Model-Based System Engineering Applied to Designing Engineering Labs to Dynamically Adapt to Industry Trends - Case in Point: The Mechatronics, Robotics and Control Lab

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ABSTRACT

This paper presents a comprehensive approach to designing a Mechatronics, Robotics, and Control (MRC) Lab, using Model-Based System Engineering (MBSE). This work is mainly motivated by the apparent need to train and develop a qualified workforce for the semiconductor industry as highlighted by the CHIPS Act. This work contributes to the enhancement of engineering education by employing MBSE tools that consider the complexity of the system and dynamically adapt to the needs of this, ever-evolving, field.

The paper demonstrates the use of No Magic Cameo Systems Modeler™ software to simulate and evaluate learning objectives and skills under various educational scenarios. These scenarios explore multiple practices for IoT and semiconductor manufacturing and focus on hands-on skills. This work leverages the partnership between academia and industry to ensure that the curriculum stays relevant and dynamically evolves by considering the latest trends in the field. This alignment is critical to equip talent that can immediately contribute to the new Smart Factories driven by Industry 5.0.

The paper summarizes the history and evolution of the CHIPS Act, highlighting significant government investment and the rapid growth in the ecosystem around these new technologies. A review of the current demands and challenges faced by the semiconductor industry is also included. More importantly, this work provides a roadmap for academic institutions, to establish laboratories and curricula that are not only in sync with current industry requirements but are also adaptive enough to accommodate future advancements.

Adoption and implementation of the presented tools will ensure that the next generation of STEM workers displays a blend of technical skills, soft skills, and digital capabilities needed due to rapid technological advancements and constantly changing work environments of the semiconductor industry.

INTRODUCTION

The teaching-learning landscape has undergone swift changes, spurred by the pandemic, leading to the rise of virtual learning, new semiconductor global initiatives, and the advent of Industry 5.0. As Stuchlikova [13] predicts, knowledge gained during a degree may become outdated by the time the course is completed, therefore it is becoming imperative that we leverage the

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latest advances in neuroscience that highlight the need to focus on building new neuron interconnects via experiential learning design to form an Integral Engineer[7].

The educational sector is currently facing several significant challenges. These include : 1) the implementation of remote labs [1], 2) the need for skills specific to the semiconductor workforce [9], and 3) the development of soft skills that are crucial for succeeding in today's job market [14][27].

This paper sets out with a clear and focused objective: to use 21st-century tools such as Model-Based Systems Engineering (MBSE) to propose the development of a laboratory that aligns with the needs of the semiconductor industry.

Objective

The central aim of this paper is to share the process under which the lab is being developed. This development process is unique and designed to meet a diverse array of requirements from both industry and various stakeholders. By doing so, the paper seeks to bridge the gap between current educational practices and the evolving demands of the semiconductor industry.

Paper Contributions:

1. System Engineering Approach: This paper contributes a detailed system engineering approach for the design of the lab. This approach is methodical and user-centric, ensuring that the lab's design and functionality cater efficiently to the end-users' needs.
2. Concept of Operations (ConOps): A significant portion of this paper is dedicated to outlining the proposed Lab Concept of Operations. This document is crafted from a user perspective, offering a clear understanding of how the lab will operate in real-world scenarios and how it will fulfill the needs of its users.
3. Integration of MBSE Tools: The paper emphasizes the integration of MBSE tools, particularly highlighting the role of Cameo Systems Modeler. These tools are crucial for the development of the lab, as they facilitate effective communication, collaboration, and the integration of diverse requirements from stakeholders.
4. Stakeholder Requirements and Industry Needs: A comprehensive analysis of stakeholder requirements and industry needs forms a core part of the paper. This analysis ensures that the lab not only meets current educational standards but is also equipped to handle future changes and demands within the semiconductor industry.

The paper provides a roadmap for academic institutions, enabling them to develop laboratories and curricula that are not only in sync with current industry requirements but are also adaptive enough to accommodate future advancements. This approach ensures the creation of a dynamic and capable workforce, ready to meet the challenges of the semiconductor industry.

Shown in Tables 1 are the key business and technological trends that will fundamentally influence higher education. These trends could include advancements in digital learning platforms, the rise of AI in personalized learning, the growing importance of data privacy and cybersecurity in education, and the increasing demand for interdisciplinary and experiential learning experiences. The growing demand for interdisciplinary and experiential learning experiences reflects the changing needs of the job market but also requires a shift in traditional teaching methodologies. Understanding and responding to these trends is crucial for educators and institutions to stay relevant and effective in delivering quality education in the 21st century.

Challenges	Technology Trends
Responding to rapid changes and complex business	Artificial intelligence
Managing ever-increasing factory complexity	Virtual/augmented reality
Meeting costs for factory and equipment productivity	IIoT (listening and sensing technologies)
Factory integration across 300 mm and 450mm technologies	Adaptive learning
Addressing the migration to smart factory	Autonomous Control
Sustainability supply chain	Digital engineering
Legislation on IA and ML	Cybersecurity

Table 1: Business and technology trends on fundamental education

In the face of the challenges and trends exposed above, integrating modern technologies into engineering education is vital [16] [5] [2]. Artificial Intelligence (AI) can optimize semiconductor manufacturing processes, while Virtual/Augmented Reality (VR/AR) offers immersive training experiences. The Industrial Internet of Things (IIoT) enhances efficiency through real-time monitoring. Adaptive learning personalizes education, ensuring each student understands at their own pace. Autonomous control systems, when understood and managed by students, can optimize operations. Digital engineering skills enable students to use advanced software integral to engineering design. Lastly, cybersecurity training is crucial to protect sensitive data in an increasingly digital world. These technologies, when integrated within the formation of future engineers, prepare them to drive innovation in the industry.

In the development of a Mechatronics, Robotics, and Control (MRC) Lab, it's essential to consider the key stakeholders and their drivers. These stakeholders, including students, educators, and industry partners, have varying needs such as practical skills, teaching resources, and skilled graduates. Stakeholders also control resources like funding, curricula, and demand, making their involvement from the beginning of the lab development critical for the lab's success. Their backing also ensures the lab's long-term sustainability through ongoing funding, curriculum integration, and student engagement. Furthermore, stakeholder input maintains the lab's relevance, especially in a rapidly evolving field like MRC. In essence, considering stakeholders is crucial for an effective, sustainable, and relevant MRC Lab that dynamically meets everyone's needs and aligns with industry trends and educational goals. Table 2 shows examples identifying stakeholders, their drivers and their respective needs.

