Emerging Issues in Mathematics for Manufacturing

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Introduction

Manufacturing is crucial to the U.S. economy even as the industry's share of employment in the economy continues to decline. On the one hand, economists warn that fewer workers may be needed for the most basic jobs on the assembly lines as processes become more automated and incorporate technological advancements. In fact, over the last 15 years, there has been a decline in manufacturing employment opportunities for jobs requiring less education.[1] On the other hand, there is real potential for growth in certain job areas, particularly middle-level jobs, such as industrial engineers, that require complex problem-solving skills. These types of jobs grew 10% between 2012 and 2018.[2] Higher skilled

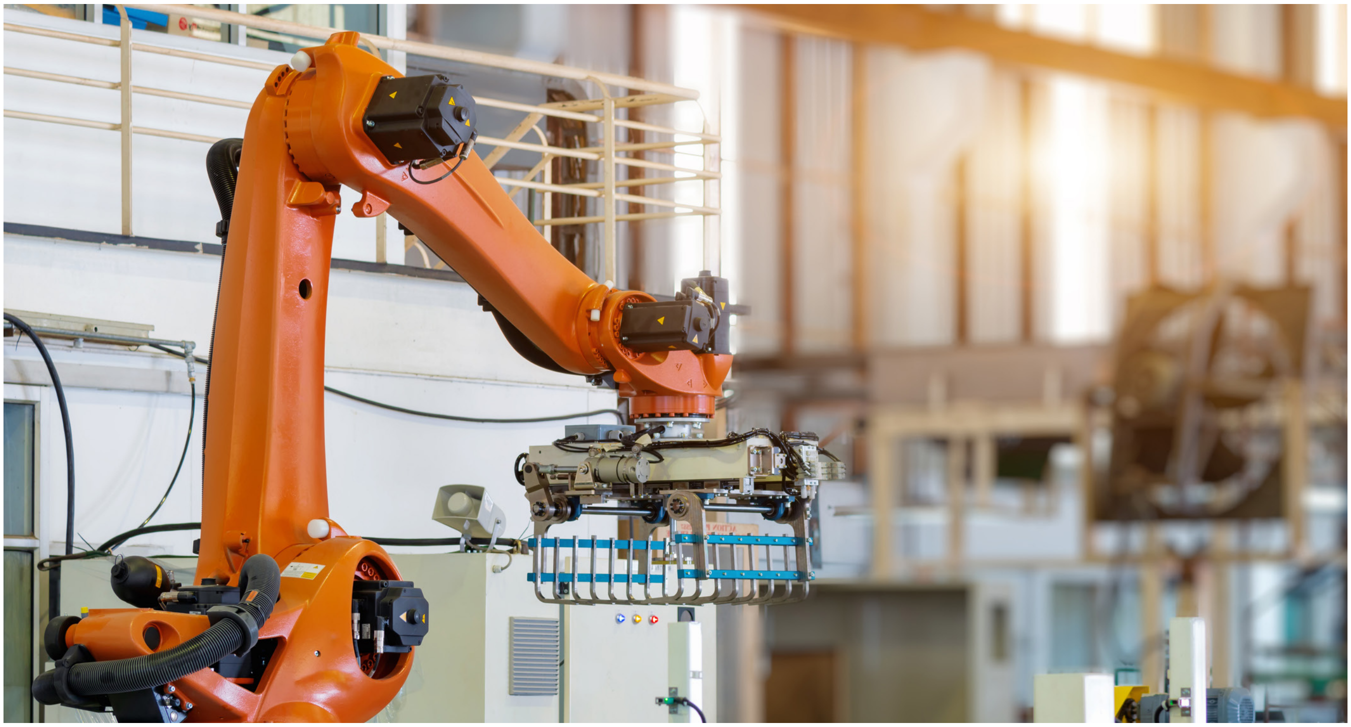
This brief examines the foundational mathematics needed to prepare individuals for success in entry-level and middle-skilled production and assembly jobs in the manufacturing industry. Mathematics is a core component of manufacturing, a field that covers a wide range of sectors including automotive and aeronautic, chemical, medical, food, computer and electronics, machinery, and more. This brief explores the limited industry guidance that identifies which mathematics competencies are required for entry-level and middle-skill manufacturing production jobs and how to prepare workers for upward mobility. Employers, credentialing organizations, apprenticeship programs, and education providers must identify the specific mathematics skills needed for entry and promotion—and remove arbitrary mathematics course and concept requirements that act as barriers—to attract a diverse and sufficient workforce.

