The Four Pillars of Manufacturing Knowledge: A Contemporary Perspective on Practical Implementation

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Abstract

The Four Pillars of Manufacturing Knowledge has undergone a substantial revision to encompass the changing landscape of advanced manufacturing, incorporating concepts such as Industry 4.0, Additive Manufacturing (AM), etc. This revised version of the Four Pillars is aligned with the original purpose to be used by industry and academia to represent the breadth and scope of manufacturing engineering based on accreditation criteria and SME's Body of Knowledge for the Certified Manufacturing Engineer and Technologist (CMfgE and CMfgT). The revised Four Pillars has changes in eleven of the twelve knowledge blocks. The Automated Systems and Control knowledge block, now renamed as Industry 4.0 and Automated Systems and Control, included the most revised topics, with only two remaining unchanged. Process Design is another knowledge block that went through major revisions with the addition of digital manufacturing topics such as: Digital Twin and Computer Aided Process Planning. Overall, this paper presents each of the new and revised topics to gain a better understanding of the implications for ongoing research and education in manufacturing worldwide. Practical examples of teaching methods, as well as laboratory applications, are provided for some of the topics that are most critical to the future of the manufacturing industry.

1. Introduction

The Four Pillars of Manufacturing Knowledge (Four Pillars) was first published in 2011 as a component of the Curricula 2015; A Four-Year Strategic Plan for Manufacturing Education (Jack, Mott et al. 2011). The concept of the Four Pillars includes foundation skills in A) Mathematics and Science and B) Personnel Effectiveness with four major categories: 1) Materials and manufacturing processes; 2) Product, tooling, and assembly engineering; 3) Manufacturing systems and operations; and 4) Manufacturing competitiveness. According to the authors (Mott and Jack 2011), the process of developing the Four Pillars was initiated by the SME through its Center for Education. Since its conception, the Four Pillars have been utilized across the country and internationally as a model for curriculum development for manufacturing engineering and manufacturing engineering technology degree programs (Mott, Bennett et al. 2012), (Mott, Stratton et al. 2012), (Wells 2012), (Nutter, Mott et al. 2013), (Nutter and Jack 2013), (Mott and Jack 2013), (Mott, Bennett et al. 2013), (Ermer 2013), (Plouff, Pung and Jack 2014), (Pung and Jack 2014), (Yip-Hoi and Newcomer 2015), (Doggett and Jahan 2016), and (Littell, Shraim and Sheets 2023).

According to the authors (Irwin, Johnson and Marzano 2022), the process for the Four Pillars revision was first initiated by the SME Manufacturing Education and Accreditation Committee in 2020. Updates to the ABET accreditation standards (ABET 2022) and SME's Body of Knowledge for CMfgE and CMfgT certification programs (SME 2020) preceded the revisions to the Four Pillars. The SME Body of Knowledge added a new category for "Digital Enterprise" focusing on the increasing impact that digital technologies have in manufacturing. It features expanded coverage of topics such as the Industrial Internet of Things (IIoT), data science, digital performance management, artificial and augmented intelligence, machine health/asset optimization, digital twins, and digital threads.

In 2021, a sample population of manufacturing experts from industry, government, and the academy was surveyed from the SME database. The existing twelve blocks of knowledge were presented to those surveyed, with the option for the respondent to either keep, remove, or edit the topics in each. Suggestions for additional topics (missing elements) in each knowledge block were also collected in the survey. SME staff performed data analysis and presentation of the survey results, after which an organized process was used to validate the suggested revisions to the knowledge blocks. Academic, industry, and government expert members from the SME Manufacturing Education and Accreditation Committee reviewed and distilled the survey results into a format to present to the manufacturing community for their input. Workshops were delivered at the 2023 ASEE, SME, and ATMAE conferences to provide feedback on the Four Pillar revisions. An interactive SME webpage was used to collect input from attendees of the conference workshops to refine the topics in each knowledge block further.

The revised version published by SME in 2024 resulted in new or revised topics in eleven of the twelve knowledge blocks. The only knowledge block without changes is Mathematics and Science. The Automated Systems and Control knowledge block, renamed as Industry 4.0 and Automated Systems and Control, included the most revised topics with just two topics remaining unchanged. Process Design is another area that experienced major revisions with topics such as Digital Twin and Computer-Aided Process Planning.

2. Methods

Due to the revisions in accreditation standards, SME's Body of Knowledge for the CMfgE and CMfgT certification programs, and the Four Pillars to include Industry 4.0 advanced manufacturing practices, how can manufacturing curriculum change to impact student understanding and application of these concepts? The answer to this question can assist educators in updating manufacturing program curricula and provide the industry with a clear picture of the knowledge, skills, and abilities (KSAs) of manufacturing graduates.

Each of the revised knowledge blocks in the Four Pillars has advanced manufacturing topics that deserve attention from industry and academia alike. Much can be learned from investigating each of the Four Pillar knowledge blocks to scrutinize the need for revised curriculum, investment in equipment, and/or development of new software in these critical areas.

First, each of the new topics and revised topics in the Four Pillars are described in detail. Next, these topics are analyzed to better understand the advances in technology that have taken place since the original version of the Four Pillars. Finally, the authors will provide practical applications for implementing the advanced manufacturing topics into the curriculum or research.

3. Results

The # 1 "Mathematics and Science" knowledge block has no changes. The # 2 "Personal Effectiveness" knowledge block has five added topics, and others are changed or combined (see Figures 1 & 2).

