured with algorithms that provide decision support for each control decision



Patterns for Modeling Operational Control

Link decision support in the controller to behaviors and actuators on the shop floor

	Sequencing	Assignment
Question	"In what order {sequence, time} should tasks be served?"	"Which resource is assigned to service the task?"
Decision Function	$\mathit{Sequence}\text{: Task} \rightarrow \mathbb{N}$	$\mathit{Assign}\text{: Task} \times \text{Resource}(s) \mapsto \text{Resource}(s)$
Actuator Function	$\text{Sequence(TaskSet)} := \text{sort(TaskSet, sequenceIndex)} = \text{TaskSet}'$	$\mathit{Assign}\text{(Task, Resource)} :=$ $\text{Task.nextProcessStep.requiredInputResource} \leftarrow \text{Resource}$
Decision Expression	$x_{lk} = 1, \quad \text{if task } l \text{ is serviced } k^{th}$	$x_l^m = 1$ if resource m is assigned to execute the next process step of task l $x_{lj}^R = 1$ if resource group R is assigned to execute the j^{th} process step of task l
Decision Support Interface	«Strategy» **Sequencing** *sequencing(out sequenceIndex : Integer [1..*], taskSet : Task [1..*])*	**ResourceAssignment** *assignment(availabletask : Task [1..*], availableResources : Resource [1..*], out resourceAssignment : Resource [1..*])*
Actuator Function – System Model Library Component	availableTasks : Task[1..*] sequenceIndex : Integer[1..*] : Sequence orderedTasks : Task[1..*]	resourceAssignment : Integer[1..*] task : Task[1] : ResourceAcquire acquiredResources : Resource[1..*] availableResource : Resource[1..*]
Actuator – System Model Library components	inTask : inDELSTask [1..*] «block» **Queue** outTask : outDELSTask [1..*]	inTask : inDELSTask [1] availableResource : inDELSResource [1..*] «block» **ResourceAcquirer** acquiredResource : outDELSResource [1..*]

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- What are Discrete Event Logistics Systems (DELS)?
- DELS-related Products
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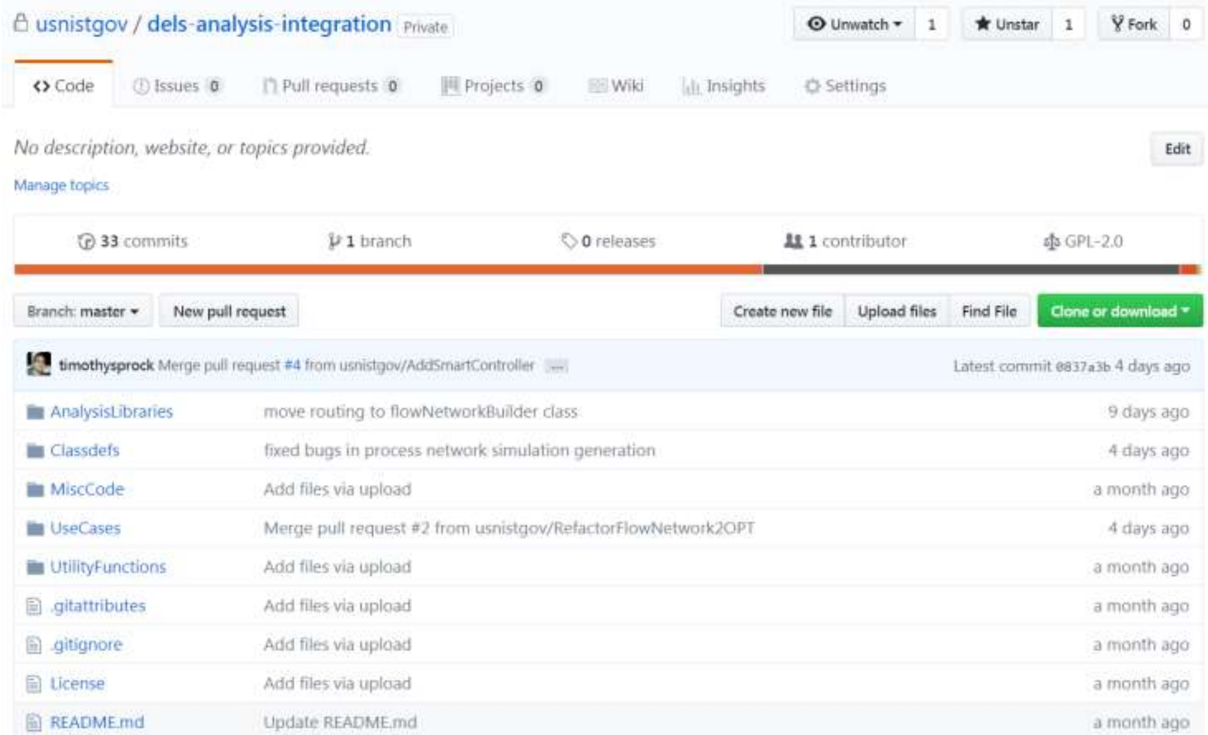
  - Documentation (DRAFT)
  - **Reference Implementation of SAI (Matlab)**

Analysis Integration

- Integrate several analysis toolboxes (Matlab)
  - Optimization: CPLEX, OPTI, Genetic Algorithm (MOEA)
  - Queuing network analysis
  - Newsvendor Network analysis (stoch opt)
  - Discrete-event simulation (SimEvents)
- Two test cases
  - Supply chain to flow network optimization to discrete event simulation (multi-fidelity)
  - DELS to queuing network to discrete event simulation
  - (PLANNED) Discrete Manufacturing Example
- Related Projects:
  - Model-based simulation optimization interoperability
  - Repeatable/reusable methods of building discrete event simulation models

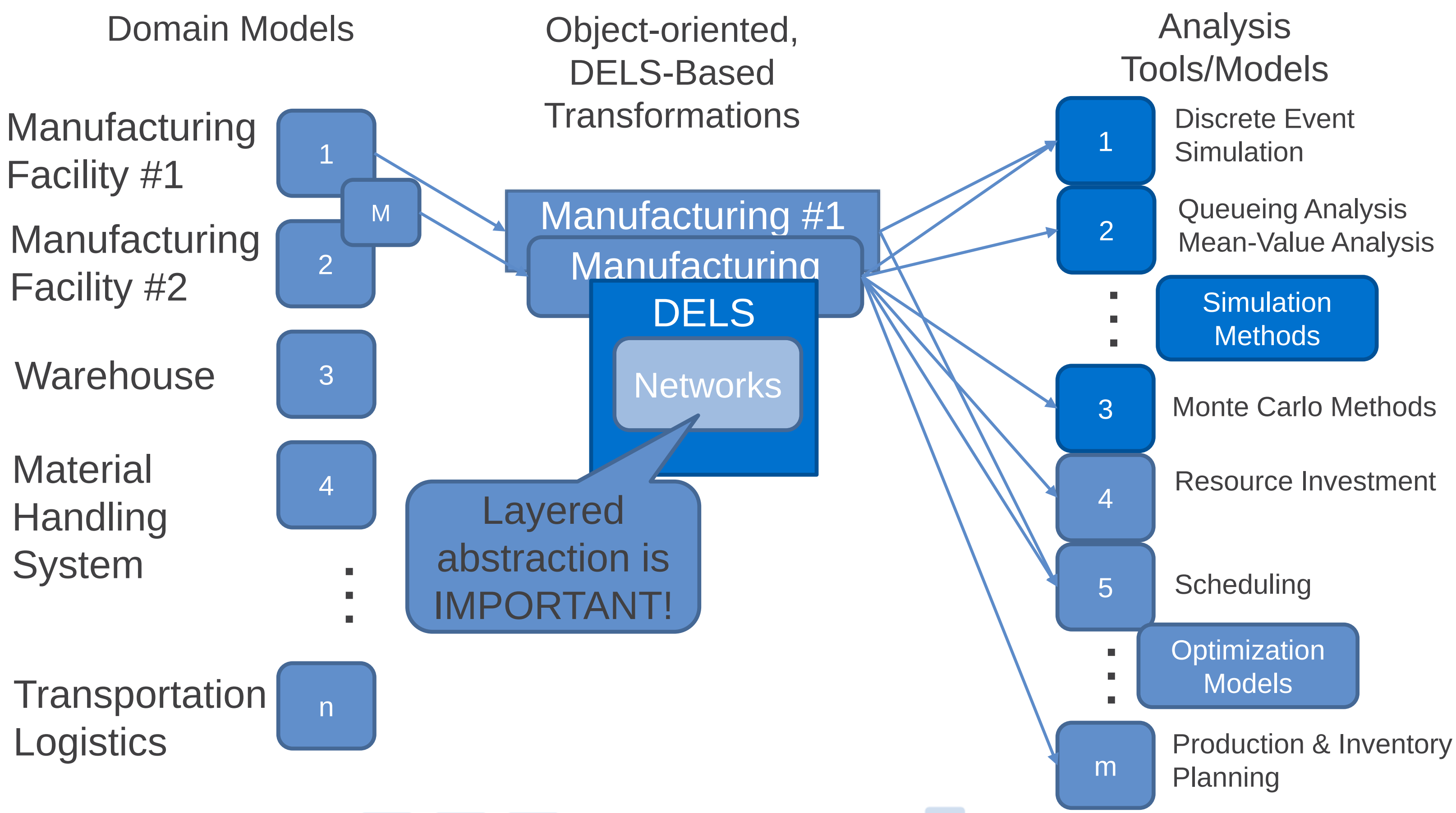


https://github.com/usnistgov/dels-analysis-integration

Email timothy.sprock@nist.gov for access

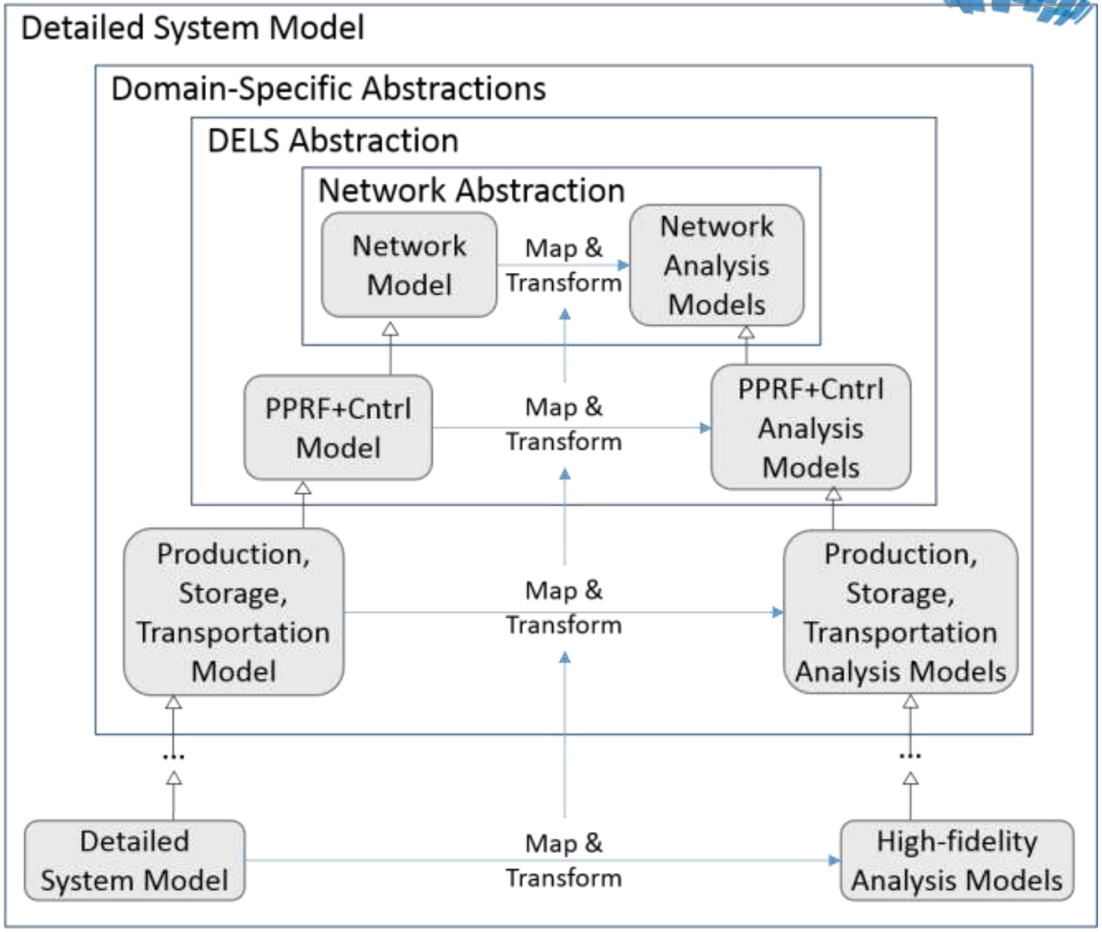
Disclaimer: **Far less mature w/ limited documentation**

System-Analysis Integration Methods: *Extending* M2M Methods Based on DELS Abstraction

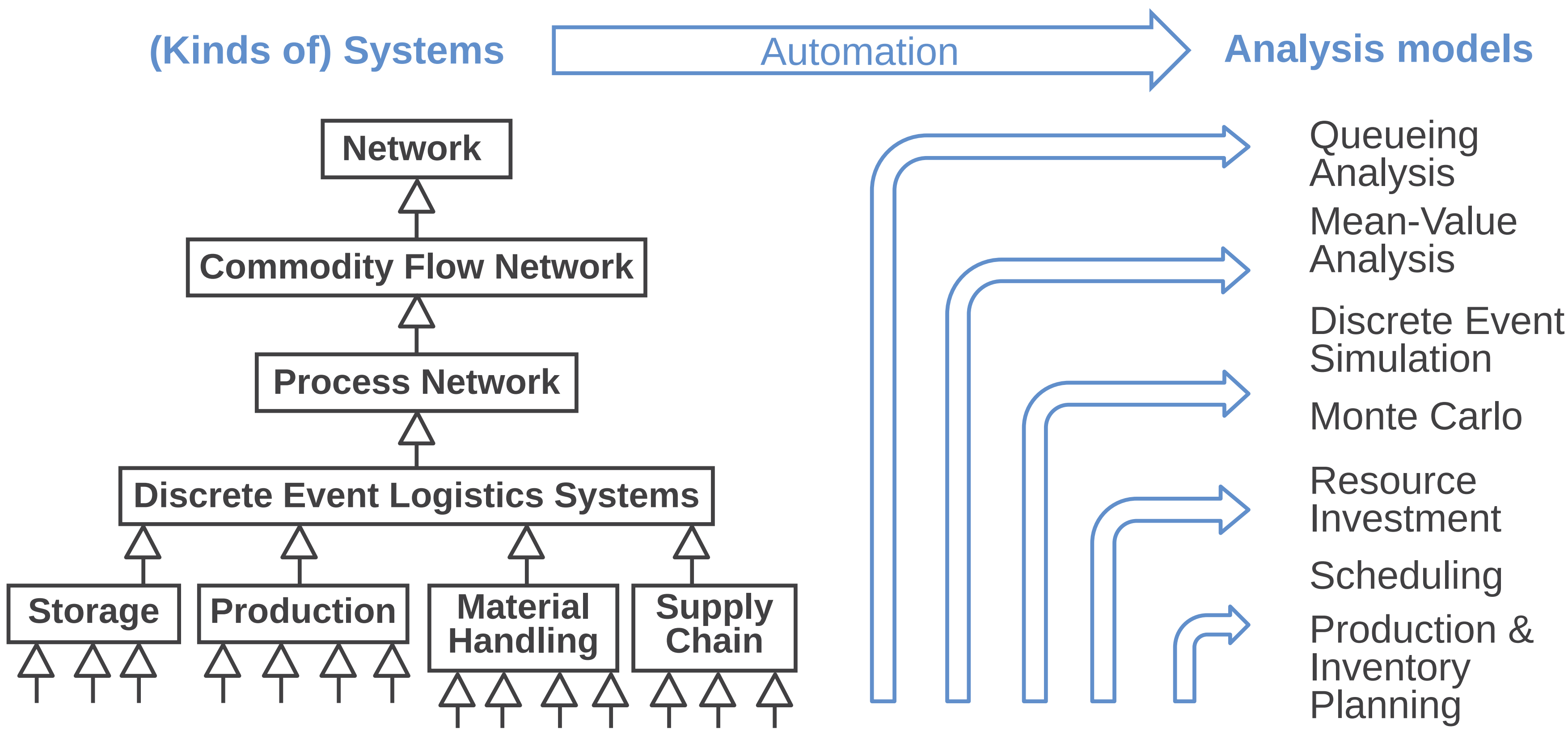


System-Analysis Integration Methods

- Use a common representation of the system under control (system model) to integrate multiple sources of information already defined and/or represented in other ways, often from heterogenous systems in incompatible formats, to create an integrated model of the system.
- Integrate system models with many kinds of analysis models, such discrete event simulation.



