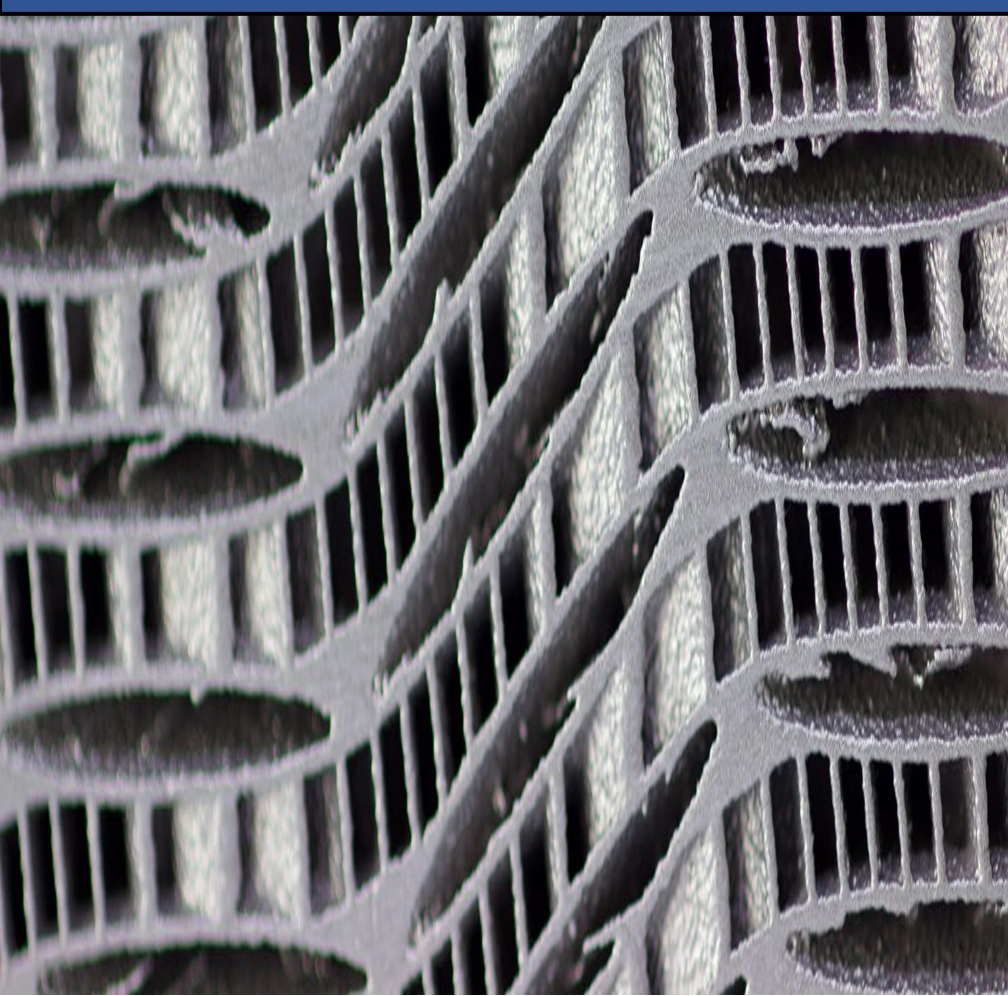
Preparing the Advanced Manufacturing Workforce: A Study of Occupation and Skills Demand in the 3D/Additive Manufacturing Industry



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Cover image: Cross-section of 3D printed heat exchanger. Photo taken by Haden Quinlan, MIT Department of Mechanical Engineering.

Acknowledgement

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Note: This report is a part of a Workforce Roadmap series that characterize technical workforce needs for advanced manufacturing areas focused on highly specialized training for jobs aligned with specific U.S. Manufacturing Institutes including integrated photonics, robotics, flexible electronics, functional fabrics, and 3D/additive manufacturing.

Executive Summary

Semi-structured interviews with operations managers in the 3D printing and additive manufacturing (3DP/AM) industry from thirty firms across the U.S. were conducted to identify workforce needs within the 3DP/AM supply chain. The interviews were focused on middle-skilled technical occupations (except for information technology occupations). Skills gaps, hiring and training challenges, and the importance of emerging technical and human skills were evaluated by firms. While there are hiring and training challenges in many of the advanced manufacturing industries, 3DP/AM firms especially face the challenge of building up talent within the industry since 3D printing and additive is currently learned informally. Firms emphasized that updates to existing curriculum could help reduce the amount of trial and error in training their employees.

Training for technical workers in the 3DP/AM industry should increase emphasis on the following skills:

- Test and evaluate for quality
- Interact with computers
- Make decisions and troubleshoot problems
- Prepare specimens, tools, or equipment
- Communicating and collaborating with engineering and management staff

There is increasing demand expected for all middle-skilled technical workers studied with significant demand expected for additive technicians and CNC tool operators. For firms where mechatronics technicians are relevant, these firms also expect this position to grow significantly.

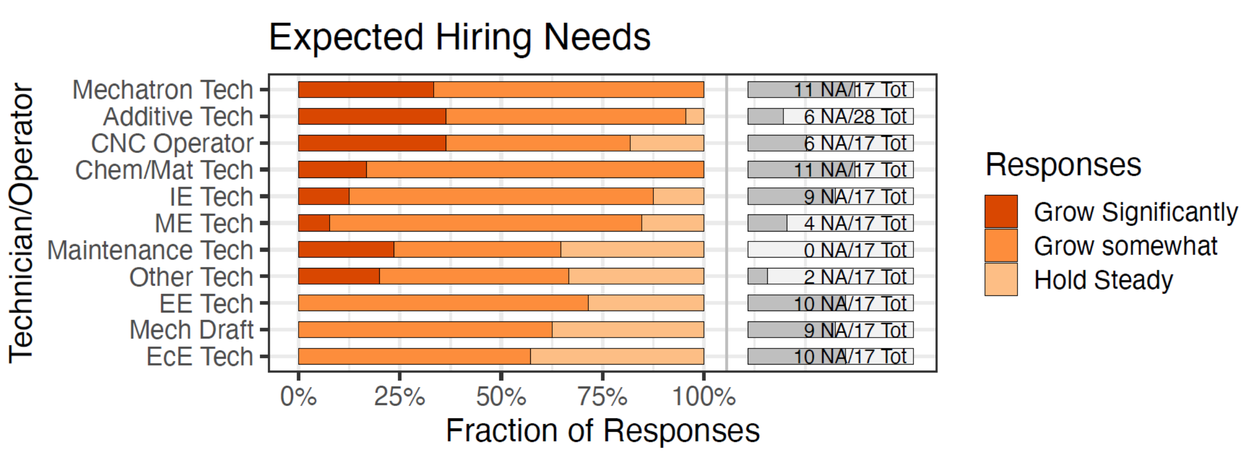

Figure ES 1Survey results on future change in demand for the technical occupations evaluated in this study. Fraction of 'Not Applicable' responses at the right of the bar.

To understand the growth trends in the 3DP/AM industry, the expected number of positions and openings within the industry was estimated. Data from the US Bureau of Labor Statistics, market intelligence reports, and survey responses were used to project both anticipated positions and openings. We estimate middle-skilled positions within this industry to grow from around 3,100 today to 19,400 by the end of the decade (see *Figure ES 2*). This translates to over 27,300 cumulative openings for middle skilled technical workers or around 2,400 new middle-skilled workers per year. Assuming a typical training program graduates about 15 students per year, the US would need more than 160 programs to meet the needs of the 3DP/AM industry. In a Massachusetts context, we estimate around

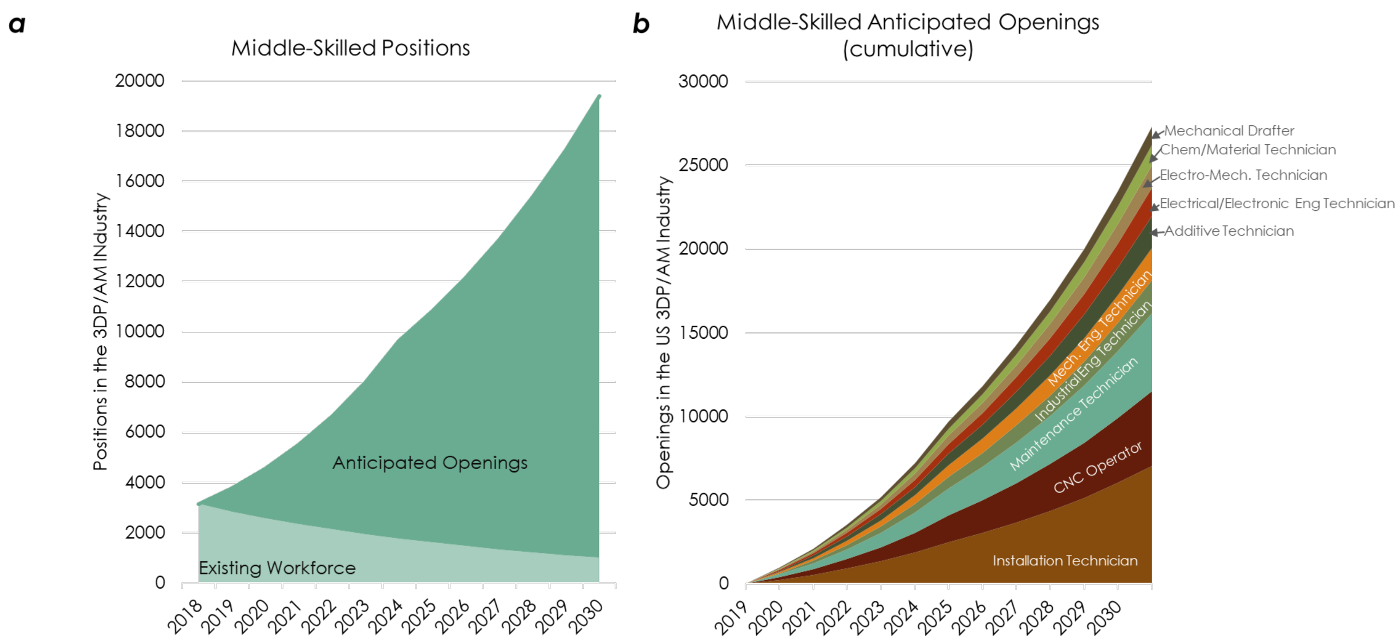

Figure ES 2. Survey results, data from the US Bureau of Labor Statistics, and market intelligence reports were used to project existing positions and expected openings for middle-skilled technical workers. (a) Shows an overview of trends. (b) Provides details by position.

540 total openings in these positions for this sector. This translates to about 48 middle-skilled openings per year, indicating the need for three educational program to train middle-skilled technical workers for the state's 3DP/AM industry.

Firms emphasized the significant hiring challenges in this industry for nearly all technical middle-skilled workers, especially for additive technicians and CNC tool operators. In terms of training, most firms explained that all middle-skilled workers require at least some training, with additive technicians, maintenance and support technicians, and CNC tool operators requiring extensive on-the-job training. Specifically, firms shared that improving training on safety for all the positions would be invaluable for the industry.

Emerging and human skill importance was evaluated for each position including a critical thinking needs assessment. An emerging technical skill that was emphasized across most of the positions was working with digital collaboration tools. Human skills are also growing in importance for technicians in advanced manufacturing industries. In particular, interview responses indicate that the following skills should be emphasized in training:

- Communicating and collaborating with engineering and management staff
- Taking initiative to learn new skills or technologies
- Independently organizing time or prioritizing skills
- Managing unfamiliar problems and situations

Many firms underscored the importance of critical thinking for all technician positions and believe it is necessary for engineering technicians. They believe engineering technicians should be able to use a systems perspective to understand failures or challenges by using a triage process. Technicians that are able to contribute to detection of errors/failures and can communicate these issues are extremely valuable for firms. Technicians can be part of the solution and therefore firms suggest more practical and hands-on training exercises to prepare them for the manufacturing floor.

Results indicate that 40% of firms expect engineering technicians to have competency in nearly all aspects of critical thinking (perceiving, hypothesizing, testing, and interpreting testing). Most other technical production workers are expected to perform hypothesis testing (50%) while 25% of the respondents expected these workers to be able to master all aspects of critical thinking.

We highlight the specific technical skills that are both increasingly important and exhibit skills gaps for six occupations: additive technicians, mechanical engineering technicians, industrial engineering technicians, mechatronics technicians, mechanical drafters and CNC tool operators.

Because the interviews focused on skills described in the Bureau of Labor Statistics O*Net dataset, it was possible to not only identify job-specific skills but also to use the taxonomy within that dataset to aggregate survey responses to more generalized classes of skills (referred to as General Task/Skill, GTS). *Figure ES 3* shows the result of that aggregation across all survey responses.

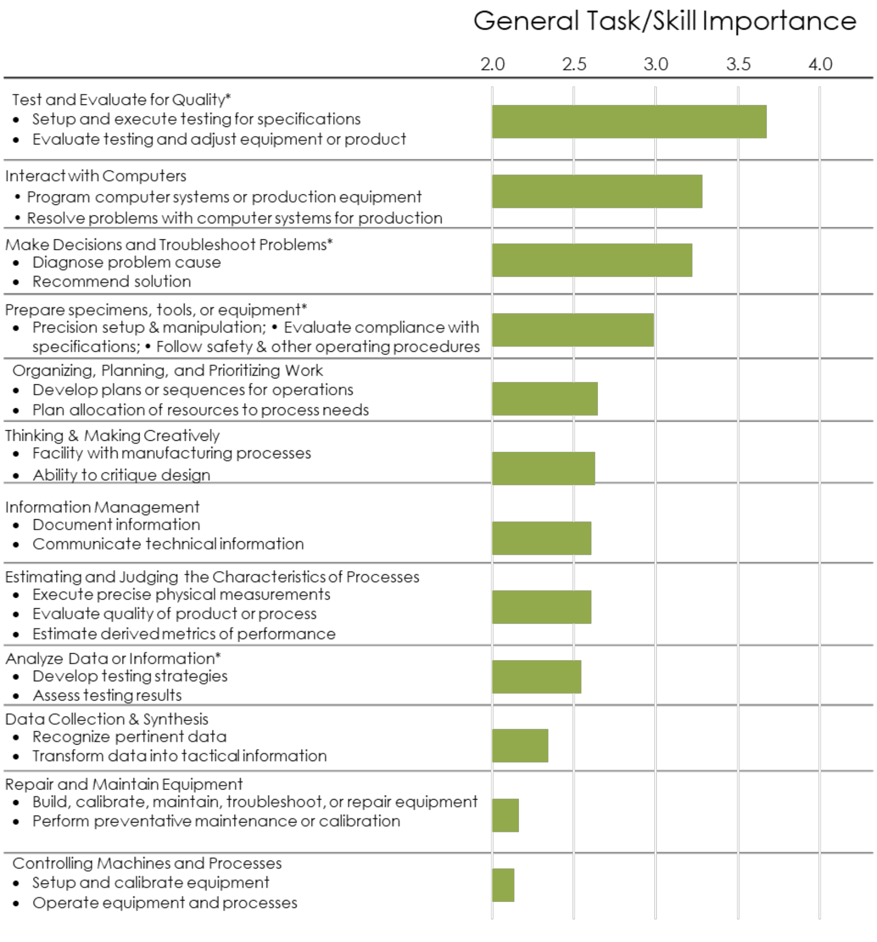

Figure ES 3 General Task/Skill (GTS) are classes that include many related specific skills. Here relevant GTS are ranked by weighted average importance of the specific skills within that class. Only GTS that are shared across at least two occupations are labeled as common and, therefore, included in this figure. Asterisks indicate skills that also have a critical gap and are of significant importance.

Looking across all middle-skilled positions, the top five generalized skills that are expected to be the most important for middle-skilled workers in the 3DP/AM industry are:

- Test and Evaluate for Quality*
- Interact with Computers
- Make Decisions and Troubleshoot Problems*
- Prepare Specimens, Tools, or Equipment*
- Organizing, Planning, and Prioritizing Work

To get a better understanding of where training resources would be best applied, we also examined whether important skills also exhibited a significant skills gap (difference between competency of new hires and that required by industry). As shown in Figure ES 4, three of the most important GTS categories of skills were also frequently flagged as exhibiting a significant skills gap.

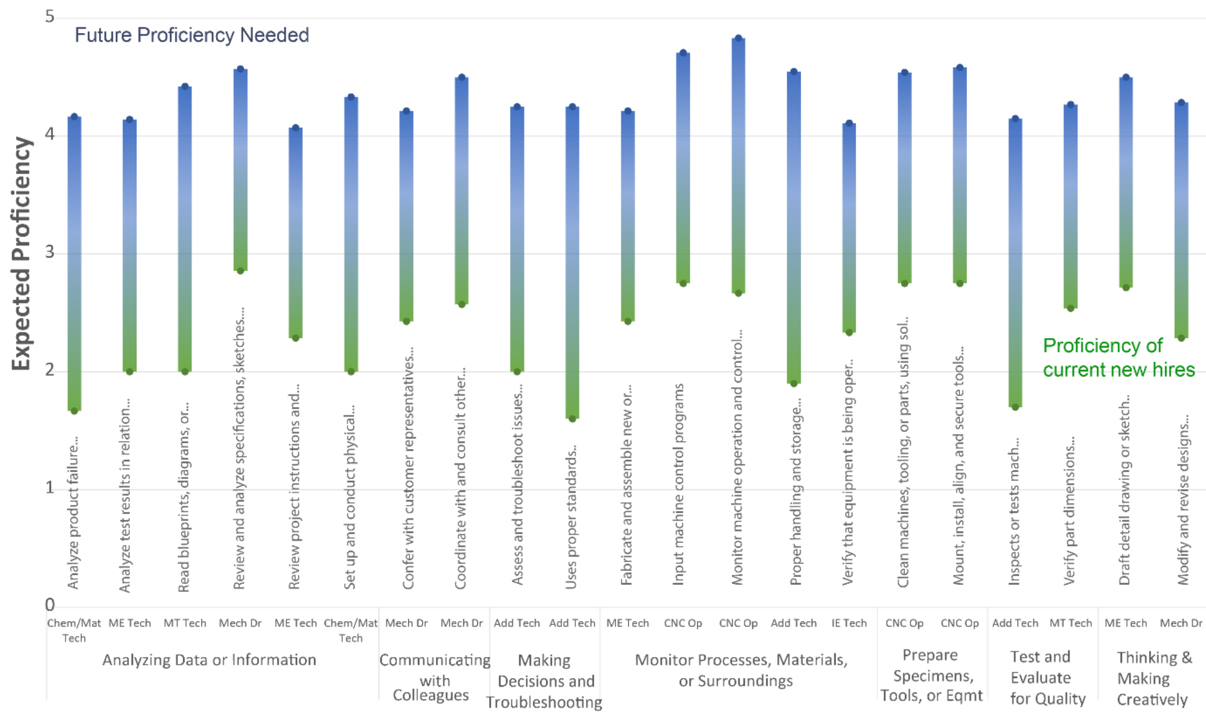

Figure ES 4 High priority skills across all positions studied in the 3DP/AM industry. The green dot represents the proficiency of current new hires and the blue dot represents the future proficiency needed for the middle-skilled level.

An emphasis in training these skills that exhibit significant training gaps, importance, and are common among multiple positions would add value to the 3DP/AM workforce. The top three ranked common skills include test and evaluate for quality, interact with computers, and make decisions and troubleshoot problems. These skills involve understanding of the entire system from tools to each piece of equipment. The remaining skills emphasize critical thinking, troubleshooting, quality testing, and communication and interpretation of technical information. Technicians in the 3DP/AM industry should also improve knowledge of quality and communication with colleagues.

For middle-skilled workers in the 3DP/AM industry, the analysis of generalized skills points to the growing importance of the abilities to ensure quality standards, troubleshoot equipment, analyze data, and communicate with supervisors, peers, and subordinates.

The results from this study demonstrate the growing opportunity for technical careers in the 3DP/AM industry across the U.S. and areas of improvement for the training and skills development for those pursuing 3DP/AM careers.

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Introduction to the Workforce Roadmapping Report Series

Manufacturing – particularly advanced manufacturing[1] – is widely recognized as important for the United States for economic, strategic, and, more recently, public health benefits. Realizing those benefits will require both critical investments and intelligent policies. One challenge facing advanced manufacturing in the US that is less widely discussed is a mismatch between the supply of qualified employees and the needs of industrial employers.

In fact, 83% of manufacturers in the United States report a shortage of qualified employees (Huang et al. 2015). A recent study by Deloitte and the Manufacturing Institute estimates that this shortage may lead to as many as 2 million manufacturing jobs going unfilled over the next decade(Giffi et al. 2018). This structural unemployment has been attributed to both evolving manufacturing technology and to a declining interest in manufacturing jobs.

Furthermore, the emergence of new technologies can initiate new structures for knowledge coordination across formerly well-defined occupational boundaries. Technological changes can impact how worker tasks and therefore skills needs evolve and influence labor- demand effects and training as shown with automation and parts consolidation (Combemale et al. 2019). For example, the introduction of CT scanners changed the balance of knowledge between radiologists and technicians. Radiologists, less familiar with complex CT topics than they were to the simpler X-ray technology, evolved to a more collaborative approach to working with technicians (Barley 1986). Similarly, Frank Gehry's complex designs strained the modular boundary between architect and builder, with the separate roles collaborating much more closely in the design and building processes (Yoo, Boland, and Lyytinen 2006). These relationships can modularize again as technologies and knowledge become more mature, only to re-integrate as new technology or market concepts arise (Christensen, Verlinden, and Westerman 2002).

In a recent study, Combemale et al. (2021) find that new technologies are likely to lead to such workforce changes explicitly within the integrated photonics industry. Specifically, they find that changes in technologies for advanced manufacturing industries impact the distribution of demand for worker skills. Their study captures the labor-demand effects of technological changes in the automation of production processes and consolidation of parts using shop-floor data from various semiconductor firms. The O*NET database was used to identify skills and abilities[2] for each optoelectronic

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[1] Advanced manufacturing includes both the application of new manufacturing processes and the production of innovative new products using either traditional or new processes.

[2] This study complements the work of Combemale et al. (2021) by focusing on O*NET work activities, detailed descriptions of worker tasks, rather than O*NET skills and abilities

occupation for each process step. Results indicate that automation of production processes would reduce the need for middle-skilled operators while conversely product integration would increase demand for middle-skilled workers. While these technical changes are not expected to reduce the number of jobs, they would be expected to change the portfolio of skills that are most valued. Furthermore, there is no reason that such trends would not carry over to other industries as the automate and develop more functionally integrated products.

In light of these needs and trends, this report aims to better characterize the evolving technical workforce needs within a specific advanced manufacturing sector – the 3D/additive manufacturing industry in the New England Region. We give particular focus to middle-skilled occupations[3] but also examine selected lower-skilled occupations that are uniquely important to this industry.