[1] Statista Research Department, 2021.

[2] Hufford, 2019.

positions are expected to continue growing at the same rate until at least 2029,[3] as manufacturing firms seek new ways to improve efficiency, manage costs, and adapt to increasing automation.

As jobs in the manufacturing industry become more technologically advanced, employers are seeking workers who have more complex mathematics (and computational) skills. However, inevitable questions emerge: Is this shift being conveyed clearly to incoming and incumbent workers as well as how they might best prepare to meet these new demands? Are apprenticeship programs, industry certificates, and community colleges able to use industry guidance effectively to develop curriculum to prepare students and employees for entry-level positions and for the ongoing learning required for upward mobility within the industry? We examined the specific mathematics requirements in sample apprenticeship programs, industry certifications, and associate degrees to identify the mathematics content of these programs, the cross-program consistency, and if there was evidence of a vertical progression of mathematics standards. Admittedly, this analysis was not comprehensive but it attempted to capture the current landscape of industry standards and trends related to mathematics education.



Expanded Opportunities for Manufacturing Workers with In-Demand STEM Skills

Jobs in the manufacturing industry are historically known for providing above-average wages and good benefits, especially for skilled positions that often require on-the-job training or some postsecondary education, but not a Bachelor of Arts degree.[4] According to Data USA, the average salary for employees in the manufacturing industry is $64,861, comparable to the salary of employees in the real estate, public administration, and wholesale trade sectors. On average, men in this industry make 1.31 times more than female employees, and Asian and White employees earn 1.24 times more than employees from historically

[3] U.S. Bureau of Labor Statistics, 2021 (June 2).

[4] Stettner, Yudken, & McCormack, 2017.

marginalized populations.[5] Women, who make up 46.8% of the total employed population, constitute only 29.5% of the manufacturing industry. Black and Latino employees are more proportionally represented in the industry, with 10.3% of the workforce being Black and 17.3% Latino, compared with the national rates of 12.1% and 17.6%, respectively.[6]

For many reasons, including the fact that U.S. wages are growing at a slower rate than wages in other developed and emerging countries,[7] employers report difficulty in finding skilled employees; industry experts estimate that 2.1 million jobs will go unfilled by 2030. In particular, middle-skilled occupations, such as assemblers and fabricators, and frontline supervisors, are expected to be among the hardest to fill, with 113,200 and 56,900 projected job openings, respectively, between 2019 and 2029.[8, 9]

While some of the skilled labor shortage can be attributed to an aging workforce and the expected retirement of older workers, it is also clear that the changing industry landscape requires students and employees to have the appropriate training to prepare them for the increasing complex, data-integrated, and automated work environment. The shift to advanced manufacturing, where workers take responsibility for programming and operating computerized machinery, calls for individuals with a strong background in the STEM disciplines, particularly mathematics, computer science, and engineering.[10] Sixty percent of manufacturing executives indicate that current employees lack sufficient math skills (without, however, explicitly stating what those skills may be).[11] This brief examines the mathematics content in existing education and training programs, discusses whether current guidance from the industry identifies the mathematics skills needed in the current and emerging industry environment, and discusses the disconnect between current training and future needs.

Existing Guidance on Mathematics Needed in Manufacturing

While there is a general sense that mathematics is increasingly necessary in today's high-tech manufacturing jobs, it is not clear what that means specifically and which mathematics competencies are key to success. One employer survey conducted in 2012–13 found that 74% of manufacturing firms required basic math skills, defined as the ability to add, subtract, multiply, divide, and handle fractions, and 38% required extended math skills, defined as the ability to "perform any category among algebra, geometry, or trigonometry; probability or statistics; or calculus or other advanced mathematics."[12] The authors stated that, in general, "the level of math that is expected is within reach of a good high school or at most community college education."

