2021 Annual INCOSE international workshop
Virtual Event
January 29 - 31, 2021

Premier Systems Engineering Workshop

Integrated Model-based Systems Engineering (*iMBSE*) in Engineering Education

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Initiative for Product Lifecycle Innovation (IPLI), IUPUI

MBSE Lightning Round

Outline

1. **Rationale**
    1. Product development: Modern products
    2. Current practice in Academia: Capstone Design Limitations in Engineering programs (ME, EnE, EE, CE, BME, IE, etc.)
    3. Document based Systems Engineering: Current limitation
2. **iMBSE: 3D extension of Capstone Design & Digitalization of SE**
    1. iMBSE characteristics & modern products
    2. 3D extension of Capstone Design
3. **Curriculum for Industry 4.0: Engineering Education 4.0**
    1. 3 Level curriculum
    2. Revised curriculum (for Engineering Education 4.0)
4. **iMBSE: Framework & Digital innovation platform for Industry 4.0**
    1. Proposed iMBSE framework
    2. Digital Innovation platform for Industry 4.0
5. **Case study: Electric skateboard**
6. **Summary & conclusions**

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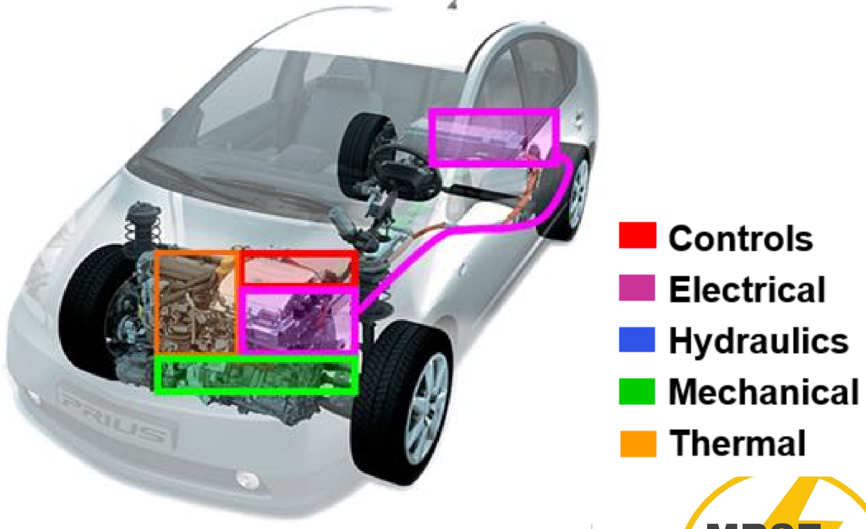
Rationale → Product Development → Modern Products

Modern products are increasingly becoming complex, typically smart connected systems or systems of systems (SoS). To develop modern products competitively, there is need to address **complexities resulting from**:

....managing:	....dealing with:
• Multiple sub-systems • Multiple engineering domains • Multiple variants and system architectures • Growth of software / electronic systems • Exploding requirements • Fast growing number of V & V • Multiple disparate tools in each domain • Multiple design groups and multiple sites	• Subsystems interactions • System integration

Example of modern product: Multi-domain, multi-subsystems, etc. SoS



Siemens PLM publication

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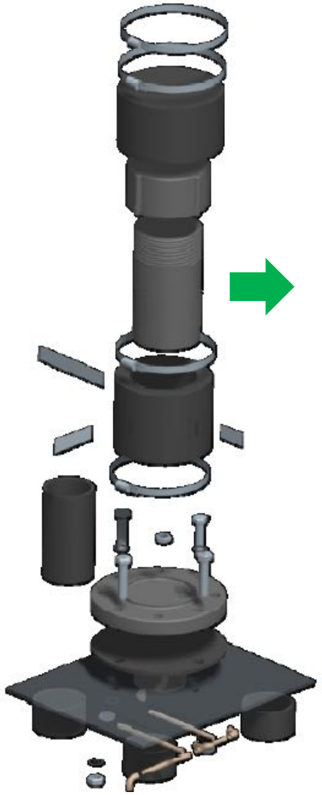
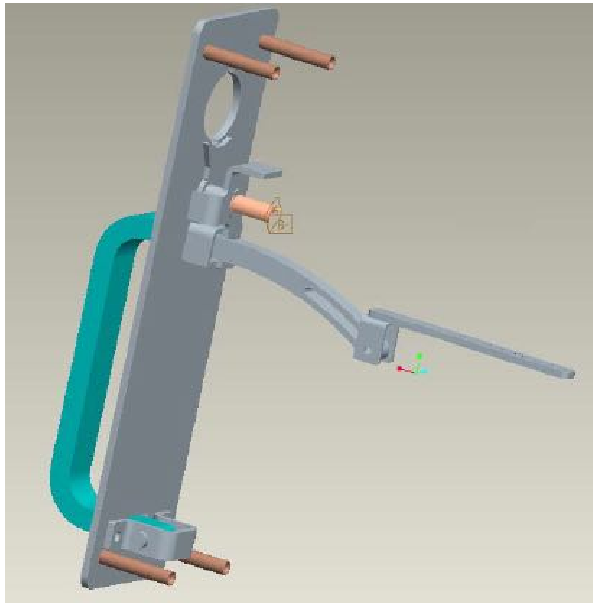
Current practice in Academia → Engineering programs: Capstone Design Limitations

Capstone Design Limitations
Simple product
Single Domain
Limited scope: "Development" (not "Lifecycle")
Limited Digitalization
Validation: Mostly through Physical prototyping



Fin Heat Transfer Apparatus



Arm-A-Door Outside Entry: Exterior Handle Assembly

Example of typical capstone design products: Mostly Mechanical

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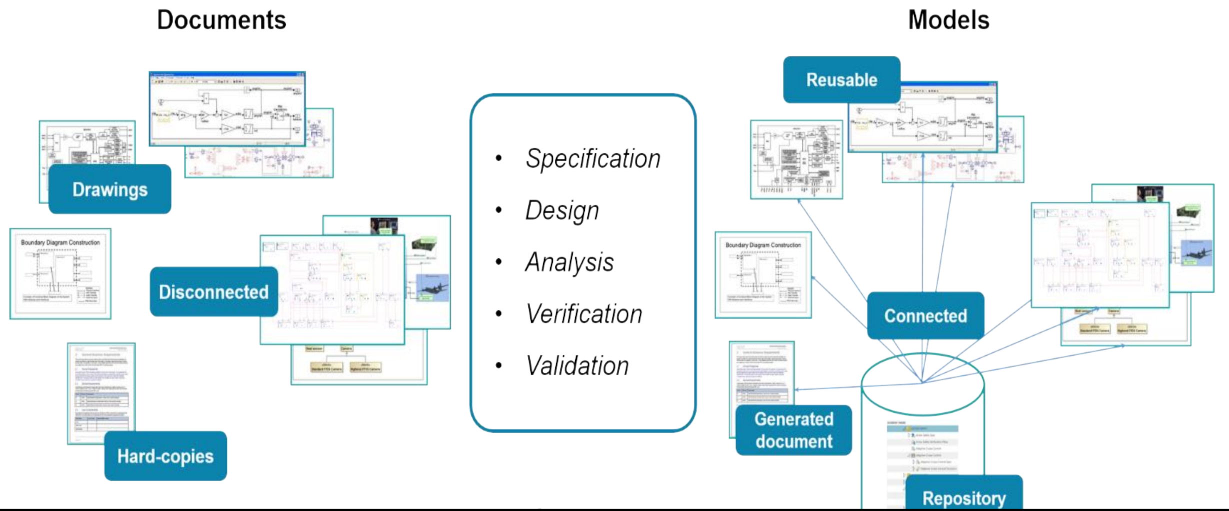
Current practice in Industry → Document-based Systems Engineering Limitations

Definition: MBSE is a model-centric (v.s. document-based) approach providing a **single point of truth** which is reflected in a set of living artefacts [INCOSEUK].



Document-based process	Model-based process
Error prone - Missing elements - Poor element traceability Vulnerable to company silos	Workflow enforced Design element based Source driven through design elements Fully integrated

The successful implementation of Model based Systems Engineering (MBSE) leads to lower cost, better quality and lower risk. These are the results of the following:

The system model allows early detection of errors and inconsistencies enabled by the ability perform analysis

The system model uses modern modeling languages with clearer semantics that lower miscommunication

The system model provides a single source of information ensures consistency between different skateholders

The system model can be used to automatically generate up to date deliverables (e.g. documents)

The system model supports multiple views to address different skateholders' needs using a single source of information

The system model helps better manage complexity

The system mode enables early debugging and refinement of requirements, including behavioral ones, through simulation of state machines

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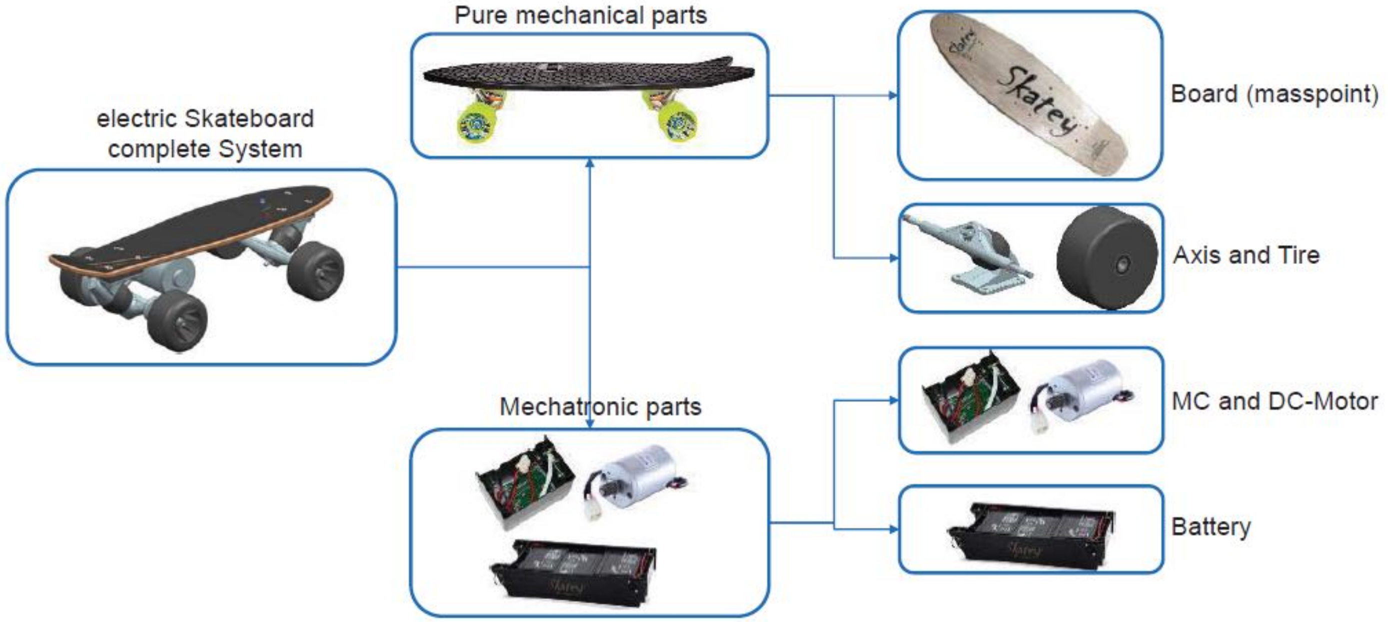
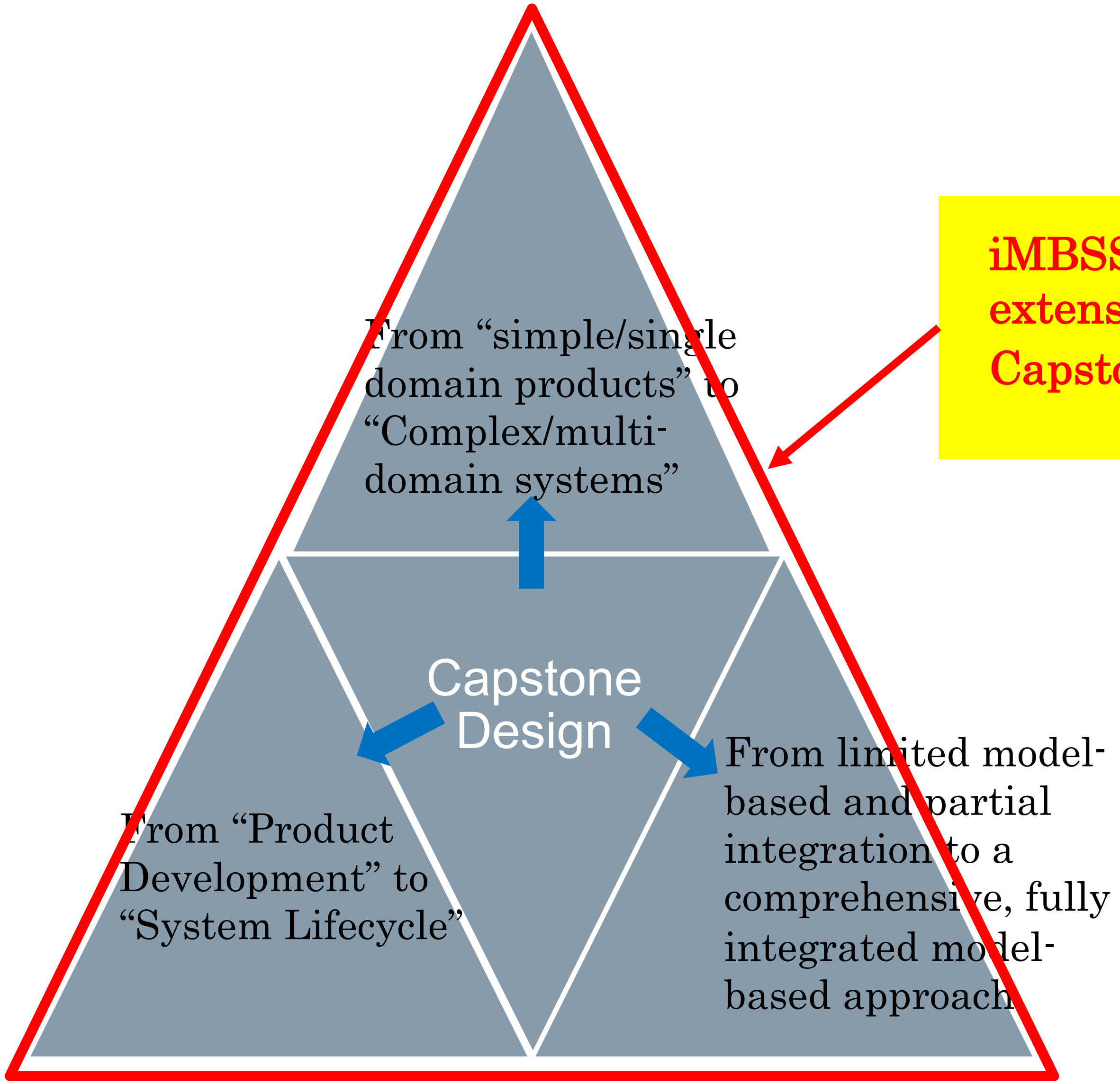
iMBSE: 3D extension of Capstone Design → iMBSE characteristics & modern products

3D extended CD driven by iMBSE
Complex product (system or SoS)
Multi Domain
Extended scope: “Lifecycle” (not just “Development”)
Full Digitalization
Validation: SIL, HIL, MIL, and Virtual prototyping



