Model-Based Systems Engineering for Design-to-Production Transition

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GLOBAL PRODUCT DATA INTEROPERABILITY SUMMIT 2014

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In both commercial and military markets, designing a modern aircraft is a daunting challenge, engaging many technical disciplines, across many organizations, to specify millions of product features and behaviors. In a very similar way, designing the manufacturing enterprise which will produce the aircraft also is a daunting challenge, engaging many technical and business disciplines, across many organizations, to specify the millions of discrete operations which support and execute production activities, and how they will be managed and controlled. For these kinds of difficult challenges, Model-Based Systems Engineering (MBSE) is emerging as a key technology for mitigating the problems of data inconsistency, communication failure, and cost of decision support analysis, with the potential to reduce time and cost, and improve results.

This presentation will summarize the process and findings of a three year investigation into the potential for MBSE to improve the design-to-production transition for a modern aircraft. Specifically, our team developed novel ideas for:

- Using leading-edge ideas from computer science to enable standards-compliant data on products and processes to be integrated with production ramp data to automate the creation of production system configuration and analysis models;
- Using leading edge computational platforms and semantic web concepts and tools to identify, evaluate, and if appropriate, correct data inconsistencies across multiple program databases;
- Using state-of-the-practice system modeling tools to add effective automation for creating the ergonomic simulations essential for designing manual production operations; and
- Using newly emerging visualization concepts and tools to make very large, very complex systems and their models more easily consumed and understood by key decision makers.

OMG SysML™ is a foundational technology for the work reported here, which has been conducted by faculty and students from the Aerospace, Industrial, and Mechanical Engineering Schools at Georgia Tech, with close collaboration by The Boeing Aerospace Company.

Agenda

- **Overview MBSE at GT**
- **Design-to-Production (D2P): Issues & Strategy**
- **Ergonomic Analysis & Simulation**
- **Production System Simulation**
- **Inconsistency Management (see Herzig, *et al* talk after lunch)**
- **Future Research**
- **Q&A**

Model-Based Systems Engineering Center

- **Director**
  - **Chris Paredis (ME) — MBSE, value-driven SE, methodology**
- **Associate Directors**
  - **Leon McGinnis (ISyE) — MBSE, OR, mfg, logistics**
  - **Russell Peak (AE) — MBSE, SysML, tool integration**
- **Associated ...**
  - **Carlee Bischop (G... ...tion, aerospace systems**
  - **Jason Brown (Arch) — MB... ...tems**
  - **Tommer Ender (GTRI) — MBSE, trad... DoD**
  - **Brian German (AE) — Value-driven SE, aerosp... systems**
  - **Doug Bodner (IPAT) — Socio-technical, organization simul.**
  - **Julie Linsey (ME) — Socio-technical, creativity, cognitive**

MBSE broadly-based at GT

MBSE as We Understand It

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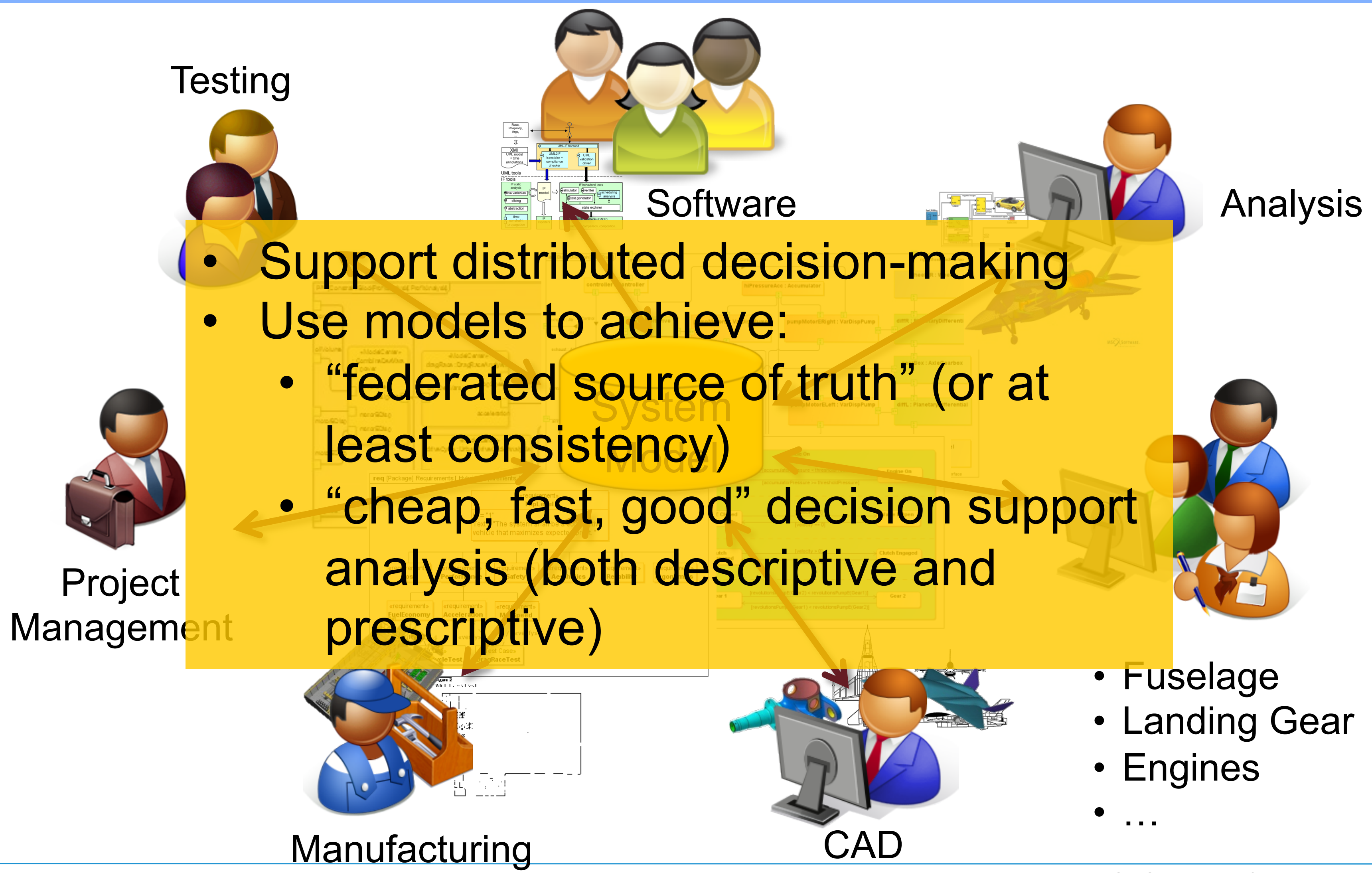
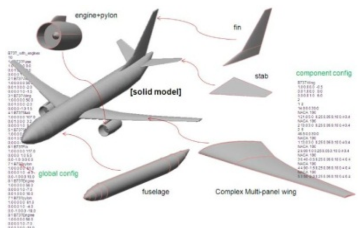


- Support distributed decision-making
- Use models to achieve:
  - "federated source of truth" (or at least consistency)
  - "cheap, fast, good" decision support analysis (both descriptive and prescriptive)

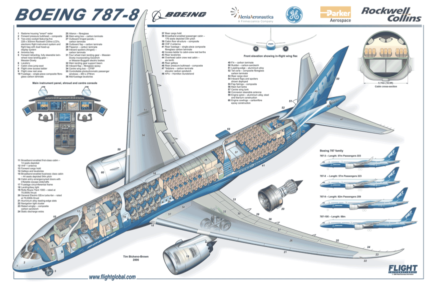
MBSEC Activities

- Research Domains
  - Manufacturing
  - Automotive
  - Heavy equipment
  - Space systems
  - Defense systems
  - Energy systems
- Education
  - Undergrad, graduate, professional masters, and executive education
  - MBSE with SysML
  - Value-driven SE
- Sponsors & Collaborators
  - *Lockheed Martin*
  - *DARPA — iFAB*
  - JPL
  - *GE Energy*
  - *Boeing*
  - *Rockwell Collins*
  - John Deere
  - Siemens
  - Ford
  - *United Technologies*
  - National Science Foundation
  - Systems Engineering Research Center

Context & Vision—What Is D2P?



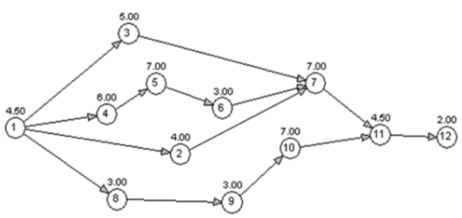
Concept to Detail



D2P

D2P Translation:
early, often, integrated

D2P



Concept to Detail

777 production line (Gail Hanusa/Boeing)

What Makes D2P Difficult?

- Integration across many knowledge domains
- Large amount of knowledge to be considered
- Strong dependence on tacit knowledge
- Short lifetime of some knowledge
  - Quickly outdated due to economic and technological changes

MBSEC D2P Research Agenda

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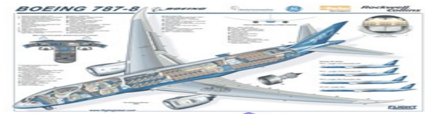
Concept to Detail



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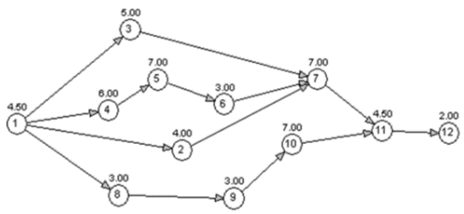


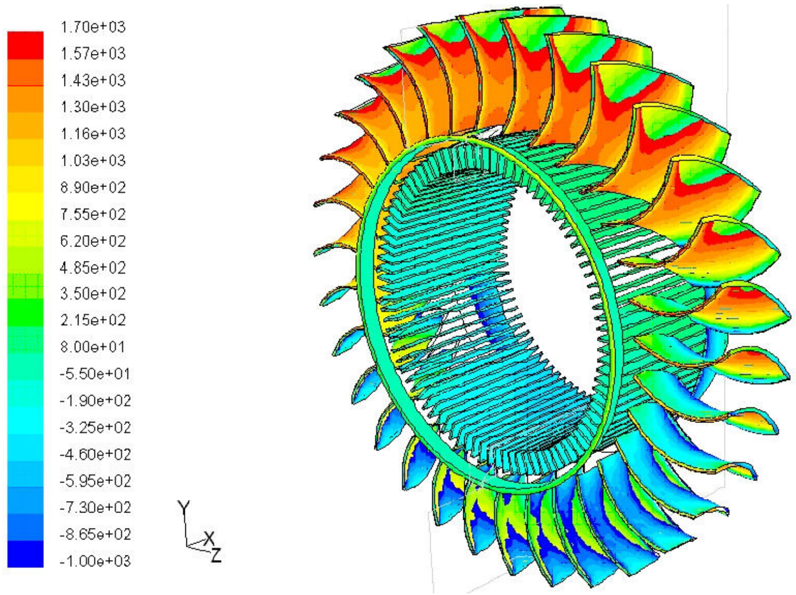
Concept to Detail

777 production line (Gail Hanusa/Boeing)

Issues:
- Ergonomics
- Production system configuration across ramps
- Information consistency across disciplines and time

Strategies:
- Cost/time for ergonomic analysis & simulation
- On-demand production system analysis using DES
- Inconsistency detection & remediation

A Useful Analogy



Standard reference architecture for 3D models

Canonical form for analysis

Generic method to extract data from an instance of 3D model and use it in an instance of the analysis

Analysis results displayed in the instance of the source 3D model

This is the kind of decision support we want for D2P.