As part of this characterization, we attempt to

- estimate the demand for middle workers by occupation type
- identify what occupations represent the most serious hiring and training challenges
- identify what skills are most important for a given occupation

An understanding of the skills required in the current workforce can aid in informing education and training programs to prepare future advanced manufacturing workers.

To explore these questions, we develop and apply a new research method because traditional sources of information about labor needs are not well suited to answer questions within advanced manufacturing. The most widely consulted source of data on the US labor market is the Occupational Information Network (O*NET) database maintained by the Bureau of Labor Statistics (BLS)(U.S. Department of Labor 2020). That database contains information about workforce needs broken down into around 1000 occupation types across more than 100 industrial sectors. Although this serves as an invaluable source of information for workforce questions, there are at least two challenges to applying it to examine needs within advanced manufacturing. First, despite the scope and detail of the O*NET database, it is difficult to isolate the needs of emerging industries within that data. It will always be the case that advanced manufacturing sectors such as photonics, robotics, and additive manufacturing will operate at the interfaces of traditional sectors and as such will not be simply mapped using conventional industrial classification systems. Secondly, there will always be

[3] Here we define middle-skilled workers as those with training beyond a high-school diploma, but short of a bachelor's degree. The terms middle-skilled worker and middle worker will be used synonymously. Middle-skilled occupations are those filled predominantly by middle-skilled workers. More formal definitions are provided in the methods section.

concern that government databases are not updated frequently enough to capture the trends within rapidly evolving industries.

Defining the 3D/Additive Manufacturing Industry

Additive manufacturing (AM) or 3D printing (3DP) technologies are transforming the manufacturing world enabling advanced capabilities including rapid prototyping, complex designs and geometries, mass customization, waste minimization, and multi-material manufacturing (Wang et al. 2020; Ngo et al. 2018). Both 3DP and AM are manufacturing processes that "create an object by sequentially adding build material in successive cross-sections, one stacked upon another" (General Electric 2022). While these process terms are often used interchangeably, there are differences that are important to note. For instance, 3DP is used for smaller production of unique objects while AM is used to manufacture objects on a mass scale and is considered a cost-saving alternative by manufacturers (General Electric 2022).

Both the materials and process parameter choices are an important part of the processing in 3DP/AM manufacturing. These decisions influence the qualities of the final part (e.g., strength, ductility, surface finish, etc.) (Additive Manufacturing 2022). The materials that are currently used in 3DP/AM are polymers, metals, composites, ceramics, and sand. Examples of industries that leverage this type of manufacturing include aerospace, automotive, medical and pharmaceutical, and many others. To understand the material and process parameter tradeoffs, a skilled workforce is needed. America Makes emphasizes the importance of building a network of stakeholders to create a workforce capable of meeting the needs of the industry(America Makes 2022). Since many 3DP/AM firms find candidates are often overqualified for technician roles (e.g., PhD graduates), training especially at the technician level can help improve the 3DP/AM workforce.

Methods

Workforce needs and gaps have been identified for the 3DP/AM industry through interviews of firms within the 3DP/AM manufacturing supply chain. Four steps were used to develop and structure the interview including: 1) discern the firms that make up the industry of interest; 2) posit occupations most relevant to those firms and skills most relevant to those occupations; 3) develop and deploy a semi-structured interview to characterize the relative importance of those occupations and skills; and 4) analyze the results to identify workforce and skills gaps (see Figure 1). More details of the research method are provided in the appendix to this report.

Discern emerging advanced manufacturing industries

The global 3DP/AM industry is expected to reach $56.1 billion by 2026(Williams 2021) . The D&B Hoovers Proprietary SIC 8-digit Code (SIC8) classification system (Cramer 2017), an expansion of the original SIC system, was used to discern the firms that comprise the 3DP/AM industry. These firms were mapped to industrial classification codes used by the Bureau of Labor Statistics (these are modifications of three to four-digit NAICS codes) to characterize workforce levels and economic activity by sector within the US economy. The specific codes and sectors that were used to represent the 3DP/AM industry are listed in Table 15 and Table 16 in the Appendix. The detailed process used to classify firms is described in the Appendix section, Detailed Methods.

Posit Relevant Occupations and Skills

Identify Relevant Occupations

To leverage the extensive surveying knowledge embedded within the US Department of Labor O*NET database(U.S. Department of Labor 2020), we use the BLS equivalent NAICS codes to identify a relevant set of occupations for our industry of interest. Specifically, occupation codes were identified using a combination of the 2018 National Employment Matrix (NEM) (U.S. Bureau of Labor Statistics 2018) and the O*NET database.

Middle-skilled workers are often defined as those with an education level beyond a high school diploma and less than a Bachelor's degree (Fuller and Raman 2017). Occupations are always held by workers with a range of education. For this research, we define middle-skilled occupations to be those for which both greater than 30% of the workforce is middle-skilled and less than 50% of the workforce is either lower-skilled or upper-skilled.

Based on these definitions, we identified 19 relevant middle-skilled positions associated with the 3DP/AM industry. To facilitate survey data collection, these were grouped into ten representative positions, as shown in bold in Table 1. This set includes six types of engineering technicians – additive, electrical / electronic, electro-mechanical, industrial, mechanical, and chemical– as well as technical maintenance personnel (e.g., mechanics, electricians), computer-numerical-controlled machine operators, and machinists.

Figure 1. Key steps in the research method applied in this study.

Table 1. Focal occupations that were evaluated in this study. Bold titles represent representative occupations that were served as proxy for the subsequent specific occupations.

Occupation	Standard Occupation Classification Code
Middle-skilled	
Additive technician*	
Electrical and electronics engineering technicians(representing)	
Electrical and electronics engineering technicians	17-3023
Electrical and electronics drafters	17-3012
Electro-mechanical technicians	17-3024
Industrial engineering technicians(representing)	
Industrial engineering technicians	17-3026
Aerospace engineering and operations technicians	17-3021
Mechanical engineering technicians	
Mechanical engineering technicians	17-3027
Mechanical drafters	17-3013
Chemical/materials technicians (representing)	
Chemical technician	19-4031
Materials scientist	19-2032
Maintenance and Support Technicians (representing)	
Industrial machinery mechanics	49-9041
Maintenance workers, machinery	49-9043
HVAC mechanics and installers	49-9021
Mobile heavy equipment mechanics, except engines	49-3042
Electrical & electronics repairers, commercial & ind. equipment	49-2094
Computer-controlled machine tool operators(representing)	
Computer-controlled machine tool operators	51-4011
Computer numerically controlled machine tool programmers	51-4012
Other Technical Production Worker (representing)	
Machinists	51-4041
Tool and die makers	51-4111

*The O*NET database does not currently include the additive technician position. Therefore, the position was modeled after the Urban Institute framework for an Additive Manufacturing Maintenance Technician(Urban Institute 2019).

Identify Relevant Skills

For each identified occupation, an associated set of competencies (skills) and tools was developed from two sources of job characterization information: the U.S. Department of Labor O*Net database (U.S. Department of Labor 2020) and a real-time labor market intelligence analytics database, Burning Glass Labor Insight™ (Burning Glass Technologies 2021). The O*Net database uses a hierarchical taxonomic approach to organize tasks and skills. (Peterson et al. 2001). The database was originally developed through survey methods to create a relational database of occupation attributes for the U.S. economy (Peterson et al. 2001)and helps create a common language for job descriptors. For each occupation, the database includes tasks in the job, tools employed in the job, and technologies employed on the job.

Using all of this information, the research team selected six to ten technical skills for each occupation based on the O*NET task descriptions to characterize their importance and any existing skills gap for these skills within the 3DP/AM industry. The specific skills explored are listed in the results plots and tables in the results section of the report.

Emerging Technical Skills

While the O*NET database provides valuable insight into the current technical skills needed for these occupations, the research team also wanted to get a sense of what skills are emerging as important within the 3DP/AM industry.

To accomplish this, we made use of two methods to identify potentially relevant emerging skills. The first method relied on discussions of the changing nature of work within the academic literature. Specifically, based on information within MIT Production in the Innovation Economy (PIE) survey (Weaver and Osterman 2017), the essential skills framework used by the Canadian government (Government of Canada 2015), and the Future of Work report (Autor, Mindell, and Reynolds 2020). Based on the authors' synthesis of these reports, we identified the following skills as potentially relevant and emerging for technical middle-skilled workers in manufacturing:

- Programming and troubleshooting automated process equipment (CNC, programmable production equipment, etc.)
- Conducting and assessing the results of statistical process control analyses or design of experiments
- Optimizing production flow based on the use of qualitative observations and quantitative analytics
- Using lean manufacturing principles (value stream mapping, minimize waste)
- Decreasing inventory and stockouts by understanding your own operations and your suppliers
- Working with digital collaboration tools (Computerized maintenance management software, connected worker platforms, workflow management, etc.)

The second method was to make use of a real-time labor market intelligence analytics database to identify emerging skills for each occupation. Burning Glass Labor Insight™ (BGLI) collects job posting data from job boards, firm websites, and job ad websites that represent more than 40,000 online resources and 3.4 million jobs (Burning Glass

Technologies 2021). Duplicate postings are removed and natural language processing methods extract the in-demand occupations, skills, and credentials. Two approaches were used to identify relevant skills list from the BGLI database. It is important to note that while we did not specifically include tools and technologies in our interviews due to limited time; however, knowledge of in-demand tools and technologies can help inform trends in the 3DP/AM industry.

In the first approach, referred to as a keyword-based query, we attempted to identify relevant skills by querying middle-skilled posting associated with manufacturing and with the keywords representing the 3DP/AM industry. Specifically, we applied the filters shown in Table 2 which yielded 32,238 job postings. Finally, we added a filter where the job title must include "technician" resulting in 5,548 postings. Comparison between these two queries (with "technician" and without), helped to highlight technician-specific skills and isolate skills that are typical for all types of middle skilled positions within the industry (e.g. Microsoft Office Suite).

Table 2. Filter criteria applied for relevant education levels and keywords in the Labor Insight™ database.

Criteria	**Filter Applied**
Time Period	07/01/2016-06/31/2021
Education	High school or vocational training or Associate's degree
Industry	Manufacturing
Keywords	Additive; 3D; 3D printing
Location	Nationwide
Title includes	Technician

In a second approach, referred to as an employer-based query, we searched for relevant and current skills by querying postings specifically associated with the two middle-skilled technician positions identified within BGLI –industrial/mechanical engineering technician or general engineering technician – and with firms specifically known to be in the 3DP/AM industry. The filtering on employer and types of occupations as shown in Table 3, resulting in 1,206,685 job postings. To once again narrow the search and reduce noise in the dataset, the "technician" filter was added, reducing the number of postings to 3,439.

Table 3. Filter criteria applied for relevant employers and occupations in the Labor Insight™ database.

Criteria	**Filter Applied**
Time Period	07/01/2016-06/31/2021
Occupation(s)	General engineering technician or industrial/mechanical engineering technician

Employer	148 3DP/AM firms
Location	Nationwide
Title includes	Technician

The top 200 technical skills and software skills were identified from both approaches and compared with the O*NET tasks, detailed work activities, tools (and examples), and technologies (and examples) associated with the three technician positions found in both databases: electrical engineering technicians, mechanical engineering technicians, and industrial engineering technicians.

To identify skills not represented in the O*NET database, we performed a two-stage assessment. First, an NLP tool, UDPipe in R (Wijffels 2021), was used to lemmatize[4] the text of both the BGLI skills and the O*NET data and, then, to identify matches between the two. Matches and partial matches of at least 25% commonality were flagged for human evaluation. Based on this, skills or tools that were present in BGLI but not in O*NET were flagged to ensure all emerging skills, tools, and technologies are identified to inform curriculum development and training.

The O*NET database is a source of comprehensive job classification information with detail and context that is needed for in person interviews. The BGLI data is uniquely able to identify emergent skills and technologies in the field, but the information can require effort to contextualize given their brevity and occasional specificity. Overall, O*NET and Burning Glass Labor Insight™ complement one another in the skills gap analysis for the 3DP/AM industry.

While there were very few skills absent in the O*NET database, we identified the skills below and assessed their importance for firms in the future during the semi-structured interviews:

- Systems Engineering
- Simulation
- Software Development/Engineering
- SolidWorks
- Prototyping

See Figure Figure 14 for a more in depth BGLI analysis. We recommend all programs monitor the importance of these skills to their local industry.

[4]Lemmatization is a linguistics process of combining the inflected parts of a word to analyze them as a single item. It is a common natural language processing technique.

Human Skills: What about "Soft" skills?

The focus of this study was to assess the training gaps associated with specific applied skills for technical workers. This focus in no way implies that the research team believes that such technical skills are more important than other non-technical skills (also known as "soft" or human skills). Research was focused on technical skills for two reasons. First, our primary goal was to develop insights to shape training programs aimed to support the 3DP/AM industry. Such programs themselves focus on technical skills and, therefore, require feedback on the same. Secondly, the interview applied in this research was of a scale that taxed most respondents. As such, tradeoffs had to be made to limit its scope and content. As a result, this study explores only a limited set of human skills including a novel analysis of critical thinking.

Although they were not the focus of this study, it is important for training programs to recognize that human skills complement technical skills, enhance employability, and improve productivity (Schulz 2008; Rao 2014). Although both industry and academia are reaching consensus that employees need human skills in addition to the technical skills taught in most STEM training programs (Kumar and Hsiao 2007), there is no consensus on which human skills are most important or even how to frame and organize human skills.

A recent study by researchers at MIT's Jameel World Education Lab attempts to bridge that gap by synthesizing more than 40 skills frameworks into the Human Skills Matrix (HSM). Their analysis found that communication and self-management skills were the most commonly identified important human skills. These were followed by creativity, problem solving, critical thinking, and teamwork. The HSM synthesizes this information into 24 non-technical skills that employees need to thrive (Stump, Westerman, and Hall 2020). These skills are grouped into four categories including Thinking, Interacting, Managing ourselves, and Leading. This framework was used to guide the selection of human skills studied here.

Specifically, we asked operations managers about the importance of these six human skills (as well as a detailed question about critical thinking) for middle-skilled manufacturing occupations:

- Effectively managing people and projects (Leading)
- Managing unfamiliar problems and situations (Thinking)
- Independently organizing time or prioritizing tasks (Managing ourselves)
- Communicating and collaborating with engineering and management staff (Interacting)
- Taking initiative to learn new skills or technologies (Managing ourselves)
- Knowing the science and engineering underlying the product (Thinking)

Critical thinking is widely cited as a skill that leads to success. Nevertheless, there are no established methods to characterize it. Here we define critical thinking as "the ability to analyze evidence and facts to form a judgment" (Gambrill 2005).To better characterize the role of critical thinking for technical middle-skilled occupations, we decompose the judgment process into the following sub-tasks:

1. Perceiving the issue – What should I measure or observe to know that a problem exists?
2. Hypothesizing about problem cause – What might be causing the problem?
3. Developing a framework for hypothesis testing – How can I confirm my hypothesis?
4. Inferring whether tests confirm the hypothesis - Does the test suggest that my hypothesis was right?
5. Communicating the outcome – How (and to whom) do I report on what has happened?

Respondents were asked to identify what aspect of critical thinking is important of technicians working at their facility.

Identifying Important, Common Skills

While it is valuable to understand the skills trends within individual occupations, in many cases, training programs or courses will need to be more broadly applicable, serving the needs of multiple types of learners. Combemale et al. (2021)also recommend that formal training must become more general for technician-level positions to be valuable in various types of advanced manufacturing industries. To that end, the research team has attempted to identify those skills that are both important and shared (common) among multiple occupations.

This was accomplished by making use of the hierarchical nature of the O*NET dataset from which occupation-specific skills were identified. Weighted average importance levels for generalized tasks/skills (GTS) and intermediate tasks/skills (ITS) were computed based on survey responses for occupation-specific tasks and skills. Details of the relationships among specific skills and higher levels of aggregation and the method of computing an importance score are described in the Appendix.

Semi-Structured Interview

Interview design

The interview is structured into four main sections:

1) firm characterization,
2) hiring and training challenges
3) workforce scaling, and
4) emerging and human skill needs including critical thinking.

In the first section of the interview, respondents were asked to identify the primary role that their firm plays in the 3DP/AM supply chain. Additionally, respondents were asked to estimate the firm's annual revenues and overall employment levels.

In the second section, respondents were asked to identify which of the focal occupations were relevant for their firm. Then for each relevant occupation they were asked whether

- Demand for that position would (Hold, Grow Somewhat, or Grow Significantly)?
- Filling an open position was (Easy, Average, or Hard)?
- In house training for new hires tends to be (Basic, Moderate, or Extensive training)?

Next, respondents were randomly assigned three relevant occupations. For each of these, they were asked to characterize the expected skill level for each position for their current technicians, the skill level of new hires for these positions, and rank the importance of the skills in 5 years compared to today. The categories for skill level included the following:

- Not applicable
- Aware of
- Familiar with
- Competent at
- Proficient with
- Mastery of

The expected importance ranks from much less important than now to much more important than now.

For each of these positions, respondents were asked to evaluate the importance of emerging skills when evaluating a new hire in five years. The importance categories included the following:

- Extremely important
- Very important
- Moderately important
- Slightly important
- Not at all important

Finally, the closing questions of the interview included in-depth questions about critical thinking and troubleshooting for technicians relevant to the respondent's firm. The respondents were asked to identify which of the judgments in the critical thinking process were most common for each technician ranging from:

- Issue perception
- Cause hypothesizing
- Hypothesis testing
- Test result inference
- Reporting and recommending

It was assumed that if a respondent chose "reporting and recommending" then they felt that the technician was capable of performing all of the previous steps as well.

To understand the importance of troubleshooting for hiring, respondents were asked to explain the relevance of this ability at their firm and how they test and train troubleshooting abilities.

Semi-Structured Interview Process

The interview responses were captured in the Qualtrics online platform(Qualtrics XM 2021) and interviews were conducted with 3DP/AM firms located throughout the U.S. Thirty responses where the respondent completed the entirety of the interview template were received and incorporated into the following results.

Results

Interviews with 30 operations managers across the 3DP/AM supply chain underscore the large growth in the industry and demand for workers. However, there are significant hiring challenges at most firms. There are also skills gaps among new and incumbent technician workers as well as a significant amount of on-the-job training required for technicians to be productive. The first section includes responses about the overall demand for middle-skilled workers and details projections for future demand. Next, hiring and training challenges of these workers are shown. Recommendations for high and moderate priority skills are detailed based on an assessment of the importance and skill gap for specific skills by position. A common skills analysis is performed to highlight skills that are important across positions in the supply chain.

Demand for occupations

Question
We expect demand for this type of position in our firm will....

3DP/AM firms indicated that the demand for the positions studied is expected to grow in the (Figure 2). The occupations expected to have the highest demand growth across the supply chain include additive technicians and CNC tool operators. Respondents indicated that CNC tool operators are particularly difficult to find and retain.

Among the occupations studied, nearly all positions are expected to experience moderate demand growth. The exception to this was the mechatronics technician and chemical/materials technician which were noted as “Not applicable” for more than 62% of respondents. This indicates that these types of workers are not common across 3DP/AM firms. However, for firms with these technicians, demand is expected to grow over time.

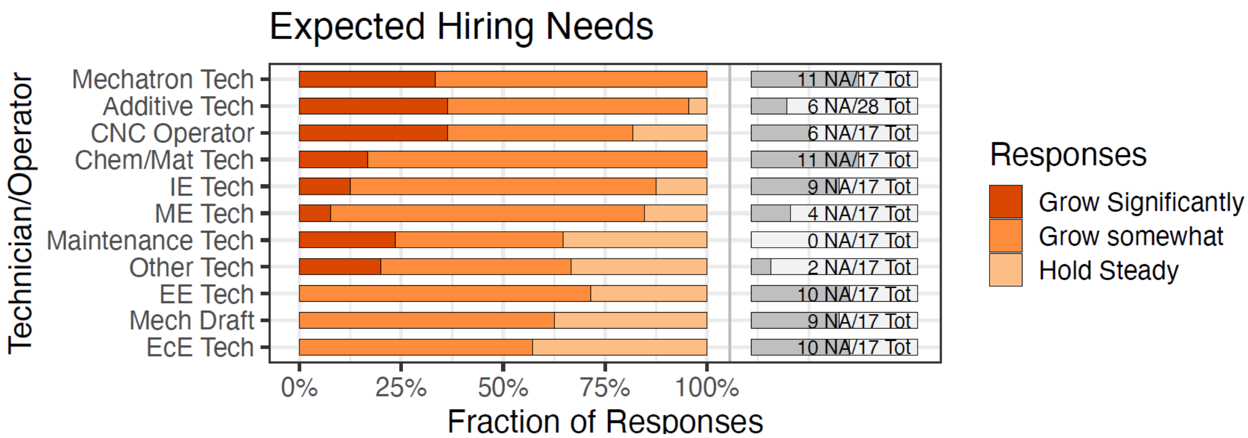

Figure 2. The technical worker occupations studied were classified according to future demand growth in the 3DP/AM industry. Fraction of 'Not Applicable' responses at the right of the bar. Firms indicated that other technical worker would likely be a quality or test technician.

The demand for each position can be summarized as follows:

Strong Growth	**Moderate Growth**	**Hold**
• Mechatronics Technician • Additive Technician • CNC Tool Operator	• Chemical/Materials Technician • Industrial Engineering Technician • Maintenance and Support Technician • Other Technical Production Worker • Mechanical Engineering Technician • Electrical Engineering Technician • Mechanical Drafter • Electronics Engineering Technician	

Workforce Demand Projections

An econometric analysis was performed to understand the growth trends in the 3DP/AM industry by estimating the expected number of positions and openings within the industry. This projection was based on three sources of data: forecasts for the overall economic activity within the U.S. 3DP/AM industry, estimates of worker intensity per dollar of economic activity within the represented sectors, and interview responses about specific staffing levels and anticipated growth in demand for specific occupations.

Estimates of economic activity within the U.S. 3DP/AM industry were assembled from two sources of market intelligence including a market research report from BCC research(Williams 2021) and the Bureau of Labor Statistic's *Projections Overview and Highlights, 2019-2029* (Dubina et al. 2020). From these sources of information, we estimate the 3DP/AM industry within the United States currently generates approximately $6.4B of revenue and is projected to grow at a rate of approximately 22.7% per year. (To be more conservative, we use this rate of growth only for the first five years of our analysis. For the latter five years, we assume 60% this rate of growth.) Estimates of workforce intensity (i.e. workers per dollar of revenue) are based on analysis of BLS data for the hybrid industry that is used here to represent the 3DP/AM industry. Since data on additive technician projections is not currently collected, we asked interview respondents how many additive technicians there would be relative to a mechanical engineering technician to use as a proxy for the estimate. Most respondents indicated that there was a 1:1 relationship between the two positions. Based on feedback from survey respondents, it is apparent that this industry makes more intensive use of engineering technicians than the conventional industries used as their proxy. To reflect this reality, half of the openings associated with machinists, tool and die makers, and prepress technicians were reallocated to technician occupations.