Example of a complex product: Multi-domain system

iMBSE: 3D extension of Capstone Design → 3D extension of CD



iMBSSE as a 3D extension of Standard Capstone Design

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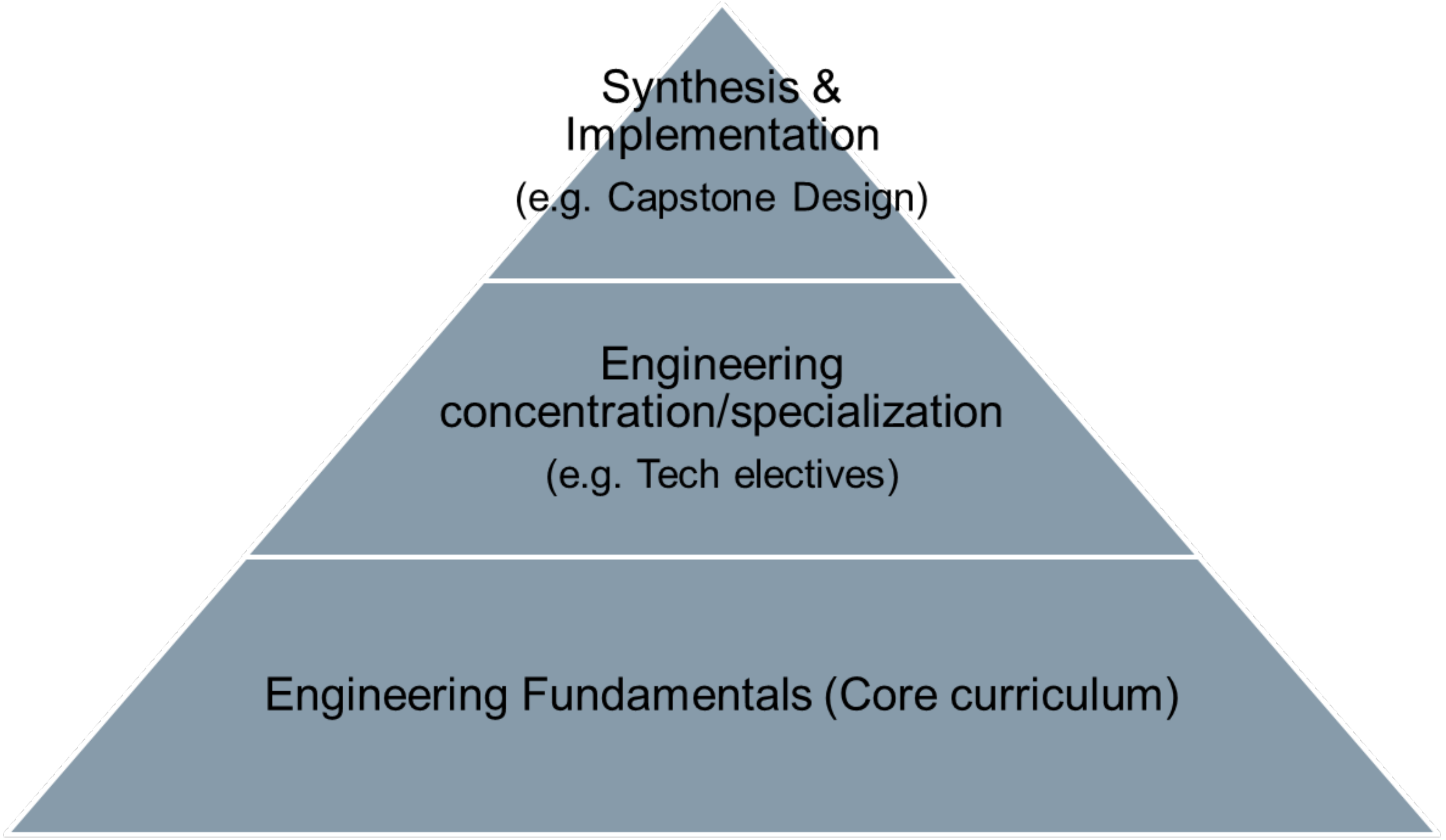
Curriculum for Industry 4.0: Engineering Education 4.0 → 3 Level curriculum



Three levels of typical Engineering curriculum (e.g. ME)

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Curriculum for Industry 4.0: Engineering Education 4.0 → Revised curriculum (Eng. Education 4.0)

New curriculum:

Integrated Model-based systems Engineering, iMBSE, or “SE” Capstone design

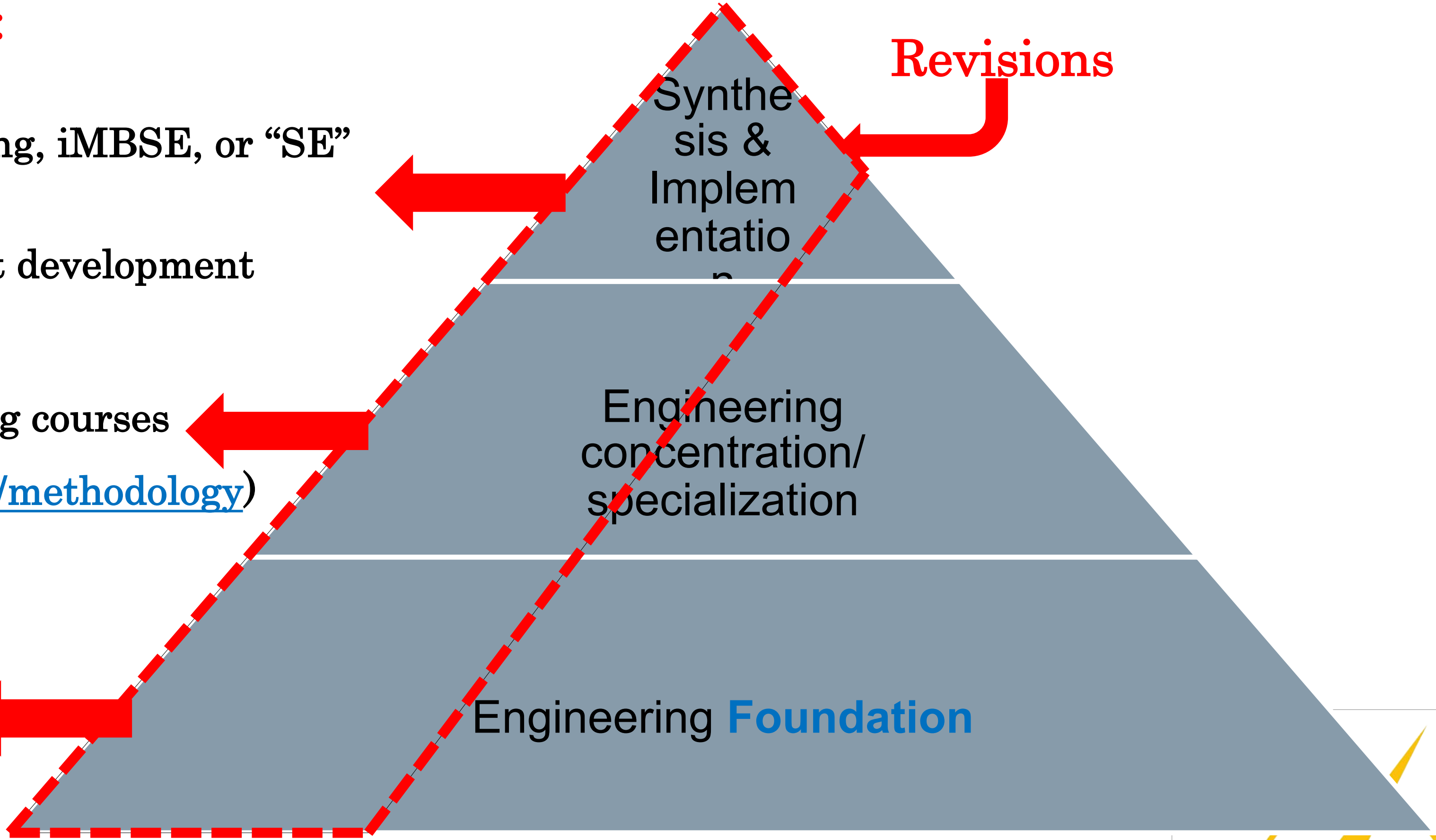
(allows: implementation in complex product development applications)

Also, adding (Industry 4.0) Enabling technologies: *AM, AR/MR/VR, IoT, Simulation, Big data and Advanced Analytics, Cloud computing, Cybersecurity, Autonomous systems, etc.* (provide: theoretical foundation and relevant specialization)

Systems Engineering courses

(provides: Approach/methodology)

Digital tools in core courses



Revised curriculum (Engineering Education 4.0)

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Curriculum for Industry 4.0: Engineering Education 4.0 → 3 Level curriculum

iMBSE curriculum

- It is a unique curriculum that demonstrates the **digitalization of the SE** (Systems Engineering) **process** through the integration of modelling and simulation continuum (in the form of MBSE) with Product lifecycle management (PLM).

- *iMBSE* is a form of MBE (Model-based Engineering) that drives the product lifecycle from the systems requirements and traces back performance to stakeholders' needs through a RFLP traceability process. At the core of this coursework is a shift of focus from theory to implementation and practice, through an *applied synthesis of engineering fundamentals and systems engineering, that is driven by a state-of-the-art digital innovation platform for product (or system) development*. The curriculum provides training to the next generation of engineers for Industry 4.0.

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Curriculum for Industry 4.0: Engineering Education 4.0 → Curriculum of Engineering Education 4.0

	SE Capstone course (iMBSE)	Typical Capstone course
Process (methodology)	SE process	Design process
Product (application)	Multi-domain system	Mechanical product
Digitalization	Integrated digital platform (to enable both digital twin and digital thread) that spans the lifecycle	Limited digital capabilities

Capstone: Traditional vs. iMBSE driven

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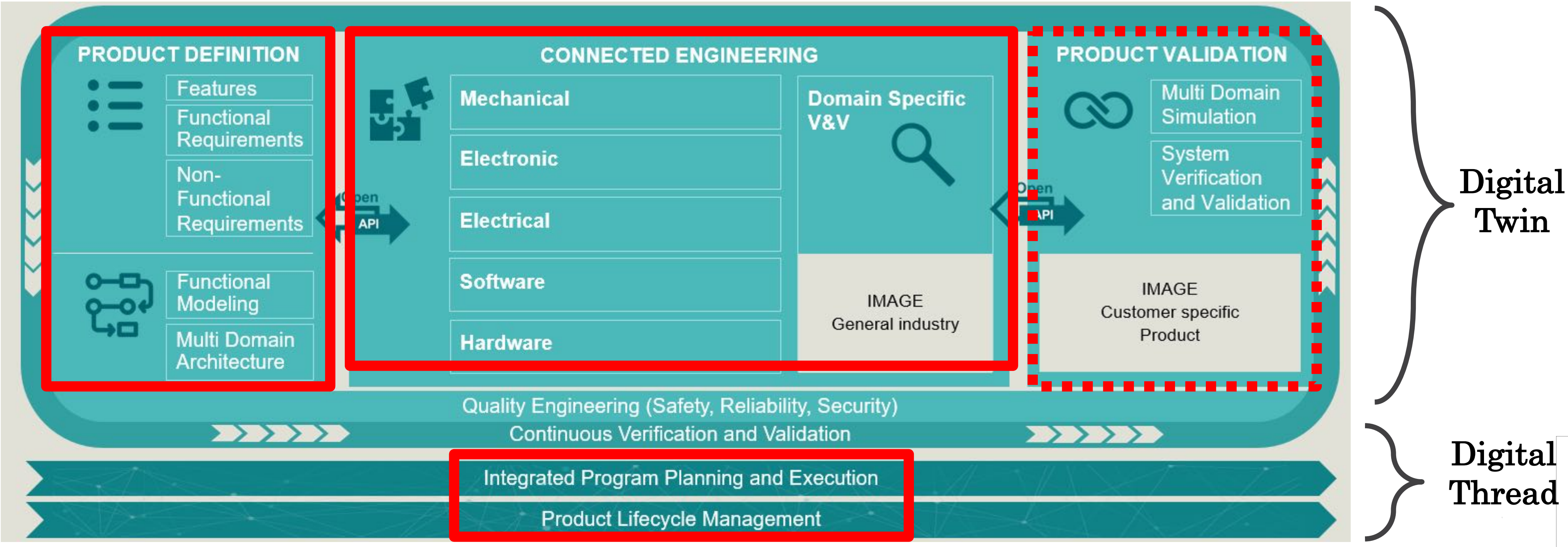
iMBSE: Framework & Digital Innovation Platform for Industry 4.0 → Proposed Siemens iMBSE framework



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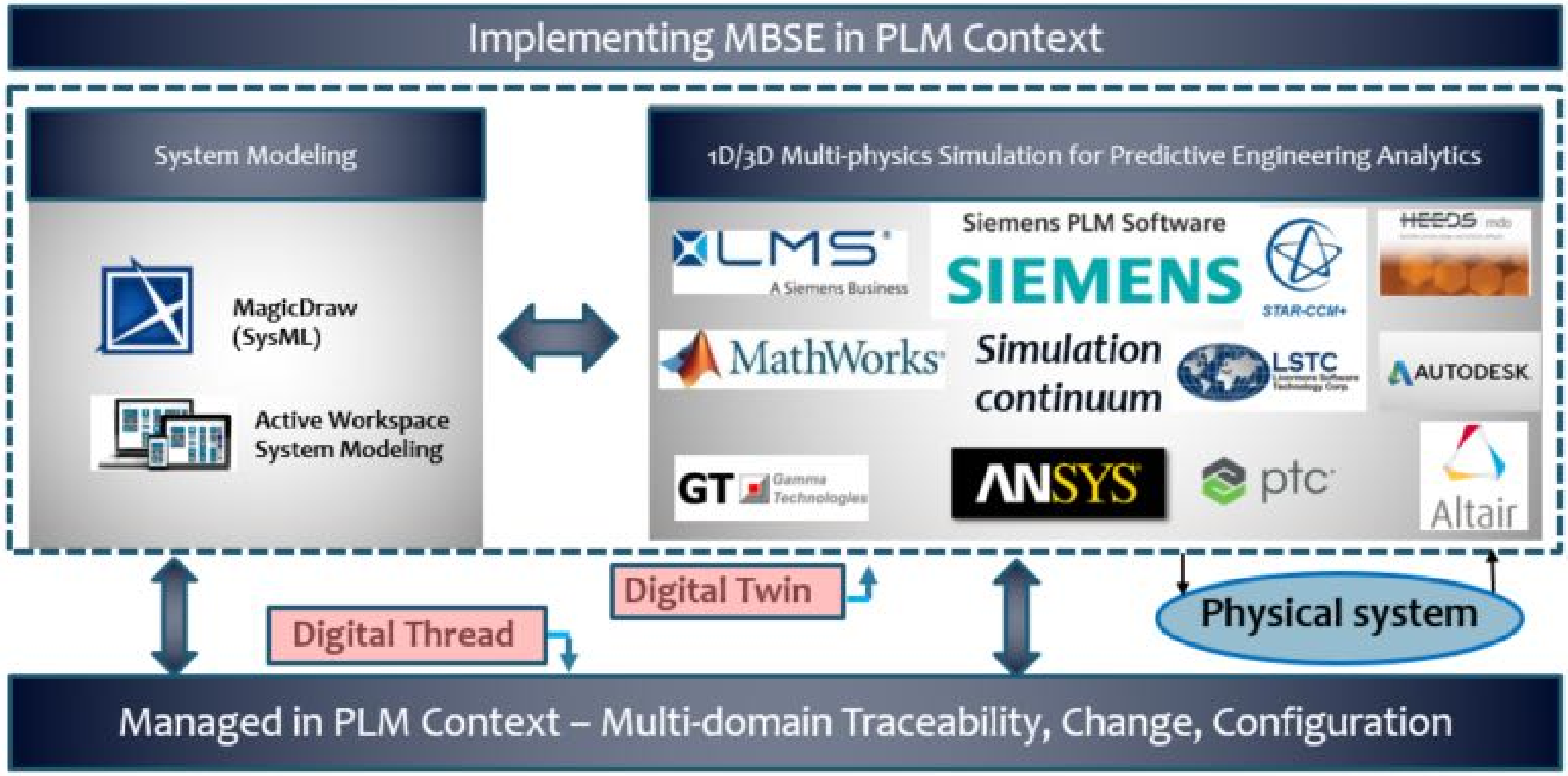
iMBSE: Framework & Digital Innovation Platform for Industry 4.0 → Digital Innovation platform for Industry 4.0



Digital Innovation platform for Industry 4.0: Integrating Digital twin with Digital thread

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iMBSE Curriculum

<u>Main characteristics</u>:

Digital twin: Multi-domain architecture integrated with domain specific simulation models

Digital Thread: PLM providing integrated platform for multi-domain product architecture, requirements, etc., supporting communication throughout product development

Traceability: Linking requirements to design artifacts

MBSE course	MBSE tools	MBSE solution
Model-based Systems Engineering (MBSE) using SysML	Cameo / MagicDraw tool	
Model-based Systems Driven Product Development (SDPD or iMBSE)	Ecosystem of software tools (Siemens digital innovation platform for iMBSE, including Capella tool)	 

MBSE curriculum: Two courses offered as part of SE program

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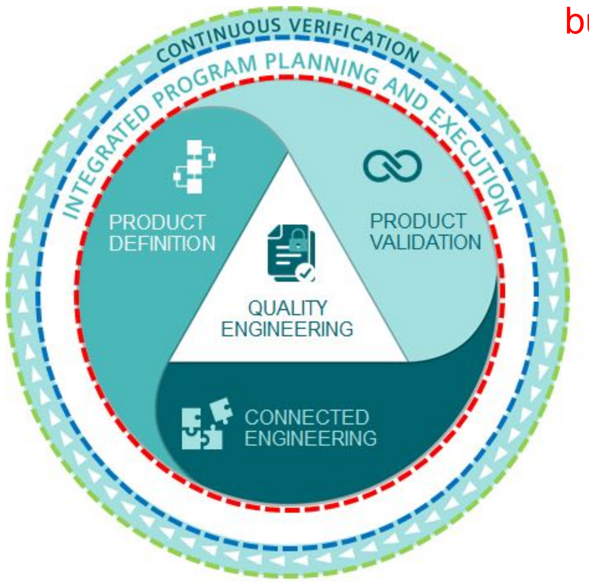
iMBSE Curriculum (cont')

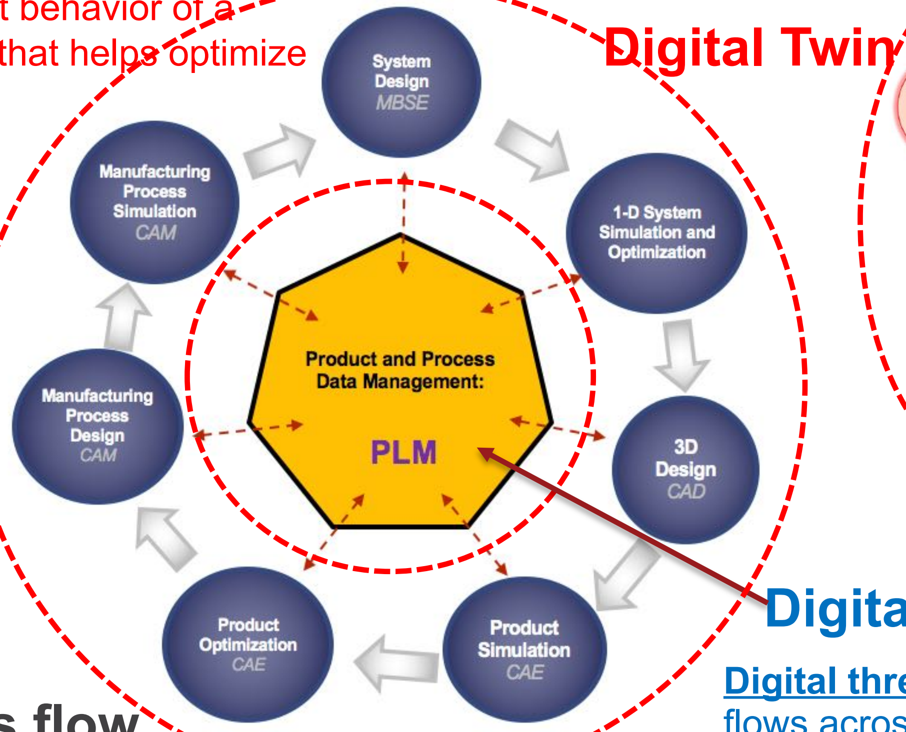
The iMBSE curriculum consists of three key elements:
1) Modelling and simulation continuum;
2) Traceability;
3) Digital thread.

