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

Hazim El-Mounayri, Purdue School of Engineering & Technology, IUPUI
Initiative for Product Lifecycle Innovation (IPLI), IUPUI

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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**
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:

<table>
<thead>
<tr>
<th>managing:</th>
<th>dealing with:</th>
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</thead>
<tbody>
<tr>
<td>• Multiple sub-systems</td>
<td>• Subsystems interactions</td>
</tr>
<tr>
<td>• Multiple engineering domains</td>
<td>• System integration</td>
</tr>
<tr>
<td>• Multiple variants and system architectures</td>
<td></td>
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<tr>
<td>• Growth of software / electronic systems</td>
<td></td>
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<tr>
<td>• Exploding requirements</td>
<td></td>
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<tr>
<td>• Fast growing number of V &amp; V</td>
<td></td>
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<tr>
<td>• Multiple disparate tools in each domain</td>
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<tr>
<td>• Multiple design groups and multiple sites</td>
<td></td>
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</tbody>
</table>

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

Example of typical capstone design products: Mostly Mechanical

Fin Heat Transfer Apparatus

Arm-A-Door Outside Entry: Exterior Handle Assembly

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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].

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 stakeholders
- 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 stakeholders’ 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

<table>
<thead>
<tr>
<th>Document-based process</th>
<th>Model-based process</th>
</tr>
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<tbody>
<tr>
<td>Error prone</td>
<td>Workflow enforced</td>
</tr>
<tr>
<td>- Missing elements</td>
<td>Design element based</td>
</tr>
<tr>
<td>- Poor element traceability</td>
<td>Source driven through design elements</td>
</tr>
<tr>
<td>Vulnerable to company silos</td>
<td>Fully integrated</td>
</tr>
</tbody>
</table>
iMBSE: 3D extension of Capstone Design → iMBSE characteristics & modern products

### 3D extended CD driven by iMBSE

<table>
<thead>
<tr>
<th>Complex product (system or SoS)</th>
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<tbody>
<tr>
<td>Multi Domain</td>
</tr>
<tr>
<td>Extended scope: “Lifecycle” (not just “Development”)</td>
</tr>
<tr>
<td>Full Digitalization</td>
</tr>
<tr>
<td>Validation: SIL, HIL, MIL, and Virtual prototyping</td>
</tr>
</tbody>
</table>

**Example of a complex product:** **Multi-domain system**
iMBSE: 3D extension of Capstone Design → 3D extension of CD

From “simple/single domain products” to “Complex/multi-domain systems”

From “Product Development” to “System Lifecycle”

From limited model-based and partial integration to a comprehensive, fully integrated model-based approach

iMBSSE as a 3D extension of Standard Capstone Design
Curriculum for Industry 4.0: Engineering Education 4.0 → 3 Level curriculum

- Synthesis & Implementation (e.g. Capstone Design)
- Engineering concentration/specialization (e.g. Tech electives)
- Engineering Fundamentals (Core curriculum)

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

(allowing 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.
(providing theoretical foundation and relevant specialization)

Revisions

Synthesis & Implementation

Engineering concentration/specialization

Systems Engineering courses
(providing: Approach/methodology)

Digital tools in core courses

Engineering Foundation

Revised curriculum (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 of Engineering Education 4.0

<table>
<thead>
<tr>
<th>Process (methodology)</th>
<th>SE Capstone course (iMBSE)</th>
<th>Typical Capstone course</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE process</td>
<td></td>
<td>Design process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product (application)</th>
<th>SE Capstone course (iMBSE)</th>
<th>Typical Capstone course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-domain system</td>
<td></td>
<td>Mechanical product</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Digitalization</th>
<th>SE Capstone course (iMBSE)</th>
<th>Typical Capstone course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated digital platform (to enable both digital twin and digital thread) that spans the lifecycle</td>
<td>Limited digital capabilities</td>
<td></td>
</tr>
</tbody>
</table>
iMBSE: Framework & Digital Innovation Platform for Industry 4.0 → Proposed Siemens iMBSE framework
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
iMBSE Curriculum

Main characteristics:

*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

<table>
<thead>
<tr>
<th>MBSE course</th>
<th>MBSE tools</th>
<th>MBSE solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model-based Systems Engineering (MBSE) using SysML</td>
<td>Cameo / MagicDraw tool</td>
<td>Ecosystem of software tools (Siemens digital innovation platform for iMBSE, including Capella tool)</td>
</tr>
</tbody>
</table>

**MBSE curriculum**: Two courses offered as part of SE program
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.

**Digital Twin**: A “live”, evolving digital replica of the historical and current behavior of a physical object of process that helps optimize business.