Note: in the balance of this section, in the interest of simplicity, we refer to technical middle-skilled positions. As was detailed earlier in this document, our analysis includes only specific occupation types. For middle-skilled occupations, the primary omission is information technology positions.

As shown in Figure 3, we estimate that currently there are ~3,100 technical middle-skilled positions in the U.S. 3DP/AM industry with that figure growing to just over 19,400 positions by the end of the decade (Figure 3a). The expected growth coupled with expected departures from the existing workforce (i.e., retirements and separations into other occupations) would lead to nearly 27,300 middle-skilled skilled technical openings over the decade.

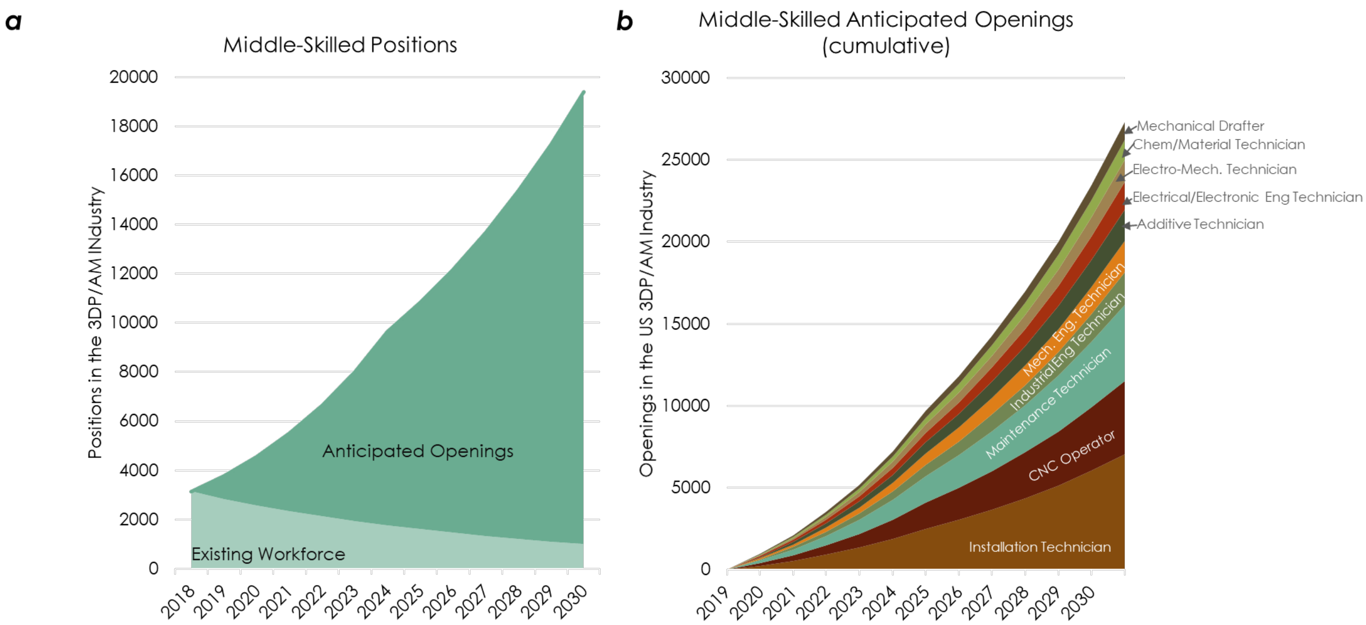

Figure 3. (a) Shows an overview of trends for middle-skilled workers in the 3DP/AM industry (b) Provides details by position. Results are based on expected demand growth, industry growth, and retirement rate.

These estimates translate into a need of about 2,400 new middle-skilled workers per year. If a typical community college program graduates 15 middle-skilled learners with these skills per year, the country will need more than 160 programs focused on the needs of the 3DP/AM industry to meet the expected industry demand for middle-skilled workers. The largest number of cumulative openings by positions is for other technical production workers, which interview respondents indicated were installation technicians in this industry.

Mapping these number to a Massachusetts context, we estimate that there are currently ~62 middle-skilled positions in this industry growing to ~385 positions by the end of the decade. The expected growth with expected departures would lead to approximately 540 cumulative middle-skilled technical openings in these positions for this sector within the state. This includes about 48 middle-skilled openings per year within the state, easily supporting three educational program to train middle-skilled technical workers for the state's 3DP/AM industry.

Hiring Challenges

Question
Filling this type of position is ....

Many firms expressed how hiring at the technician level is one of their biggest challenges (Figure 4) and many feel there is a worker shortage since positions are open for at least 3 to 4 months. For many, this has led to a backlog of work and firms have been turning to purchasing automated equipment to handle the workload. However, respondents also described that these machines still require a thinking human to be a part of the process. There is a significant need to build up talent within the 3DP/AM industry.

When asked about how long it typically takes to hire for these positions, most positions require at least 30-60 days to hire with 50% or more indicating more than 60 days for all positions *except* for industrial engineering technician, electrical engineering technician, and mechanical engineering technician. Respondents from smaller firms shared that they feel it can be a big risk to hire and train new employees at this time because many ultimately leave for a larger firm. These results suggest a low supply of technical middle-skilled workers as well as a challenge of attracting and retaining workers in this industry.

In comparing the demand and hiring results, most of the positions are difficult to hire for and are positions expected to have moderate to significant growth in the future. Both the additive technician and CNC tool operator position have significant growth expected and are difficult to hire compared to the other positions studied. These results suggest an emphasis on training and attracting additive technicians and CNC tool operators to meet the demands of the industry.

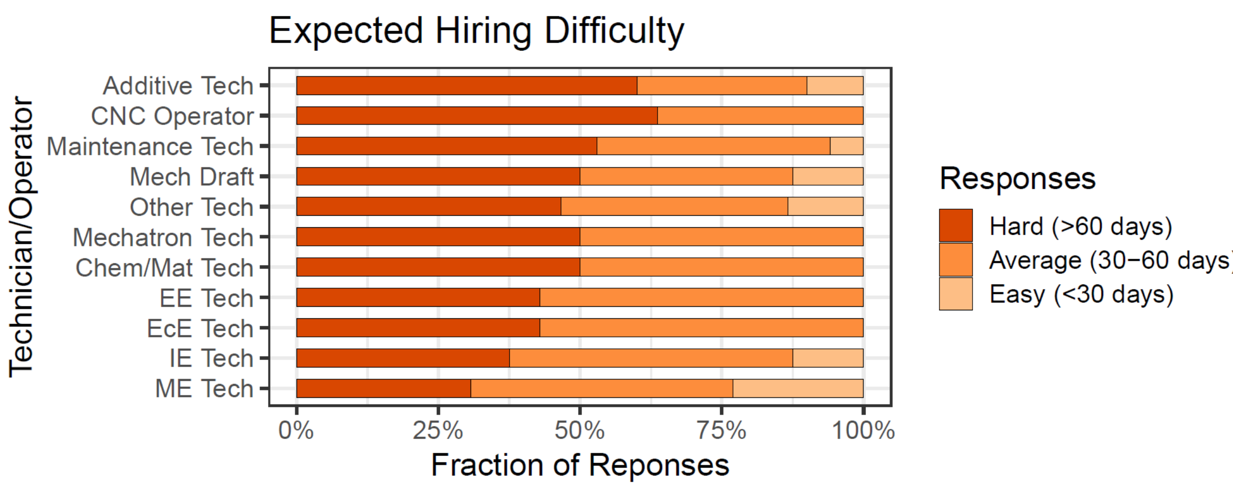

Figure 4 The difficulty of hiring middle-skilled positions was assessed for the 3DP/AM industry (n=30). Most positions were found to be difficult to fill.

The hiring difficulty for each position can be summarized as follows:

Considerable hiring effort	Moderate	Nominal
• Additive Technician • CNC Tool Operator • Mechanical Drafter • Maintenance and Support Technician • Other Technical Production Worker • Mechatronics Technician • Chemical/Materials Technician	• Electrical Engineering Technician • Electronics Engineering Technician • Industrial Engineering Technician • Mechanical Engineering Technician	

Training Effort Required

Question
New hires typically require training that is …

The amount of on-the-job training for each occupation was also evaluated by respondents as extensive, some, or basic orientation only. Many respondents shared that it is rare to find individuals with formal training in 3DP/additive and therefore most firms require at least some training (see Figure 5). For roles such as additive technician or maintenance and support, 3DP/AM firms look for individuals with a mechanical aptitude and interest in the area since most have not been exposed to additive or 3D printing in previous roles or training but are generally easier to train.

Smaller firms explained that while they want to give their technicians extensive on-the-job training, they don't have the capacity or resources to do so. To help address this, firms suggested a rotational internship program where interns would be exposed to a number of different 3DP/AM practices and could receive cross-training. While some training is company specific, respondents suggested additional or improved training in the following areas:

- Safety
- Basic computer skills
- CAD software (e.g., Solid Works)

- 3DP software (e.g., Magics)
- Business knowledge (e.g., operating costs)
- Design for additive concepts/design rules
- Material properties
- Geometric dimensioning and tolerancing (GD&T)

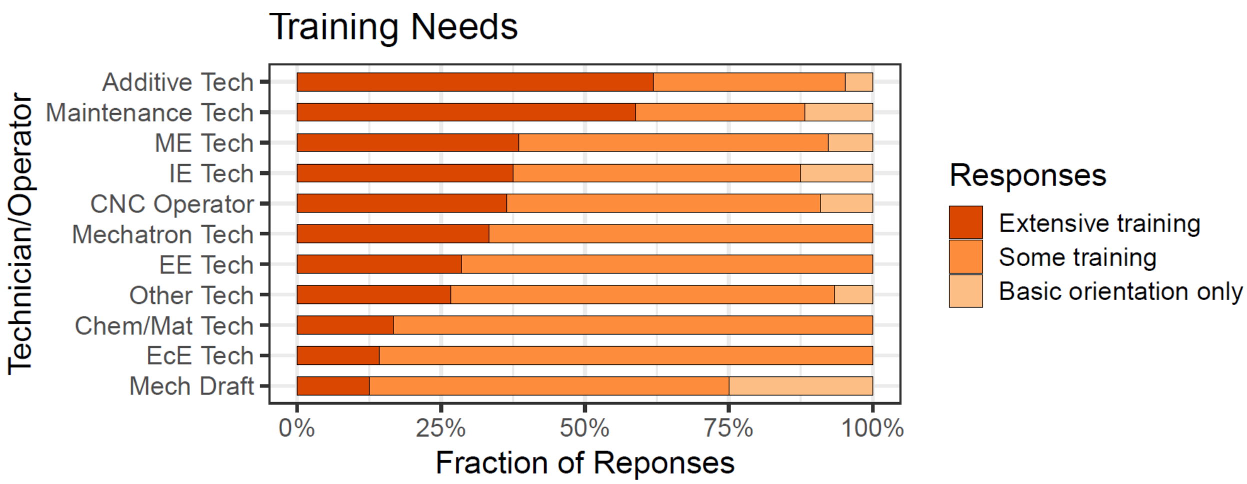

Figure 5 The training required for each position was assessed as extensive, some training, or basic orientation only (n=30). Most positions require at least some training with additive and maintenance and support technicians requiring significant on-the-job training.

In comparing the training effort results to the hiring challenge results, we observe that additive technicians, maintenance and support technicians, and CNC tool operators are all positions that require significant training and are difficult positions for firms to fill.

Industry Recognized Certification Program

Question
How do you feel about the following statement: "Industry-Recognized Certifications and Credentials would be useful for the advanced 3DP/AM manufacturing industry."

During the interviews, the firms were asked to rank how they felt about job-specific industry-recognized certification and credentialing programs to assist with hiring from strongly disagree to strongly agree (Figure 6). The goal of these programs would be to aid in identifying qualified candidates and to provide opportunities for more workers. Most respondents (74%) either strongly agreed or agreed with the statement that industry specific credentials would be useful for the 3DP/AM industry. Several respondents (8%) disagreed and the remaining respondents indicated that they were neutral regarding certification programs.

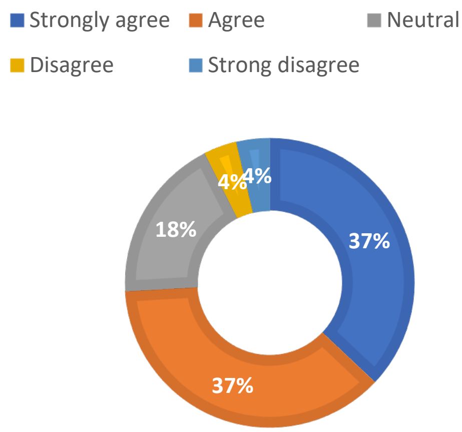

Figure 6 Reactions regarding certification and credentialing programs to improve hiring in the 3DP/AM industry.

Respondents that agreed with credentialing felt that certifications are useful but are not a hiring decision factor. Certifications do allow for firms to make objective decisions about salaries and bonuses, which firms felt helped them make more equitable decisions. Recommended credentials/certifications for 3DP/AM are Solid Works, Autodesk, or other CAD software. Other respondents indicated that while they strongly agree with certifications, they feel that there needs to be a hands-on component and not just an online test in order for them to be truly useful. For those that disagreed, they felt that these programs are often expensive and therefore create additional barriers. While the certifications can be useful for more general topics, they are often not relevant to what firms do every day in this industry. All in all, most firms agreed that these programs signal interest but they are not required for hiring at this time.

Skills required for In-Demand Positions

Results from the semi-structured interviews underscore the demand for middle-skilled workers, hiring challenges, and training gaps across all positions studied. The training gaps for each occupation were explored in detail for 8-10 specific skills where respondents were asked to rank the skill level for existing workers, new hires, and the importance of the skill in five years compared to today. The research team identified skills that were classified as high priority or moderate priority. High priority skills are those that have a large gap between existing workers and new hires and were also ranked as having high future importance. Moderate priority skills are those with either a large gap or were ranked as much more important or skills that fell in the mean range of the data for both categories. For those skills that were not ranked as high or moderate priority, the research team recommends these skills be re-evaluated for inclusion in the curricula for that occupation.

There were a sufficient number of responses (n>=5) to characterize six positions including additive technician, mechanical engineering technician, industrial engineering technician, mechatronics technician, mechanical drafter, and CNC tool operator. Since there are significant training gaps for these workers, we highlight opportunities to improve training programs for the future.

Table 4 Occupation descriptions for the six positions with a sufficient number of responses.

Occupation Title	Description
Additive Technician	Maintain and repair additive manufacturing and 3-D printing equipment. Maintain the additive manufacturing machinery and equipment at the highest possible level and ensure the productivity and safety of the entire production team.
Mechanical Engineering Technicians (SOC Code 17-3027.00)	Apply theory and principles of mechanical engineering to modify, develop, test, or calibrate machinery and equipment
Industrial Engineering Technicians (SOC Code 17-3026.00)	Apply engineering theory and principles to problems of industrial layout or manufacturing production. May perform time and motion studies on worker operations in a variety of industries to establish standard production rates or improve efficiency
Mechatronics Technician (SOC Code 17-3024.00)	Operate, test, maintain, or adjust unmanned, automated, servomechanical, or electromechanical equipment. May operate unmanned submarines, aircraft, or other equipment to observe or record visual information at sites such as oil rigs, crop fields, buildings, or for similar infrastructure, deep ocean exploration, or hazardous waste removal. May assist engineers in testing and designing robotics equipment.
Mechanical Drafter (SOC Code 17.3013.00)	Prepare detailed working diagrams of machinery and mechanical devices, including dimensions, fastening methods, and other engineering information.
CNC Tool Operators (SOC Code 9161.00)	Operate computer-controlled tools, machines, or robots to machine or process parts, tools, or other work pieces made of metal, plastic, wood, stone, or other materials. May also set up and maintain equipment.

Additive Technician

Survey responses for additive technicians are shown in Figure 7. Recommendations for training of additive technicians based on these results are summarized in Table 5.

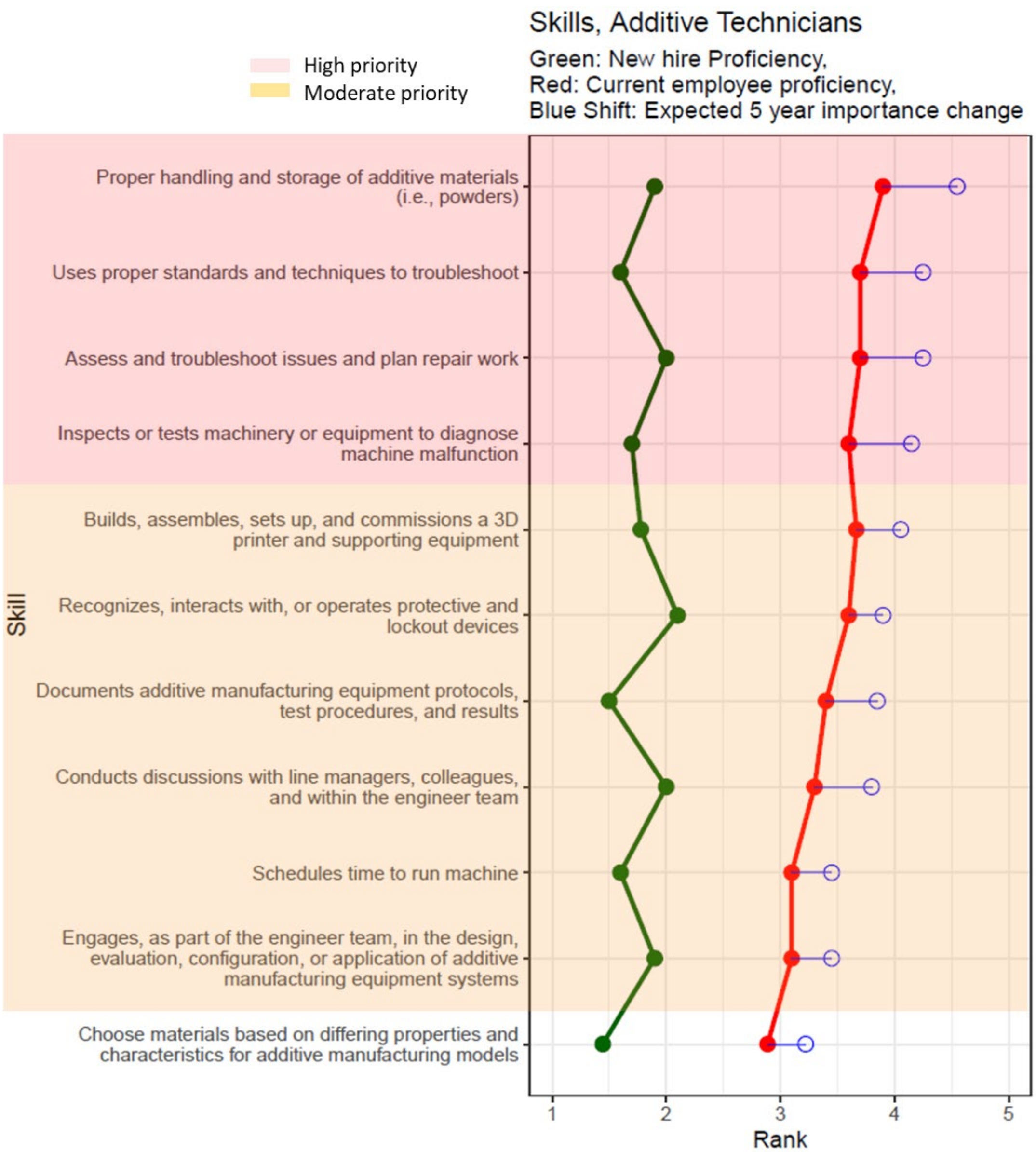

Figure 7. The gaps and expected future importance of skills for additive technicians are shown with high priority skills highlighted in red and moderate priority skills highlighted in orange.

Table 5. Recommended changes in the training of additive technicians in the 3DP/AM industry. The red skills are those that are high priority and the orange skills are those that are ranked as moderate priority and therefore have a skill gap and are also important in the future.

Recommendation	Skill	Full Skill Description
Emphasize training on…	Troubleshoot and follow standard protocols	Proper handling and storage of additive materials (i.e., powders)
		Uses proper standards and techniques to troubleshoot
		Assess and troubleshoot issues and plan repair work
	Inspect equipment	Inspects or tests machinery or equipment to diagnose machine malfunction
Improve training on…	Assemble and maintain 3D/additive machinery	Builds, assembles, sets up, and commissions a 3D printer and supporting equipment
		Recognizes, interacts with, or operates protective and lockout devices
	Understand, evaluate, and maintain quality	Documents additive manufacturing equipment protocols, test procedures, and results
	Collaborate and coordinate with team members	Conducts discussions with line managers, colleagues, and within the engineer team
		Schedules time to run machine
		Engages, as part of the engineer team, in design, evaluation, configuration, or application of additive manufacturing equipment systems
Maintain training/evaluate training on…	Choose proper materials	Choose materials based on differing properties and characteristics for additive manufacturing models

Mechanical Engineering Technician

Survey responses for mechanical engineering technicians are shown in Figure 8. Recommendations for training of mechanical engineering technicians based on these results are summarized in Table 6.