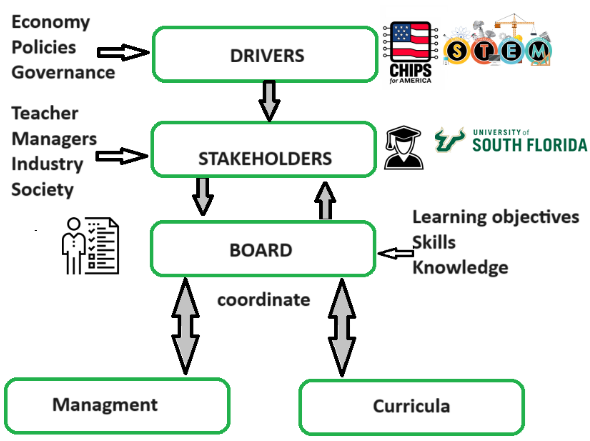


Figure 1: Macro-model of Drivers and Educational Management

Stakeholders	Needs	Drivers
Government	Quality education, Well-formed citizen.	Education policies, approval rate, Geopolitical situations, Chips Act.
Society	Well-formed Professionals, Economically productive.	Job market, individual and collective desires, economy, technological trends.
School Management	Delivery of high-quality education that maximizes revenue at minimal cost, Increasing institutional reputation, Creation of satisfied alumni who will contribute to the institution's long-term viability, Well-formed Professionals, Individuals capable of performing professionally, Operational efficiency.	Educational economics and demographics, Regulatory policies and laws, social necessities, learning, technological trends.
Industry	Well-formed workforce, Workforce capable of achieving their goals, Feedback.	Innovation, competencies, technological trends, workforce training, economics.
Teachers	Reliable information, Learning process, Synergy with industry, Identify improvement points.	Learning, communication, technological trends, teaching methods.
Students	Being engaged, Feel himself/herself as part of the process.	Learning, engagement, trends, communication.

Table 2: Stakeholders and educational governance drivers

Table 2 presents a structured view of the educational landscape, where the first column identifies the key stakeholders involved, the second column outlines their specific expectations from the education system, and the third column indicates the factors that might affect these expectations. For instance, society seeks to cultivate individuals who are not only well-educated but also contribute economically, influenced by elements such as job markets, communal and personal ambitions, societal norms, economic conditions, and prevailing technological advancements. The information regarding stakeholders, alongside their needs and influencing drivers, extends beyond what is shown in Table 2. Stakeholders are categorized as either direct or indirect based on their engagement with educational processes.

Direct stakeholders include those actively participating in educational activities, such as school administrators, parents, faculty, and students. In contrast, indirect stakeholders may not be directly engaged in day-to-day educational activities but have vested interests in the outcomes, like governments and the broader society such as industry. Figure 1 further illustrates the interplay between the educational participants, their driving factors, and the governance of educational institutions.

Towards the development of the Mechatronics, Robotics, and Control (MRC) Lab roadmap. The roadmap will act as a Concept of Operations (ConOps) from an end-user perspective. The motivation for using Model-Based Systems Engineering (MBSE) techniques is to facilitate the communication, collaboration, and integration of different stakeholders and their requirements, as well as to ensure the traceability, consistency, and verification of the system design [32][17]. Among the various MBSE tools available, Cameo Systems Modeler was selected due to its widespread adoption and usage in various industries, including aerospace, defense, automotive, and more, to design and analyze complex systems and architectures. It starts by presenting all the requirements from different stakeholders such as semiconductor industry suppliers, academia, and automation and control trends 2030 for future engineer skill sets. Then it formulates the lab experiments design and learning objectives that will cover the requirements needed for the future workforce in the semiconductor industry, including the workers/engineers/technicians for the supplier companies. In addition, it presents a roadmap for academic institutions to design engineering courses or labs that will cater to the current and future needs of the industry. Furthermore, it uses Cameo Systems Modeler to create Measures of Effectiveness (MoEs) and run different simulation scenarios and requirement validation. The paper concludes with a discussion on how academic institutions need to transform their curricula to attend to the current and future needs of the industry.

LITERATURE REVIEW

The Global Semiconductor Industry Trends

The semiconductor industry has been a cornerstone of technological advancement, with a significant impact on various sectors. The Foundry/Fabless industry model [33] is a significant paradigm in the semiconductor industry that was firmly established by 2020. This model had been in place for over a decade and had become the foundational structure of the new semiconductor industry [25][30][15]. In this model, two types of companies exist Fabless companies and Foundries.

Fabless companies are those that do not have fabrication facilities. These companies focus on the design and development of semiconductor chips. They create the architecture and functionality of the chips but do not manufacture the physical chips themselves. This allows them to concentrate on innovation and design, reducing the need for substantial capital investment in manufacturing facilities. Companies like Apple, Google, Facebook, Qualcomm, NVIDIA, and Broadcom fall into this category. Despite not having their own manufacturing capabilities, these companies have been extremely successful in designing their own chips.

On the other hand, Foundries are companies that specialize in the manufacturing of chips. They own and operate the fabrication facilities where the physical chips are produced. Foundries take the designs from the fabless companies and manufacture the chips based on those designs. This allows them to specialize in manufacturing processes and technologies, improving efficiency and scale.

By 2020, this model had allowed companies that had never been involved in semiconductor manufacturing to design their own chips and have them produced outside the US. This has led to a global distribution of semiconductor production and has allowed companies to leverage global efficiencies and expertise [3][34][4].

The Pandemic Influence

The advent of the COVID-19 pandemic in 2020 exposed the fragility of globalized supply chains and underscored the indispensable role of semiconductors in today's society. This revelation has spurred major semiconductor nations, including the USA and Europe, to consider establishing their own domestic semiconductor manufacturing facilities [23].

