Advanced Four Pillars of Manufacturing Knowledge

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Abstract

The Four Pillars of Manufacturing Knowledge, first published in 2011, has been undergoing a revision process to encompass the changing landscape of advanced manufacturing, such as incorporating Industry 4.0 concepts. In 2021, a sample population of manufacturing experts from industry, government, and the academy were surveyed from the SME (the Society of Manufacturing Engineers) 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.

After the completion of the survey and subsequent data analysis, 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 initial survey, subsequent revisions, and a year-long validation process have resulted in an updated version of the Four Pillars of Manufacturing Knowledge ready for dissemination. This revised version of the Four Pillars is aligned with the original purpose. It is intended to be used by industry and academia to represent the breadth and scope of manufacturing engineering based on accreditation criteria and SME Certification Body of Knowledge. Because this scope is a moving target, the intention is to continually revisit the topics in the knowledge blocks annually, considering the continuous input from manufacturing experts.

The revision process resulted in changes to eleven of the twelve knowledge blocks. The only knowledge block without changes was 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.

Overall, this paper presents the facts of the revised four foundational pillars of manufacturing engineering. By comprehensively exploring these pillars, we aim to provide a holistic understanding of the multifaceted nature of manufacturing engineering and its pivotal role in driving innovation, efficiency, and sustainability in modern industry. Through ongoing research and collaboration, we strive to further advance these pillars, contributing to the continual evolution and enhancement of manufacturing

practices worldwide. The aim is for the Advanced Four Pillars to be a living document with periodic reviews to remain current.

Four Pillars Background

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 [1] (see Figure 1). 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. Mott et. al. [2] credits the process of developing the Four Pillars to the Society of Manufacturing Engineers (SME) through its Center for Education. Robert L. Mott is Professor Emeritus, School of Engineering, Department of Engineering Management, Systems and Technology, at the University of Dayton. Mott was a member of the Steering Committee of the SME Manufacturing Education & Research Community (SME-MERC), and Senior Staff of the NSF-sponsored National Center for Manufacturing Education located at University of Dayton. The Four Pillars is aligned with the February 2012 report, A National Strategic Plan for Advanced Manufacturing developed by the National Science and Technology Council, part of the Executive Office of the President [3] developed during the offshoring era of manufacturing.

Figure 1: SME Four Pillars [1]

Since the Four Pillars was introduced in 2011, several manufacturing education researchers, [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15] [16] and [17] have used the Four Pillars to describe curriculum development processes. 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.

The SME Manufacturing Education and Research Community and the SME Center for Education were combined into one entity in approximately 2010. The combined group of manufacturing educators and industry representatives is named the SME Manufacturing Education and Accreditation Committee (MEAC). This Committee has an SME liaison who is the Industry Development and Technical Activities Senior Manager. MEAC is led by an Executive Committee composed of the Chair, Past Chair, and Vice Chair with a

Committee of sixteen manufacturing experts representing both academia and industry. MEAC functions in an advisory role to the SME Board of Directors. The Committee is an International Standing Committee reporting to the Executive Committee and is responsible for the following:

- The Committee's primary responsibility is to represent SME in activities related to the accreditation globally of manufacturing education programs in engineering, engineering technology, industrial technology and related manufacturing education programs.
- It coordinates representation and input on accreditation visits, processes and policies, defining appropriate requirements for manufacturing programs and advocating for and promoting the quality of manufacturing programs through accreditation.

According to authors [18], the process for the Four Pillars revision was first initiated by the SME MEAC in 2020. Updates to the ABET accreditation standards [19] and the SME body of knowledge for the certification of manufacturing engineers and manufacturing technologists [20] 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.

Updating the Four Pillars

In 2020 a sample of manufacturing experts from industry, government, and the academy taken from the SME database were surveyed. The existing twelve blocks of knowledge were presented with the option for the respondent to either keep, remove or edit the topics in each. The first question was to determine if the respondent had any changes to recommend for the topics listed in the subject area. If they answered "no" the survey would progress to the next subject area. If they answered "yes" the survey would allow them to drag the topics to a "keep", "remove" or "edit" box. If they moved any topic to the "edit" box, additional prompts asked the respondent how they would edit the topic. Finally, a question was added at the end for any additional topics to be included for that subject area.

