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

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Unrestricted

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Outline

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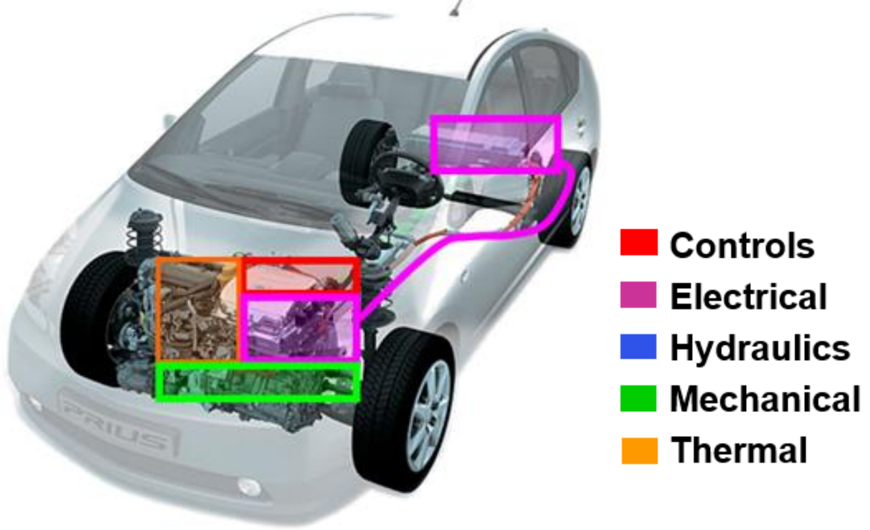
Rationale

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

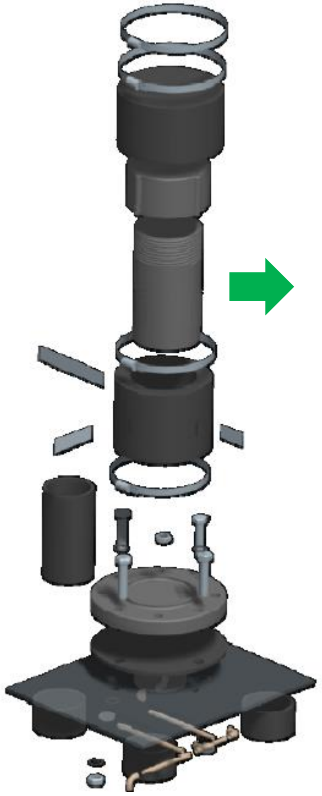


Siemens PLM publication

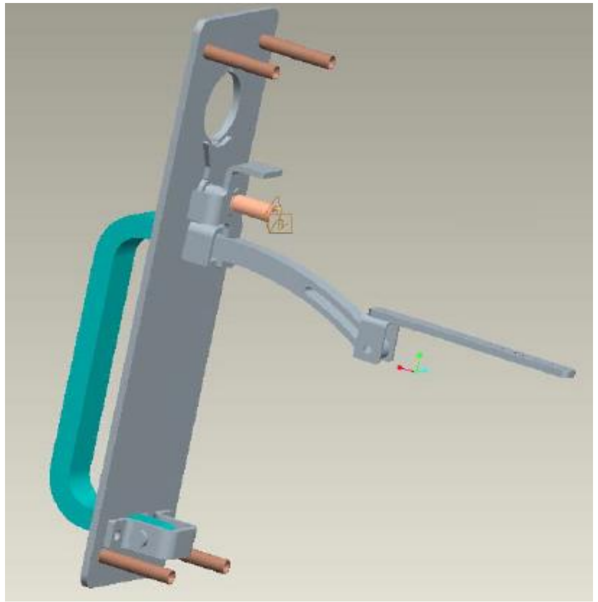
Current practice in Academia

Current practice in Academia → Engineering programs (ME, EnE, EE, CE, BME, IE,…): 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



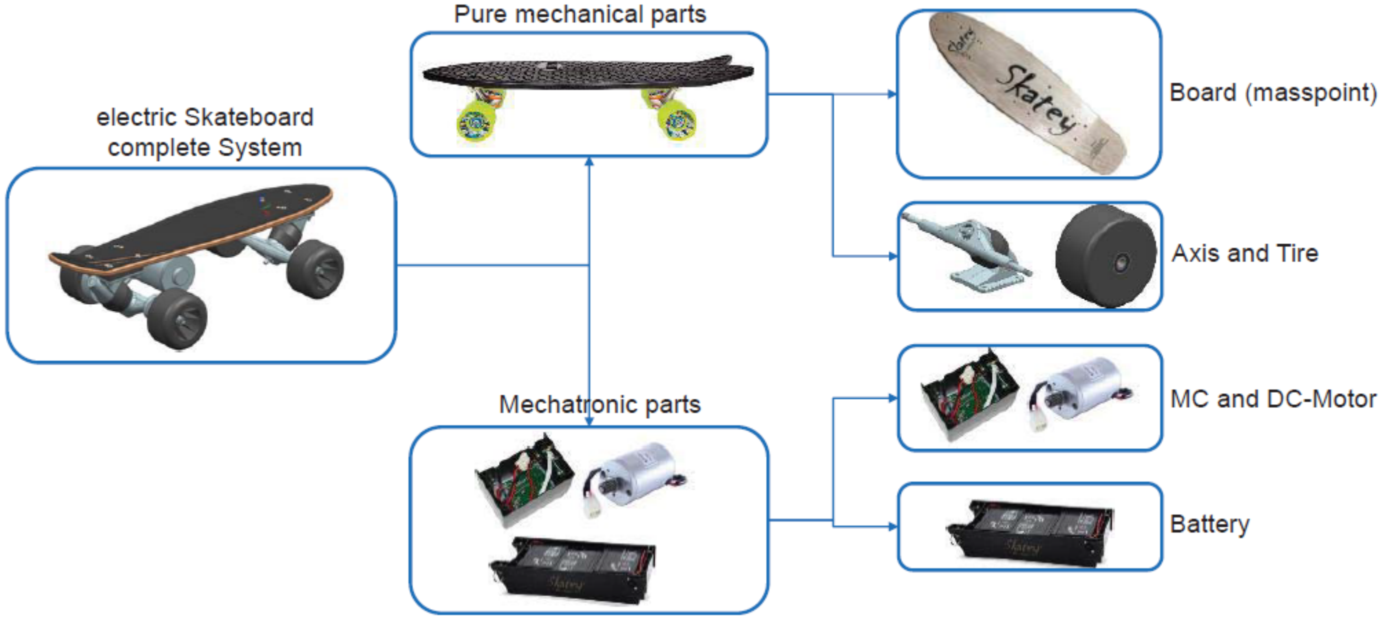
Arm-A-Door Outside Entry: Exterior Handle Assembly

Example of typical capstone design products: Mostly <u>Mechanical</u>

iMBSE: 3D extension of Capstone Design

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

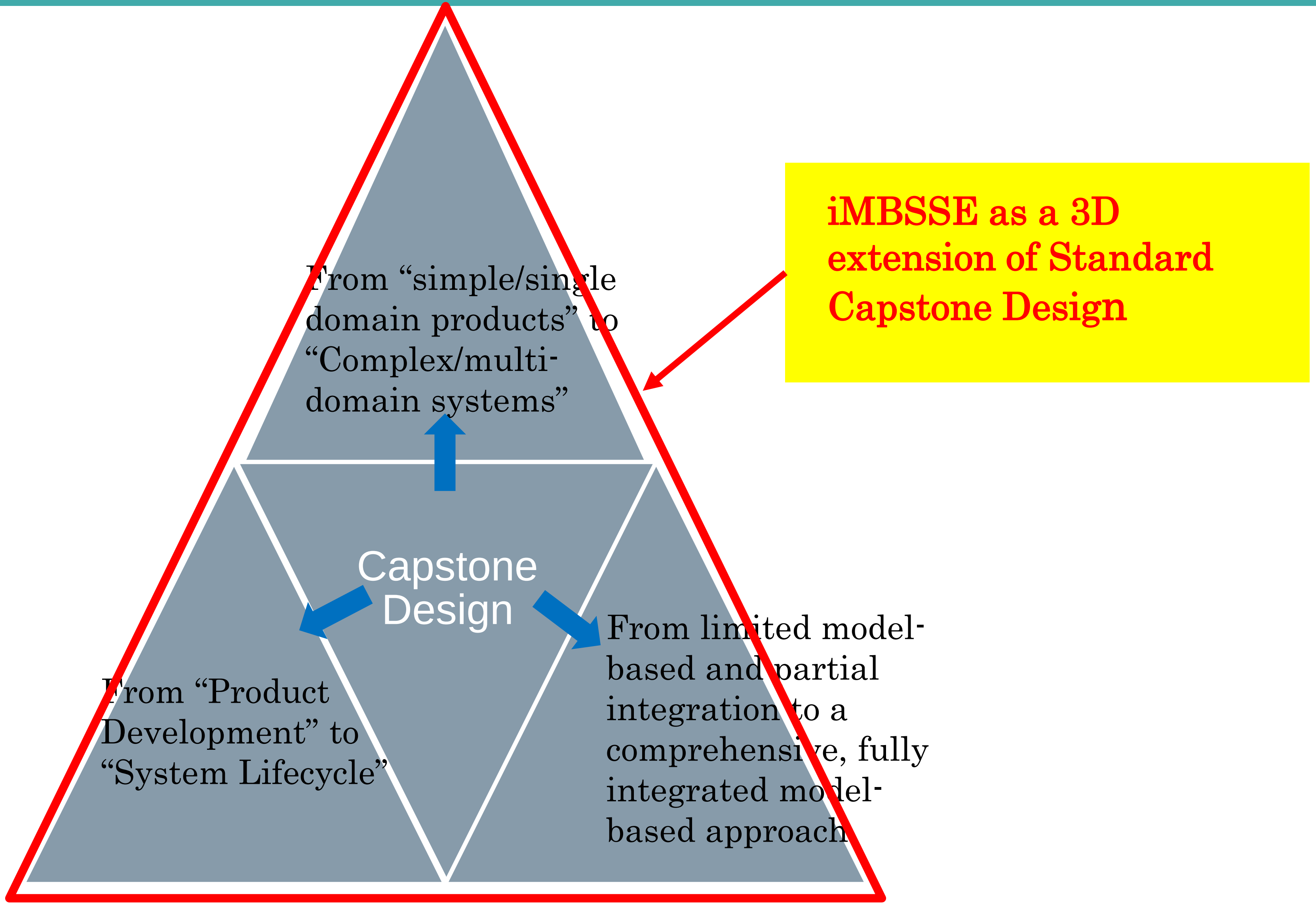
3D extended CD driven by iMBSE
Complex product (system or SoS)
Multi Domain
Extended scope: "Lifecycle" (not just "Development")
Full Digitalization
Validation: SIL, HIL, MIL, and Virtual prototyping