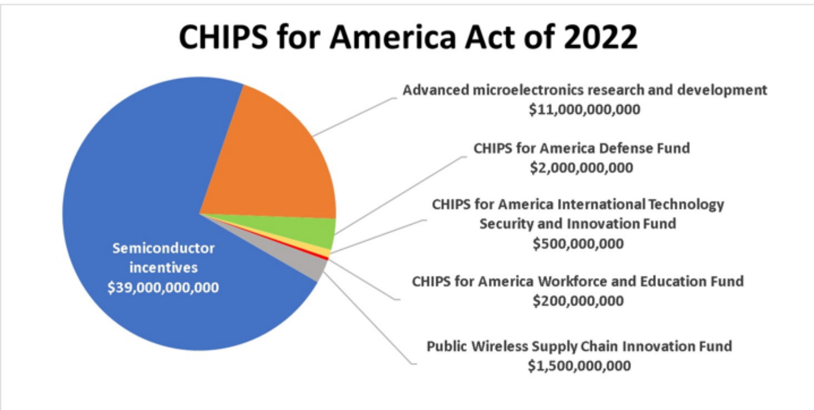
This shift towards self-reliance in critical sectors such as semiconductor manufacturing necessitates a strategic reevaluation of supply chain management. It requires countries to adapt their educational systems and workforce strategies to cater to the demands of these domestic manufacturing initiatives in the next three to five years. These strategies will ensure a robust and resilient semiconductor industry capable of withstanding future crises [19][22].

Governments have recognized to revitalize and strengthen their domestic manufacturing initiatives focusing on enhancing supply chain resilience, technological leadership, job creation, and workforce development. In response to these objectives, the government introduced the CHIPS Act on August 9, 2022 [21][31][24].

Over time, governments have initiated various funding programs to target different sectors within the semiconductor industry. This first allocation of financial resources and projected spending under the CHIPS for America Act from 2022 to 2026 is illustrated in Figure 2. The data presented in this figure is sourced from articles by Forrester [11] and the National Taxpayers Union [18].

The CHIPS for America program is part of the National Institute of Standards and Technology (NIST) and is dedicated to revitalizing the domestic semiconductor industry and creating good-paying jobs in communities across the country. The CHIPS Research and Development Office is investing $11 billion into developing a robust domestic Research and Development ecosystem, and the CHIPS Program Office is dedicating $39 billion to provide incentives for investment in facilities and equipment in the United States.

Table 3 illustrates a summary of the funding sources from the government for the semiconductor industry from 2022 till the present. Substantial investments are being made to strengthen the semiconductor supply chains, ensuring that funding is specifically allocated to these critical areas. Therefore, the CHIPS Act required active participation from various government agencies, the industry sector, and academia. The collaboration of these stakeholders, including manufacturers, educational institutions, and regional governments, is central to building a robust and self-sufficient semiconductor infrastructure in the U.S.



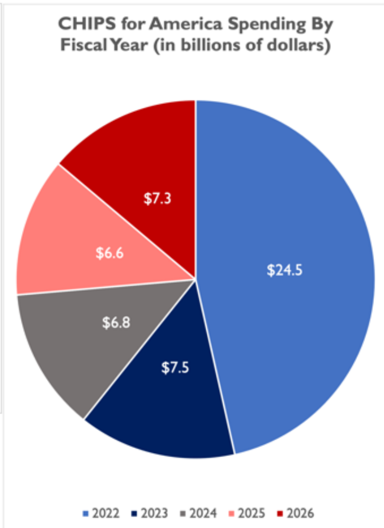


Figure 2: Financial Allocation and Projected Spending of the CHIPS for America Act (2022-2026) Sourced from Article [11] and [18]

Educational Institutions' Role in the Semiconductor Workforce Development

Based on the above trends, Academic institutions are leading the charge in preparing the next generation of engineers and technicians by establishing state-of-the-art engineering laboratories and designing specialized courses. These academic programs aim to provide not only a

Year	Funding Source	Purpose
2022	CHIPS and Science Act	$52 billion investment to revitalize America's domestic semiconductor industry and strengthen economic and national security
2022	CHIPS for America	$11 billion administered by the U.S. Department of Commerce for semiconductor research and Development programs, including the National Semiconductor Technology Center, National Advanced Packaging Manufacturing Program, CHIPS Metrology Program, and CHIPS Manufacturing USA Institute
2023	Workforce Development	The Act recognizes the importance of skilled labor in this sector and allocates $200 million to develop the semiconductor workforce through job training and graduate school programs. The goal is to prepare more American workers for the industry, which is projected to require an additional 90,000 workers by 2025.
2023	Supply Chain Security	Funding opportunities are also available for smaller supply chain projects and businesses, focusing on the construction, expansion, or modernization of facilities for semiconductor materials and manufacturing equipment. This initiative is part of a broader strategy to strengthen supply chain resilience.
2024	Boost Economic Growth and Innovation in Communities Across America	U.S. regions that are emerging as innovation ecosystems and receiving over $530 million of investment catalyzed by the U.S. National Science Foundation's (NSF) Regional Innovation Engines program NSF Regional Innovation Engine Awardees: **Central Florida**

Table 3: Summary of government funding towards the semiconductor industry (2022-present)

theoretical understanding of semiconductor technology but also practical and hands-on experiences with industry tools and processes. Universities are increasingly partnering with industry leaders to ensure their curricula stay relevant. Internships and cooperative education programs serve as vital links between academic learning and industrial practice, preparing graduates to be not just job-ready but also innovative contributors to the semiconductor industry's growth and resilience [20][29][6].

Technical Skill set Required for the Semiconductor Workforce

Continuing the discussion: Figure 3 introduces a cyclical graph that illustrates the interconnected Ecosystem of Suppliers and Customers in the Semiconductor industry, highlighting the interconnections between suppliers and customers.

Table 4 outlines the suppliers for the foundries and the technical skills required by engineers working for supplier companies in the foundries OSAT sector. It highlights three key suppliers: Applied Materials Inc., Lam Research Corporation, and KLA Corporation.

- Applied Materials Inc. specializes in the development and manufacturing of equipment for semiconductor production. Engineers here need knowledge and skills in semiconductor device physics, vacuum technology, robotics, automation, software programming for equipment control, and CAD for equipment design.