The survey was fielded from May 26 - June 14, 2021, online to approximately 350 subjects with 75 returned, yielding a response rate of approximately 21%. The topic of Automated Systems and Control had a large portion of the topics that were suggested to be removed or edited (see Figure 2).

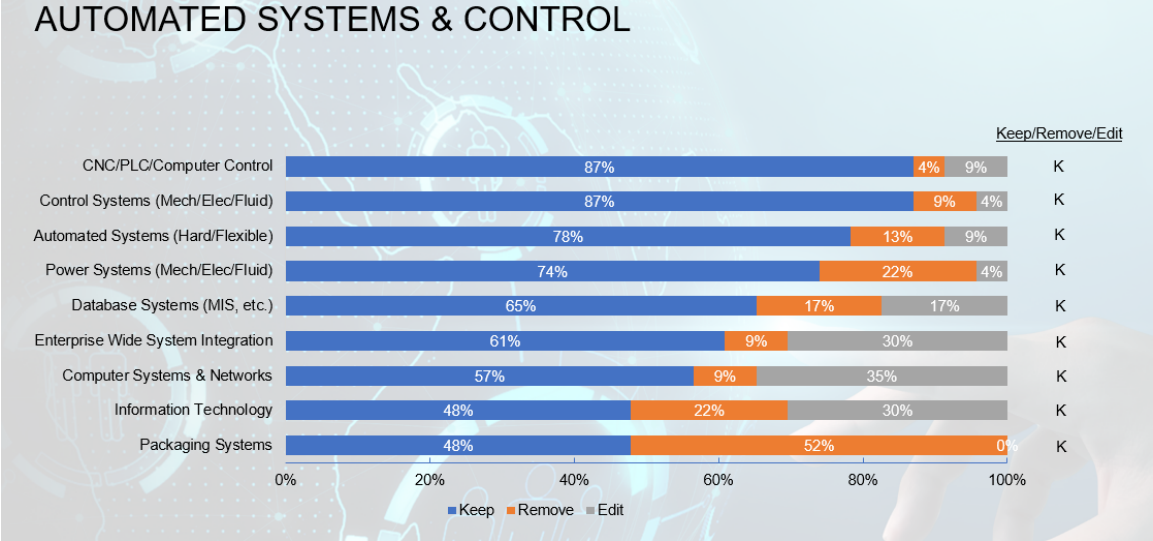

Figure 2: Survey Results - Automated Systems & Control

Each of the remaining eleven subject areas have similar sets of data. The results were included in a 90-page PowerPoint slide deck provided by SME Technical Activities for the MEAC for distillation and validation.

Four Pillars Workshop Validation Process

The MEAC reviewed the results of the survey resulting in presentations made at two Four Pillars Workshops reviewing the twelve revised knowledge blocks compared to the original Four Pillars knowledge blocks. The purpose of these workshops was to validate the survey results and revisions made by the MEAC. Attendees of the workshop were also provided a link to an online SME portal for submitting additional suggestions for revisions following the workshops.

The first of these workshops was hosted by the ASEE Manufacturing Division during the June 2023 ASEE Annual Conference held in Baltimore, Maryland. The Four Pillars Workshop was presented by SME MEAC Committee Members as a five-person panel discussion with approximately 15-20 attendees. The workshop was 1.5 hours formatted to provide the audience background information on the Four Pillars revision process followed by presentation of the revised twelve knowledge blocks. Information gleaned from the audience of manufacturing experts was integrated into the revised Four Pillars.

