

Aligning Mathematics Preparation with Next-Generation Precision Manufacturing: A Curriculum Map and Competency Framework

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Abstract

The precision manufacturing industry has long been viewed as a field grounded primarily in hands-on proficiency and shop-floor experience, leading many training pathways to underemphasize academic preparation, particularly mathematics, but rapid advances in closed-loop control, in-process sensing, advanced metrology, and data-driven manufacturing are reshaping workforce expectations and exposing a growing mismatch between traditional training content and the quantitative reasoning now required for setup, inspection, troubleshooting, and optimization. As a result, insufficient mathematical proficiency has become a persistent barrier to student success in machinist training programs and to workforce upskilling for next-generation technologies that demand stronger spatial reasoning, measurement and tolerance interpretation, uncertainty-aware thinking, and basic data literacy. This study reviews and maps the mathematics curriculum embedded in machinist training programs, evaluates how well current topic coverage and sequencing align with advanced coursework and evolving machining technologies, identifies gaps and fragmentation in where key concepts are introduced and reinforced across math and technical courses, and offers actionable recommendations, such as contextualized integration, competency-based alignment, and targeted bridge modules, to strengthen curriculum coherence and support progression from entry-level preparation to technician- and engineer-level pathways in modern precision manufacturing.

Introduction

Next-generation precision manufacturing, characterized by closed-loop manufacturing control, in-process sensing and diagnostics, and AI/data-driven manufacturing systems, faces a growing workforce shortage in the U.S. that threatens both productivity and technology adoption [1]–[3]. Recent industry analysts estimate that U.S. manufacturing will need about 3.8 million new workers between 2024–2033, yet around 1.9 million of those roles could go unfilled if the skills and applicant gaps persist [1]. Even in occupations central to precision manufacturing, labor demand is sustained by replacement needs: the U.S. Bureau of Labor Statistics projects ~34,200 annual openings for machinists and tool-and-die makers and ~87,900 annual openings for metal and plastic machine workers in coming ten years, largely due to retirements and workforce turnover [4], [5].

Despite the scale of demand, the training capacity of U.S. precision manufacturing programs is inherently constrained. High-quality machining education requires low student-to-equipment ratios, extensive supervised lab time, and access to costly assets such as CNC mills/lathes, tooling, metrology systems (e.g., CMMs), and up-to-date CAD/CAM software. These capacity

constraints are amplified by rapidly evolving smart-manufacturing technologies and the need for continual reinvestment in laboratory facilities and equipment to keep coursework current [6]. Apprenticeship models can help address capacity, but they depend on employer participation and mentoring bandwidth, which can fluctuate with production cycles and local economic conditions. As a result, even where programs exist, throughput may not scale quickly enough to meet projected openings, especially for advanced, digitally enabled roles that require deeper training in programming, inspection, and process control [6].

More critically, the current U.S. training pipeline for precision manufacturing remains uneven in both capacity and content alignment. Most preparation occurs through community college machining and manufacturing technology programs, career and technical education (CTE) centers and vocational high schools, employer-led apprenticeships, and short-term certificate or credential pathways (e.g., CNC operation, CAM fundamentals, basic inspection). These pathways excel at building hands-on competence, safety, and procedural confidence; however, mathematics instruction is often positioned as a prerequisite rather than an integrated, continuously reinforced skill embedded across machining, metrology, and process-control learning experiences. Prior work on contextualized math in CTE has shown that quantitative reasoning is frequently present but implicit in technical coursework unless it is intentionally surfaced and taught [7]. Consequently, graduates may be able to operate equipment reliably under familiar conditions, yet struggle to generalize quantitative reasoning to new parts, new inspection requirements, or data-rich troubleshooting scenarios, precisely the capabilities needed in digitally enabled precision manufacturing environments [3], [7].