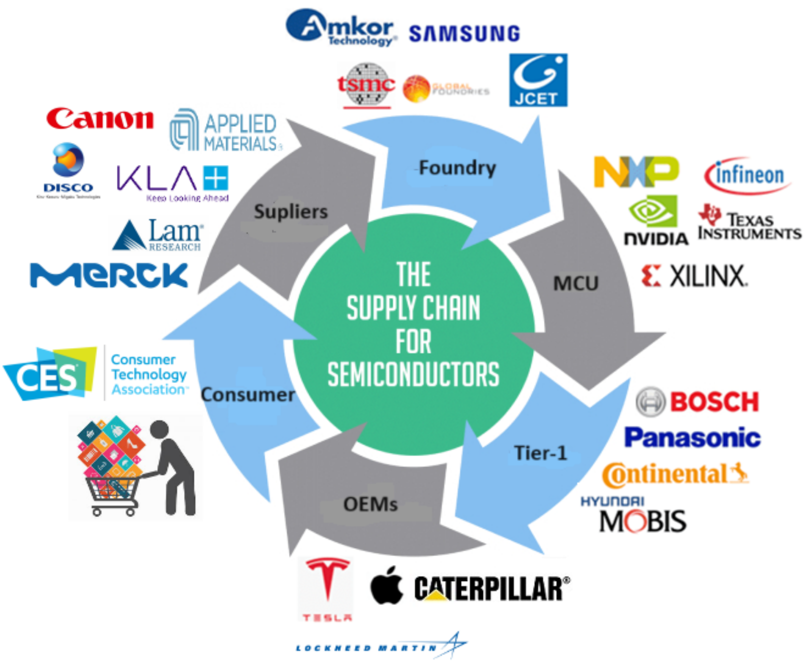


Figure 3: The Interconnected Ecosystem of Suppliers and Customers in the Semiconductor Industry

Supplier for Foundry	**Equipment Description**	**Required Technical Skills for Engineers**
Applied Materials Inc.	Development and manufacturing of equipment for semiconductor production.	Semiconductor device physics, Vacuum technology, Robotics, Automation, Software programming for equipment control, CAD for equipment design, Lam Research Corporation
Lam Research Corporation	Equipment for etching, thin film deposition, and surface treatment.	Thin film materials science, Plasma etch and deposition processes, Fluid dynamics for gas and chemical delivery systems, Advanced process control (APC), Statistical process control (SPC), Cleanroom protocol
KLA Corporation	Inspection, metrology, and analysis equipment for semiconductors.	Advanced metrology techniques, Image processing, Computer vision, Artificial intelligence, Machine learning for defect analysis, Big data analytics, Precision engineering

Table 4: Summary of technical skills required by engineers working for supplier companies in the Foundry OSAT sector

- Lam Research Corporation focuses on etching, thin film deposition, and surface treatment. Requires knowledge and skills in thin film materials science, plasma etch and deposition processes, fluid dynamics for gas and chemical delivery systems, Advanced Process Control (APC), Statistical Process Control (SPC), and cleanroom protocol.
- KLA Corporation is known for inspection, metrology, and analysis equipment for semiconductors. Engineers should have knowledge and skills in advanced metrology techniques, image processing, computer vision, artificial intelligence, machine learning for defect analysis, big data analytics, and precision control engineering.

These skill sets are crucial for the effective development of Engineering courses and labs, which integrate multiple engineering disciplines. By analyzing these skills, we can ascertain how educational institutions can tailor their programs to better prepare students for roles within these supplier companies, thereby strengthening the overall semiconductor supply chain.

This paper applies the methodology of System Engineering (SE) to drive its stakeholder requirements from the needs of Suppliers and Customers in the Semiconductor Industry, see Figure 3. and Table 4 show the Technical skillset requirement for the semiconductor supplier companies. The paper is designed to pinpoint and elaborate on the skills and expertise that these suppliers need to establish an Engineering Lab effectively. Such a lab is crucial for enhancing the semiconductor industry's capabilities, as it merges mechanical engineering, electronics, computer science, and control engineering — all of which are vital for the innovation and production of semiconductors. This approach will assist in identifying ways for educational institutions to modify their programs, enhancing the preparedness of students for roles in these supplier companies. Consequently, it strengthens the resilience of the entire semiconductor supply chain.

Model-Based Systems Engineering (MBSE) Methodology

Model-Based Systems Engineering (MBSE) is a methodology that leverages models to support the entire lifecycle of a system, from its inception and design to verification, validation, and eventual decommissioning. Unlike traditional engineering approaches that rely on text-based documents and manual processes, MBSE employs digital modeling and simulation techniques to design complex systems[10]. These models provide a visual and interactive representation of system components and their interconnections, making it especially valuable for intricate systems and interfaces. By using digital models, MBSE enhances efficiency, reduces the risk of errors, improves communication among engineering teams, and ensures information consistency throughout the project's lifecycle. The benefits of MBSE include better stakeholder understanding, reduced errors, early issue detection, cost and time savings, and adaptability to various project sizes and complexities. It is a versatile approach applicable across domains, supporting product development throughout the entire lifecycle

MBSE encompasses activities such as analyzing user needs, specifying system requirements, creating models to represent different aspects of the system, conducting simulations and tests for verification, implementing and maintaining the system. As a cost-effective approach, MBSE allows timely exploration and documentation of system characteristics. By validating these characteristics early, models facilitate rapid feedback on requirements and design decisions, contributing to efficient system development. Whether in aerospace, automotive, or other domains, MBSE plays a crucial role in achieving robust and reliable systems by placing models at the center of system design.

There are three pillars of Model-Based Systems Engineering (MBSE): the modeling systems language, the modeling tool, and the methodology[28]:

1. Modeling Language: Languages are essential for expressing system models. MBSE relies on standardized modeling languages to represent system components, their interactions, and behaviors. Unified Modeling Language (UML) and SysML (Systems Modeling Language) are commonly used in MBSE. UML provides a general-purpose modeling framework, while SysML extends it specifically for systems engineering. UML diagrams (such as use case diagrams, class diagrams, and sequence diagrams) help visualize system architecture, requirements, and interactions. SysML diagrams (such as block definition

diagrams, activity diagrams, and parametric diagrams) focus on system aspects relevant to engineering.

2. Methodology: A robust methodology guides the systematic application of MBSE throughout the system lifecycle. Requirements Engineering: Start by capturing stakeholder needs and translating them into system requirements. Use models to represent these requirements. Model Development: Create models that depict system structure, behavior, and interfaces. Iteratively refine and validate these models. Simulation and Analysis: Leverage models for simulations, trade studies, and performance analysis. Assess system behavior under various conditions. Verification and Validation: Verify that the system meets requirements and validate its performance against expectations. Configuration Management: Manage model versions, changes, and baselines. Collaboration and Communication: Facilitate communication among multidisciplinary teams using shared models. Tools:

3. Modeling Tools: Specialized software tools enable the creation, visualization, and manipulation of system models. Examples include CAMEO Simulation Toolkit, Enterprise Architect, MagicDraw, and Papyrus. Simulation Tools: These tools allow dynamic analysis of models. They simulate system behavior, performance, and interactions. Requirements Management Tools: Track and manage requirements, ensuring traceability from models to stakeholder needs. Version Control Systems: Essential for managing model versions and collaborative development. Integration with Other Tools: MBSE tools should seamlessly integrate with other engineering tools (such as CAD software, simulation packages, and project management tools).