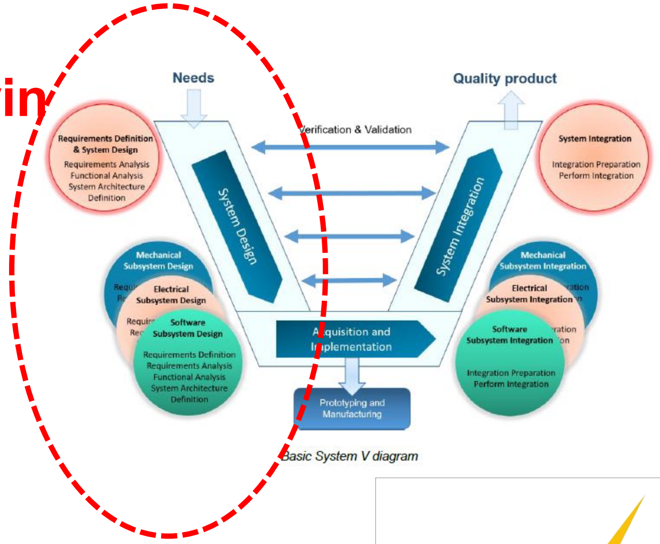
The digital thread is implemented using **PLM** as the backbone to support the integration of the different models used throughout the development cycle.



Implementation in SDPD curriculum

Digital twin: A "live", evolving digital replica of the historical and current behavior of a physical object of process that helps optimize business





iMBSE process flow

Digital Thread

Digital thread: Connects data flows across lifecycle

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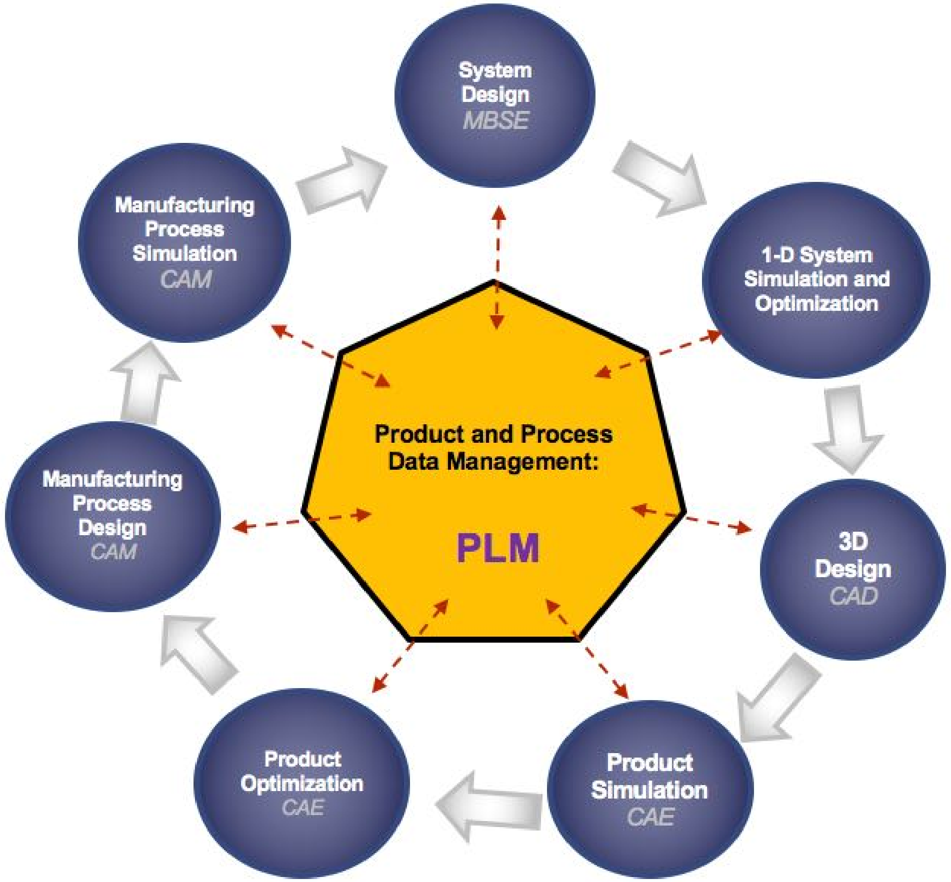
Case study: Electric Skateboard → iMBSE implementation workflow



Electric Skateboard – iMBSE implementation workflow

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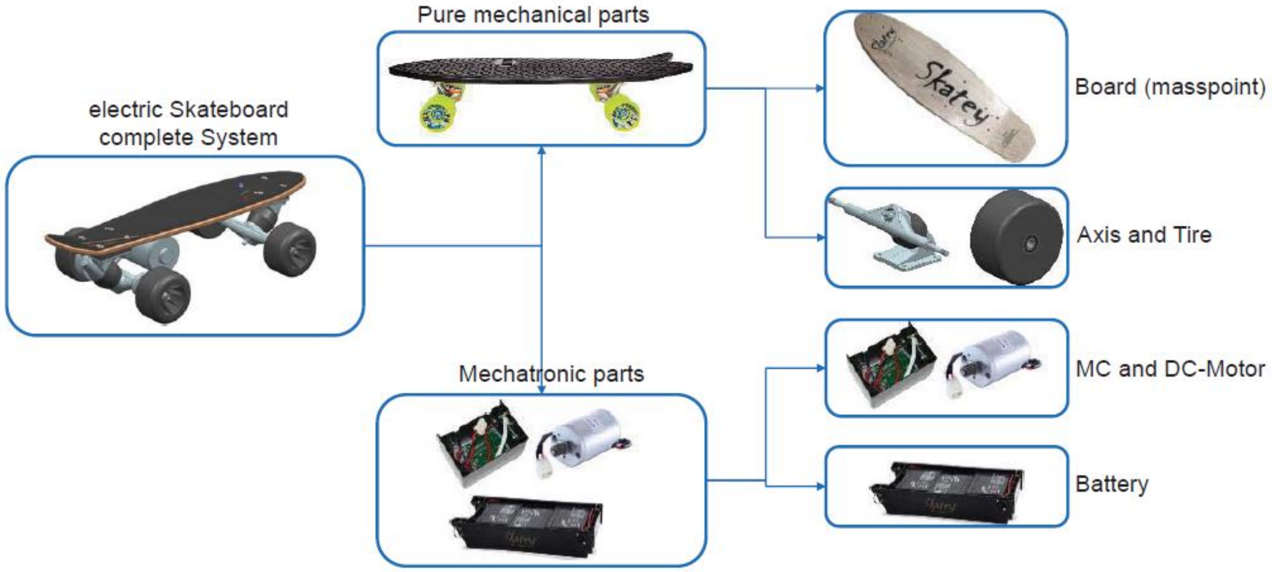
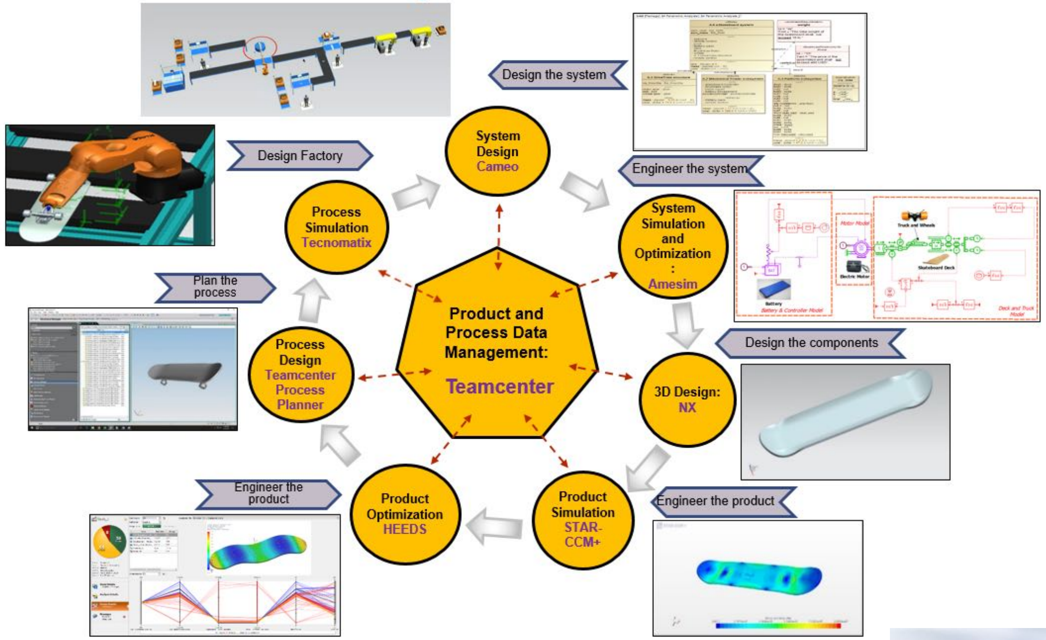
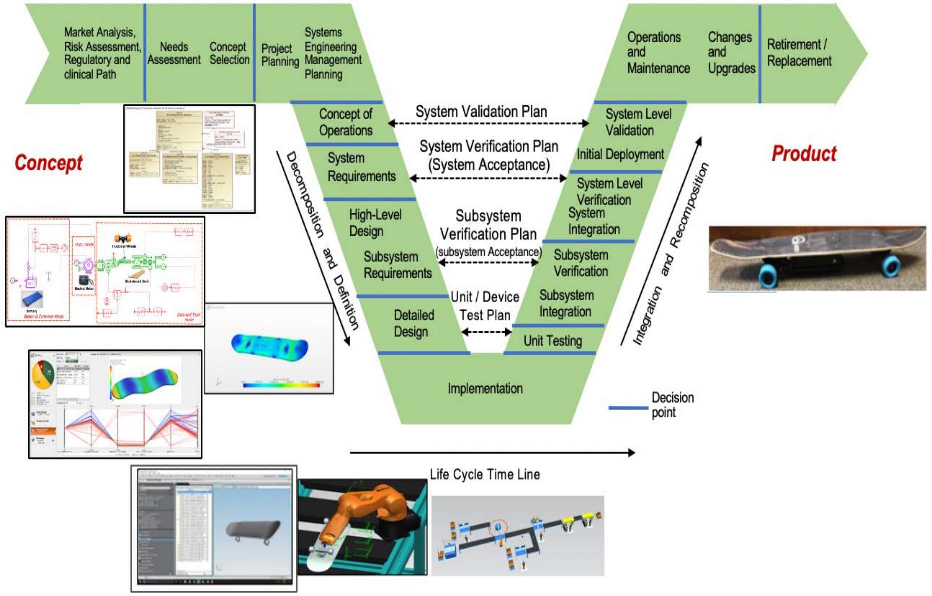
Practice – Case studies → Electric Skateboard/Longboard



Electric Skateboard as a multi-domain system

Practice – Case studies → Electric Skateboard/Longboard





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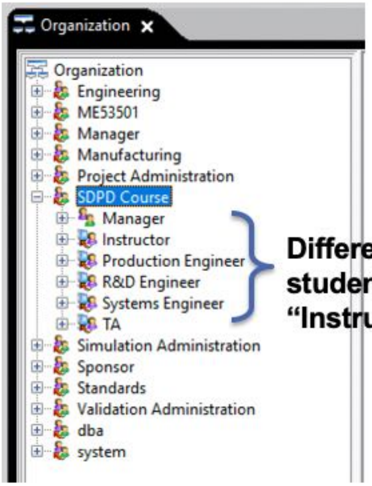
Practice –Case Studies → Electric Longboard: Project Workflow (Project Definition and Planning)

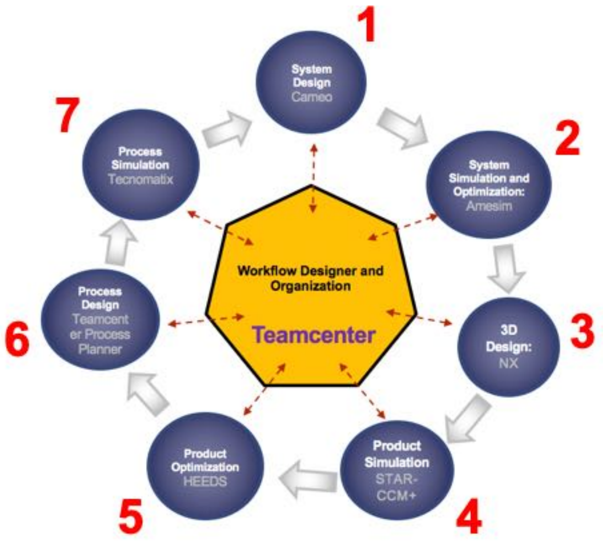
- Creating groups/teams and assigning roles for each team member

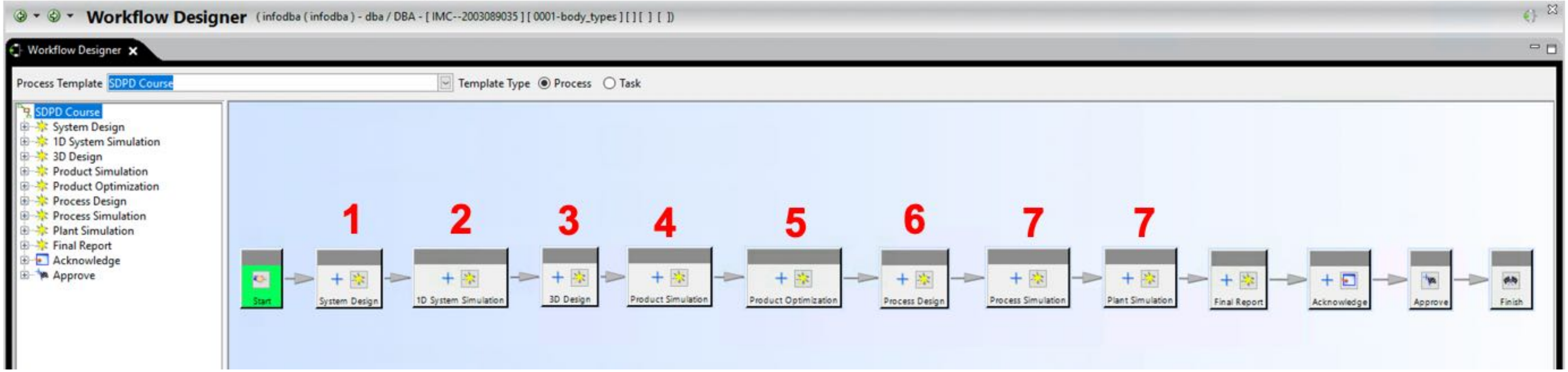
Creating workflow process template describing individual tasks and the task sequence required to model the workflow process

Teamcenter Workflow



Different roles (all for students except "Instructor" and "TA")