The presentation slide example (see Figure 3) represents the revisions made to the Automated Systems & Control knowledge block. The left side of the slide shows the topics from the original Four Pillars with strikethrough indicating topics that have been deleted, combined, edited or moved to another knowledge block. The right side of the slide shows the items highlighted in yellow that have been added or edited. For instance, the topics “Information Technology” and “Database Systems, (MIS, etc.)” have been replaced by the topic “Informatics and Data Science (Information Technologies, Database Systems).

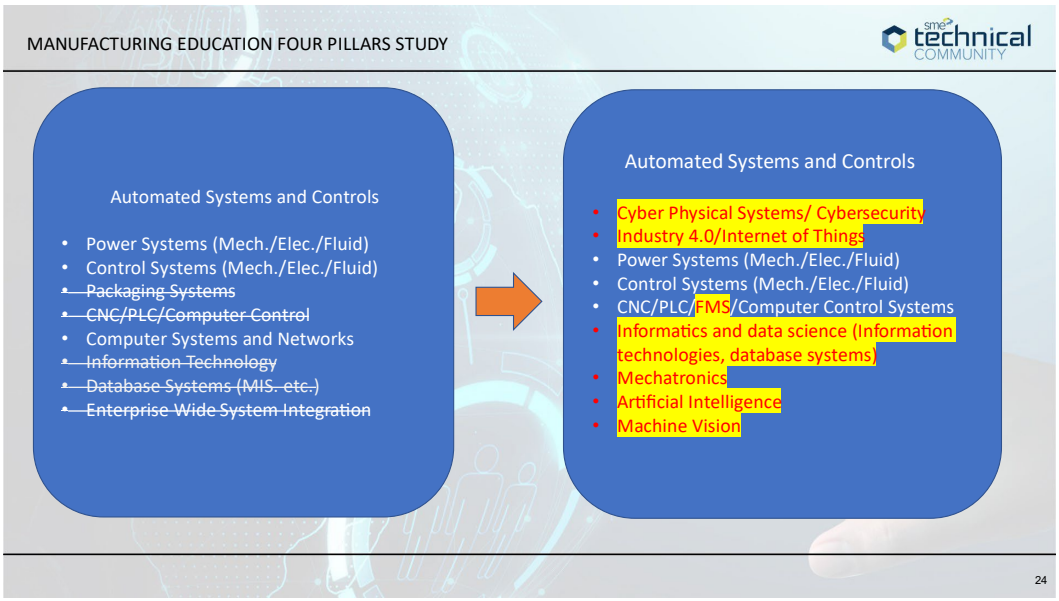

Figure 3: ASEE Four Pillars Workshop - Automated Systems & Controls

Feedback from this session lead to additional revisions that were subsequently presented to manufacturing experts at the October 2023 ATMAE Annual Conference held in Atlanta, Georgia. This presentation was delivered as a three-person panel discussion of MEAC Members with approximately 20-30 attendees. The same format of slides was used but knowledge blocks had been revised from input from the previous workshop and following discussion by the MEAC at an in-person meeting in July 2023 in Baltimore, Maryland. The presentation slide example (see Figure 4) indicates the modification to the knowledge block title with the addition of "Industry 4.0" resulting from the previous workshop and subsequent discussions.

The input from both ASEE and ATMAE workshops as well as the North American Manufacturing Research Institution of SME (NAMRI/SME) were validation of the revision process. The ASEE Manufacturing Division has many members from both industry, government, and academia that were made aware of the efforts underway to revise the Four Pillars. Likewise, the ATMAE organization has representation from industry, government, and academia that are members of their Manufacturing Division or closely related programs. The MEAC received input from both ABET and ATMAE accredited program faculty during this process. Industry and government input also came from the NAMRI/SME community.

