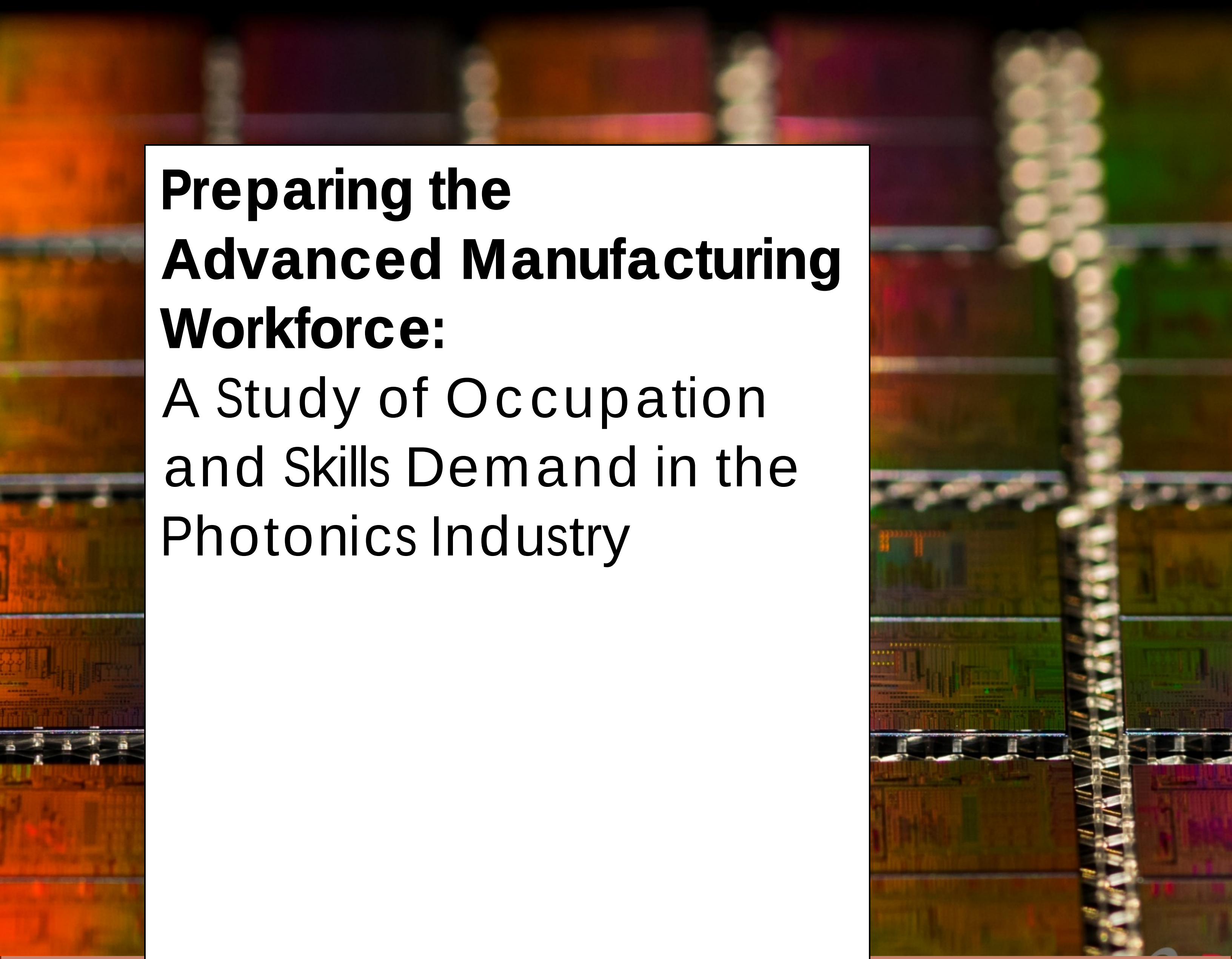


Preparing the Advanced Manufacturing Workforce:

A Study of Occupation and Skills Demand in the Photonics Industry

February 2021

Randolph Kirchain, Elizabeth Moore, Frank R Field, Sajan Saini, and George Westerman

Cover image: AIM Photonics chips designed by Precision Optical Transceivers and the RIT Integrated Photonics Group. Photo taken by Michael L. Fanto, RIT

ACKNOWLEDGEMENT

THE AUTHORS WOULD LIKE TO THANK BOTH THE MIT OFFICE OF OPEN LEARNING AND AIM ACADEMY FOR THE RESOURCES THAT MADE THIS STUDY POSSIBLE. ADDITIONALLY, WE ARE INDEBTED TO THE OPTICAL SOCIETY OF AMERICA, THE MIT MICROPHOTONICS CENTER, AND CENTER FOR OPTICAL MATERIALS SCIENCE AND ENGINEERING TECHNOLOGIES (COMSET) AT CLEMSON UNIVERSITY. WITHOUT THESE THREE GROUPS, THE SURVEY THAT UNDERPINS THIS STUDY WOULD NOT HAVE BEEN SUCCESSFUL.

Executive Summary

The MIT research team developed and deployed a survey to operations managers in the fiber optics and silicon-based integrated photonics supply chain (which we refer to herein as the "photonics industry") throughout the United States. Participating firms ranged from raw materials suppliers to device manufacturers to systems integrators.

> Training for technical workers in the photonics industry should increase emphasis on
>
> - Fabrication processes and methods
> - Design of tests (for product or process quality) and interpretation of test data
> - Diagnosis and troubleshooting of processing issues
> - Collaboration and communications with other parts of the firm
> - Fundamental science and engineering underlying photonic technologies

Respondents were asked to characterize demand, hiring challenges, and training gaps for most middle-skilled technical occupations (all technical occupations except those involved in information technology) and four selected lower-killed occupations (electronics assemblers, semiconductor processors, optical equipment operators, and ceramics equipment operators). Additionally, respondents were asked to rank the importance of specific technical skills, tools, and technology for three relevant occupations randomly selected from this list. The focus in this document on technical skills is not intended to imply that non-technical skills are not equally important for workers to thrive. Instead, we focus on technical skills to provide targeted feedback to training programs and out of purely practical considerations to limit survey scale and scope.

Overall, interviews and survey results indicate that there is strong and growing demand for technical workers in the US fiber optics and integrated photonics industry. (See Figure ES 1.)

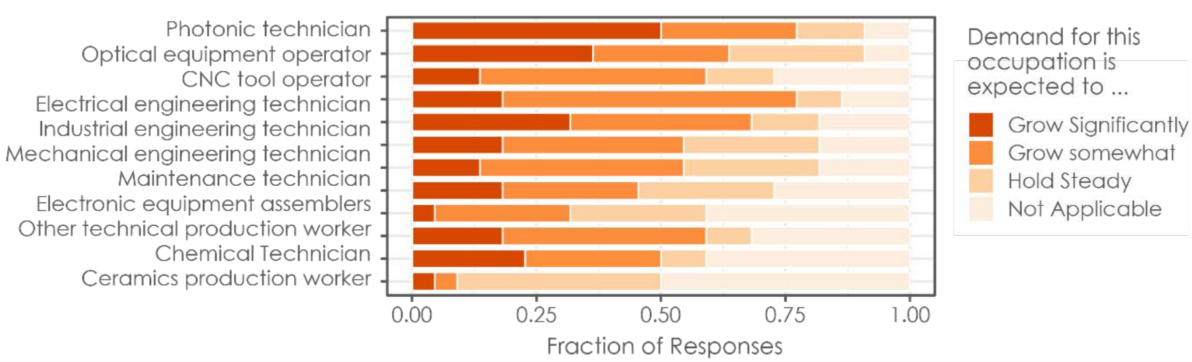


Figure ES 1. Survey results on future change in demand for the technical occupations evaluated in this study. These results are for firms primarily focused on silicon integrated photonics and systems. Results for firms primarily focused on fiber cabling are consistent and show in Figure 2