Knowledge is deleted from this list because it was found to be too general of a term. The added topics are *Emotional Intelligence* (the ability to recognize, understand, and manage your own and other people's emotions), *Diversity, Equity & Inclusiveness (DEI)* (organizational frameworks and practices that promote fair treatment and full participation of all people), *Social Responsibility* (where a person works and cooperates with other people and organizations for the benefit of the community), *Ethics* (moral principles that govern a person's behavior), and *Innovation and Creativity* (process of initiating something new and turning it into practical and valuable solutions) (see Table 1).

The #3 "Engineering Sciences" knowledge block has only two changes. The topic of Electrical Cir-

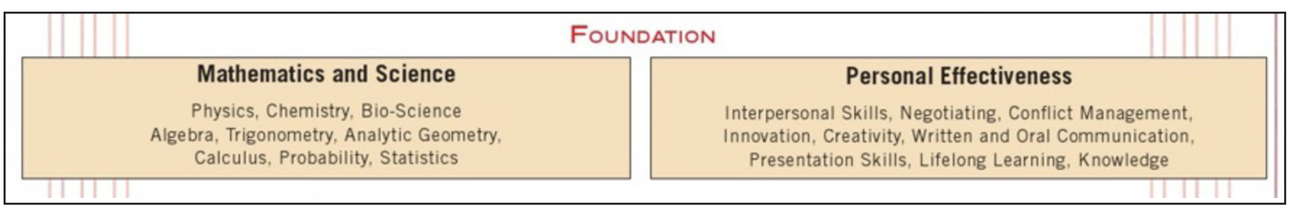

Figure 1. Original Foundation knowledge blocks.

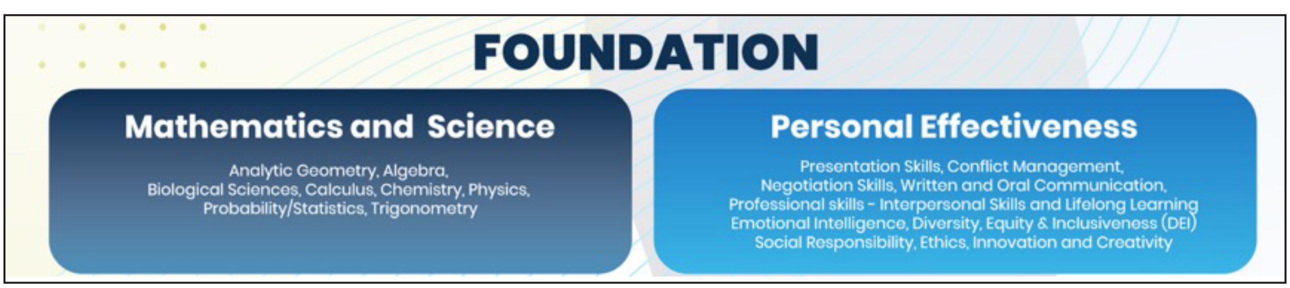

Figure 2. Revised Foundation knowledge blocks.

Table 1. Personal Effectiveness (block 2).

Topic	Changed to	Combined with
Interpersonal Skills	Professional skills - **Interpersonal Skills and Lifelong Learning**	Lifelong Learning
Negotiating	Negotiation **skills**	
Innovation	Innovation **and creativity**	Creativity

cuits/Electronics is renamed to Electrical Circuits/ Electronics/*Instrumentation*. Secondly, the topic of *Material Science* is added (see Figures 3 & 4).

The #4 "Material" knowledge block is renamed to "Engineering Materials" that has three deleted topics, which are *Nanotechnology, Foams, and Hybrids* (see Figures 5 & 6). Other topics are incorporated into the new topics (see Table 2), and the *New/Advanced Materials* topic is added, which encompasses the many new alloys possible with laser sintering capabilities. Also, this topic is used to capture a wider range of materials without having to add every new material that is utilized, and to keep it generic in a sense.

The #5 "Manufacturing Processes" knowledge block has one deleted topic, which is *Hand Tool Use and Machine Operating* (see Figures 7 & 8). Other topics are incorporated into the new topics (see Table 3).

The added topics are *AM Processes* (building three-dimensional objects layer by layer from a digital 3D model), *Biomanufacturing* (using biological systems to produce biomaterials for industrial products), *Nano-*

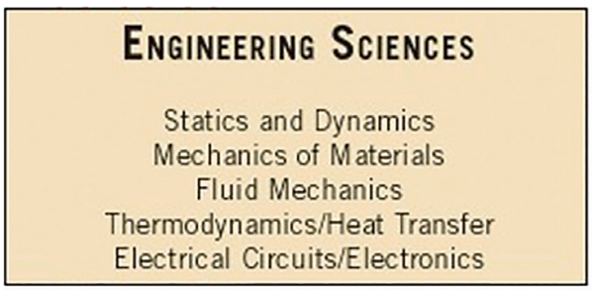

Figure 3. Original Engineering Sciences.

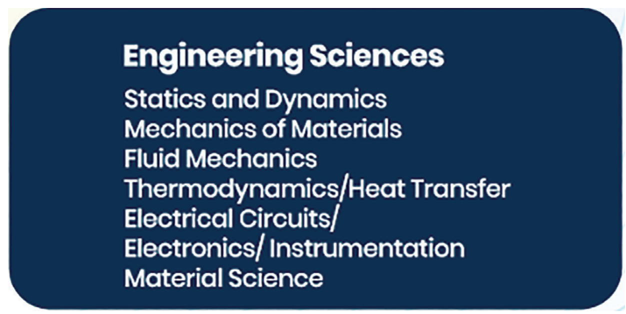

Figure 4. Revised Engineering Sciences

Figure 5. Original Materials.