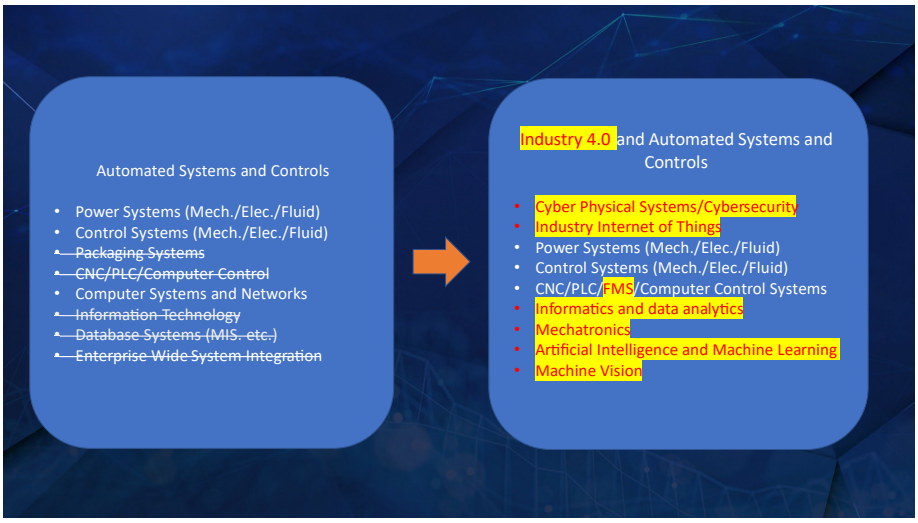

Figure 4: ATMAE Four Pillars Workshop – Industry 4.0 and Automated Systems and Controls

Four Pillars Validation Analysis

There were changes to eleven of the twelve knowledge blocks in the Four Pillars. These differences are categorized as deletions, topics that moved to other knowledge blocks, or added topics. Each knowledge block is analyzed here to help understand the differences from the original Four Pillars (also see Appendix B Table of Abbreviations).

The # 2 "Personal Effectiveness" knowledge block has six added topics, and others are changed or combined (see Table 1). **Knowledge is deleted** from this list and the **added topics are:**

- **Presentation skills**
- **Emotional Intelligence**
- **Diversity, Equity & Inclusiveness (DEI)**
- **Social Responsibility**
- **Ethics**
- **Innovation and Creativity**

Table 1: Personal Effectiveness (block 2)

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

The #3 “Engineering Sciences” knowledge block has only two changes. The topic of Electrical Circuits/ Electronics is renamed to Electrical Circuits/ Electronics/ **Instrumentation**. Secondly, the topic of **Material Science** is added.

The #4 “Material” knowledge block is renamed to “Engineering Materials” that has **three deleted topics: Nanotechnology, Foams, and Hybrids**. Other topics are incorporated into the new topics (see Table 2) and the following **topic is added:**

- **New/Advanced Materials**

Table 2: Engineering Materials (block 4)

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

The #5 “Manufacturing Processes” knowledge block has **one deleted topic: Hand Tool Use and Machine Operation**. Other topics are incorporated into the new topics (see Table 3) and the following **topics are added:**

- **Additive Manufacturing Processes**
- **Biomanufacturing**
- **Nanomanufacturing**
- **Non-Traditional Manufacturing**

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

The #6 "Product Design" knowledge block has **one deleted topic, Concurrent Engineering** and other topics have been moved, changed, moved (see Table 4). The **added topics are:**

- **Generative Design**
- **Systems Engineering**
- **Product Lifecycle Management, LCA tools and ELM**
- **Design Thinking**

Table 4: Product Design (block 6)

Topic	**Changed to**	**Moved to**
Simulation/Engineering Design	Simulation/Engineering Design/**Digital Twin**	
Design for X (Mfg/Assy/Maint)	Design for X (Mfg/Assy/Maint/**Remfg/ Recycling, Sustainability etc.)**	
Thermodynamics/Heat Transfer		Manufacturing Processes

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

- **CAD/CAM/CIM/Computer Integrated Manufacturing**
- **Model-Based Process Design**
- **Revision Control and Data Management**
- **Tool and Equipment Selection**
- **Process Planning and Development/Computer Aided Process Planning (CAPP)**
- **MRL/TRL/New Process/New Product Introduction**