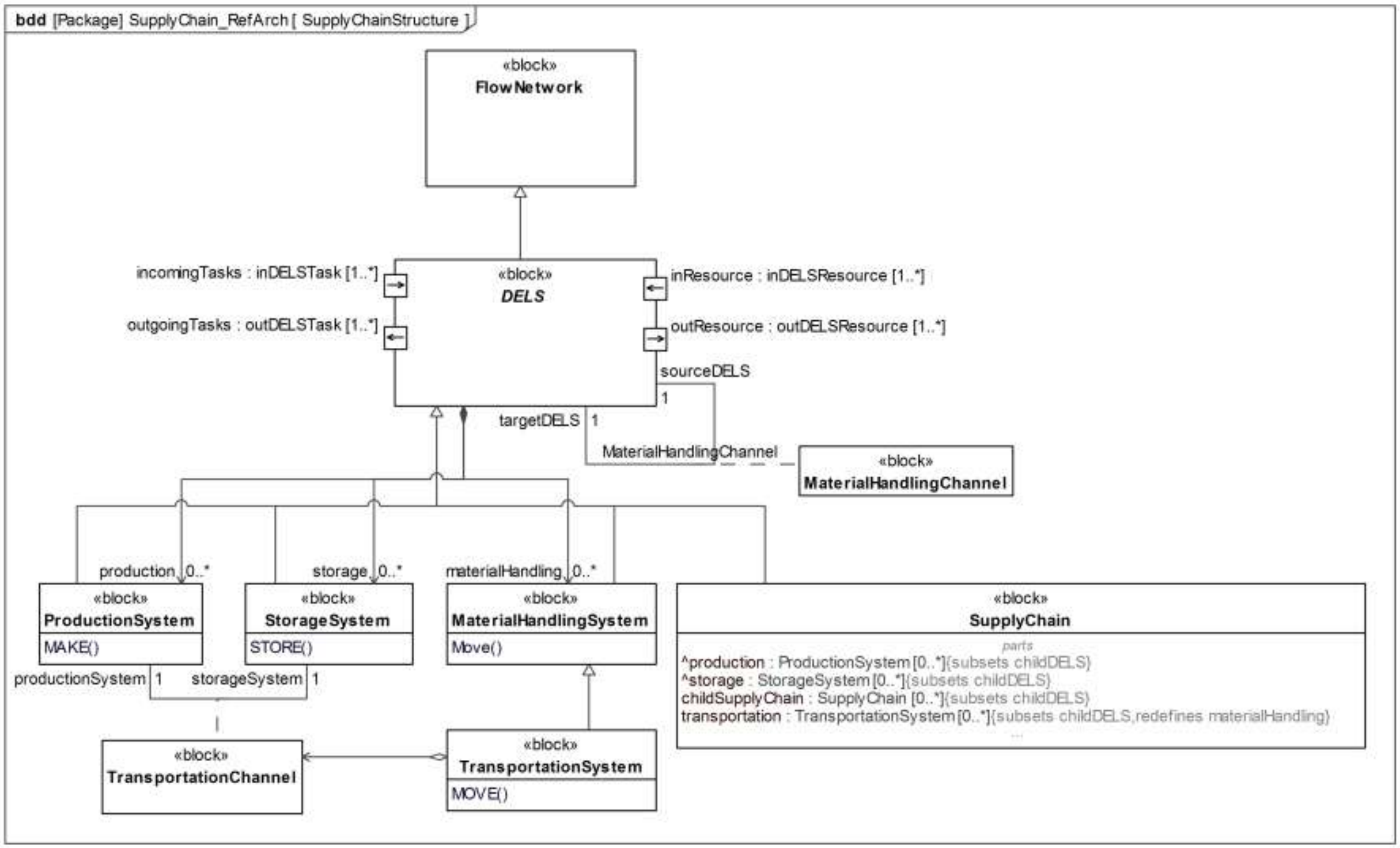
DELS Analysis



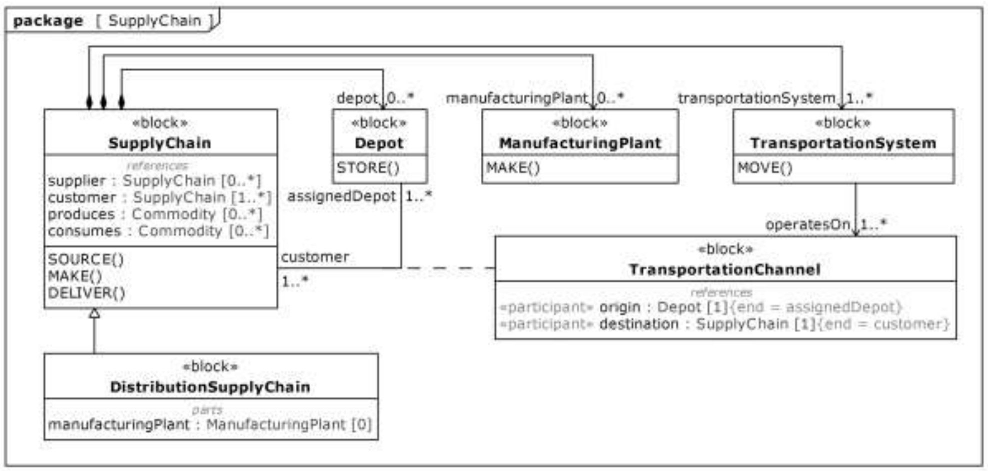
SAI Methods - Abstraction

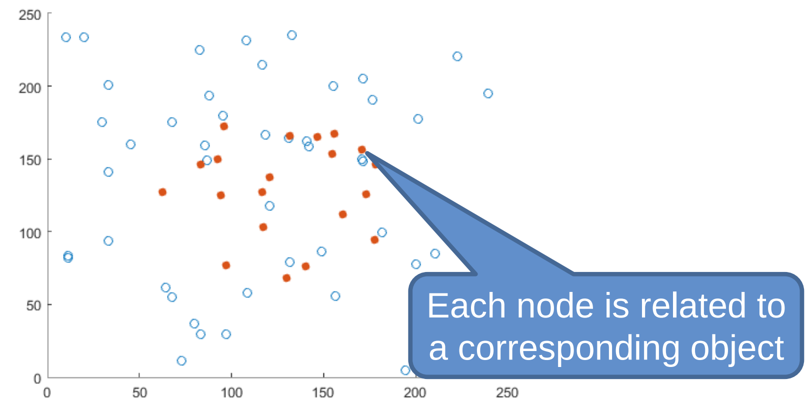
Supply Chain Case Study:

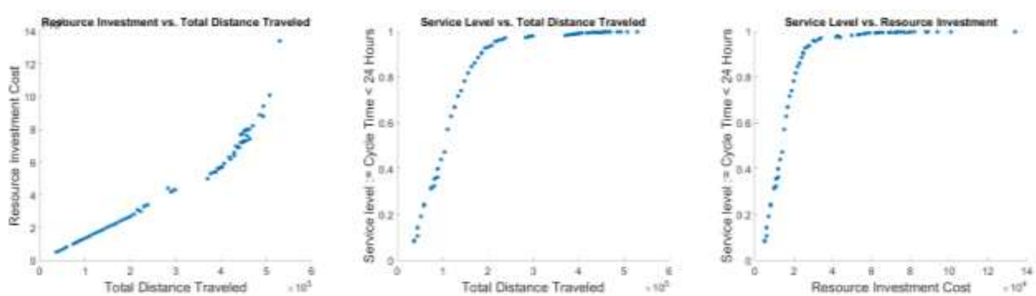
- Want to use optimization models based on the Flow Network abstraction
- Want to generate simulation models from the DELS abstraction



System-Analysis Integration – Use Case







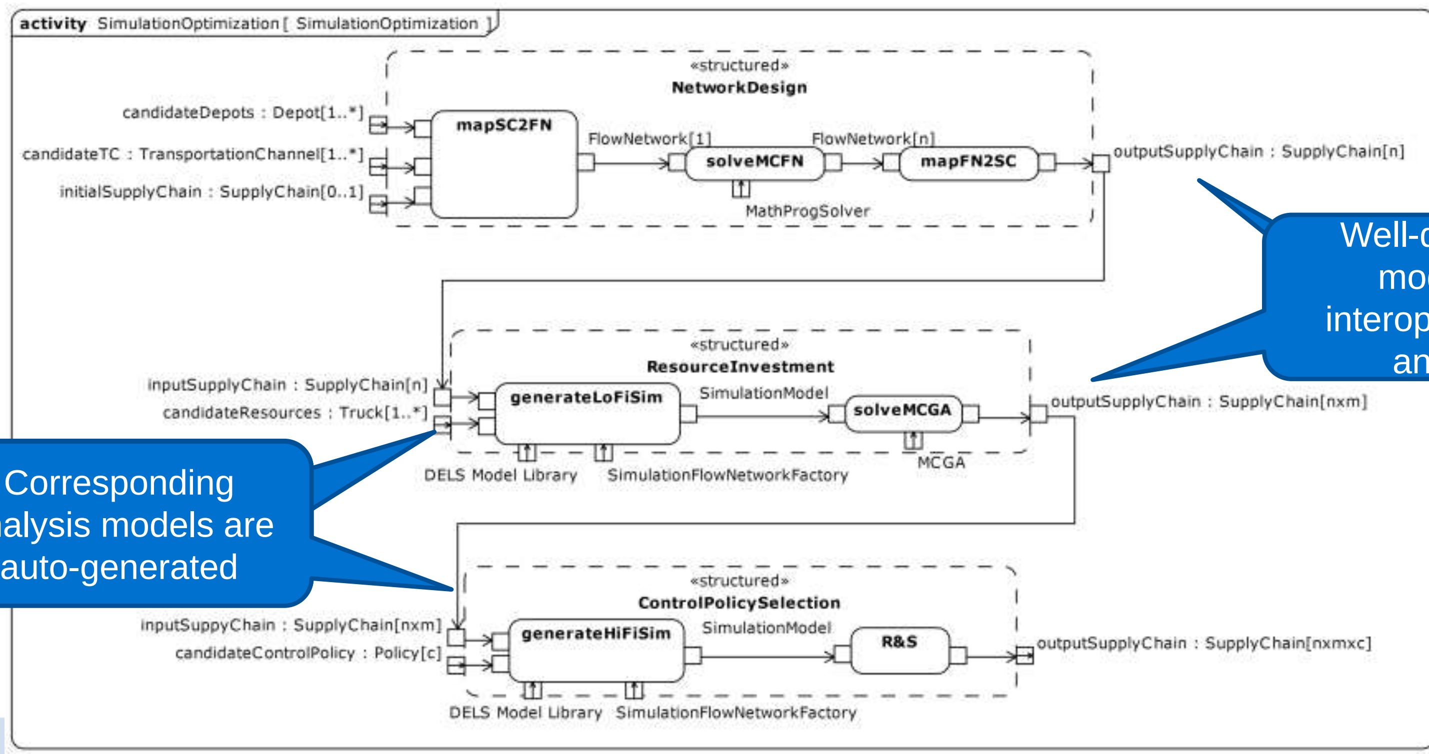
Strategy:

- Start with a system model or a reference model
- Generate an analysis model from the system model
- Use analysis model to support design decision making
- OR connect to an optimization model and search for candidate designs

Analysis Methodology Overview

Hierarchical design methodology uses tailored simulation optimization methods at each level to optimize the structure, behavior, and control of the DELS

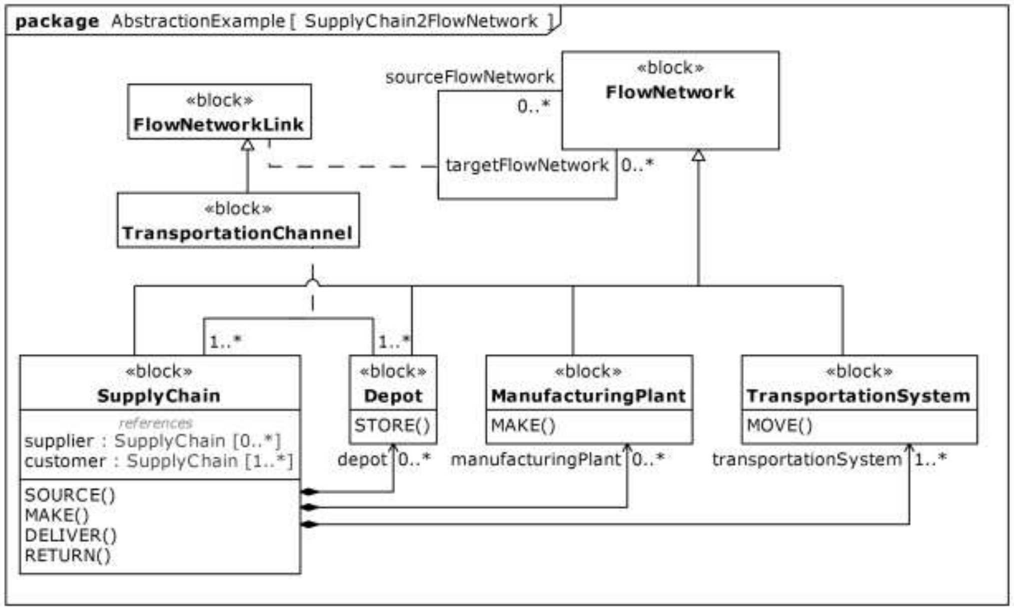
- Generate a large number of candidate solutions with corresponding simulation models specified at varying levels of aggregate, approximation, and resolution



Well-defined system model supports interoperability among analysis tools

Corresponding analysis models are auto-generated

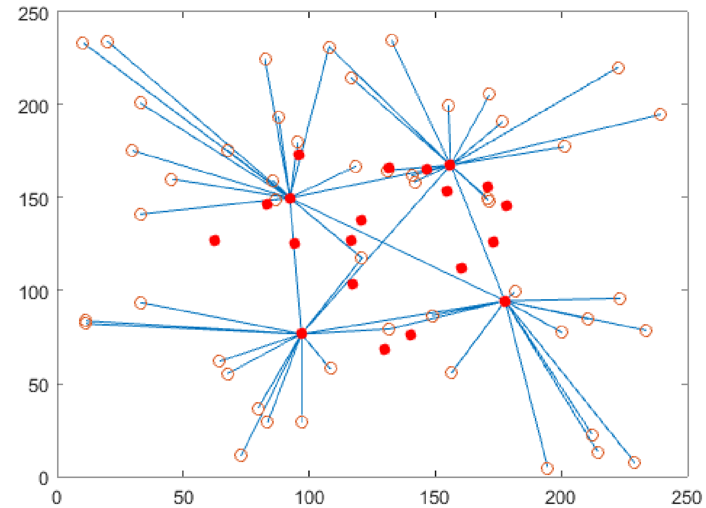
Optimize Network Structure – Where to put the depots?