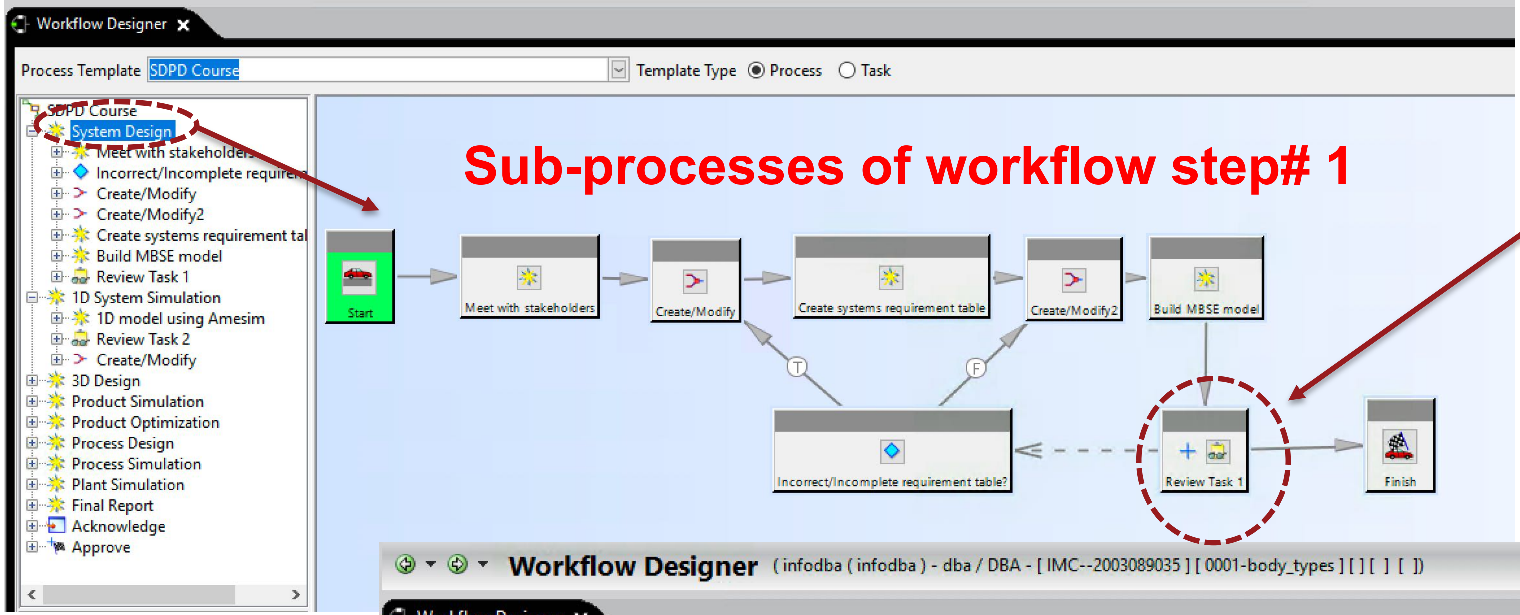


MBSE Lightning Round

Practice – Case studies → Electric Longboard: Project Workflow (Project definition and Planning)

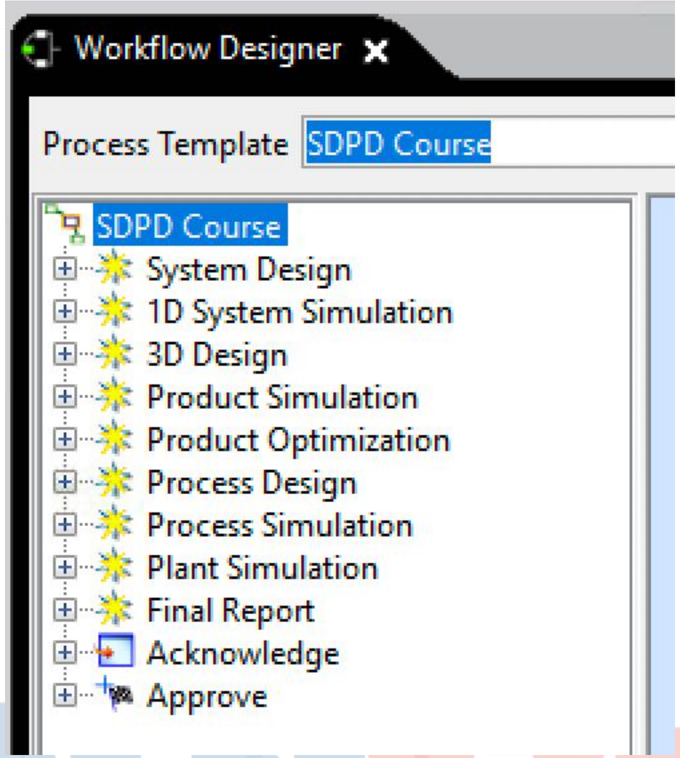
Teamcenter Workflow

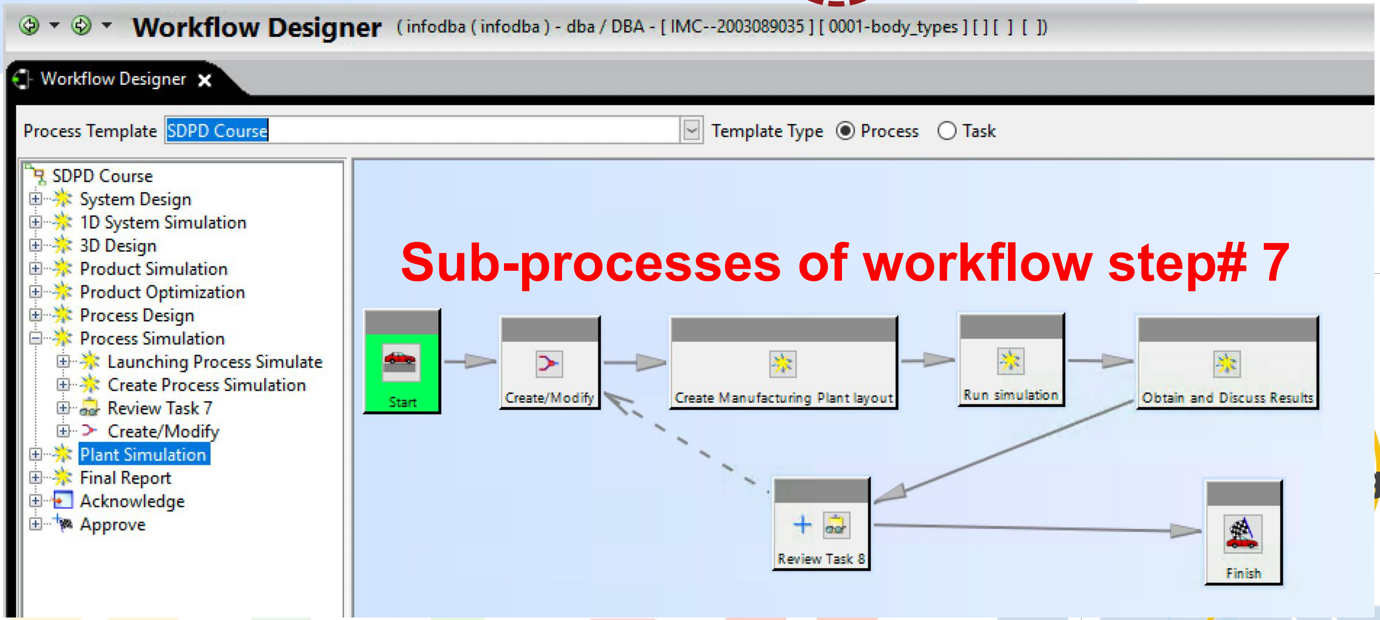
- Each task defines a set of actions, rules, and resources used to accomplish that task



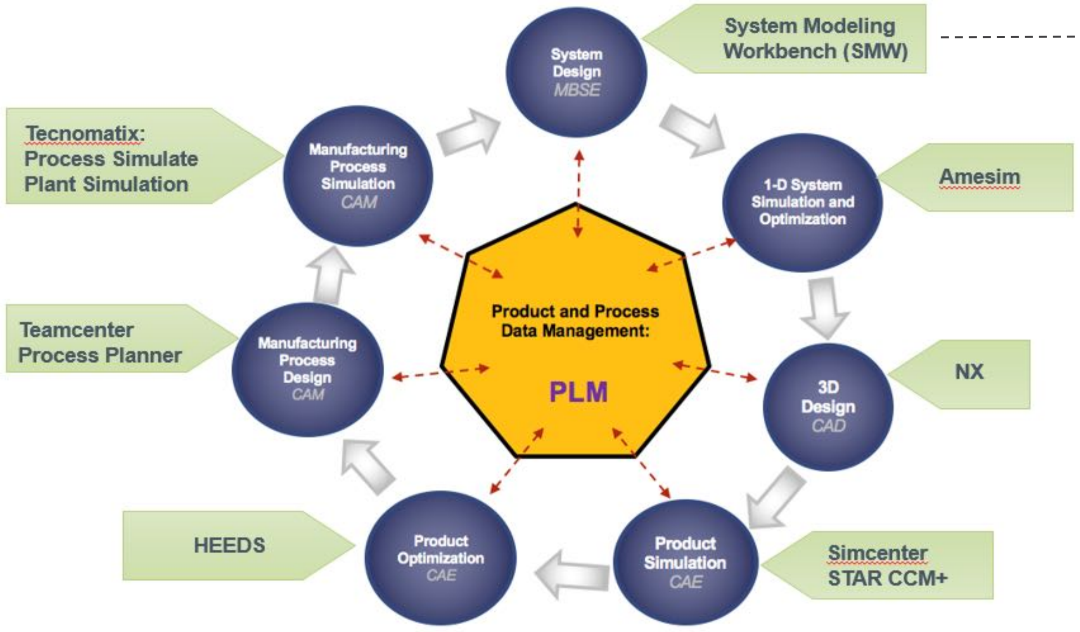
Review by TA

Workflow steps





Practice – Case studies → Electric Longboard: System architecture using Systems Modeling Workbench/Cameo



iMBSE implementation workflow

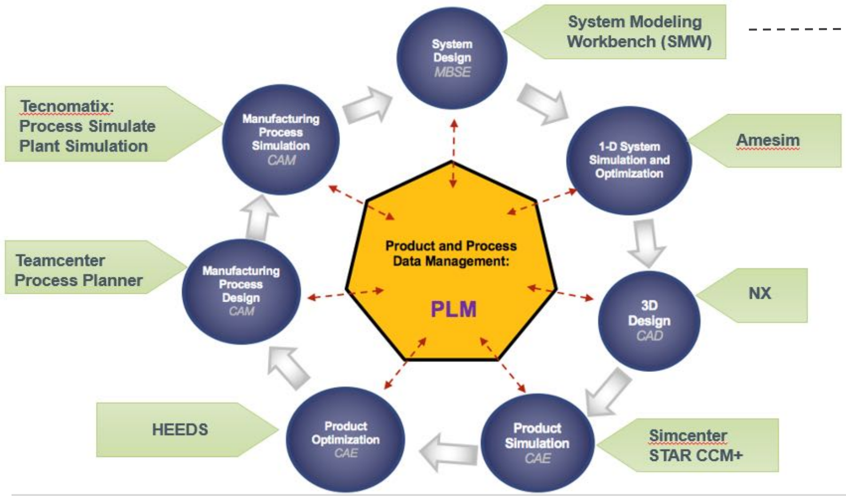
- Model Based Systems Engineering (MBSE)
- Create a systems model and a single source of information
- Requirements, structure, behaviors
- General insight of purpose of creating the Skateboard

Deliverable: System Architecture of Electric Skateboard

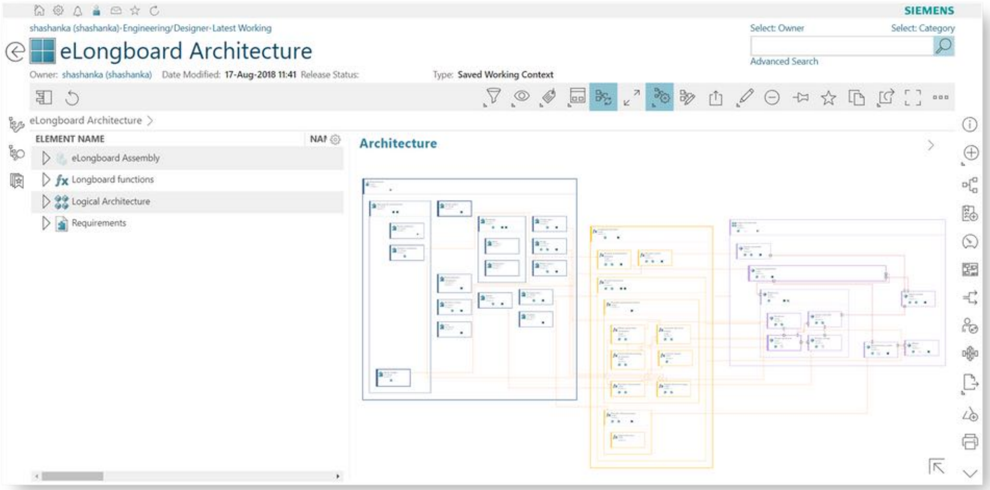
#	Name	Text
1	1 SN01	The system shall transport the user at least 10 miles at an average speed of 10 miles per hour in a single charge
2	1.1 SN01-1	The system shall transport user with a speed greater than 10 meter per second
3	1.2 SN01-2	The system shall transport user for at least 10 miles in a single charge
4	2 SN02	The user shall be able to control the speed and stop within safe distance
5	2.1 SN02-1	The user shall be able to control the speed
6	2.2 SN02-2	The user shall be able to stop within safe distance
7	4 SN03	The skateboard shall stop within safe distance
8	5 SN04	The skateboard shall have speed setting for Novice, Regular and expert levels
9	6 SN05	The skateboard shall use commercially available off the shelf materials (COTS)
10	7 SN06	The skateboard shall use readily available energy source with sufficient energy to meet daily needs
11	8 SN07	The system shall have a portable controller to energize the skating engine, control speed and monitor operation status

Stakeholder requirements

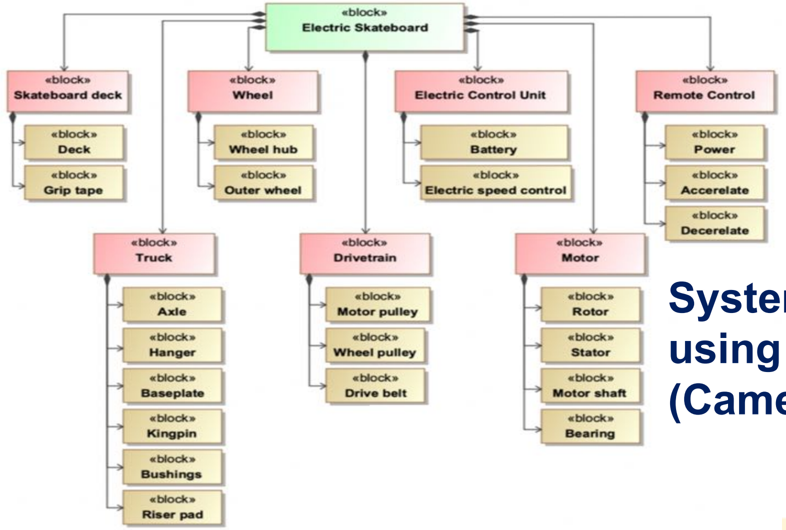
Practice – Case studies → Electric Longboard: System architecture using Systems Modeling Workbench/Cameo



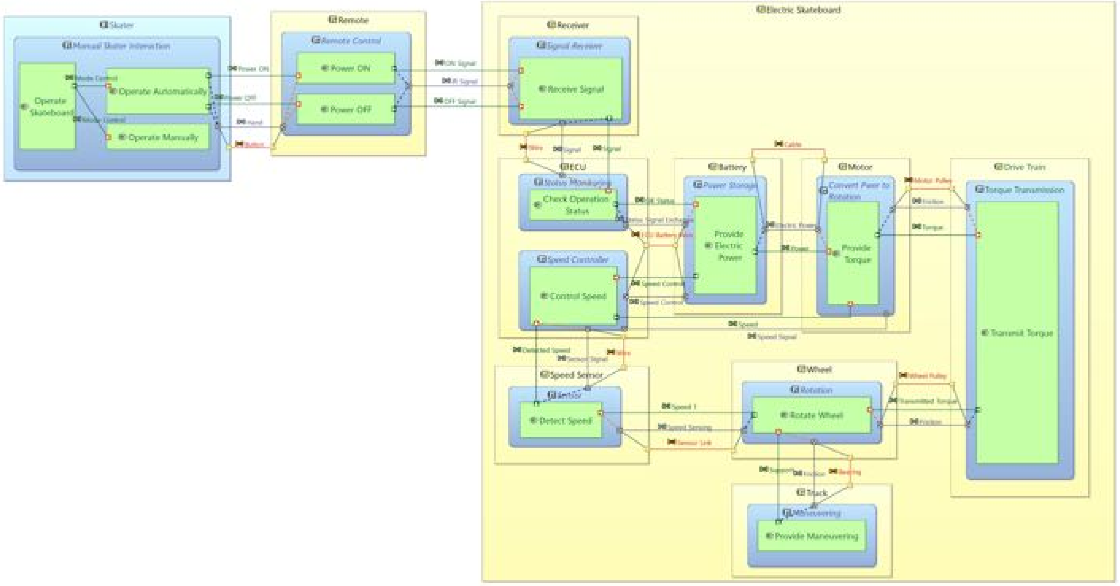
iMBSE implementation workflow



System architecture (Siemens SMW)



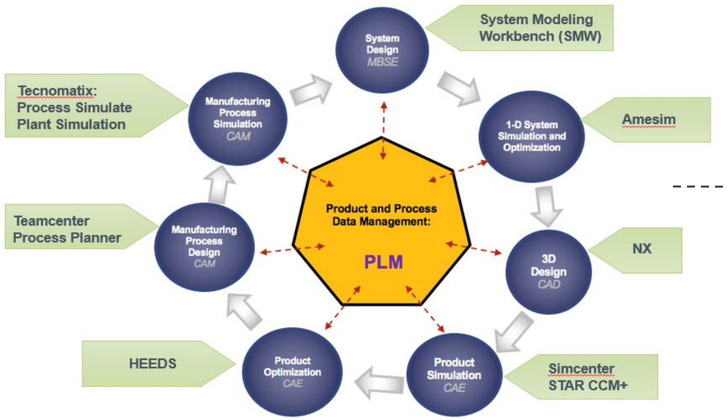
System structure using BDD diagram (Cameo)