To address this gap, many U.S. precision machining and advanced-manufacturing programs are shifting from “math-first” prerequisite structures to contextualized, integrated, and supported mathematics instruction delivered within technical coursework. A common strategy is “Math-in-CTE,” in which manufacturing/CTE and mathematics faculty jointly identify the quantitative reasoning embedded in lab tasks (e.g., feeds and speeds, setup trigonometry, tolerance interpretation, and measurement reasoning) and redesign instruction so students practice these concepts repeatedly through authentic shop problems—improving mathematics outcomes without sacrificing technical competency [7].

However, scaling integrated math models still faces practical barriers, especially for students who intend to continue from two-year pathway programs into four-year engineering or engineering-technology degrees. While contextual “Math-in-CTE” instruction can strengthen job-relevant quantitative skills, it often does not align neatly with the traditional, credit-bearing math sequences used by universities for placement and prerequisite enforcement (e.g., precalculus and calculus readiness), which can create a transfer bottleneck even for students who perform well in technical labs. In response, many systems have expanded co-requisite and accelerated math models, placing students directly into gateway, credit-bearing courses while providing concurrent support, which have been shown to improve gateway math completion relative to traditional prerequisite remediation in multiple contexts [8], [9]. In parallel, math-pathways reforms (e.g., statistics/quantitative reasoning pathways alongside a calculus path) aim to better align math requirements with students’ programs of study and improve progression through credit-bearing coursework [10].

To mitigate these pathway and scalability challenges, programs are pursuing more formalized, system-level solutions that align contextual math with four-year expectations while preserving its relevance to precision manufacturing. These include transfer-aligned competency maps and common assessments/portfolio artifacts; expanded co-requisite and accelerated models; and regionally coordinated pathway work (e.g., articulation and bridge mechanisms) to clarify how contextualized competencies support continued study and advancement [8]–[10]. To improve consistency at scale, programs are also investing in shared instructional resources and digital modules using authentic shop data so that integrated mathematics is delivered with comparable rigor while directly supporting advanced competencies in programming, inspection, and data-driven process control [3], [10].

A further challenge is that new technologies in precision manufacturing are pushing mathematics beyond “shop arithmetic” toward model-based, data-centric, and automation-focused reasoning, making it harder to design coherent math preparation. Smart manufacturing frameworks emphasize metrics-driven process control, diagnostics/prognostics, and data analytics to convert manufacturing data into actionable decision support [2], [3]. In-process sensing and monitoring in machining (e.g., cutting force, vibration, acoustic emission, and temperature) similarly require time-series reasoning and basic signal concepts to distinguish noise from meaningful process signatures and to support tool-condition assessment and chatter detection [11], [12]. Together, these rising quantitative demands must be layered into already crowded, lab-intensive programs, reinforcing the need for integrated, transfer-aware mathematics preparation that supports both workforce readiness and upward educational mobility [3], [6].

In this study, we evaluate the mathematics education embedded in precision manufacturing training programs in New York State’s Finger Lakes region and examine how well these quantitative expectations align with both K–12 preparation and postsecondary degree pathways. Building on the challenges described above, we developed a comprehensive competency map that links core precision manufacturing tasks to the underlying mathematical topics required for successful performance. This map is intended to serve as a practical framework for training providers to identify where critical math concepts are introduced, reinforced, and assessed across courses and lab experiences, pinpoint gaps or redundancies that hinder learner progression, and support targeted curriculum redesign, including contextualized modules and “bridge” content, to improve student readiness for advanced roles and for continued study in two-year and four-year engineering/engineering-technology programs.

Case Study

To develop a detailed and practice-oriented understanding of how mathematics is currently positioned within precision manufacturing training, we examined a precision machining program offered by a community college in New York State’s Finger Lakes region. The program provides multiple Precision Machining & Tooling pathways, including an A.A.S. in Precision Machining and a one-year certificate designed for rapid entry into the workforce. Instruction emphasizes modern machining and manufacturing workflows, such as CNC machining, CAD/CAM-enabled

design-to-manufacture processes, and advanced shop technologies. Within this program, mathematics preparation and attainment are structured through several mechanisms:

- **Entry requirements**, in which students must demonstrate specified levels of prior high school mathematics or meet placement thresholds on the ACCUPLACER assessment;
- **A required semester-long mathematics course** tailored to machining operations to support degree/certificate completion;
- **Embedded applied mathematics** integrated across technical courses to reinforce quantitative reasoning in context; and
- For A.A.S. students, the option to take **higher-level mathematics electives** during the second year to support transfer and advancement pathways.