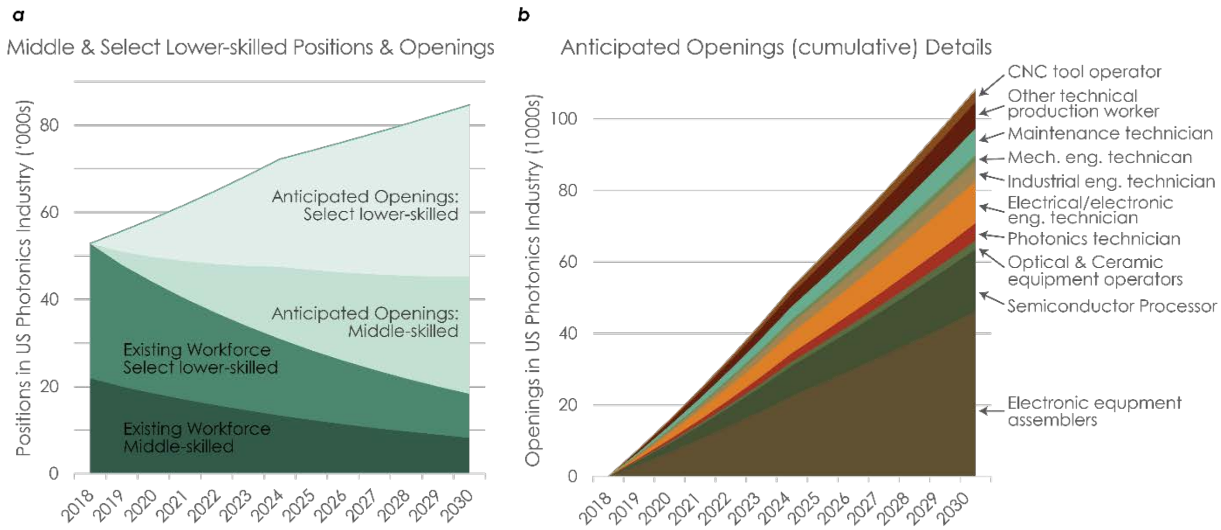


Figure ES 2. Survey results, data from the US Bureau of Labor Statistics, and market intelligence reports were used to project existing positions and expected openings for middle-skilled technical workers and four selected lower-skilled technical workers. (a) Shows an overview of trends. (b) Provides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

Specifically, as shown in Figure ES 2, we project middle-skilled and our focal lower-skilled positions within this industry to grow from around 58,000 today to nearly 85,000 by the end of the decade. Accounting for expected retirement and separations, this translates into around 42,000 cumulative middle-skilled openings over that time period or a need for around 3,500 new middle-skilled workers per year. This includes a cumulative of over 22,500 engineering technician openings averaging over 2,200 per year. These numbers suggest the country needs about 140 training programs to meet the engineering technician needs of the photonics industry. We also estimate over 61,000 cumulative openings or around 5,500 openings per year for the selected lower-skilled occupations that were evaluated as part of this study. This level of demand may support over 180 certificate programs nationally to train lower-skilled workers for the photonics industry

Mapping these number to a Massachusetts context, we estimate about 90 middle-skilled (including 70 engineering technician) and 200 lower-skilled openings per year in the photonics industry in the state; easily supporting five educational programs for training middle-skilled engineering technician workers.