It is unlikely, however, that the average U.S. high school student would be exposed to such a wide range of mathematical concepts. While math requirements vary by state and district, most high schoolers are likely to follow the prevailing mathematics pathway of Algebra I, Geometry, and Algebra II.[13] Only after completing these courses are students then able to access more advanced courses such as precalculus/calculus, statistics, or computer science, provided these advanced courses are even offered at their schools. As a result, very few students (especially students in low-income areas or from historically marginalized populations) take these

5 Data USA, n.d.

6 U.S. Bureau of Labor Statistics, 2021 (January 22).

7 Giffi, Dollar, & Gangula, 2015.

8 Wellener, Reyes, Ashton, & Moutray, 2021.

9 See Figure 3 in Deloitte and The Manufacturing Institute, 2021.

10 Roberson, 2017.

11 Giffi et al., 2015.

12 Osterman & Weaver, 2014.

13 Moussa, Barnett, Brathwaite, Fay, & Kopko, 2020.

more advanced math courses,[14] and even fewer are likely to complete both calculus and statistics before they graduate.[15] Trigonometry is not usually emphasized in the high school curriculum, although some concepts may be integrated into precalculus or geometry. Therefore, the claim that most high school graduates would have mastered this broad range of math skills is unsupported. Moreover, it is not unusual for community college students to simply repeat the same math courses they took in high school, so it is not clear that postsecondary enrollment in traditional math courses would ensure the necessary broader mathematics proficiency.[16]

This disconnect between the mathematics topics typically learned in high school or community college and the variety of math skill expectations for entry-level manufacturing jobs highlights the need for increased guidance from the manufacturing industry regarding the mathematical competencies necessary for the changing landscape. This disconnect also stresses the need for collaboration among training and education organizations to ensure that students and employees are provided with adequate instruction to promote access and the opportunity for advancement.

Since the release of Osterman and Weaver's report in 2014, the demand for skilled workers has increased, with mathematics being one of the key desired skills. Today's manufacturers often cite a wide range of desired mathematics skills that go beyond basic operations and include blueprint reading; basic programming and computer data analytics; geometry specifics such as knowledge of Cartesian coordinate systems; trigonometry and elementary calculus; and measurement and estimation, statistics, linear equations, and algebraic expressions.[17, 18, 19, 20]

[14] Sparks, 2018.

[15] U.S. Department of Education, National Center for Education Statistics, 2016.

[16] Ngo, 2019.

[17] CareerOneStop, U.S. Department of Labor, Employment and Training Administration, 2020.

[18] Jusko, 2012.

[19] Klaess, 2019.

[20] Roberson, 2017.

Typically, entry-level manufacturing production roles require only a high school diploma and perhaps some postsecondary education, with the expectation that workers can be trained on the job. Currently, workers with less than a four-year college degree represent about 60% of the manufacturing workforce.[21] However, in the past 20 years, there has been an increase in the percentage of the manufacturing workforce that holds a college degree or higher, from less than 30% in 2000 to more than 40% in 2020. There has been a corresponding decrease in the percentage of workers with a high school diploma or less.[22]

Perhaps due to this history of not requiring formal degrees, there is a lack of clarity from manufacturing professional organizations about the core academic content knowledge, including mathematics, needed in the various roles or to facilitate employees' advancement. The industry has focused more on defining technical skills and competencies as evidenced by the skills standards and training programs developed by several of the national professional organizations, including the Manufacturing Skills Standards Council (MSSC),[23] the Manufacturing Skills Institute (MSI),[24] and the Manufacturers' Association.[25] These organizations, and others, have developed a number of industry certifications and apprenticeship programs to help manufacturing production workers develop skills needed to meet the changing industry requirements. Community colleges and universities also offer a wide assortment of certificates, associate degrees, and bachelor degrees in the field of manufacturing and industrial engineering.

21 Stettner et al., 2017.

22 Hufford, 2019.

23 https://www.msscusa.org/about-mssc/

24 http://manufacturingskillsinstitute.org/

25 https://mascpa.org/apprenticeships/

Mathematics in Apprenticeships

Approximately 2,000 registered apprenticeship programs in manufacturing are governed by standards approved by the U.S. Department of Labor's Office of Apprenticeship and State Apprenticeship Agencies.[26] Apprenticeship provides a structured learning opportunity, combining paid on-the-job training with related classroom instruction provided at community colleges, technical schools, online, or at the job site. The classroom instruction component, which includes core mathematics, is intended to complement on-the-job learning, and the curriculum is determined by the employer sponsor. Consequently, the content, skills, and amount of mathematics included, and the instructional time, vary widely depending on the apprenticeship track and the individual employer sponsor.