Figure 6. Revised Engineering Materials.

Table 2. Engineering Materials (block 4).

Topic	Changed to
Natural Materials	**Bio**/Natural Materials

Figure 7. Original Manufacturing Processes.

Figure 8. Revised Manufacturing Processes.

Table 3. Manufacturing processes (block 5).

Topic	Changed to	Moved to
Material Removal	Material Removal/**Subtractive Processes**	
Hot and Cold Forming Processes	**Material** Forming Processes **(bulk, sheet)**	
Bulk and Continuous Flow	**Material Forming Processes** (bulk, sheet)	
Heat Treatment	Heat Treatment/**Heat Transfer or Thermal Processes**	
Fabrication	**Joining and** Fabrication **and Finishing**	
Joining, Welding, and Assembly	Assembly	
Finishing	**Joining and Fabrication** and Finishing	
Material Handling and Packaging		Production System Design

manufacturing (production of nanoscale materials, structures, devices, and systems), and *Non-Traditional Manufacturing* (utilizing energy forms other than mechanical cutting forces, like thermal, chemical, or electrical energy, to remove material or create shapes).

The #6 "Product Design" knowledge block has some topics that have been changed or moved (see Figures 9,10 & Table 4).

The added topics are *Generative Design* (AI-driven iterative process to explore and generate multiple

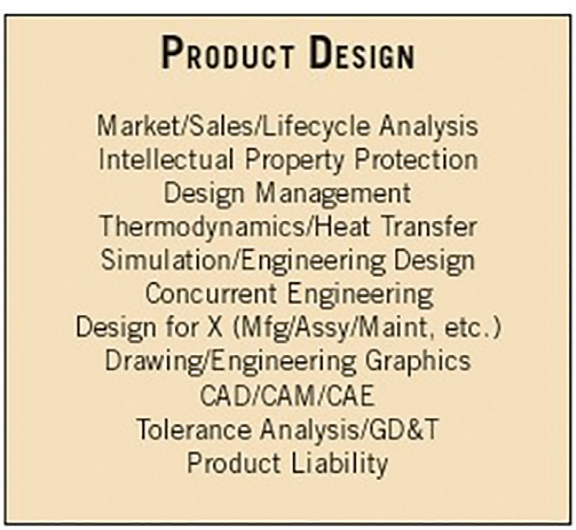

Figure 9. Original Product Design.

Figure 10. Revised Product Design.

Table 4. Product Design (block 6).

Topic	Changed to	Moved to
Simulation/Engineering Design	Simulation/Engineering Design/ **Digital Twin**	
Concurrent Engineering		Quality and Continuous Improvement
Design for X (Mfg/Assy/Maint)	Design for X (Mfg/Assy/Maint/**Rem-fg/Recycling, Sustainability etc.)**	
Thermodynamics/Heat Transfer		Manufacturing Processes

design solutions based on specific constraints for design optimization), Systems Engineering (managing complex systems to ensure they meet requirements and function effectively throughout their lifecycle), *Product Lifecycle Management* (managing a product's journey from initial concept to end-of-life), *LCA tools and ELM* (Life Cycle Assessment tools are software solutions for Engineering Lifecycle Management), and *Design Thinking* (meeting users' needs by understanding them, generating ideas, and testing solutions).

The #7 "Process Design" knowledge block has two deleted topics, which are *Print Reading and Rapid Prototyping* (see Figures 11 & 12). Other topics have been changed and/or combined (see Table 5).

The topics added are *CAD/CAM/CIM/Computer Integrated Manufacturing* (using computer systems to control and integrate all aspects of the manufacturing process), *Model-Based Process Design* (using simulation to understand the behavior of a concept or existing physical system), *Revision Control and Data Management* (system that tracks changes to files over time), *Tool and Equipment Selection* (based on precision required, production volume, and availability of resources) *Process Planning and Development/Computer Aided Process Planning (CAPP)* (encompassing everything from identifying a need to implementing and monitoring the process), *MRL/TRL/New Process/New Product Introduction* (Manufacturing Readiness Level and Technology Readiness Level are frameworks that go hand in hand and used to assess the maturity of a given technology, component or system from a manufacturing perspective).

The #8 "Equipment/ Tool Design" knowledge block has only two changes. The topic of Cutting Tool Design was changed to Cutting Tool *Selection and* Design. The topic added is *Real Time Adaptive Control design for tool condition monitoring*, for exam-

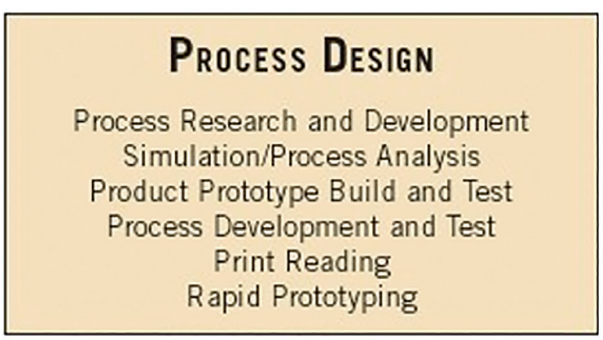

Figure 11. Original Process Design.

Figure 12. Revised Process Design.

Table 5. Process Design (block 7).

Topic	Changed to
Process Research and Development	Process Research **and Design**
Simulation/Process Analysis	Simulation/Process Analysis**/Digital Twin**

Figure 13. Original Equipment/Tool Design.

Figure 14. Revised Equipment/Tool Design.

ple, using in-process data to identify abnormal loads for protecting the cutting tool by lowering feed rate automatically (see Figures 13 & 14).