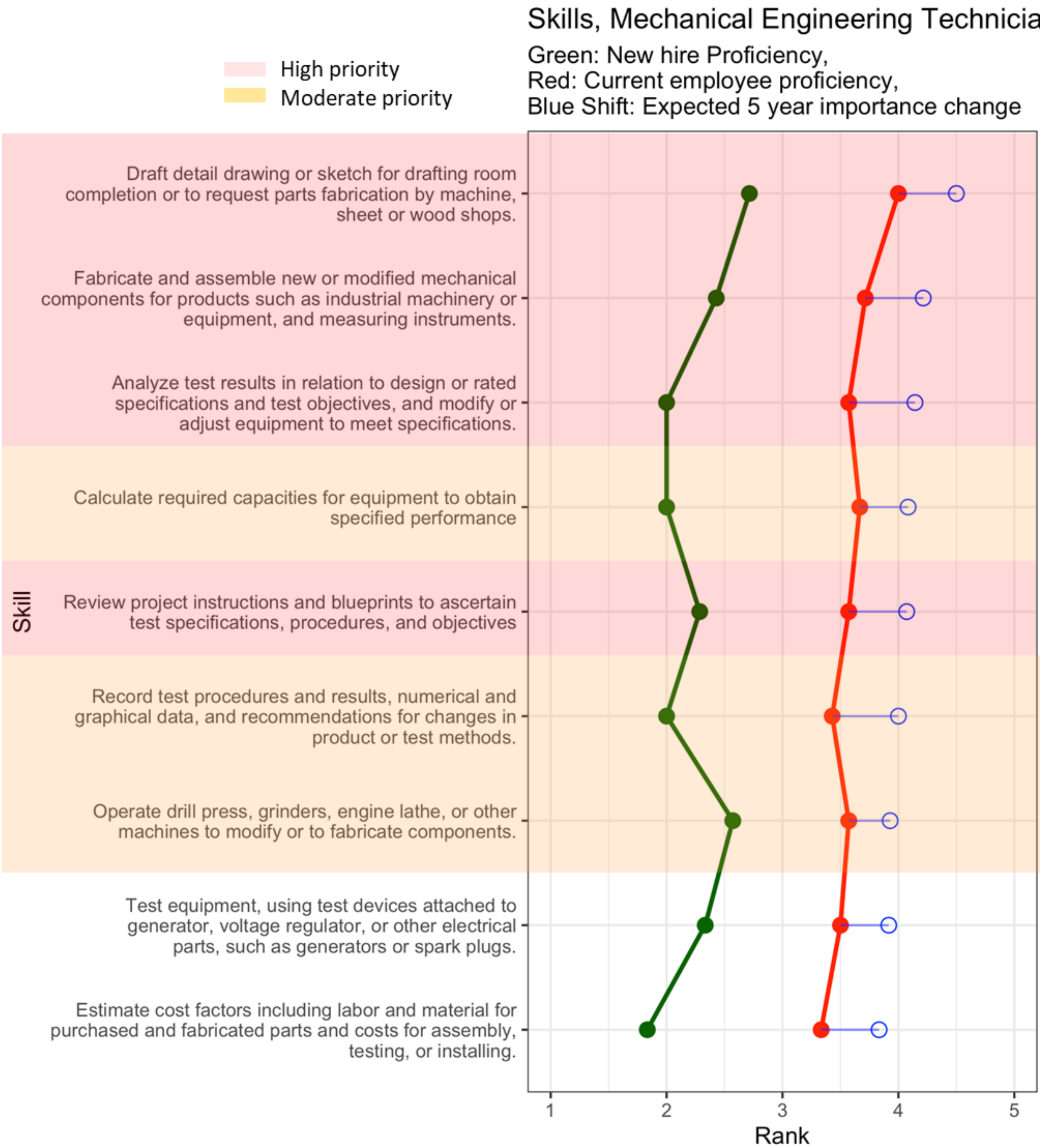

Figure 8. The gaps and expected future importance of skills for mechanical engineering technicians are shown with high priority skills highlighted in red and moderate priority skills highlighted in orange.

Table 6. Recommended changes in the training of mechanical engineering technicians in the 3DP/AM industry. The red skills are those that are high priority and the orange skills are those that are ranked as moderate priority and therefore have a skill gap and are also important in the future.

Recommendation	Skill	Full Skill Description
Emphasize training on…	Drafting for fabrication	Draft detail drawing or sketch for drafting room completion or to request parts fabrication by machine, sheet or wood shops.
	Fabrication methods	Fabricate and assemble new or modified mechanical components for products such as industrial machinery or equipment, and measuring instruments.
	Understand, evaluate, and maintain quality	Analyze test results in relation to design or rated specifications and test objectives, and modify or adjust equipment to meet specifications.
		Review project instructions and blueprints to ascertain test specifications, procedures, and objectives
Improve training on…	Recommend changes in product or process design	Record test procedures and results, numerical and graphical data, and recommendations for changes in product or test methods.
	Operate specific equipment	Operate drill press, grinders, engine lathe, or other machines to modify parts tested or to fabricate experimental parts for testing.
		Calculate required capacities for equipment to obtain specified performance
Maintain training/evaluate training on…	Understand, test, and maintain quality	Test equipment, using test devices attached to generator, voltage regulator, or other electrical parts, such as generators or spark plugs.
	Estimate operating costs	Estimate cost factors including labor and material for purchased and fabricated parts and costs for assembly, testing, or installing.

Industrial Engineering Technician

Survey responses for industrial engineering technicians are shown in Figure 9. Recommendations for training of industrial engineering technicians based on these results are summarized in Table 7.

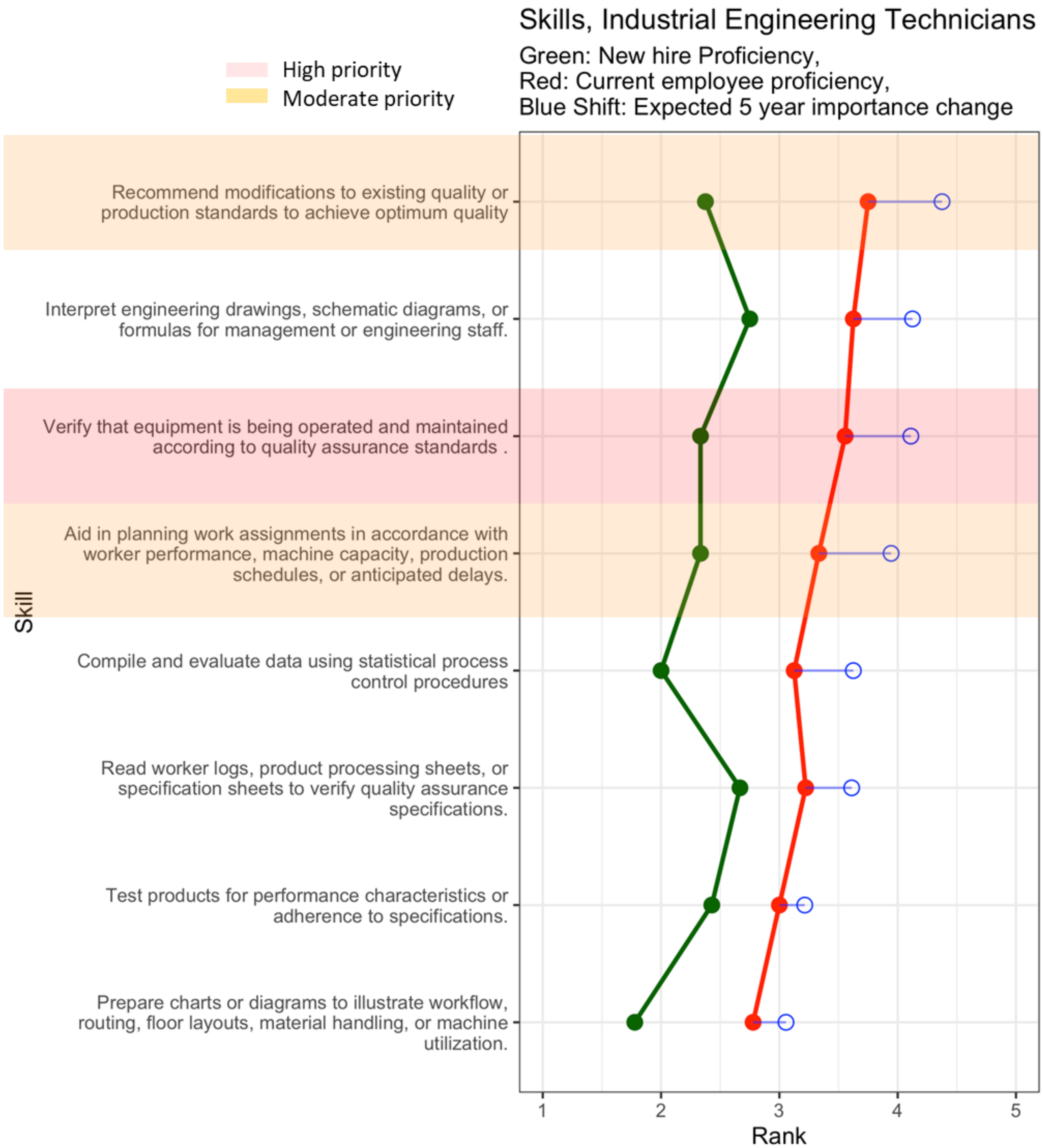

Figure 9. The gaps and expected future importance of skills for industrial engineering technicians are shown with high priority skills highlighted in red and moderate priority skills highlighted in orange.

Table 7. Recommended changes in the training of industrial engineering technicians in the 3DP/AM industry. The orange skills are those that are ranked as moderate priority and therefore have a skill gap and are also important in the future.

Recommendation	Skill	Full Skill Description
Emphasize training on…	Maintain product and process quality assurance standards	Verify that equipment is being operated and maintained according to quality assurance standards.
Improve training on…	Recommend operational & procedural changes	Aid in planning work assignments in accordance with worker performance, machine capacity, production schedules, or anticipated delays.
		Recommend modifications to existing quality or production standards to achieve optimum quality
Maintain training/evaluate training on…	Communication with engineering and management	Interpret engineering drawings, schematic diagrams, or formulas for management or engineering staff.
	Test, analyze and respond to process data	Compile and evaluate statistical data to determine and maintain quality and reliability of products.
		Test products for performance characteristics or adherence to specifications.
	Maintain product and process quality assurance standards	Read worker logs, product processing sheets, or specification sheets to verify quality assurance specifications.
	Communication with engineering and management	Prepare charts or diagrams to illustrate workflow, routing, floor layouts, material handling, or machine utilization.

Mechatronics Technician

Survey responses for mechatronics technicians are shown in Figure 10. Recommendations for training of mechatronics technicians based on these results are summarized in Table 8.

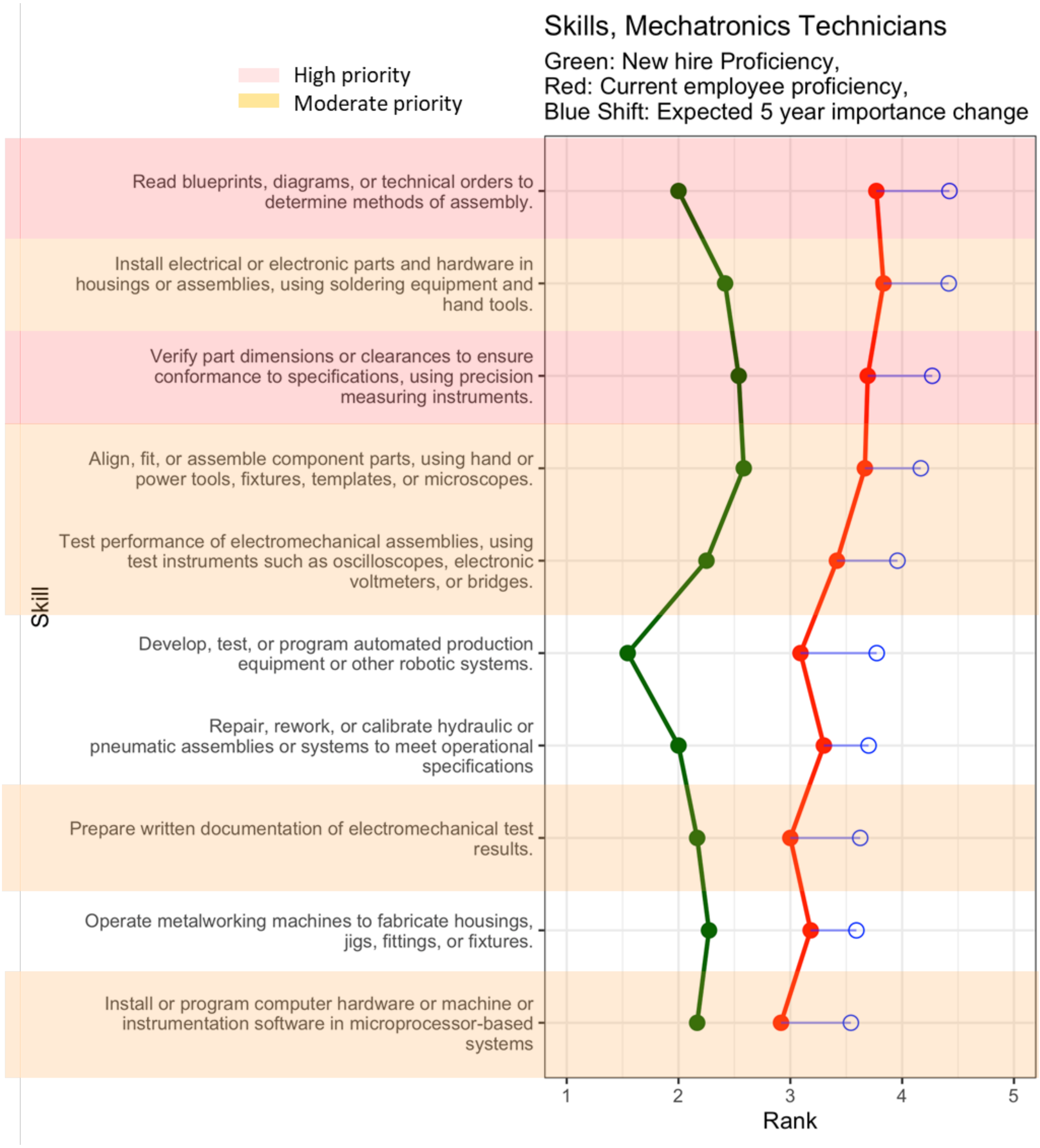

Figure 10 The gaps and expected future importance of skills for mechatronics technicians are shown with high priority skills highlighted in red and moderate priority skills highlighted in orange.

Table 8 Recommended changes in the training of mechatronics technicians in the 3DP/AM industry. The orange skills are those that are ranked as moderate priority and therefore have a skill gap and are also important in the future.

Recommendation	Skill	Full Skill Description
Emphasize training on…	Fabricate components and systems	Install electrical or electronic parts and hardware in housings or assemblies, using soldering equipment and hand tools.
		Align, fit, or assemble component parts, using hand or power tools, fixtures, templates, or microscopes.
Improve training on…	Understand, evaluate, and maintain quality	Read blueprints, diagrams, or technical orders to determine methods of assembly.
		Verify part dimensions or clearances to ensure conformance to specifications, using precision measuring instruments.
	Fabricate components and systems	Install electrical or electronic parts and hardware in housings or assemblies, using soldering equipment and hand tools.
		Align, fit, or assemble component parts, using hand or power tools, fixtures, templates, or microscopes.
	Use test instruments	Test performance of electromechanical assemblies, using test instruments such as oscilloscopes, electronic voltmeters, or bridges.
	Prepare reports	Prepare written documentation of electromechanical test results.
	Use test instruments	Test performance of electromechanical assemblies, using test instruments such as oscilloscopes, electronic voltmeters, or bridges.
Maintain training/evaluate training on…	Develop, test, and program hardware systems	Develop, test, or program automated production equipment or other robotic systems
	Hydraulic or pneumatic assembly repair	Repair, rework, or calibrate hydraulic or pneumatic assemblies or systems to meet operational specifications
	Operate metalworking machines	Operate metalworking machines to fabricate housings, jigs, fittings, or fixtures

CNC Tool Operator

Survey responses for CNC tool operators are shown in Figure 11. Recommendations for training of CNC tool operators based on these results are summarized in Table 9.

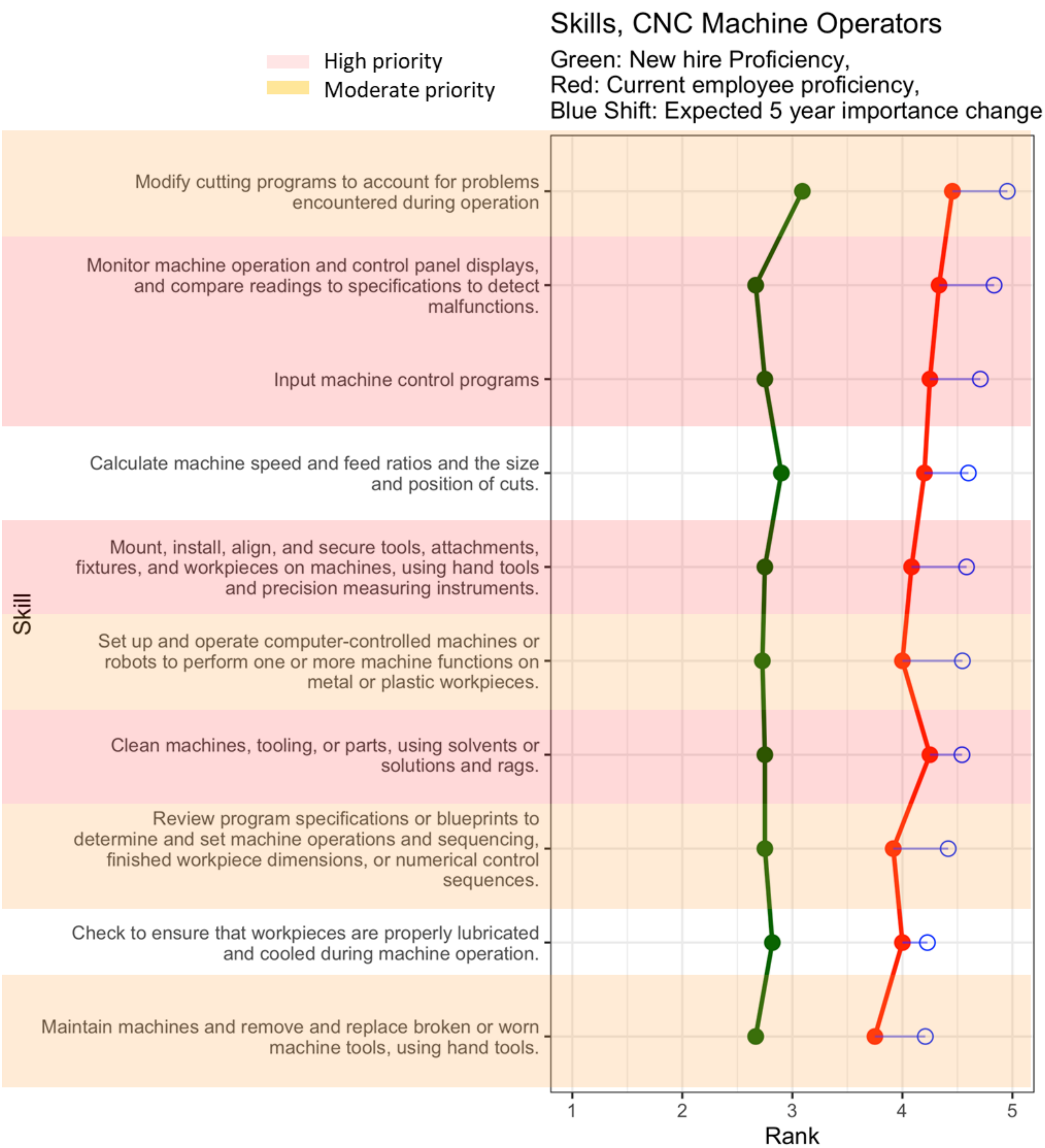

Figure 11. The gaps and expected future importance of skills for CNC tool operators are shown with high priority skills highlighted in red and moderate priority skills highlighted in orange.

Table 9 Recommended changes in the training of CNC tool operators in the 3DP/AM industry. The orange skills are those that are ranked as moderate priority and therefore have a skill gap and are also important in the future.

Recommendation	Skill	Full Skill Description
Emphasize training on…	Monitor and maintain machines	Monitor machine operation and control panel displays, and compare readings to specifications to detect malfunctions.
		Input machine control programs
		Mount, install, align, and secure tools, attachments, fixtures, and workpieces on machines, using hand tools and precision measuring instruments.
		Clean machines, tooling, or parts, using solvents or solutions and rags.
Improve training on…	Troubleshoot and operate machines	Modify cutting programs to account for problems encountered during operation
		Set up and operate computer-controlled machines or robots to perform one or more machine functions on metal or plastic workpieces.
	Assess specifications or blueprints	Review program specifications or blueprints to determine and set machine operations and sequencing, finished workpiece dimensions, or numerical control sequences.
	Machine operation and maintenance	Maintain machines and remove and replace broken or worn machine tools, using hand tools.
		Clean machines, tooling, or parts, using solvents or solutions and rags.
Maintain training/evaluate training on…	Calculate machine speeds and feed ratios	Calculate machine speed and feed ratios and the size and position of cuts.
	Machine operation and maintenance	Check to ensure that workpieces are properly lubricated and cooled during machine operation.

Mechanical Drafter

Survey responses for mechanical drafters are shown in Figure 12. Recommendations for training of mechanical drafters based on these results are summarized in Table 10.

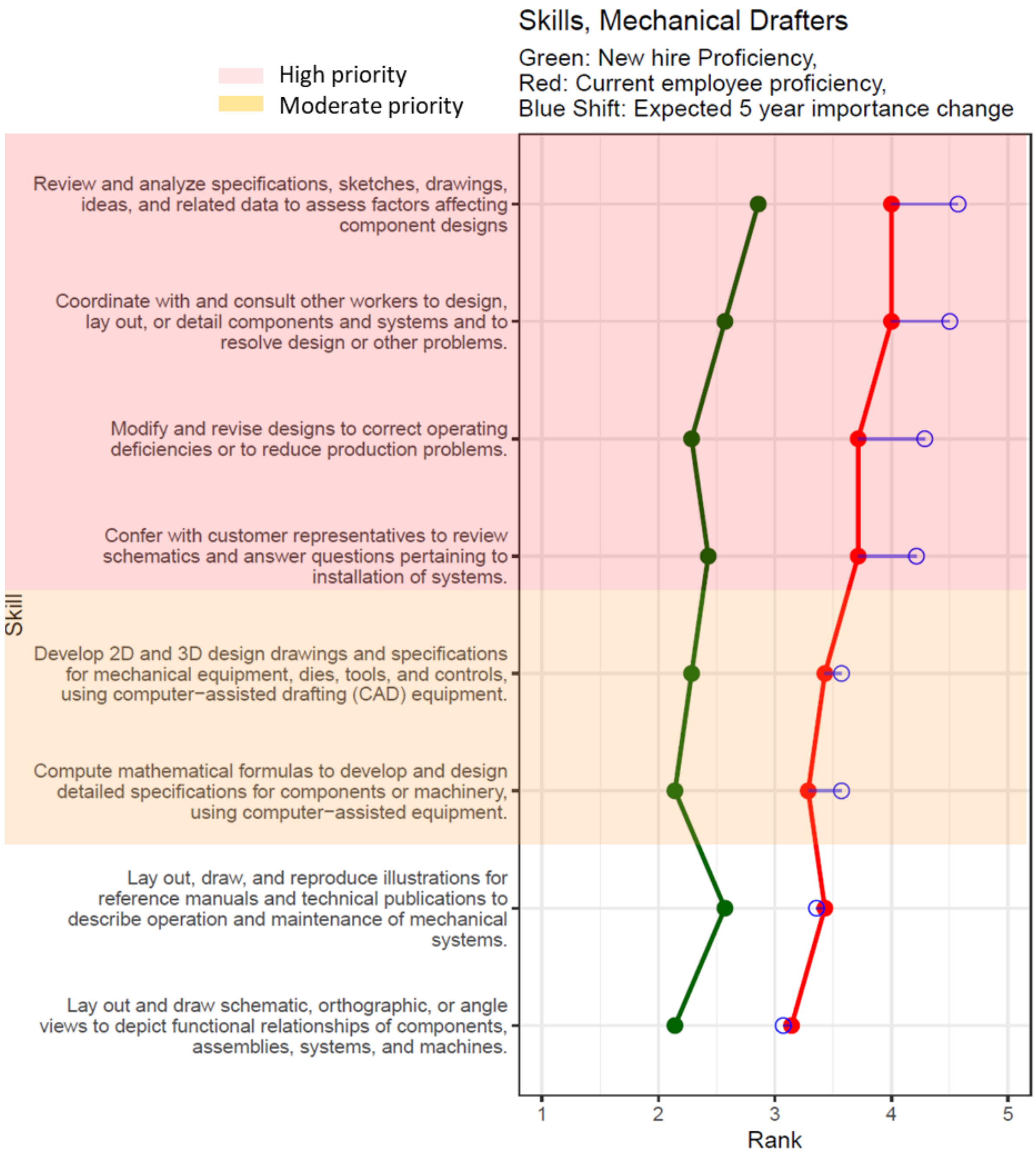

Figure 12 The gaps and expected future importance of skills for mechanical drafters are shown with high priority skills highlighted in red and moderate priority skills highlighted in orange.

