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

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Outline

1. **Rationale**
   1. Product development: Modern products

2. **Current practice in Academia**
   1. Engineering programs (ME, EnE, EE, CE, BME, IE, etc.): Capstone Design Limitations

3. **iMBSE: 3D extension of Capstone Design**
   1. iMBSE characteristics & modern products
   2. 3D extension of Capstone Design

4. **Curriculum for Industry 4.0: Engineering Education 4.0**
   1. 3 Level curriculum
   2. Revised curriculum (for Engineering Education 4.0)

5. **iMBSE: Framework & Digital innovation platform for Industry 4.0**
   1. Proposed iMBSE framework
   2. Digital Innovation platform for Industry 4.0

6. **Case study: Electric skateboard**

7. **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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<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>
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<tr>
<td>Growth of software / electronic systems</td>
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<td>Exploding requirements</td>
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<td>Fast growing number of V &amp; V</td>
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<tr>
<td>Multiple disparate tools in each domain</td>
<td></td>
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<tr>
<td>Multiple design groups and multiple sites</td>
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Example of modern product: Multi-domain, multi-subsystems, etc. SoS
Current practice in Academia → Engineering programs (ME, EnE, EE, CE, BME, IE,...): Capstone Design Limitations

<table>
<thead>
<tr>
<th>Capstone Design Limitations</th>
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<tbody>
<tr>
<td>Simple product</td>
<td></td>
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<tr>
<td>Single Domain</td>
<td></td>
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<tr>
<td>Limited scope: “Development” (not “Lifecycle”)</td>
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<tr>
<td>Limited Digitalization</td>
<td></td>
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<tr>
<td>Validation: Mostly through Physical prototyping</td>
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</table>

Example of typical capstone design products: Mostly Mechanical

- Fin Heat Transfer Apparatus
- Arm-A-Door Outside Entry: Exterior Handle Assembly
### iMBSE: 3D extension of Capstone Design

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

<table>
<thead>
<tr>
<th>3D extended CD driven by iMBSE</th>
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<tbody>
<tr>
<td>Complex product (system or SoS)</td>
</tr>
<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

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

Three levels of typical Engineering curriculum (e.g. ME)
Curriculum for Industry 4.0: Engineering Education 4.0

Revised curriculum (Engineering 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/VR/MR, 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

Synthesis & Implementation

Engineering concentration/specialization

Engineering Foundation

Revised curriculum (Engineering Education 4.0)
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

<table>
<thead>
<tr>
<th>Work Package</th>
<th>SE Capstone course (iMBSE)</th>
<th>Typical Capstone course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process (methodology)</td>
<td>SE process</td>
<td>Design process</td>
</tr>
<tr>
<td>Product (application)</td>
<td>Multi-domain system</td>
<td>Mechanical product</td>
</tr>
<tr>
<td>Digitalization</td>
<td>Integrated digital platform (to enable both digital twin and digital thread) that spans the lifecycle</td>
<td>Limited digital capabilities</td>
</tr>
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</table>

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
Digital Innovation platform for Industry 4.0: Integrating Digital twin with Digital thread
Case study: Electric Skateboard

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

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

- 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>1.1 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>1.2 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>2 SN02</td>
<td>The user shall be able to control the speed and stop within safe distance</td>
</tr>
<tr>
<td>5</td>
<td>2.1 SN02-1</td>
<td>The user shall be able to control the speed</td>
</tr>
<tr>
<td>6</td>
<td>2.2 SN02-2</td>
<td>The user shall be able to stop within safe distance</td>
</tr>
<tr>
<td>7</td>
<td>4 SN03</td>
<td>The skateboard shall stop within safe distance</td>
</tr>
<tr>
<td>8</td>
<td>5 SN04</td>
<td>The skateboard shall have speed setting for Novice, Regular and expert levels</td>
</tr>
<tr>
<td>9</td>
<td>6 SN05</td>
<td>The skateboard shall use commercially available off the shelf materials (COTS)</td>
</tr>
<tr>
<td>10</td>
<td>7 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>8 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
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

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

iMBSE implementation workflow

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

NX:
• Design and modelling of skateboard

Deliverable: 3D model of Electric Skateboard

iMBSE implementation workflow
**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**

- **Deliverable: 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

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
Manufacturing Process simulation using Tecnomatix

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
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

Deliverable: Simulation model of Electric skateboard production line

iMBSE implementation workflow
Traceability

Practice – Case studies → Electric Longboard: Traceability

Electric Skateboard/Longboard RFLP
Traceability

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
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 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)

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

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)

<table>
<thead>
<tr>
<th>Deflection 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>
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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

<table>
<thead>
<tr>
<th>Current Engineering Education landscape</th>
<th>Engineering Education for Industry 4.0</th>
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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

Summary & conclusions

Teamcenter as the digital thread in iMBSE framework

“Digital Twin” in iMBSE framework

iMBSE = Digital twin + Digital thread