One example is the Industrial Manufacturing Technician (IMT) apprenticeship, a program that prepares production workers through an 18-month or 3,000-hour experience. For the IMT program, the guidance from the MSSC states that related instruction should include an Industrial Math course that provides applied mathematics instruction from a review of basic arithmetic; basic algebra; applications based on geometry; and right triangle trigonometry, oblique angle trigonometry, and compound angles.[27] A different registered apprenticeship program approved by the federal government, the Mechatronic Technician apprenticeship, specifies 45 hours of blueprint and schematic reading and 45 hours of applied algebra, geometry, and plane trigonometry.[28]

Research shows that, in some areas, employees who complete an apprenticeship program have access to higher wage jobs upon completion of the program compared with employees who do not participate in the program.[29] Larger firms tend to offer more apprenticeships than smaller firms, and while these opportunities are considered an effective training strategy, they are not currently widely available across the industry,[30] possibly contributing to the employment inequities mentioned earlier in this brief.

Mathematics in Industry Certifications

Industry certifications can be earned by demonstrating competence in specific job-related skills and may include some foundational academic content, including mathematics. The Certified Production Technician 4.0 (CPT 4.0) program developed by MSSC, for example, consists of five stackable credentials, one of which is "quality practices and measurement." MSSC strongly recommends that individuals seeking the certification have a 9th grade mathematics level so they can engage in mathematics applications including geometric dimensioning and tolerancing, basic measurement, and use of precision measurement tools.[31] Such a requirement, however, seems irrelevant, considering that an individual's mathematics proficiency will vary widely depending on the math courses offered or required by 9th grade in a particular school district and state. One might assume "9th grade" implies completion of Algebra I, but this ill-defined curriculum standard again highlights the possible disenfranchisement of students in low-income areas or from historically marginalized populations.

Another example is the Manufacturing Technician Level 1 certification offered by MSI. This credential awards completion of three core competency areas, one of which is "math and measurement," ensuring that workers can operate precision machinery, troubleshoot as needed, and use diagnostic and statistical tools. Mathematics competencies focus on measurement, some algebra skills, and "math for quality."[32]

26 U.S. Department of Labor, n.d.

27 U.S. Department of Labor Employment and Training Administration Office of Apprenticeship, 2014.

28 AFL-CIO Working for America Institute, ApprenticeshipUSA, 2017.

29 Akala, 2020.

30 Workcred, 2018.

31 https://www.msscusa.org/certification/production-certification-cpt/

32 Manufacturing Skills Institute, 2021.

List of Mathematics Skills from the Manufacturing Technician Level 1 Certification

Section 1: Mathematics and Measurement

Measurement (33%)

Demonstrate:

1. Use a decimal inch machinist's rule to measure a length.
2. Use a U.S. ruler and tape measure to measure a length.
3. Use a metric ruler.
4. Measure liquids and weights in Metric and U.S. customary units.
5. Convert between common fraction inches and decimal inches.
6. Convert between U.S. customary units and SI metric units.

Math for Manufacturing (66%)

Algebra (33%)

1. Perform correct order of operation to simplify mathematical expressions.
2. Generate linear equations with one unknown for situations described in text.
3. Solve simple linear equations with one unknown.

Math for Quality (33%)

1. Read and interpret histograms, bar charts, line graphs, and scatter plots.
2. Interpret descriptive statistics: mean, median, mode, and range.
3. Demonstrate qualitative reasoning for situations involving statistical data and probabilities.

Section 2: Spatial Reasoning & Manufacturing Technology

Spatial Reasoning (21%)

1. Visually translate from 2D drawings to 3D images and back.
    a. Identify different views for given isometric drawing of an object.
    b. Identify the different elements of an object in various views.
2. Predict behavior of visual representations of simple mechanisms.