Example of a complex product: Multi-domain system

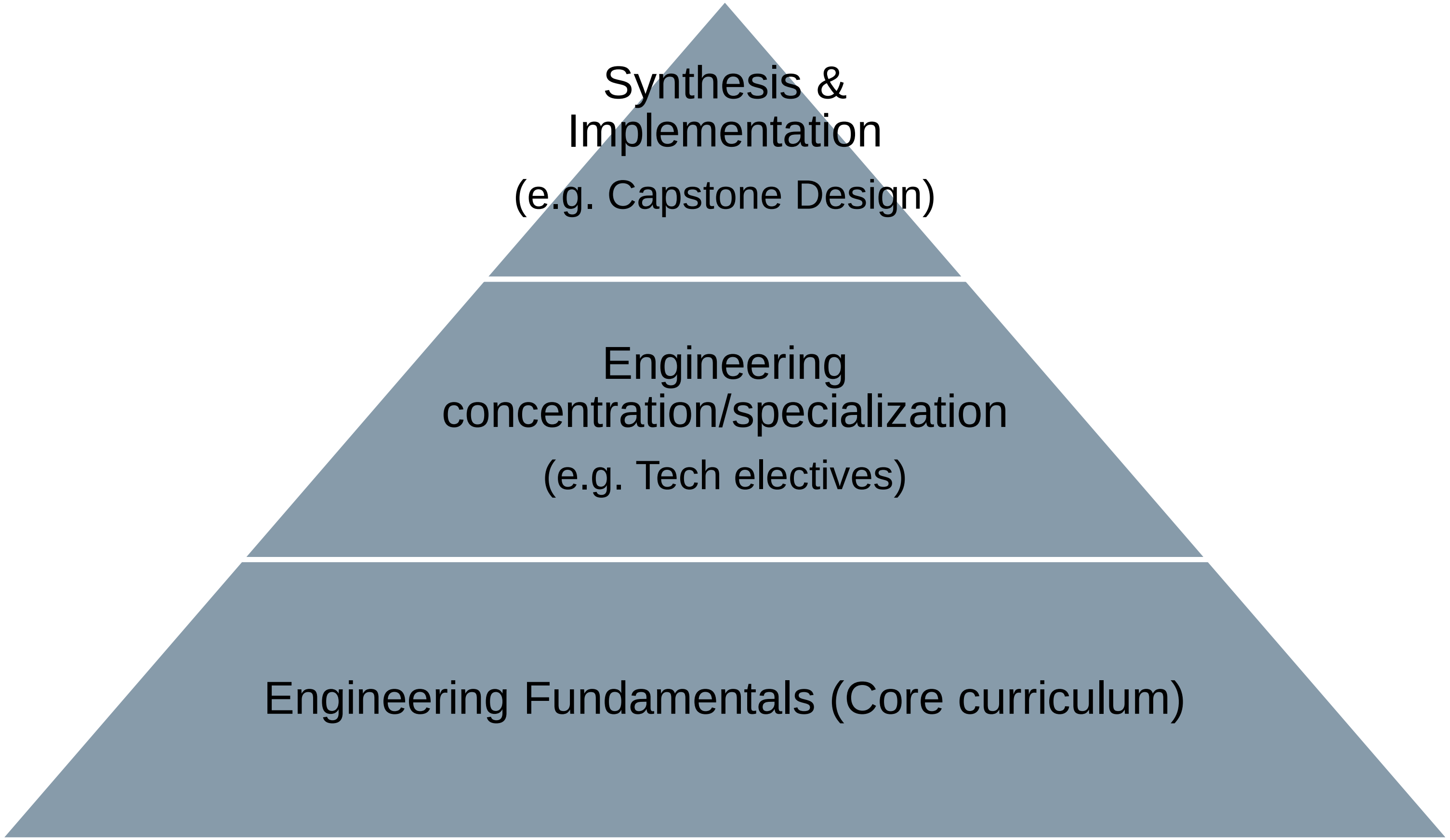
iMBSE: 3D extension of Capstone Design

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



Curriculum for Industry 4.0: Engineering Education 4.0

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



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

Curriculum for Industry 4.0: Engineering Education 4.0

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

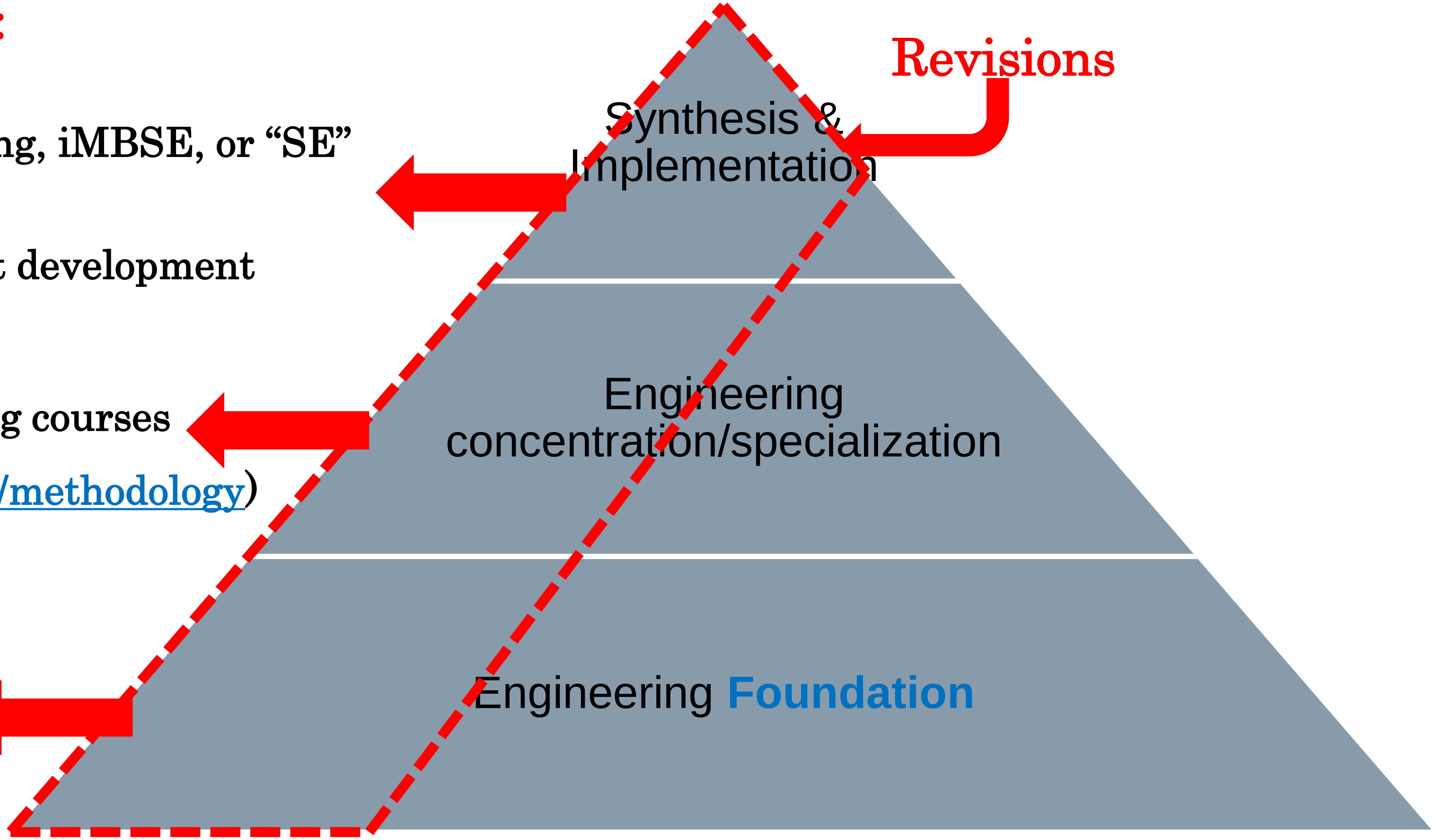
(allows: implementation in complex product development applications)

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)

Curriculum for Industry 4.0: Engineering Education 4.0

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.

Curriculum for Industry 4.0: Engineering Education 4.0

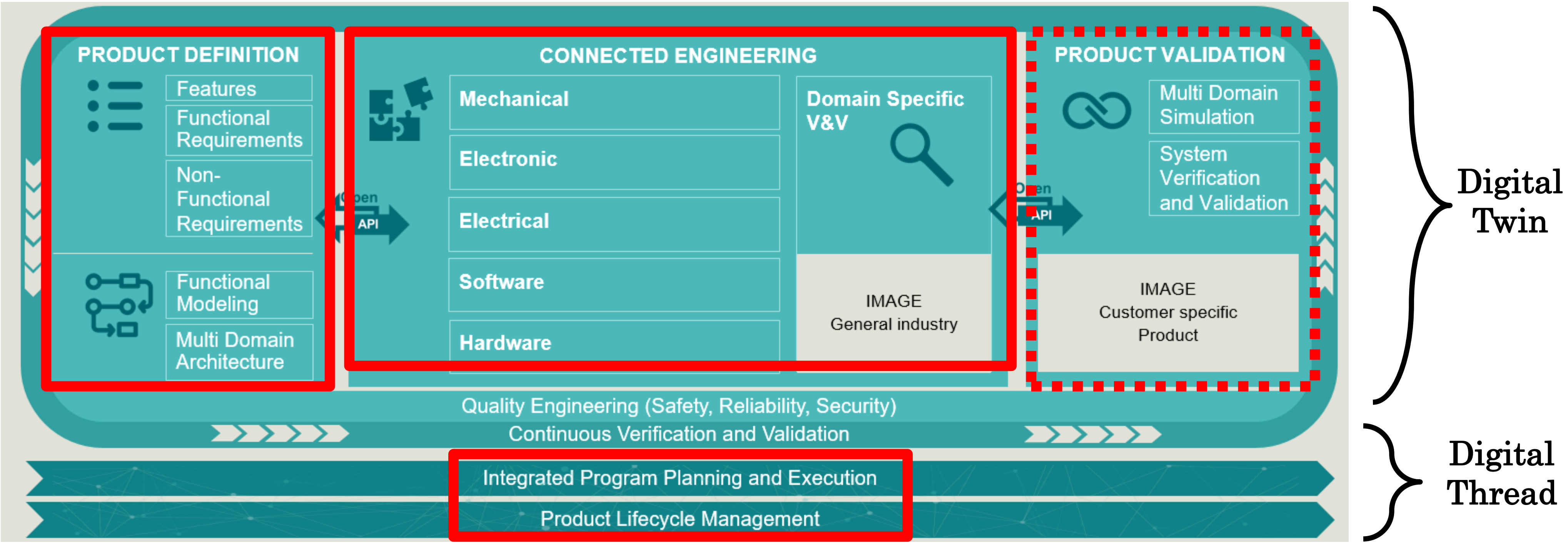
Curriculum for Industry 4.0: Engineering Education 4.0 → Curriculum of Engineering Education 4.0

	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

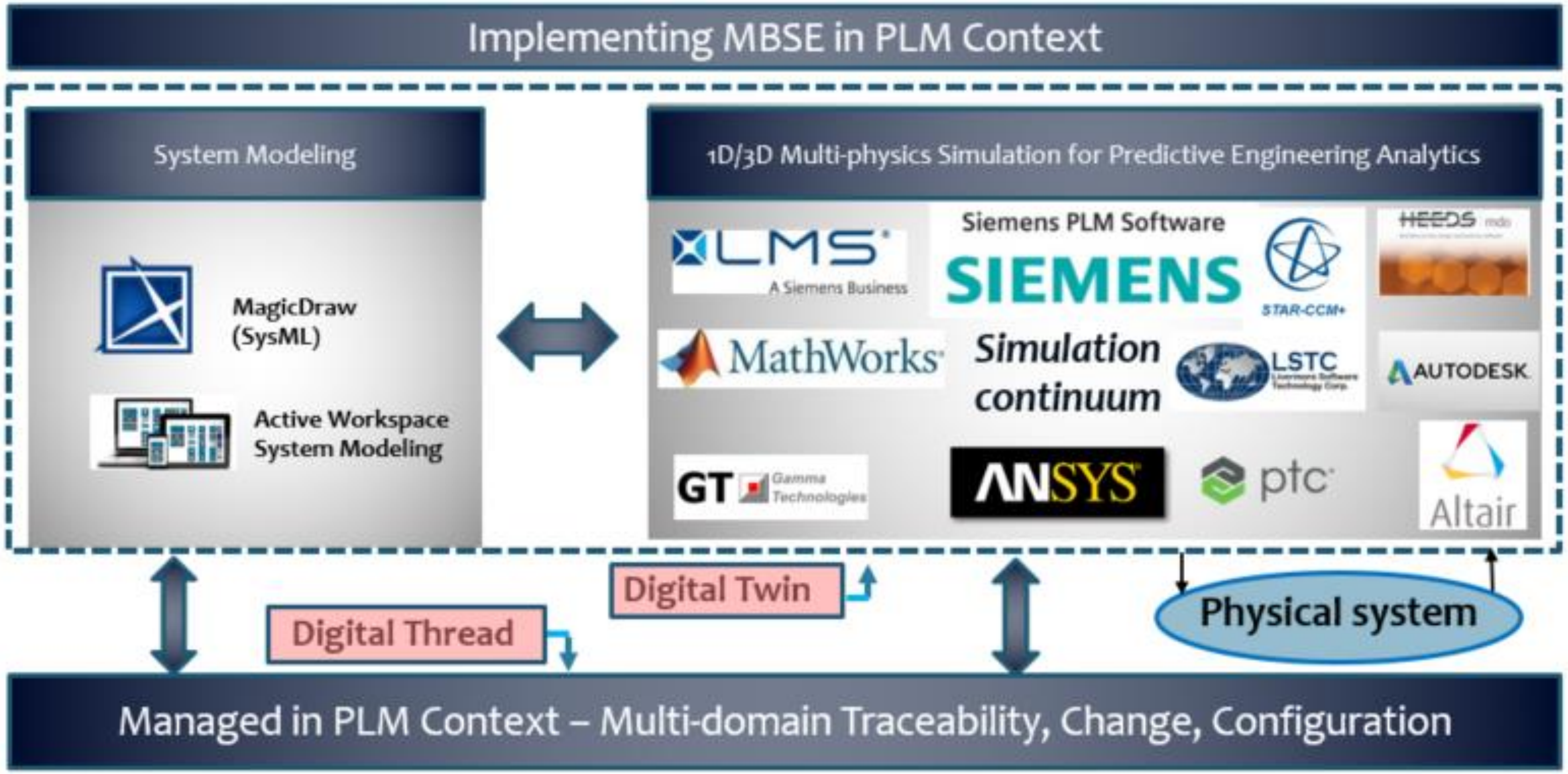
iMBSE: Framework & Digital Innovation Platform for Industry 4.0

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



iMBSE: Framework & Digital Innovation Platform for Industry 4.0

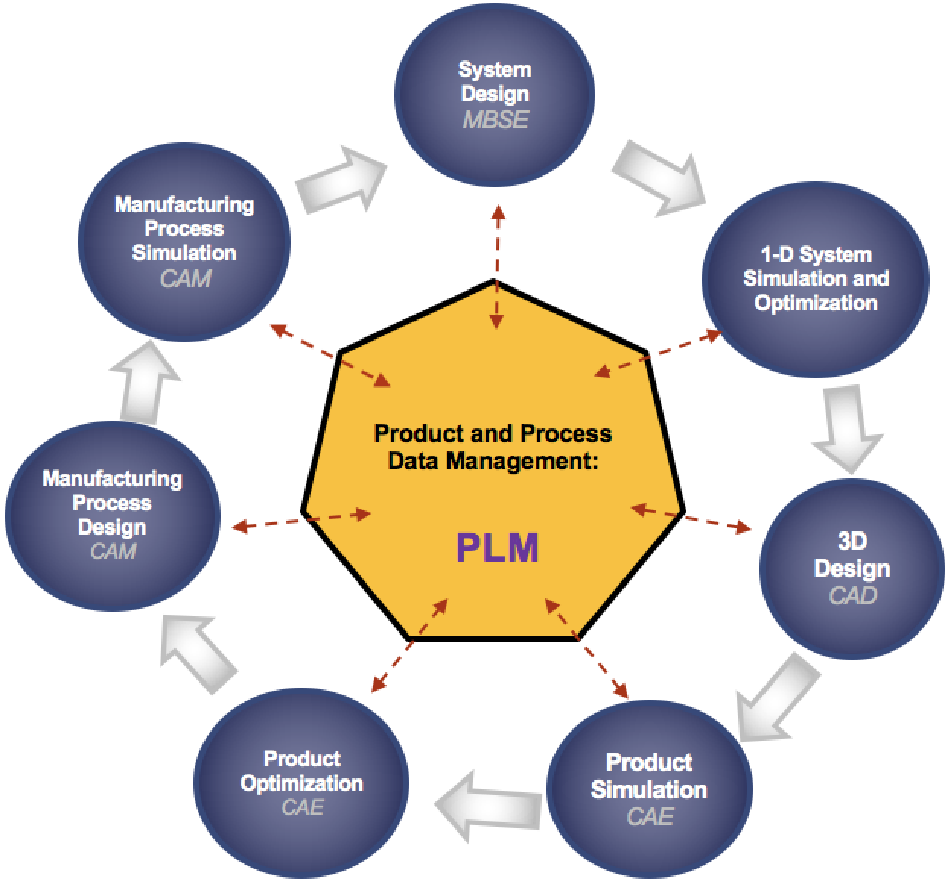
iMBSE: Framework & Digital Innovation Platform for Industry 4.0 → Digital Innovation platform for Industry 4.0