Firms identified strong, growing demand and / or hiring challenges for every type of technical occupation that was evaluated in this study. Of the occupations studied, five were notable as experiencing both strong or moderate growth in demand and representing moderate to challenging hiring effort to the firm. Those occupations were:

- Photonics Technicians
- Electrical/Electronic Engineering Technicians
- Computer-controlled (CNC) Machine Tools Operators
- Optical Equipment Operators
- Semiconductor Processors

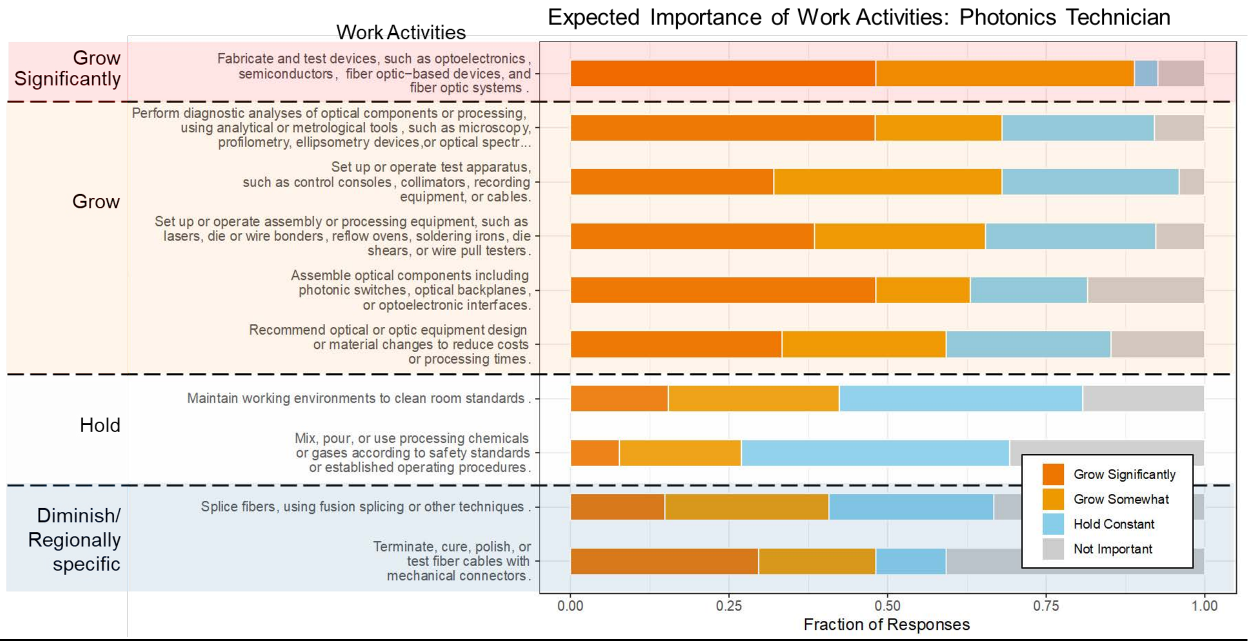


Figure ES 3. The expected importance of the skills for photonics technicians. Survey respondents were asked to indicate the trend in importance for that skill from grow significantly to not important. Categories at the left are a synthesis of overall survey results generated by the research team.

Interestingly, survey respondents identified these same five positions as requiring extensive on-the-job training for new hires. Together, these results make it clear that there are both real opportunities for technical careers within the photonics industry and for improved training for these occupations.

The occupation that received the most comment was photonic technicians. Survey respondents were asked what skills were becoming more important for photonic technicians over the next five years. (See Figure ES 3.) Based on those results, we see a clear need for photonics technicians to receive more extensive training on how to:

- Fabricate and assemble optical systems
- Diagnose and resolve process or product problems
- Design and execute testing
- Recommend design changes

Because of specific implementation decisions, we did not receive sufficient responses to comment on the technical skill needs for all five of the critical positions. We did receive feedback on the importance of specific technical skills for photonic technicians, electrical/electronic engineering technicians, and optical equipment operators. Additionally, because the skills include in the survey were derived from work activities described in the Bureau of Labor Statistics O*Net dataset, it was possible to use the hierarchy within that dataset to aggregate survey responses to more generalized classes of skills (referred to as General Task/Skill, GTS). Figure ES 4 shows the result of that aggregation across all survey responses. Specifically, we plot the weighted average skill importance for all of the specific skills included in a GTS class. These overall results make