Table 10 Recommended changes in the training of mechanical drafters in the 3DP/AM industry. The orange skills are those that are ranked as moderate priority and therefore have a skill gap and are also important in the future.

Recommendation	Skill	Full Skill Description
Emphasize training on…	Review designs and coordinate with other workers	Review and analyze specifications, sketches, drawings, ideas, and related data to assess factors affecting component designs
		Coordinate with and consult other workers to design, lay out, or detail components and systems and to resolve design or other problems
		Modify and revise designs to correct operating deficiencies or to reduce production problems
		Confer with customer representatives to review schematics and answer questions pertaining to installation of systems
Improve training on…	Use CAD equipment for design	Develop 2D and 3D design drawings and specifications for mechanical equipment, dies, tools, and controls, using CAD equipment.
		Compute mathematical formulas to develop and design detailed specifications for components or machinery, using computer-assisted equipment.
Maintain training/evaluate training on…	Lay out and draw mechanical systems	Lay out, draw, and reproduce illustrations for reference manuals and technical publications to describe operation and maintenance of mechanical systems.
		Lay out and draw schematic, orthographic, or angle views to depict functional relationships of components, assemblies, systems, and machines

Identifying the high priority skills gaps

Across all positions, there were 21 skills that were classified as high priority – exhibiting both high future importance and a significant skills gap (i.e., the gap between the proficiency of new hires are the level of proficiency needed in the future). These skills and their skills gap are shown in Figure 13 where the blue dot indicates the future proficiency needed and the green dot represents the proficiency of current new hires.

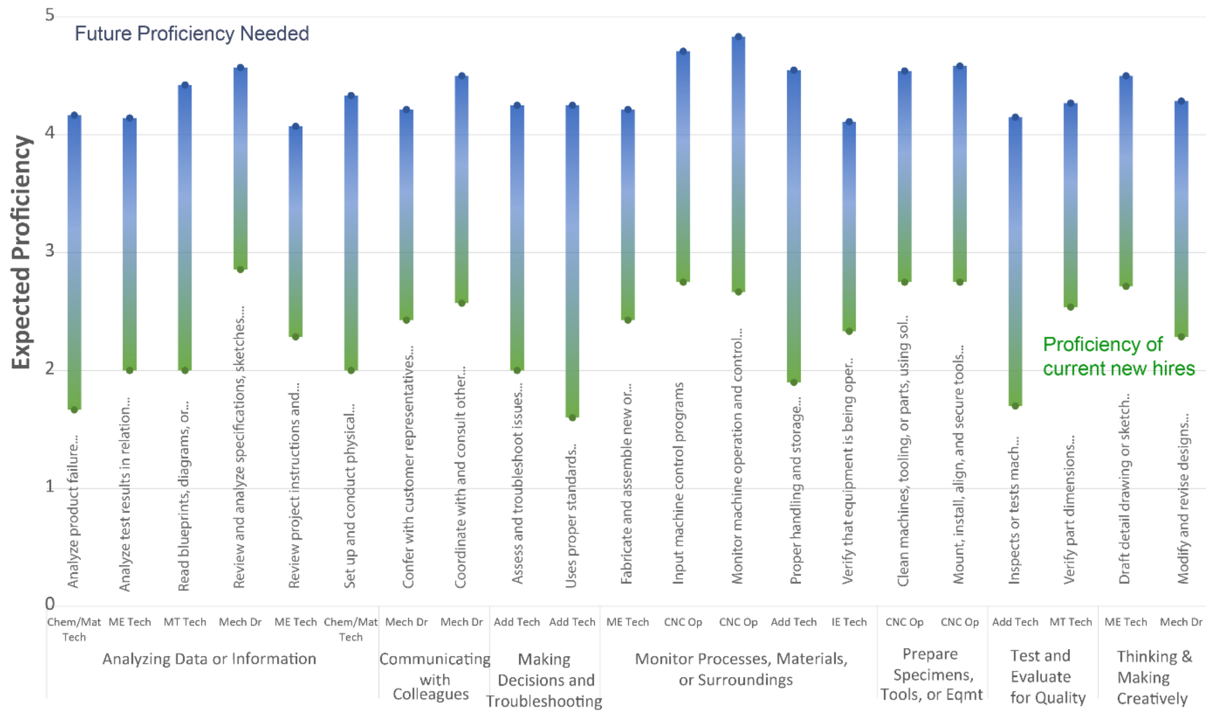

Figure 13 High priority skills across all positions studied in the 3DP/AM industry. The green dot represents the proficiency of current new hires and the blue dot represents the future proficiency needed for the middle-skilled level.

These high priority skills are all associated with one of seven generalized skill categories. These are:

- Analyzing Data or Information
- Communicating with Colleagues (Supervisors, Peers, Subordinates)
- Making Decisions and Troubleshooting Problems
- Monitor Processes, Materials, or Surroundings
- Prepare Specimens, Tools, or Equipment
- Test and Evaluate for Quality
- Thinking & Making Creatively

Notably, this same set represent three of the eight most important generalized skills (see section Identifying Important Common Skills). Firms regularly emphasized the importance of data analysis, troubleshooting skills, communication, and quality for technicians in this emerging field.

Emerging and Human skill needs

Along with assessing current technical skills for each position, respondents also were asked to consider the importance of specific emerging and human skills for middle-skilled technical workers. Emerging skills were identified through two approaches – review of the workforce development literature and analysis of the BGLI database.

Real-Time Skills Analysis from Burning Glass Labor Insight™ (BGLI)

In an in-depth assessment of the BGLI skill results by position type, the comparison of the employer and keyword datasets found that ~80% of the skills and technologies highlighted by the BGLI database (at least 5% of postings for all positions) were present within the O*NET characterization of the focal occupations. Those that were not present were classified as one of the following:

- Emerging skill, tool, or technology: The real-time database captured an emergent skill or technology that has not been updated in the O*NET database.
- Value-added human skill: A human skill that is not specifically captured in the survey conducted here or within the O*NET database. (e.g., customer service or sales skills for technicians) but that is valuable in this industry.
- Value-added cross-training: Skills that are outside of the definition of the specified occupation but which represent valuable additional skills for some employers. (e.g., industrial engineering skills for mechanical engineering technicians)
- Context-specific skills: Skills that are valuable to particular employers because of the specifics of their operations, market, or other business conditions (e.g., HVAC or packaging design skills for mechanical engineering technicians)

The real-time labor market intelligence analytics data complements the O*NET database because it enables the identification of emerging trends in technical skills and knowledge and software skills and technologies in the 3DP/AM industry. For each of the relevant positions present in BGLI, the most frequently observed skills are shown in Figure 14. Specifically, Figure 14a shows all skills present in at least 5% of postings for the electrical engineering technicians including both those included in the O*NET framework (dark red columns) and those that are not. To better focus on uniquely identified skills, Figure 14b, c, and d, plot only the skills absent in O*NET for the electrical/electronic (EE), mechanical (ME), and industrial (IE) technicians.

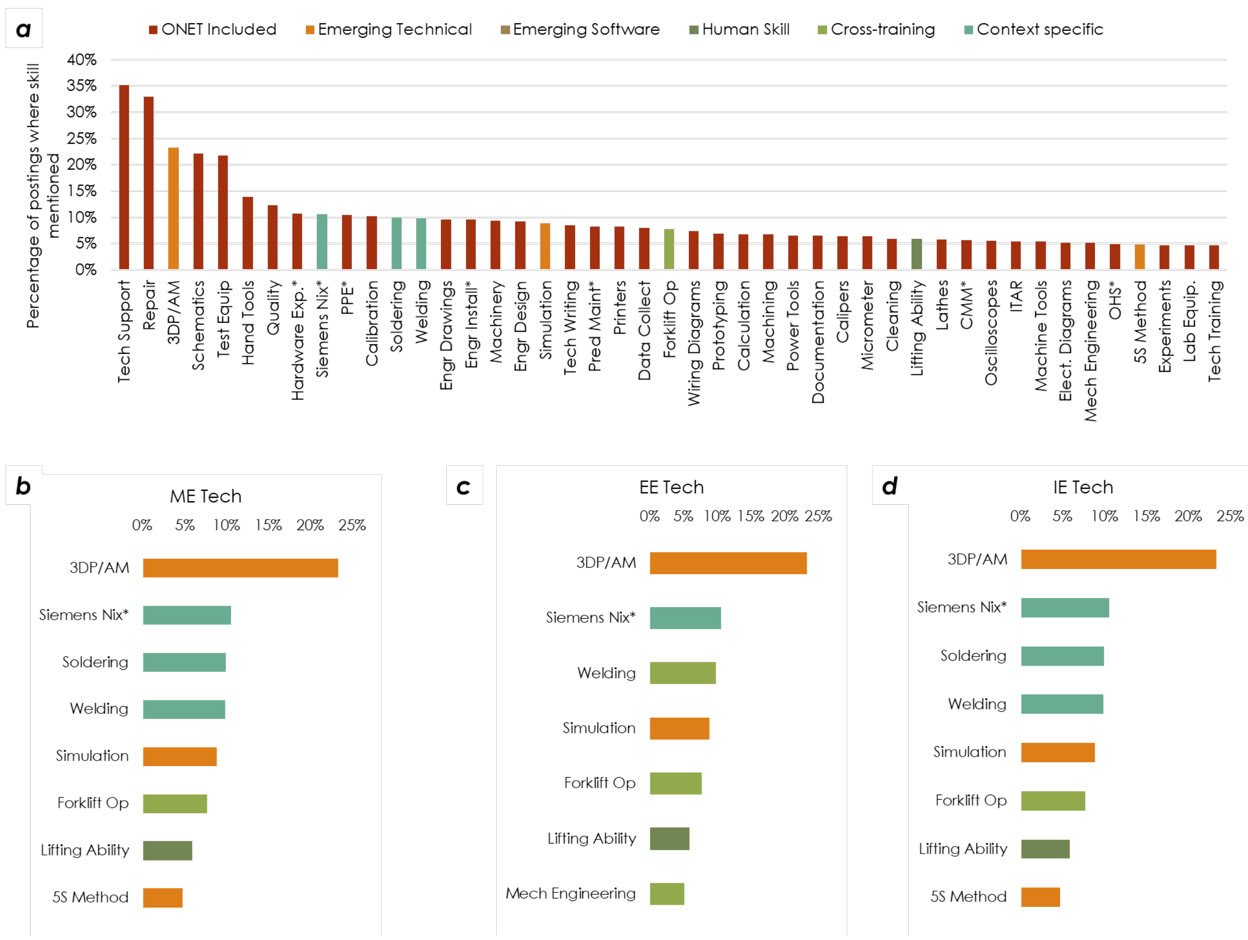

Figure 14 The most frequently observed skills in the BGLI for mechanical engineering technicians categorized as ONET included, emerging technical, emerging software, human skill, cross-training, or context specific (a). The skills that were not found in ONET are also shown for each of the positions in b-d.

**Full skill names include: 3D printing/additive, Siemens Nixdorf, Predictive/Preventative Maintenance, Electronics Industry Knowledge, Programmable Logic Controller Programming, Electrical Diagrams/Schematics, Hardware Experience, Electrical Distribution Systems, Computer Hardware/Software Knowledge, Personal Protective Equipment (PPE), Coordinate Measuring Machine (CMM).*

Overall, a majority of the technical skills from the BGLI database are well represented in the O*NET database. Of those skills not present with in the O*Net database, the most frequently requested skill by 3D printing and additive manufacturing industry was knowledge of 3D printing and additive manufacturing (3DP/AM) – found in more than 20% of postings. Other emerging skills of note include simulation and 5S Methodology. These survey questions about these two emerging skills were added to the semi-structured interviews. Since 3D printing technologies are ostensibly definitional to the additive technician skillset, further questions about the importance of 3D printing knowledge risked undermining the legitimacy of the interviewer.

Cross-training skills that are common and complement conventional disciplinary training include forklift operation, welding, and knowledge of other disciplines. Skills that are context specific across all positions include soldering, welding, and Siemens Nixdorf.

During the semi-structured interviews, we asked firms about the future importance of the two skills flagged by the BGLI analysis and not apparently present within the O*Net dataset – simulation and systems engineering / 5S methods. In Table 11., we show the results for each skill by occupation. The value in each cell indicates the percent of respondents that believe the skill will be important for hiring in the next five years. Most respondents indicated neither simulation nor systems engineering/5S methods were important for middle-skilled technical worker (but generally commented that these were skills expected of higher-level workers, such as engineers).

Table 11Emerging technical skills highlighted in the BGLI database. The blue bar indicates the percentage of respondents that expect this skill to be important for hiring in the next five years by technician type.

Technician Type	Simulation	Systems Engineering / 5S Method
Additive Technician	5%	0%
Chemical/Materials Technician	17%	0%
Computer-Controlled Machine Tool Operator	9%	0%
Electrical Engineering Technician	0%	14%
Electro-Mechanical and Mechatronics Technician	0%	17%
Electronics Engineering Technician	14%	14%
Industrial Engineering Technician	0%	13%
Maintenance and Support Technicians	0%	6%
Mechanical Drafter	25%	13%
Mechanical Engineering Technician	0%	8%
Other Technical Production Worker	7%	0%

Emerging and Human Skill Interview Results

Because importance was evaluated identically for both emerging and human skills, these results are presented together in Figure 15 and summarized in Table 12. Blue text is used to distinguish human from technical skills.

Emerging skill needs

Along with assessing technical skills for each position, respondents also were asked to consider the importance of emerging skills over the next five years. This same set of skills was presented to respondents for each of the technical occupations. The importance of each of the emerging skills is shown for the operator and technician occupations (see Figure 15).

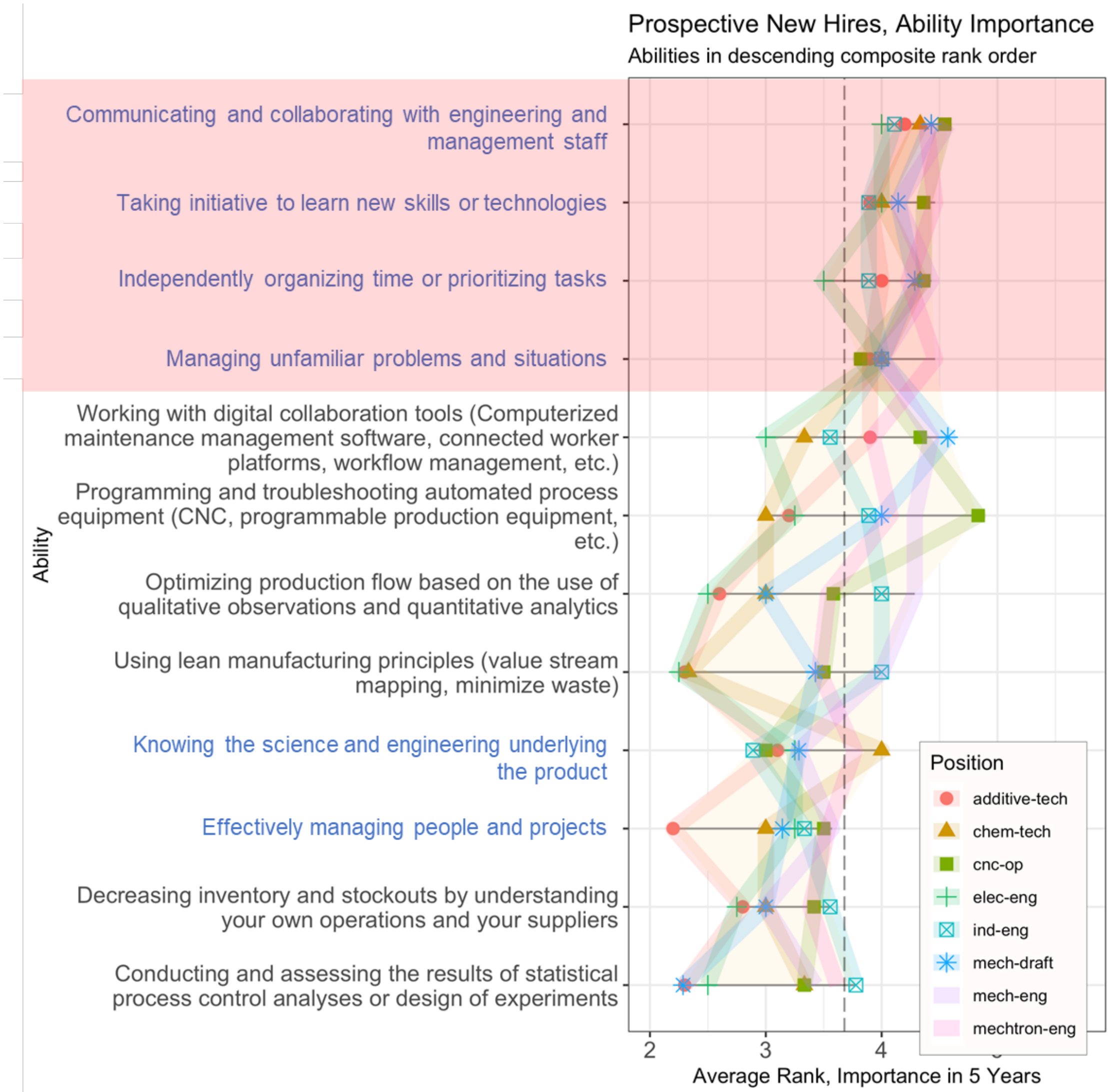

Figure 15 The expected importance of emerging skills was ranked as much less important than now, less important than now, as important than now, more important than now, and much more important than now. The first four skills, highlighted in red, are those that are important across all the positions studied. The remaining skills have varying levels of importance that are specific to each position. Skills in blue represent emerging human skills.

Table 12.Recommendations for emerging skill training across all technicians (red) and for job-specific roles.

Emphasize training for…								Full Skill Description
Add Tech	Chem/Mat	CNC	EE	IE	MD	ME	MT	Communicating and collaborating with engineering and management staff
X	X	X	X	X	X	X	X	Taking initiative to learn new skills or technologies
X	X	X	X	X	X	X	X	Independently organizing time or prioritizing skills
X	X	X	X	X	X	X	X	Managing unfamiliar problems and situations
X		X			X	X	X	Working with digital collaboration tools (Computerized maintenance management software, connected worker platforms, workflow management, etc.)
		X		X	X	X	X	Programming and troubleshooting automated process equipment (CNC, programmable production equipment, etc.)
				X		X		Optimizing production flow based on the use of qualitative observations and quantitative analytics
				X		X		Using lean manufacturing principles (value stream mapping, minimize waste)
	X						X	Knowing the science and engineering underlying the product
								Effectively managing people and projects
								Decreasing inventory stockouts by understanding your own operations and your suppliers
				X				Conducting and assessing the results of statistical process control analyses or design of experiments

These results indicate that all technician training programs for 3DP/AM should put an emphasis on: 1) communicating and collaborating; 2) taking initiative to learn new skills or technologies; and 3) independently organizing time or prioritizing skills. Many firms recommended apprenticeship or rotational internship programs to help improve these human skills. Skills such as decreasing inventory stockouts, effectively managing people and projects, and conducting and assessing the results of statistical process control analyses were expected more for engineers than technicians.

Interview results underscore the value of troubleshooting and critical thinking. Troubleshooting was emphasized as one of the most critical skills for technicians in the 3DP/AM industry. Several respondents explained that troubleshooting is 95% of the technician job. Firms have found that screening employee's hobbies can help identify whether a person is able to troubleshoot or not. Hobbies that include a mechanical component (e.g., mechanic for cars) or at-home 3D printing have been found to be helpful indicators for firms.

Critical thinking skill needs

When trying to define what is meant by critical thinking, one definition is "the ability to analyze evidence and facts to form a judgment"(Gambrill 2005). More practically, we can classify these judgments with the following levels of critical thinking:

1. Perceiving the issue – What should I measure or observe to know that a problem exists?
2. Hypothesizing about problem cause – What might be causing the problem?
3. Developing a framework for hypothesis testing – How can I confirm my hypothesis?
4. Inferring whether tests confirm the hypothesis - Does the test suggest that my hypothesis was right?
5. Communicating the outcome – How (and to whom) do I report on what has happened?

Respondents were asked to identify what level of critical thinking is expected of technicians. Responses were grouped by engineering technician positions and other technical workers shown in Figure 16.