Supporting Ergonomic Analysis

- **From checklists to requirements verification**
- **Ergonomic simulation with Jack**

Primary Contributors for this Topic

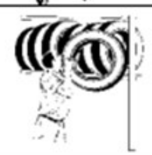
Boeing PI:	Michael Christian
Georgia Tech PI:	Russell Peak (AE/ASDL)
Research Engineers:	Selcuk Cimtalay, Miyako Wilson
Undergraduate Students:	Ryan Andersen, Rohan Deshmukh, Ivan Gomes, Stephanie Macleod

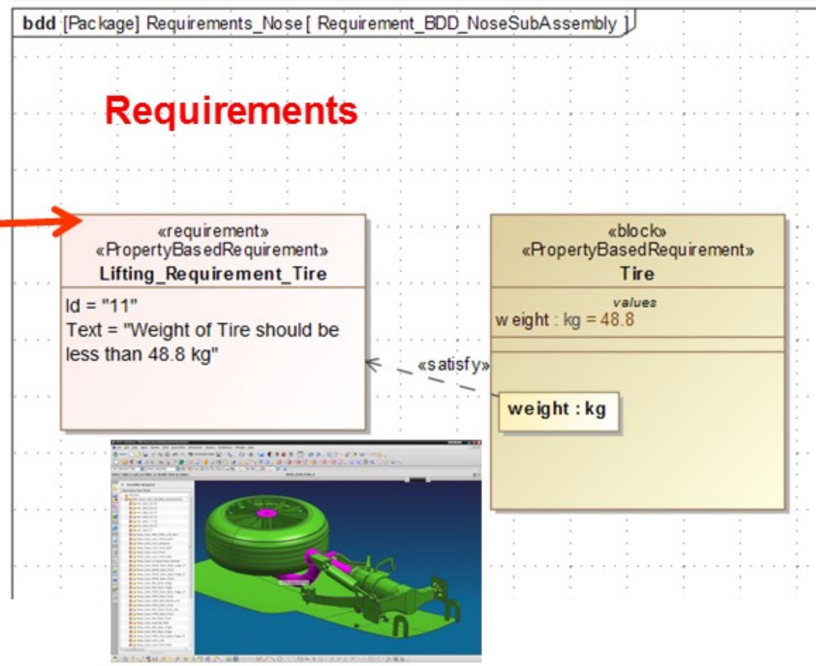
Tools for Ergonomics Work

Purpose	Tools	Company
System Modeling	MagicDraw 17.0.3	NoMagic
Ergonomics Analysis	Jack 7.1 & 8.0.1	Siemens
Integration/Automation	Model Center 10.2 & 11.0	Phoenix Integration
System Modeling Integration	MBSE Pak Plug-In 2.0	Phoenix Integration
SysML Parametrics Equation Solving	ParaMagic 17.0.2	InterCAX
CAD –Design/Assembly (Parameterization & Standardization)	NX 8, 8.5 ; SolidWorks 2011	Siemens, Dassault

From Checklist to Requirements Verification

Safety Checklist

Heavy, Frequent or Awkward Lifting (A simple scale can be used to determine the weight of materials)		
	**10.** Lifting object weighing more than 75 pounds once per day or more than 55 pounds more than 10 times per day.	☐
	**11.** Lifting objects weighing more than 10 pounds if done more than twice per minute, more than 2 hours total per day.	☐
	**12.** Lifting objects weighing more than 25 pounds above the shoulders, below the knees or at arms length more than 25 times per day.	☐



- Safety checklist is conservatively transformed into requirements. Parts' weight property should be satisfied by weight requirement.
- System model links requirements to structure element block(part) and its value (weight).
- Automatic and flexible checks can be done via MBSE Pak plug-in

Translate Checklist to Requirements

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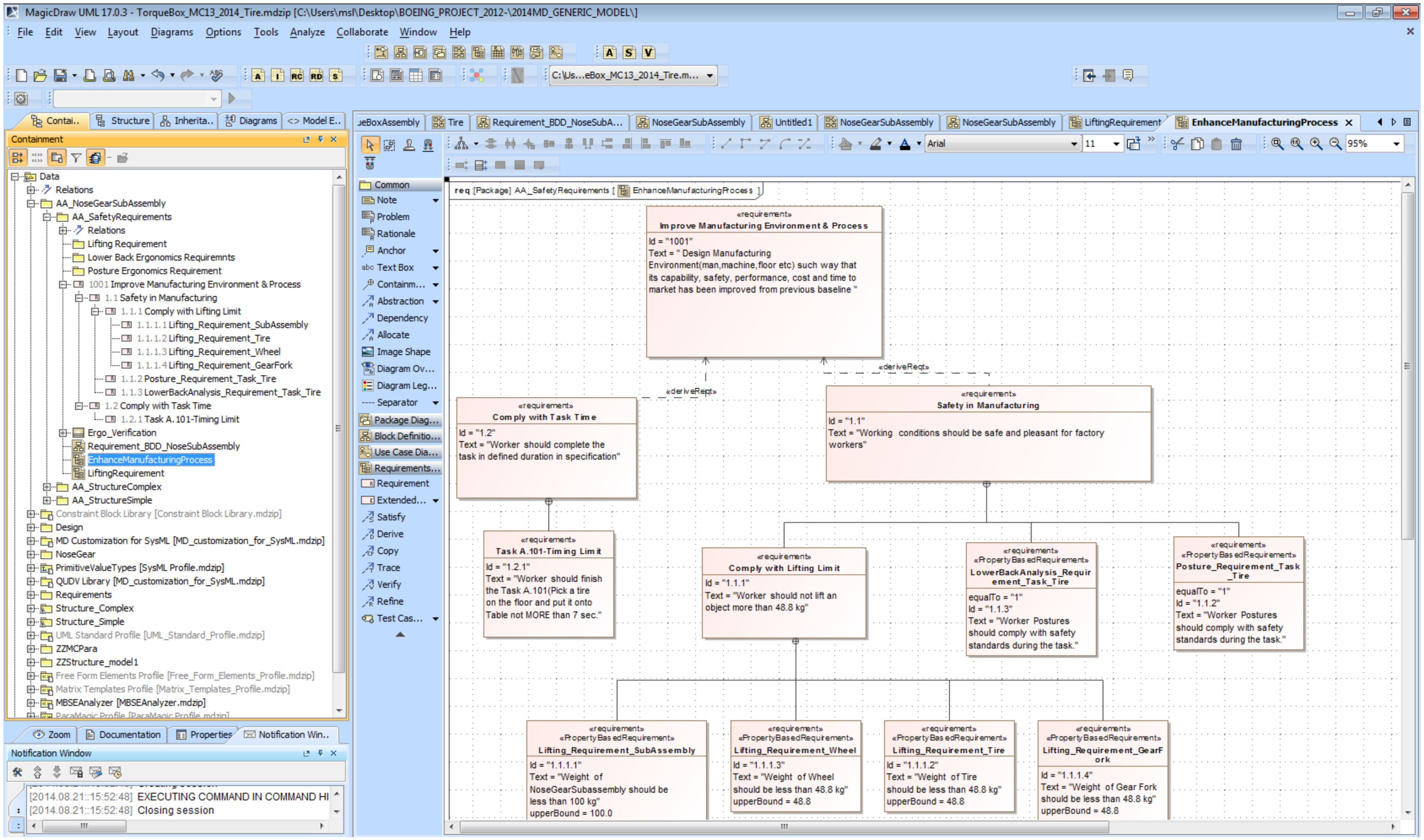

Link Product Design to Requirements

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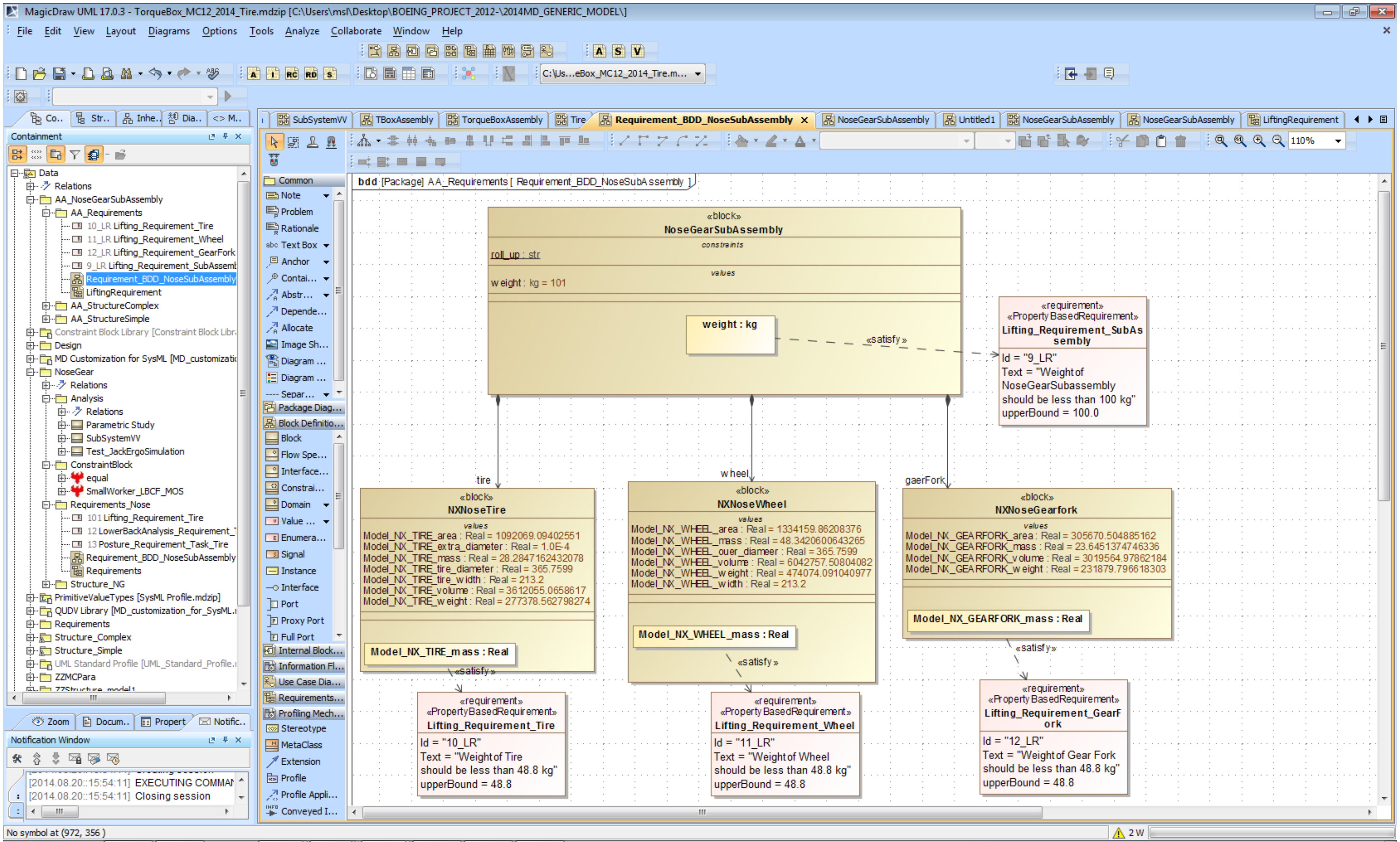