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**

The #8 "Equipment/ Tool Design" knowledge block has only one change. The **topic added is:**

- **Real Time Adaptive Control design for tool condition monitoring**

The #9 "Production System Design" knowledge block has **two deleted topics: Infrastructure/Plant Location, and Waste Management** and other topics have been changed and/or combined (see Table 6). The **topics added are:**

- **ERP/MES**
- **Material Handling and Packaging Systems**

Table 6: Production System Design (block 9)

Topic	**Changed to**	**Moved to**
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	

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

- **Cyber Physical Systems/Cybersecurity**
- **Industry Internet of Things**
- **Mechatronics**
- **Artificial Intelligence and Machine Learning**
- **Machine Vision**

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

- **Concurrent Engineering**
- **Problem Solving and Root Cause Corrective Action**
- **Quality Management Systems (QMS)**

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 &** Field Service
Factor Analysis (DOE/Correlation)	**Design of Experiments** (DOE)

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

- **Competitive Analysis Including Intellectual Property**
- **Risk Management**
- **Problem Analysis and Solving**
- **Knowledge Management (Capture and reuse)**

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

Advanced Four Pillars Final Dissemination

Following the panel presentations at the Four Pillars Workshops, the SME Technical Communications Department has developed a newly revised Four Pillars document. The Advanced Four Pillars will be published in its entirety in an upcoming white paper to be available online from the SME website (see Figure 5).

Figure 5 SME Advanced Four Pillars

An example of the final revised version of the "Industry 4.0 and Automated Systems and Controls" knowledge block (see Figure 6) is identical to the version that was presented at the ATMAE Four Pillars Workshop but has been reformatted.

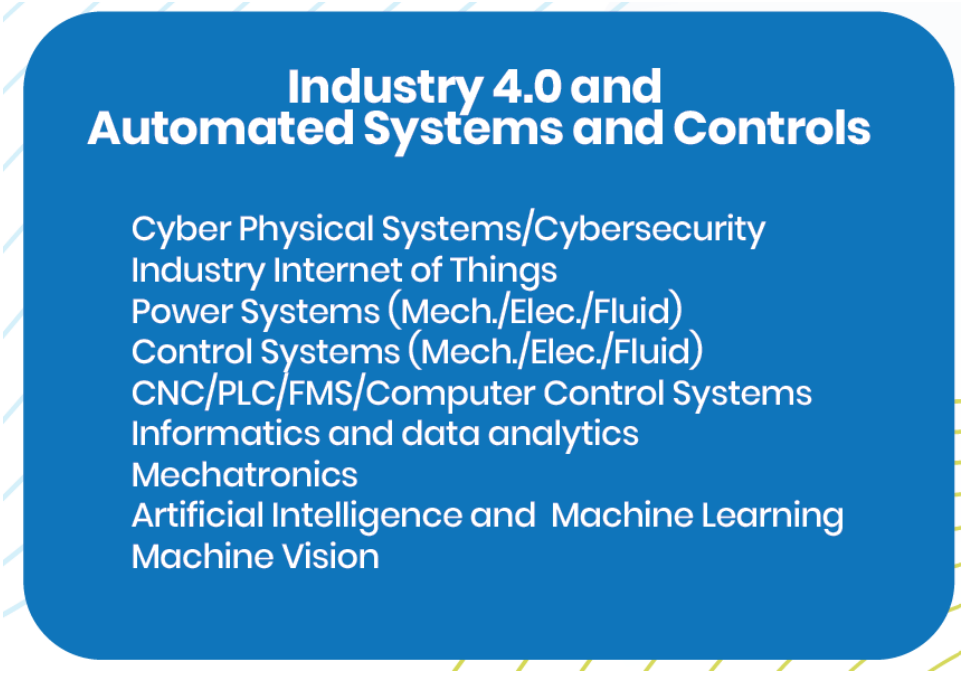

Figure 6: Newly developed knowledge block on Industry 4.0 and Automated Systems and Controls

Conclusions & Recommendations

The 75 responses (21% response rate) to the initial survey have been validated by an extensive group of manufacturing experts in several manufacturing workshops at

national/international conferences. The Advanced Four Pillars will be disseminated widely in professional society meetings such as ASEE, ATMAE, SME, and others that are involved with education and accreditation of manufacturing and related named programs.