The #9 "Production System Design" knowledge block has two deleted topics, which are *Infrastructure/ Plant Location and Waste Management* (see Figures 15 & 16). Other topics have been changed and/or combined (see Table 6).

The topics added are *ERP/MES* (Enterprise Resource Planning and Manufacturing Execution Systems are used to optimize manufacturing processes by monitoring, tracking, documenting, and controlling throughout the entire production lifecycle), and *Material Handling and Packaging Systems* (the processes and equipment used to move, store, protect, and control materials and products throughout their lifecycle).

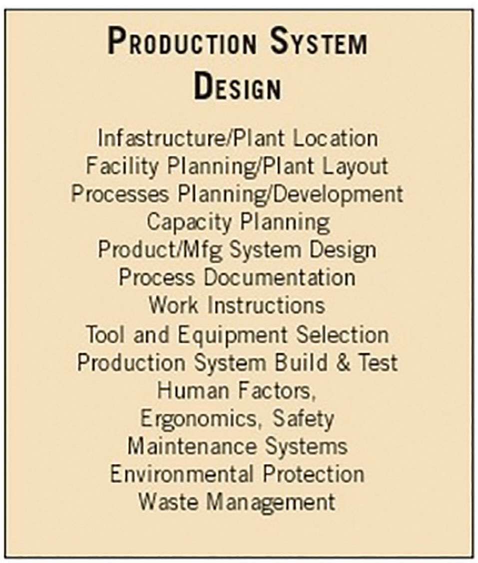

Figure 15. Original Production System Design.

Figure 16. Revised Production System Design.

Table 6. Production System Design (block 9).

Topic	Changed to	Moved to
Product/Mfg System Design	Manufacturing System Design	
Process Planning/Development	Process Planning and Development/**Computer Aided Process Planning (CAPP)**	Process Design
Tool and Equipment Selection		Process Design
Environmental protection	Environmental **Sustainability and** Protection	

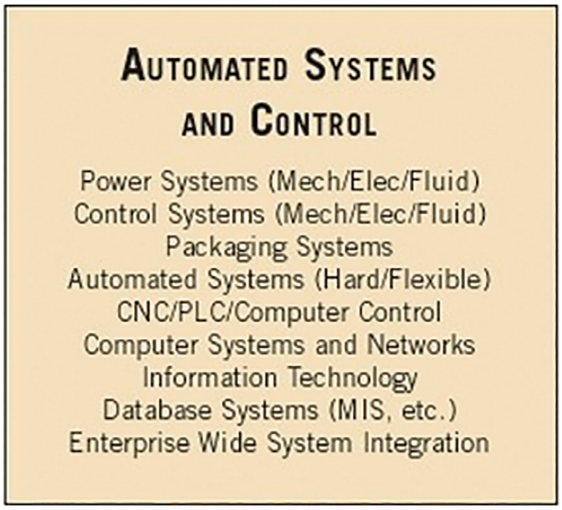

Figure 17. Original Automated Systems and Control.

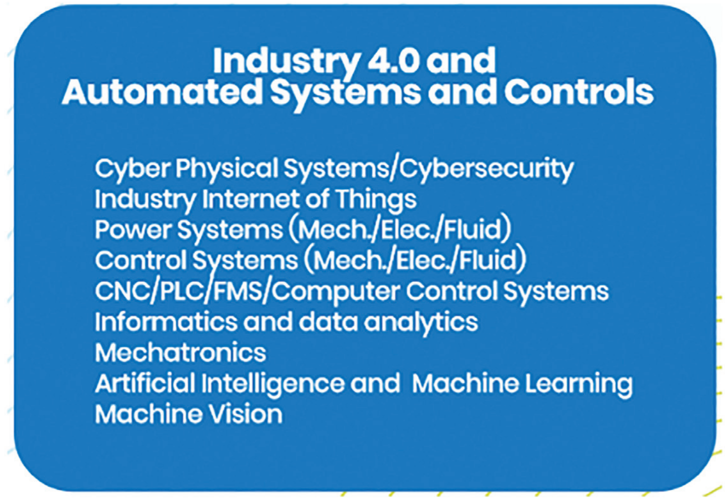

Figure 18. Revised industry 4.0 and Automated Systems and Control.

Table 7. Industry 4.0 and Automated Systems and Controls (block 10).

Topic	Changed to
CNC/PLC/Computer Control	CNC/PLC/**FMS/Computer Control** Systems
Computer Systems and Networks	CNC/PLC/**FMS**/Computer Control **Systems**
Information Technology	**Informatics** and data analytics
Database Systems (MIS. etc.)	Informatics **and data analytics**

The #10 "Automated Systems and Controls" renamed to "*Industry 4.0* and Automated Systems and Controls" knowledge block has two deleted topics, which are *Packaging Systems*, and *Enterprise Wide System Integration* (see Figures 17 &18). Other topics have been changed and/or combined (see Table 7).

The topics added are *Cyber Physical Systems/Cybersecurity* (addressing vulnerabilities of systems that integrate computing, communication, and physical processes), *Industry Internet of Things* (use of smart sensors, actuators and other devices interconnected to enhance industrial processes), *Mechatronic*s (integration of mechanical, electrical, and computer systems to create intelligent machines and automated processes), *Artificial Intelligence and Machine Learning* (allowing machines to learn from data without being explicitly programmed), and *Machine Vision* (using cameras to interpret images with algorithms to perform tasks like automatic inspection).