Cameo Systems Modeler excels in simulating complex systems and analyzing real-world scenarios [8]. This capability is vital in an educational setting, as it allows educators and students to visualize, experiment with, and understand the intricacies of mechatronics, robotics, and control systems in a controlled, yet dynamic environment. Through its advanced simulation features, Cameo Systems Modeler can replicate a wide array of scenarios that students might encounter in the semiconductor industry, providing them with invaluable insights into system behaviors, performance metrics, and potential challenges. Furthermore, the software's ability to model and simulate systems in real time enables a hands-on learning experience that is both immersive and interactive. This aspect of Cameo Systems Modeler is particularly beneficial in demonstrating the impacts of different variables and decisions, thus equipping future engineers with the critical thinking and problem-solving skills necessary for effective decision-making in complex, real-world situations. By integrating Cameo Systems Modeler into the curriculum, educational institutions can significantly enhance the practical relevance of their programs, aligning academic training more closely with the evolving demands of the industry.

METHODOLOGY

Formulating Stakeholder Requirements for Multidisciplinary MRC Lab

Building upon the technical skills that were identified earlier, stakeholder requirements for the Agile Design of the Mechatronics, Robotics, and Control (MRC) Lab have been established. The primary objective is to create a lab syllabus that is specifically tailored to enhance certain knowledge and skills. The aim is to ensure that the lab's curriculum effectively equips students for their future roles. The design approach adopts a multidisciplinary perspective, guaranteeing that the lab is well-designed to facilitate the learning of the required skills and competencies.Table 5 illustrates the stakeholder requirements. Students taking the MRC lab, will all be Electrical Engineering students from University of South Florida , however, the students taking the lab course will be from different EE tracks such as Power Systems, Embedded Systems, Wireless Systems, etc. The teams formed within the lab for group assignments will be formed using the Multi-criteria Team formation method explained in [26]. Multi-criteria team formation will allow for diverse grouping of students i.e., with different EE tracks experience and with diverse student demographics. The Lab will be an independent course within the undergraduate/graduate courses catalog.

The MRC lab will also engage with industry partners such as (ABB in the robotic area, Rockwell International in industrial controls, and National Instruments for data acquisition and control systems) these companies are major suppliers for the semiconductors industry, furthermore, the proposed MRC Lab engagement with industry will come through a comprehensive approach that includes 1) internships and capstone projects, which will integrate industry expertise directly within the MRC laboratory environment. 2) Curriculum development joined with industry to equip students with practical, in-demand skills, attracting their employability and positioning them as prime candidates for roles within the industry, especially in the context of Industry 5.0. 3) Field trips to smart manufacturing facilities will provide exposure to real-world manufacturing processes, enabling students to understand the infrastructure of manufacturing plants and visualize their real-time implementation. By implementing these

ID	Stakeholder Requirement	Stakeholder Requirements Description
SHR 1.1	Understand the complex automation systems, including programming, maintenance, and integration with other systems	
SHR 1.1.1	Programming Skills	Students should have proficiency in programming languages commonly used in automation systems, such as Python, C++, or Java. They should be able to write, debug, and optimize code.
SHR 1.1.2	Hardware Design	Students should have an understanding of the hardware used in automation systems, including sensors, actuators, and controllers, is necessary. including how components interact within the system.
SHR 1.1.3	System Integration	Students should have the ability to integrate automation systems with other hardware and software systems. This includes understanding APIs, data exchange formats, and network protocols.
SHR 1.1.4	System Maintenance	Students should understand the lifecycle of automation systems and be able to perform routine maintenance tasks. This includes troubleshooting, system updates, and managing backups
SHR 1.1.5	Documentation	Stakeholders should be able to create clear and comprehensive documentation for the automation systems. This includes system specifications, user manuals, and maintenance guides

Table 5: Stakeholder Requirements

strategies, the MRC lab will cultivate an educational setting that prepares graduates to make meaningful contributions as soon as they enter the workforce.

This approach to the design, of the MRC Lab reflects a multidisciplinary perspective, integrating aspects of mechatronics, robotics, and control to create a dynamic environment for learning and innovation. Here, students, researchers, and practitioners can engage in practical problem-solving, collaborate across disciplines, and develop new technologies and solutions focused on robotic dexterity and precision.

Furthermore, the Measures of Effectiveness (MOEs) for the MRC Lab, as detailed in Table 6, are defined and related to the stakeholder requirements. They are operational measures of success that are closely aligned with the lab's mission and operational objectives, evaluated in the intended operational environment under specific conditions. This alignment ensures that the MRC Lab not only meets its immediate objectives but also remains adaptable and relevant in the rapidly evolving field of automation.

Curriculum for the MEC lab: Goals and Learning Objectives

Case in point: Semiconductor Industry

1. **Focus Area:** General
   Learning Objective: Understand the fundamentals and different subsets and areas of knowledge involved in wafer cutting equipment and their application in semiconductor manufacturing. Understand the principles of operation and semiconductor manufacturing processes. Quality analysis and defects in the various wafer-cutting processes.
   Practice: Supervised operation of wafer cutting equipment, modification, and testing of different configurations such as wafer cutting power, speed and distance, and their impact on the material. Use of microscopes and magnifying glasses to examine cut wafers and identify defects such as cracks, burns, and distortions.
   Technical skill: Handling of laser wafer cutting equipment. Management of measurement and analysis equipment. Basic knowledge of semiconductors and materials.
   Soft Skill: Teamwork: effectively collaborate in groups to operate and maintain the equipment. Problem-solving: identify and solve technical problems during the wafer-cutting process.
   Key performance Indicator: Practical tests of equipment handling. Presentation of a detailed quality analysis report of the cut detailing the analysis of the defects found and discussion about their possible causes and solutions, as well as their relationship with the variables of the wafer-cutting process.