Physical Architecture of E-board (using Capella tool)

MBSE Lightning Round

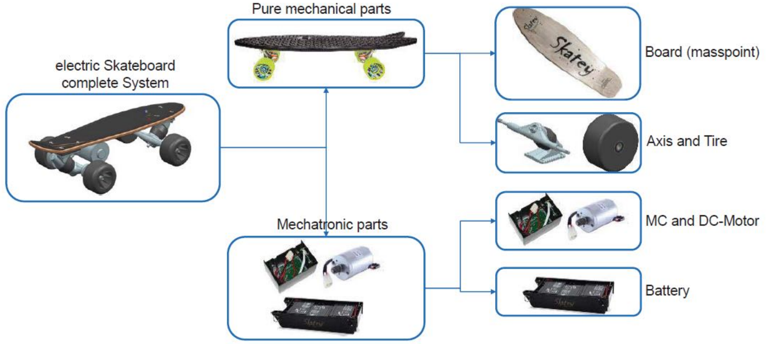
Practice – Case studies → Electric Longboard: 1D simulation and optimization using Amesim



LMS Imagine. Lab Amesim:

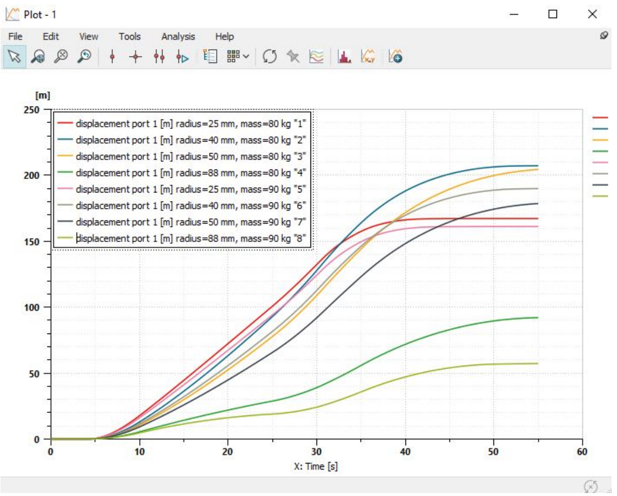
- Modeling and analysis of multi-domain systems
- Create 1D system simulation
- Graphical representation of the whole system
- Performance plots of the skateboard as the output
- Outputs caused by different user's weight

Deliverable: System Architecture of Electric Skateboard

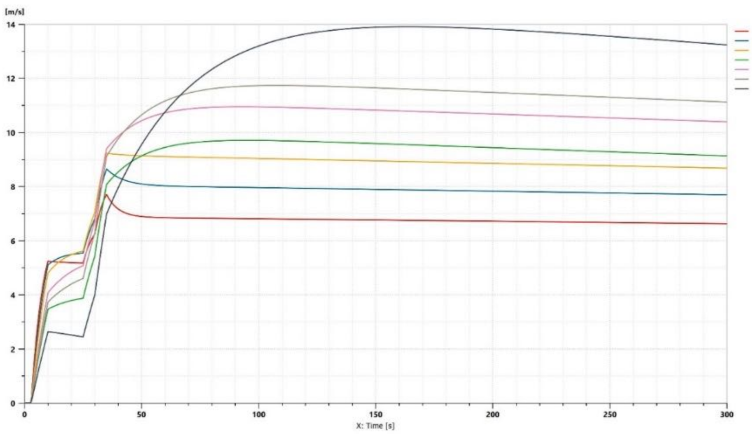


Electric Skateboard: Multi-domain System

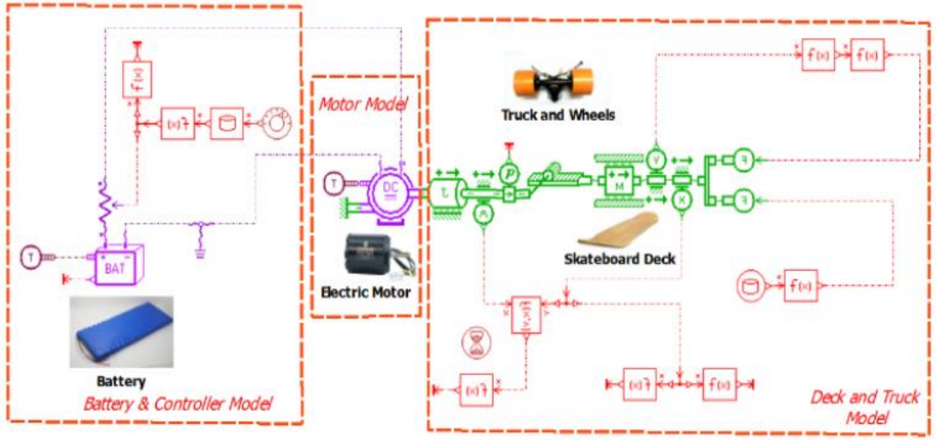
iMBSE implementation workflow



Displacement for different wheel radius & user's weight



Max. velocity for different wheel radius



1D multi-domain system simulation model (Siemens Amesim)

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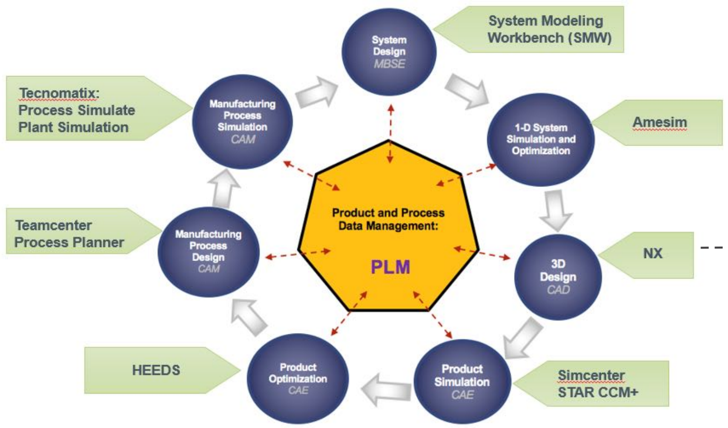
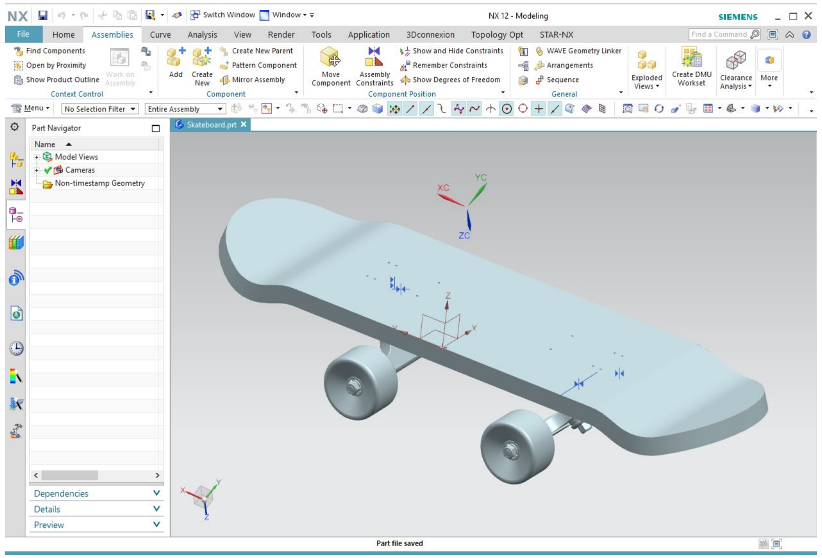
Practice – Case studies → Electric Longboard: 3D modeling using NX CAD



iMBSE implementation workflow

NX:
- Design and modelling of skateboard

Deliverable: 3D model of Electric Skateboard



3D model of Skateboard

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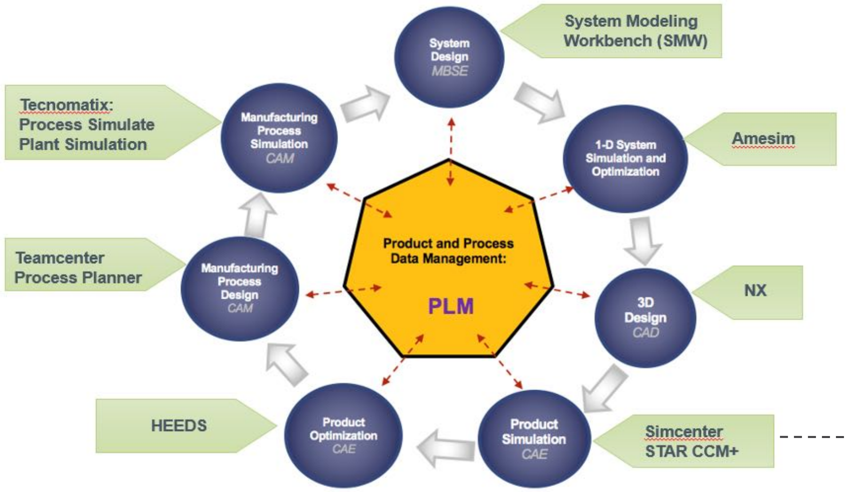
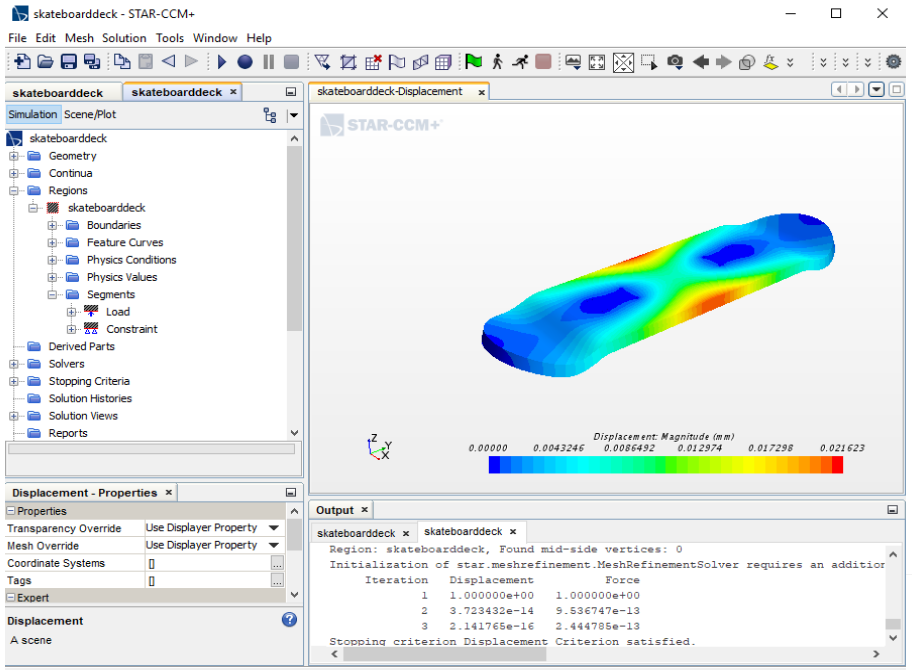
Practice – Case studies → Electric Longboard: 3D simulation using NX Nastran / Star-CCM+



Star-CCM+ / Nastran:

- CFD and Structural analysis
- The structural analysis of the board with static loads 200 lb
- Von-Mises stress and displacement of the board



iMBSE implementation workflow

Deliverable: 3D Simulation model of Electric Skateboard

3D simulation: Von-Mises stress in skateboard deck

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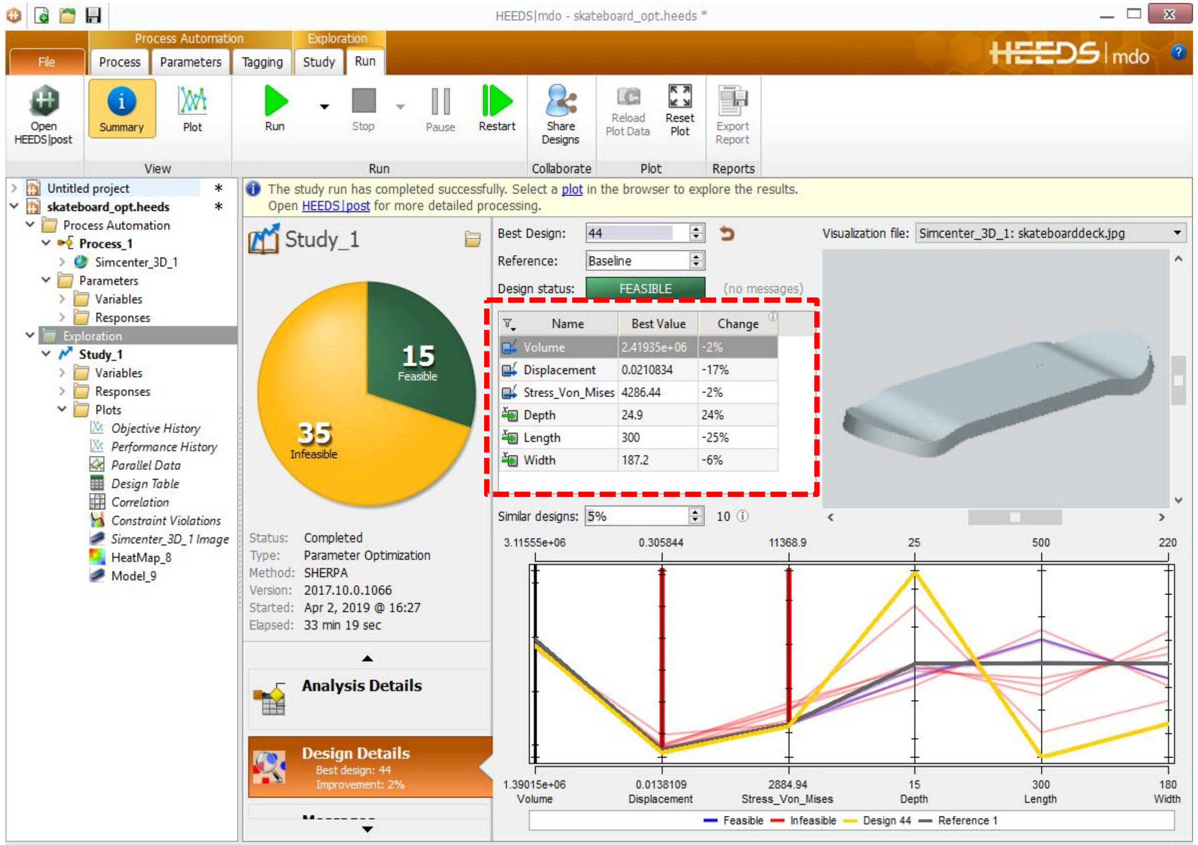
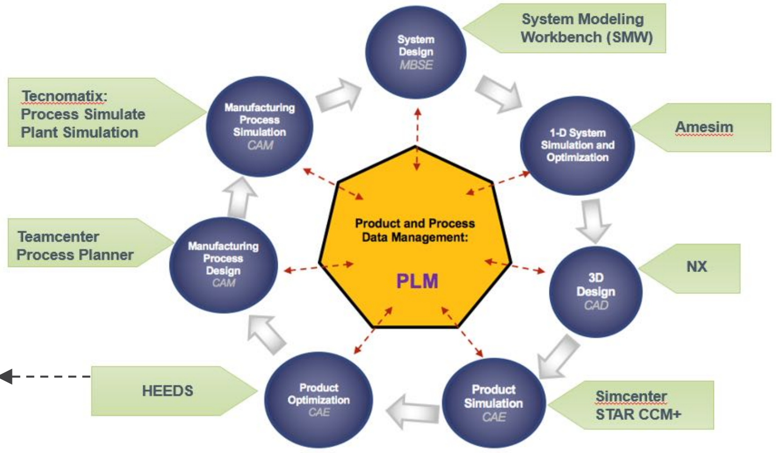
Practice – Case studies → Electric Longboard: 3D optimization using HEEDS