Link CAD Model to SysML Model

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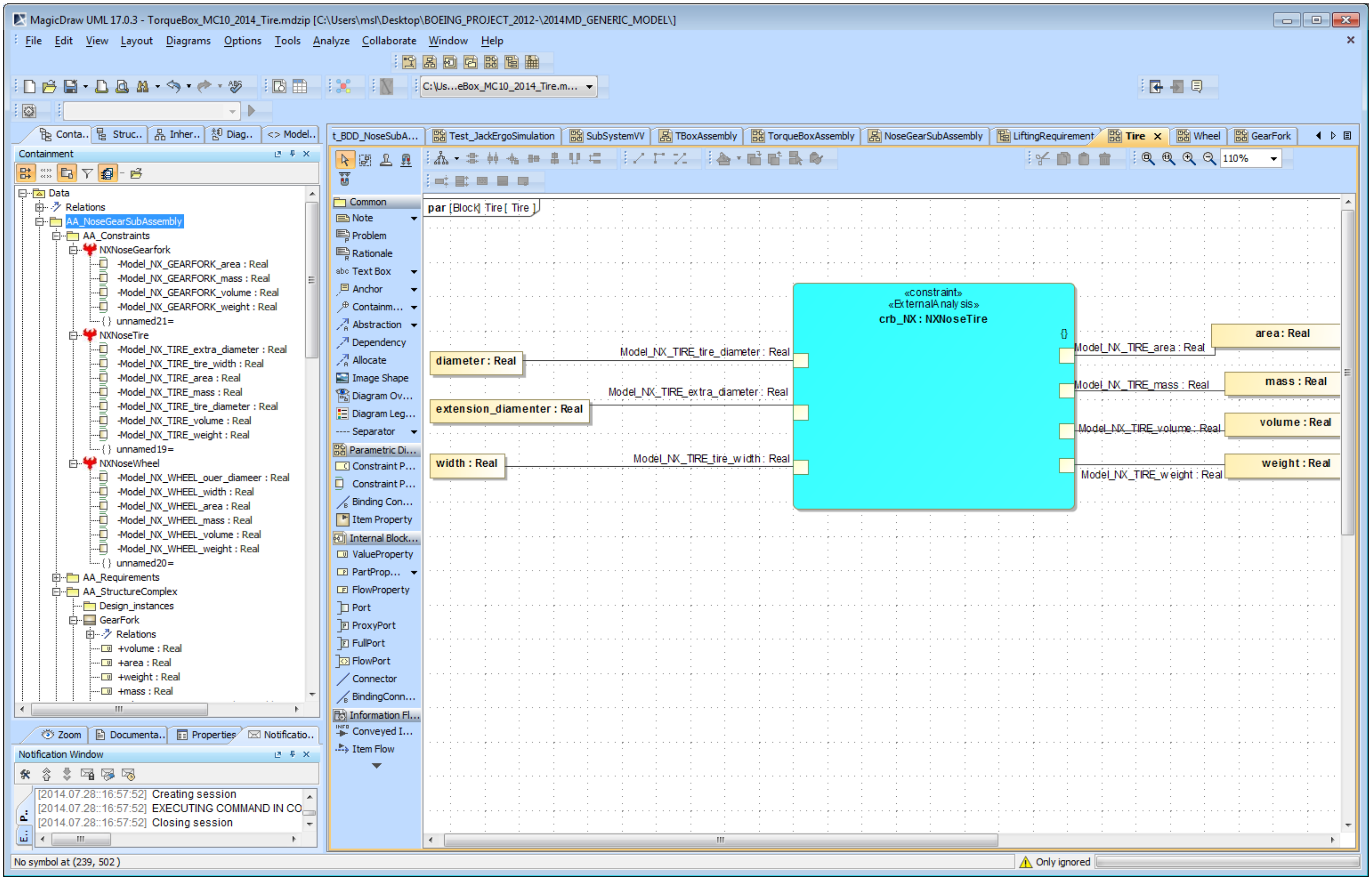

Analyze Conformance Using MBSEPak

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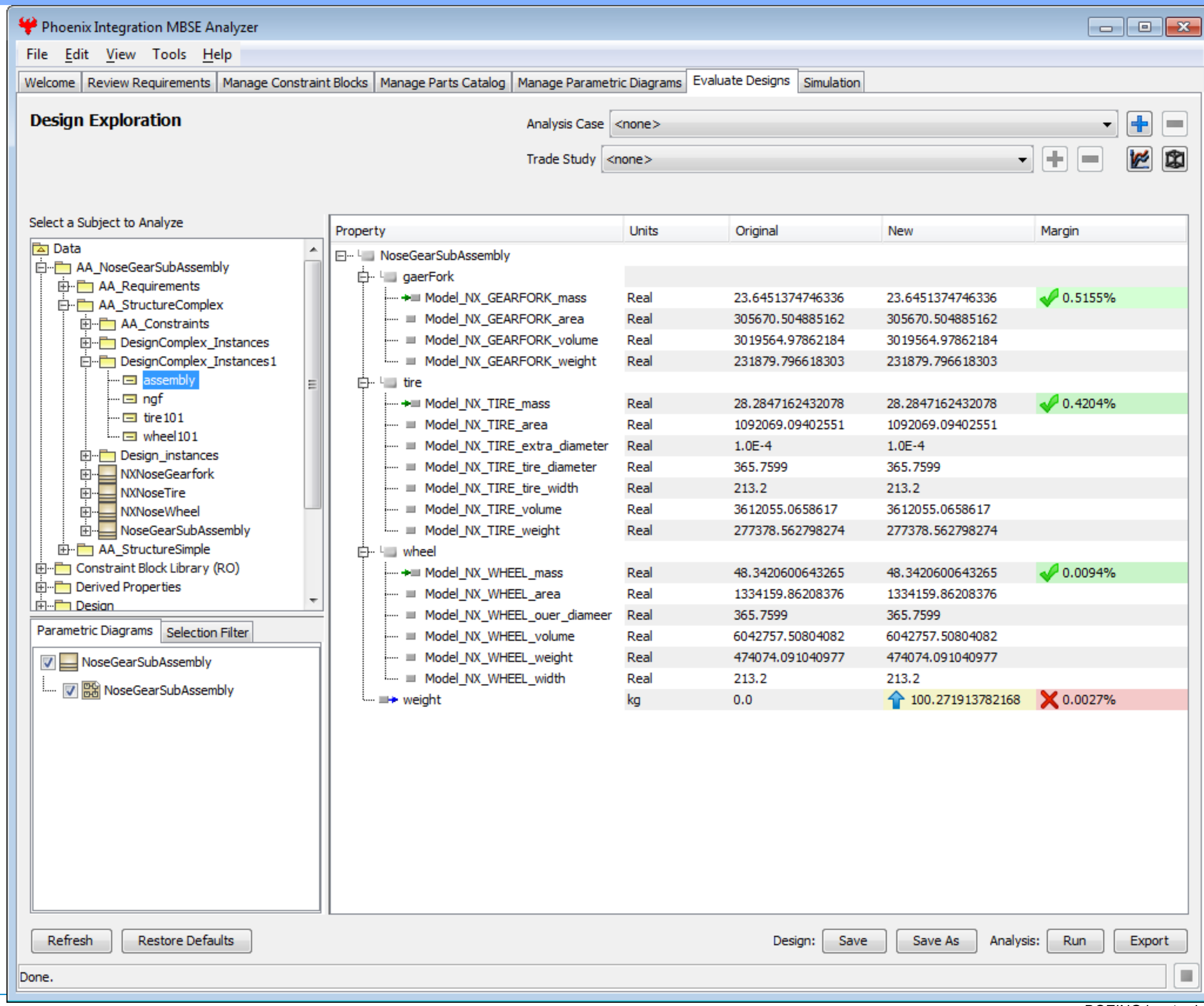

Ergonomic Simulation with Jack

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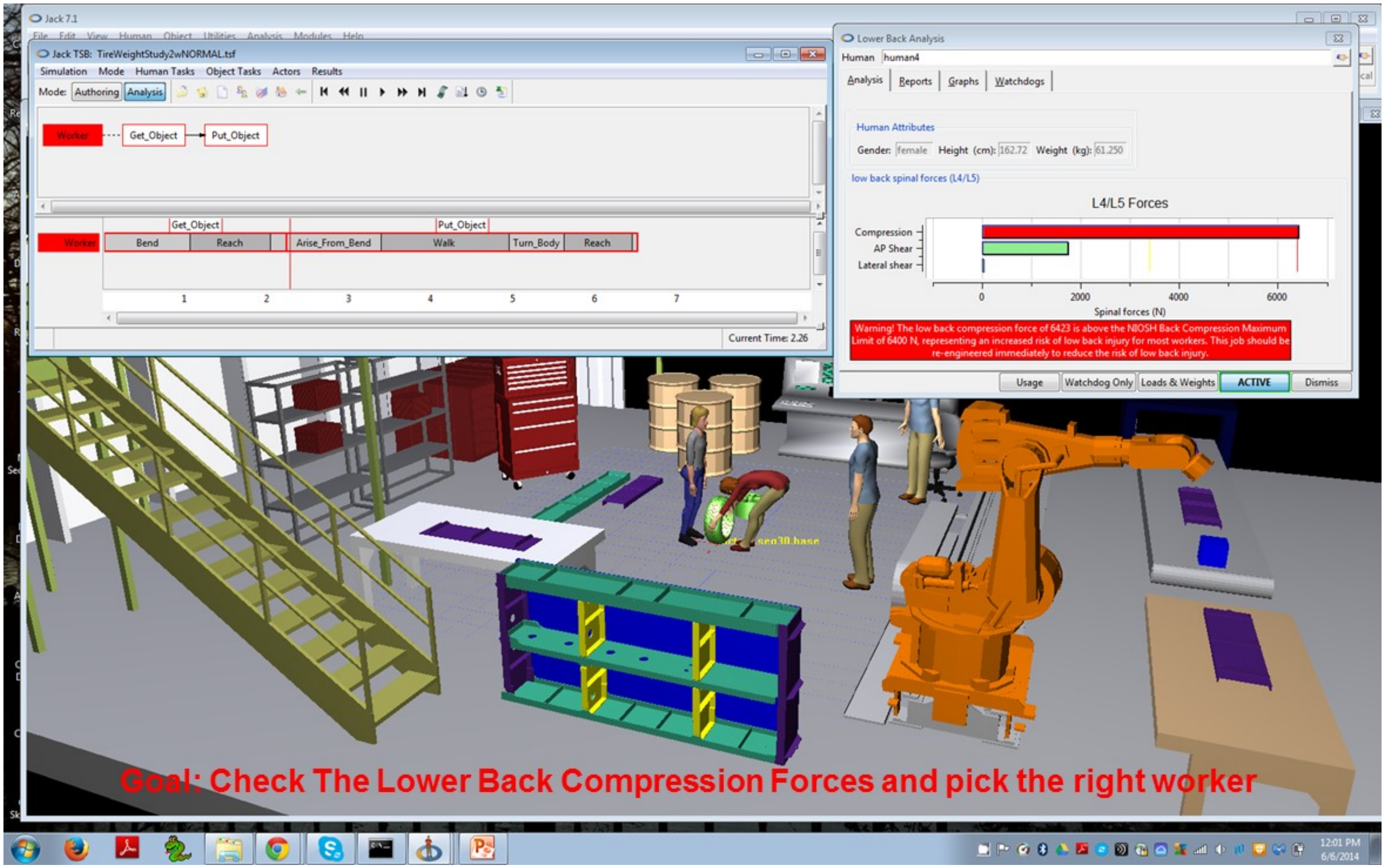

Just Two Problems

- **Creating the simulation**
  - **Very time consuming to create the models**
  - **Integrating product data, process data, resource data, workstation configuration data**
- **Interpreting the results**
  - **Forces computed at every simulated time step**
  - **Can be quite voluminous**