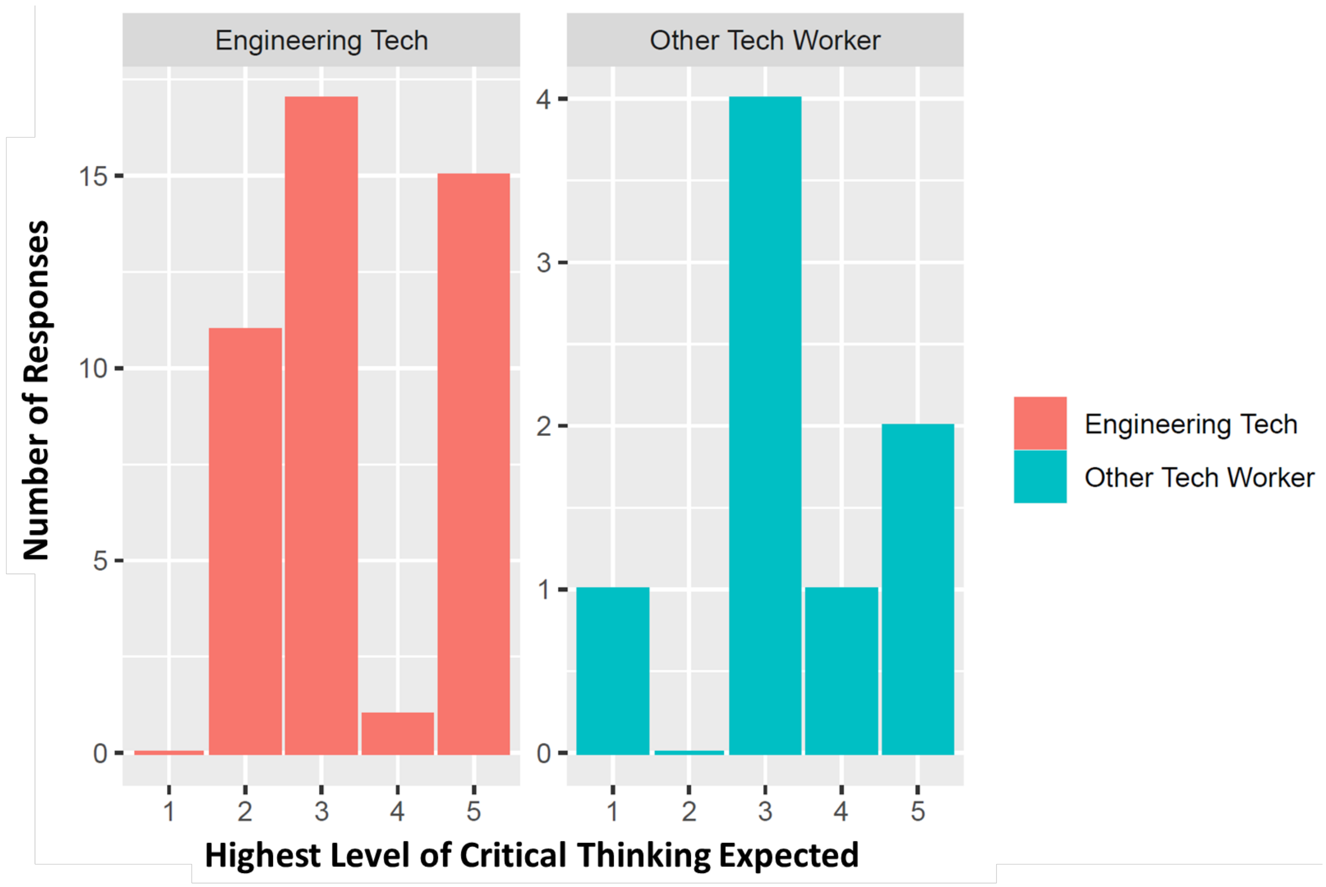

Figure 16. Respondents valued critical thinking skills for all occupations studied. However, most respondents expect a higher level of critical thinking for engineering technicians. While there are respondents that expect the highest level for other technical workers as well, a majority of respondents expect other technical workers to develop a framework for hypothesis testing.

Firms believe critical thinking is necessary for engineering technicians. They believe engineering technicians should be able to use a systems perspective to understand failures or challenges by using a triage process. Technicians that are able to contribute to detection of errors/failures and can communicate these issues are extremely valuable for firms. Technicians can be part of the solution and therefore firms suggest more practical and hands-on training exercises to prepare them for the manufacturing floor.

Results indicate that 40% of firms expect engineering technicians to have competency in nearly all aspects of critical thinking (perceiving, hypothesizing, testing, and interpreting testing). Most other technical production workers are expected to perform hypothesis testing (50%) while 25% of the respondents expected these workers to be able to master all aspects of critical thinking.

Identifying Important Common Skills

To understand the skills needed broadly at the middle-skill occupation level, the research team has identified skills that are both shared (common) and important across multiple occupations to enable training programs to be relevant for companies across the 3DP/AM supply chain. Figure 17 shows the eight highest weighted average importance scores for the general task/skill (GTS) level ranked from highest to lowest.

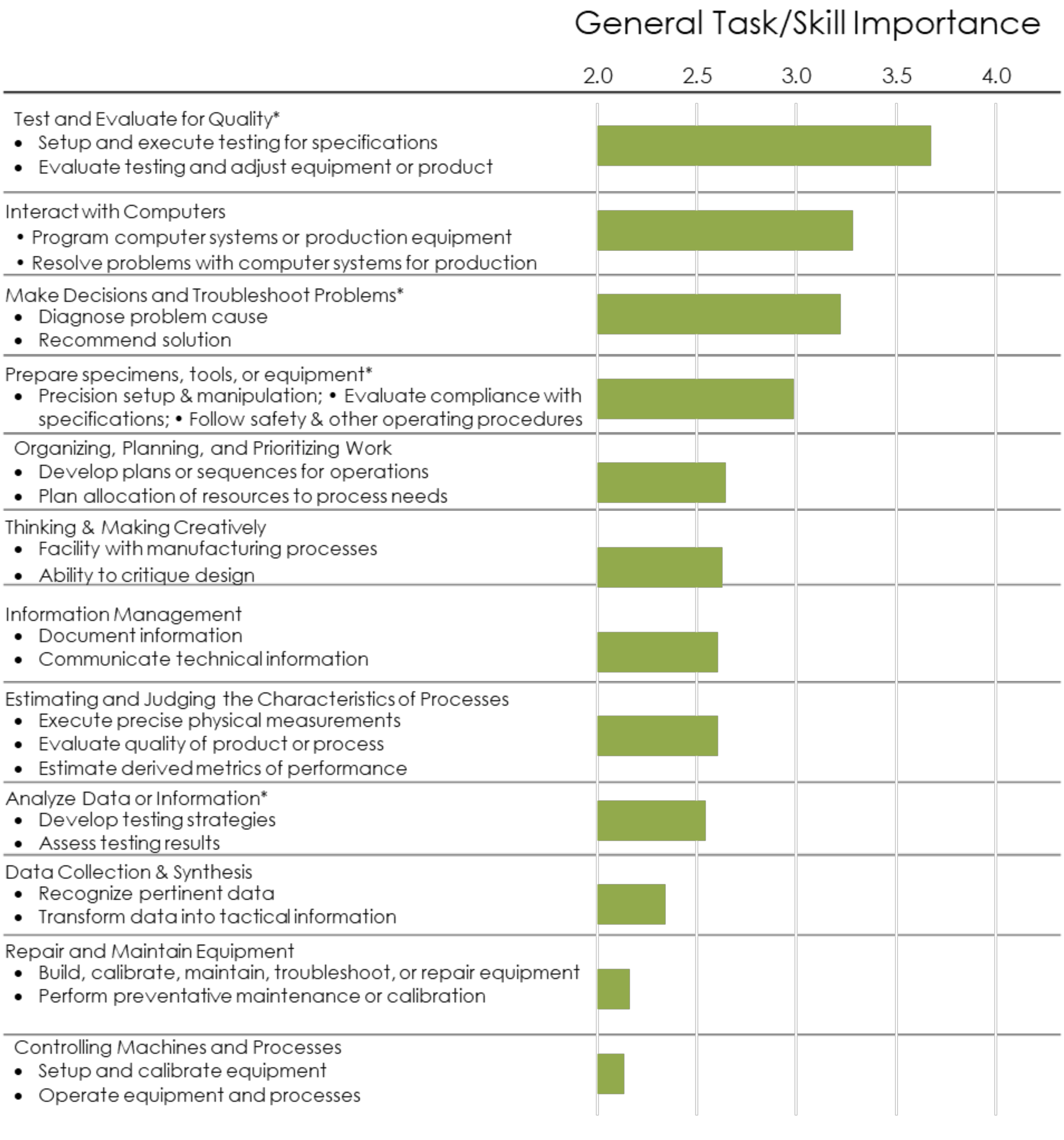

Figure 17 General Task or Skill ranked by weighted average importance of the skills within that class. Only GTS that are shared across at least two occupations are labeled as common and, therefore, included in this figure.

The top three ranked common skills include test and evaluate for quality, interact with computers, and make decisions and troubleshoot problems. These skills involve understanding of the entire system from tools to each piece of equipment. The remaining skills emphasize critical thinking, troubleshooting, quality testing, and communication and interpretation of technical information. Table 13 to Table 14 provide details on the underlying specific skills associated with these GTS. Details for all GTS are provided in the appendix.

Details on Common Skills

Table 13 shows the underlying categorization and score detail for the highest ranked GTS, "Test and Evaluate for Quality." This skillset involves critical thinking skills and an understanding of quality assurance including "develop, test, or program equipment" or "modify cutting programs to account for problems." This skillset was especially important for mechatronics technicians and CNC tool operators. The second highest ranked GTS, "Interacting with Computers" underscores the importance of understanding how to operate and program automated production equipment. This skill was especially important for mechatronics technicians and CNC tool operators.

Table 13. Details of skill importance for General Task/Skill "Monitor Processes, Materials, or Surroundings" and its sub classes and skills. (-nr- indicates insufficient responses to report a meaningful average).

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Test and Evaluate for Quality	3.7	Program computer systems or production equipment.	3.7	Modify cutting programs to account for problems encountered during operation	4.3									X
				Input machine control programs	4.0									X
				Set up and operate computer-controlled machines or robots to perform one or more machine functions on metal or plastic workpieces.	3.8									X
				Develop, test, or program automated production equipment or other robotic systems.	2.4						X			
Interacting With Computers	3.3	Read documents or materials to inform work processes.	3.3	Read blueprints, diagrams, or technical orders to determine methods of assembly.	3.3						X			
				Review project instructions and blueprints to ascertain test specifications, procedures, and objectives	2.9									X

Table 14 shows the details of the scoring for the third highest ranked GTS, "Making Decisions and Troubleshooting Problems." This skillset requires the physical workmanship to monitor and inspect equipment, the cognitive understanding of how the machine functions, and troubleshooting skills to understand how to address malfunctions. This skillset was especially important for additive technicians and CNC tool operators.

Table 14. Details of skill importance for General Task/Skill "Prepare specimens, tools, or equipment" and "Repairing and Maintaining Equipment" and their sub classes and skills. (-nr- indicates insufficient responses to report a meaningful average).

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Making Decisions and Troubleshooting Problems	3.2	Monitor equipment operation.	3.5	Monitor machine operation and control panel displays, and compare readings to specifications to detect malfunctions.	4.2									X
				Check to ensure that workpieces are properly lubricated and cooled during machine operation.	3.2									X
				Inspects or tests machinery or equipment to diagnose machine malfunction	3.1							X		
		Monitor operations to ensure adequate performance.	3.3	Proper handling and storage of additive materials (i.e., powders)	3.8							X		
				Verify that equipment is being operated and maintained according to quality assurance standards .	2.8									
		Monitor safety or security of work areas, facilities, or properties.	3.1	Recognizes, interacts with, or operates protective and lockout devices	3.1							X		
		Monitor operations to ensure compliance with regulations or standards.	2.1	Read worker logs, product processing sheets, or specification sheets to verify quality assurance specifications.	2.1									

Results Summary

Semi-structured interviews with operations managers in the 3D printing and additive manufacturing (3DP/AM) industry from thirty firms across the U.S. were conducted to identify workforce needs within the 3DP/AM supply chain. The interviews were focused on middle-skilled technical occupations (except for information technology occupations). Skills gaps, hiring and training challenges, and the importance of emerging technical and human skills were evaluated by firms. While there are hiring and training challenges in many of the advanced manufacturing industries, 3DP/AM firms especially face the challenge of building up talent within the industry since 3D printing and additive is currently learned informally. Firms emphasized that updates to existing curriculum could help reduce the amount of trial and error in training their employees.

There is increasing demand expected for all middle-skilled technical workers studied with significant demand expected for additive technicians and CNC tool operators. For firms where mechatronics technicians are relevant, these firms also expect this position to grow significantly.

To understand the growth trends in the 3DP/AM industry, the expected number of positions and openings within the industry was estimated. Data from the US Bureau of Labor Statistics, market intelligence reports, and survey responses were used to project both anticipated positions and openings. We estimate middle-skilled positions within this industry to grow from around 3,100 today to 19,400 by the end of the decade (see *Figure ES 2*). This translates to over 27,300 cumulative openings for middle skilled technical workers or around 2,400 new middle-skilled workers per year. Assuming a typical training program graduates about 15 students per year, the US would need more than 160 programs to meet the needs of the 3DP/AM industry. In a Massachusetts context, we estimate around 540 total openings in these positions for this sector. This translates to about 48 middle-skilled openings per year, indicating the need for three educational program to train middle-skilled technical workers for the state's 3DP/AM industry.

Firms emphasized the significant hiring challenges in this industry for nearly all technical middle-skilled workers, especially for additive technicians and CNC tool operators. In terms of training, most firms explained that all middle-skilled workers require at least some training, with additive technicians, maintenance and support technicians, and CNC tool operators requiring extensive on-the-job training. Specifically, firms shared that improving training on safety for all the positions would be invaluable for the industry.

Emerging and human skill importance was evaluated for each position including a critical thinking needs assessment. An emerging technical skill that was emphasized across most of the positions was working with digital collaboration tools. Human skills are also growing in importance for technicians in advanced manufacturing industries. In particular, interview responses indicate that the following skills should be emphasized in training:

- Communicating and collaborating with engineering and management staff
- Taking initiative to learn new skills or technologies
- Independently organizing time or prioritizing skills
- Managing unfamiliar problems and situations

Many firms underscored the importance of critical thinking for all technician positions and believe it is necessary for engineering technicians. They believe engineering technicians should be able to use a systems perspective to understand failures or challenges by using a triage process. Technicians that are able to contribute to detection of errors/failures and can communicate these issues are extremely valuable for firms. Technicians can be part of the solution and therefore firms suggest more practical and hands-on training exercises to prepare them for the manufacturing floor.

Results indicate that 40% of firms expect engineering technicians to have competency in nearly all aspects of critical thinking (perceiving, hypothesizing, testing, and interpreting testing). Most other technical production workers are expected to perform hypothesis testing (50%) while 25% of the respondents expected these workers to be able to master all aspects of critical thinking.

We highlight the specific technical skills that are both increasingly important and exhibit skills gaps for six occupations: additive technicians, mechanical engineering technicians, industrial engineering technicians, mechatronics technicians, mechanical drafters and CNC tool operators.

Because the interviews focused on skills described in the Bureau of Labor Statistics O*Net dataset, it was possible to not only identify job-specific skills but also to use the taxonomy within that dataset to aggregate survey responses to more generalized classes of skills (referred to as General Task/Skill, GTS).

Looking across all middle-skilled positions, the top five generalized skills that are expected to be the most important for middle-skilled workers in the 3DP/AM industry are:

- Test and Evaluate for Quality*
- Interact with Computers
- Make Decisions and Troubleshoot Problems*
- Prepare Specimens, Tools, or Equipment*
- Organizing, Planning, and Prioritizing Work

To get a better understanding of where training resources would be best applied, we also examined whether important skills also exhibited a significant skills gap (difference between competency of new hires and that required by industry). Three of the most important GTS categories of skills were also frequently flagged as exhibiting a significant skills gap.

An emphasis in training these skills that exhibit significant training gaps, importance, and are common among multiple positions would add value to the 3DP/AM workforce. Technicians in the 3DP/AM industry should also improve knowledge of quality and communication with colleagues.

For middle-skilled workers in the 3DP/AM industry, the analysis of generalized skills points to the growing importance of the abilities to operate, maintain, and troubleshoot equipment, analyze data, ensure quality standards, and communicate with supervisors, peers, and subordinates.

The results from this study demonstrate the growing opportunity for technical careers in the 3DP/AM industry across the U.S. and areas of improvement for the training and skills development for those pursuing 3DP/AM careers.

Appendix

Literature review and gap analysis

Past efforts to characterize skills gaps and fulfill workforce needs have been successful in increasing employment opportunities specifically for middle-skilled workers. In Pennsylvania, a National Science Foundation (NSF) grant provided funding to develop community college programs in the area of nanofabrication (Hallacher, Fenwick, and Fonash 2002) through professional development workshops for educators and new curricula for students. Through these efforts, community college graduates from targeted nanofabrication programs received more than seven job offers on average upon graduation. There were also regional benefits of new nanofabrication facilities locating to Pennsylvania as a result of the increased workforce and skill development of Pennsylvania community college graduates. In an NSF funded workshop for additive manufacturing (AM), stakeholders evaluated the current state, workforce needs, and future trends to inform research and education and training for the upcoming workforce (Huang et al. 2015) . Their findings suggest the university-community college partnership model can enable a well-trained AM workforce through sharing of lectures, knowledge via educator workshops, web resources, and laboratory spaces for hands-on training. Participants in the workshop recommended future funding opportunities through America Makes, the NSF, and other federal agencies for AM education and curricula development. With support for feeder programs, a stable workforce of well-trained, low-cost, entry-level technicians will continue to grow (Foy and Iwaszek 1996). In addition to curricula development, internship opportunities will also be necessary for the up-and-coming workforce to obtain the on-the-job experience necessary to fill these critical gaps (Hardcastle and Waterman-Hoey 2010).

While curricula have been developed for emerging manufacturing areas in the past (e.g. nanofabrication), this is the first development of a roadmap method to assess workforce gaps and needs across several advanced manufacturing industries. This research provides a method to classify emerging advanced manufacturing industries, identify companies within the industry, and leverage industry expertise to inform workforce development needs. In BLS, these emerging manufacturing industries are organized broadly, and as a result, the industries are not immediately apparent. To address these limitations, we've developed a systematic, data-driven method for classifying advanced manufacturing industries and an industry stakeholder informed education roadmap on current priority and future accelerating jobs and training needs. The education roadmap will provide recommendations for community college, certificate programs, and instructors on how to upgrade their curricula and matriculate more competitive technician candidates, for targeted hiring in advanced manufacturing industry clusters across the US. This method is performed in four steps: 1) classification of emerging advanced manufacturing industries, 2) survey development leveraging industry expertise, 3) survey assessment by experts, and 4) survey distribution, response analysis and recommendations. To demonstrate the method for classifying and assessing employment needs for an advanced manufacturing industry, the method is applied to a case study of the photonics industry.

Detailed Methods

To characterize workforce needs within advanced manufacturing industries we have relied primarily on interviewing firms within that industry. Development and deployment of the semi-structured interview followed a process involving four major steps.

Discern emerging advanced manufacturing industries

The discernment process aims to identify a sufficiently large sample of firms that are representative of the advanced manufacturing sector of interest and to identify how these firms are currently classified in some relevant industrial classification system. This classification system will be referred to as the discernment system. This information will play two roles in subsequent analyses. First these firms will be the target of surveys and interviews. Second, the classifiers associated with these firms will be used to estimate employment intensity from BLS databases.

The first step in this classification process was to identify firms that are representative for the industry of interest. We refer to these firms as archetypes. This is an inherently manual, expert-based process. For the 3DP/AM industry, archetype firms were identified through a number of methods, including querying member listing from relevant professional associations[5] and expert elicitation. Once archetypes were identified, they were queried within the discernment system. The most common economic activity type (EAT) codes associated with those firms within the discernment system were cataloged. This set of codes serves as one definition of our industry of interest and were used to identify a larger set of similar firms.

[5] In this case, we specifically queried the membership roster of America Makes, a Manufacturing USA institute based in Youngstown, OH.

To leverage data catalogued by the US BLS, firms must be identified using the North American Industrial Classification System (NAICS)(Dalziel 2007). If the discernment system is not NAICS (as it was not in our case study here), then it is necessary to create an empirical mapping between the two systems. Here we do this by using the discernment system to identify a larger set of firms of the same type as the archetypes and then identifying the prevailing NAICS codes used to characterize those firms.

The North American Industrial Classification Systems (NAICS)

Industry classification systems reflect a country's economic output, trade, and employment (Dalziel 2007). The NAICS is a framework that is used widely for firm classification. NAICS was developed in 1997. It captures a large number of business types including those in the service industry (BLS). In the NAICS system, firms are identified using their production processes and the codes are updated every five years to reflect changes in industry titles and descriptions. The industries and sectors are classified with two to six digits, where the higher number of digits represents a greater detailed classification of the industry.

While the NAICS system may be more representative than its predecessor, the SIC system, many researchers have found limitations in classifying industries based on their production processes (Kile and Phillips 2009). For instance, Dalziel (2007) explains that eight non-diversified communications equipment manufacturers are classified in four separate industries and two separate sectors despite being major competitors. Other limitations include addressing the rapid changes in technology advancements. While there are many different types of software companies, all firms that develop software are classified with the same code, 511210, Software Publishers (Dalziel 2007). In classifying emerging industries, such as those in the advanced manufacturing space, it can be challenging to identify the boundaries of the industry and assign a NAICS code that is accurately representative of a firm's activities. For example, when searching the NAICS database for "photonics", the NAICS code assigned is 541715, Research and Development in the Physical, Engineering, and Life Sciences (except Nanotechnology and Biotechnology). Although photonics can be classified under this code, botany and agricultural research also share this classification. This shows yet another limitation of the NAICS system; the NAICS codes are often too broad to capture the specifics of an emerging industry. As a result, it can be difficult to capture the current employment statistics for an advanced manufacturing industry and understand the existing workforce gaps.

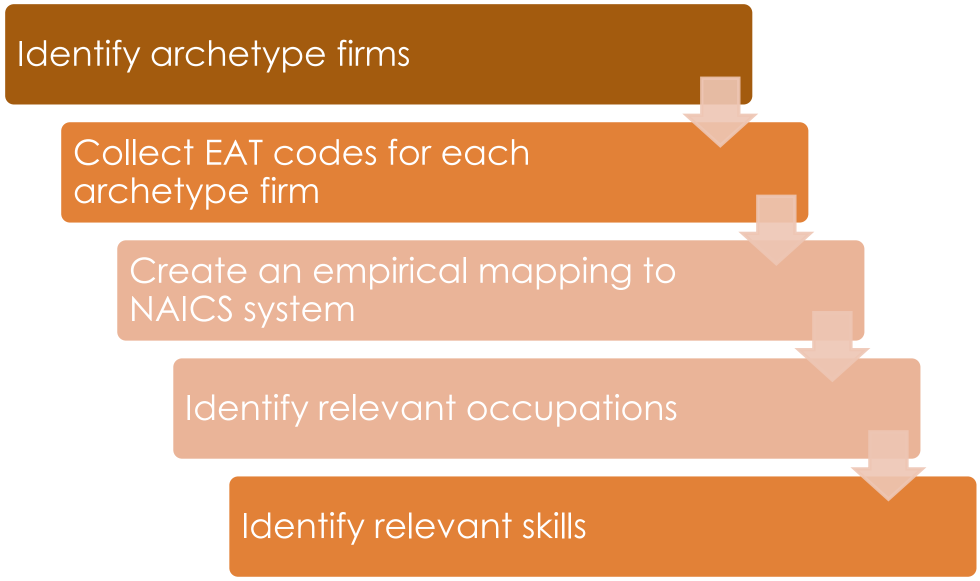

Figure 18 5-step process for discerning emerging advanced manufacturing industries.

The global 3DP/AM industry is expected to reach $56.1 billion by 2026(Williams 2021). Table 15 lists eight companies that were identified as archetypes for the 3DP/AM industry.