ID	Criteria	Definition
SHR 1.1.4.1	Knowledge Assessment	Test or Quiz Score understanding of the lifecycle of automation systems should be between 80 and 100
SHR 1.1.4.2	Practical Examination	Practical Examination Score should be between 70 and 100 for malfunctioning automation system
SHR 1.1.4.3	Peer and Instructor Reviews	Peer and Instructor Reviews Score for Student understanding and skill on the subject should be more than 60

Table 6: MOE for Stakeholder Requirements (SHR 1.1.4)

2. **Focus Area:** Control
   Learning Objective: Program Programmable Logic Controllers (PLCs) and automated control systems. Know and determine the need for fine-tuning and calibration of machinery for precision in process execution.
   Practice: Programming practice of a real PLC connected to a wafer-cutting machine. Adjustment and calibration of wafer-cutting parameters (power, speed, focus) using the PLC. Implementation of self-calibration according to set point changes.
   Technical skill: PLC programming. Calibration and adjustment of control systems. Analytical thinking: analyze and adjust control systems to optimize performance.
   Soft Skill: Attention to detail. Analytical thinking. Fault detection.
   Key performance Indicator: Accuracy in the configuration of control parameters. Response time in control adjustments. Presentation of data analysis of the calibration process and the adjustments made and of each controller used.

3. **Focus Area:** Mechanical/Mechatronics
   Learning Objective: Design and integration of mechanical systems and electronic components in wafer cutting equipment. Analysis of mechatronic systems and their efficiency.
   Practice: Learn to integrate mechanical and electronic components in a wafer-cutting equipment prototype. Integration of sensors and actuators, and connection with the electronic control system. Initial programming and functional testing of the prototype.
   Technical skill: Mechanical design. Integration of mechatronic systems.
   Soft Skill: Innovation and creativity: develop innovative solutions to improve the efficiency of mechatronic systems. Interdisciplinary collaboration: work with specialists in other areas to integrate complex systems.
   Key performance Indicator: Effectiveness in the integration of mechanical and electronic components. Innovation in design solutions, support report of the different configurations used or analyzed, and the reason for the implemented methodology.

4. **Focus Area:** Electrical/Electronic
   Learning Objective: Design, assembly, and testing of electronic circuits for wafer cutting systems, analysis and troubleshooting in electrical and electronic systems.
   Practice: Electronic circuit design (EDA) to simulate the designed circuit, with a focus on functionality and efficiency. Mounting of the circuit on a prototype board or PCB, following the previously made design. Practical tests to evaluate the skill in the use of electronic diagnostic tools.
   Technical skill: Circuit design. Analysis of electrical and electronic systems.
   Soft Skill: Attention to detail: Precision in the design and assembly of electronic components. Diagnostic skills: identify and solve problems in electrical/electronic systems.
   Key performance Indicator: Quality in the design and assembly of circuits. Ability to identify and solve electrical problems. Analysis report and support of the circuit used.

Case in point: Internet of Things(IoT)

1. **Focus Area:** General
   Learning Objective: Understand IoT/IIoT principles and their application in automated pick-and-place systems for inventory and quality management. Analyze data-driven production efficiency.
   Practice: Set up an IoT-enabled pick-and-place system to simulate an assembly line. Use IoT sensors to track the speed and accuracy of the picking process, and monitor inventory levels for alerts. Students will learn to analyze the data collected to understand production flow and efficiency.
   Technical skill: Understanding of IoT/IIoT platforms. Data analytics and inventory management.
   Soft Skill: Collaborative problem-solving. Analytical skills for process improvement.
   Key performance Indicator: Accuracy and speed of the pick-and-place system. Effectiveness of inventory level alerts and system optimizations based on data collected. Technical report and support of the project for the increase of production.

2. **Focus Area:** Control
   Learning Objective: Develop and program IoT/IIoT-based control systems for optimized pick-and-place operations and real-time monitoring.
   Practice: Implement a control solution using a PLC that integrates with IoT devices for real-time monitoring of a pick-and-place system. Students will use IoT to automatically adjust system parameters for optimal speed and accuracy. Optional: apply machine learning for predictive maintenance to prevent downtime.
   Technical skill: Advanced PLC programming for IoT integration. Real-time system monitoring and adjustments.
   Soft Skill: Remote teamwork and communication. Proactive approach to system maintenance.
   Key performance Indicator: Responsiveness and adaptability of the control system. Increase productivity based on the speed of the work and delete dead time between transitions. Data analysis report and support of the solution based on the production results.

3. **Focus Area:** Mechanical/Mechatronics
   Learning Objective: Design and construct a mechatronic system with IoT/IIoT for efficient and intelligent pick-and-place operations.
   Practice: Design a mechatronic tool that incorporates IoT sensors and actuators to facilitate automated pick-and-place actions. The system should also be capable of remote diagnostics. Students will focus on designing a system that can adapt to different device sizes and weights with minimal manual intervention.
   Technical skill: Design for adaptability and scalability of mechatronic components with IoT.
   Soft Skill: Innovation in design. Project management across disciplines, following requirements, planning, and critical solutions.
   Key performance Indicator: Effectiveness in the integration of mechanical and electronic components. Innovation in design solutions, support report of the different configurations used or analyzed, and the reason for the implemented methodology.

4. **Focus Area:** Electrical/Electronic

Learning Objective: Create IoT/IIoT-based electronic circuits that enable smart pick-and-place operations and seamless data flow for production analytics.
Practice: Assemble and test an IoT-based electronic circuit that controls a pick-and-place system. Students will ensure that the circuit can reliably communicate with cloud services for data acquisition, processing, and triggering alerts for inventory management. They will also explore the integration of RFID or barcode scanners for real-time tracking.
Technical skill: Electronic circuit design for IoT connectivity. Cloud computing and data processing.
Soft Skill: Attention to detail. Adaptability to integrate various IoT devices and platforms.
Key performance Indicator: Attention to detail. Adaptability to integrate various IoT devices and platforms. Analysis report and support of the circuit used.