Prior to enrollment, the community college's advising guidelines indicate that students' mathematics proficiency is determined through a placement assessment that categorizes performance into ten levels. Based on the resulting placement level, students are directed into the appropriate preparatory sequence: those placing at Levels 2–3 are recommended to take pre-algebra; Levels 4–5 to take elementary algebra; Level 6 to take intermediate algebra; and Levels 7–8 to take college algebra. Students who place at Levels 9–10 are deemed eligible to enroll in precalculus and calculus.

Table 1. Students' performance in mathematics placement exam (2015 ~ 2024).

Math Level	Term									
	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Level 1	9	7	16	13	5	5	7	4	3	1
Level 2	15	14	20	22	16	18	41	22	25	42
Level 3	11	10	13	8	14	2	1	0	0	0
Level 4	23	23	17	20	5	7	8	12	8	28
Level 5	2	4	5	6	0	8	13	19	6	17
Level 6	34	33	35	29	37	20	7	4	6	8
Level 7	0	0	0	0	22	10	9	4	2	7
Level 8	15	18	18	26	24	26	7	6	8	9
Level 9	2	9	5	7	13	3	4	5	7	4
Level 10	2	12	8	5	7	6	2	11	8	9
Unknown	21	18	17	26	25	17	12	36	56	32
Total	134	148	154	162	168	122	111	123	129	157

(Levels 1 - 10 represent different mathematical levels from basic to advanced.)

Table 1 summarizes ten years of mathematics placement results (2015–2024) for students entering the precision machining program. Across cohorts with reported placement levels, the mean placement remained relatively stable around the mid-level range (overall Mean Level $\approx$ 5.11), with a notable dip in 2021 (Avg. Level = 4.10) following the COVID-19 disruption. However, the distribution is consistently broad: student placements span all ten levels each year, with an average within-year standard deviation of approximately 2.63 levels (range: $\sim$ 2.28–3.05).

This wide spread indicates substantial heterogeneity in incoming mathematical preparation, complicating the design of a single math sequence that can effectively support both underprepared learners and those ready for more advanced quantitative work.

Under the college’s advising guidance, students placing in Levels 1–4, who received low grade in quantitative algebra and statistics, are generally routed into imputed-credit (developmental) mathematics that does not count toward degree credit requirements. Table 2 suggests that this placement outcome is common: over 2015–2024, about 45% of students with a reported placement level (515 of 1,148) placed at Level 4 or below, with the proportion exceeding 50% in several years (e.g., 2015, 2021, and 2024). This pattern implies that a substantial share of incoming students may need additional, non-credit math coursework before progressing efficiently through the program’s machining-focused mathematics course and into higher-level technical content, potentially increasing time-to-completion and creating barriers to advancement toward degree completion and further education pathways. Conversely, roughly 10% of students placed at Levels 9–10, indicating readiness for more advanced, four-year college–level mathematics; these students are likely to have already mastered the content of the required course and may benefit from more rigorous quantitative enrichment.

Table 2. Historical student participation and grade distribution in mathematics for machinists.

Term	A	B	C	D	F	W	Total
	304	159	73	27	53	46	662
Fall 2015	13	8	5		11	5	42
Spring 2016	32	11	2	1	2	5	53
Summer 2016	4	3	4				11
Fall 2016	14	15	3			1	33
Spring 2017	33	7	4	2	1	5	52
Fall 2017	27	5	3		1	4	40
Spring 2018	9	8	3	1	2		23
Summer 2018	8	1					9
Fall 2018	7	9	4	4	12	1	37
Spring 2019	29	15	10	3	2	2	61
Fall 2019	24	8	9	2	2	3	48
Spring 2020	23	7	8	4	8	8	58
Summer 2020	4	6		1	1	1	13
Fall 2020	11	4	1		2	3	21
Spring 2021	10		1	2	1		14
Summer 2021		3	1			4	8
Fall 2021	2	2	3		2	1	10
Spring 2022	6	1	3				10
Fall 2022	11	7	4	2	2	1	27
Fall 2023	19	21	1	3	3	1	48
Spring 2024	6	3	1	1	1		12
Fall 2024	12	15	3	1		1	32