**Digital Thread**: Connects data flows across lifecycle.

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

Digital Thread: Connects data flows across lifecycle

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Implementation in SDPD curriculum

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iMBSE process flow
Case study: Electric Skateboard → iMBSE implementation workflow

Electric Skateboard – iMBSE implementation workflow

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Electric Skateboard as a **multi-domain** system
Practice – Case studies → Electric Skateboard/Longboard
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

Different roles (all for students except “instructor” and “TA”)

Teamcenter Workflow

1. System Design
2. 3D Design
3. 3D Simulation
4. Project Simulation
5. Product Optimization
6. Process Design
7. Process Simulation
Practice – Case studies → Electric Longboard: Project Workflow (Project definition and Planning)

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

Workflow steps

Teamcenter Workflow

Sub-processes of workflow step# 1

Sub-processes of workflow step# 7

Review by TA

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

- 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**

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

**Stakeholder requirements**

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

iMBSE implementation workflow

System structure using BDD diagram (Cameo)

Physical Architecture of E-board (using Capella tool)
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

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

Displacement for different wheel radius & user’s weight

Max. velocity for different wheel radius

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

iMBSE implementation workflow

Deliverable: 3D model of Electric Skateboard

NX: - Design and modelling of skateboard

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

Deliverable: 3D Simulation model of Electric Skateboard

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

3D simulation: Von-Mises stress in skateboard deck
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

Optimization of 3D geometry of skateboard deck
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
Practice – Case studies → Electric Longboard: Manufacturing Process simulation using Tecnomatix

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

Deliverable: Simulation model of Electric skateboard assembly

iMBSE implementation workflow

Simulation of Skateboard assembly
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

Deliverable: Simulation model of Electric skateboard production line

iMBSE implementation workflow

Simulation of Skateboard production line (Top: 2D; Bottom: 3D)
Electric Skateboard/Longboard RFLP
Practice – Case studies → Electric Longboard: Traceability → TC ↔ NX

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

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

iMBSE implementation workflow

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

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 for predicting system’s performance: Max. velocity, etc.

Deliverable: System design that meets requirements

• 1D Simulation model
• 0D requirement model
Practice – Case studies → Electric Longboard: Summary of digital implementation

Implementing iMBSE workflow: Summary of deliverables
Practice – Cases studies → Electric Longboard: Validation

Simulation results from Amesim 1D (Digital twin)

Experimental results from Optical Encoder (Physical)

<table>
<thead>
<tr>
<th>Velocity m/s (no load condition)</th>
<th>Amesim</th>
<th>Optical Encoder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.8</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Electric Saktuboard/Longboard Validation: Max. velocity
Electric Longboard Validation: Deformation

<table>
<thead>
<tr>
<th>Deformation mm</th>
<th>Flex Sensor</th>
<th>Simcenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flex 1</td>
<td>0.91</td>
<td>0.7</td>
</tr>
<tr>
<td>Flex 2</td>
<td>1.71</td>
<td>1.354</td>
</tr>
<tr>
<td>Flex 3</td>
<td>3.3</td>
<td>3.45</td>
</tr>
</tbody>
</table>
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
Engineering Education: Traditional vs. Industry 4.0

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

The proposed iMBSE workflow is about the “Digitalization” of the SE process.
Summary & conclusions

Teamcenter as the digital thread in iMBSE framework

“Digital Twin” in iMBSE framework

iMBSE = Digital twin + Digital thread

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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.**
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.

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.

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)

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