Using Jack Simulation

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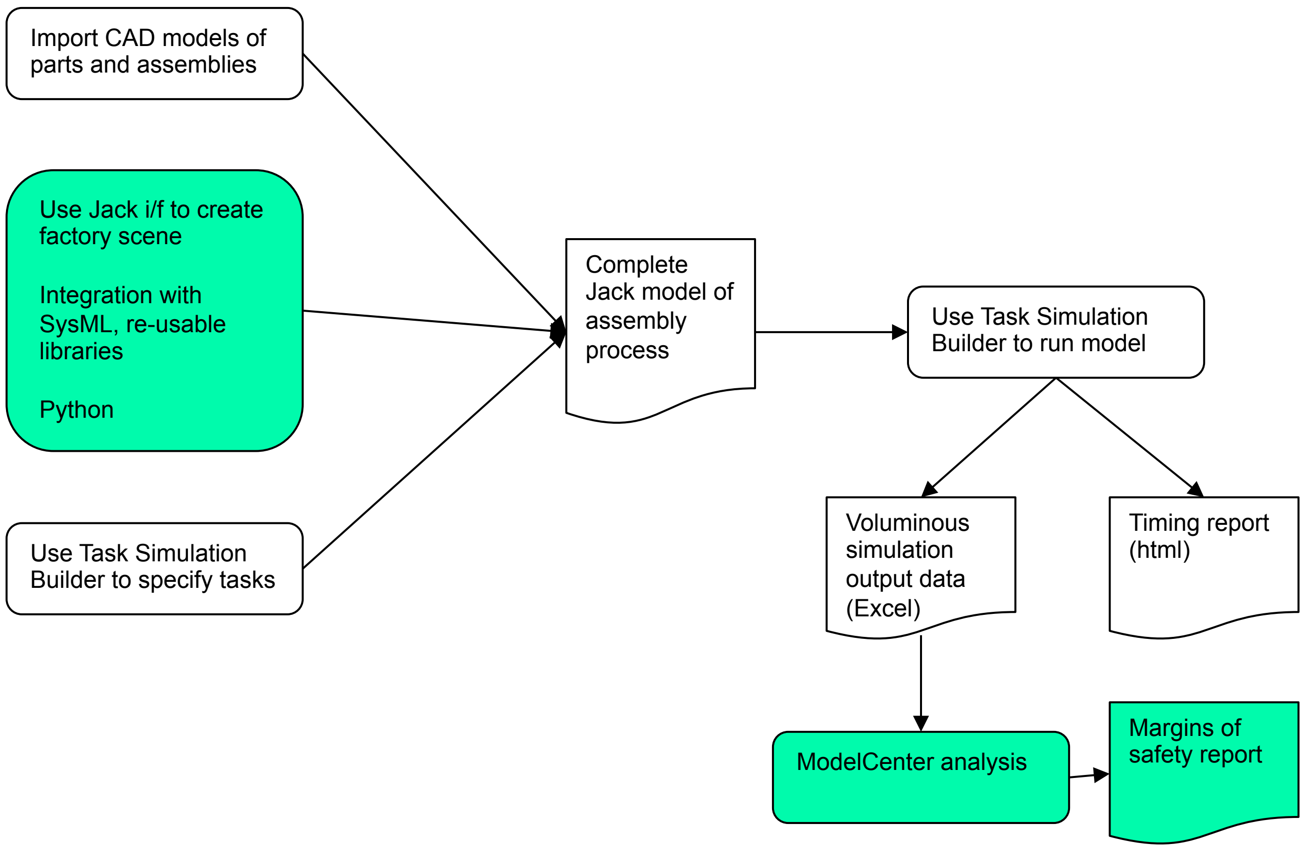

Integrating Jack with System Modeling

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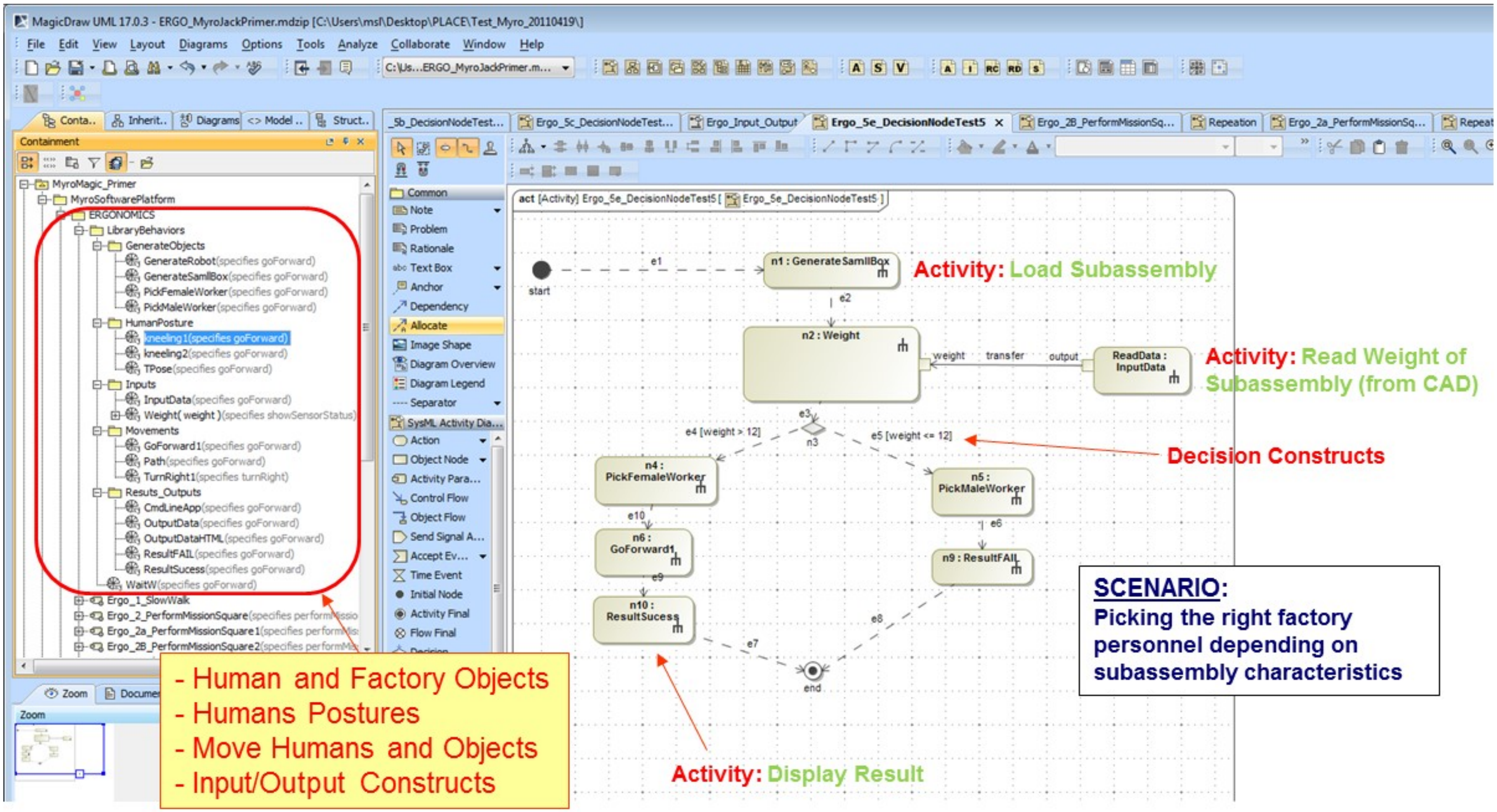

Processing the Simulation Output Data

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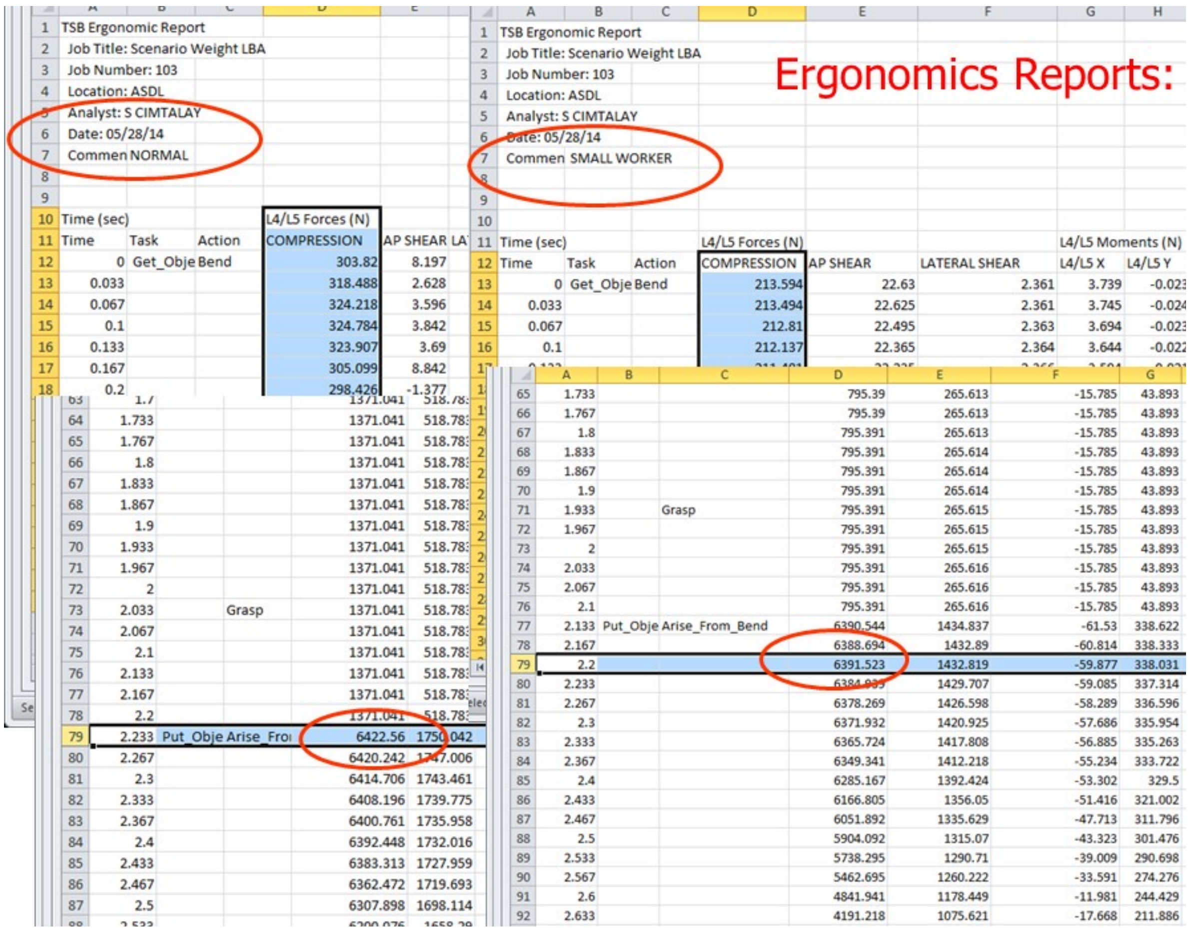