The program’s required course, Advanced Manufacturing Math, is designed as an applied bridge between foundational mathematics and the quantitative demands of advanced manufacturing technicians. In alignment with this objective, the course emphasizes core arithmetic, geometry, and right-triangle trigonometry, framed through precision-manufacturing applications. To address wide variation in incoming preparation, instruction prioritizes essential concepts and skills in a lecture-based format, while more complex, contextualized applications are distributed across subsequent technical courses. This scaffolded approach supports baseline competency for most learners and provides additional time and reinforcement for students who enter underprepared; correspondingly, the majority of students are able to complete the course successfully with satisfactory grades, including those initially performing below level. At the same time, the approach limits the depth and pace of mathematical treatment within the required course, particularly for students ready for more advanced quantitative study, which may help explain limited transfer outcomes, as evidenced by the absence of transfers from the program to four-year institutions despite the existence of articulated pathway agreements with local colleges.

In addition to the lecture-based coverage of core mathematical concepts, the program embeds applied quantitative skills throughout multiple technical courses to reinforce reasoning and problem solving in authentic precision-manufacturing contexts (Table 3). This “distributed” integration model is increasingly common across manufacturing training programs and, in some cases, is used to partially or fully replace standalone mathematics courses in order to emphasize immediate workplace relevance. However, when mathematical content is fragmented across courses and introduced primarily as needed for specific tasks, students may have limited opportunities to recognize underlying connections among topics, develop a coherent progression of ideas, or build sufficient fluency for novel problems. This raises a central instructional challenge: ensuring that contextualized math integration strengthens, rather than dilutes, students’ cumulative quantitative preparation for advanced technical learning and longer-term advancement pathways.

Table 3. Curriculum Map of Mathematics Topics across Precision Manufacturing Courses.

Math Topics	Courses offered by the Precision Manufacturing Program				
	Manufacturing Math	Dimensional Metrology	CNC Machine Tool Programming	CNC Mill Set-up	CNC Lathe Set-up
Common Fractions and Decimal Fractions	✓				
Ratio, Proportion, and Percentage			✓	✓	✓
Linear Measurement		✓		✓	✓
Fundamentals of Algebra	✓	✓	✓		
Fundamentals of Plane Geometry	✓		✓		
Trigonometry	✓	✓	✓		
Compound Angles	✓	✓	✓		
Computer Numerical Control (CNC)	✓		✓	✓	✓

Necessity of Pursuing Advanced Studies and the Role of Mathematics

Precision manufacturing occupations typically fall into three categories, including operator, technician, and engineer, each with distinct responsibilities and corresponding educational preparation (Table 4). As the manufacturing sector continues to upgrade technologies and processes, demand is shifting toward technician- and engineer-level roles. Preparation for these positions requires not only conceptual knowledge acquired through lecture-based coursework, but also substantial hands-on experience. Consequently, workers who initially enter the field through entry-level programs or positions are increasingly expected to pursue additional education to qualify for advanced roles. Well-aligned, clearly articulated curricula across educational levels can facilitate this upward progression. However, many programs are designed primarily for a single educational tier, and unaddressed barriers between levels can impede learners from continuing their studies.

Table 4. Precision manufacturing roles matrix: responsibilities, training, and mathematical competencies.