Even though not named individually, robotics is an integral part of the automation and controls knowledge block. Robotics is a method of implementing the manufacturing processes and automation systems described. For instance, *Machine Vision* is a method commonly used in a robotic work cell to improve efficiency, but can also be used in conjunction with conveyor systems or other material handling devices. As described by authors (Ma and Pecen 2024) the use of a robotic arm can be incorporated into an undergraduate course to incorporate experiential learning of industrial robotics. When the topic of Mechatronics is used in the Four Pillars, it is assumed that robotics is included as a major component of that system.

The #11 "Quality and Continuous Improvement" knowledge block has two deleted topics that are *Statistical Control Methods and Problem Analysis & Solving Integration* (see Figures 19 & 20). Other topics have been changed and/or combined (see Table 8).

The topics added are *Problem Solving and Root Cause Corrective Action* (identifying, analyzing, and addressing the underlying causes of problems to prevent recurrence), and *Quality Management Systems (QMS),* which document an organization's processes/procedures that implement policies to reduce waste, increase efficiency, and improve customer satisfaction.

The #12 "Manufacturing Management" knowledge block has three deleted topics, which are *Global Competition, Organizational Design and Management*, and *Education & Training* (see Figures 21 & 22). Other topics have been changed and/or combined (see Table 9).

The topics added are *Competitive Analysis Including Intellectual Property* (understanding competitor's

Figure 19. Original Quality and Continuous Improvement.

Figure 20. Revised Quality and Continuous Improvement.

Table 8. Quality and Continuous Improvement (block 11).

Topic	Changed to
Capability Analysis	**Process** Capability Analysis
Metrology	Metrology **and Instrumentation**
Continuous Improvement/Lean	Continuous Improvement **and** Lean **Mfg**
Customer and Field Service	Customer **Focus**
Customer and Field Service	**Consumer and** Field Service
Factor Analysis (DOE/Correlation)	**Design of Experiments** (DOE)

Figure 21. Original Mfg. Management.

Figure 22. Revised Mfg. Management.

Table 9. Manufacturing Management (block 12).

Topic	Changed to
Strategic Planning	Strategic Planning **Including: Social, Environmental, Governance, and DEI**
Social Responsibility	Strategic Planning Including: **Social**, Environmental, Governance, and DEI
Project Management	**Leadership** and Project Management
Labor Relations	**Workforce Development** – Personnel Management/**Labor Relations**
Personnel Management	**Workforce Development – Personnel Management/**Labor Relations

IP assets to make strategic decision-making and innovation based on their strengths, weaknesses, and potential threats), *Risk Management* (recognizing potential problems, hazards, or uncertainties that could arise within an organization or project), *Problem Analysis and Solving* (investigating the nature of a problem, its causes, and potential impacts), and *Knowledge Management* (capture and reuse) which involves capturing, organizing, sharing, and reusing knowledge to improve decision-making.

4. Discussion

Apart from the Mathematics and Science knowledge block, all others have new or revised topics. The *Automated Systems and Control* knowledge block, renamed as *Industry 4.0 and Automated Systems and Control*, included the most revised topics, with just two topics remaining unchanged. *Process Design* is another area that has experienced major revisions with topics such as *Digital Twin* and *Computer Aided Process Planning*. Therefore, it is most appropriate to provide practical applications for implementing these topics into the curriculum or research.

Laboratory facilities at higher education institutions need to be transformed into places where students can learn both the traditional manufacturing processes in addition to analyzing data gathered from sensors installed on equipment. Options are typically limited for adding new courses in 2-year and 4-year undergraduate programs or graduate degrees, but enhancements can be made to existing courses to implement the automation and controls aspect of manufacturing.

As described by the authors (Labyak and Wagner 2024), a traditional foundry can be transformed to perform real-time monitoring of material temperatures during casting, rolling, forging, or stamping processes by installing temperature or force sensors and digital cameras to record and timestamp the process to optimize performance and reduce variation. Furthermore, the collected data can enable the development of process emulators to simulate the steps of a process before the actual production begins to increase efficiency through intelligent routing (see Figures 23 & 24).

Extrusion is a manufacturing process that is common to a foundry, which can also benefit from im-

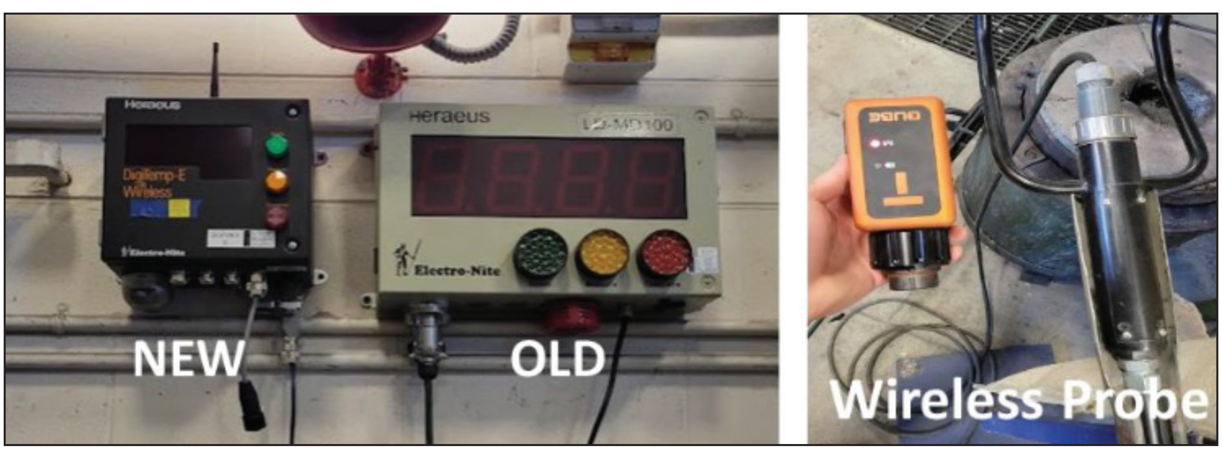

Figure 23. Wireless temperature display module and wireless probe.