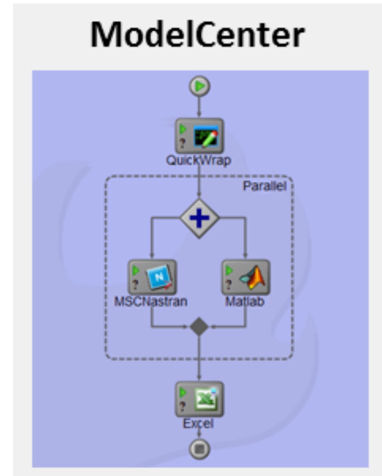

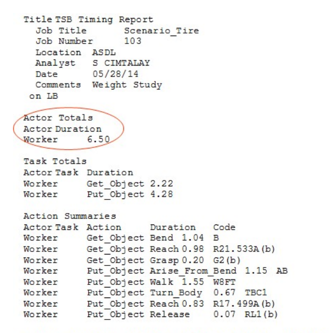

```
Title TSB Timing Report
  Job Title      Scenario_Tire
  Job Number     103
  Location  ASDL
  Analyst   S CIMTALAY
  Date      05/28/14
  Comments  Weight Study
 on LB

Actor Totals
Actor Duration
Worker     6.50

Task Totals
Actor Task  Duration
Worker     Get_Object 2.22
Worker     Put_Object 4.28

Action Summaries
Actor Task  Action      Duration   Code
Worker     Get_Object Bend  1.04  B
Worker     Get_Object Reach 0.98  R21.533A(b)
Worker     Get_Object Grasp 0.20  G2(b)
Worker     Put_Object Arise_From_Bend  1.15  AB
Worker     Put_Object Walk  1.55  W8FT
Worker     Put_Object Turn_Body  0.67  TBC1
Worker     Put_Object Reach 0.83  R17.499A(b)
Worker     Put_Object Release    0.07  RL1(b)

Report generated by Task Simulation Builder - Jack 7.1
```

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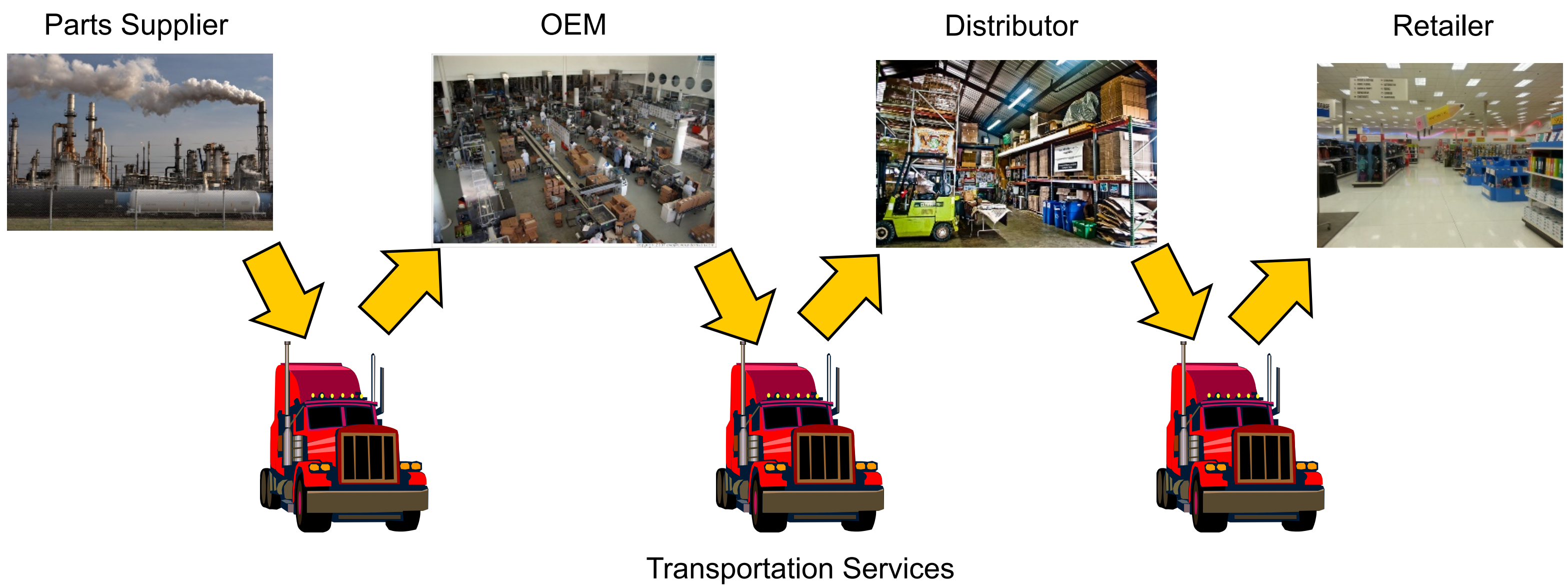
Summary

- **Formalize checklists**
  - **Opportunities to automate**
  - **Opportunities to capture tacit knowledge**
- **Make ergo simulation more effective**
  - **Formal linkage from product models to ergo simulation**
  - **Automating transformation from process models to ergo simulation models**
  - **Automating output analysis**

On-Demand Production System Analysis



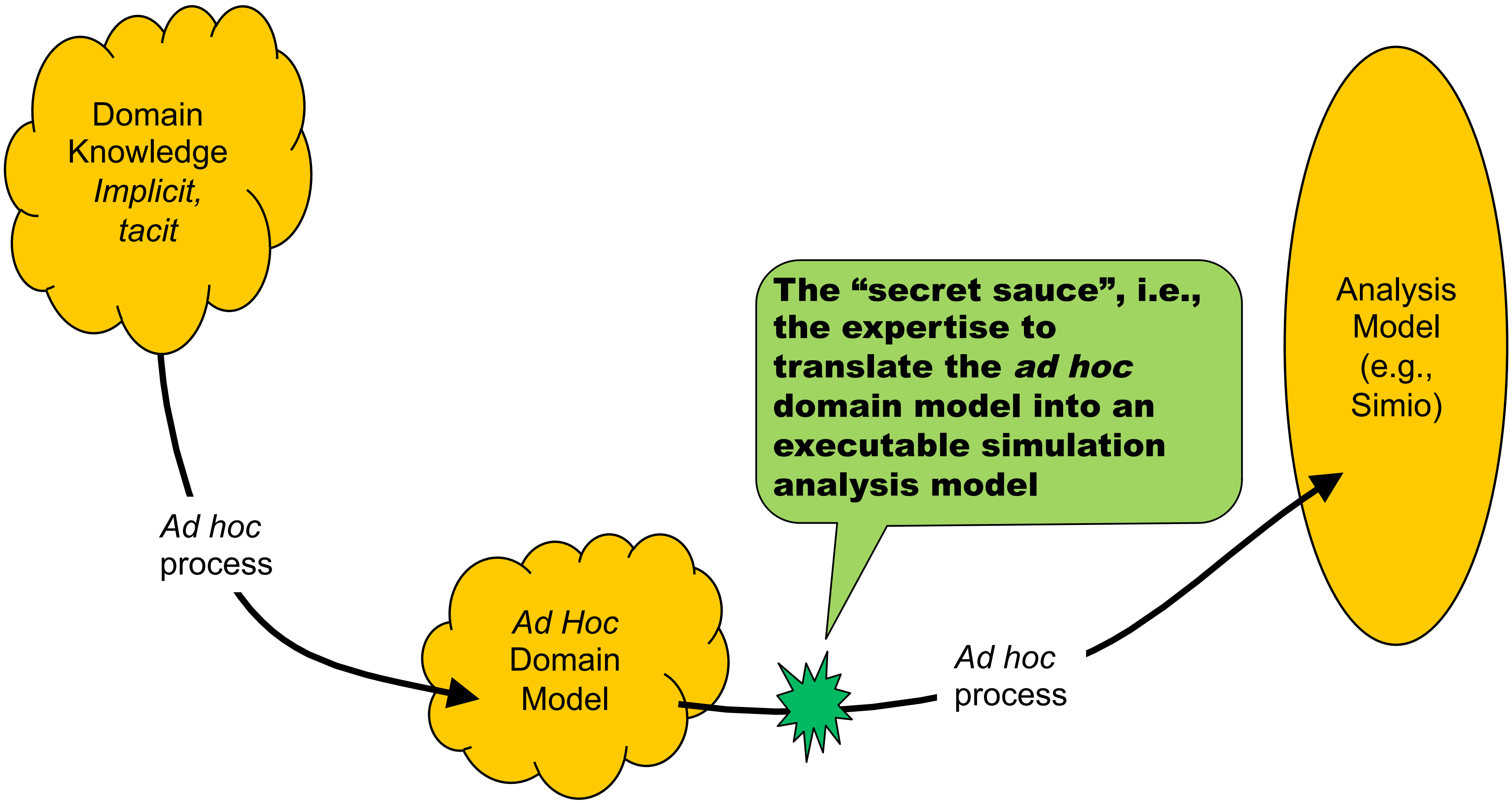
Units of flow move through a network of resources, which transform the units of flow in some way—location, age, configuration, information, etc.

Transformations can be adequately described by their start and end events, and by the summary description of the state change accomplished.

Some Caveats

- **We focus on analyses we already know how to do—don't need to "invent" anything new, just need to implement/deploy (but as new methods …)**
- **I'll focus on simulation, although our goal is to incorporate other analyses, e.g., factory physics, queuing, optimization, …**
- **Our work builds on earlier work on MDA and on manufacturing simulation "generators" (MPSG, CMSD, …)**

Production System Simulation Today



Fundamental Dilemma

- **If you want to provide "simulation on demand", then in some fashion, you have to capture the knowledge about how a simulation "expert" translates a (usually informal) system description into a simulation model *and make it computational*.**
- **What is the process for "simulation on demand" and where in the process should you capture the "simulation modeling" knowledge?**

The Contributors

- **Professor Edward Huang, now at GMU**
- **Dr. Kysang Kwan, now at Samsung**
- **Dr. Volkan Ustun, now at USC Institute for Creative Technologies**
- **Dr. Ola Batarseh, now at now at Avera McKennan Hospital, Sioux Falls, SD**
- **Dr. George Thiers, now post-doc at GT**
- **Tim Sprock, PhD student at GT**

Today's Story

- **Two different strategies for capturing the analysis modeling knowledge that we've demonstrated**
- **Current work that is very promising**
- **Future directions**

Straightforward (i.e., Brute Force) Approach

- **Use SysML stereotypes to create a *domain-specific language***
- **Resources as *blocks*, processes as *call actions*, process plans as *activities***
- **Figure out how to create the Arena model, then capture that understanding in an *ATL script***
- **Build the instance model in SysML, export as XMI, model-to-model transformation with ATL, executable Arena model**
- **Order of magnitude reduction in the time to build Arena simulations**