	Operator (CNC/Manual)	Technician (Manufacturing/Process/Metrology/CAM)	Engineer (Mfg/ME/Process/Quality)
Primary Role	Run machines to make parts safely and to spec	Enable/optimize production: setups, troubleshooting, fixturing, inspection, light programming	Design/industrialize processes, own capability, cost, quality, automation & scalability
Typical Scope	Individual machine/cell; follows documented process	Multiple machines/cells; improves/maintains processes	Value stream/line or product family; creates processes & standards
Tools & Software	CNC controls, gages, calipers/mics, basic SPC sheets	CAD/CAM (Fusion/Mastercam/NX), CMM software, probe macros, PLC/HMI basics, advanced metrology	CAD/CAM/CAE, PLM/ERP, statistical tools, simulation, automation/robotics toolsets
Math Depth	Fractions/decimals; unit conversions; right-triangle trig; feeds/speeds; % tolerance used	All operator math + 1D stack-ups; fits; GD&T position math; MRR/HP; regression basics; G-code/CRC geometry	All technician math + calculus/linear algebra basics; tolerance analysis; DOE/ANOVA; reliability; queuing/capacity; cost modeling
Education (Typical)	HS/GED + bootcamp/apprenticeship or employer training	Certificate or AAS (2-yr) in machining/manufacturing technology; strong experience	BS in Manufacturing/Mechanical/Industrial Engineering (MS preferred in regulated/high-precision sectors)
Typical Career Path	Trainee → Operator → Lead/Cell Lead	Senior Tech → Process/Quality/CAM Tech → Supervisor	Manufacturing/Quality/Process Engineer → Senior/Staff → Manager/ME Leader/Continuous Improvement

Among these barriers, mathematics is frequently cited by educational institutions as one of the most prevalent and consequential challenges. To address workforce shortages, many precision manufacturing programs have adopted an enrollment-expansion strategy that reduces mathematics prerequisites in order to attract a broader student population. At the same time, longstanding perceptions in some K–12 settings, often based on the historically low math requirements of certain technical programs, continue to reinforce an outdated view that mathematics is unnecessary for technical education. As a result, many students enter the pathway with limited expectations for mathematical preparation. Moreover, even when precision manufacturing programs offer lecture-based mathematics courses, these courses are often developed and delivered within technical training units rather than mathematics departments. This separation can limit transferability and create a weak linkage to the higher-level mathematics coursework typically required for advanced credentials and degree pathways.

To better prepare the workforce for future precision manufacturing industry, mathematics should serve as a foundational language for precision manufacturing, enabling learners to move beyond procedural task execution toward informed decision-making in setup, machining, inspection, and process improvement. Foundational skills, such as arithmetic and unit conversion, algebra, geometry, and trigonometry, are routinely applied in blueprint interpretation, coordinate and offset calculations, feeds-and-speeds selection, CNC programming, and dimensional inspection. As precision manufacturing increasingly incorporates automation, advanced metrology, and data-enabled process monitoring, stronger mathematical preparation is also needed to interpret measurement results, reason about tolerance and uncertainty, understand process variation (e.g., SPC concepts), and troubleshoot systematic errors. From this perspective, minimizing mathematics requirements may broaden short-term access, but it can inadvertently weaken students' readiness for advanced coursework and reduce transferability to higher-level credentials. Therefore, mathematics instruction should be intentionally integrated with manufacturing contexts and aligned across certificate, associate, and bachelor-level curricula to support both workforce readiness and continued educational progression.

Guidance of Mathematical Requirements for Precision Manufacturing Education

To provide general guidance on the mathematical content appropriate for different levels of precision manufacturing education, we developed the checklist shown in Table 5. The checklist identifies fifteen core quantitative topics and specifies the expected level of mastery for each of three industry roles, i.e., operator, technician, and engineer, using the A/W/P depth key (Awareness, Working, and Proficient). In addition, each topic is mapped to the core precision manufacturing training requirements (e.g., print reading and GD&T, metrology and quality, CNC operation, CAM workflow, and setup/prove-out) to ensure that the recommended mathematics coverage is directly connected to authentic workplace tasks and competencies.