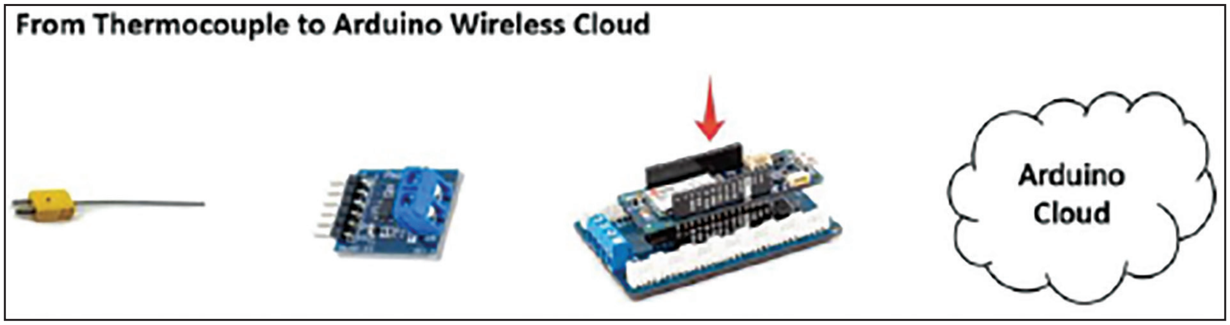

Figure 24. Mold temperature data acquisition using Arduino with wireless capabilities.

plementing pressure and speed controls. Adding the sensing of exiting extruded material temperature can be done with an infrared pyrometer to provide feedback as well as data collection for optimization.

A Digital Twin can be developed to replicate any equipment or process, enabling real-time monitoring and analysis. In a traditional machine shop, Digital Twins can be created for CNC machines and AM systems using computational methods, including artificial intelligence, to enhance energy efficiency, tool wear prediction, preventive maintenance, and product quality management (see Figures 25 & 26).

For example, a Digital Twin can be implemented using Azure Digital Twin Explorer and Azure 3D Scene, both accessible through the Azure Portal (portal.azure.com) with an Azure for Students subscription, which offers $100 in free credit for 12 months. This setup allows for remote monitoring and control of AM equipment via a smartphone or other devices, helping to detect overheating or malfunctions early and prevent material waste and downtime.

The Digital Twin curriculum revisions described here were added to a course offered in the spring semester 2025, renamed as *Industrial Digital Twin Systems*, and changed from the previous course name of *Industrial Systems Simulation*. The previous version was focused on creating simulation models of various industrial systems to analyze and experiment with characteristics of real-life systems for the purpose of engineering process improvement and production. The revised course meets the original course objectives but with principles and architecture of Digital Twins used to optimize systems using real-time data, enhancing decision-making, and operational efficiency in smart industrial environments. The course evaluation and responses from students after implementation of the course revisions were very positive. The end of the course evaluation had 16/16 (100%) response rate. Using a scale of 1-5 from "1=Strongly Disagree" to "5=Strongly Agree", the average of the seven questions was 4.16, indicating a good level of satisfaction following these course revisions. Chal-

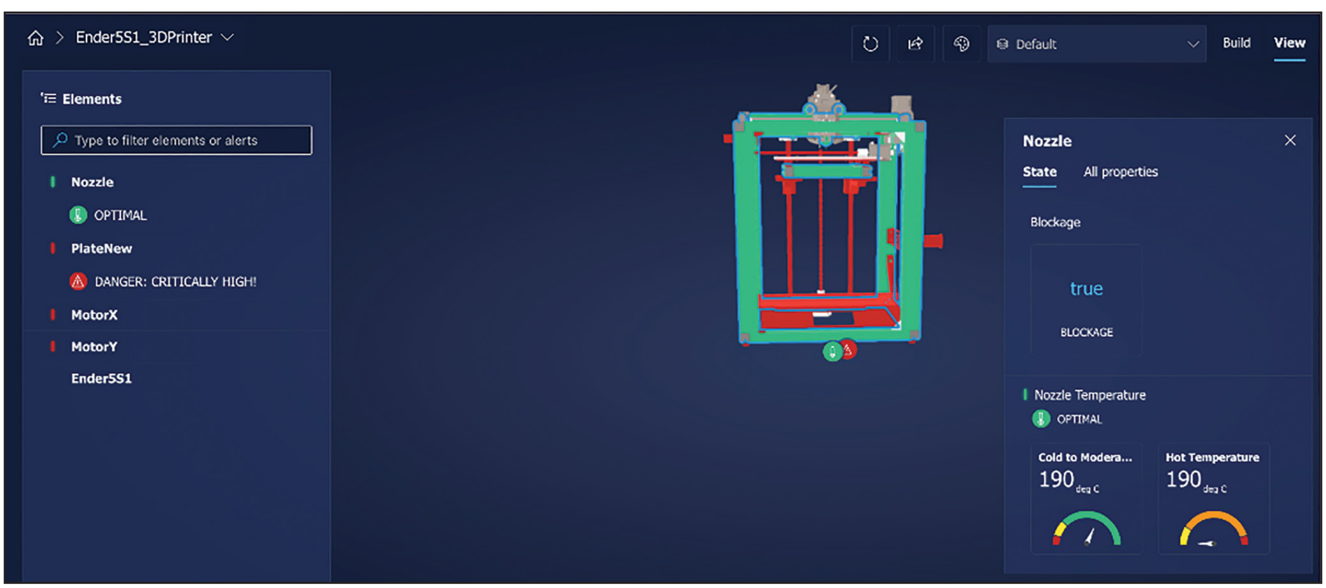

Figure 25. Example 3D printer digital twin created in the Azure software.