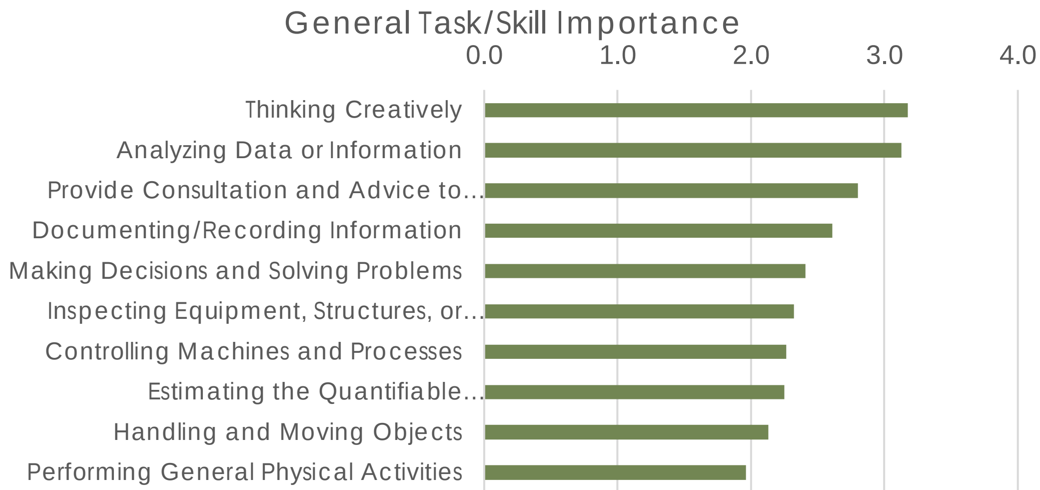


Figure ES 4. General Task/Skill (GTS) are classes that include many related specific skills. Here relevant GTS are ranked by weighted average importance of the specific skills within that class. Only GTS that are shared across at least three occupations are labeled as common and, therefore, included in this figure.

clear the growing importance of critical thinking and decision making on the part of middle-skilled workers within the photonics industry.

In light of these results concerning generalized skills and examining the responses across all technical workers, there is a clear trend to increasing importance of skills in

- Fabrication processes and methods
- Design of tests (for product or process quality) and interpretation of test data
- Diagnosis and troubleshooting of processing issues
- Collaboration and communications with other parts of the firm

In this study, the focus was on understanding and evaluating technical skills gaps. We explicitly did not ask respondents to evaluate soft skills; however, we acknowledge the significance of these skills in addressing workforce challenges and worker employability. The increasing importance of these specific technical skills is consistent with survey responses about the importance of generalized skills. Specifically, we found that survey respondents expect increasing importance for technical workers to be skilled in

- Fundamental science and engineering of the firm's technology
- Statistical methods to interpret data
- Collaboration

In the end, it is clear that there are many opportunities for technical careers in the photonics industry for both middle-skilled and lower-skilled workers. Correspondingly, there are key opportunities to improve the training for persons pursuing those careers.

Table of Contents

Introduction

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 occupation for each process step. Results indicate that automation of production

[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

processes would reduce the need for middle-skilled operators while conversely component 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.

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 fiber optics and silicon-based integrated photonics supply chain (which we refer to herein as the “photonics industry”) in the United States. 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 next generation advanced manufacturing workers. This is particularly important for the photonics industry. As discovered in a set of 30 interviews at 12 different firms in the U.S., Europe, and East Asia, there is currently a lack of specialized training and education resources for the photonics industry and most firms rely heavily on in-house, on-the-job training for technicians and operators (Combemale and Fuchs 2020).