This checklist is intended to support instructors and curriculum designers in developing, revising, and evaluating mathematics requirements at both the course and program levels, including certificate, associate, and bachelor-degree pathways. By making role-specific expectations explicit, the checklist can also help identify gaps, redundancies, and potential barriers that may limit student progression across educational levels. Finally, the checklist provides a transparent reference for students and advisors to understand and compare the mathematical expectations associated with different pathways, supporting informed decision-making and more coherent planning for continued study and career advancement in precision manufacturing.

Table 5. Mapping core mathematics foundations to precision manufacturing training requirements and role-based depth.

Core Topic	Description / Scope	A/W/P Depth Key by Role			Core Precision Manufacturing Training Requirements					
		Operator	Technician	Engineer	Multi-axis CNC + CAM/Simulation	Cobots	In-process Sensing & Diagnostics	IIoT + Real-time Data	Advanced Metrology / On-machine Measurement	AI/ML for Quality & Maintenance
3D coordinate frames & transformations	Arithmetic, estimation, significant digits, rounding; interpreting numeric settings/results	W	P	P	✓	✓	✓	✓	✓	✓
Spatial geometry & applied trigonometry for orientation	Unit consistency, inch–mm, compound units, rates (“per time”), scaling	W	P	P	✓	✓	✓	✓	✓	✓
Parametric geometry for toolpaths & surfaces	Rearranging equations, solving for unknowns, constraint checks, sanity checks	A	W	P	✓	✓	✓	✓	✓	✓
Numerical discretization, resolution & interpolation	Practical geometry; circles/arcs; area/volume; basic 3D forms for setups/features	W	P	P	✓	✓			✓	
Kinematics & motion constraints	Angles, tapers, tool orientation reasoning; triangle trig in setup/verification	A	W	P	✓	✓			✓	
Time-series reasoning	Planes/lines/vectors/normals; dot/cross intuition for orientation/fit	A	W	P	✓	✓			✓	✓
Signal concepts & intuitive filtering	Datums, offsets, rotations; frame-to-frame transforms (part–machine–robot)	A	W	P	✓	✓			✓	
Applied statistics & threshold setting	Parametric intuition for curves/surfaces underlying CAM toolpaths and surface generation	A	W	P	✓					
SPC & process capability interpretation	Step size/resolution; sampling; interpolation; simulation step effects	A	W	P	✓	✓	✓	✓		✓
Metrology geometry & datum-based measurement	Position/orientation basics; interpolation; speed/accel limits; motion reasoning	A	W	P	✓	✓				
Measurement uncertainty, bias & error propagation	Feeds/speeds, chip load, MRR, cycle time; tradeoffs (finish/accuracy/tool life)	W	P	P	✓		✓	✓		✓
ML + optimization literacy for manufacturing decisions	Probing/CMM/scan basics; calibration concepts; scaling; coordinate-based inspection math	W	P	P	✓			✓	✓	✓

Depth key: *A* = Awareness (recognize/interpret), *W* = Working (apply with guidance), *P* = Proficient (independent, can troubleshoot/extend)

Mathematical Requirements for Future Precision Manufacturing

In response to ongoing technological advances, precision manufacturing is rapidly expanding beyond traditional machining competencies to include a range of digitally enabled and automation-intensive practices. Emerging technologies are increasingly being adopted across the industry. These developments elevate the quantitative expectations placed on the workforce, requiring learners to apply mathematics not only for routine calculations, but also for spatial reasoning, coordinate transformations, data interpretation, and evidence-based decision making. As a result, future precision manufacturing education must incorporate more advanced and integrated mathematical competencies that support troubleshooting, optimization, and validation within complex cyber-physical production systems, while still maintaining clear pathways from entry-level preparation to technician- and engineer-level roles.

Key emerging technologies and their associated mathematical requirements include:

High-speed, multi-axis CNC machining and advanced CAM/simulation, such as 5-axis toolpath generation, collision avoidance, feed optimization, and digital verification, significantly increase the mathematical demands of precision manufacturing. Effective use of these tools requires applied trigonometry and spatial geometry to reason about angles, rotations, and tool orientations, as well as intuition for parametric curves and surfaces that underlie modern toolpath strategies. Practitioners also need numerical reasoning to understand step size, discretization, and simulation resolution, and must weigh optimization tradeoffs among cycle time, surface finish, accuracy, and tool life when selecting machining parameters and validating programs.