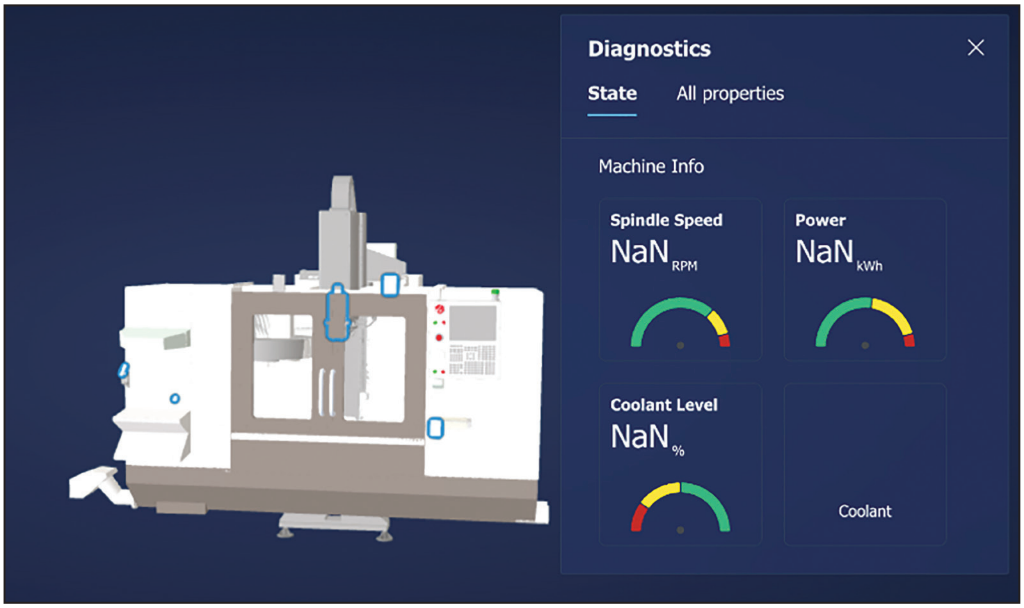

Figure 26. Example Haas mill digital twin created in the Azure software.

lenges facing the instructor were some difficulties encountered in obtaining Azure licensing and some students were not familiar with some of the programming languages used.

Adding a computer equipped with sensors for vibration, temperature, and energy usage that can interact with the controller of computer numerical control (CNC) equipment can provide an opportunity to collect useful data. Computers interconnected with existing CNC equipment have other advantages, such as directly downloading CNC programs generated using computer-aided manufacturing (CAM) software. The computer can connect to 3D scanning equipment for part verification and inspection. The computer can also be used to review videos for equipment safe operating procedures (SOPs) and tracking user safety training. Various sensors to monitor machining parameters for manufacturing research topics can include use time, milling spindle rpm, feed rates, lathe rpm, spindle forces, or tool forces (see Figures 27-29).

In this example, the goal is to adjust the spindle speed and feed rate to their optimal values. The optimization of the machining process improves the sustainability of the process. Minimizing chatter and vibration in the milling process can reduce energy consumption and extend tool life.

Other new topics added to the Four Pillars, such as *Generative Design*, can be easily incorporated into existing engineering graphics courses in CAD design. *AM* methods can be introduced to students in graphics and/or product design courses. Projects that incorporate AM technologies can introduce students to the pros and cons of the seven ASTM AM categories from the viewpoint of product purpose: form, fit, and function.