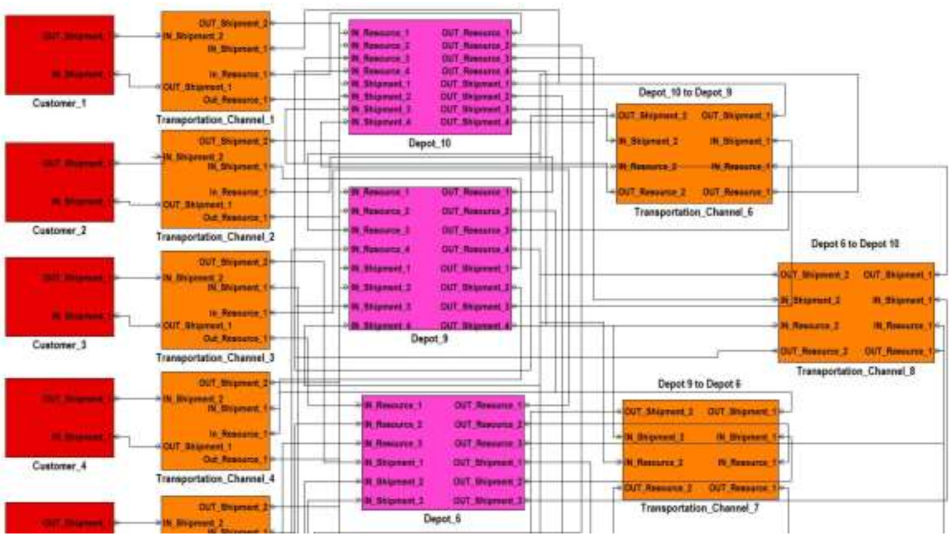
- Abstract the Supply Chain model to a Flow Network model that forms the backbone of the analysis model
  - Aggregate and approximate the flows and costs
- Solve MCFN using a COTS solver (CPLEX)

Goal: Reduce the computational requirements of optimizing the distribution network structure.

Strategy: Formulate and solve a corresponding multi-commodity flow network and facility location problem.

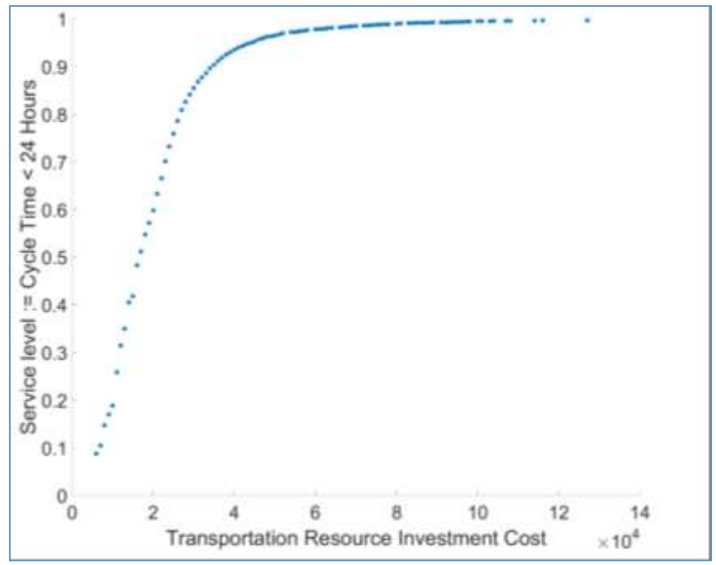


Resource Selection – How many trucks?



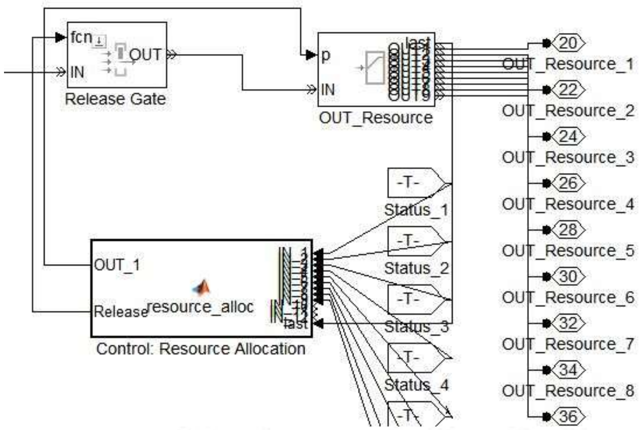
Goal: Capture and evaluate the behavioral aspects of the system using discrete event simulation.

Strategy: Generate a DES that simulates a probabilistic flow of commodities through the system.



- For each candidate supply chain network structure, generate a portfolio of solutions to the fleet sizing problem
- Trade-off cycle time/service level and resource investment cost

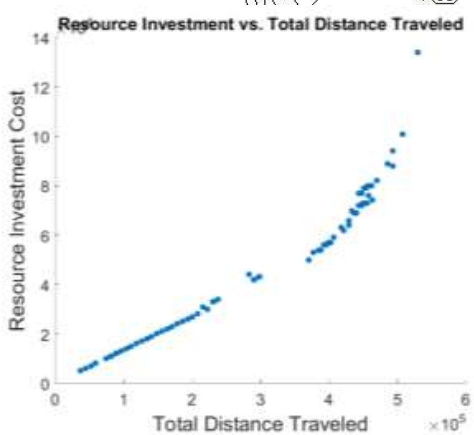
Configure Control Policies – Which Truck? When?

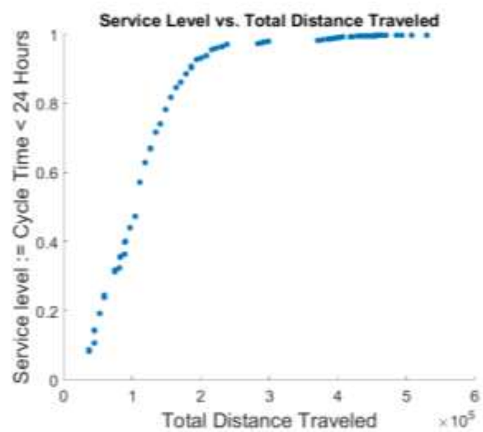


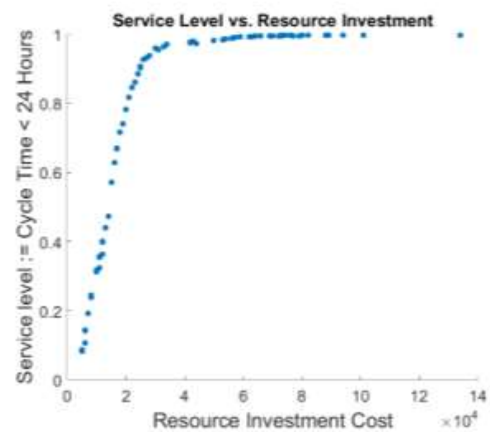
Goal: Select and design a detailed specification of the control policies for assigning trucks to pickup/dropoff tasks at customers.

Strategy: Generate a high-fidelity simulation that is detailed enough to fine-tune resource and control behavior.

Trade-off Service Level, Capital Costs, and Travel Distance

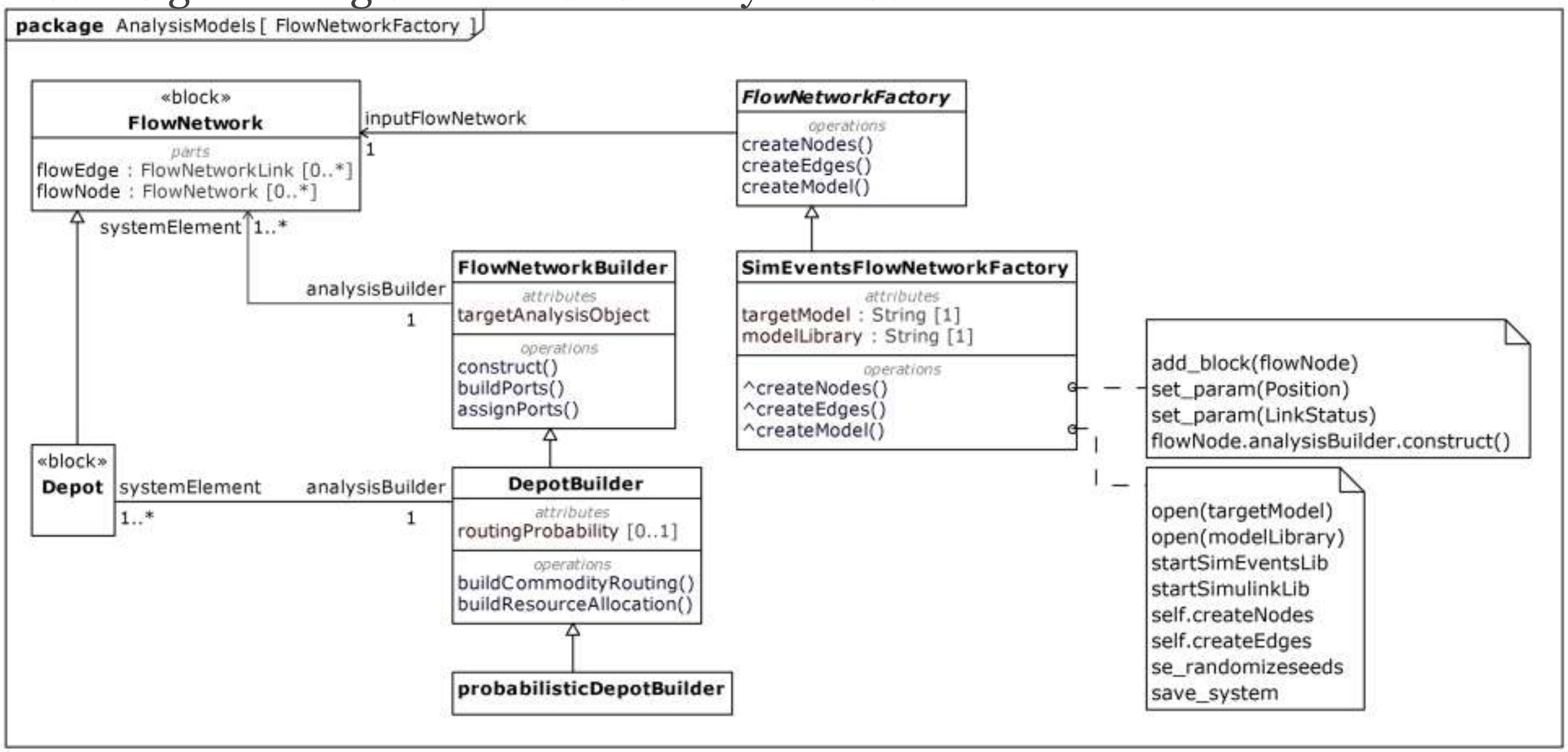






Build Platform-specific Adapters for COTS Discrete Event Simulation Tools

- Reusable, generic methods for generating simulation models from PIM system model inputs
- Gain some insight into general ways to build generic simulations (COTS tools have very different specifications)
- Extend methods to generating other kinds of analysis models



On-going Work

- Focus on smart manufacturing
  - Integrate manufacturing library (m-SysML) from DARPA iFab project
  - Develop case study – possibly leading to a model-based virtual testbed
- Continue to refine the operational control model library
- Mature the system-analysis integration reference implementation
  - Add case studies to support manufacturing and operational control
  - Identify other discrete event simulation platforms for integration
    - Work towards PIM of discrete event simulation for manufacturing operations

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MBSE Tools, Inc: Generating Analysis Methods from System Models

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Metrics that Matter (Manufacturing)

Customer Experience & Responsiveness
- On-Time Delivery to Commit
- Manufacturing Cycle Time
- Time to Make Changeovers

Quality
- Yield
- Customer Rejects/ Return Material Authorizations/ Returns
- Supplier's Quality Incoming

Efficiency
- Throughput
- Capacity Utilization
- Overall Equipment Effectiveness (OEE)
- Schedule or Production Attainment

Inventory
- WIP Inventory/Turns

Compliance
- Reportable Health and Safety Incidents
- Reportable Environmental Incidents
- Number of Non-Compliance Events / Year

Maintenance
- Planned vs. Emergency Maintenance Work Order Fraction
- Downtime in Proportion to Operating Time

Flexibility & Innovation
- Rate of New Product Introduction
- Engineering Change Order Cycle Time

Costs & Profitability
- Total Manufacturing Cost per Unit Excluding Materials
- Manufacturing Cost as a Percentage of Revenue
- Net Operating Profit
- Productivity in Revenue per Employee
- Average Unit Contribution Margin
- Return on Assets/Return on Net Assets
- Energy Cost per Unit
- Cash-to-Cash Cycle Time
- EBITDA
- Customer Fill Rate/ On-Time Delivery/ Perfect Order Fraction