Collaborative robots (cobots) are becoming common in precision manufacturing for machine tending, inspection handling, deburring, and assembly, often supported by vision or force sensing. Using them effectively requires mathematics beyond routine shop calculations, including 3D coordinate frames and transformations (tool/work offsets and rotations), applied trigonometry and geometry, and basic kinematics for defining robot position and orientation. Cobot tasks also rely on quantitative understanding of motion planning concepts such as interpolation and speed/acceleration limits, highlighting the rising math demands of automation-enabled production.

In-process sensing and diagnostics, such as monitoring cutting force, vibration, acoustic emission, and temperature for tool-condition assessment and chatter detection, introduce essential quantitative skills for modern precision manufacturing. Effective use of these technologies requires time-series reasoning (e.g., sampling and trend interpretation), basic signal concepts to distinguish noise from meaningful process signatures and apply intuitive filtering, and statistics to set thresholds and manage false-alarm risk. Practitioners must also work fluently with units and rates, using “change over time” reasoning to interpret dynamic process behavior and translate sensor data into actionable decisions.

Industrial IoT (IIoT) and real-time data infrastructure, such as connected machines, dashboards, and streaming shop-floor data, enable “smart manufacturing” feedback loops but also expand the quantitative demands on the workforce. Practitioners must develop data literacy

and applied statistics to interpret rates, aggregates, and correlations, along with time-series fundamentals to recognize patterns, shifts, and drift in live process signals. Reliable decision making also depends on measurement integrity, including correct handling of units, scaling, and sensor calibration. Finally, IIoT-enabled monitoring is most effective when integrated with SPC, requiring users to interpret control-chart behavior and translate data trends into timely process adjustments.

Advanced metrology and on-machine measurement, such as CMM inspection, probing, laser/optical scanning, and adaptive verification, raise the mathematical expectations for precision manufacturing roles. Practitioners must apply 3D geometry (e.g., planes, circles, and vectors) and coordinate transformations to work effectively with datum reference frames and measurement coordinate systems. They also need strong GD&T and tolerance reasoning to translate design intent into inspection plans and acceptance decisions. Finally, reliable measurement-based control requires uncertainty-aware thinking, including practical understanding of repeatability, bias, and how measurement variation can propagate into quality judgments and process adjustments.

AI and machine-learning tools for quality and maintenance, such as anomaly detection, predictive maintenance, vision-based inspection, and process prediction or optimization, are increasingly used to support decision making in precision manufacturing. Applying these tools effectively requires a practical foundation in probability and statistics to interpret distributions, outliers, and confidence, along with basic understanding of regression and classification for modeling and diagnosis. Users also benefit from linear-algebra intuition (e.g., features and vectors) to make sense of model inputs and similarity measures, and from introductory optimization concepts to understand how models balance error minimization and tradeoffs when tuning processes or setting decision thresholds.

To better reflect the advanced mathematical demands of the future precision manufacturing industry within the proposed checklist (Table 6), Tier-2 mathematics competencies are introduced through 12 additional core topics, as summarized in Table 6. These topics capture quantitative skills that extend beyond foundational arithmetic and algebra to support modern, digitally enabled manufacturing practices such as multi-axis machining, advanced metrology, automation, and data-driven process monitoring. Each topic is evaluated using an explicit mastery-level expectation for different industry roles (e.g., operator, technician, and engineer), allowing the framework to distinguish between awareness, working knowledge, and proficient application. In addition, the Tier-2 topics are systematically mapped to core precision manufacturing training requirements to clarify where and how these competencies are applied in practice and to guide curriculum planning, instructional emphasis, and workforce pathway design.

Table 6. Mapping Tier-2 mathematics topics to future precision manufacturing training requirements and role-based depth.