A key benefit to industry credentials is that they are more easily obtained and less expensive than a degree; they also give workers a portable, well-recognized means of demonstrating their skills.[33] In addition, community colleges and universities may choose to recognize these certifications and award advanced standing credit in related degree programs for individuals who want to further their studies.

Mathematics in Community College Associate Degrees

Workers with some college credits and those with associate degrees have access to a broader range of job opportunities than those with a high school education. Additionally, having an associate degree in any of

[33] Carnevale, Ridley, Cheah, Strohl, & Campbell, 2019.

the engineering technologies, including Industrial Production Technologies and Manufacturing Technician, results in higher pay than having associate degrees in other fields.[34]

Two-year associate degrees tend to require at least one, if not more, foundational mathematics course. For example, at Ivy Tech Community College in Indiana, the Manufacturing Production and Operations AAS program requires an Applied Technical Mathematics general education course[35] and a Shop Mathematics course, which is described in the catalog as "[a] review of basic operations of numbers, fractions, and decimals. Covers the practical mathematics that every machinist is expected to use in the shop and in the creation and maintenance of tools, fixtures, and industrial devices. Applies math to special calculations such as taper angles, gearing ratios, gearing systems, and cutting speeds and feeds."[36]

At Ferris State University in Michigan, the Manufacturing Technology AAS degree program[37] requires three general education mathematics courses:[38]

> Intermediate Algebra: A study of complex fractions, first and second degree equations and inequalities, exponents, radicals, and introduction to complex numbers, logarithms, and systems of equations.
>
> Trigonometry: An elementary course in plane trigonometry. Includes the trigonometric functions, their properties, solution of right and oblique triangles, radian measure, graphs, identities, trigonometry equations, vectors, and applications. Related topics in Geometry included.
>
> Advanced Algebra and Analytical Trigonometry: Quadratic equations, inequalities, straight lines, graphing equations, functions and inverse functions, exponential and logarithmic functions, trigonometry from an analytical point of view, sequences, mathematical induction, and the binomial theorem.

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34 Carnevale, Garcia, Ridley, & Quinn, 2020.

35 Ivy Tech Community College, n.d. MATH 122, Applied technical mathematics. https://docs.google.com/document/d/1_f9od0Uwfx3wZQsDwETX5jGQU-7VggM46tiCR6Fsh-s4/edit

36 Ivy Tech Community College, n.d. MPRO 101, Shop mathematics. https://docs.google.com/document/d/13_fisDefCon3dTprSgE2G41xTYCWIncLsqltH-jHDjtU/edit

37 Ferris State University, 2020.

38 https://www.ferris.edu/catalog/current/courses/math.htm

Ray Prendergast's textbook *Math for Manufacturing*,[39] which is intended for community college manufacturing students, includes the following table of contents:

UNIT 1: DECIMALS
UNIT 2: FRACTIONS
UNIT 3: TOLERANCES
UNIT 4: PERCENT
UNIT 5: ANGLES AND TRIANGLES
UNIT 6: SHOP PROBLEMS
UNIT 7: BEYOND ARITHMETIC
UNIT 8: TRIANGLES AND THE PYTHAGOREAN THEOREM
UNIT 9: SINES, COSINES, TANGENTS
UNIT 10: STATISTICAL PROCESS CONTROL

These concepts are traditionally covered across multiple courses including Elementary Algebra, Intermediate Algebra, Geometry, Trigonometry, and Elementary Statistics.

The examples above from apprenticeships, industry certifications, and associate degree programs and texts show how, in these loosely layered education and training options, the required mathematics is described at a general level, with no explicit vertical progression of mathematics standards. It appears that the manufacturing industry has focused more on defining how technical job skills can be developed and assessed through stackable and connected learning experiences, rather than paying more attention to the development of academic foundational skills, including mathematics.

A Need for Clarity in Manufacturing Education and Training

In order for manufacturers to achieve their growth targets and remain competitive, they need to attract and retain a diverse population of employees with the necessary skills to advance within the profession and to drive productivity gains. One of the key skills required to adapt to the manufacturing jobs of tomorrow is mathematics, but not necessarily the mathematics needed for manufacturing in the past. There is little specific guidance or consistency on the foundational mathematics skills needed and on how students and employees should continue to deepen their mathematical knowledge to access higher skilled positions.