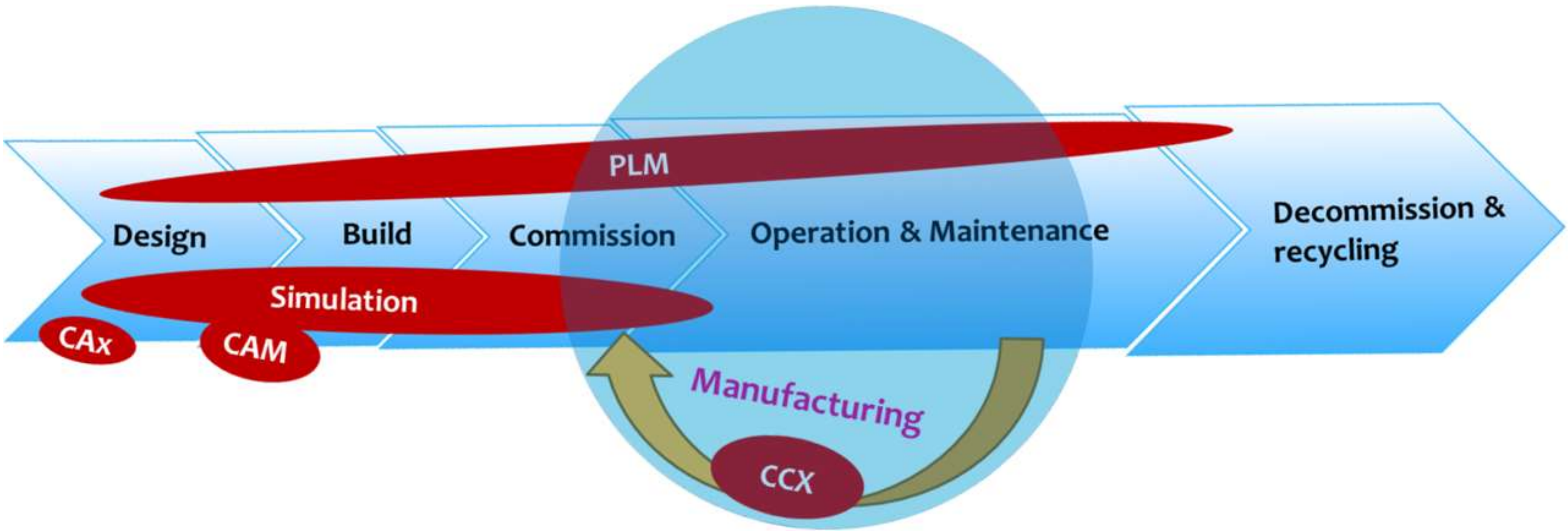
Source: MESA survey, 2013-2014
"Manufacturing Metrics That Really Matter"

Metrics that Matter (Supply Chain)

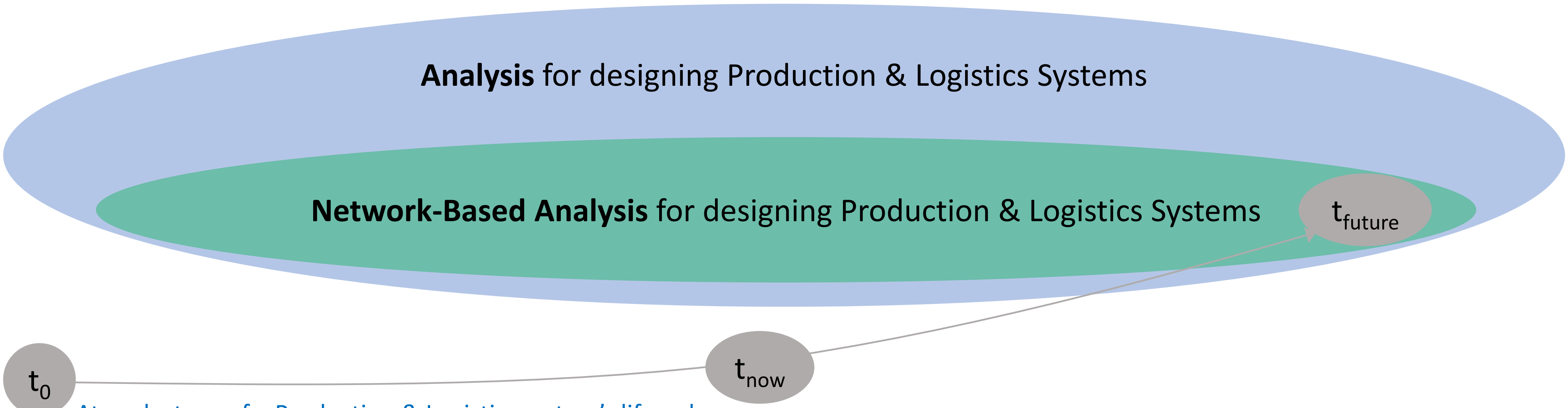
Level 1 Strategic Metrics	Performance Attributes				
	Customer-Facing			Internal-Facing	
	Reliability	Responsiveness	Agility	Costs	Assets
Perfect Order Fulfillment	√				
Order Fulfillment Cycle Time		√			
Upside Supply Chain Flexibility			√		
Upside Supply Chain Adaptability			√		
Downside Supply Chain Adaptability			√		
Overall Supply Chain Value-At-Risk			√		
Supply Chain Management Cost				√	
Cost of Goods Sold				√	
Cash-To-Cash Cycle Time					√
Return on Supply Chain Fixed Assets					√
Return on Working Capital					√

Source: Supply Chain Operations Reference Model (SCOR) 10.0

Metric evaluation is not just a data-analysis problem



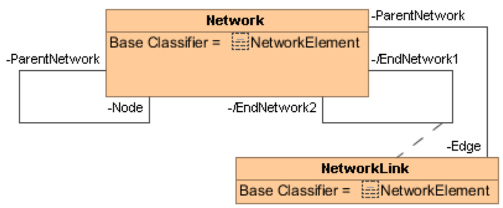
Source: Lu, Morris, and Frechette,
NIST IR 8107, Feb 2016

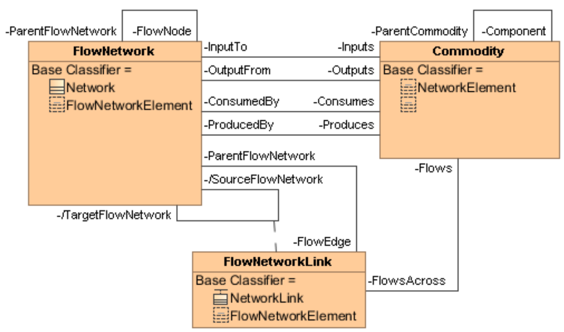


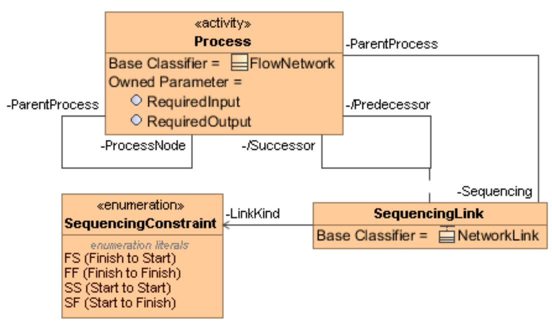
At each stage of a Production & Logistics system's lifecycle:

- What types of **metrics** or **questions** are important?
- What **information about the system** is available?
- What **analysis types** can evaluate metrics or answer questions using that information?
- What do **answers** look like, and how are they inferred from analysis output?

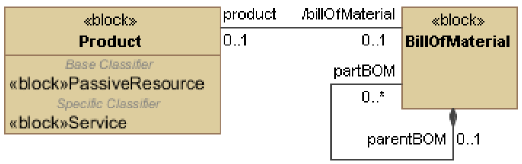
- What are **design tools** for P&L systems?
- What are **semantics** and **syntax** of design information?
- What is **broken**, if anything, about contemporary practices for analysis formulation?
- What does a **better way** look like?

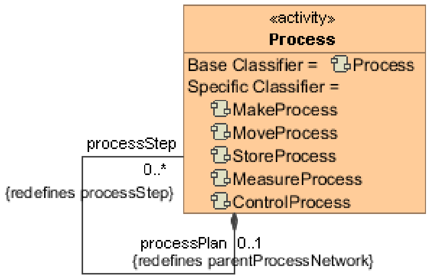


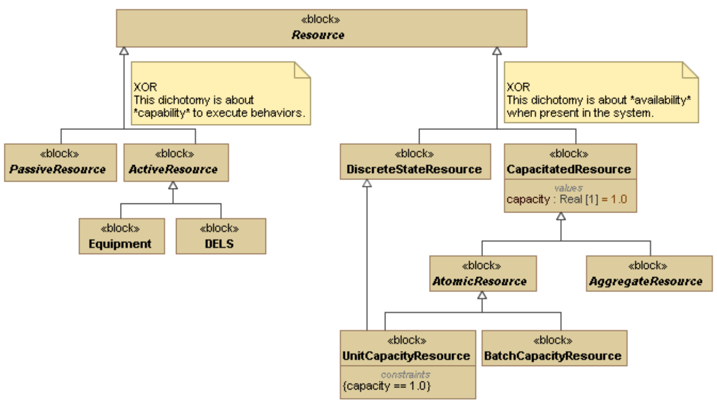


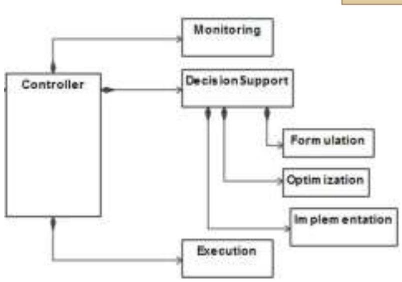


Domain-Specific Questions	Analytical Questions
Describe: Network Scale, Structure, and Navigability	*Graph Theory*: Connected, Acyclic, Bipartite, Order, Size, Density, Clique Number, Diameter, Walks, Paths, Subgraphs (coverings, cliques, independent sets, packings), Labelings (colorings)
Describe: Flow Statistics *Proscribe*: High-Level Capacity Planning	*Statistical Analyses* *Network Optimization*: Matching, Assignment, Multi-Commodity Flow, Transportation, Circulation, Optimized Flow (max flow volume, min flow cost, …)
Describe: Cycle Time Statistics *Predict*: Uncontrolled State Evolutions Performance Measures	*PERT/CPM Analysis*: Slack, Critical Path *Petri Net Analysis*: Reachability, Safeness, Liveness *Markov Chain Analysis*: Equilibrium *Queueing Theory Analysis*: Throughput, Cycle Time, Work-In-Process, Utilization, Bottlenecks *Discrete-Event Simulation*: (arbitrary performance measures and statistics)







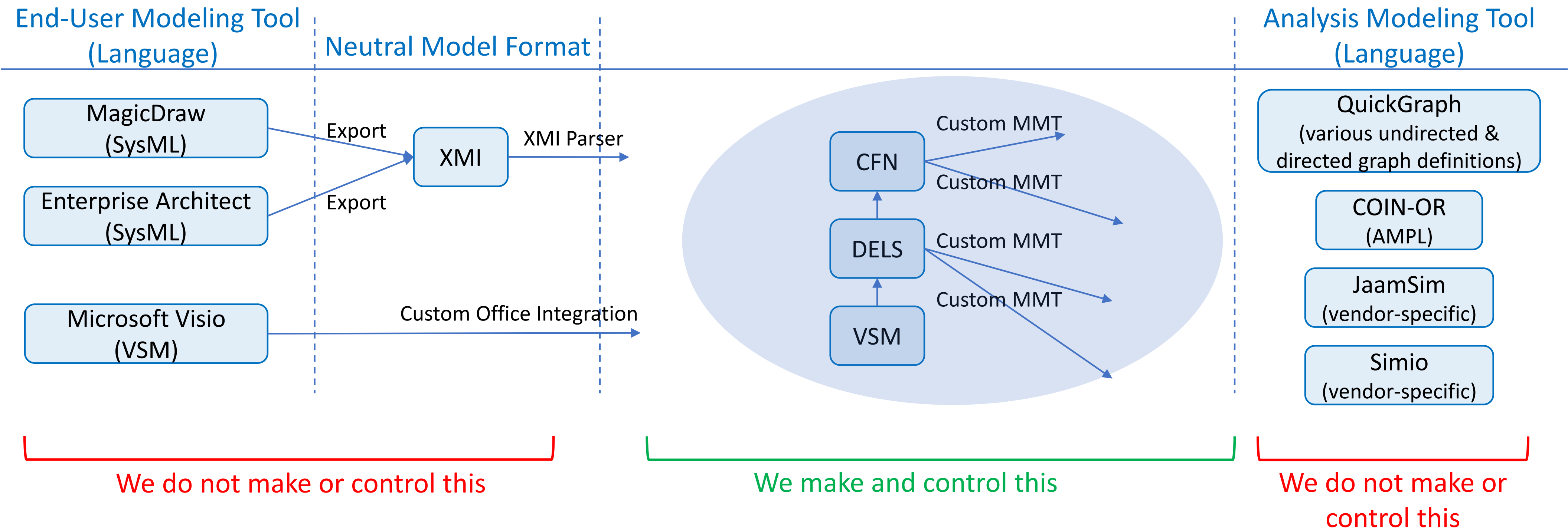


Domain-Specific Questions	Analytical Questions
Describe: Availability of product information, and its integration with process & resource information	*Model Queries*
Predict: Performance Measures	*Queueing Theory Analysis*: Throughput, Cycle Time, Work-In-Process, Utilization, Bottlenecks *Discrete-Event Simulation*: (arbitrary performance measures and statistics)
Describe, Predict: Capability, Capacity, Performance *Proscribe*: High-Level Capacity Planning	*Discrete-Event Simulation* *Network Optimization*: Matching, Assignment, Multi-Commodity Flow, Transportation, Circulation, Optimized Flow (max flow volume, min flow cost, …)
Predict, Proscribe: Admission, Sequencing, Resource Assignment, Resource State Change, Dynamic Process Planning	*Discrete-Event Simulation* *Simulation-Optimization*

Lifecycle		Concept, Early-Stage Design	Late-Stage Design, Build	Commission	Operation & Maintenance
What You Know	*Product*	Partial EBOM	EBOM, partial MBOM	EBOM, MBOM	EBOM, MBOM, regular engineering changes
	Process	Make	Make, Measure, Test, partial Move & Store	Make, Measure, Test, Move, Store, partial Control	Make, Measure, Test, Move, Store, Control
	Resource	Work Unit: Capability	Work Unit, partial Work Center: Capability, partial Capacity	Work Unit, Work Center, partial Area: Capability, Capacity, partial Performance	Work Unit, Work Center, Area: Capability, Capacity, Performance
	Facility	n/a	Location, partial Channel	Location, Channel	Location, Channel, Geometry
	Control	n/a	*Admission*, partial *Sequencing* (How to prioritize orders? Is expediting allowed? Are changeovers allowed?), partial *Resource Assignment* (Job shop or dedicated lines?)	*Admission*, *Sequencing*, *Resource Assignment*, partial *Scheduling* (Make to engineer, order, or stock? Push or pull?), partial *Resource State Changes*, partial *Dynamic Process Planning* (Is material handling scheduled or requested? How to prioritize requests? When is storage allowed?)	Admission, Sequencing, Resource Assignment, Scheduling, Resource State Changes, Dynamic Process Planning
What You Can Do	*Describe*	**(Product)** Does every part have a part number? A make/buy decision? If make, a process plan? Design for Manufacturing and Assembly (DFMA) analysis results? **(Process)** Does every *make* process have a make-to specification? A resource capable of its execution? **(Resource)** Are all capability, capacity, and performance requirements allocated to resources?	**(Product)** Same questions, with a richer set of parts. **(Process)** Same questions, with a richer set of processes. Gross execution capacity per process? Max execution rate per process, given standard hours estimates? **(Resource)** Downtime causes? Changeover time estimates? Material movement requirements per part? Inter-resource channel requirements? **(Facility)** Sizing requirements for Work Units & Work Centers? Storage geometry constraints?	**(Product)** Same questions, with a richer set of parts. Preliminary quality statistics? **(Process)** Same questions, with a richer set of processes. Max operational cost per process? Gross execution capacity & max execution rate per logistical process? Contingency-triggered alternatives? **(Resource)** Downtime statistics and costs per resource? Changeover statistics and costs? Max material handling rate per channel? **(Facility)** Sizing requirements per channel? Per storage buffer? Per Area? **(Control)** TH, CT, WIP statistics? Critical path? Emerging bottlenecks?	*Operational data is now available.* **(Product)** Quality statistics? **(Process)** Process alternatives upon contingencies? Waste? **(Resource)** Utilization, downtime, and changeover statistics. Material handling statistics. **(Facility)** Channel congestion statistics? Storage overflow statistics? **(Control)** Statistics for TH, CT, WIP, on-time deliveries, and other metrics (see SCOR)?
	Predict	Lower & upper bounds on expected TH, CT, WIP, given fixed resources?	Refined lower & upper bounds on expected TH, CT, WIP, given fixed resources? Expected critical path? Potential bottlenecks?	Expected TH, CT, WIP? Expected critical path? Potential bottlenecks? Expected schedule delays or travelled work fractions, per process?	(For alternatives and scenarios: How bad?) Expected and worst-case TH, CT, WIP, on-time deliveries, schedule delays or travelled work fractions? Expected critical path and bottlenecks?
	Prescribe	Lower & upper bounds on resource requirements, given fixed TH, CT, WIP requirements?	Refined lower & upper bounds on resource requirements, given fixed TH, CT, WIP requirements? Lower & upper bounds on material handling capacity? Projected storage buffers? Preliminary facility layout?	Expected resource requirements for make, measure, test processes? Expected resource requirements for move & store processes? Storage buffer capacities? Facility layout?	(For alternatives and scenarios: How to respond?) If a shortage of part type P, what to do? If an outage of machine instance M, what to do? How to respond to changing external demand? Which technologies to adopt, and when?