Core Topic	Description / Scope	A/W/P Depth Key by Role			Core Precision Manufacturing Training Requirements								
		Operator	Technician	Engineer	Shop & Machine Safety	Print Reading & GD&T	Metrology & Quality	Materials & Tooling	Machining Fundamentals	CNC Operation	Programming Essentials	CAM Workflow	Setup & Prove-Out
Number sense & arithmetic	Whole-number operations, estimation, rounding, order of operations	W	P	P	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fractions, decimals, and mixed numbers	Conversions and operations; precision and rounding in decimal contexts	W	P	P	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ratio, proportion, and percent	Scaling, proportional reasoning, percent change; common shop applications	W	P	P	✓		✓	✓	✓	✓	✓	✓	✓
Units, dimensional analysis, and conversions	Unit consistency; inch-mm conversion; rates and compound units	W	P	P	✓	✓	✓	✓	✓	✓	✓	✓	✓
Measurement fundamentals	Resolution vs accuracy; significant digits; selecting and using measurement tools	W	P	P	✓	✓	✓	✓	✓	✓	✓	✓	✓
Shop metrology calculations	Calipers, micrometers, and verniers; interpreting readings; basic inspection math	W	P	P		✓	✓	✓	✓	✓	✓	✓	✓
Geometry for manufacturing	Perimeter/area/volume; circles/arcs; triangles; practical layout geometry	W	P	P	✓	✓	✓	✓	✓	✓	✓	✓	✓
Angles & trigonometry (applied)	Right-triangle trigonometry; tapers; sine-bar-style angle reasoning	A	W	P	✓	✓		✓	✓	✓	✓	✓	✓
Algebraic manipulation and formula use	Rearranging equations; solving for unknowns; constraints and checks	A	W	P	✓			✓	✓	✓	✓	✓	✓
Coordinate systems and spatial reasoning	XY/Z coordinates; offsets; bolt circles; sign conventions; spatial reasoning	A	W	P		✓			✓	✓	✓	✓	✓
Machining process math	SFM/RPM, feed rate, chip load, MRR, cycle-time estimates; power/torque force	W	P	P	✓			✓	✓	✓	✓	✓	✓
Tolerancing and GD&T quantitative reasoning	Limits and fits, tolerance bands, datum-based reasoning; acceptance decisions	A	W	P		✓	✓	✓	✓	✓	✓	✓	✓
Data literacy & technical documentation	Tables/charts; job travelers; revision control; traceability; recording inspection	W	P	P	✓		✓	✓	✓	✓			
Statistics for quality (practical)	Variation and distributions intuition; outliers; basic SPC/control-chart	A	W	P			✓		✓				
Measurement uncertainty (practical)	Repeatability vs bias; uncertainty-aware pass/fail decisions; propagation intuition	A	W	P			✓		✓				

Depth key: *A* = Awareness (recognize/interpret), *W* = Working (apply with guidance), *P* = Proficient (independent, can troubleshoot/extend)

Conclusions

This study highlights a growing gap between the mathematics preparation embedded in many precision manufacturing training pathways and the rising quantitative demands of next-generation, digitally enabled manufacturing. Using a community-college case study, we show that incoming students exhibit wide variability in math readiness, that a substantial portion are

routed into non-credit developmental math, and that mathematics is often treated as a prerequisite or fragmented across technical courses, supporting short-term task performance but limiting coherent, transferable quantitative development for advanced roles and four-year pathways. To address this challenge, we propose a role- and task-aligned mathematics competency framework that maps core quantitative foundations to precision manufacturing training requirements and specifies expected mastery levels for operators, technicians, and engineers using an A/W/P depth key; we further extend the framework with Tier-2 competencies that reflect emerging needs in multi-axis machining and CAM/simulation, automation and cobots, in-process sensing, IIoT data interpretation, advanced metrology, and AI/ML-enabled quality and maintenance. Together, these contributions provide a practical tool for curriculum redesign, gap identification, and pathway alignment, supporting both workforce readiness and continued educational progression.

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