Perhaps in recognition of this challenge, there have been some recent calls for a defined curriculum and clearer pathways to ensure that workers can continually upskill and access the advanced manufacturing jobs. For instance, a 2012 report from the Society of Manufacturing Engineers found that innovative educational approaches will be critical in rebuilding the pipeline of manufacturing professionals and recommended that educators, industry, professional organizations, and government agencies work to develop manufacturing curricula that ensure consistency and quality.[40] Although not a mathematics-focused report, RAND's 2020 analysis of education and training programs in advanced manufacturing concluded that the industry should

[39] Prendergast, 2018.

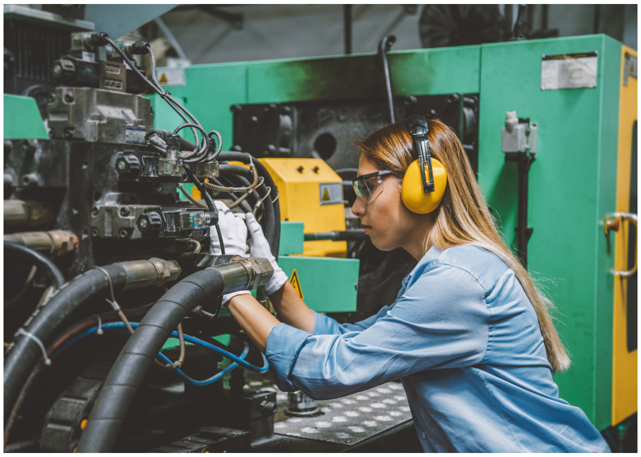
[40] Society of Manufacturing Engineers, 2012.

undertake a highly detailed assessment of workforce development needs—presumably both technical and academic—which could then be used to inform curriculum development.[41]

A well-defined core curriculum that specifies the mathematics competencies required for specific manufacturing roles and advancement, and how the content should be taught and assessed in ways that are aligned with job expectations, would support other recent industry efforts to attract a new generation of workers. This curriculum could also promote manufacturing careers by providing learning opportunities in K–12 through career and technical education and STEM initiatives that then lead to stackable credentials and degree programs. Manufacturing, like many industries being transformed by automation and digitalization, will need to engage a more diverse population of future workers by building awareness of promising career opportunities in the field and by offering clear and equitable education and training pathways and on-the-job supports.

Conclusion and Suggestions for Moving Forward

This brief raises questions about the lack of industry guidance on the mathematics concepts that students and workers need to succeed in entry-level and middle-level manufacturing production jobs and to advance within the field. Manufacturers report skills gap challenges and suggest that specific math skills will be increasingly critical as manufacturing operations become more automated. Yet without a well-defined foundational curriculum, firms are left on their own to devise in-house training and/or form relationships with education and training providers that may vary widely in the delivery, breadth, and depth of core content.[42]



The current lack of consensus and clarity among employers, education and training providers, and credentialing organizations allows mathematics skill requirements and expectations to act as a barrier to equitable employment and advancement. It may also be preventing the next generation of students from finding their way into these living-wage jobs and careers.

We suggest convening a taskforce with representatives from the manufacturing industry; mathematics, computer science, and statistics education; manufacturing/engineering education; and the credentialing organizations to address this important challenge. The taskforce could delve more deeply into the mathematics required for manufacturing and the specific key concepts and applications derived from the various branches of arithmetic, algebra, geometry, trigonometry, statistics, and calculus, as well as basic programming and data analytics, needed to be successful. Having the relevant partners work together on the specifics of a core mathematics curriculum that could serve as a foundation for manufacturing education and training would greatly help the field as it looks to prepare for tomorrow's economy.

[41] Andrew, Marler, Lastunen, Acheson-Field, & Popper, 2020.

[42] Jusko, 2013.

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We focus in particular on strategies for improving student engagement, motivation, persistence, and achievement.

The Center was founded in 1991 at The University of Texas at Austin. Our staff members have expertise in leadership, literacy, research, program evaluation, mathematics and science education, policy and systemic reform, and services to high-need populations.

For more information about the Dana Center Mathematics Pathways (DCMP), see www.dcmathpathways.org.