Optimization of 3D geometry of skateboard deck

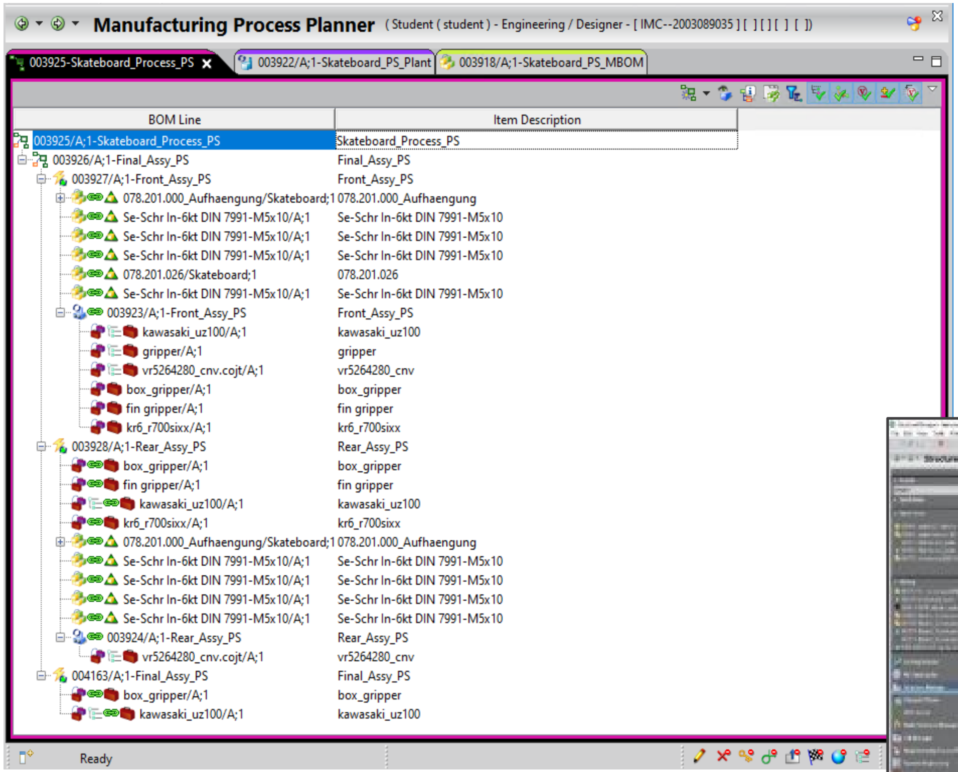
HEEDS (Hierarchical Evolutionary Engineering Design System):
- Optimization for better and more robust solutions within a given design space



<u>Deliverable</u>:
Optimized 3D deck geometry

iMBSE implementation workflow

Practice – Case studies → Electric Longboard: Manufacturing process design using MPP



BOM Line	Item Description
003925/A;1-Skateboard_Process_PS	Skateboard_Process_PS
003926/A;1-Final_Assy_PS	Final_Assy_PS
003927/A;1-Front_Assy_PS	Front_Assy_PS
078.201.000_Aufhaengung/Skateboard;1	078.201.000_Aufhaengung
Se-Schr In-6kt DIN 7991-M5x10/A;1	Se-Schr In-6kt DIN 7991-M5x10
Se-Schr In-6kt DIN 7991-M5x10/A;1	Se-Schr In-6kt DIN 7991-M5x10
Se-Schr In-6kt DIN 7991-M5x10/A;1	Se-Schr In-6kt DIN 7991-M5x10
078.201.026/Skateboard;1	078.201.026
Se-Schr In-6kt DIN 7991-M5x10/A;1	Se-Schr In-6kt DIN 7991-M5x10
003923/A;1-Front_Assy_PS	Front_Assy_PS
kawasaki_uz100/A;1	kawasaki_uz100
gripper/A;1	gripper
vr5264280_cnv.cojt/A;1	vr5264280_cnv
box_gripper/A;1	box_gripper
fin gripper/A;1	fin gripper
kr6_r700sixx/A;1	kr6_r700sixx
003928/A;1-Rear_Assy_PS	Rear_Assy_PS
box_gripper/A;1	box_gripper
fin gripper/A;1	fin gripper
kawasaki_uz100/A;1	kawasaki_uz100
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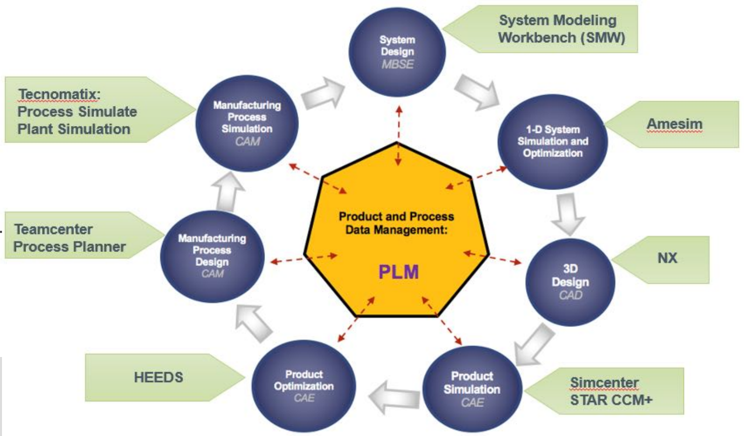
Se-Schr In-6kt DIN 7991-M5x10/A;1	Se-Schr In-6kt DIN 7991-M5x10
Se-Schr In-6kt DIN 7991-M5x10/A;1	Se-Schr In-6kt DIN 7991-M5x10
003924/A;1-Rear_Assy_PS	Rear_Assy_PS
vr5264280_cnv.cojt/A;1	vr5264280_cnv
004163/A;1-Final_Assy_PS	Final_Assy_PS
box_gripper/A;1	box_gripper
kawasaki_uz100/A;1	kawasaki_uz100

BOM of Skateboard

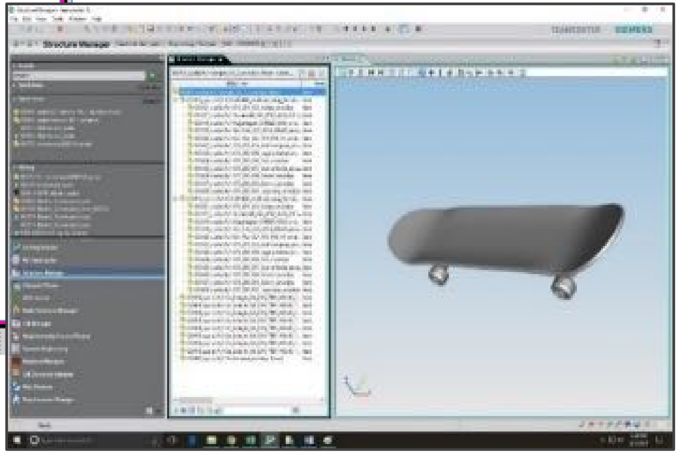
Teamcenter Manufacturing Process Planner (MPP):

- Product Lifecycle Management (PLM)
- Develop product and manufacturing process
- Manage manufacturing data, process, resource and plant information
- Seamless alignment between engineering bill of materials (BOM), manufacturing BOM and the manufacturing bill of process (BOP)



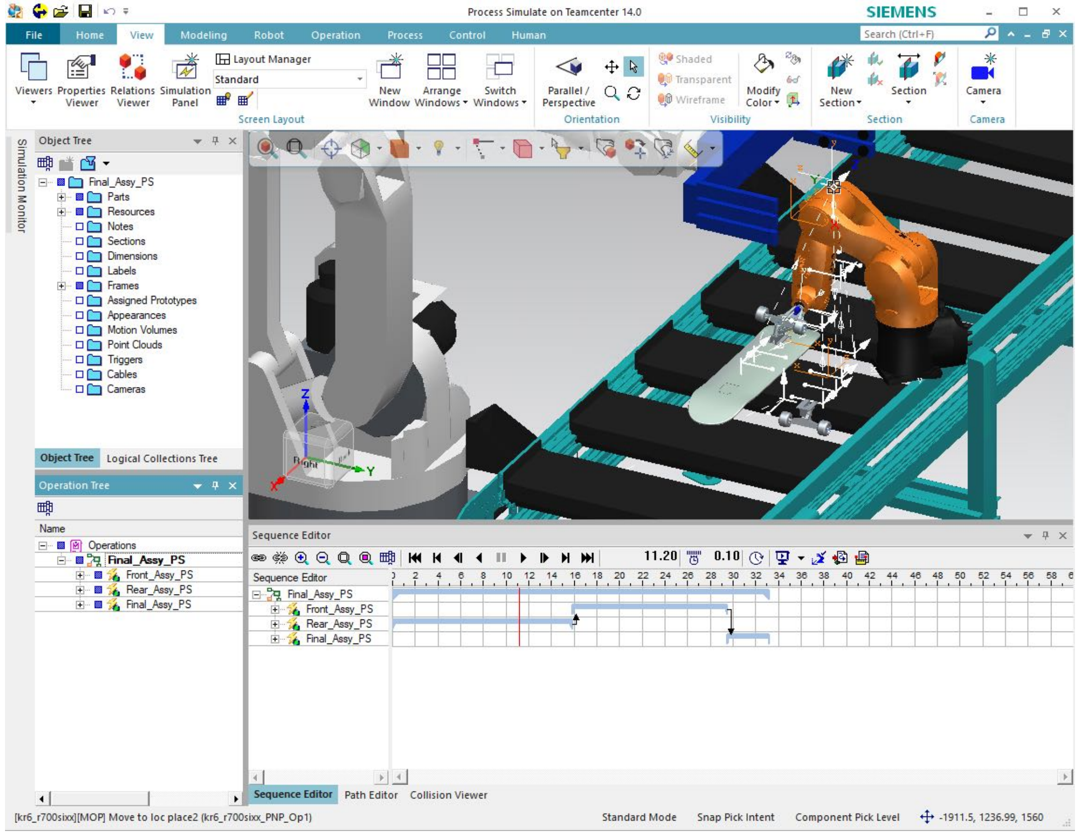
Deliverables: Manufacturing Process (BOM, BOP, etc.) of Electric skateboard assembly

iMBSE implementation workflow



MBSE Lightning Round

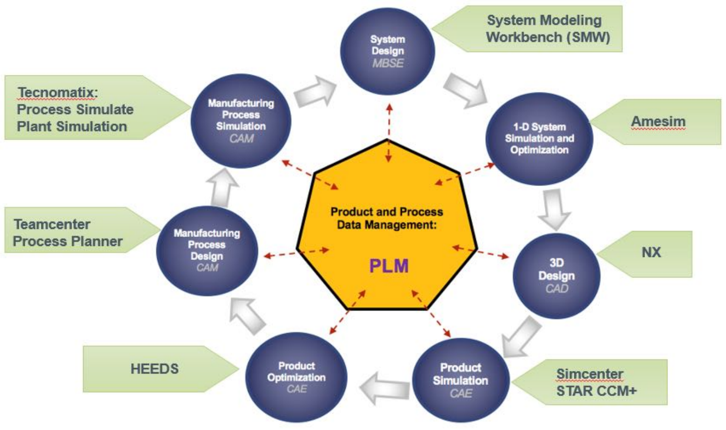
Practice – Case studies → Electric Longboard: Manufacturing Process simulation using Tecnomatix



Simulation of Skateboard assembly

Tecnomatix Process Simulate :
- Simulation and optimization of production systems and processes
- Taking skateboard through assembly
- Verify reachability and collision clearance
- Simulating the full assembly sequence of the product and the required tools

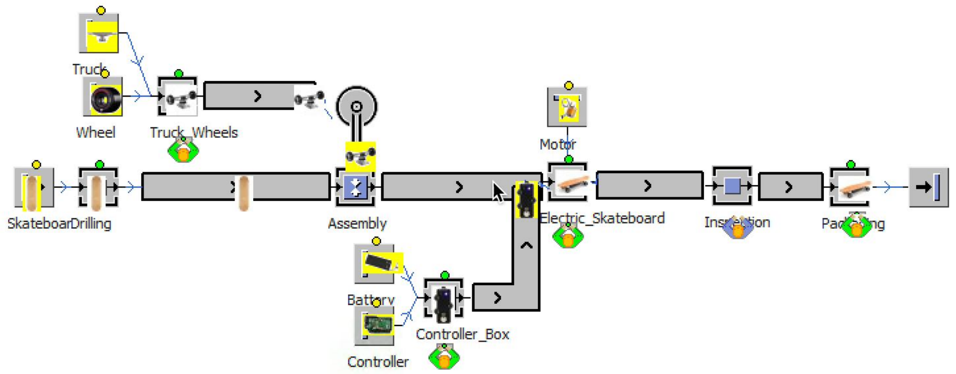
<u>Deliverable</u>: Simulation model of Electric skateboard assembly



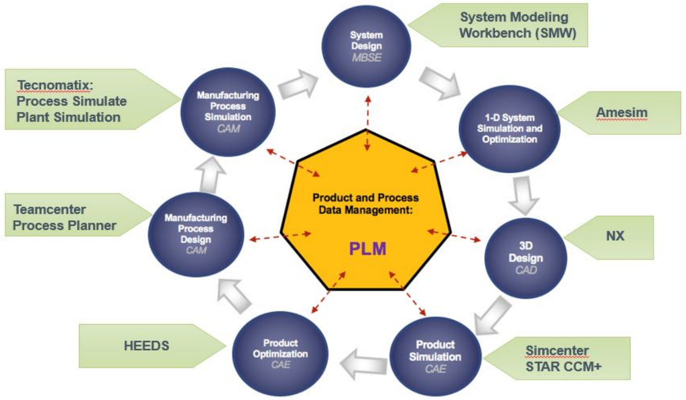
iMBSE implementation workflow

MBSE Lightning Round

Practice – Case studies → Electric Longboard: Plant Simulation using Tecnomatix

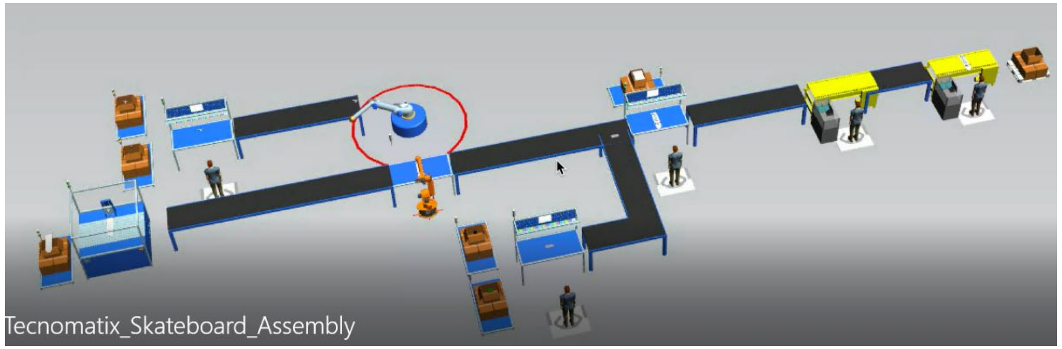


Tecnomatix Process Plant Simulation:
- Simulation and optimization of production systems and processes
- Taking skateboard through production
- Simulating the full production of the product



<u>Deliverable</u>: Simulation model of Electric skateboard production line

iMBSE implementation workflow



Simulation of Skateboard production line (Top: 2D; Bottom: 3D)