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

Case study: Electric Skateboard

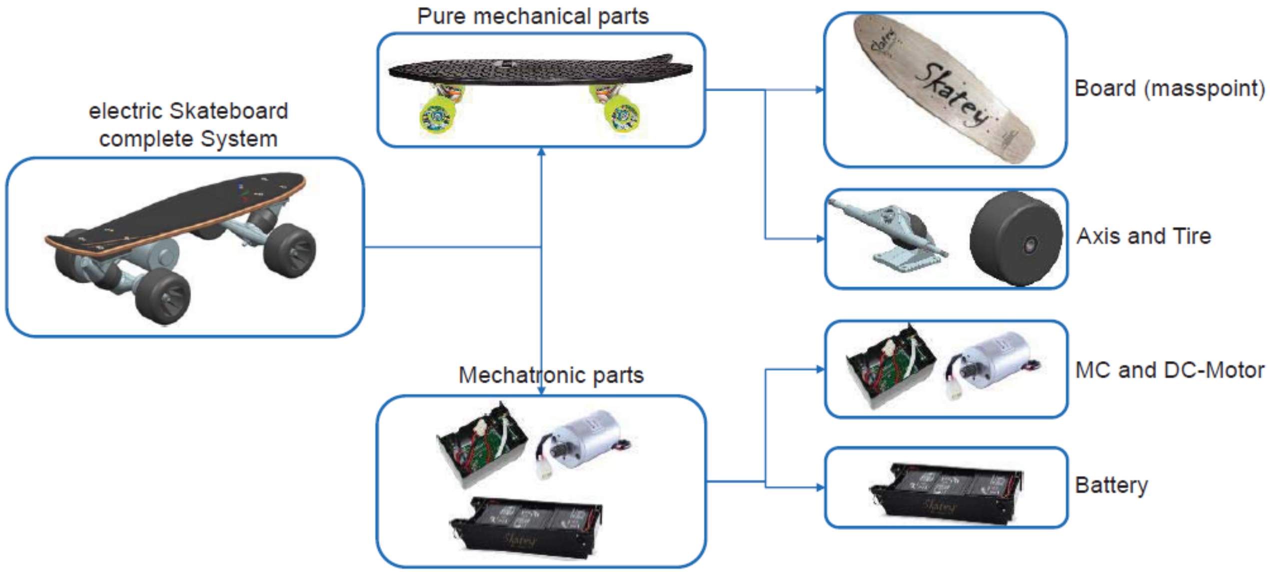
Case study: Electric Skateboard → iMBSE implementation workflow



Electric Skateboard – iMBSE implementation workflow

Electric Skateboard/Longboard

Practice – Case studies → Electric Skateboard/Longboard

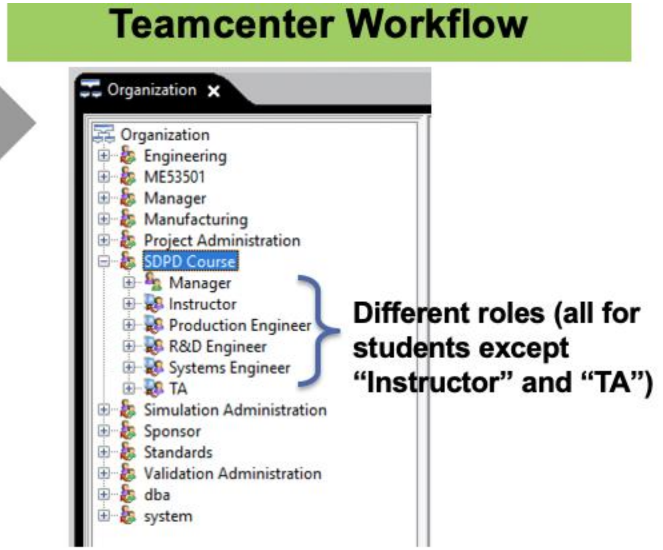


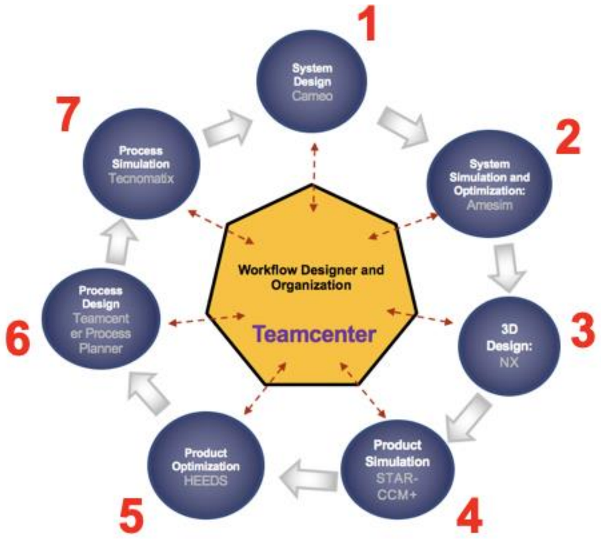
Electric Skateboard as a multi-domain system

Project Workflow

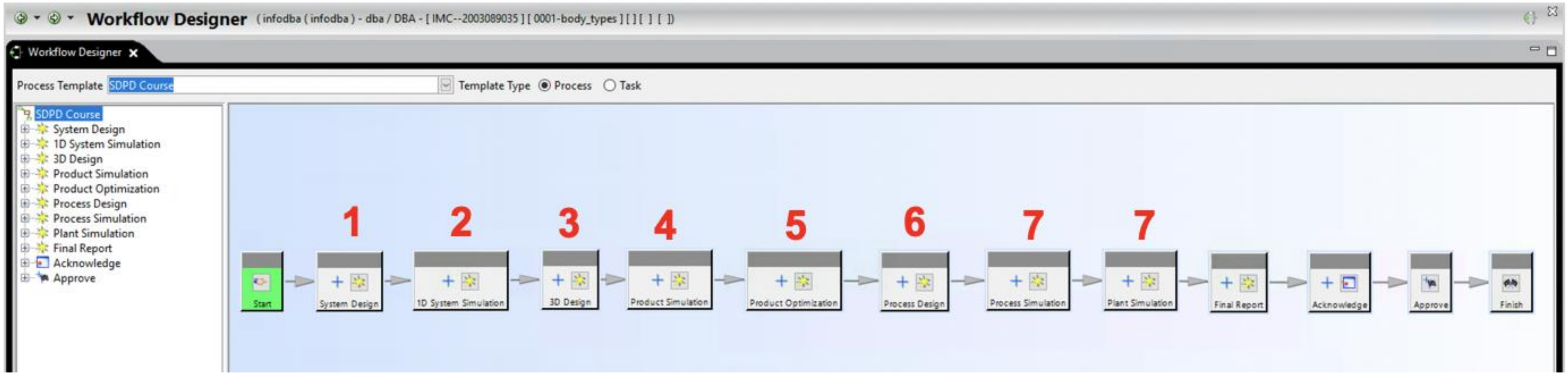
Practice –Case Studies → Electric Longboard: Project Workflow (Project Definition and Planning)

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



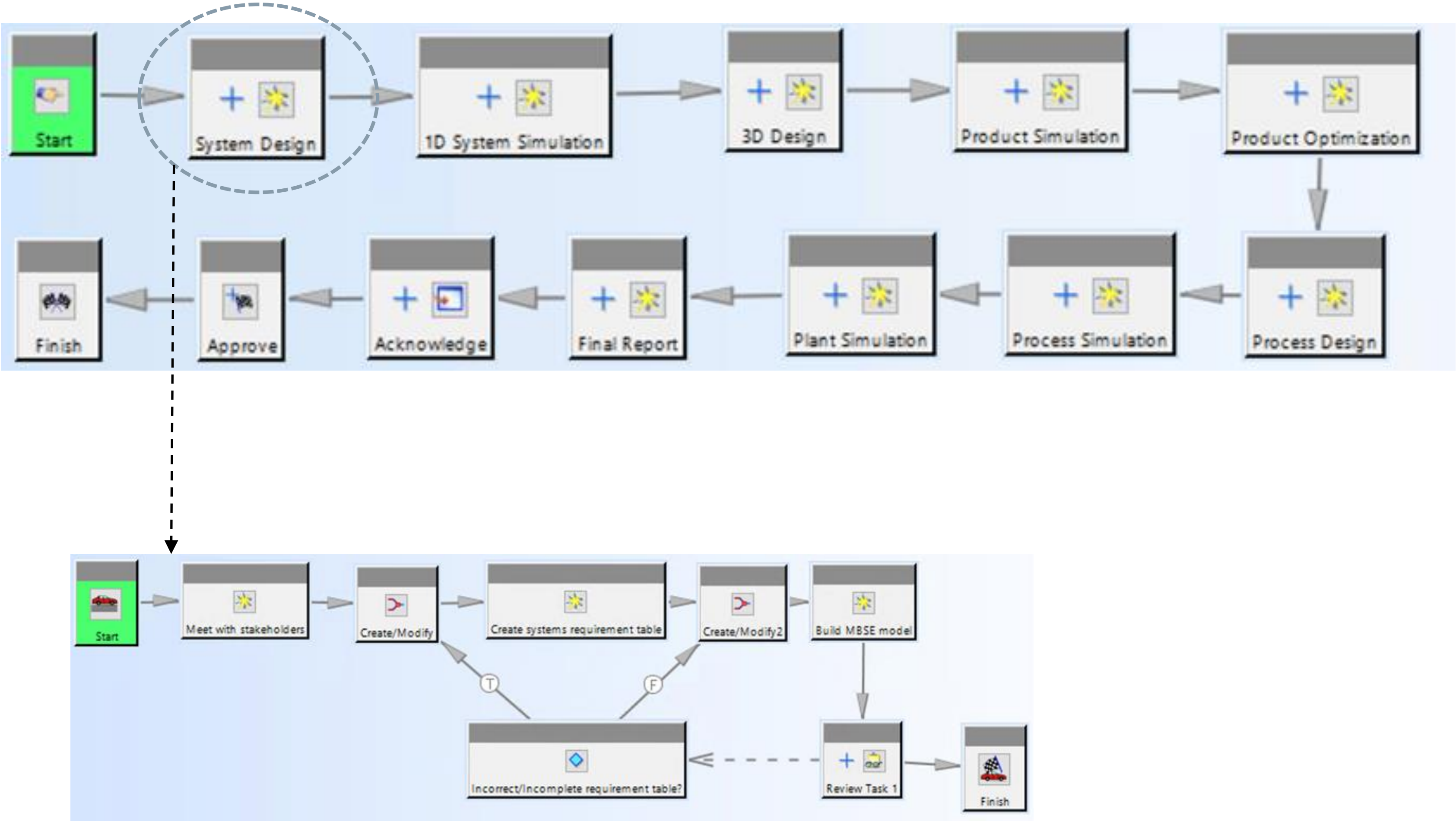


Creating workflow process template describing individual tasks and the task sequence required to model the workflow process



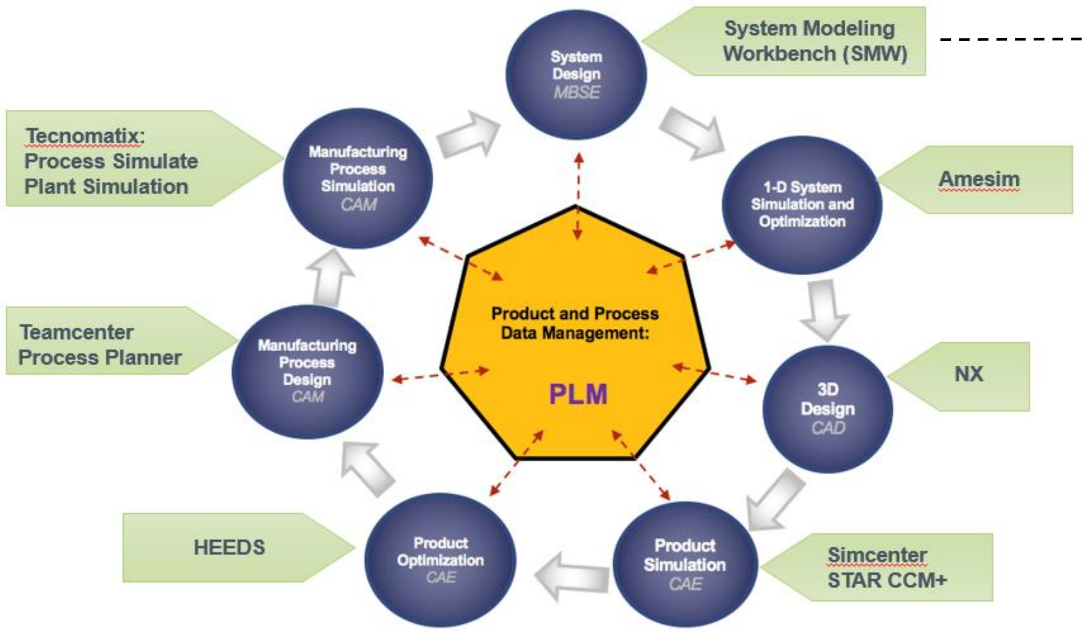
Project Workflow

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



System architecture using SMW (Systems Modeling Workbench)