EAT codes for several industrial classification systems were collected for each archetype firm using the D&B Hoovers business database (Dun and Bradstreet 2020). Here we elected to use the D&B Hoovers Proprietary SIC 8-digit Code (SIC8) classification system (Cramer 2017), an expansion of the original SIC system, to discern the industry. Table 15 shows the SIC8 and NAICS EAT codes for the archetype firms. If a primary and secondary code are provided, both codes are listed. This process was repeated for all the archetype companies for the industry to help develop a description of the firms based on the industrial classification codes.

Table 15 3DP/AM industry classification archetype examples

Company	US Standard Industrial Classification – DB Hoovers Expanded Version (SIC8)	North American Industrial Classification System (NAICS)
3Degrees, LLC	73790203 – Online services technology consultants	541512 – Computer Systems Design Services
Additive Technologies	33130201 – Alloys, additive, except copper	331110 – Iron and steel mills and ferroalloy manufacturing
3D Systems Corporation	73720000 – Prepackaged software	511210 – Software publishers
Stratasys	5770000 – Computer peripheral equipment, nec	334118 – Computer Terminal and other computer peripheral equipment manufacturing
FormLabs	27590000 – Commercial printing, nec	323111 – Commercial printing (except screen and books)
SLM Solutions	36990202 -- Laser welding, drilling, and cutting equipment	35590000 – Other industrial machinery manufacturing
AON3D	35550000 – Printing trades machinery	333244 – Printing machinery and equipment manufacturing
Additive Industries North America, Inc.	39990000 – Manufacturing industries, nec	39990000 – Manufacturing industries, nec

Using the D&B Hoovers companies database, we identified the 1,640 unique firms with more than 20 employees that are classified by one of the 8 SIC8 codes. These firms are classified into one of eight NAICS codes. These three codes are listed in Table 16. Occupation data available from the BLS is organized in a truncated version of NAICS, with most industries organized at the three- or four-digit level. As such, Table 16 also lists the three BLS equivalent codes that capture this same scope for the 3DP/AM industry.

Table 16. Most common NAICS codes for firms identified as in the 3DP/AM industry. These codes capture 98% of firms identified.

NAICS Code	NAICS Description	BLS Equivalent Code
333999	All Other Miscellaneous General-Purpose Machinery Manufacturing	3330A1
323111	Commercial printing (except screens and books)	323100
333244	Printing machinery and equipment manufacturing	333200

In summary, we discern the 3DP/AM industry as firms classified as one of the 8 codes within the SIC8 system which maps to the three BLS equivalent industrial classification codes 3330A1, 323100, and 333200. Effectively, we are defining the industry of interest as a hybrid of these industries. This hybrid industry description, will be used to identify relevant occupations.

Posit Relevant Occupations and Skills

Identify Relevant Occupations

To leverage the extensive surveying knowledge embedded within the O*NET database(U.S. Department of Labor 2020), we use the BLS equivalent NAICS codes to identify a relevant set of occupations for our industry of interest.

Specifically, occupation codes were identified using a combination of the 2018 National Employment Matrix (NEM) (U.S. Bureau of Labor Statistics 2018) and the O*NET database. Using this dataset, we identified occupations that met the following criteria:

- Associated with the industry of interest (as defined by the codes identified previously)
- Technical in nature (see next paragraph)
- Primarily held by middle-skilled workers (see two paragraphs down)
- Represented more than 0.1% of the workforce across the defined industry

The definition of technical work is inherently subjective. For our purposes here, we limit our search to jobs associated with the Standard Occupational Classification (SOC) codes listed in Table 17. That includes occupations involved in mathematics, architecture, engineering, life, physical, and social sciences, installation, maintenance, repair, and production. Computer related positions were excluded because in early test interviews we learned that skills for those positions would not be influenced by the specific industry.

Table 17. Standard Occupational Classification codes considered in this study.

Standard Occupation Classification Code (2-digit level)	Class Name
15-0000	Computer and mathematical occupations (excluding 15-1: Computer occupations)
17-0000	Architecture and engineering occupations
19-0000	Life, physical, and social science occupations
49-0000	Installation, maintenance, and repair occupations
51-0000	Production occupations

Middle-skilled workers are often defined as those with an education level that is greater than a high school diploma and less than a Bachelor's degree (Fuller and Raman 2017). Occupations are always held by workers with a range of education. For this research, we define middle-skilled occupations to be those for which both greater than 30% of the workforce is middle skilled and less than 50% of the workforce is either lower-skilled or upper-skilled.

Based on these definitions, we identified 19 relevant middle-skilled positions associated with the 3DP/AM industry. To facilitate survey data collection, these were grouped into ten representative positions, as shown in bold in Table 18.

Table 18. Focal occupations that were evaluated in this study. Bold titles represent representative occupations that were served as proxy for the subsequent specific occupations.

Occupation	Standard Occupation Classification Code
Middle-skilled	
Additive technician*	
Electrical and electronics engineering technicians(representing)	
Electrical and electronics engineering technicians	17-3023
Electrical and electronics drafters	17-3012
Electro-mechanical technicians	17-3024
Industrial engineering technicians(representing)	
Industrial engineering technicians	17-3026
Aerospace engineering and operations technicians	17-3021
Mechanical engineering technicians	17-3027
Mechanical drafters	17-3013
Chemical/materials technicians (representing)	
Chemical technician	19-4031
Materials scientist	19-2032
Maintenance and Support Technicians (representing)	
Industrial machinery mechanics	49-9041
Maintenance workers, machinery	49-9043
HVAC mechanics and installers	49-9021
Mobile heavy equipment mechanics, except engines	49-3042
Electrical & electronics repairers, commercial & ind. equipment	49-2094
Computer-controlled machine tool operators(representing)	
Computer-controlled machine tool operators	51-4011
Computer numerically controlled machine tool programmers	51-4012
Other Technical Production Worker (representing)	
Machinists	51-4041
Tool and die makers	51-4111

*The O*NET database does not currently include the additive technician position. Therefore, the position was modeled after the Urban Institute framework for an Additive Manufacturing Maintenance Technician(Urban Institute 2019)

Identify Relevant Skills

For each identified occupation, an associated set of competencies (skills) and tools was developed from the U.S. Department of Labor O*Net database, an online tool for career exploration and job analysis (U.S. Department of Labor 2020). The O*Net database uses a hierarchical taxonomic approach to organize tasks and skills. (Peterson et al. 2001). The database was originally developed through survey methods to create a relational database of occupation attributes for the U.S. economy (Peterson et al. 2001)and helps create a common language for job descriptors. An example of tools and competencies collected is shown in Figure 19 for an Electrical Engineering Technician.

Electrical Engineering Technician

Competencies:

- Diagnose, test, or analyze the performance of electrical components, assemblies, or systems.
- Calculate design specifications or cost, material, and resource estimates, and prepare project schedules and budgets.
- Compile and maintain records documenting engineering schematics, installed equipment, installation or operational problems, resources used, repairs, or corrective action performed.
- Set up and operate standard or specialized testing equipment.
- Review, develop, and prepare maintenance standards.
- Install or maintain electrical control systems, industrial automation systems, or electrical equipment, including control circuits, variable speed drives, or programmable logic controllers.
- Design or modify engineering schematics for electrical transmission and distribution systems using computer-aided design (CAD) software.
- Supervise the construction or testing of electrical prototypes, according to general instructions and established standards.

Tools:

- Microcontrollers (e.g., Programmable logic controllers PLC)
- Electronic measuring probes (e.g., Probe stations)
- Multimeters
- Voltage or current meters (e.g., Analog current meters, Digital voltmeters DVM, Standing wave ratio SWR meters)
- Network analyzers
- Frequency analyzers (e.g., Spectrum analyzers)
- Frequency counters or timer or dividers (e.g., Microwave frequency counters)
- Reflectometers (e.g., Optical time domain reflectometers OTDR)
- Signal generators
- Development environment software
- Program testing software
- Analytical or scientific software

Figure 19 Competencies and tools associated with the job title electrical engineering technician.

Emerging Technical Skills

While the O*NET database provides valuable insight into the current technical skills needed for these occupations, the research team also wanted to get a sense of what skills are emerging as important within the 3DP/AM industry.

To accomplish this, we made use of two methods to identify potentially relevant emerging skills. The first method relied on discussions of the changing nature of work within the academic literature. Specifically, based on information within MIT Production in the Innovation Economy (PIE) survey (Weaver and Osterman 2017), the essential skills framework used by the Canadian government (Government of Canada 2015), and the Future of Work report (Autor, Mindell, and Reynolds 2020). Based on the authors' synthesis of these reports, we identified the following skills as potentially relevant and emerging for technical middle-skilled workers in manufacturing:

- Programming and troubleshooting automated process equipment (CNC, programmable production equipment, etc.)
- Conducting and assessing the results of statistical process control analyses or design of experiments
- Optimizing production flow based on the use of qualitative observations and quantitative analytics
- Using lean manufacturing principles (value stream mapping, minimize waste)
- Decreasing inventory and stockouts by understanding your own operations and your suppliers
- Working with digital collaboration tools (Computerized maintenance management software, connected worker platforms, workflow management, etc.)

The second method was to make use of a real-time labor market intelligence analytics database to identify emerging skills for each occupation. Burning Glass Labor Insight™ (BGLI) collects job posting data from job boards, firm websites, and job ad websites that represent more than 40,000 online resources and 3.4 million jobs (Burning Glass Technologies 2021). Duplicate postings are removed and natural language processing methods extract the in-demand occupations, skills, and credentials. Two approaches were used to identify relevant skills list from the BGLI database. It is important to note that while we did not specifically include tools and technologies in our interviews due to limited time; however, knowledge of in-demand tools and technologies can help inform trends in the 3DP/AM industry.

In the first approach, referred to as a keyword-based query, we attempted to identify relevant skills by querying middle-skilled posting associated with manufacturing and with the keywords representing the 3DP/AM industry. Specifically, we applied the filters shown in Table 19 which yielded 32,238 job postings. Finally, we added a filter where the job title must include "technician" resulting in 5,548 postings. Comparison between these two queries (with "technician" and without), helped to highlight technician-specific skills and isolate skills that are typical for all types of middle skilled positions within the industry (e.g. Microsoft Office Suite).

Table 19. Filter criteria applied for relevant education levels and keywords in the Labor Insight™ database.

Criteria	**Filter Applied**
Time Period	07/01/2016-06/31/2021
Education	High school or vocational training or Associate's degree
Industry	Manufacturing
Keywords	Additive; 3D; 3D printing
Location	Nationwide
Title includes	Technician

In a second approach, referred to as an employer-based query, we searched for relevant and current skills by querying postings specifically associated with the two middle-skilled technician positions identified within BGLI –industrial/mechanical engineering technician or general engineering technician – and with firms specifically known to be in the 3DP/AM industry. The filtering on employer and types of occupations as shown in Table 20, resulting in 1,206,685 job postings. To once again narrow the search and reduce noise in the dataset, the "technician" filter was added, reducing the number of postings to 3,439.

Table 20. Filter criteria applied for relevant employers and occupations in the Labor Insight™ database.

Criteria	**Filter Applied**
Time Period	07/01/2016-06/31/2021
Occupation(s)	General engineering technician or industrial/mechanical engineering technician
Employer	148 3DP/AM firms
Location	Nationwide
Title includes	Technician

The top 200 technical skills and software skills were identified from both approaches and compared with the O*NET tasks, detailed work activities, tools (and examples), and technologies (and examples) associated with the three technician positions found in both databases: electrical engineering technicians, mechanical engineering technicians, and industrial engineering technicians.

To identify skills not represented in the O*NET database, we performed a two-stage assessment. First, an NLP tool, UDPipe in R (Wijffels 2021), was used to lemmatize[6] the text of both the BGLI skills and the O*NET data and, then, to identify matches between the two. Matches and partial matches of at least 25% commonality were flagged for human evaluation. Based on this, skills or tools that were present in BGLI but not in O*NET were flagged to ensure all emerging skills, tools, and technologies are identified to inform curriculum development and training.

The O*NET database is a source of comprehensive job classification information with detail and context that is needed for in person interviews. The BGLI data is uniquely able to identify emergent skills and technologies in the field, but the information can require effort to contextualize given their brevity and occasional specificity. Overall, O*NET and

[6]Lemmatization is a linguistics process of combining the inflected parts of a word to analyze them as a single item. It is a common natural language processing technique.

Burning Glass Labor Insight™ complement one another in the skills gap analysis for the 3DP/AM industry.

While there were very few skills absent in the O*NET database, we identified emerging skills and interviewed firms about their importance to their hiring decision over the next five years. The results can be seen below.

Electrical Engineering Technician

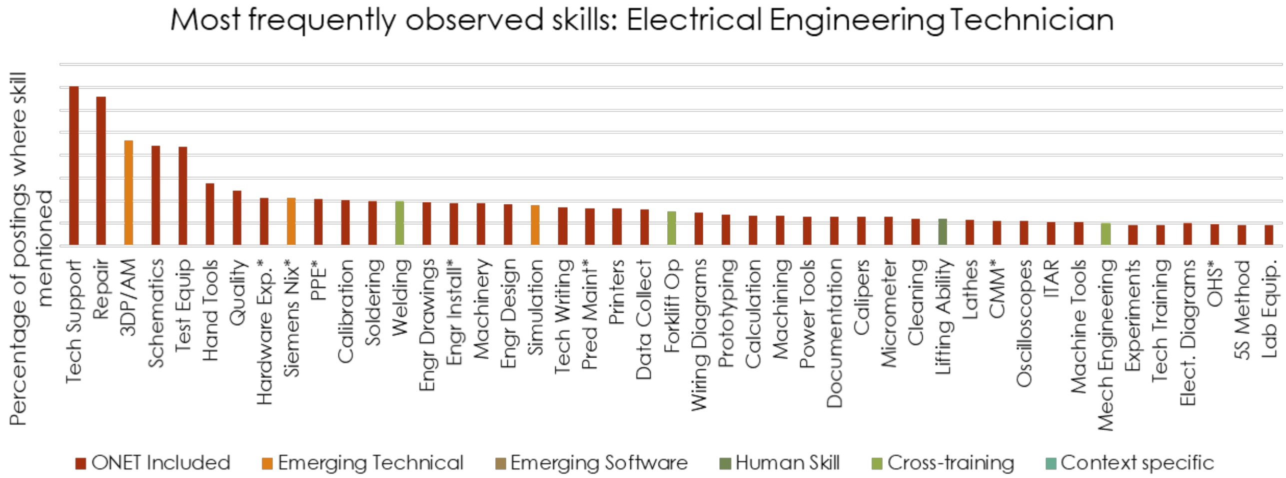

Figure 20 The most frequently observed skills for electrical engineering technicians classified as ONET included, emerging technical, emerging software, human skill, cross-training, or context specific.

Table 21 Skills in at least 5% of postings for electrical engineering technicians from the employer and keyword approach. The maximum percentage of postings where the skill was mentioned was reported.

Skill	Skill Category	Percent of postings skill mentioned
Technical Support	ONET Included	35%
Repair	ONET Included	33%
3D Printing / Additive Manufacturing (AM)	Emerging Technical	23%
Schematic Diagrams	ONET Included	22%
Test Equipment	ONET Included	22%
Hand Tools	ONET Included	14%
Quality Assurance and Control	ONET Included	12%
Hardware Experience	ONET Included	11%
Siemens Nixdorf Hardware	Emerging Technical	11%
Personal Protective Equipment (PPE)	ONET Included	10%
Calibration	ONET Included	10%
Soldering	ONET Included	10%
Welding	Cross-training	10%
Engineering Drawings	ONET Included	10%

Engineering Design and Installation	ONET Included	10%
Machinery	ONET Included	9%
Engineering Design	ONET Included	9%
Simulation	Emerging Technical	9%
Technical Writing / Editing	ONET Included	8%
Predictive / Preventative Maintenance	ONET Included	8%
Printers	ONET Included	8%
Data Collection	ONET Included	8%
Forklift Operation	Cross-training	8%
Wiring	ONET Included	7%
Prototyping	ONET Included	7%
Calculation	ONET Included	7%
Machining	ONET Included	7%
Power Tools	ONET Included	7%
Engineering Documentation	ONET Included	6%
Calipers	ONET Included	6%
Micrometers	ONET Included	6%
Cleaning	ONET Included	6%
Lifting Ability	Human Skill	6%
Lathes	ONET Included	6%
Coordinate Measuring Machine (CMM)	ONET Included	6%
Oscilloscopes	ONET Included	5%
International Traffic in Arms Regulations (ITAR)	ONET Included	5%
Machine Tools	ONET Included	5%
Mechanical Engineering	Cross-training	5%
Experiments	ONET Included	5%
Technical Training	ONET Included	5%
Electrical Diagrams / Schematics	ONET Included	5%
Occupational Health and Safety	ONET Included	5%
5S Methodology	ONET Included	5%
Laboratory Equipment	ONET Included	5%

Mechanical Engineering Technician

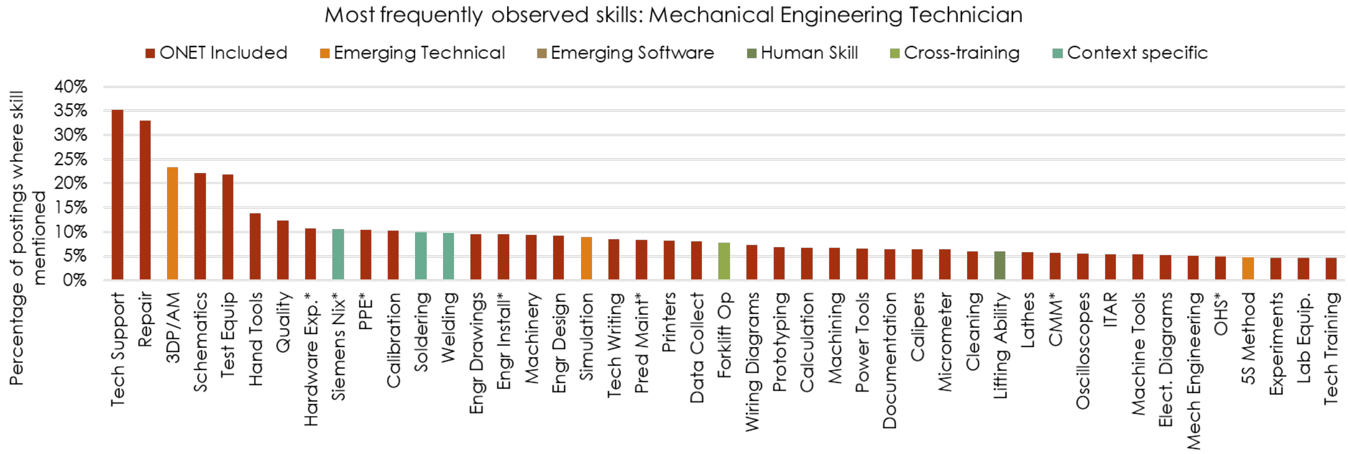

Figure 21 The most frequently observed skills for mechanical engineering technicians classified as ONET included, emerging technical, emerging software, human skill, cross-training, or context specific.

Table 22 Skills in at least 5% of postings for mechanical engineering technicians from the employer and keyword approach. The maximum percentage of postings where the skill was mentioned was reported.

Skill	Skill Category	Percentage of postings skills mentioned
Technical Support	ONET Included	35%
Repair	ONET Included	33%
3D Printing / Additive Manufacturing (AM)	Emerging Technical	23%
Schematic Diagrams	ONET Included	22%
Test Equipment	ONET Included	22%
Hand Tools	ONET Included	14%
Quality Assurance and Control	ONET Included	12%
Hardware Experience	ONET Included	11%
Siemens Nixdorf Hardware	Context Specific	11%
Personal Protective Equipment (PPE)	ONET Included	10%
Calibration	ONET Included	10%
Soldering	Context Specific	10%
Welding	Context Specific	10%
Engineering Drawings	ONET Included	10%
Engineering Design and Installation	ONET Included	10%
Machinery	ONET Included	9%
Engineering Design	ONET Included	9%
Simulation	Emerging Technical	9%
Technical Writing / Editing	ONET Included	8%
Predictive / Preventative Maintenance	ONET Included	8%

Printers	ONET Included	8%
Data Collection	ONET Included	8%
Forklift Operation	Cross-training	8%
Wiring	ONET Included	7%
Prototyping	ONET Included	7%
Calculation	ONET Included	7%
Machining	ONET Included	7%
Power Tools	ONET Included	7%
Engineering Documentation	ONET Included	6%
Calipers	ONET Included	6%
Micrometers	ONET Included	6%
Cleaning	ONET Included	6%
Lifting Ability	Human Skill	6%
Lathes	ONET Included	6%
Coordinate Measuring Machine (CMM)	ONET Included	6%
Oscilloscopes	ONET Included	5%
International Traffic in Arms Regulations (ITAR)	ONET Included	5%
Machine Tools	ONET Included	5%
Electrical Diagrams / Schematics	ONET Included	5%
Mechanical Engineering	ONET Included	5%
Occupational Health and Safety	ONET Included	5%
5S Methodology	Emerging Technical	5%
Experiments	ONET Included	5%
Laboratory Equipment	ONET Included	5%
Technical Training	ONET Included	5%

Industrial Engineering Technicians

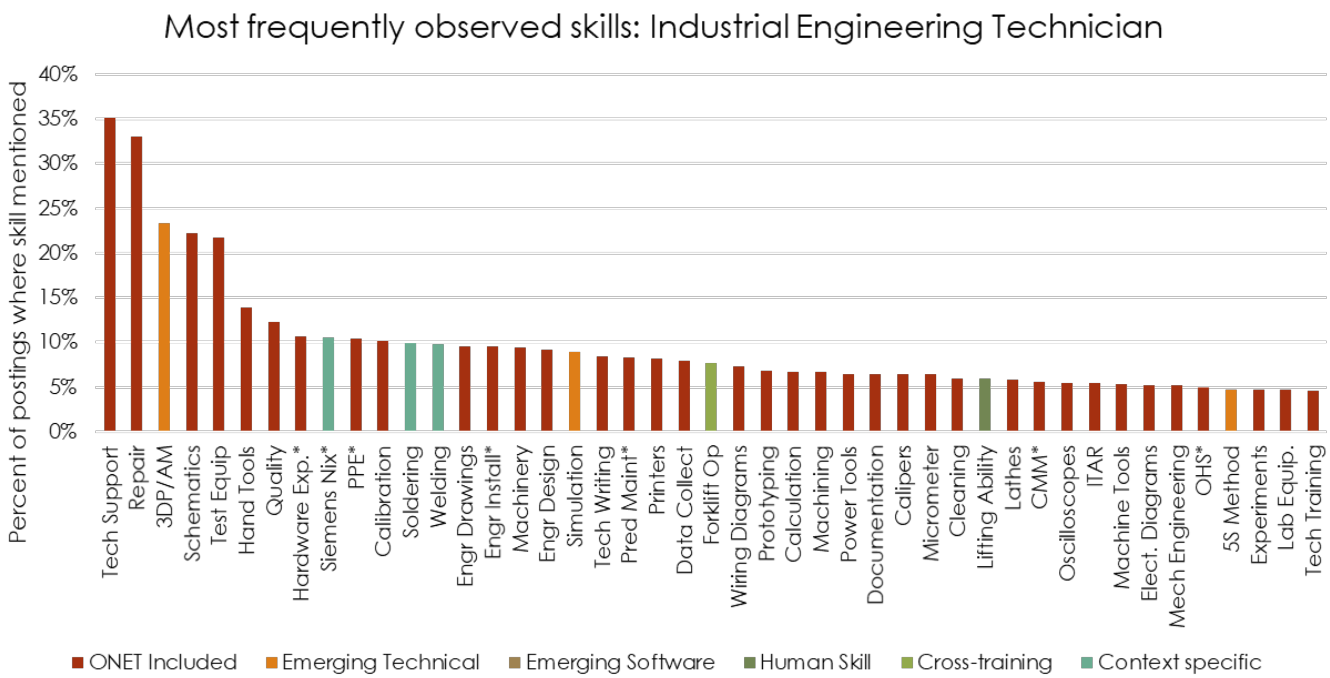

Figure 22 The most frequently observed skills for industrial engineering technicians classified as ONET included, emerging technical, emerging software, human skill, cross-training, or context specific.