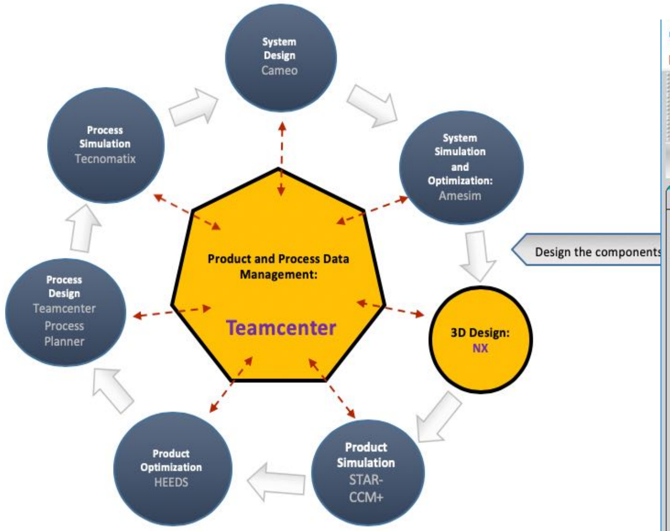
MBSE Lightning Round

Practice – Case studies → Electric Longboard: Traceability

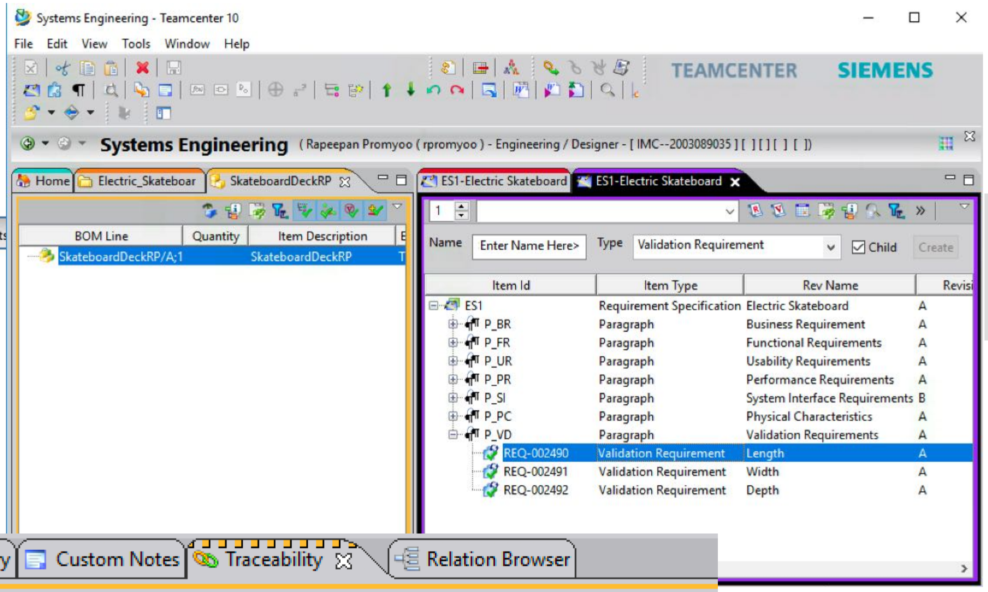
Electric Skateboard/Longboard RFLP

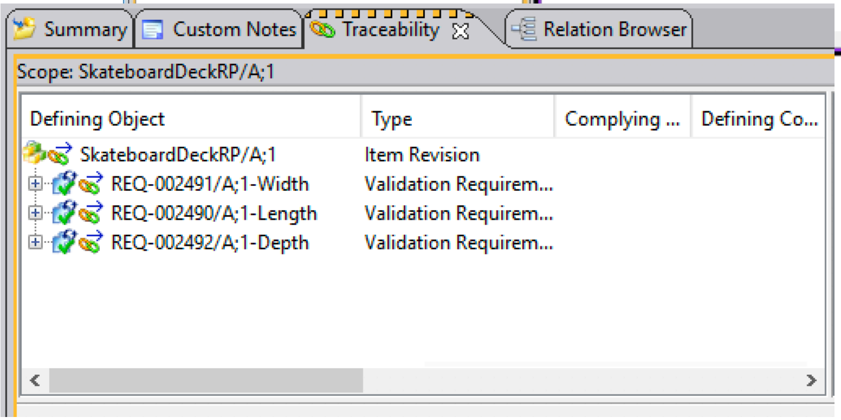
MBSE Lightning Round

Practice – Case studies → Electric Longboard: Traceability → TC ↔ NX



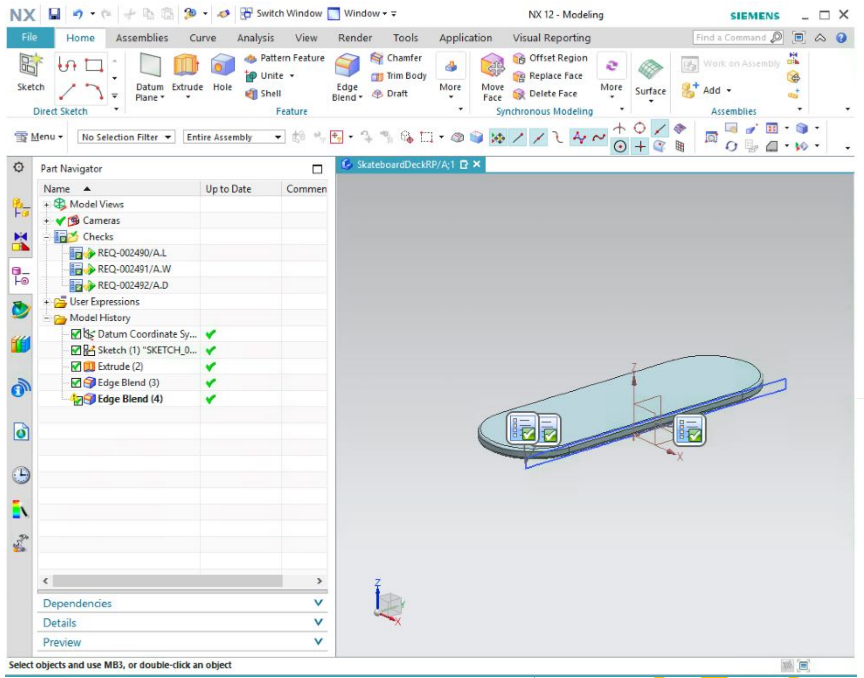
iMBSE implementation workflow



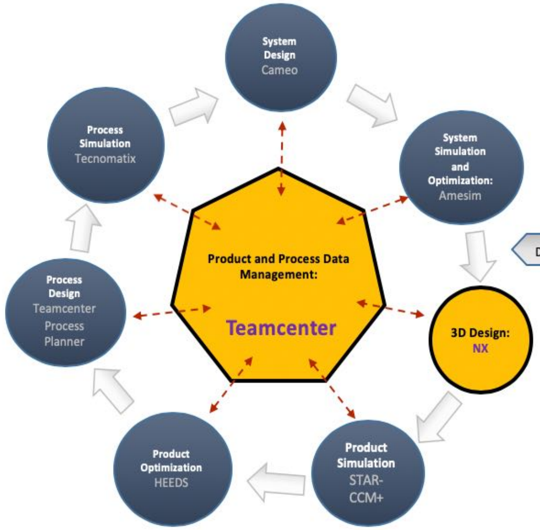


- NX Design
- Create traceability between requirements and Design geometry (3D model)

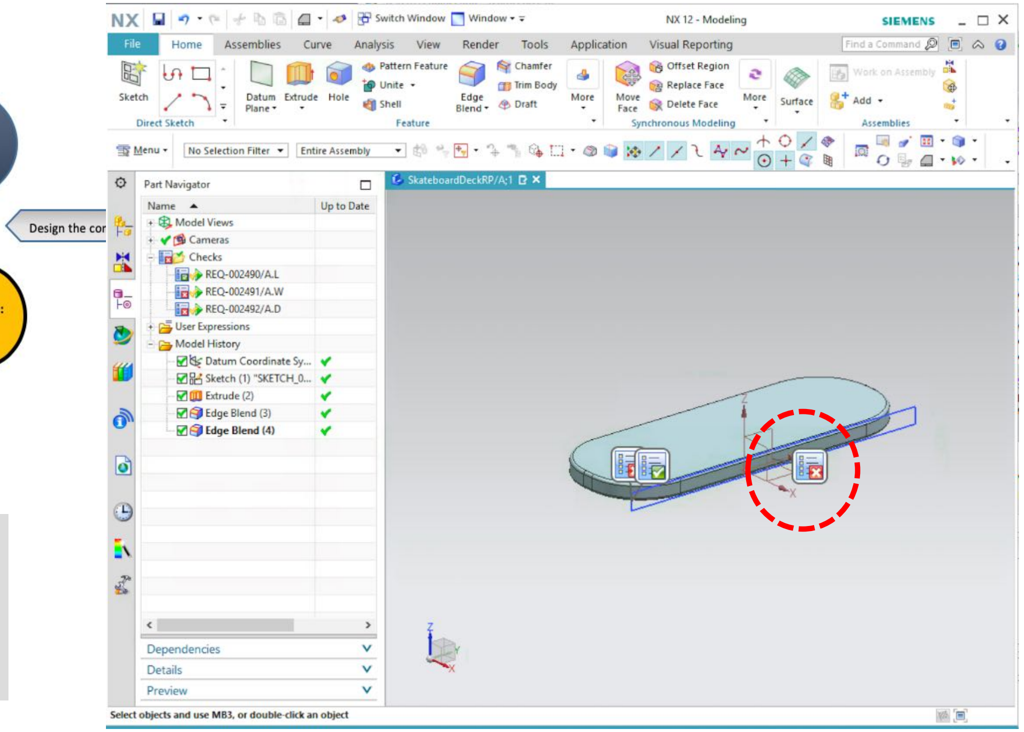
Deliverable: 3D NX design linked to validation requirements in TC SE

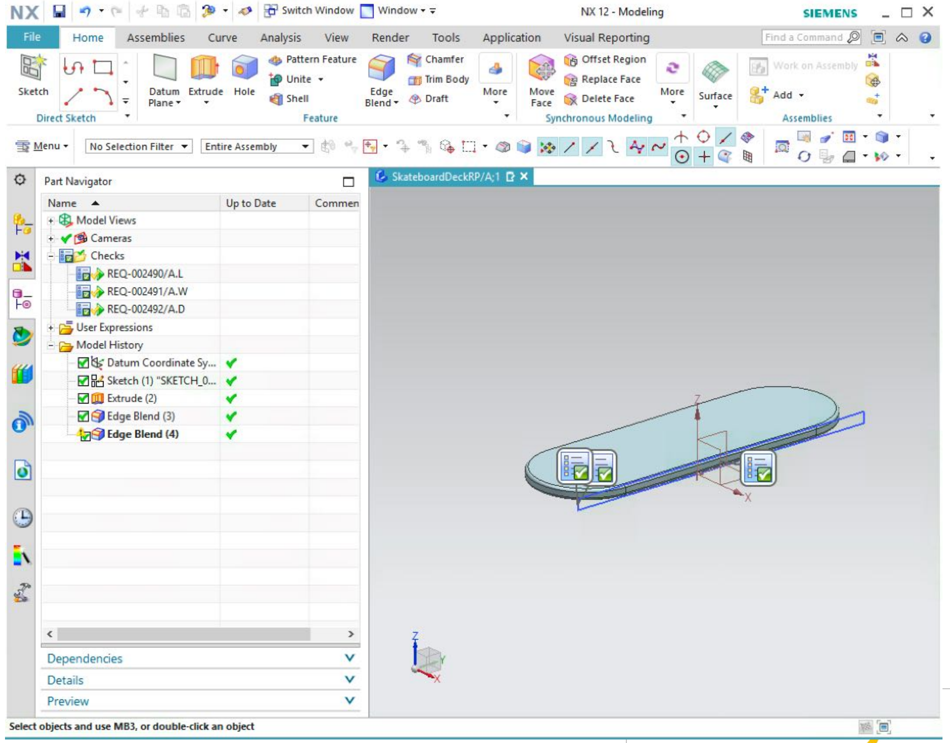


Practice – Case studies → Electric Longboard: Traceability → TC ↔ NX (cont')



iMBSE implementation workflow

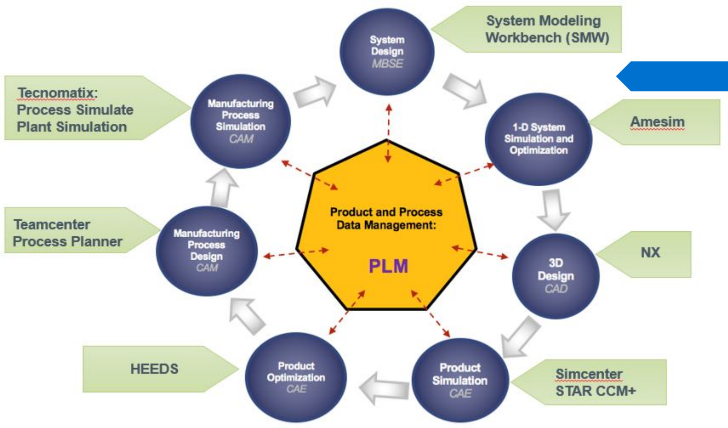




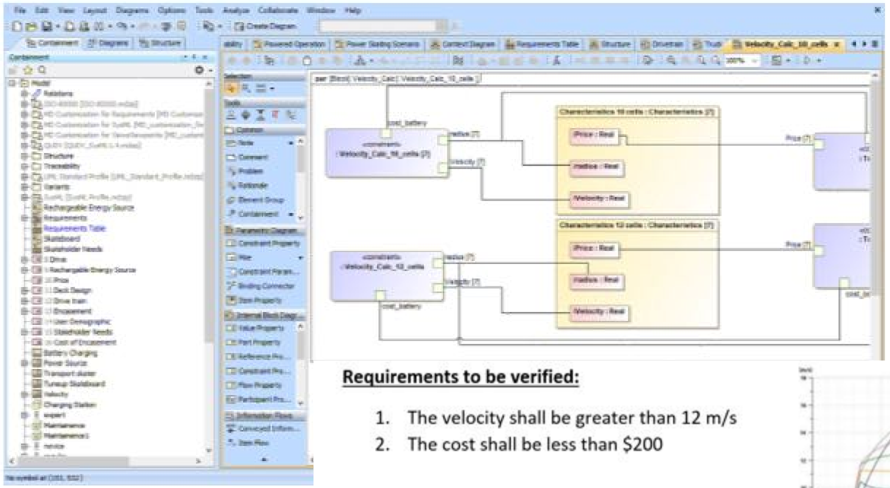
The validation results failed two of the requirements.

The validation results passed all the requirements.

Practice – Case studies → Electric Longboard: Traceability → Cameo ↔ Amesim



iMBSE implementation workflow



0D requirements model

- 1D Simulation model
- 0D requirement model

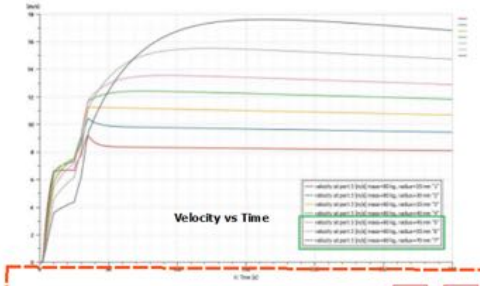
<u>Deliverable</u>: System design that meets requirements

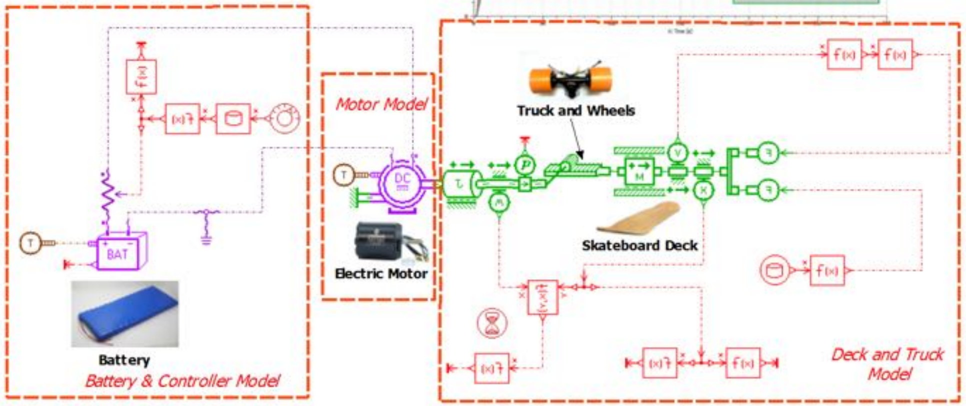
Requirements to be verified:

1. The velocity shall be greater than 12 m/s
2. The cost shall be less than $200

Parameters to be varied:

1. Wheel radius
2. Battery size (# of cells)

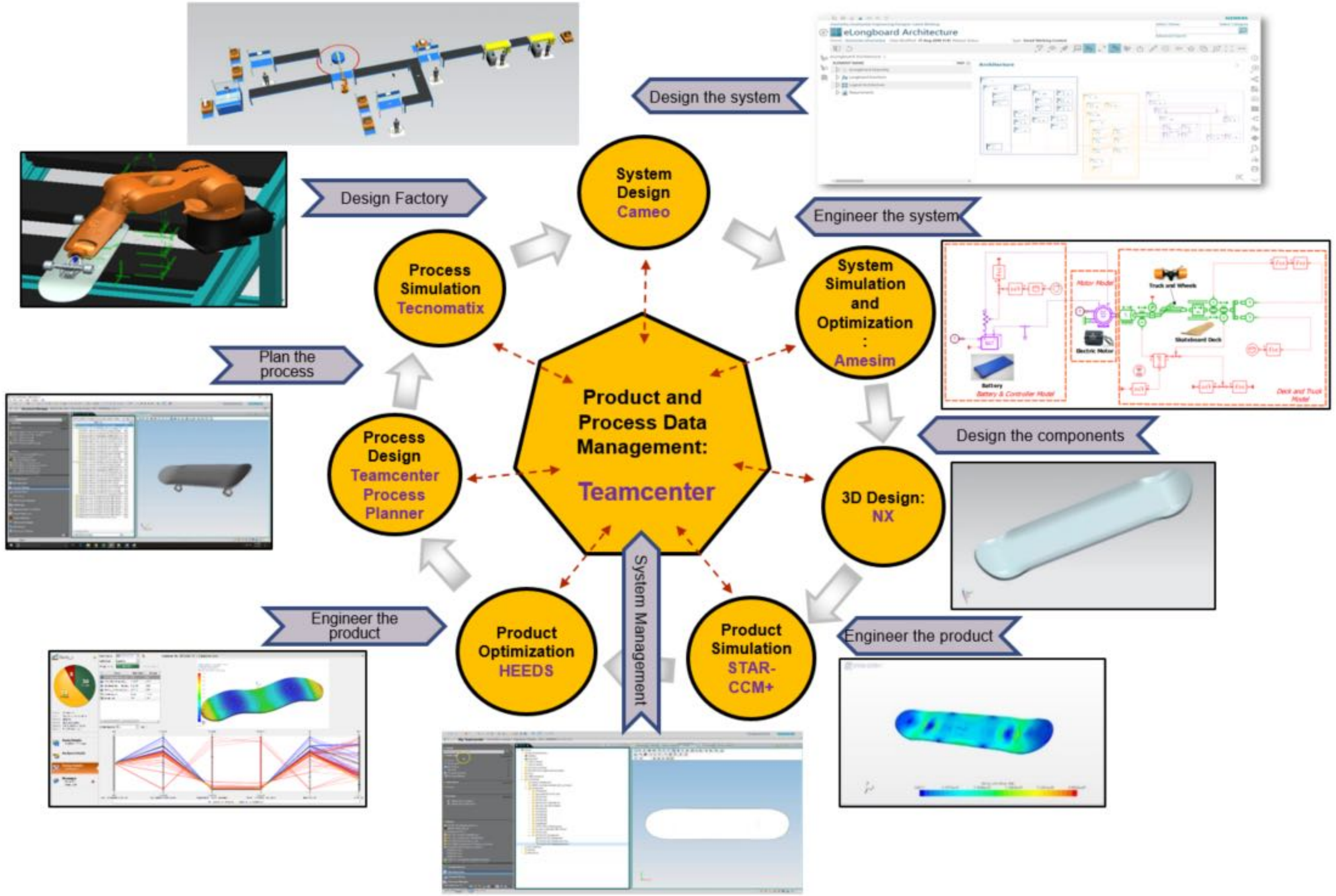




1D Simulation for predicting system's performance: Max. velocity, etc.