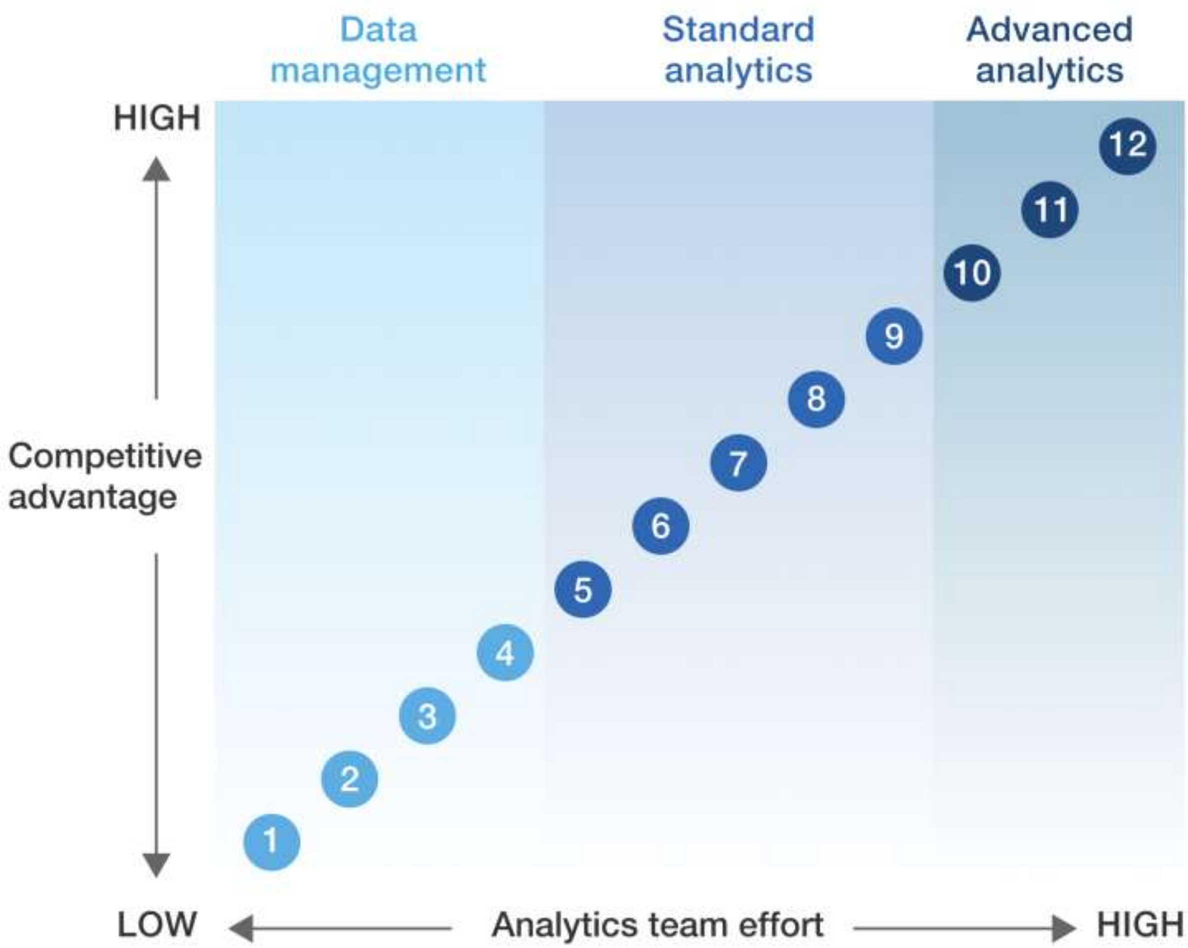
Operations Research Analysis Type	Analysis Languages	Analysis Solvers
Graph Theory, to evaluate: Connected, Acyclic, Bipartite, Order, Size, Density, Clique Number, Diameter, Walks, Paths, Subgraphs (coverings, cliques, independent sets, packings), Labelings (colorings)	DGML DotML GraphML XGMML …	QuickGraph …
Network Optimization, to evaluate: Matching, Assignment, Multi-Commodity Flow, Transportation, Circulation, Optimized Flow (max flow volume, min flow cost, …)	AMPL (structured text) OSiL (XML)	COIN-OR
PERT/CPM Analysis, to evaluate: Slack, Critical Path	BPMN	…
Petri Net Analysis, to evaluate: Reachability, Safeness, Liveness	PNML	ProM? CPN Tools?
Queueing Theory Analysis, to evaluate: Throughput, Cycle Time, Work-In-Process, Utilization, Bottlenecks	PMIF	???
Discrete-Event Simulation, to evaluate: (Arbitrary Performance Measures and Statistics)	???	JaamSim

Missing Columns:
- Specification of the Model-to-Model *Transformation*
- The Analysis Model *Formulation* (independent of data)



End-User Modeling Tool (Language)
Neutral Model Format
Analysis Modeling Tool (Language)
MagicDraw (SysML)
Enterprise Architect (SysML)
Microsoft Visio (VSM)
Export
Export
XMI
XMI Parser
Custom Office Integration
CFN
DELS
VSM
Custom MMT
Custom MMT
Custom MMT
Custom MMT
QuickGraph (various undirected & directed graph definitions)
COIN-OR (AMPL)
JaamSim (vendor-specific)
Simio (vendor-specific)
We do not make or control this
We make and control this
We do not make or control this

Advantage vs effort matrix



Data
1. Raw data
2. Clean data

Standard reporting
3. Standard reports
4. Ad hoc queries

Descriptive analytics and dashboards
5. Data filtering
6. Alerts
7. Clustering
8. Trend forecasting
9. Statistical analysis

Advanced analytics
10. Predictive analytics[1]
11. Optimization and simulation modeling
12. Prescriptive techniques

[1]Includes machine learning (supervised and unsupervised), artificial intelligence, and deep learning.

Source: McKinsey, 2018

Using SysML® and Systems Engineering for Manufacturing System Modeling

Eugenio Rios, Manufacturing & Systems Engineering
Greg Pollari, Advanced Manufacturing & Engineering Technology

MAY 2019

Transferring Engineering Data to Manufacturing

Applying New Knowledge

Problem:

Manufacturing (automated assembly lines) getting intermittent Design data for machine place parts

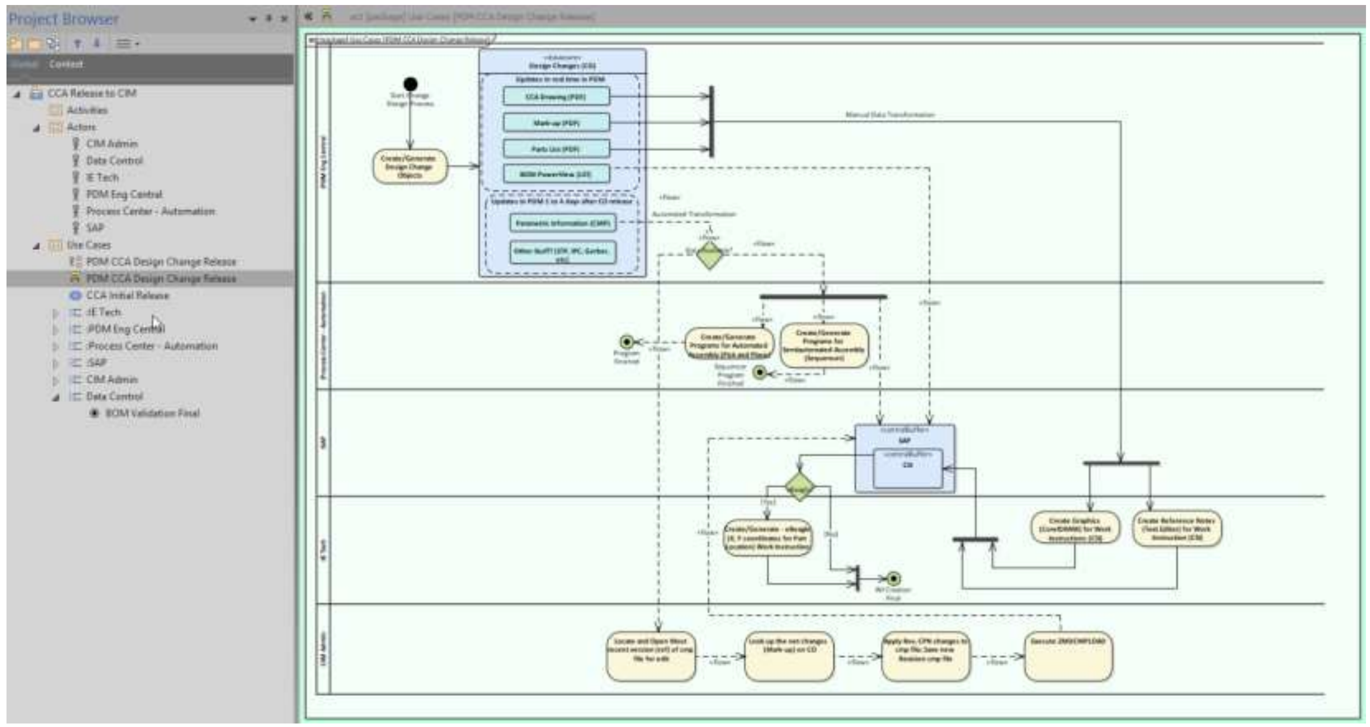
Path to solution:

- Created model of our Computer Integrated Manufacturing system to view data flow from Design Engineering to Manufacturing
- Identified gap (manufacturing data no longer produced for changes to existing products)
- Brought awareness of gap to Design Engineering through graphical view of model.
- Solution put in place

Transferring Engineering Data to Manufacturing

Journey to Modeling

Activity diagram shows data flow from Design to Manufacturing for Automated Assembly



Discovery
Uncovered Design data point of use in Assembly

A Methodology to Predict the Impact of Additive Manufacturing on the Aerospace Supply Chain

Bill Bihlman
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1 There are effectively three design/build advantages for additive manufacturing, each targeting lightweighting for aerospace

AM Design/Build Advantages

Organic Shape Optimization

Internal Lattice Configuration

*Part Consolidation**

AM (3D printing) is the process of adding material – as opposed to removing material – to create structural parts/components

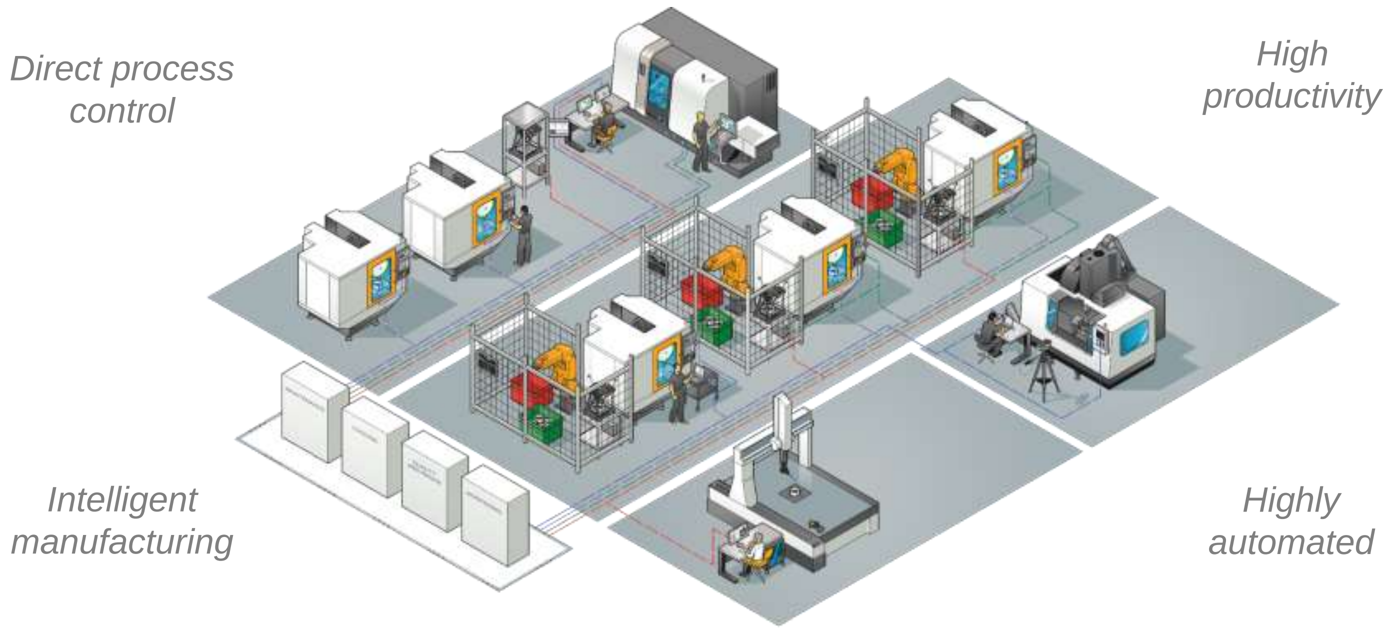
Source: secondary, GE

* GE LEAP fuel nozzle tip

1

Conclusions from this research have implications for the factory-of-the-future and Industry 4.0 at large