Modeling Knowledge in Transformation

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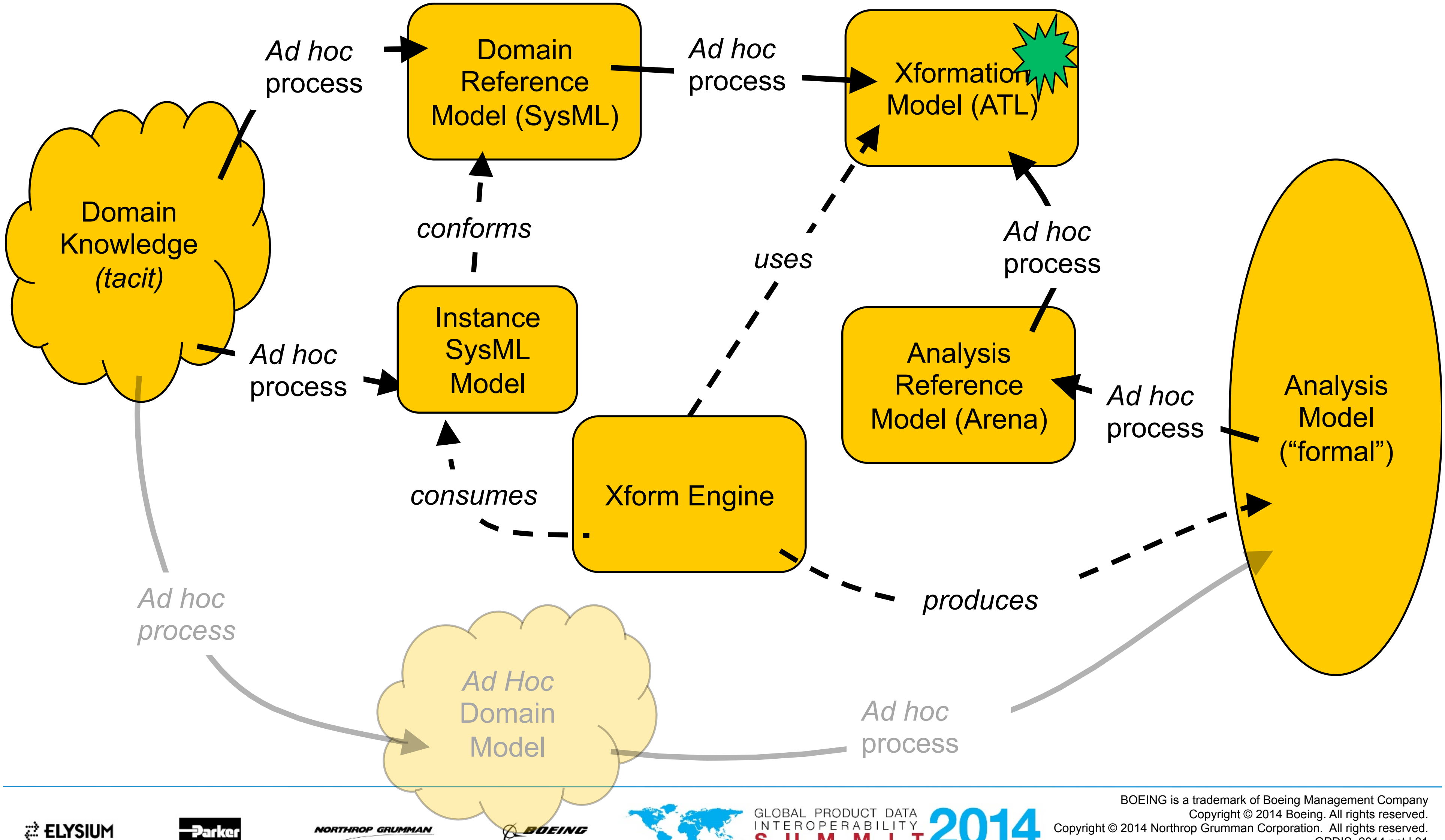


Assessment

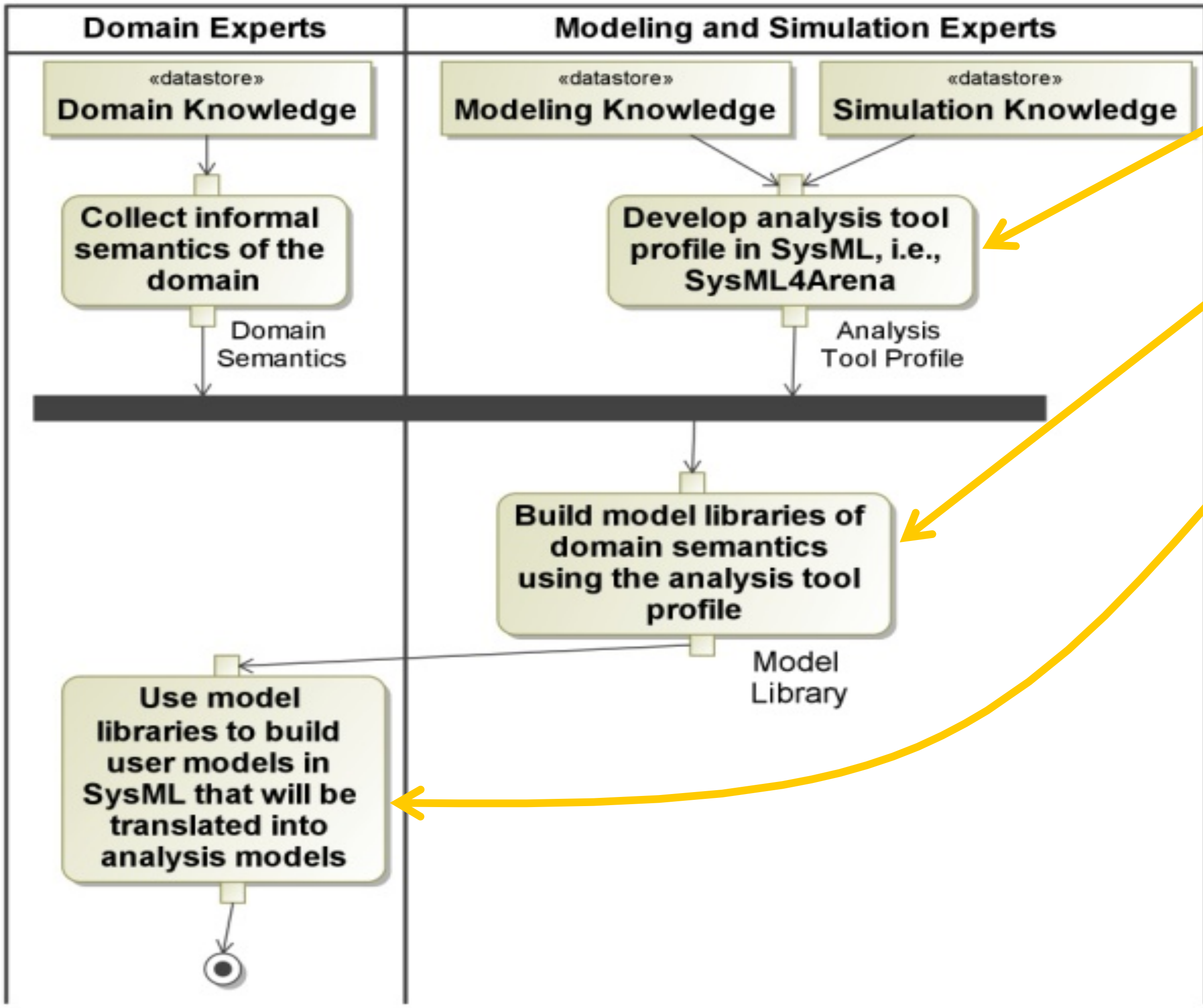
- **This works, and is generic, however,**
  - **Creating the script requires understanding the domain reference model, how to model in the target analysis language, AND the transformation scripting language—three kinds of expertise**
  - **Very fragile—every extension of the DSL wrecked the transformation script**
  - **We conveniently ignored control (by making all material flow control decisions default to FCFS or its equivalent)***
- **We think there's a better way…**

* By the way, almost all production system simulations today have a "local" control paradigm, where all material flow control decisions are made locally

A (Much) Better Strategy

- **Instead of putting the "simulation modeling knowledge" in the ATL script, put it in the DSL itself**
  - **Create a profile which contains a SysML analog for every modeling construct in Arena (SysML4Arena)**
  - **Use the SysML4Arena profile to create "user modeling objects" in the DSL**
- **Create the ATL script once (1-to-1 mapping!)**
- **Can continue to extend the DSL to capture additional domain semantics without changing the ATL script (as long as everything you need is in Arena and in SysML4Arena)**

Process Summary



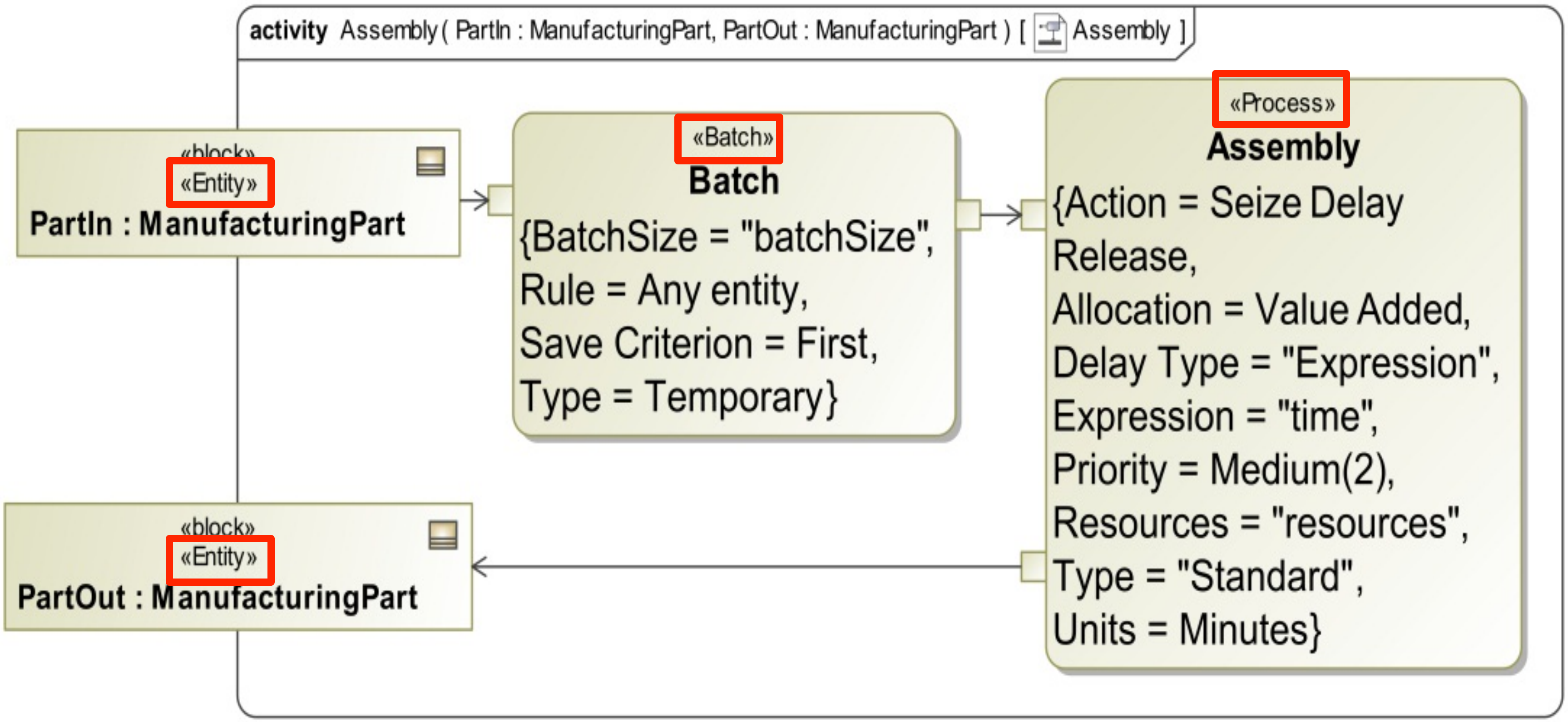
In summary:

1. Profile for the analysis tool, i.e. SysML4Arena.
2. Model library for domain semantics, i.e. manufacturing systems
3. Instance model that uses domain library and will automatically generate DES model, i.e Arena.