Eleven of the twelve knowledge blocks have new or revised topics. 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 (see Appendix A). The complete revised version of the Advanced Four Pillars will be available from the SME Four Pillars white paper.

In conclusion, this paper underscores the revisions of the Four Pillars of Manufacturing Knowledge in shaping modern industry. By elucidating their interconnectedness and pivotal roles, we advocate for continued research and development in these areas to drive innovation and progress in manufacturing practices worldwide.

Acknowledgements

Thank you to the assistance of all the members of the SME MEAC, the ASEE Manufacturing Division, ASEE Annual Conference Four Pillars Workshop attendees, ATMAE Conference Four Pillars Workshop attendees, NAMRI SME Board of Directors and NAMR - SME Conference attendees for their assistance reviewing and provided valuable inputs.

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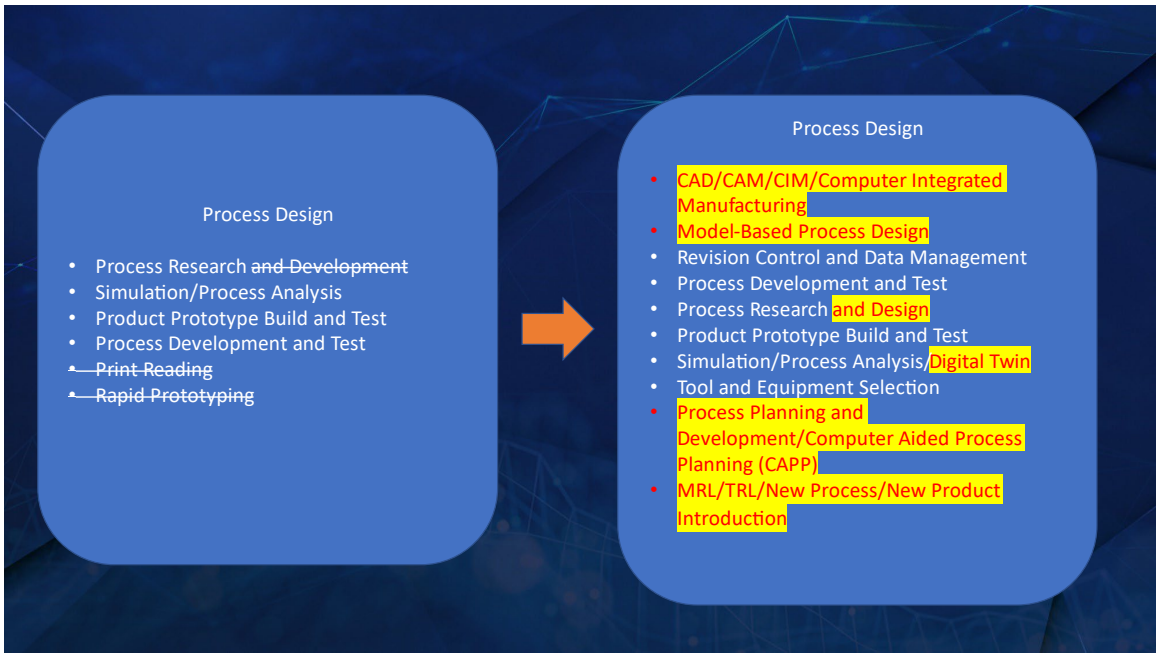
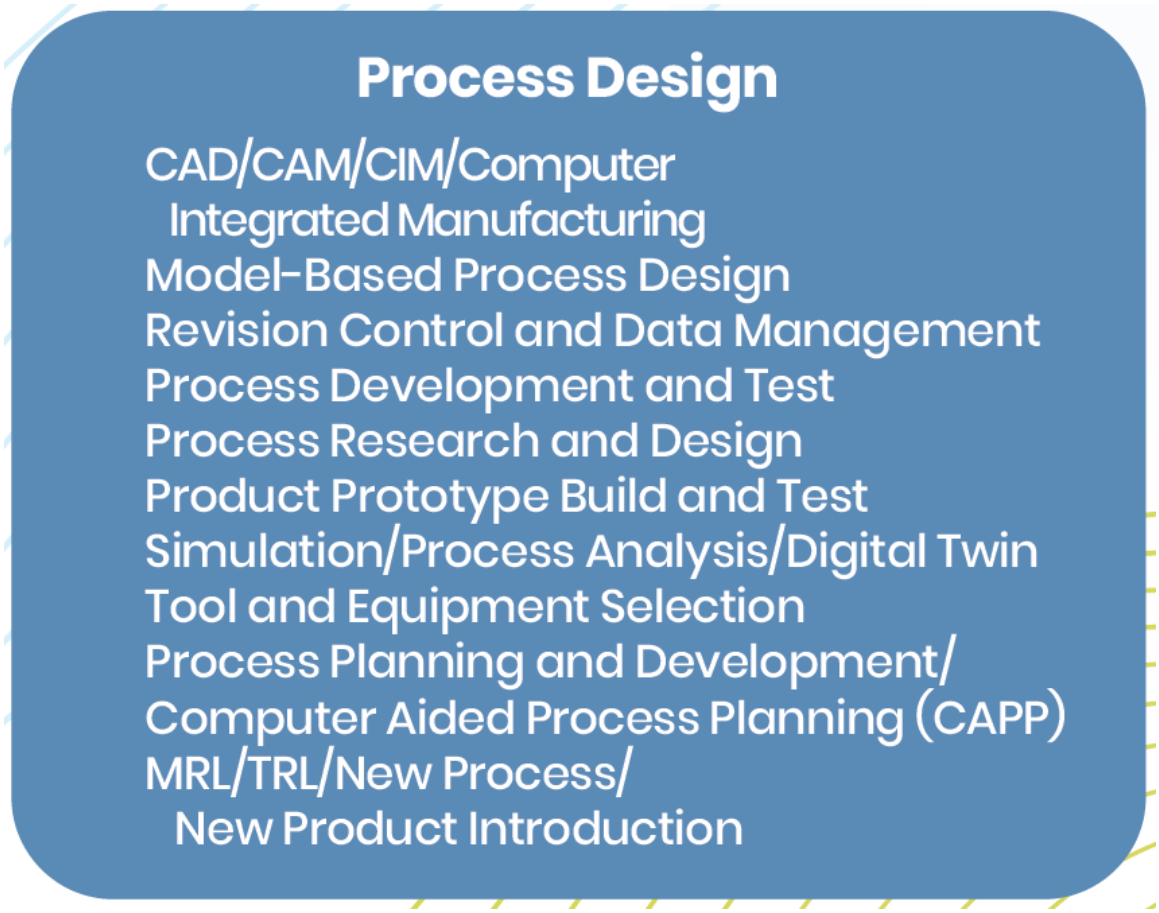
Appendix A: SME Four Pillars - Process Design





Appendix B: Table of Abbreviations

Abbreviation	Meaning
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CIM	Computer Integrated Manufacturing
CNC	Computer Numerical Control
DEI	Diversity, Equity, Inclusion
DOE	Design of Experiments
ELM	Engineering Lifecycle Management
ERP	Enterprise Resource Planning
FMEA	Failure Mode and Effects Analysis
FMS	Flexible Manufacturing System
GD&T	Geometric Dimensioning & Tolerancing
LCA	Life Cycle Assessment
MES	Manufacturing Execution System
MIS	Manufacturing Information System
MRL	Manufacturing Readiness Level
PLC	Programable Logic Control
QMS	Quality Management System
TRL	Technology Readiness Level