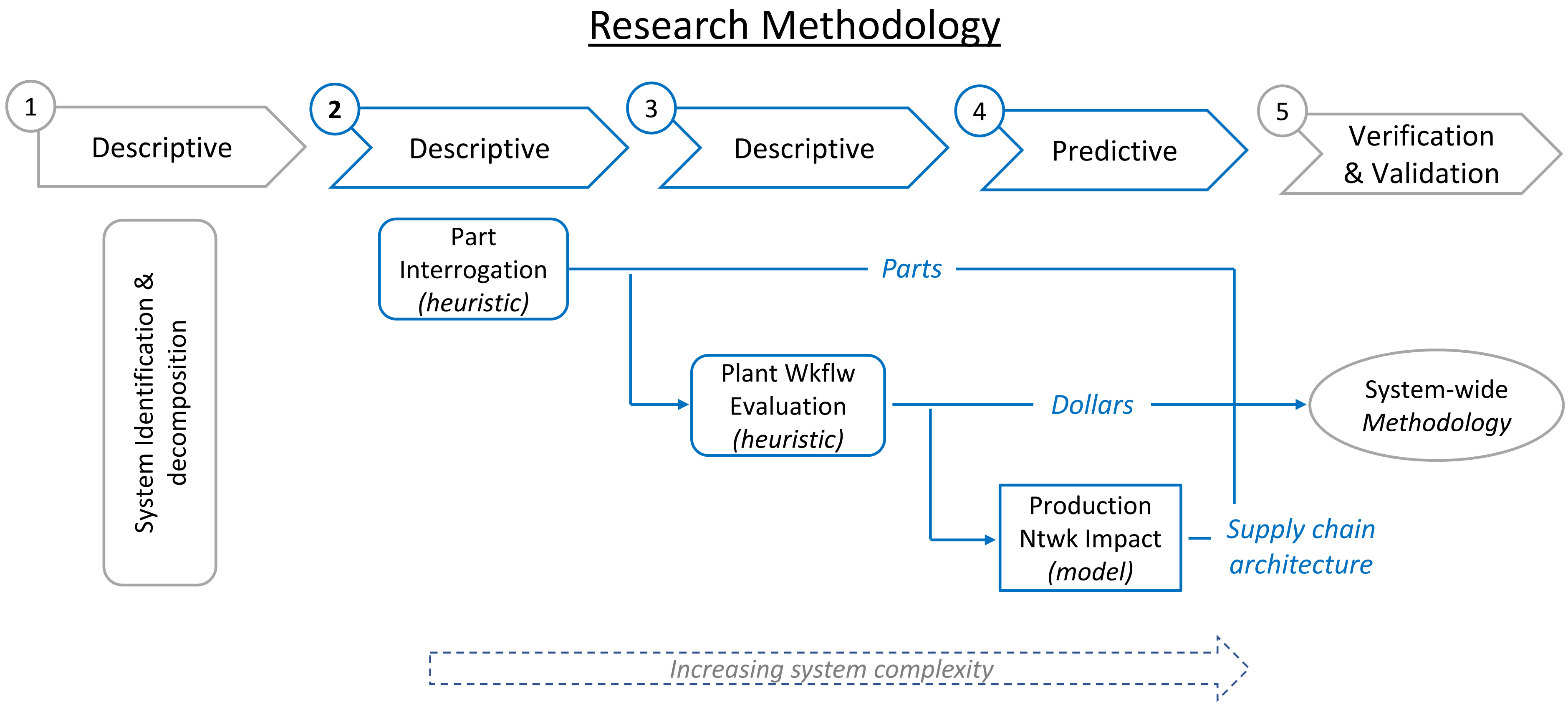
Notional Factory of the Future



Additive fits GE's business model to lead in technologies that leverage *systems integration, material science, services*, and *digital productivity*.
David Joyce, President & CEO of GE Aviation

Source: Renishaw, GE

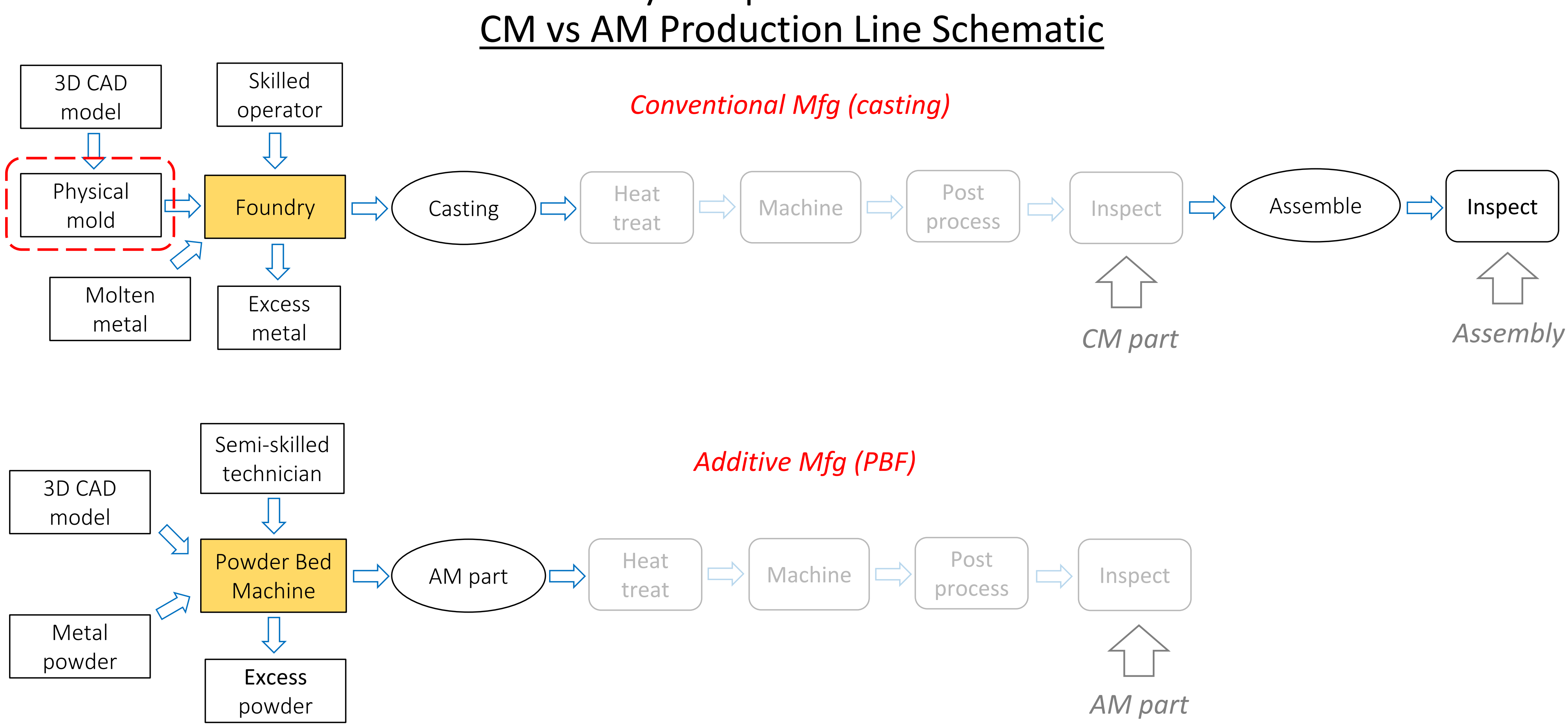
2 The methodology is a multi-step process that eventually estimates the impact on the aerospace production network



Source: desc vs pred per Hindle and Vidgen 2018

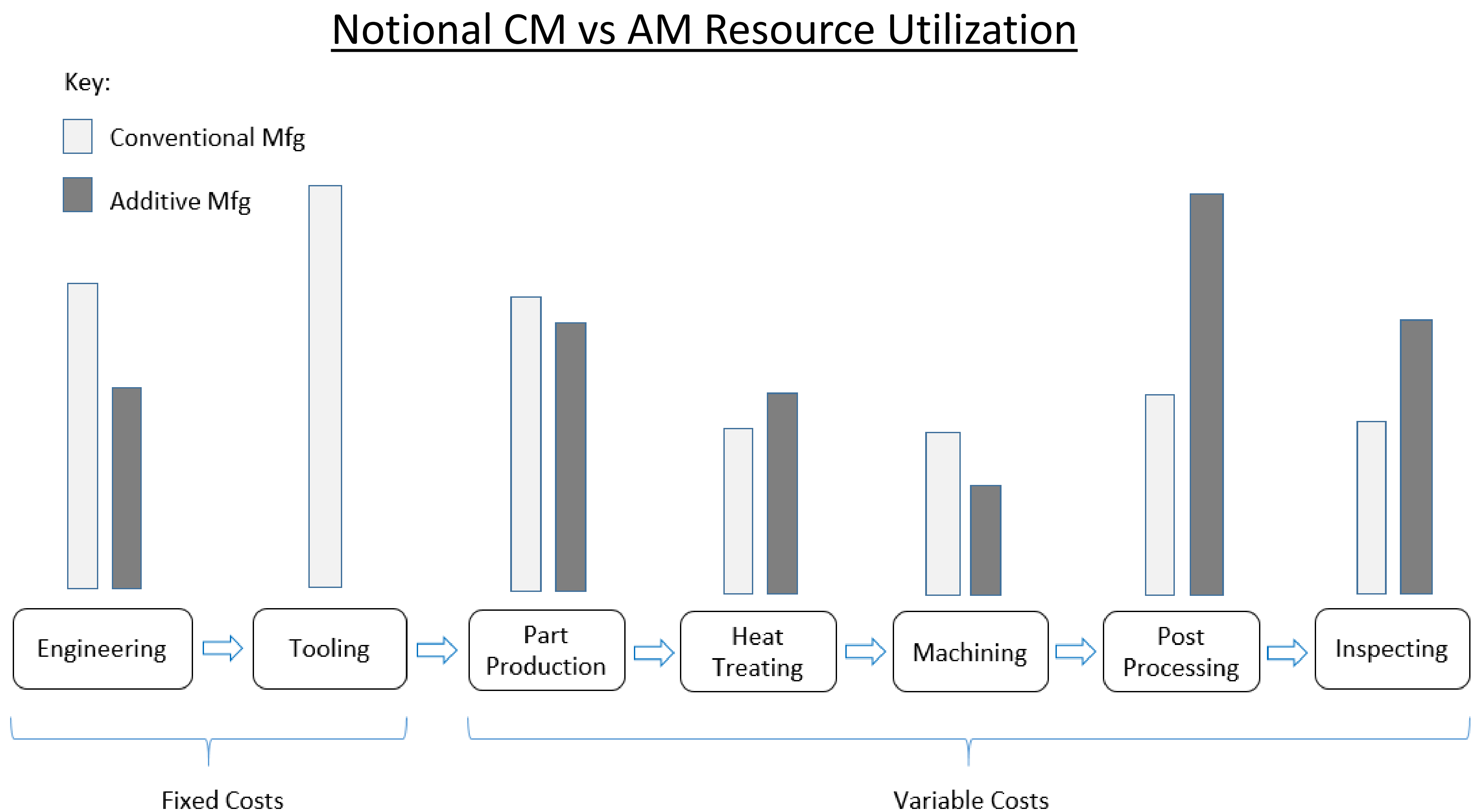
2

Conventional manufacturing includes an initial tooling step, and often a final assembly step



Source: analysis

2 In general, there are more resources consumed early during CM, whereas AM is more resource intensive towards the end of the process



Source: analysis

2020 Annual INCOSE international workshop
Torrance, CA, USA
January 25 - 28, 2020

Robert Malone

The Boeing Company

Boeing Future Production Systems Development Concepts and Approach

www.incose.org/IW2020

Presentation Outline

1. Systems Engineering Approach
2. Current State
3. Future State
4. Conclusion

Presentation Outline

1 → 2 → 3 → 4

1. Systems Engineering Approach
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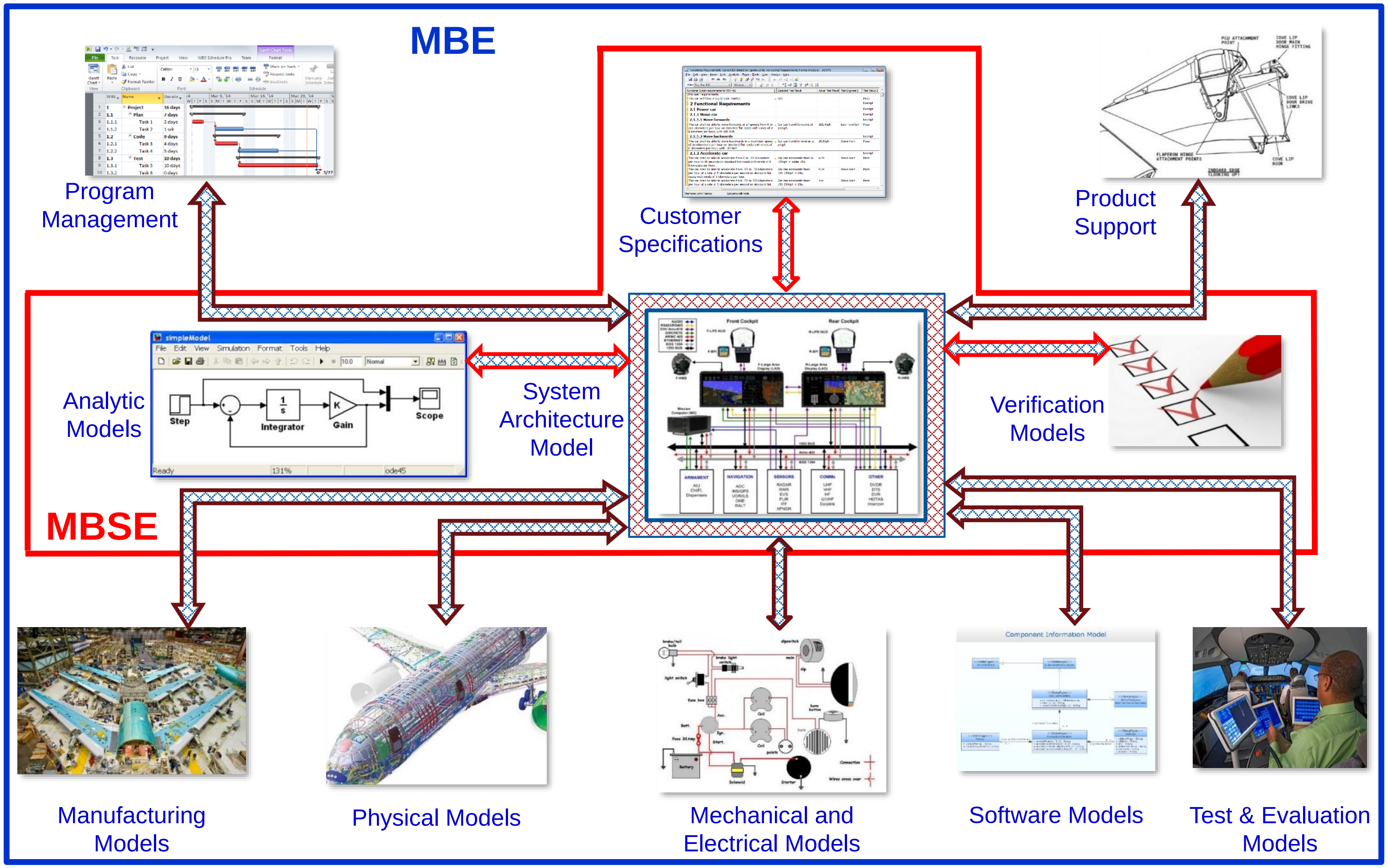
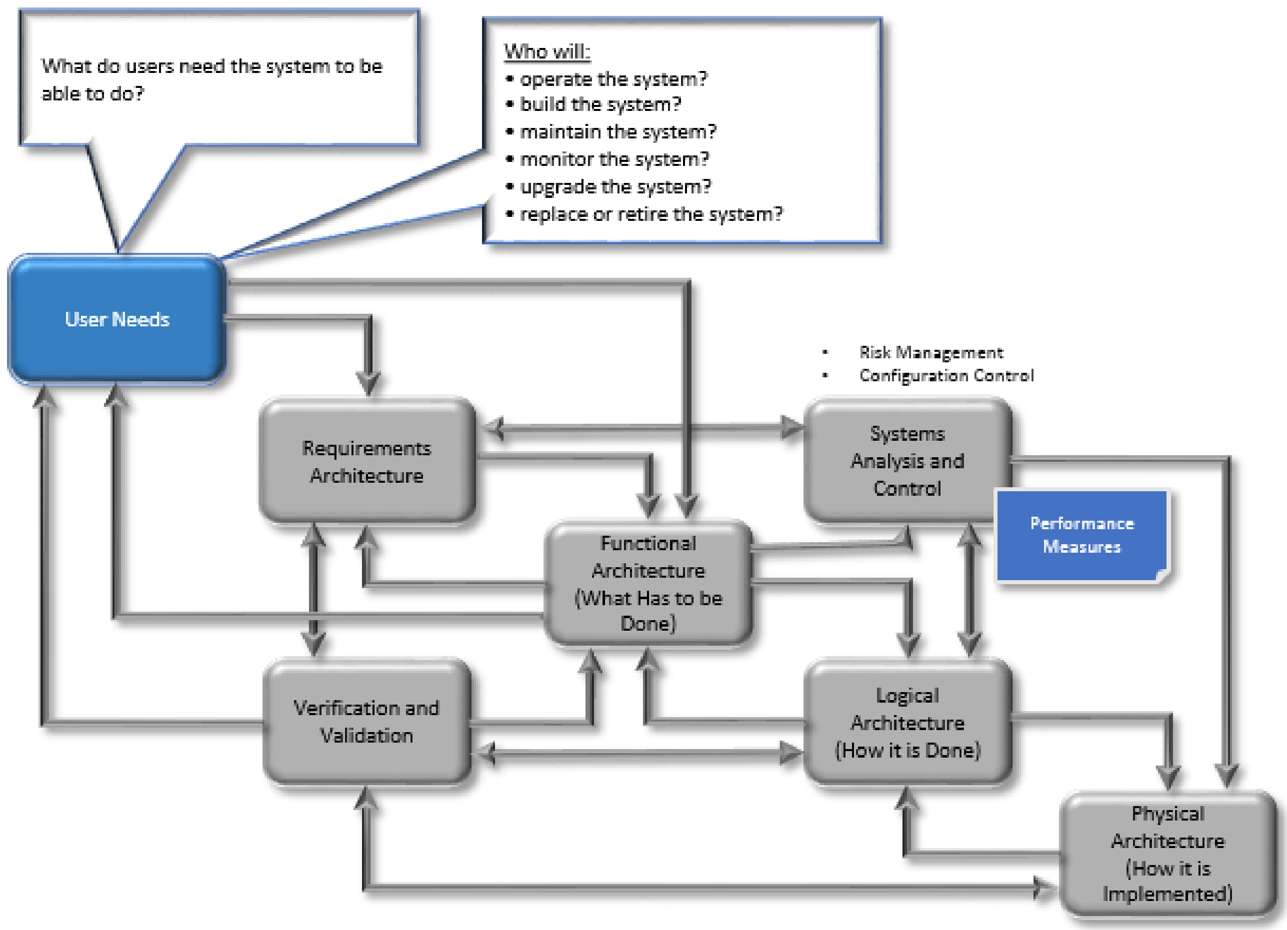
MBSE is a Set of Models