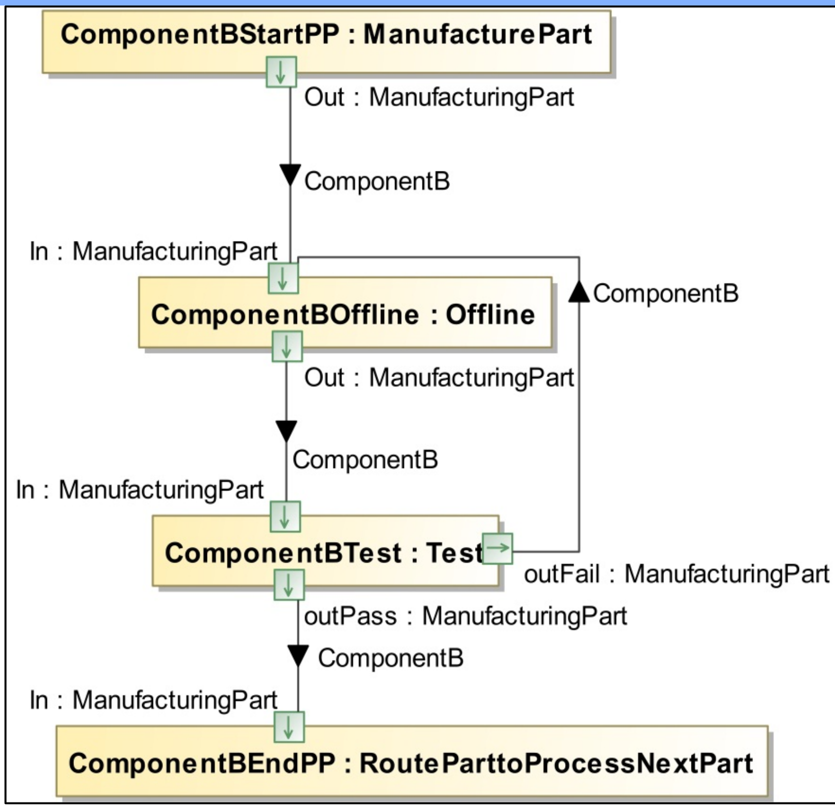
Manufacturing System Library using SysML4Arena

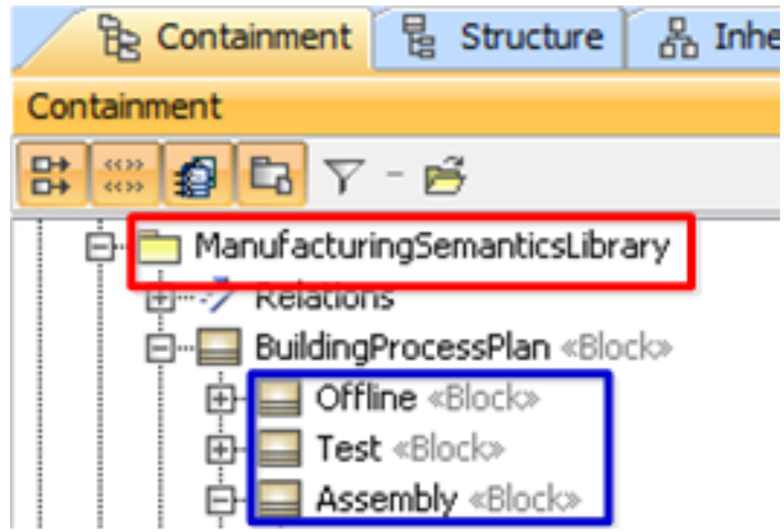
- **Assembly process**

Arena Stereotypes pulled from customized menus



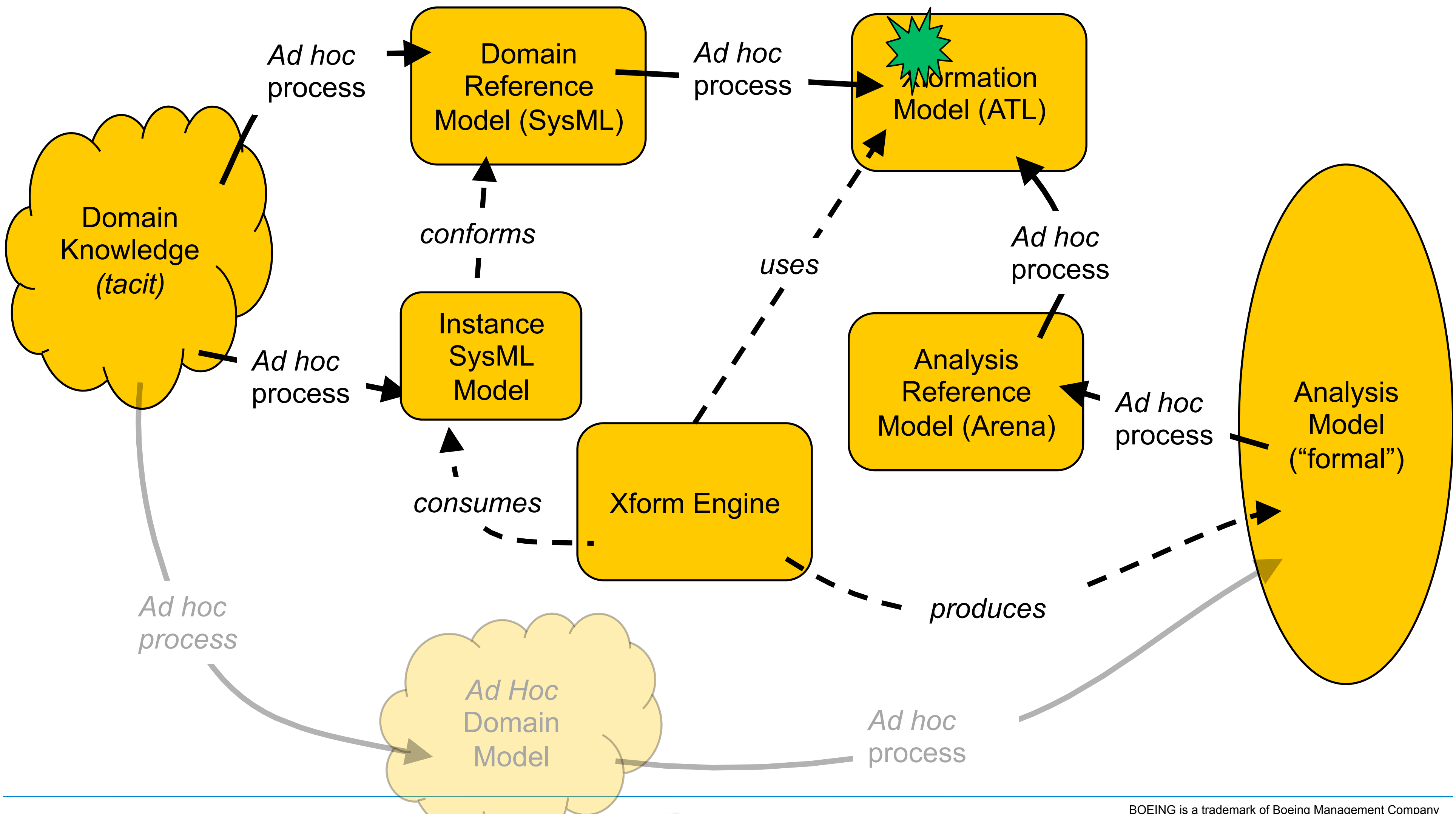
Use Model Library – Process Plans





The process plan is composed of SysML part properties which are type of manufacturing processes (Offline, Test, etc.)stored in the ManufacturingSemanticsLibrary

Modeling Knowledge in DSL



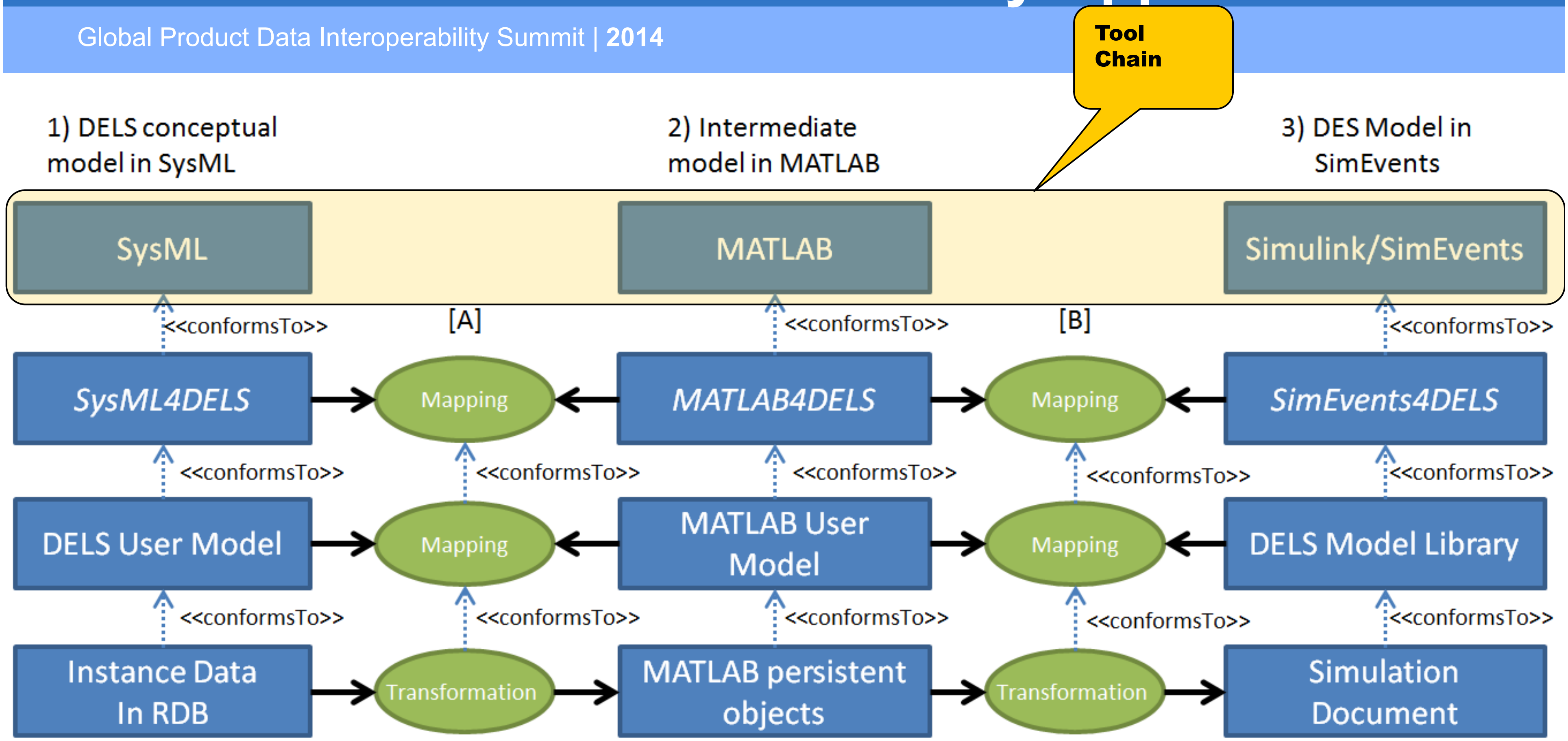
Assessment

- **Solves the problem of maintaining the transformation script, by moving the simulation modeling knowledge from ATL to the DSL**
- **Capturing the simulation modeling knowledge requires expertise in SysML, the SysML-based DSL and in the target analysis modeling language—three kinds of expertise (traded ATL for SysML…)**
- **Still no explicit concept of "control" because that's not really a strong feature of Arena (or frankly, any other widely used DES language…)**
- **We think there's an even better approach…**

Current R&D Activities: Software Factory Approach

- Everything flows from the domain reference architecture
- Simulation experts work from the domain reference architecture to:
  - Create and maintain a simulation model library from which components can selected (or cloned) and configured to create an executable simulation model
  - Allow users to create and register their own variations of components
  - Because simulation components conform to the SysML schema
    - Reduced ambiguity in creating the resulting simulation component and its interface
    - Enables debugging the simulation component in its native environment
- Software factory concepts implemented in MatLab™ and simulation components implemented in SimEvents™

Overview of the Software Factory Approach



To accomplish the transformation seamlessly, we need three things:

1. Relational Database (and instance data) that conforms to Reference Architecture (SysML)
2. MATLAB class definitions (classdefs) that conform to Reference Architecture (SysML)
3. SimEvents Model Library objects that conform to Reference Architecture (SysML)