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

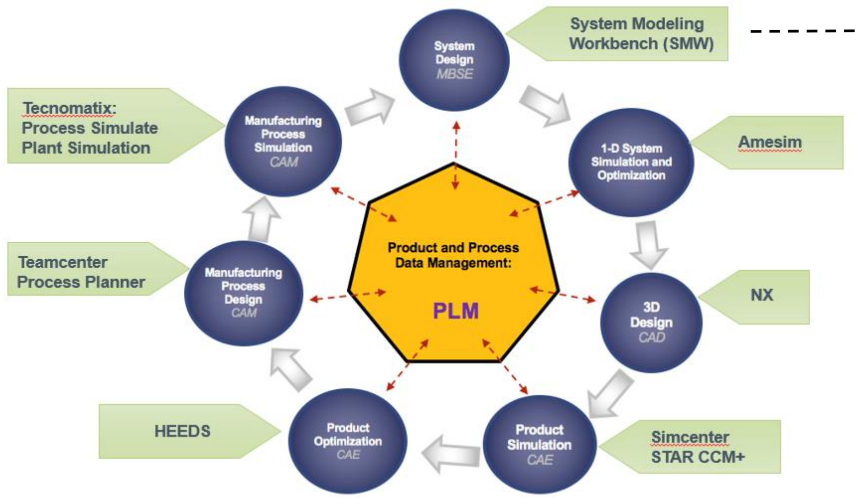
Deliverable: System Architecture of Electric Skateboard

#	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

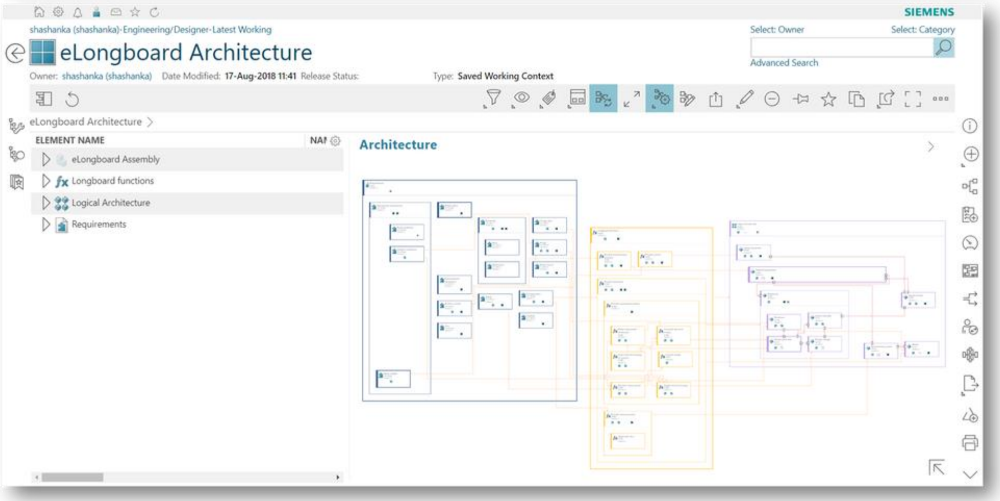
Stakeholder requirements

System architecture using SMW (Systems Modeling Workbench)

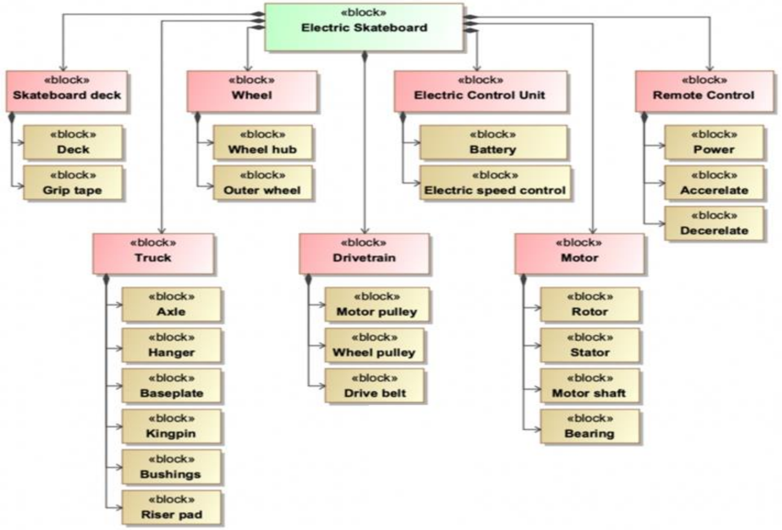
Practice – Case studies → Electric Longboard: System architecture using Systems Modeling Workbench/Cameo



iMBSE implementation workflow



System architecture (Siemens SMW)

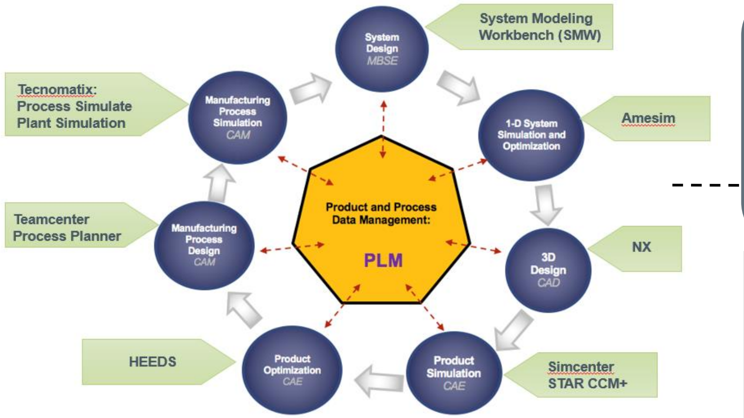


System structure using BDD diagram (Cameo)

HERE (10/15/20)

1D simulation and optimization using Amesim

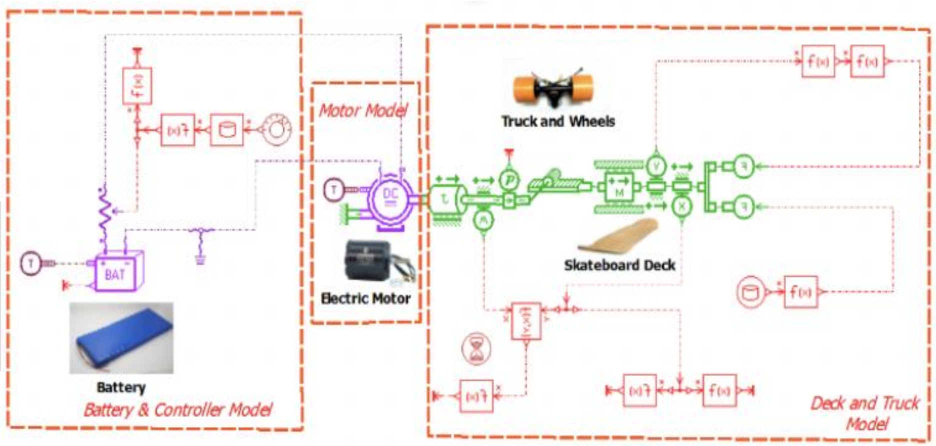
Practice – Case studies → Electric Longboard: 1D simulation and optimization using Amesim



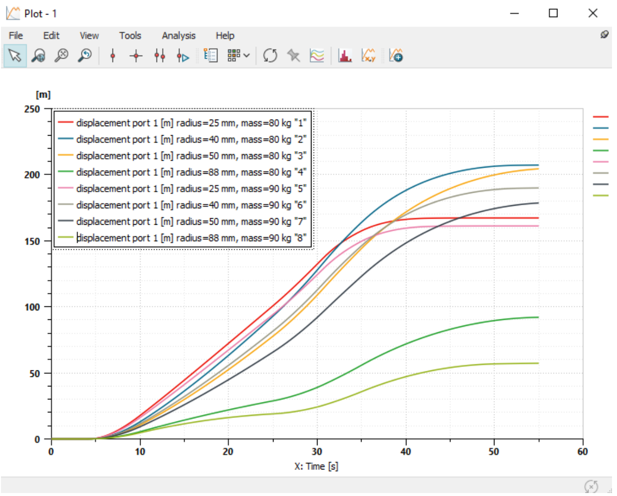
iMBSE implementation workflow

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

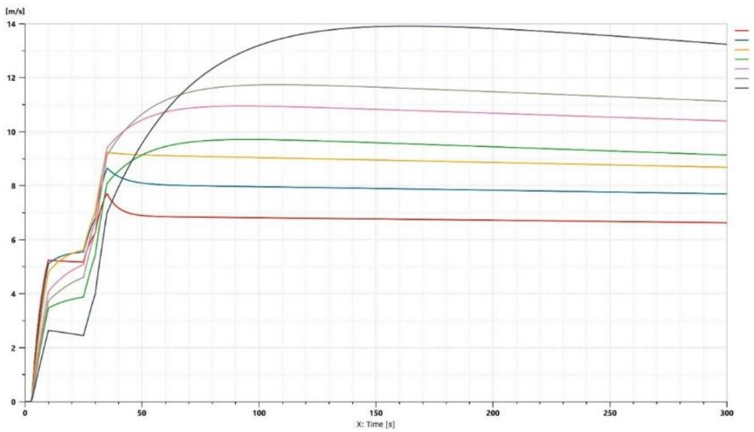
<u>Deliverable</u>: System Architecture of Electric Skateboard



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



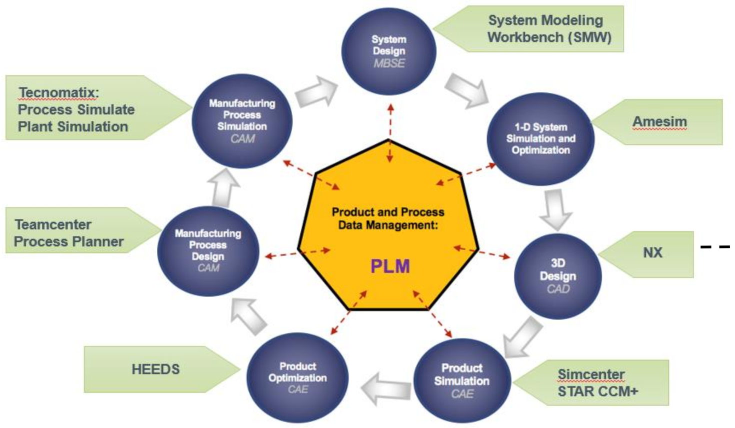
Displacement for different wheel radius & user's weight



Max. velocity for different wheel radius

3D modeling using NX CAD

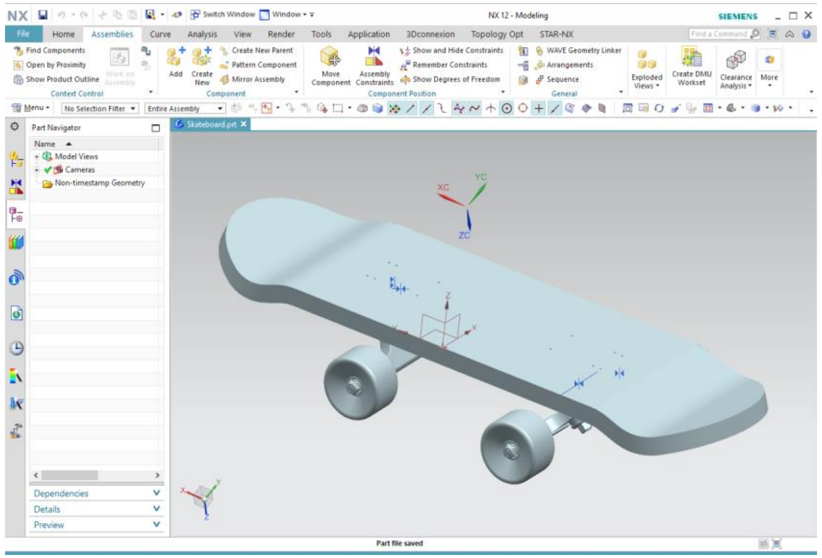
Practice – Case studies → Electric Longboard: 3D modeling using NX CAD



iMBSE implementation workflow

NX:
- Design and modelling of skateboard

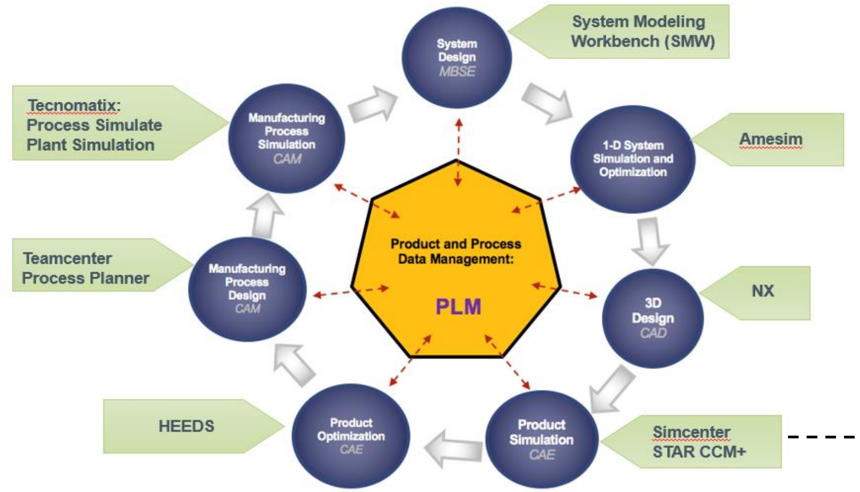
<u>Deliverable</u>: 3D model of Electric Skateboard



3D model of Skateboard

3D simulation using NX Nastran / Star-CCM+

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

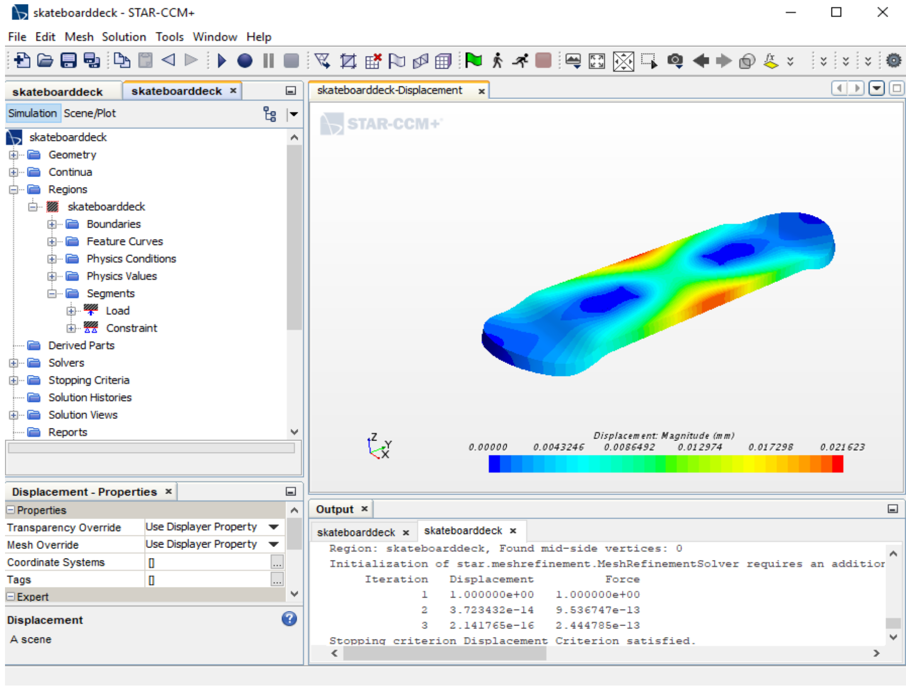


Star-CCM+ / Nastran:

- 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

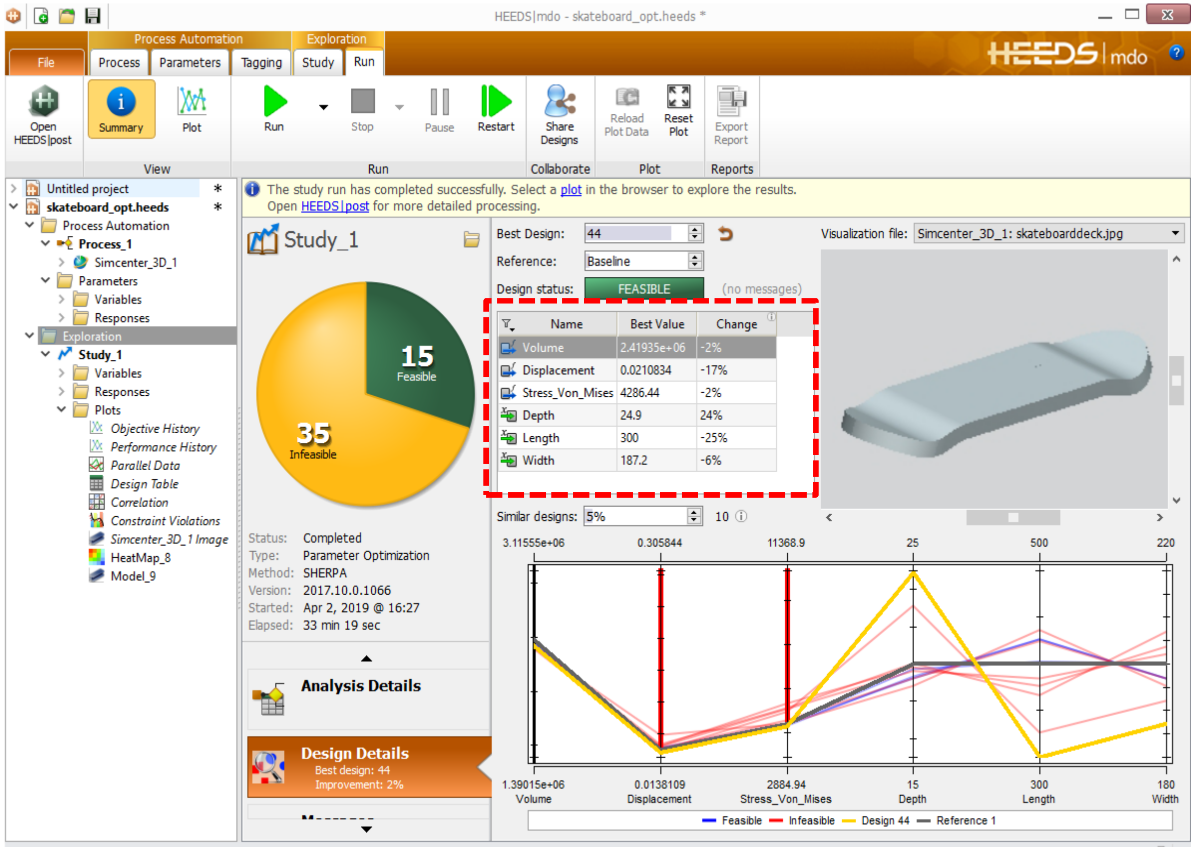
<u>Deliverable</u>: 3D Simulation model of Electric Skateboard



3D simulation: Von-Mises stress in skateboard deck

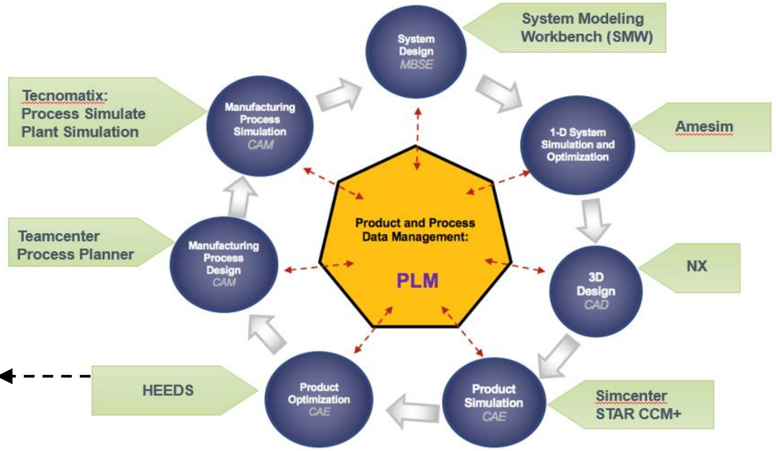
3D optimization using HEEDS

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



HEEDS (Hierarchical Evolutionary Engineering Design System):

- Optimization for better and more robust solutions within a given design space



Deliverable:
Optimized 3D deck geometry

iMBSE implementation workflow

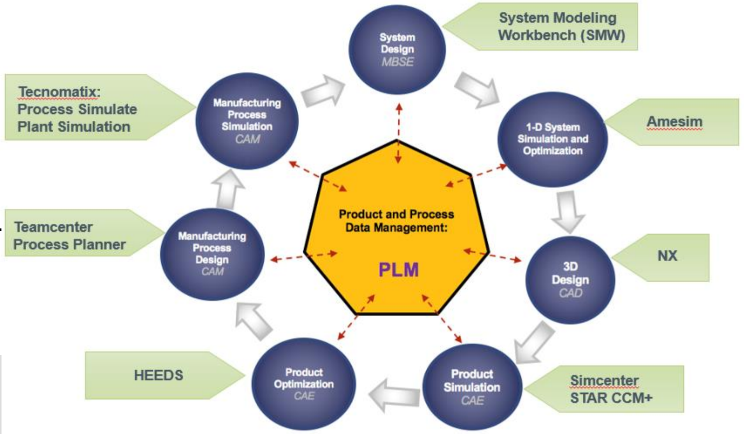
Optimization of 3D geometry of skateboard deck

Manufacturing process design using MPP

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

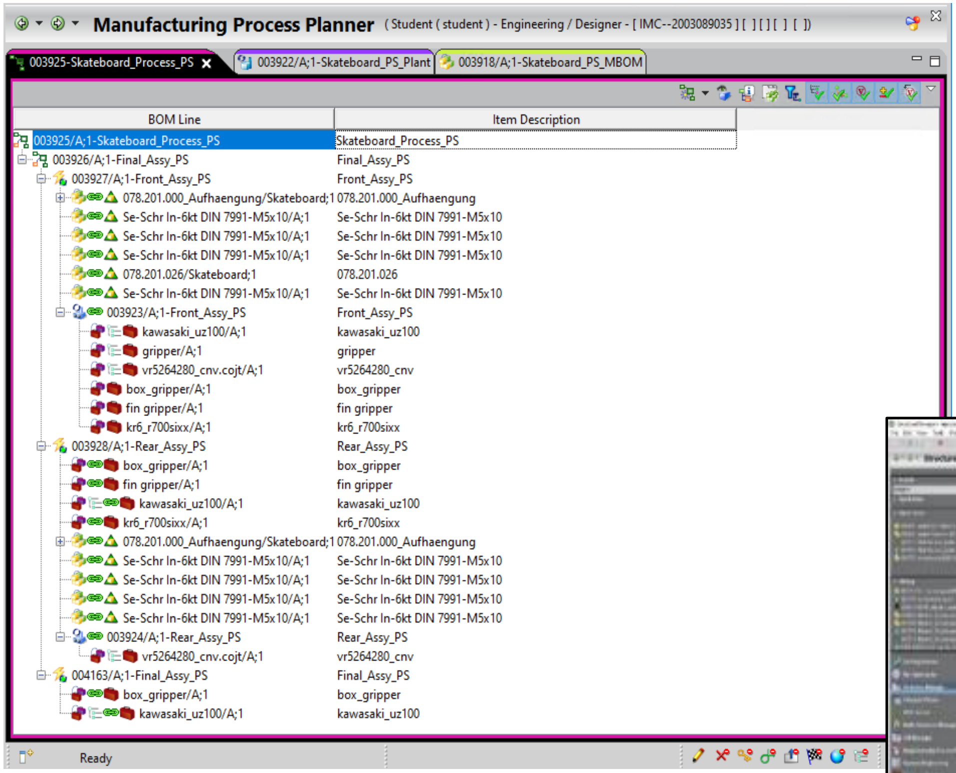
Teamcenter Manufacturing Process Planner (MPP):

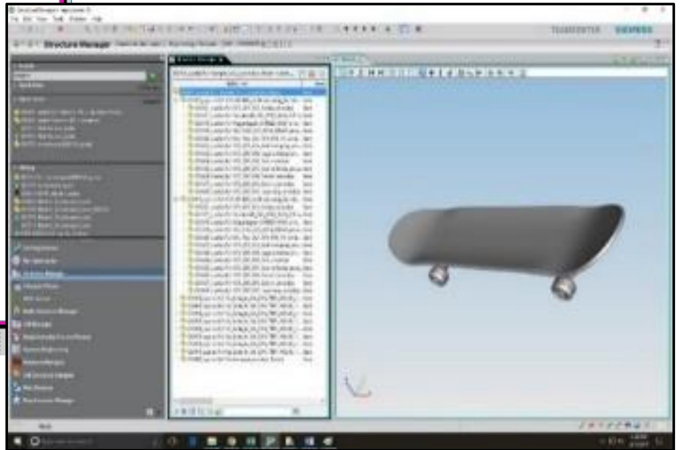
- Product Lifecycle Management (PLM)
- Develop product and manufacturing process
- Manage manufacturing data, process, resource and plant information
- Seamless alignment between engineering bill of materials (BOM), manufacturing BOM and the manufacturing bill of process (BOP)