RESULT: IMPLEMENTATION WITH CAMEO SYSTEM MODULAR

Requirement Verification by Simulating Multiple Scenarios

In this section, The Cameo Systems Modeler (CSM) for implementation within the framework of Model-Based Systems Engineering (MBSE) was used, as defined by the INCOSE Systems Engineering Vision 2020 [12]. MBSE is recognized as the formalized application of modeling to support system requirements, design analysis, verification, and validation activities from the conceptual design phase through development and subsequent life cycle phases. CSM is instrumental in transitioning from stakeholder requirements to the verification and validation stages by facilitating the creation and use of system models or a set of models. These models, typically developed using the Systems Modeling Language (SysML), are crucial in verifying system requirements, architecture, and design quality. They also play a vital role in lowering the risk and cost of system development by surfacing issues early, enhancing productivity through reuse of system artifacts, and improving communications among the system development team. For instance, in the design of the Mechatronics, Robotics, and Control (MRC) Lab, stakeholder requirements are first identified and transformed into effective system models using CSM. These models, encompassing both structural and behavioral diagrams, form the foundation for developing the simulation architecture and design. This approach underscores the effectiveness of CSM in ensuring that the systems engineering process aligns with stakeholder requirements and meets the simulation requirements through rigorous verification and validation.

Scenario Description

To assess student performance across various modules, including both software and hardware systems, within the laboratory environment. Each module contains multiple assessments, and the simulation in CAMEO systems serves as a tool to evaluate a student's performance across these diverse modules, offering an overview of their capabilities. The design of these simulations is rooted in the laboratory's defined learning objectives and goals, which are directly aligned with stakeholder requirements. Through the simulation of different scenarios—each representing a student's interaction with a module— a matrix and measure of effectiveness (MOE) based on these objectives is applied. This process allows for requirement verification

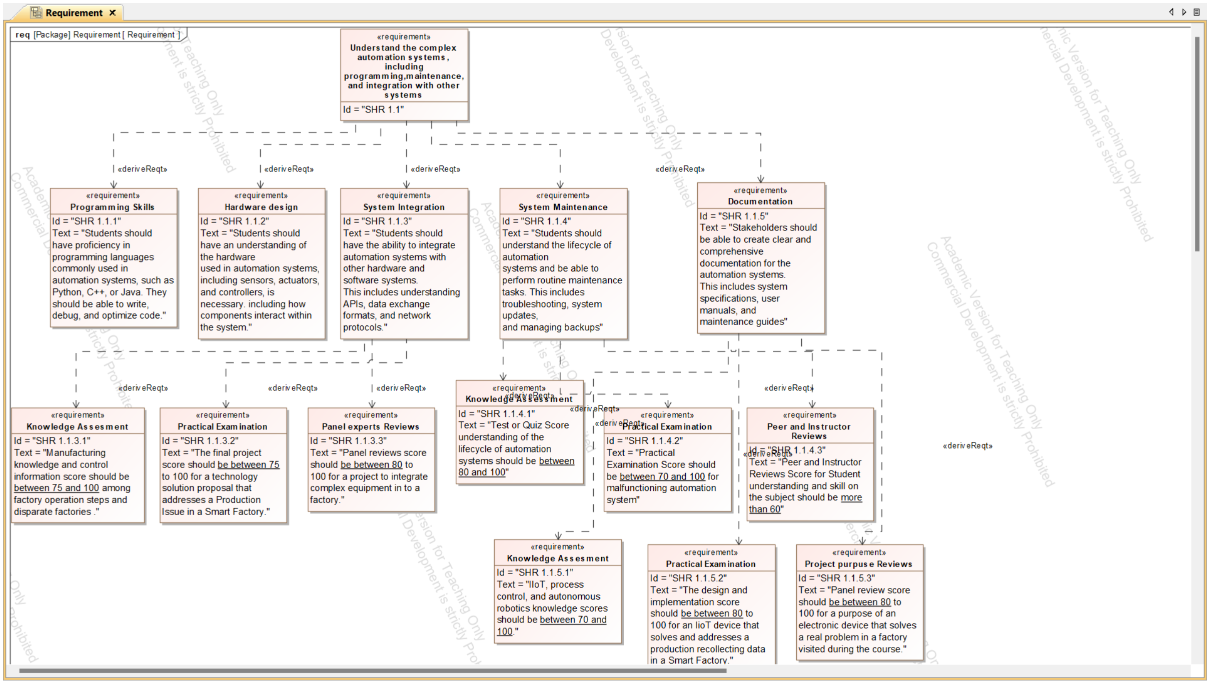


Figure 4: Requirement Diagram from CSM

and validation, creating a series of case points that represent different potential student outcomes. For instance, within the context of controls and IoT laboratory experiments, specific lab practices equipped with hardware such as PLCs and DC motors, each designed with learning objectives that correspond to semiconductors industry requirements have been developed. By adjusting these experiments through instructional design, various scenarios to evaluate how well the lab meets these numerous requirements can be simulated. This iterative process, driven by the instructional design, enables to refine experiments continuously and assess the alignment with industry standards and needs. The modeling requirement diagram in the Contextual Structure Modeling (CSM) for the Design and MRC Lab was created, see Figure 4. The diagram provided a clear and concise representation of the system requirements, depicting the interactions between different components of the lab. It included elements such as programming skills, hardware design, system integration, system maintenance, and documentation. The CSM diagram effectively captured the complexity of the lab environment, providing a comprehensive view of the system requirements.

Course: MRC Lab experiment No.5 ”Mechanical/Mechatronics”
Participants: Students taking the MRC Lab course, along with the course instructor and lab facilitators, i.e., TAs.
Objective: To simulate a verification criterion that quantitatively and qualitatively assesses whether students meet the proficiency standards for different aspects of automation systems. The simulation aims to validate student readiness for engaging with real-world challenges in the manufacturing industry and smart factory operations.

Verification Criteria: System Integration for Automation Systems

- **Knowledge Assessment (SHR 1.1.3):**

  - *Description:* Assessing manufacturing knowledge and control information.
  - *Pass Criteria:* Students must identify control devices such as sensors and actuators and demonstrate an understanding of their roles in automation systems.
  - *Fail Conditions:* Students fail to identify or incorrectly identify control devices and their functions.

- **Practical Examination (SHR 1.1.3):**
  - *Description:* Students are required to deliver a final project with a score between 75 to 100.
  - *Pass Criteria:* Students must effectively utilize technology solutions for a Production Issue in a Smart Factory.
  - *Fail Conditions:* Students fail to effectively identify or use technology solutions.

- **Panel Experts Reviews (SHR 1.1.3):**
  - *Description:* Panel review scores should range from 80 to 100 for projects integrating complex equipment in a factory.
  - *Pass Criteria:* Students develop projects that integrate complex equipment in factory settings effectively.
  - *Fail Conditions:* Students fail to develop or integrate projects effectively.