Overview of the Software Factory Approach

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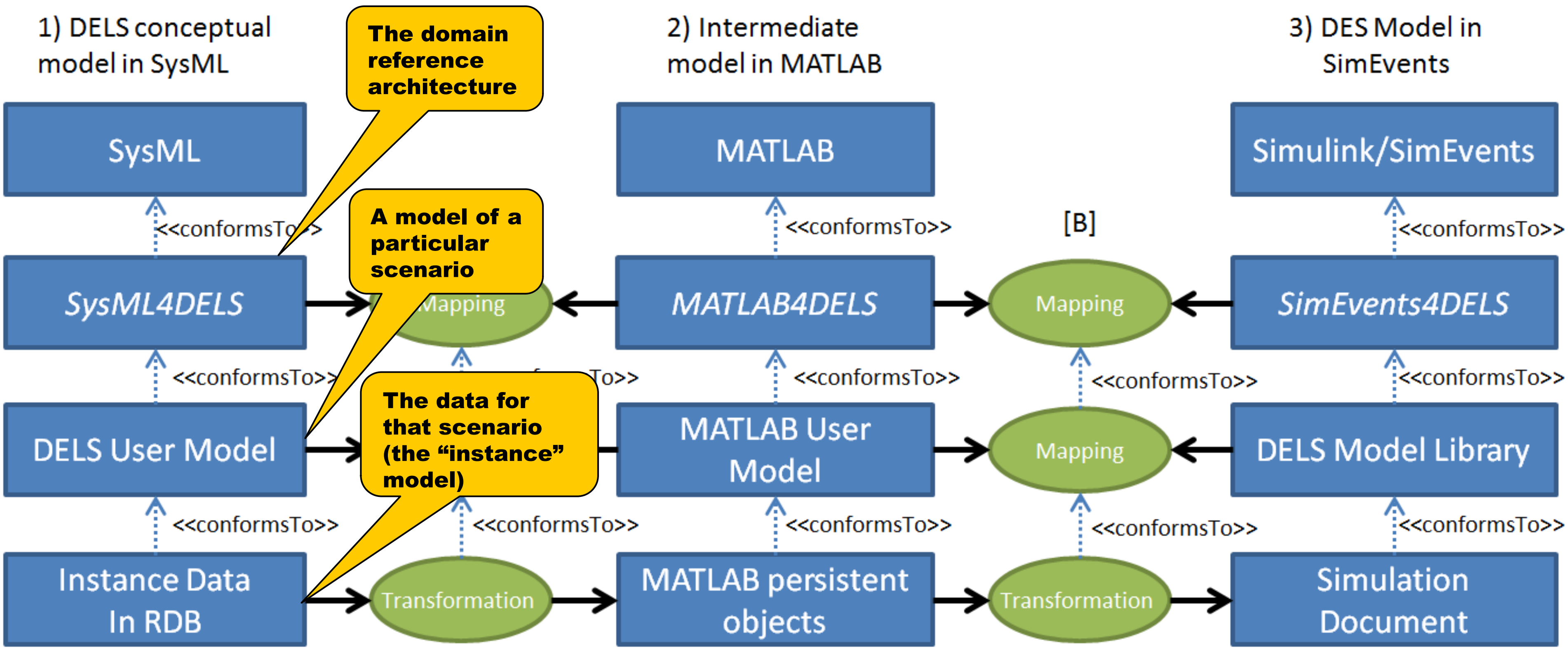

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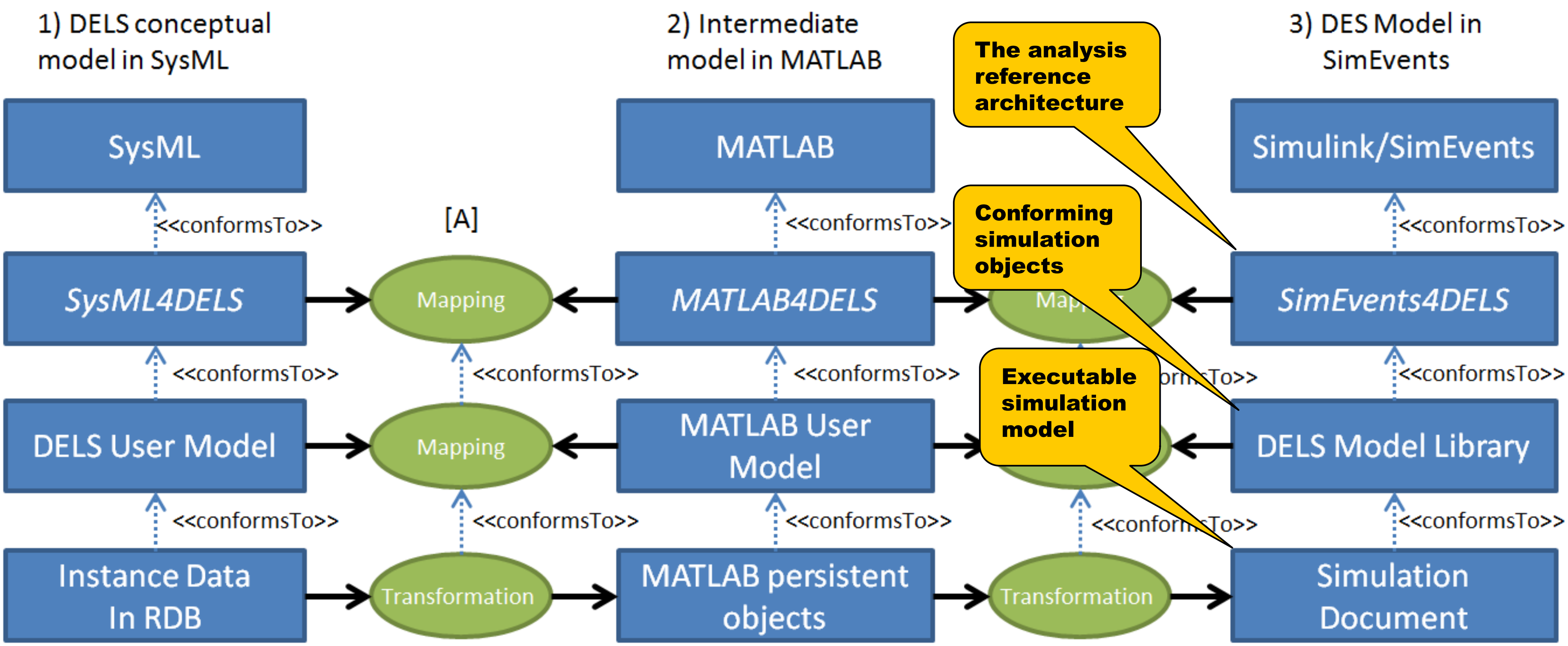

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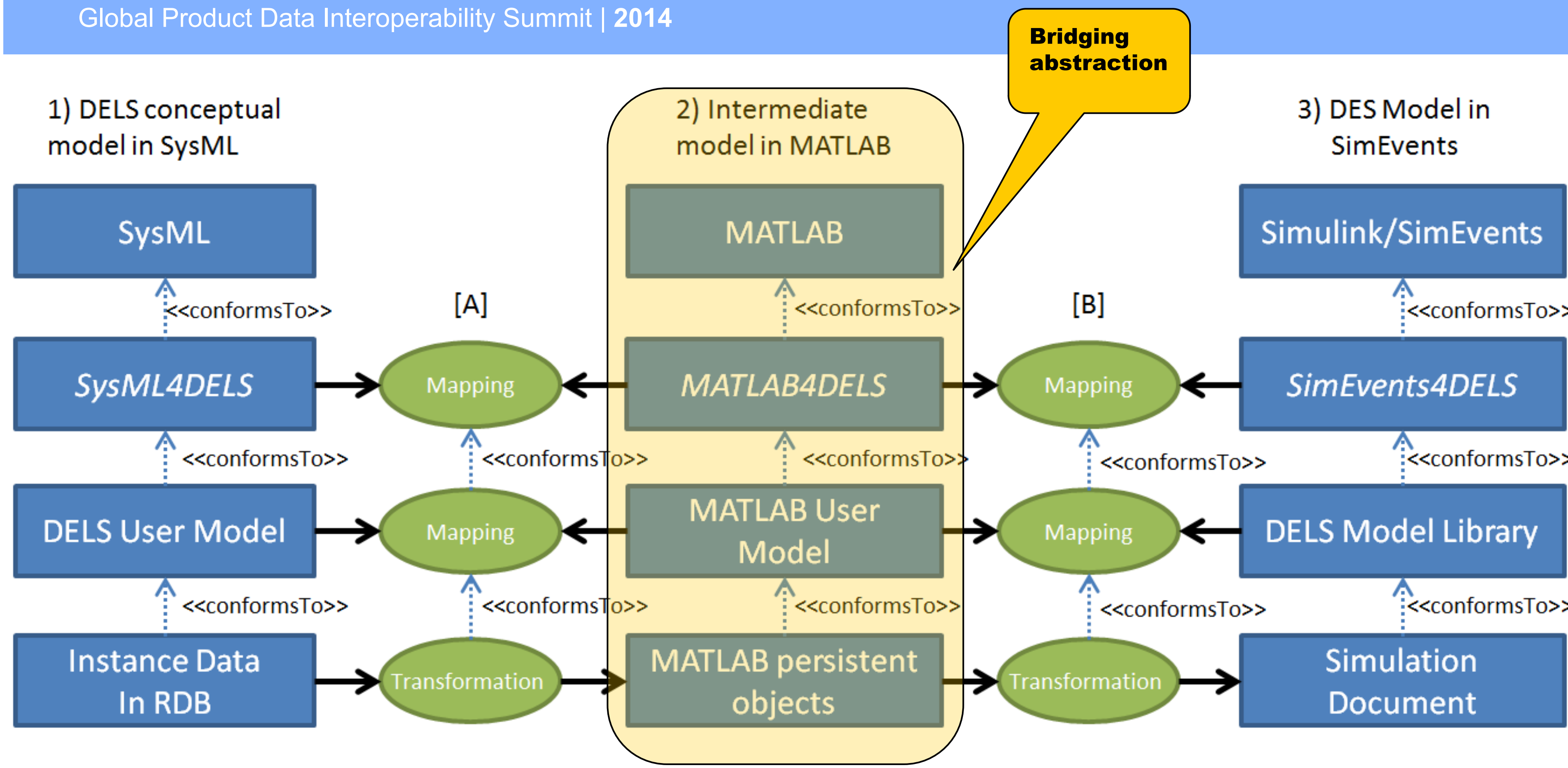

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Assessment

- **This seems like a much more robust and reusable approach to "simulation on demand"**
- **Now the simulation expert needs only to be able to interpret the SysML model and create the simulation components—the graphical nature of SysML *should* support this**
- **Is it reproducible with other target simulation languages? Is there an open API?**

Summary

- **Developed and demonstrated several technologies for creating production system simulation models "on demand"**
- **Potential for more than "order of magnitude" reduction in time/cost for production system simulations**
- **Most recent approaches easily extended to other kinds of analysis, e.g., optimization, "factory physics", financial, etc.**
- **Looking for "field test" sites and partners**

Going Forward

- **MBSE Center aspires to transform D2P by creating and deploying breakthrough technologies for supporting production system design decision making**
- **A major focus is on making simulation a much more affordable tool for production system designers**
- **Production system control is a challenge, but we believe we have the tools now to meet the challenge**
- **The ultimate payoff is better decision making, lower cost and lower risk**

Summary

- **Research on supporting ergonomic analysis of production operations**
- **Research on supporting operational simulation of production systems**
- **Research on inconsistency detection and mitigation (presentation by S. Herzig after lunch)**

Acknowledgements

- **The Boeing Aerospace Company's generous support of Georgia Tech and this research project, and Howard Appelman's management of the program**

- **Mr. Mike Christian for his patience in mentoring our research team**