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

iMBSE implementation workflow

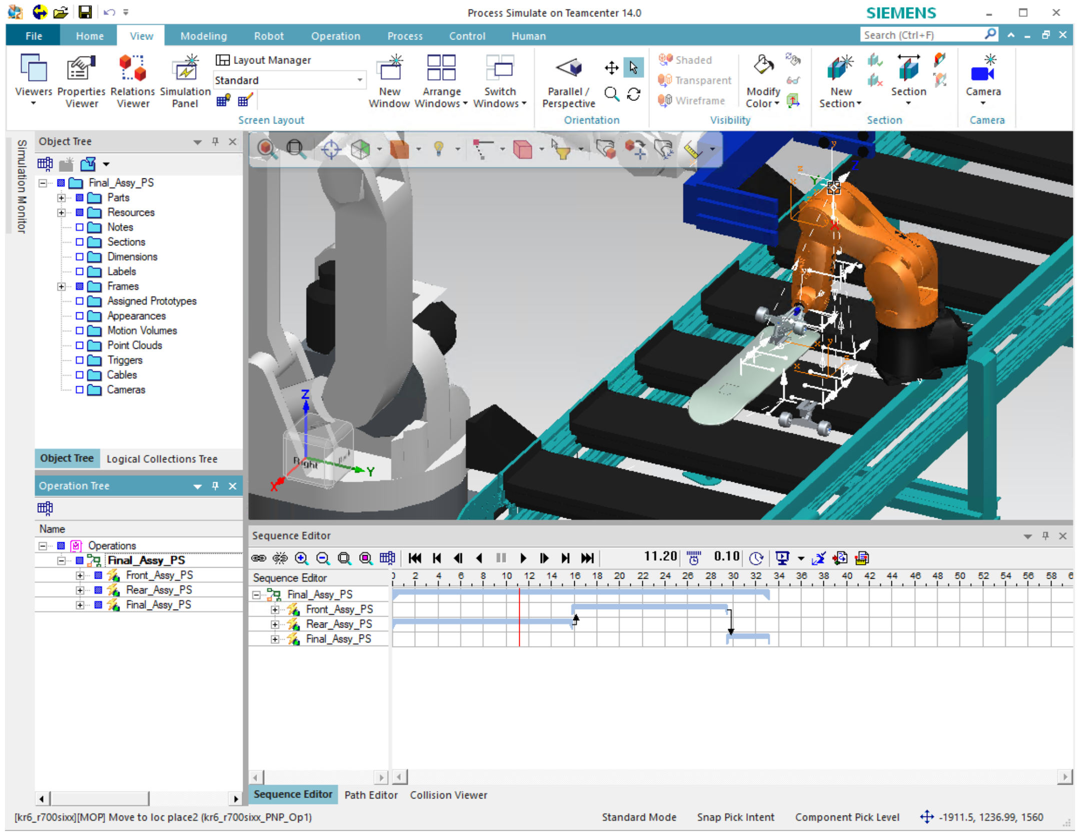




BOM of Skateboard

Manufacturing Process simulation using Tecnomatix

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

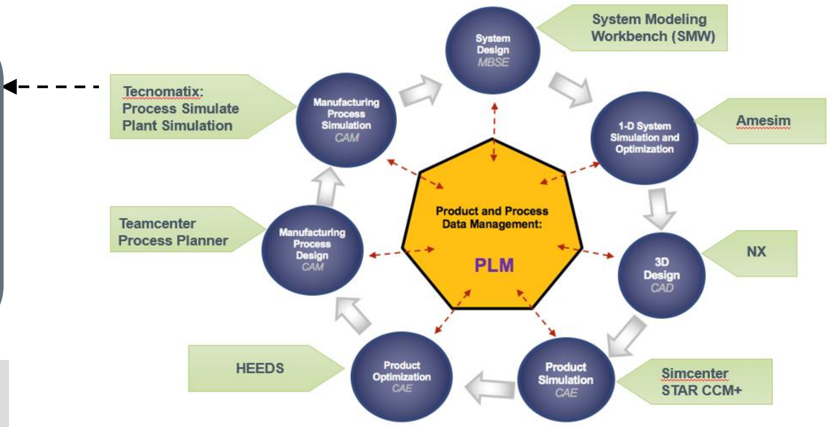


Simulation of Skateboard assembly

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

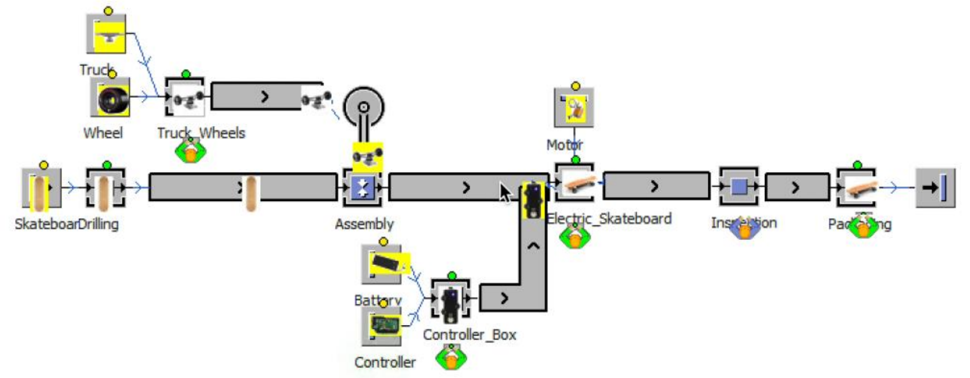
<u>Deliverable</u>: Simulation model of Electric skateboard assembly



iMBSE implementation workflow

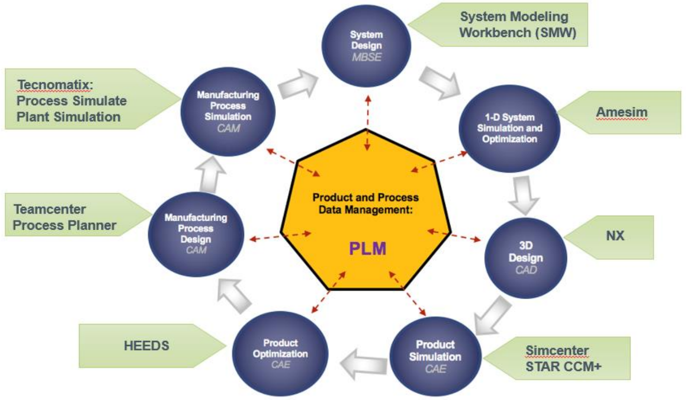
Plant simulation using Tecnomatix

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

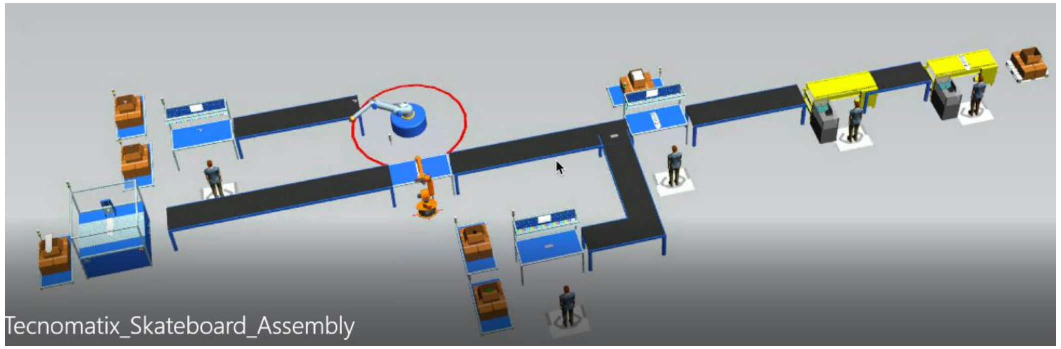


Tecnomatix Process Plant Simulation:
- Simulation and optimization of production systems and processes
- Taking skateboard through production
- Simulating the full production of the product

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



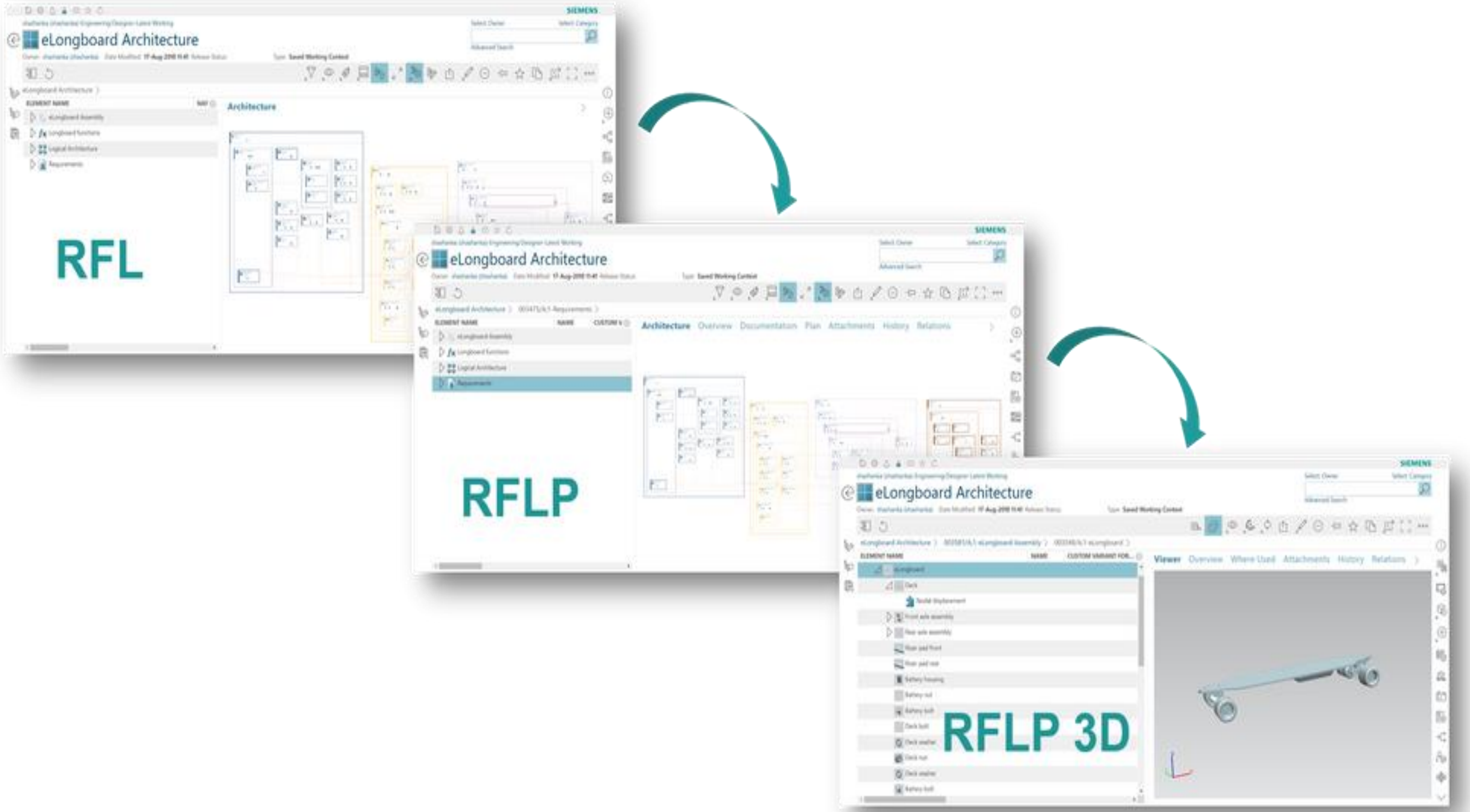
iMBSE implementation workflow



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

Traceability

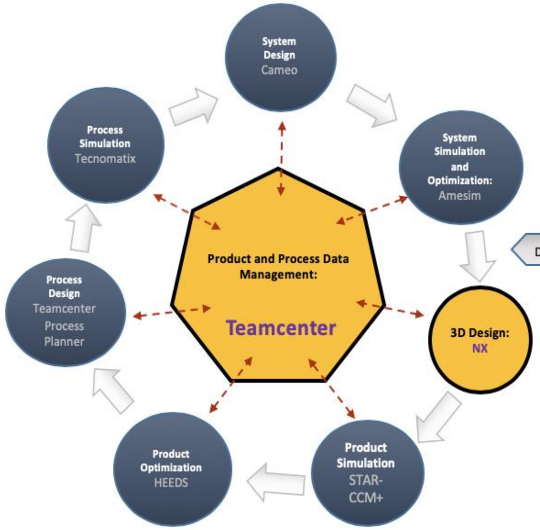
Practice – Case studies → Electric Longboard: Traceability



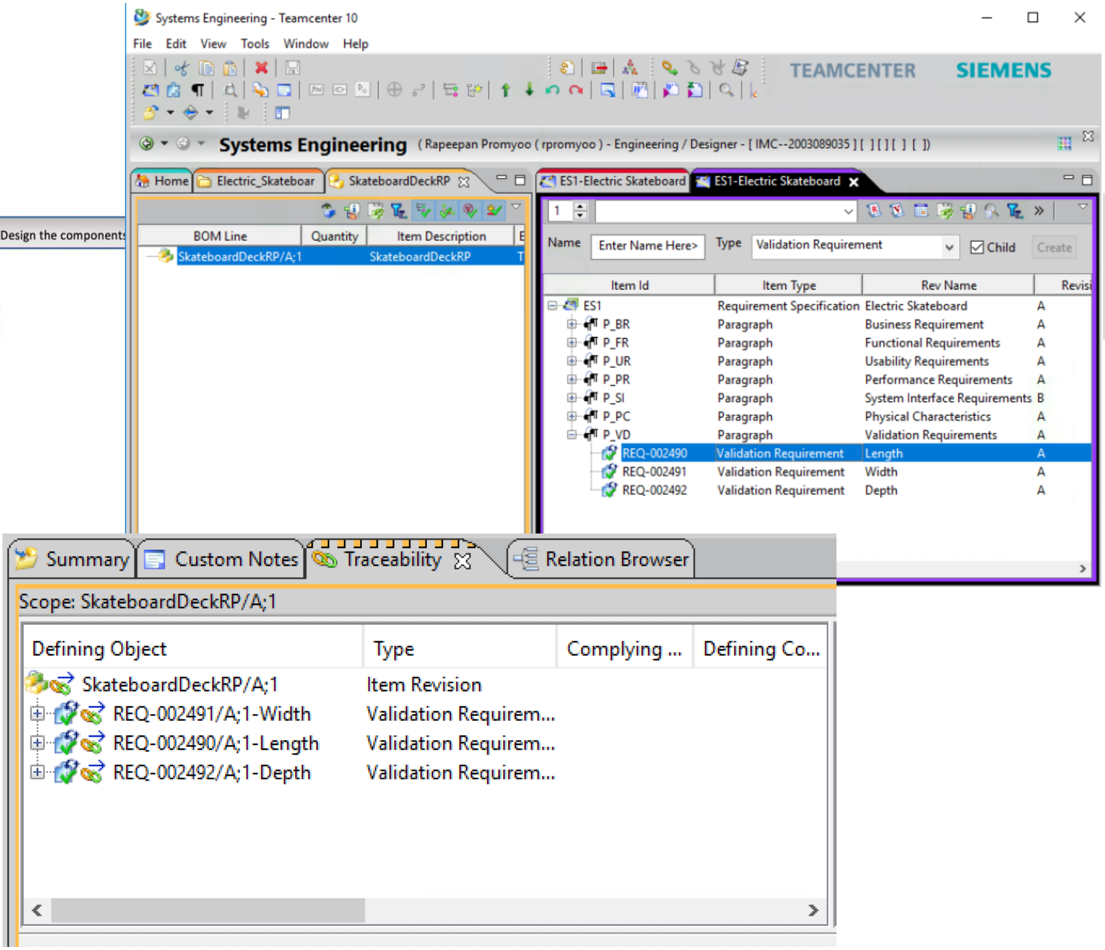
Electric Skateboard/Longboard RFLP

Traceability

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

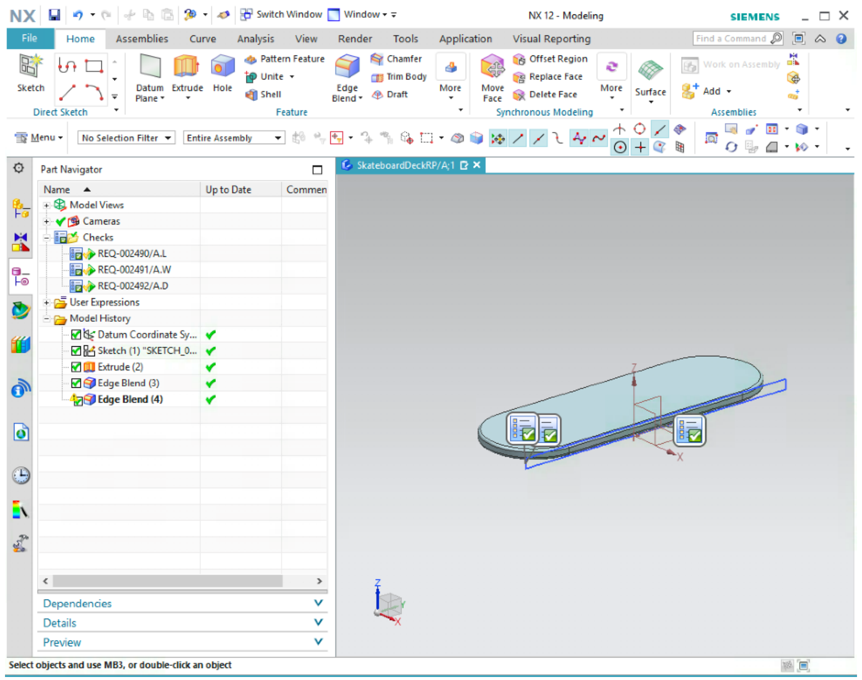


iMBSE implementation workflow



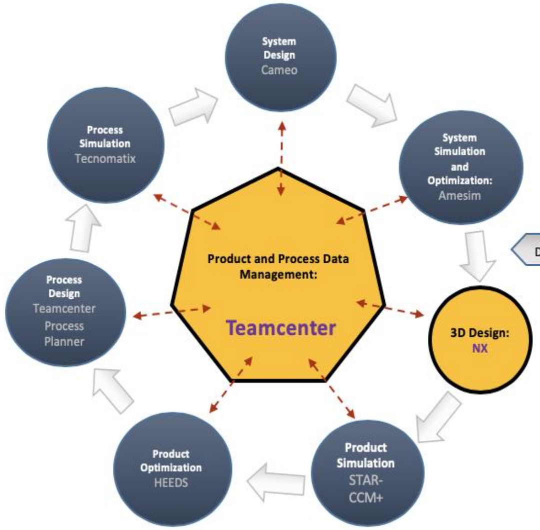
- NX Design
- Create traceability between requirements and Design geometry (3D model)