Systems Engineering Approach

- Production systems often a byproduct of product design
  - Product designed -> means of production devised
- Production systems design constrained by product design
  - Suboptimal production systems performance
- Approach for future Production Systems is to treat them as systems in their own right
  - Independent of what is being created
- Employ classic Systems Engineering (SE) approach
  - Architecture data captured as models
  - Models used to assess Key Performance Parameters (KPPs)
  - Integrate Internet of Things (IoT)
  - Develop digital twin (surrogate)

Classic Systems Engineering Approach



Presentation Outline

1 Systems Engineering Approach

2 Current State

3 Future State

4 Conclusion

Current State

- Interviews
- Common Themes from Interviews
- Areas for Improvement Identified in Interviews

Current State

- Interviews
  - User needs gathered during seven interview sessions
  - Interviewees executive stakeholders
  - Moderators experienced production and systems engineers
  - Catalyst questions
    - “What does the production system need to accomplish to be successful”
    - “What prevents our success today”

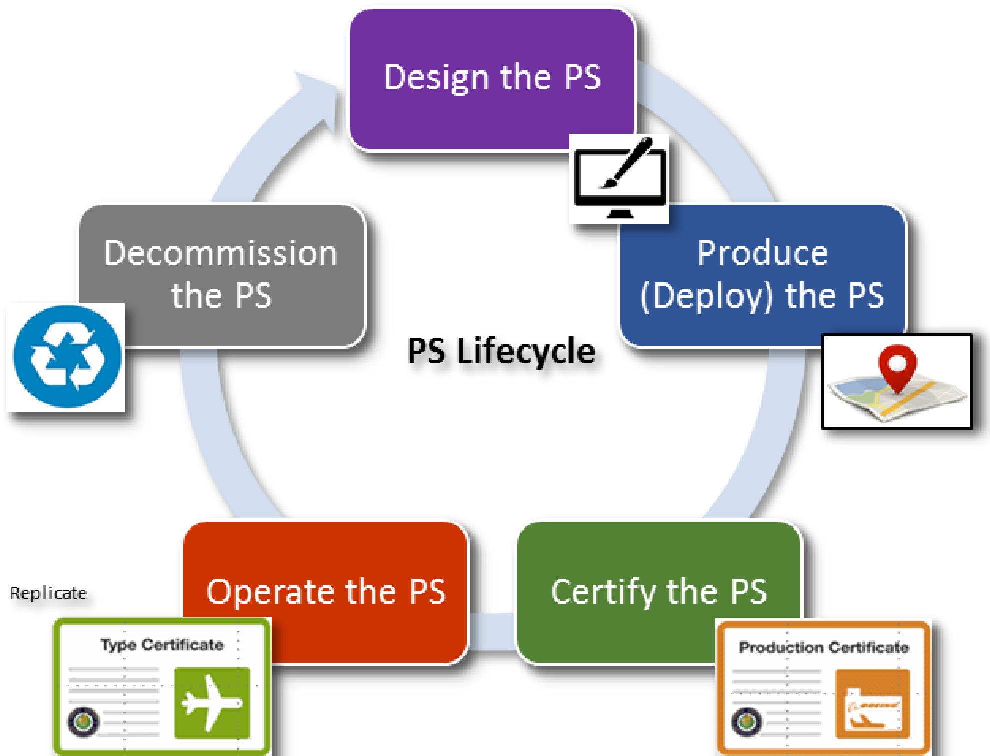
Current State

- Common Themes from Interviews
  - Production Systems Definition: Systems that transform raw materials (using people, processes, assets and information) into finished products, delivers the finished products to customers, and supports the finished products in service.
  - Mission: Produce and support Boeing platform products throughout their operational lifecycle.
  - Recursive operational lifecycle
  - Valued Production Systems Characteristics
    - Quality
    - Stability and repeatability
    - Flexibility and adaptability
    - Productivity

Current State

- Common Themes from Interviews
  - Valued Production Systems Characteristics
    - Quality
      - Quality through inspection during and quality instilled through process control
      - Enable manufacturing teams to readily differentiate normal and non-normal build processes
    - Stability and repeatability
      - Efficiency and repeatability, both in terms of the process steps that are executed, and in the overall execution time
      - Detailed understanding of the variables that contribute to process variability (including an understanding of acceptable variability)
    - Flexibility and adaptability
      - Ensure the Production System is designed and configured to be able to handle uncertainty
      - Designed-in level of resilience to support adaptability and flexibility
    - Productivity
      - Unit of output per unit of input
      - Quality, process reliability, dispatch reliability, and operational availability all impact productivity by either reducing units of output (delivered product) or increasing the units of input (cost)
      - Extended process times engendered by low process and dispatch reliability, and low operational availability, increase the resources required to produce a unit of output, since the resources are unnecessarily deployed longer to produce the same output

Production Systems Operational Lifecycle



Current State

- Areas for Improvement Identified in Interviews
  - Process Reliability
    - Standard process execution times are necessary
  - Resiliency
    - Achieve the same rate of production regardless of changes to Production System inputs
    - Ability to anticipate upcoming disruptions, and be able to be flexible in the face of disruptions and adapt effectively to disruption
  - Verification and Validation
    - Reduce manual inspection and associated costs by making equipment and production processes reliable to the point that quality products ensured though the use of these equipment and processes
  - Logistics
    - Includes entire value stream: part flow; materials and traffic management internal to facilities; external logistics from the suppliers; and, logistics between suppliers
    - Reduce logistics inefficiencies
    - Greater emphasis on logistics design and architecting with impacts of sourcing decisions traded against overall Production System performance

Presentation Outline

1	2	3	4
Systems Engineering Approach	Current State	Future State	Conclusion

Future State

- Development and Design Concepts
- Metrics
- Approach
- Improving Production Systems Performance using Digital Twins

Future State

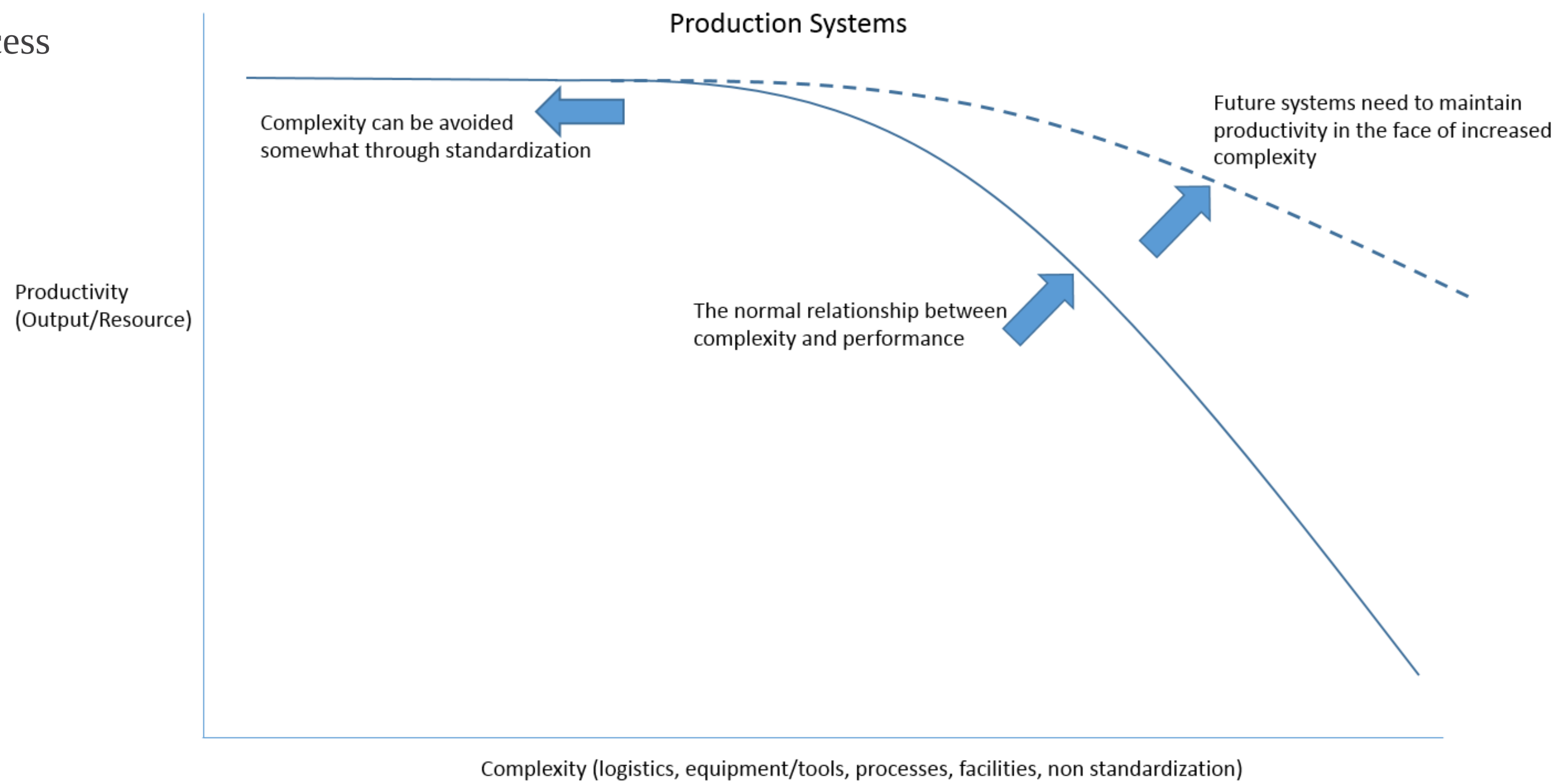
- Development and Design Concepts
  - Resiliency (Vaneman, 2014)
    - Ability to adapt to changing conditions (natural and man-made), and rapidly recover from adverse events and disruptions
    - Resilient architectures can maintain necessary operational functions, with high probability of success and shorter periods of reduced capabilities gated process incorporation:
      - Avoidance
      - Robustness
      - Recovery
      - Reconstitution

Development and Design Concepts

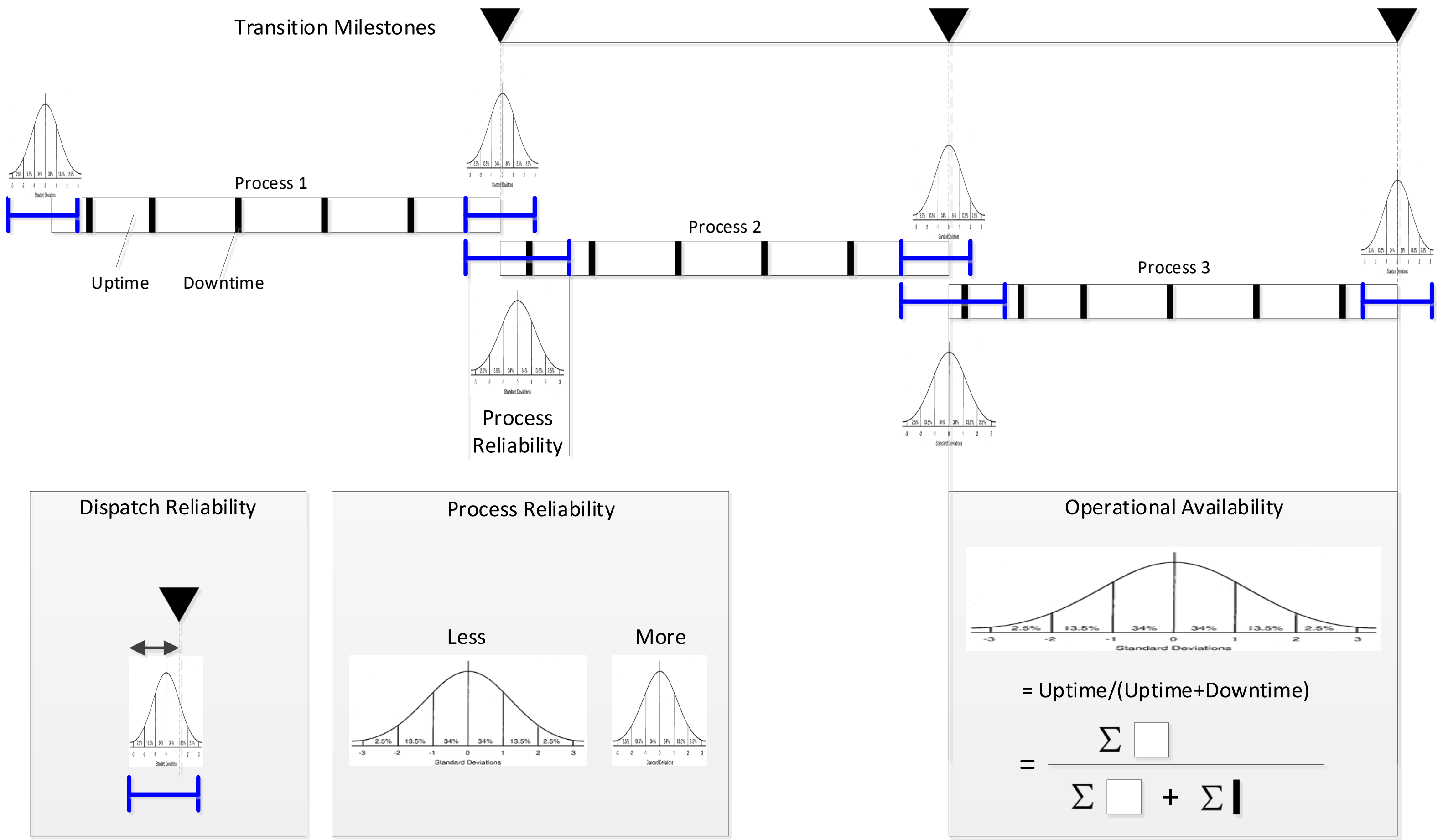
- Production System Productivity vs. Complexity

- PS complexity increases, productivity decreases (Sarkis, 1997)
- Caused by decrease in process reliability?