MBSE Lightning Round

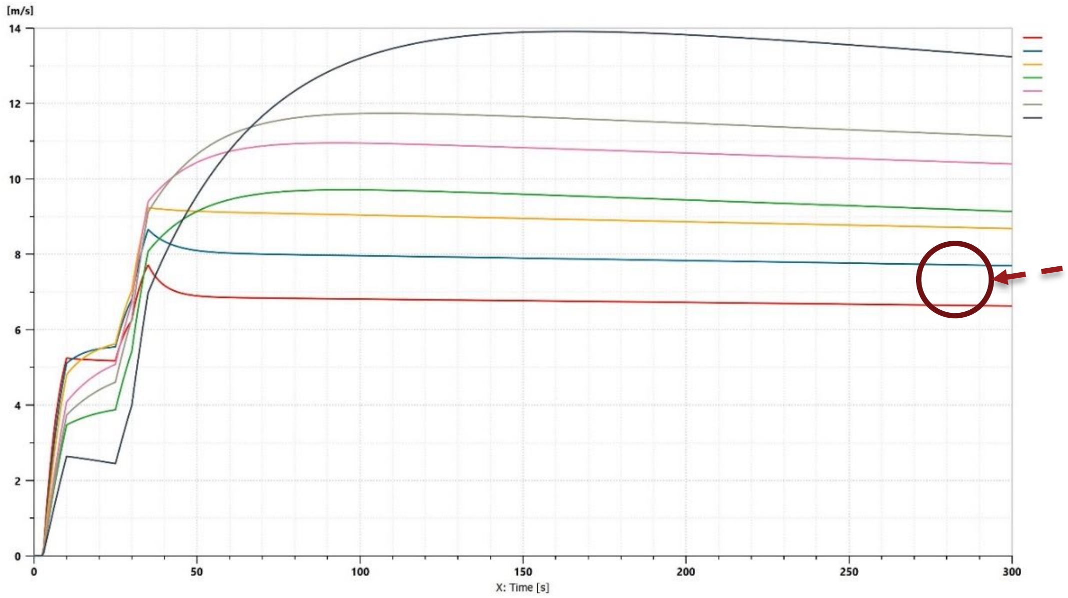
Practice – Case studies → Electric Longboard: Summary of digital implementation



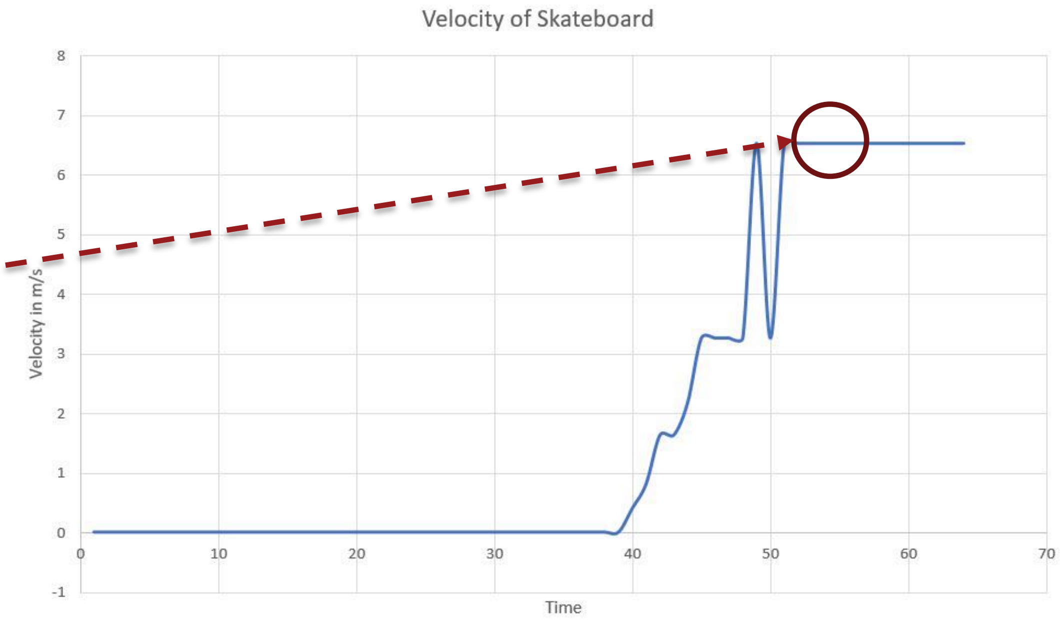
Implementing iMBSE workflow: Summary of deliverables

MBSE Lightning Round

Practice – Cases studies → Electric Longboard: Validation



Simulation results from Amesim 1D (Digital twin)



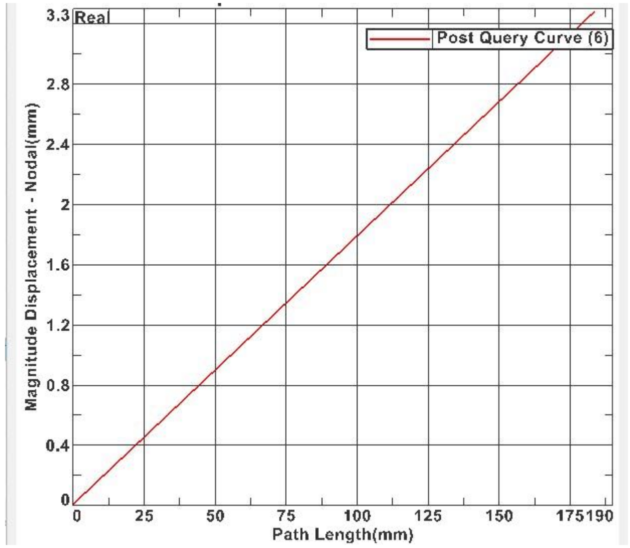
Experimental results from Optical Encoder (Physical

Velocity m/s (no load condition)	
Amesim	6.8
Optical Encoder	6.6

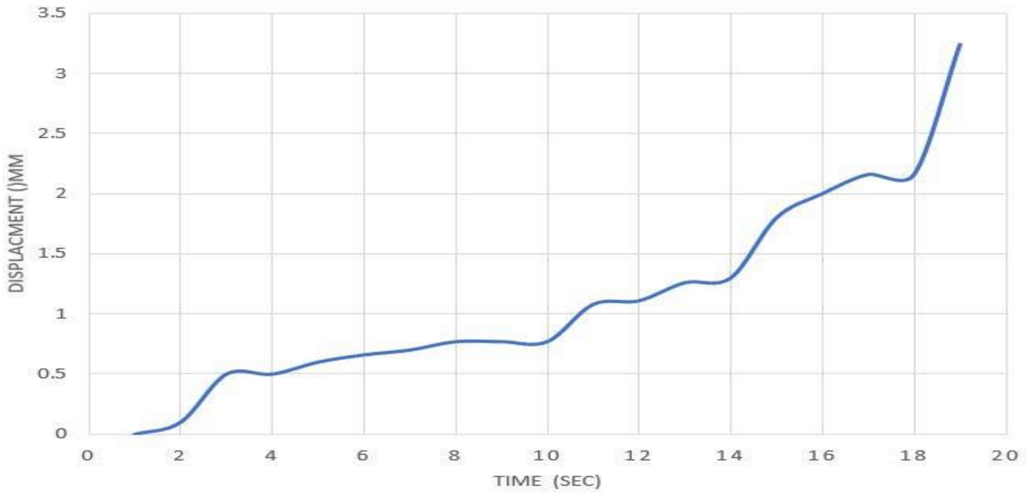
Electric Saketboard/Longboard Validation: Max. velocity

MBSE Lightning Round

Practice – Case studies → Electric Longboard: Validation



Simulation results from Simcenter 3D (Digital twin)



Experimental results from Flex Sensors (Physical twin)

Deflection mm	Flex Sensor	Simcenter
Flex 1	0.91	0.7
Flex 2	1.71	1.354
Flex 3	3.3	3.45

Electric Longboard Validation: Deformation

MBSE Lightning Round

Summary & conclusions

Key aspects of iMBSE implementation for the electric skateboard

1. Modeling and Simulation Continuum
2. Traceability
3. Digital Thread

Industry 4.0: Current challenges/Limitation faced by Academia

1. Lack of education (curriculum/certification) for Industry 4.0, including iMBSE, MBE, Digital twin, Digital Thread, etc.
2. MBE/iMBSE skills not clearly articulated/defined by industry
3. Cost of infrastructure (both hardware and software)
4. Limited ability to deliver graduates with the required skills to support/drive the digital transformation
5. Limited ability to support the needs of industry for the digital transformation

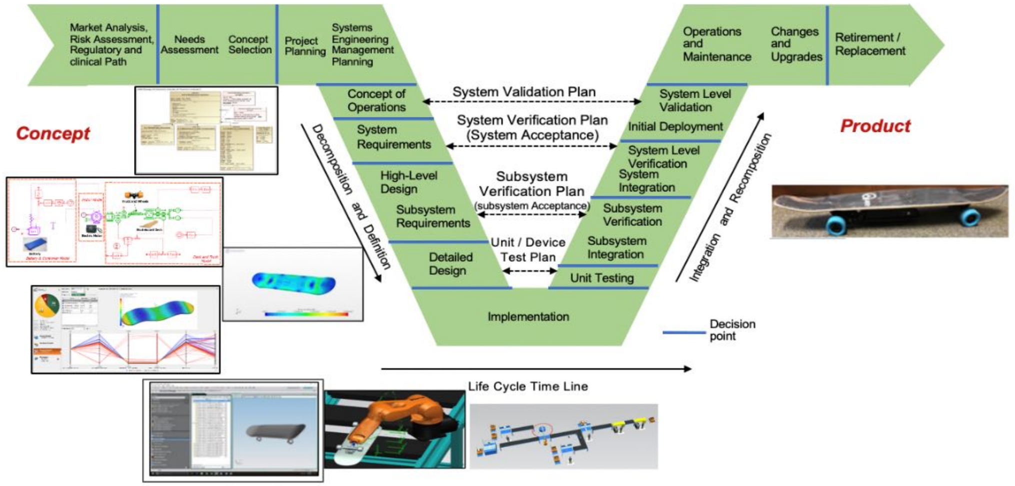
MBSE Lightning Round

Summary & conclusions

Engineering Education: Traditional vs. Industry 4.0

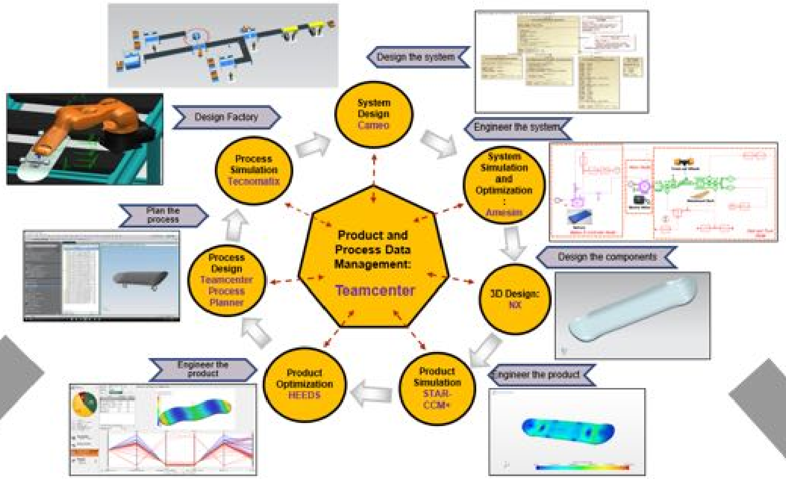
Current Engineering Education landscape	Engineering Education for Industry 4.0
Single domain/discipline	Multi-disciplinary, Integrated
Technology/Tools taught by technology programs/community colleges	Offered by Engineering colleges (4 year)
Limited relevance to Industry practice, including Industry 4.0	Driven by Industry (consortium): Applied as well as closely relevant/related engineering curriculum to Industry 4.0

The proposed iMBSE workflow is about the "Digitalization" of the SE process

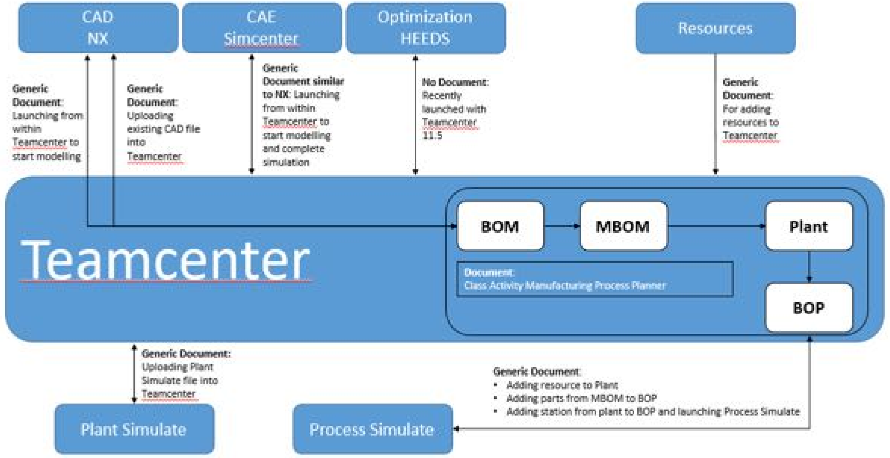


MBSE Lightning Round

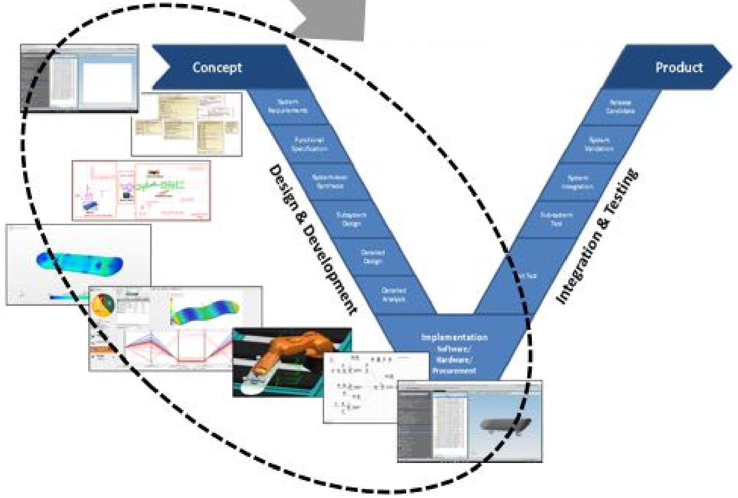
Summary & conclusions



Teamcenter as the digital thread in iMBSE framework



"Digital Twin" in iMBSE framework



iMBSE = Digital twin + Digital thread

Summary & conclusions

BENEFITS FOR STUDENTS:

SDPD (or MB-SDPD) curriculum allows a paradigm shift in engineering education, for improved synthesis of engineering knowledge and its implementation in different modern product lifecycle applications

SDPD approach and framework allows student (teams) to successfully complete modern product development within the timeline of one semester, which is a paradigm shift in engineering education.

BENEFITS FOR INDUSTRY:

Greater innovation in product development
Increased efficiency
Faster time-to-market
Increased adaptability/agility/customization
Knowledge re-use
Better ability to comply with standards

overall, ***MBSE (SDPD) can lead to significant competitive advantage***.

MBSE Lightning Round

Siemens Integrated Model-based Systems Engineering (iMBSE) Course for Universities – Theory, Practice, and Case Study

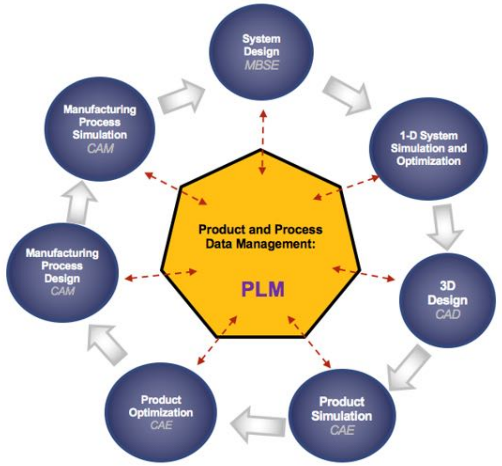
MBSE Course

Theory | **Practice** | **Case study**

Theory: This part of the course consists of lecture material on MBSE, covering the underlying theory of the subject, a detailed overview focusing on MBSE and its relation to SE, as well as Siemens iMBSE framework. In addition, it covers the three pillars of MBSE solution (Methodology, Language, and Tools), and present two of the most applicable solutions, and compares them.

Case study: This part of the course demonstrates the implementation of iMBSE using an Electric skateboard/longboard ("E-board") as the case study. A workflow consisting of 7 major steps integrated through a PLM platform is documented in details. The workflow is implemented using Siemens tools.

Practice: This part of the course provides training on the different Siemens tools used to implement the iMBSE workflow for the E-board case study. Tools include, SMW, Amesim, NX, Simcenter (Nastran), HEEDS, MPP, Tecnomatix, and Teamcenter (AW, Rich Client, and SE)



MBSE Lightning Round

2021 Annual INCOSE international workshop
Virtual Event
January 29 - 31, 2021

Premier Systems Engineering Workshop

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