Table 23 Skills in at least 5% of postings for industrial engineering technicians from the employer and keyword approach. The maximum percentage of postings where the skill was mentioned was reported.

Skill	Skill Category	Percentage of postings skills mentioned
Technical Support	ONET Included	35%
Repair	ONET Included	33%
3D Printing / Additive Manufacturing (AM)	Emerging Technical	23%
Schematic Diagrams	ONET Included	22%
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Machinery	ONET Included	9%
Engineering Design	ONET Included	9%
Simulation	Emerging Technical	9%
Technical Writing / Editing	ONET Included	8%
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Occupational Health and Safety	ONET Included	5%
5S Methodology	Emerging Technical	5%
Experiments	ONET Included	5%
Laboratory Equipment	ONET Included	5%
Technical Training	ONET Included	5%

Human Skills: What about "Soft" skills?

The focus of this study was to assess the training gaps associated with specific applied skills for technical workers. This focus in no way implies that the research team believes that such technical skills are more important than other non-technical skills (also known as "soft" or human skills). Research was focused on technical skills for two reasons. First, our primary goal was to develop insights to shape training programs aimed to support the 3DP/AM industry. Such programs themselves focus on technical skills and, therefore, require feedback on the same. Secondly, the interview applied in this research was of a scale that taxed most respondents. As such, tradeoffs had to be made to limit its scope and content. As a result, this study explores only a limited set of human skills including a novel analysis of critical thinking.

Although they were not the focus of this study, it is important for training programs to recognize that human skills complement technical skills, enhance employability, and improve productivity (Schulz 2008; Rao 2014). Although both industry and academia are reaching consensus that employees need human skills in addition to the technical skills taught in most STEM training programs (Kumar and Hsiao 2007), there is no consensus on which human skills are most important or even how to frame and organize human skills.

A recent study by researchers at MIT's Jameel World Education Lab attempts to bridge that gap by synthesizing more than 40 skills frameworks into the Human Skills Matrix (HSM). Their analysis found that communication and self-management skills were the most commonly identified important human skills. These were followed by creativity, problem solving, critical thinking, and teamwork. The HSM synthesizes this information into 24 non-technical skills that employees need to thrive (Stump, Westerman, and Hall 2020). These skills are grouped into four categories including Thinking, Interacting, Managing ourselves, and Leading. This framework was used to guide the selection of human skills studied here.

Specifically, we asked operations managers about the importance of these six human skills (as well as a detailed question about critical thinking) for middle-skilled manufacturing occupations:

- Effectively managing people and projects (Leading)
- Managing unfamiliar problems and situations (Thinking)
- Independently organizing time or prioritizing tasks (Managing ourselves)
- Communicating and collaborating with engineering and management staff (Interacting)
- Taking initiative to learn new skills or technologies (Managing ourselves)
- Knowing the science and engineering underlying the product (Thinking)

Critical thinking is widely cited as a skill that leads to success. Nevertheless, there are no established methods to characterize it. Here we define critical thinking as "the ability to analyze evidence and facts to form a judgment" (Gambrill 2005).To better characterize the role of critical thinking for technical middle-skilled occupations, we decompose the judgment process into the following sub-tasks:

1. Perceiving the issue – What should I measure or observe to know that a problem exists?
2. Hypothesizing about problem cause – What might be causing the problem?
3. Developing a framework for hypothesis testing – How can I confirm my hypothesis?

4. Inferring whether tests confirm the hypothesis - Does the test suggest that my hypothesis was right?

5. Communicating the outcome – How (and to whom) do I report on what has happened?

Respondents were asked to identify what aspect of critical thinking is important of technicians working at their facility.

Identifying Important, Common Skills

While it is valuable to understand the skills trends within individual occupations, in many cases, training programs or courses will need to be more broadly applicable, serving the needs of multiple types of learners. To that end, the research team has attempted to identify those skills that are both important and shared (common) among multiple occupations.

This was accomplished by making use of the hierarchical nature of the O*NET dataset from which occupation-specific skills were identified. To create the survey administered for this project, the research team identified occupation-specific skills from the list of Tasks within the O*NET dataset. In that context, Tasks are the most specific representation of occupation requirements. Tasks are related to more generalized classifications of skills as represented in Figure 23. Specifically, Tasks can be associated with many Detailed Work Activities which are each associated with only one Intermediate Work Activity which are themselves associated with only one General Work Activity. (To maintain a more consistent terminology in this report, we will refer to these classifications as Detailed Tasks/Skills (DTS), Intermediate Tasks/Skill (ITS), and General Tasks/Skills (GTS), respectively.)

Because of this hierarchical relationship, it was possible to compute an average skill importance at any level of aggregation. To do this, a weighting was assigned to each level of response for each specific skill (Importance will Grow Significantly = 5, Grow= 3, Hold = 1, Not important = 0). Then weighted averages of these importance levels were computed for each specific task or skill and the corresponding DTS, ITS, and GTS. For this set of occupations, the DTS level of aggregation did not provide useful insights. As such, it is not discussed further in the results section.

These weighted importance scores were then used to identify the most important GTS and ITS across all of the occupations considered in this survey. From these important skills we identify those that are shared by at least three occupations and refer to this set as important, common (as in shared) skills.

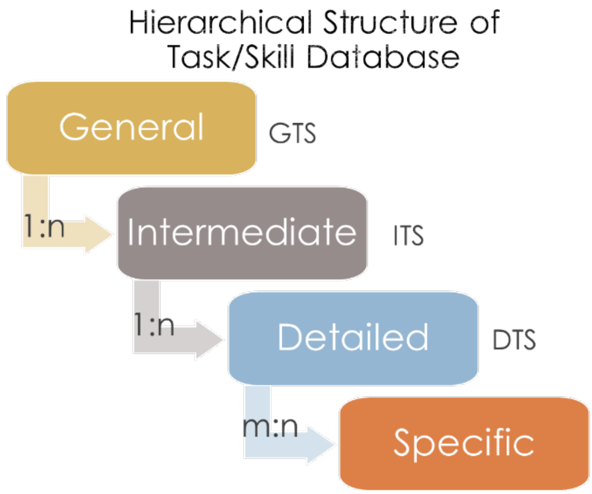


Figure 23. Hierarchical structure of the task/skill database used in this study. Survey respondents were asked about occupation specific (orange level) tasks or skill. 1:n indicates a one (parent) to many (child) relationship. m:n indicates a many to many relationship. The hierarchies are defined within the O*NET database.

Semi-Structured Interview

Interview design

The interview is structured into four main sections:

5) firm characterization,
6) hiring and training challenges
7) workforce scaling, and
8) emerging skill needs.

In the first section of the interview, respondents were asked to identify the primary role that their firm plays in the 3DP/AM supply chain. Additionally, respondents were asked to estimate the firm's annual revenues and overall employment levels.

In the second section, respondents were asked to identify which of the focal occupations were relevant for their firm. Then for each relevant occupation they were asked whether

- Demand for that position would (Hold, Grow Somewhat, or Grow Significantly)?
- Filling an open position was (Easy, Average, or Hard)?
- In house training for new hires tends to be (Basic, Moderate, or Extensive training)?

In the final section of the survey, respondents were randomly assigned three relevant occupations. For each of these, they were asked to characterize the expected skill level for each position for their current technicians, the skill level of new hires for these positions, and rank the importance of the skills in 5 years compared to today. The categories for skill level included the following:

- Not applicable
- Aware of
- Familiar with
- Competent at
- Proficient with
- Mastery of

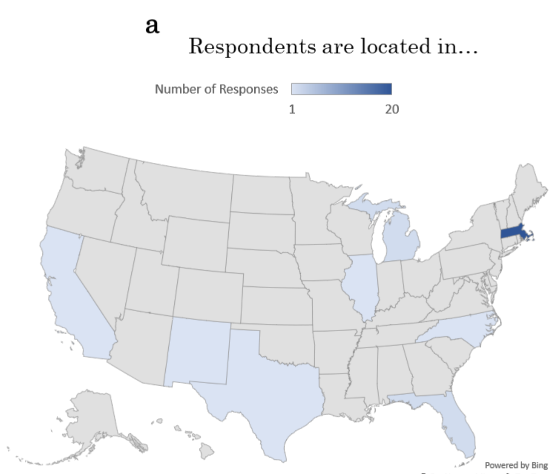
The expected importance ranks from much less important than now to much more important than now.

Semi-Structured Interview Process

The interview responses were captured in the Qualtrics online platform(Qualtrics XM 2021) and interviews were conducted with 3DP/AM firms mainly located in the New England area with some responses nationwide. Thirty responses where the respondent completed the entirety of the interview template were received and incorporated into the following results.

Respondent Demographics

Survey respondents came from a broad array of firms. As shown in Figure 24a, a majority of the respondents came from Massachusetts, with a few firms from other states. Firms ranged in size from as few as 4 employees to as many as 205,000. The median firm size was 104 employees. Annual revenue ranged from $0.2M to $ 79,000M with a median of $18M per year (Figure 24b).



b

	Annual Revenue (million USD)	Size of Firm (Headcount)
Median	$18	104
Mean	$5,360	9,400
Min	$0.2	4
Max	$79,000	205,000

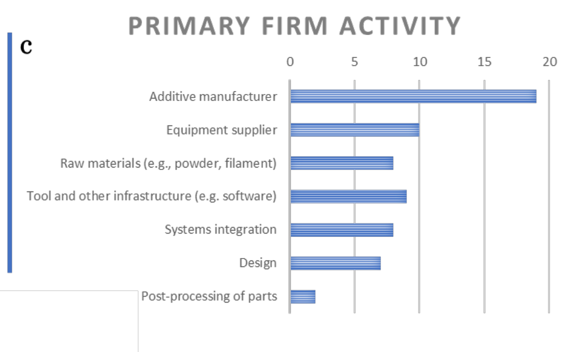


Figure 24. Distribution of respondent location, size, revenue, and primary supply chain activity.

Firms were asked to identify their role in the supply chain. There was a range of primary activities for each firm (see Figure 24c) with a majority focused on additive manufacturing and equipment suppliers.

Common Important Skills

The following pages contain the details of survey responses for each specific skill organized by Intermediate Task/Skill (ITS) and by General Task/Skill (GTS). In the subsequent tables, occupation titles are abbreviated as listed in Table 24.

Table 24. Focal occupations that were evaluated in this study and abbreviated title used in GTS / ITS tables

Occupation	Abbreviation
Industrial engineering technicians	Ind Eng T
Electrical and electronics engineering technicians	ElecEng T
Mechanical engineering technicians	MechEng T
Chemical technicians	Chemical T
Computer-controlled machine tool operators	CNC Oper
Mechanical and mechatronics engineering technician	MechaTron T
Additive technicians	Add T
Mechanical drafters	Mech Dr T

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Test and Evaluate for Quality	3.7	Program computer systems or production equipment.	3.7	Modify cutting programs to account for problems encountered during operation	4.3									X
				Input machine control programs	4.0									X
				Set up and operate computer-controlled machines or robots to perform one or more machine functions on metal or plastic workpieces.	3.8									X
				Develop, test, or program automated production equipment or other robotic systems.	2.4						X			
Interacting With Computers	3.3	Read documents or materials to inform work processes.	3.3	Read blueprints, diagrams, or technical orders to determine methods of assembly.	3.3						X			
				Review project instructions and blueprints to ascertain test specifications, procedures, and objectives	2.9									
														X

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Making Decisions and Troubleshooting Problems	3.2	Monitor equipment operation.	3.5	Monitor machine operation and control panel displays, and compare readings to specifications to detect malfunctions.	4.2									X
				Check to ensure that workpieces are properly lubricated and cooled during machine operation.	3.2									X
				Inspects or tests machinery or equipment to diagnose machine malfunction	3.1							X		
		Monitor operations to ensure adequate performance.	3.3	Proper handling and storage of additive materials (i.e., powders)	3.8							X		
				Verify that equipment is being operated and maintained according to quality assurance standards .	2.8									
		Monitor safety or security of work areas, facilities, or properties.	3.1	Recognizes, interacts with, or operates protective and lockout devices	3.1							X		
		Monitor operations to ensure compliance with regulations or standards.	2.1	Read worker logs, product processing sheets, or specification sheets to verify quality assurance specifications.	2.1									

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Prepare specimens, tools, or equipment	3.0	Position workpieces or materials on equipment.	3.8	Mount, install, align, and secure tools, attachments, fixtures, and workpieces on machines, using hand tools and precision measuring instruments.	3.8									X
														X
		Set up equipment.	3.7	Set up and conduct chemical experiments, tests, and analyses, using techniques such as chromatography, spectroscopy, physical or chemical separation techniques, or microscopy.	3.3				X					
		Install commercial or production equipment.	3.3	Splice fibers, using fusion splicing or other techniques.	4.0									
				Install electrical or electronic parts and hardware in housings or assemblies, using soldering equipment and hand tools.	3.3						X			
		Disassemble equipment.	3.1	Maintain machines and remove and replace broken or worn machine tools, using hand tools.	3.1									X
		Prepare specimens or materials for testing.	2.7	Prepare chemical solutions for products or processes, following standardized formulas, or create experimental formulas.	2.7				X					
		Assemble equipment or components.	2.7	Align, fit, or assemble component parts, using hand or power tools, fixtures, templates, or microscopes.	3.1						X			

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Prepare specimens, tools, or equipment				Builds, assembles, sets up, and commissions a 3D printer and supporting equipment	2.8							X		
				Assemble optical components including photonic switches, optical backplanes, or optoelectronic interfaces.	2.0									
				Set up or operate assembly or processing equipment, such as lasers, die or wire bonders, reflow ovens, soldering irons, die shears, or wire pull testers.	1.5									
				Build, calibrate, maintain, troubleshoot, or repair electrical instruments or testing equipment.	1.1			X						
		Fabricate devices or components.	2.5	Fabricate and assemble new or modified mechanical components for products such as industrial machinery or equipment, and measuring instruments.	3.1									
				Operate drill press, grinders, engine lathe, or other machines to modify or to fabricate components.	2.5									
				Operate metalworking machines to fabricate housings, jigs, fittings, or fixtures.	2.2						X			
				Fabricate and test devices, such as optoelectronics, semiconductors, fiber optic-based devices, and fiber optic systems .	2.0									
		Adjust equipment to ensure adequate performance.	2.2	Repair, rework, or calibrate hydraulic or pneumatic assemblies or systems to meet operational specifications	2.0						X			
		Prepare industrial materials for processing or use.	0.5	Mix, pour, or use processing chemicals or gases according to safety standards or established operating procedures.	0.5									

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Organizing, Planning, and Prioritizing Work	2.6	Plan work activities.	2.6	Aid in planning work assignments in accordance with worker performance, machine capacity, production schedules, or anticipated delays.	2.6									
												X X		

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Thinking & Making Creatively	2.6	Diagnose system or equipment problems.	3.3	Uses proper standards and techniques to troubleshoot	3.3							X		
				Assess and troubleshoot issues and plan repair work	3.1							X		
		Determine resource needs of projects or operations.	2.8	Calculate machine speed and feed ratios and the size and position of cuts.	3.6									X
				Calculate required capacities for equipment to obtain specified performance	2.9									
				Prepare electrical project cost or work-time estimates.	0.9			X						
		Determine operational methods or procedures.	1.6	Choose materials based on differing properties and characteristics for additive manufacturing models	1.9							X		
				Determine appropriate methods for fabricating and joining materials.	1.3									
				Plan method or sequence of operations for developing or testing experimental electronic or electrical equipment.	1.1			X						

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Information Management	2.6	Evaluate designs, specifications, or other technical data.	3.0	Coordinate with and consult other workers to design, lay out, or detail components and systems and to resolve design or other problems.	3.7									
				Review and analyze specifications, sketches, drawings, ideas, and related data to assess factors affecting component designs and the procedures and instructions to be followed.	2.3									
		Analyze biological or chemical substances or related data.	2.7	Set up and conduct chemical experiments, tests, and analyses, using techniques such as chromatography, spectroscopy, physical or chemical separation techniques, or microscopy.	3.3				X					
				Conduct chemical or physical laboratory tests to assist scientists in making qualitative or quantitative analyses of solids, liquids, or gaseous materials.	2.0				X					
		Analyze performance of systems or equipment.	2.4	Analyze test results in relation to design or rated specifications and test objectives, and modify or adjust equipment to meet specifications.	2.9									
				Analyze product failure data and laboratory test results to determine causes of problems and develop solutions.	2.8									
				Interpret test information to resolve design-related problems.	2.3			X						
				Compile and evaluate data using statistical process control procedures	1.8									
		Analyze data to improve operations.	2.0	Perform diagnostic analyses of optical components or processing, using analytical or metrological tools, such as microscopy, profilometry, ellipsometry devices,or optical spectrum analyzers.	2.0									

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Estimating and Judging the Characteristics of Products or Processes	2.6	Repair tools or equipment.	3.1	Assess and troubleshoot issues and plan repair work	3.1							X		
		Maintain tools or equipment.	2.4	Maintain machines and remove and replace broken or worn machine tools, using hand tools.	3.1									X
				Engages, as part of the engineer team, in the design, evaluation, configuration, or application of additive manufacturing equipment systems	2.1							X		
				Repair, rework, or calibrate hydraulic or pneumatic assemblies or systems to meet operational specifications	2.0						X			
		Maintain electronic, computer, or other technical equipment.	1.1	Build, calibrate, maintain, troubleshoot, or repair electrical instruments or testing equipment.	1.1			X						

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Analyzing Data or Information	2.5	Inspect commercial, industrial, or production systems or equipment.	3.1	Recognizes, interacts with, or operates protective and lockout devices	3.1							X		
				Inspects or tests machinery or equipment to diagnose machine malfunction	3.1							X		
		Inspect completed work or finished products.	2.6	Verify part dimensions or clearances to ensure conformance to specifications, using precision measuring instruments.	3.0						X			
				Inspect electrical project work for quality control and assurance.	1.5			X						
		Test performance of equipment or systems.	2.5	Builds, assembles, sets up, and commissions a 3D printer and supporting equipment	2.8							X		
				Test equipment, using test devices attached to generator, voltage regulator, or other electrical parts, such as generators or spark plugs.	2.7									
				Test performance of electromechanical assemblies, using test instruments such as oscilloscopes, electronic voltmeters, or bridges.	2.5						X			
				Develop, test, or program automated production equipment or other robotic systems.	2.4						X			

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Analyzing Data or Information				Terminate, cure, polish, or test fiber cables with mechanical connectors.	1.5									
				Set up or operate test equipment to evaluate performance of developmental parts, assemblies, or systems under simulated operating conditions.	1.4			X						
		Test characteristics of materials or products.	1.2	Test products for performance characteristics or adherence to specifications.	1.2		X							

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Data Collection & Synthesis	2.3	Design industrial systems or equipment.	3.1	Fabricate and assemble new or modified mechanical components for products such as industrial machinery or equipment, and measuring instruments.	3.1									
		Design electrical or electronic systems or equipment.	2.6	Compute mathematical formulas to develop and design detailed specifications for components or machinery, using computer-assisted equipment.	3.1									
				Develop, test, or program automated production equipment or other robotic systems.	2.4			X			X			
		Design computer or information systems or applications.	2.2	Install or program computer hardware or machine or instrumentation software in microprocessor-based systems	2.2						X			
		Create visual designs or displays.	2.2	Draft detail drawing or sketch for drafting room completion or to request parts fabrication by machine, sheet or wood shops.	3.6									
				Uses proper standards and techniques to troubleshoot	2.4									
				Confer with customer representatives to review schematics and answer questions pertaining to installation of systems.	1.9									
				Modify and revise designs to correct operating deficiencies or to reduce production problems.	1.8									
				Prepare charts or diagrams to illustrate workflow, routing, floor layouts, material handling, or machine utilization.	1.6			X						

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Repairing and Maintaining Equipment	2.2	Maintain operational records.	2.5	Documents additive manufacturing equipment protocols, test procedures, and results	2.5							X		
		Present research or technical information.	2.5	Write technical reports or prepare graphs or charts to document experimental results.	2.5				X					
		Document technical designs, procedures, or activities.	2.2	Record test procedures and results, numerical and graphical data, and recommendations for changes in product or test methods.	2.7									
				Prepare written documentation of electromechanical test results.	2.2						X			
				Write procedures for the commissioning of electrical installations.	0.9			X						
		Prepare documentation for contracts, applications, or permits.	0.4	Prepare, review, or coordinate ongoing modifications to electrical system specifications or plans.	0.4			X						

General Task / Skill	GTS Import	Intermediate Task / Skill	ITS Import	Specific Task or Skill	Task Import	Photonic T	Ind Eng T	ElecEng T	Chemical T	MechEng T	MechT	Add Tech	Mech Dr	CNC Op
Controlling Machines and Processes	2.1	Communicate with others about specifications or project details.	2.5	Schedules time to run machine	2.2							X		
				Engages, as part of the engineer team, in the design, evaluation, configuration, or application of additive manufacturing equipment systems	2.1							X		
		Advise others on business or operational matters.	2.4	Recommend modifications to existing quality or production standards to achieve optimum quality	3.2									
				Review new product plans and make recommendations for material selection, based on design objectives such as strength, weight, heat resistance, electrical conductivity, and cost.	0.7									
				Recommend optical or optic equipment design or material changes to reduce costs or processing times.	0.5									
		Communicate with others about operational plans or activities.	2.3	Conducts discussions with line managers, colleagues, and within the engineer team	2.3							X		
		Coordinate with others to resolve problems.	1.9	Collaborate with electrical engineers or other personnel to identify, define, or solve developmental problems.	1.9			X						
		Advise others on the design or use of technologies.	1.1	Provide technical assistance in resolving electrical engineering problems encountered before, during, or after construction.	1.1			X						

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