<u>Notional Curve</u>



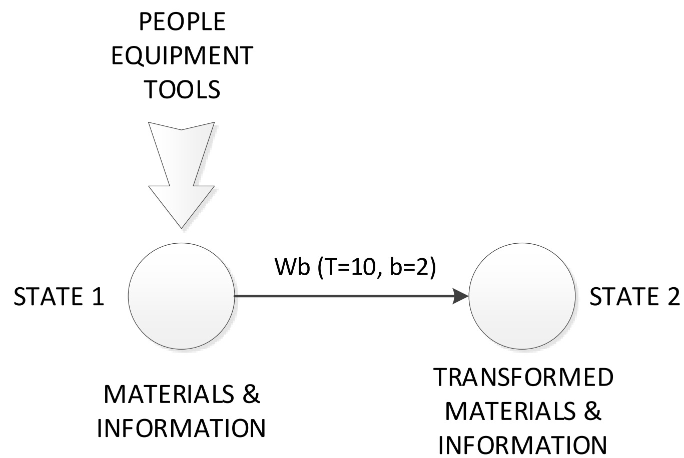
Metrics


Transition Milestones
Process 1
Process 2
Process 3
Uptime
Downtime
Process Reliability
Dispatch Reliability
Process Reliability
Less
More
Operational Availability
= Uptime/(Uptime+Downtime)
=
Σ
Σ
+
Σ

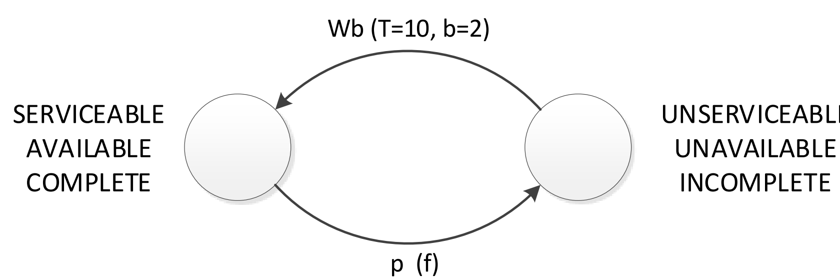
Approach

- Discrete Event Models to Analyze Process Reliability and Operational Availability

- Nature of production system processes makes them amenable to discrete event (state-transition) modeling
    - (Lefranc (1998), Long, Zeiler, & Bertsche (2016)
    - Long, Zeiler, & Bertsche (2018)
    - van der Aalst (1994)
    - Zhou and Venkatesh (1999)).



a. Process Reliability



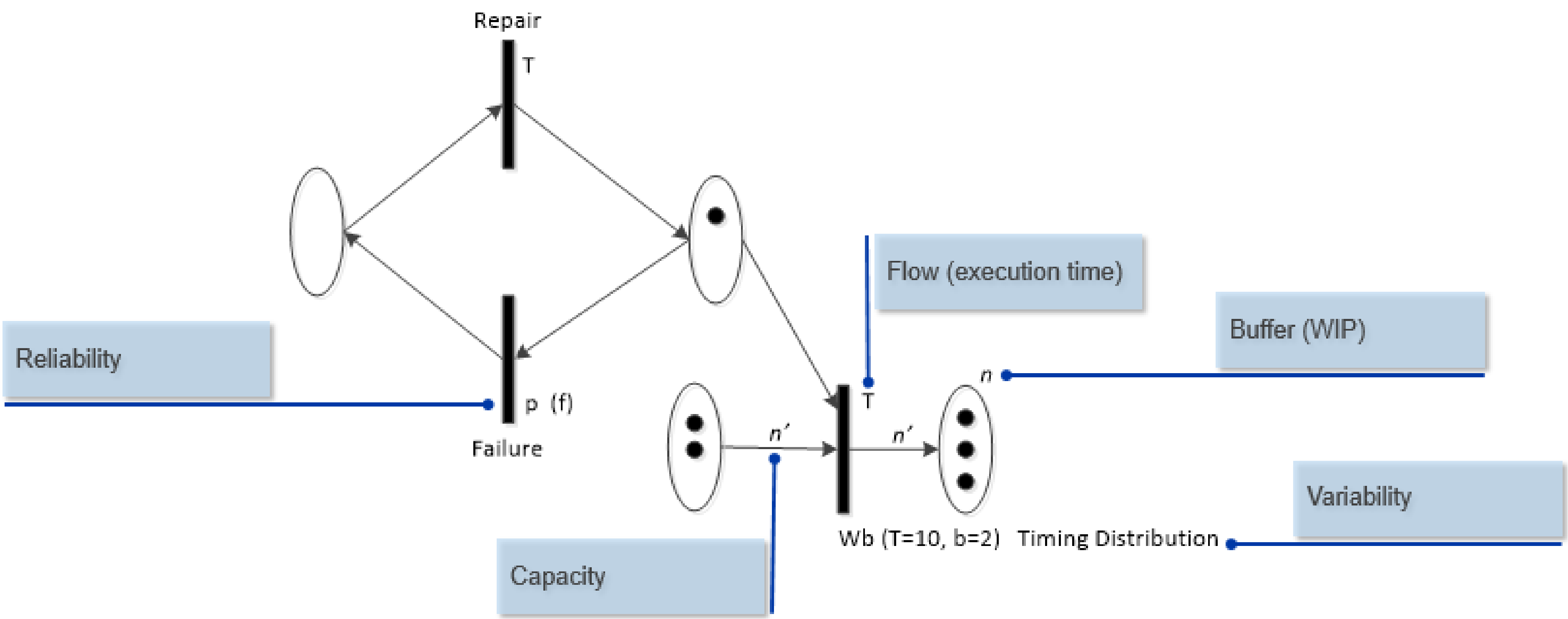
a. Operational Availability

Future State

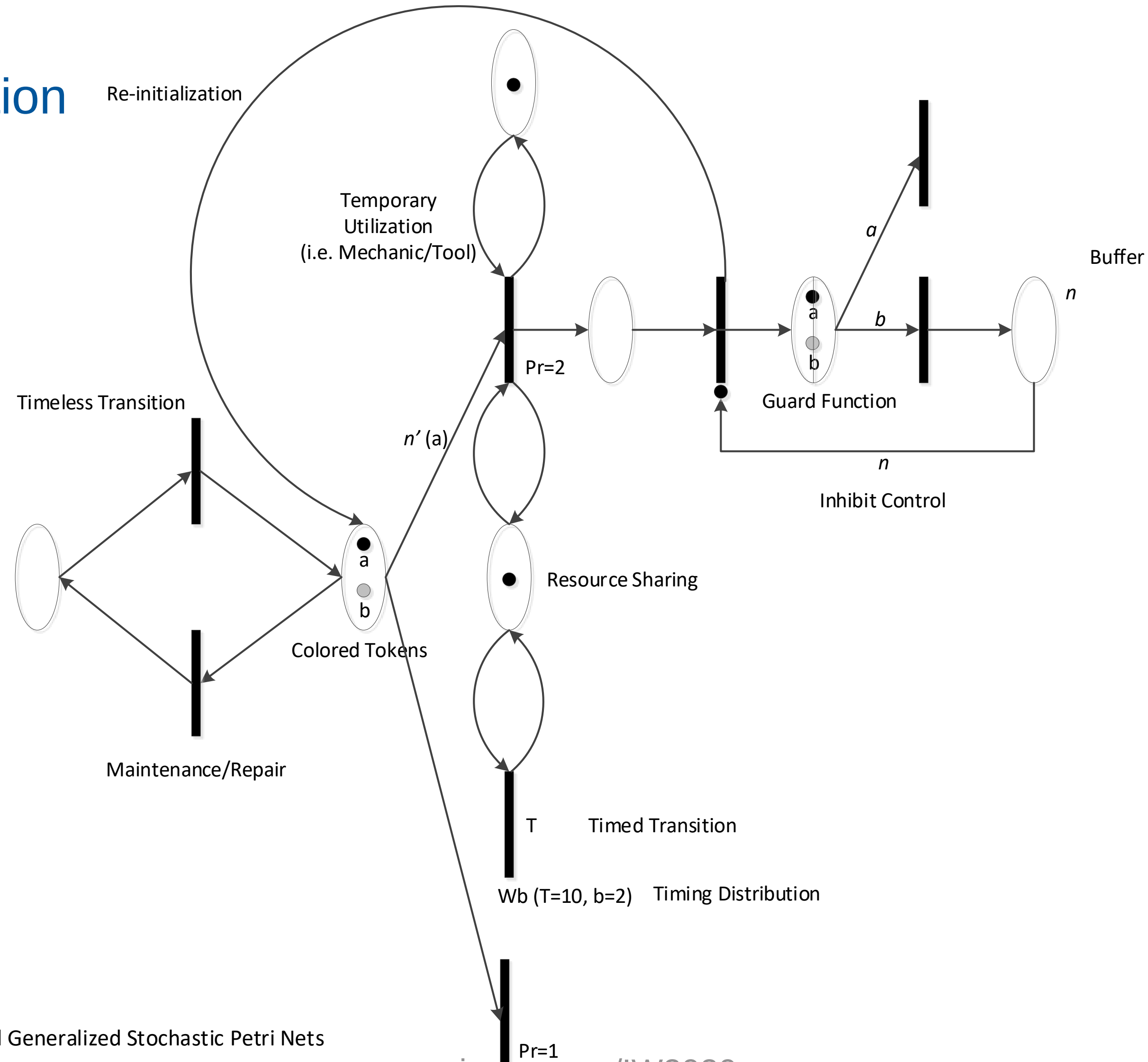
- Improving Production Systems Performance Using Digital Twins
  - Convert discrete event network models to digital twin of deployed Production System
  - Estimates in models replaced with actual in-service data, increasing the validity of the models
  - Increased value of models in developing future iterations of Production Systems

Petri Net Analysis Parameters

All parameters are assessed concurrently when model analysis executed

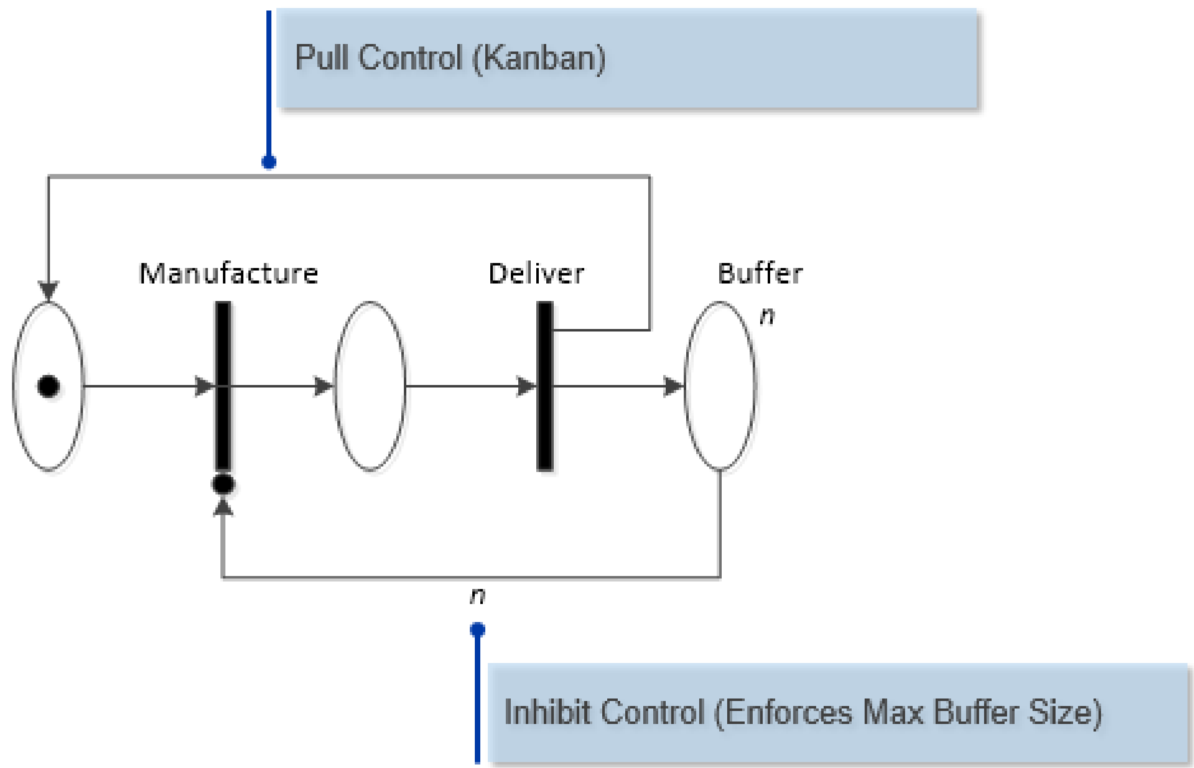


Petri Net
Resource Competition



Colored Generalized Stochastic Petri Nets

Petri Net Production System Control Constructs



Presentation Outline

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Conclusion

- Production systems performance improved by treating them as systems in their own right
- Production systems development and design will be more successful if guided by a rigorous set of SE processes

References

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Questions?

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