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

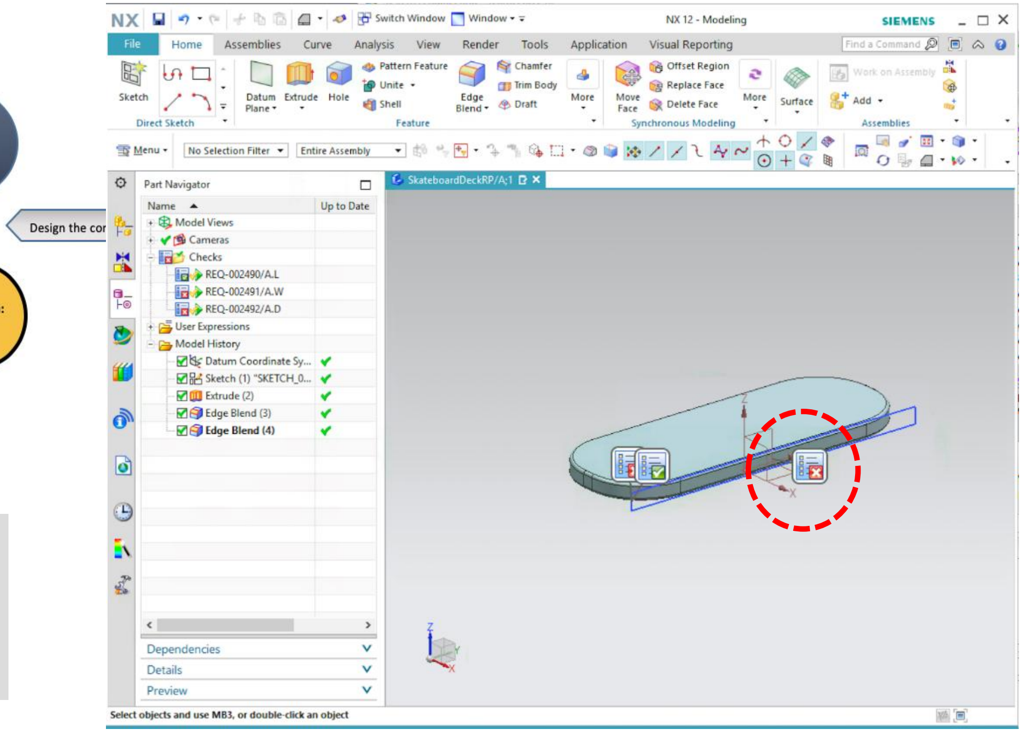


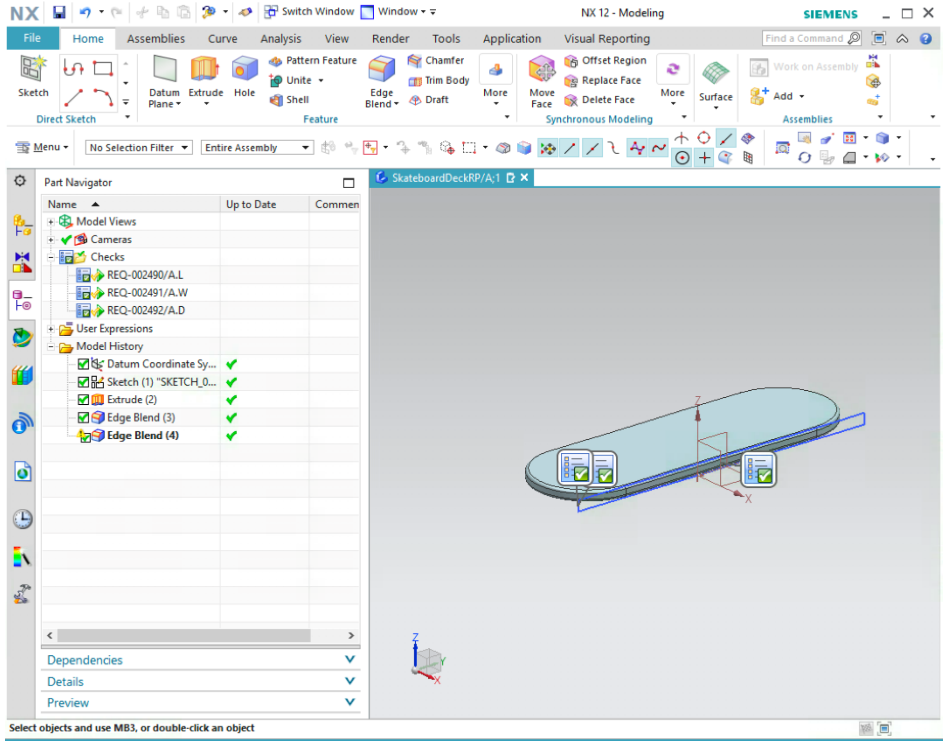
Traceability

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



iMBSE implementation workflow



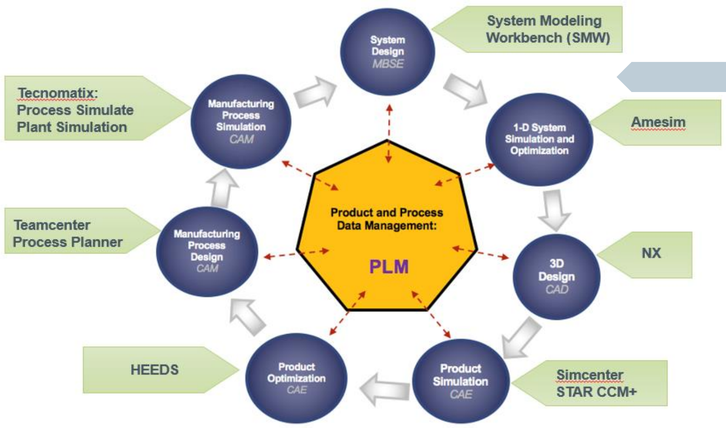


The validation results failed two of the requirements.

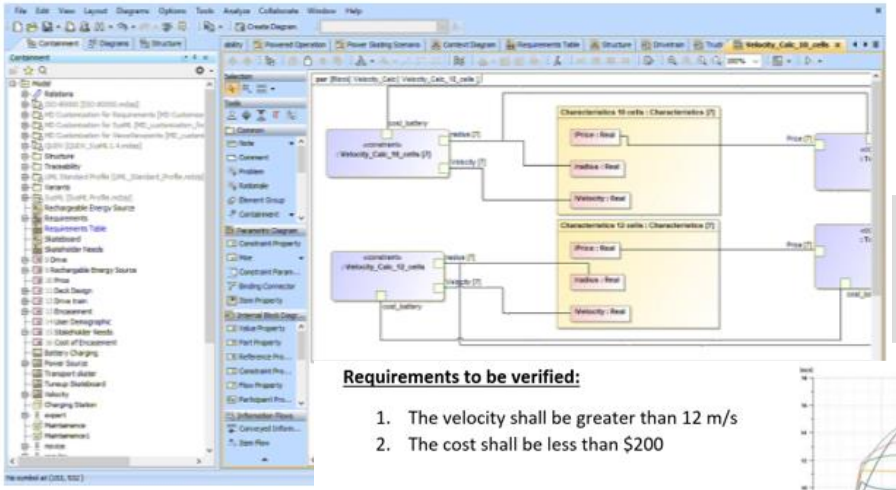
The validation results passed all the requirements.

Traceability

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



iMBSE implementation workflow



0D requirements model

- 1D Simulation model
- 0D requirement model

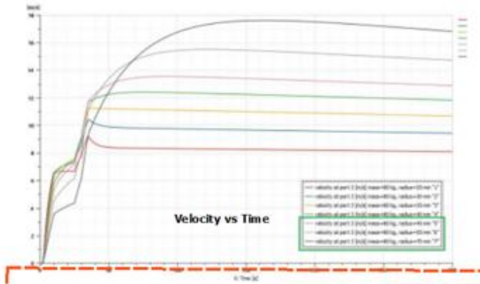
<u>Deliverable</u>: System design that meets requirements