Simulation Verification: Requirement V&V:

The outcome criteria will be utilized to determine whether students have achieved the specified scores, ensuring they have the necessary skills for effective performance in automation system environments. Successfully meeting the criteria will qualify them for advanced roles in manufacturing and smart factories.

The scenario-based requirement simulation verification was conducted to validate the requirements of the MRC Lab. Different scenarios representing typical lab activities were simulated, including different pass and fail score scenarios See Figure 5. The scenario-based simulations provided valuable insights into the practical functionality of the lab, confirming its readiness for effective teaching and learning of mechatronics.

The modeling requirement diagram in CSM and the scenario-based requirement simulation verification have proven to be effective tools for designing and validating the requirements for design of MRC Lab. These results ensure that the lab is well-equipped to provide a comprehensive, practical, and safe learning environment for students.

This methodology allows for an understanding of how each student scenario—ranging from high to low grades—maps onto the industry's requirements. It highlights the flexibility and adaptability of the tool used for these simulations (the CAMEO software), emphasizing its capacity to supply a wide array of educational levels and institutional requirements.

CONCLUSION

The use of Model-based Systems Engineering for the design and development of a Mechatronics, Robotics, and Control (MRC) Lab is not just beneficial, but essential. The complex, Requirement

Verification Status: Pass Fail

#	Id	Name	Text	Derived	Property	Bou
1	SHR 1.1.1	SHR 1.1.1 Programming Skills	Students should have proficiency in programming languages commonly used in automation systems, such as Python, C++, or Java. They should be able to write, debug, and optimize code.	SHR 1.1 Understand the comple		
2	SHR 1.1.2	SHR 1.1.2 Hardware design	Students should have an understanding of the hardware used in automation systems, including sensors, actuators, and controllers, is necessary. including how components interact within the system.	SHR 1.1 Understand the comple		
3	SHR 1.1.3.1	SHR 1.1.3.1 Knowledge Assesment	Manufacturing knowledge and control information score should be between 75 and 100 among factory operation steps and disparate factories .	SHR 1.1.3 System Integration	KnowledgeAssessment : Test or Quiz Score	[75;100]
4	SHR 1.1.3.2	SHR 1.1.3.2 Practical Examination	The final project score should be between 75 to 100 for a technology solution proposal that addresses a Production Issue in a Smart Factory.	SHR 1.1.3 System Integration	PracticalExamination : Practical Examinatio	=75
5	SHR 1.1.3.3	SHR 1.1.3.3 Panel experts Reviews	Panel reviews score should be between 80 to 100 for a project to integrate complex equipment in to a factory.	SHR 1.1.3 System Integration	Peer&Instructor Reviews : Peer and instruct	=80
6	SHR 1.1.3	SHR 1.1.3 System Integration	Students should have the ability to integrate automation systems with other hardware and software systems. This includes understanding APIs, data exchange formats, and network protocols.	SHR 1.1 Understand the comple		
7	SHR 1.1.4.1	SHR 1.1.4.1 Knowledge Assessment	Test or Quiz Score understanding of the lifecycle of automation systems should be between 80 and 100	SHR 1.1.4 System Maintenance	KnowledgeAssessment : Test or Quiz Score	[80;100]
8	SHR 1.1.4.2	SHR 1.1.4.2 Practical Examination	Practical Examination Score should be between 70 and 100 for malfunctioning automation system	SHR 1.1.4 System Maintenance	PracticalExamination : Practical Examinatio	[70;100]
9	SHR 1.1.4.3	SHR 1.1.4.3 Peer and Instructor Reviews	Peer and Instructor Reviews Score for Student understanding and skill on the subject should be more than 60	SHR 1.1.4 System Maintenance	Peer&Instructor Reviews : Peer and Instruct	>60
10	SHR 1.1.4	SHR 1.1.4 System Maintenance	Students should understand the lifecycle of automation systems and be able to perform routine maintenance tasks. This includes troubleshooting, system updates, and managing backups	SHR 1.1 Understand the comple		
11	SHR 1.1.5.1	SHR 1.1.5.1 Knowledge Assesment	IIoT, process control, and autonomous robotics knowledge scores should be between 70 and 100.	SHR 1.1.5 Documentation	KnowledgeAssessment : Test or Quiz Score	[70;100]
12	SHR 1.1.5.2	SHR 1.1.5.2 Practical Examination	The design and implementation score should be between 80 to 100 for an IioT device that solves and addresses a production recollecting data in a Smart Factory.	SHR 1.1.5 Documentation	PracticalExamination : Practical Examinatio	=80
13	SHR 1.1.5.3	SHR 1.1.5.3 Project purpuse Reviews	Panel review score should be between 80 to 100 for a purpose of an electronic device that solves a real problem in a factory visited during the course.	SHR 1.1.5 Documentation	Peer&Instructor Reviews : Peer and Instruct	=80
14	SHR 1.1.5	SHR 1.1.5 Documentation	Stakeholders should be able to create clear and comprehensive documentation for the automation systems. This includes system specifications, user manuals, and maintenance guides	SHR 1.1 Understand the comple		
15	SHR 1.1	SHR 1.1 Understand the complex automation systems, including programming,maintenance, and integration with other systems				

Filter is not applied. **15** rows are displayed in the table.

Figure 5: Requirement Verification & Validation

multidisciplinary nature of MRC, which integrates mechanical, electronics, computer science, control engineering, and robotics, necessitates a flexible and iterative approach.

MBSE, with its emphasis on iterative development, continuous integration, and stakeholder involvement, aligns thoroughly with the needs of the MRC Lab. It allows for the accommodation of changes and improvements at any stage of the development process, ensuring that the end result is a lab that is up-to-date with the latest advancements in the field and meets the needs of all stakeholders. Moreover, It promotes a collaborative environment where ideas and solutions can be shared and implemented rapidly. This is particularly important in a multidisciplinary field like MRC, where the integration of different engineering disciplines is key to innovation. By adopting Model-based Systems Engineering and tools such as CAMEO, the paper ensures the course curricula are not only equipped with the latest technology but also dynamically adaptable to future industry trends. This proposed approach will provide students with a learning environment that is reflective of the industry, preparing them for the challenges they will face in their careers. In conclusion, moving forward requires a continued commitment to embracing and adapting the MBSE-based approach, ensuring alignment with the dynamic evolution of technology and industry trends.

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