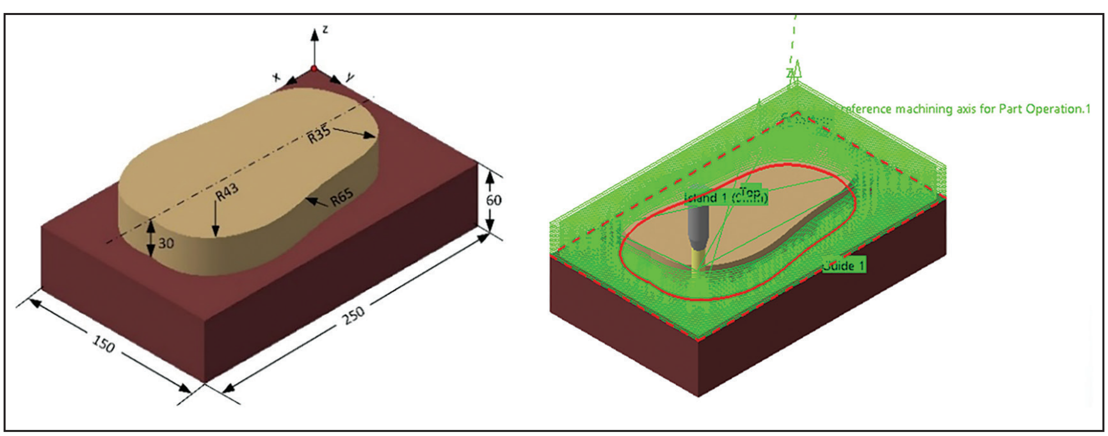

Figure 27. Sample part used for vibration and current monitoring,

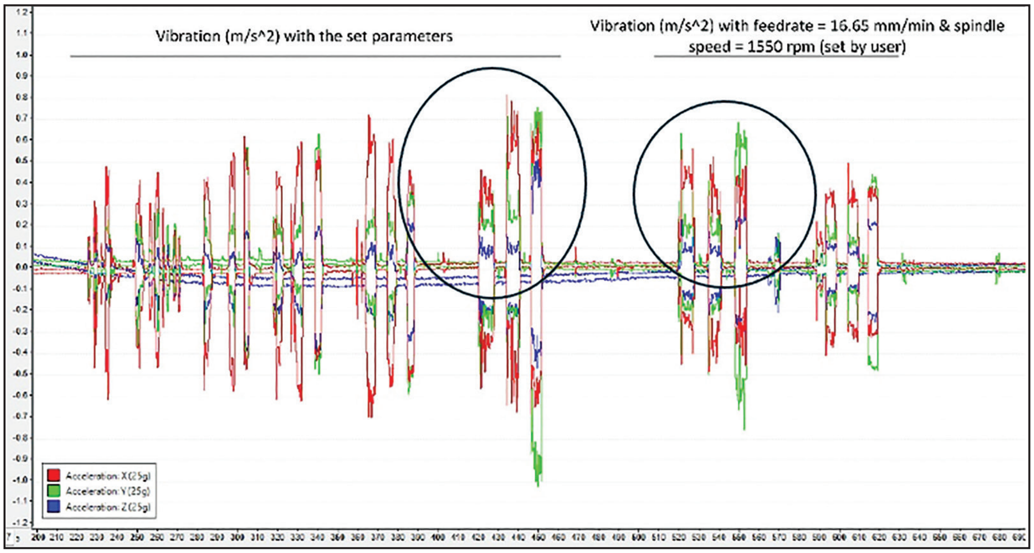

Figure 28. Example vibration during the machining of the sample part.

All added and revised topics in the Four Pillars are important to include in the education of manufacturing students. Some topics can be addressed in undergraduate courses, whereas others may be more appropriate for graduate education with a heavy emphasis on analysis. Some topics can encompass an entire semester of a course, and others can be presented in a single lesson. As an industry professional, it is important to understand the topics that manufacturing program graduates possess. As illustrated by authors (Labyak & Irwin 2023), the Four Pillars can be used for continuous improvement to analyze new or existing manufacturing curricula.

5. Implementation of Revisions

A variety of barriers may exist facing industry and academia alike in implementing some of the Four Pillar topics into the curriculum. There are things like the added equipment cost, training to update faculty or manufacturing personnel in new technology, and space required to set up new laboratories. Some potential strategies to overcome these are submitting proposals for state, federal, or private foundations in support of these initiatives. Manufacturing professionals and educators can benefit from industry and society conferences that offer training sessions in digital technologies, robotics, and automation. Also, there are opportunities for faculty to be trained in new technologies through outreach activities offered by NSF-sponsored projects.

6. Conclusions

The revision of *The Four Pillars of Manufacturing Knowledge* reflects the evolving landscape of advanced manufacturing, integrating Industry 4.0 concepts and aligning with updated accreditation standards and SME's Body of Knowledge for CMfgE and CMfgT certification programs. With significant

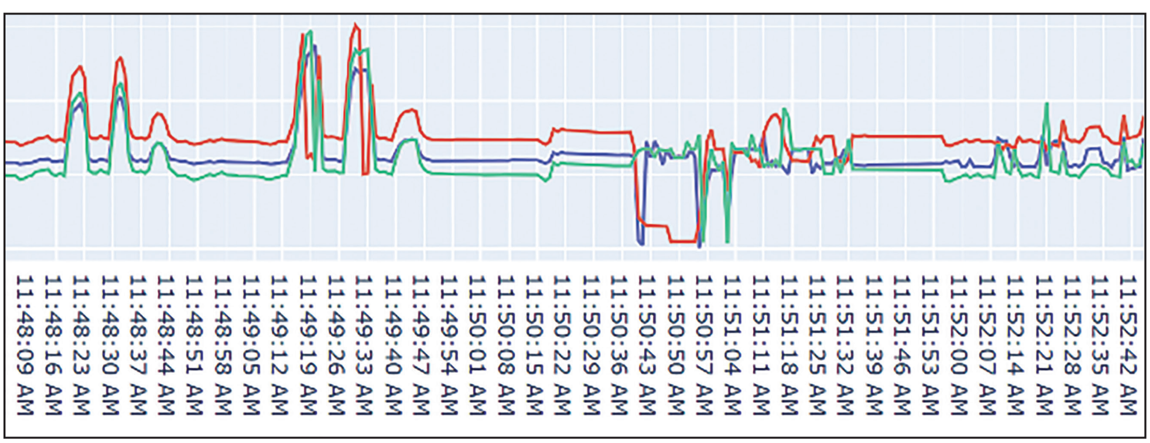

Figure 29. Example current (in ampere) during the machining of the sample part.

changes in eleven of the twelve knowledge blocks, this updated framework ensures that both academia and industry have a comprehensive model for modern manufacturing education. The most substantial revisions, particularly in the Industry 4.0 and Automated Systems and Control, as well as Process Design, highlight the growing importance of digital technologies, automation, and data-driven decision-making in manufacturing.

By examining these changes and providing practical applications for education and research, this paper serves as a valuable resource for educators, industry professionals, and policymakers. The insights gained from this study will help shape the future of manufacturing curricula, ensuring that graduates are equipped with the necessary skills to thrive in an increasingly digital and automated industry.

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