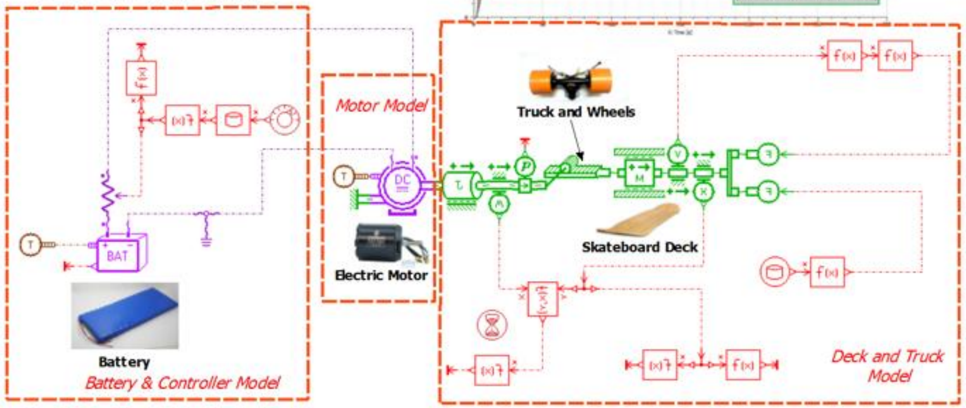
<u>Requirements to be verified:</u>

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

<u>Parameters to be varied:</u>

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

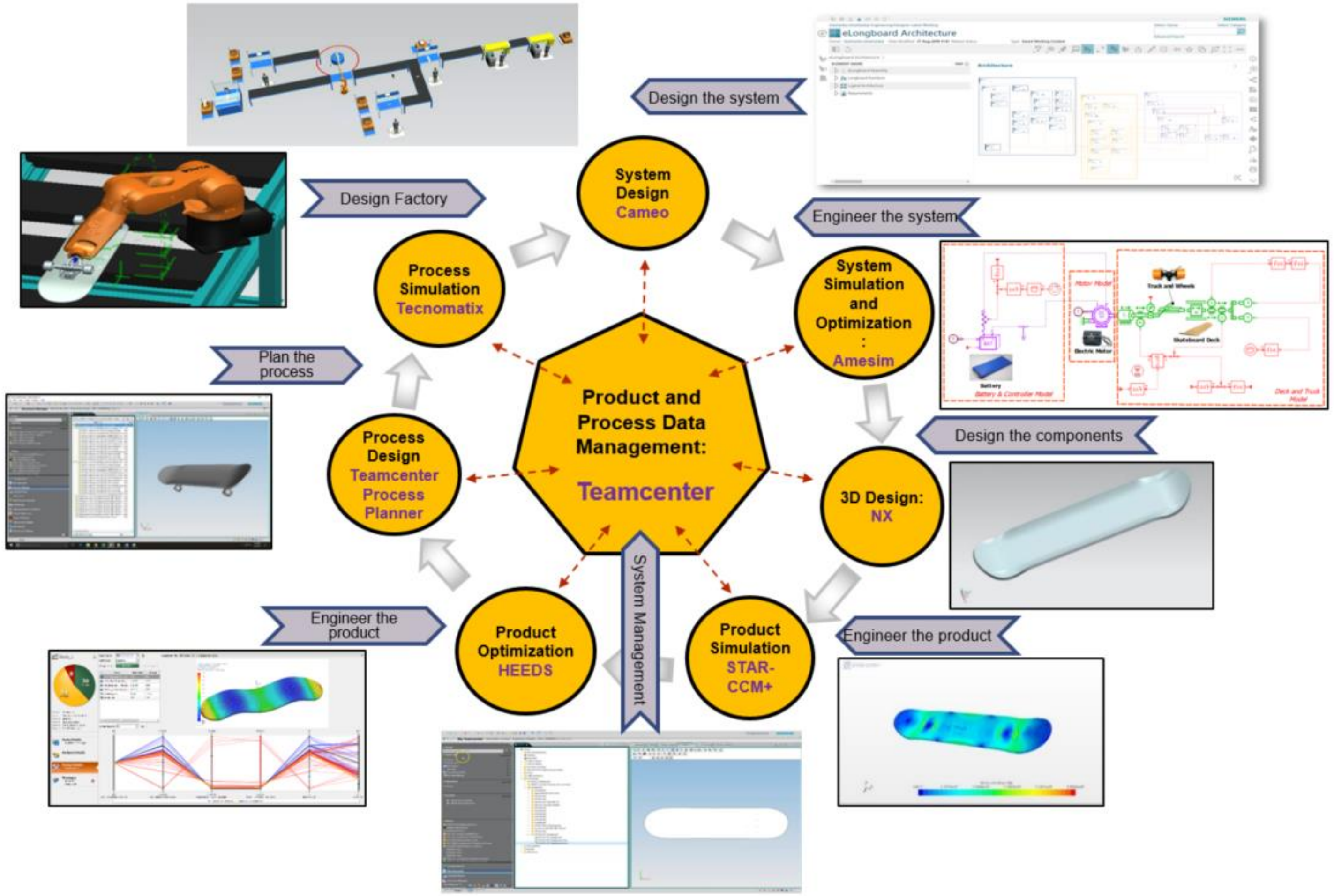




1D Simulation for predicting system's performance: Max. velocity, etc,

Electric longboard iMBSE implementation: Summary

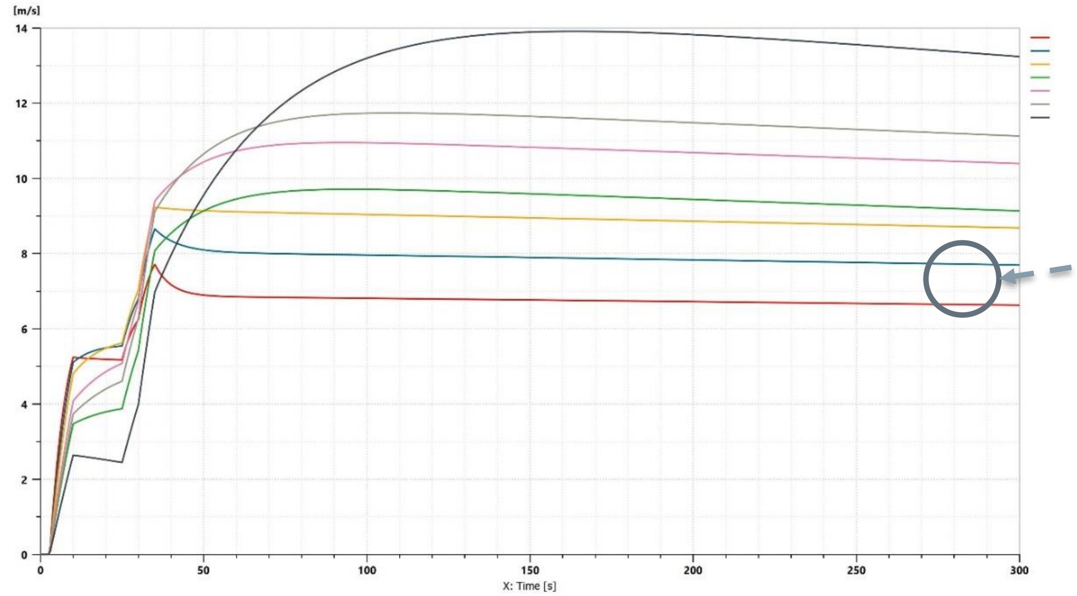
Practice – Case studies → Electric Longboard: Summary of digital implementation



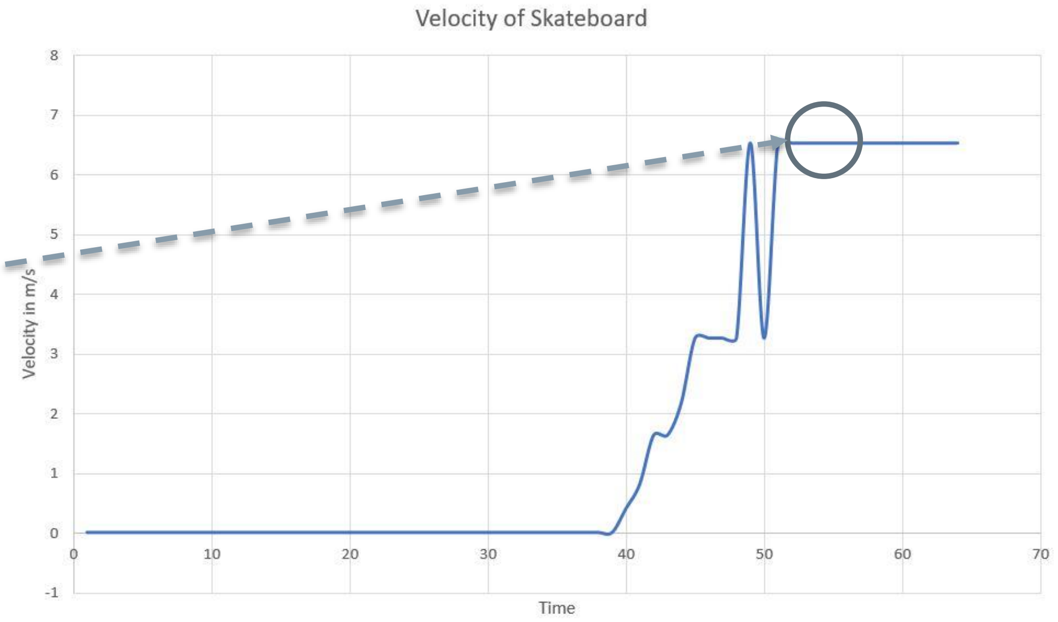
Implementing iMBSE workflow: Summary of deliverables

Electric Longboard: Validation

Practice – Cases studies → Electric Longboard: Validation



Simulation results from Amesim 1D (Digital twin)



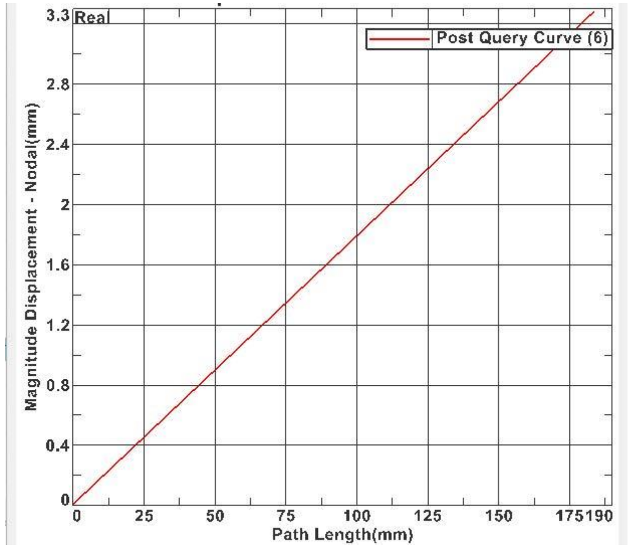
Experimental results from Optical Encoder (Physical

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

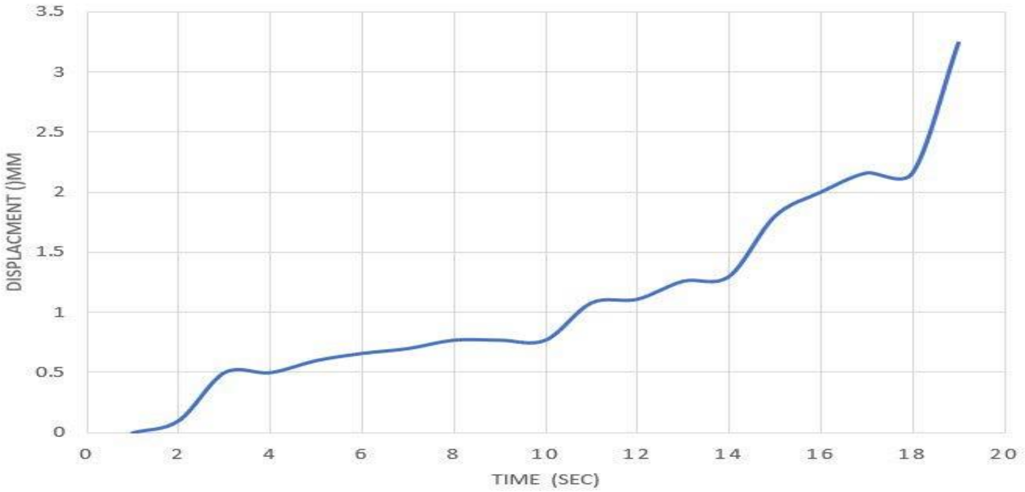
Electric Saketboard/Longboard Validation: Max. velocity

Electric Longboard: Validation

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

Summary & Conclusions

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

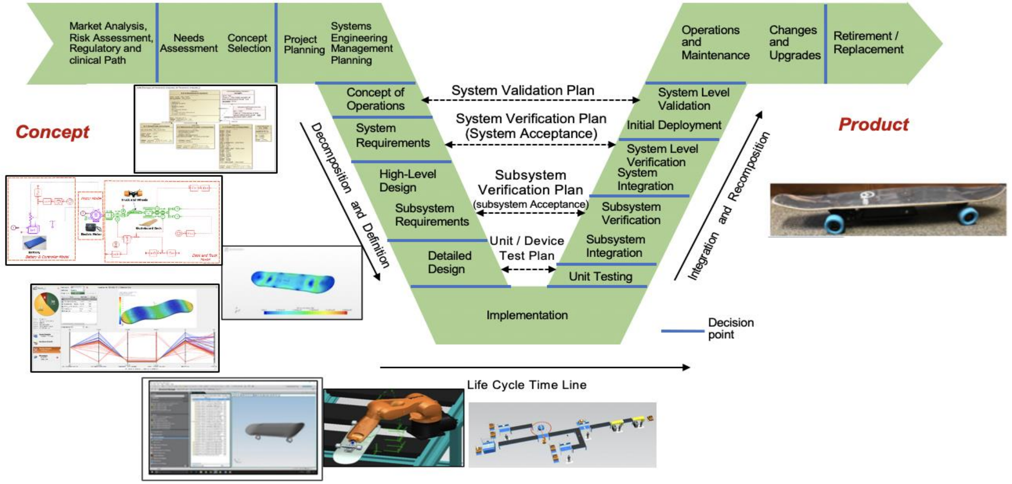
Summary & Conclusions

Summary & conclusions

Engineering Education: Traditional vs. Industry 4.0

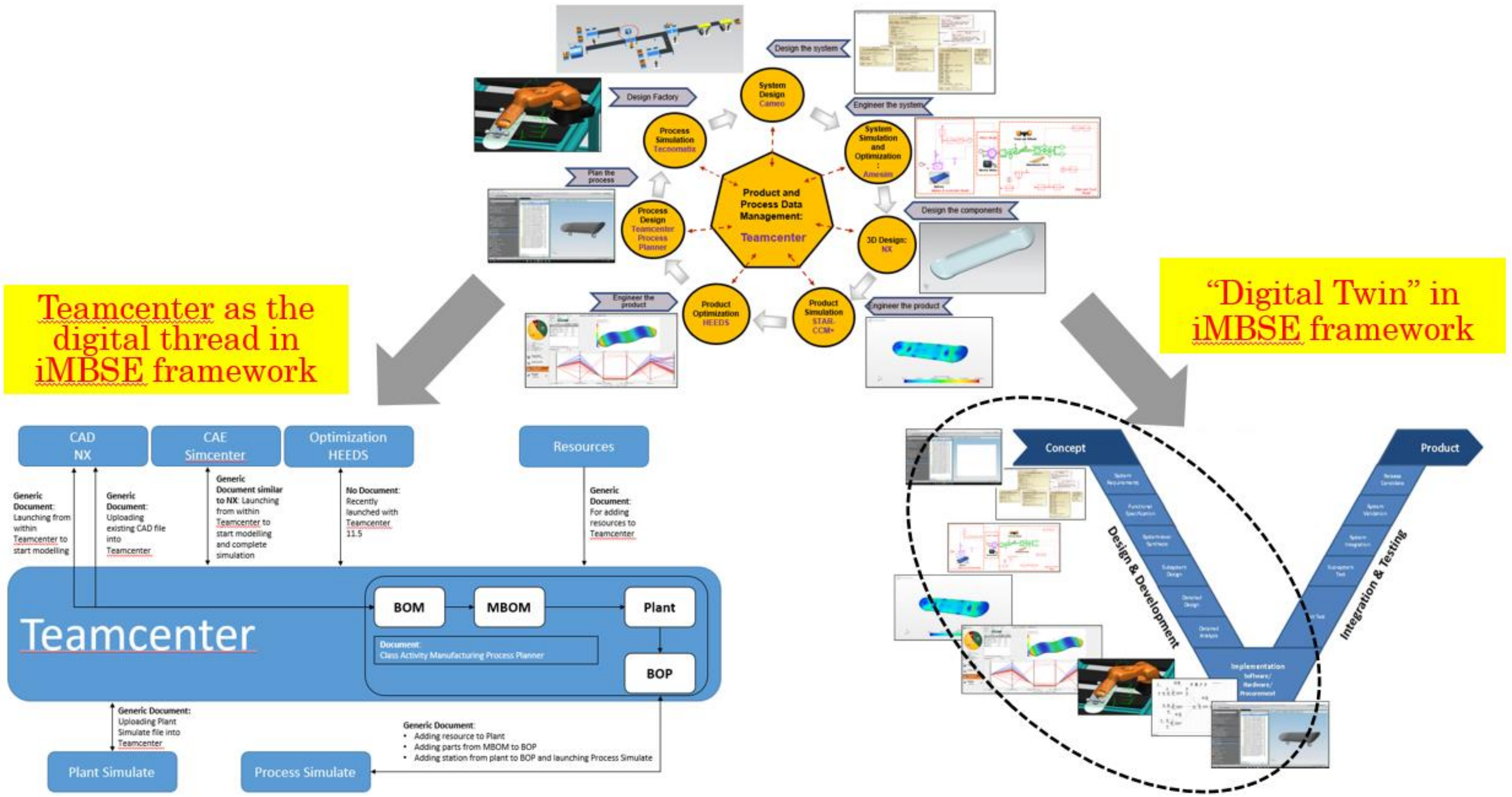
Current Engineering Education landscape	Engineering Education for Industry 4.0
Single domain/discipline	Multi-disciplinary, Integrated
Technology/Tools taught by technology programs/community colleges	Offered by Engineering colleges (4 year)
Limited relevance to Industry practice, including Industry 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



Summary & Conclusions

Summary & conclusions



iMBSE = Digital twin + Digital thread