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

[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.

using conventional industrial classification systems. Secondly, there will always be concern that government databases are not updated frequently enough to capture the trends within rapidly evolving industries.

What are fiber optics and integrated photonics technologies, and why are they important?

The fiber optics industry left the laboratory and entered public spaces in 1977 (Alwayn 2004; Shumate 2008). Since then, fiber optics have transformed global communications into an ultralow transmission loss(Hecht 2020), ultrahigh bandwidth "telecom" standard(Yu and Zhou 2010), upon which the modern internet with its concomitant applications of cloud computing (Zhou et al. 2010) and data storage/delivery are fundamentally dependent. Several significant innovations (Gupta and Ballato 2007) have marked the maturity of this forty-plus year workhorse communications technology, including the innovations of ultralow loss materials design(Thomas et al. 2000), optical amplification(Mears 2003), signal dispersion management(Ainslie and Day 1986), high performance laser diodes(Kobayashi and Mito 1988; Koch and Koren 1990), and multi-channel wavelength division multiplexed data capacity(Kahn and Ho 2004).

The adoption of fiber optics communications and sensors networks in naval and aviation transportation (Dandridge and Cogdell 1991; Sanders et al. 1996)has paved the way for its modern iteration in 21st century cloud computing: namely, the (i) rewiring of massively growing internet data centers(Schmidtke 2019) and local area networks to facilitate the new datacom industry. At the same time, the explosive growth of a cellular/wifi wireless communications technology in the last twenty-five years has led to a new race to enhance wireless bandwidth with near- to terahertz scale carrier frequencies. The rapid attenuation of higher wireless frequencies is now leading to the (ii) innovation of 5G-over-fiber expansion to the telecom network (Fujimoto et al. 2019; Blumenthal et al. 2020). Finally, the emergence of (iii) an Internet of Things (Chen and Okada 2020)and (iv) augmented imaging technologies(Braud et al. 2017) are increasing demand for more high capacity fiber LAN networks within buildings and next-generation automobiles. These four industry growth areas will increasingly drive volume demand for fiber optics globally, with *iterative* innovations to the design, processing, and installation skills developed over the last three decades.

Application areas (i)-(iv), in addition to nascent- to early-stage technologies such as (v) quantum computing(Slussarenko and Pryde 2019) and (vi) neuromorphic computing(Shastri et al. 2021), are driving *disruptive* innovation to the design, processing, and packaging of silicon-based integrated photonics chips—the optical analog of a microelectronics integrated circuit (IC) computer chip. These photonic integrated circuit (PIC) chips conceive micron- to centimeter-scale miniature optical networks on a planar platform (the mature silicon-on-insulator wafer technology, used widely in microelectronics). PICs leverage the lithography-based technology of the silicon IC industry(De Dobbelaere et al. 2018), to create microscale communications links—

mimicking the key device components of a fiber optics network—out of waveguide structures primarily made from silicon, silicon nitride, or germanium/germanium alloy materials. Early research into this technology spanned the mid-nineties to early 2010s, and the last ten years have observed a manufacturing-mature phase emerge with the development of process design kits, design for manufacture and test insights, and evolution of chip packaging(Jhoja et al. 2014; Carroll et al. 2016).

PIC chips' initial impact was envisioned to transform IC chips into microscale telecom networks, characterized by a dense integration of photonic and electronic devices components that would enable ultrahigh computation rates with minimal generation of a heat load(Atabaki et al. 2018). Since then, the micron-scale design of PIC components has inspired novel architectures(Pérez et al. 2017) that uniquely enhance wireless transceiver(Marpaung, Yao, and Capmany 2019), lab-on-a-chip sensor(Washburn and Bailey 2011), LiDAR imaging(Sun et al. 2013), and quantum computing applications(Pant et al. 2019). As consumer demand for novel on-demand functionalities grows and systems proliferate in application areas (i)-(vI), silicon-based PICs will chart the production path and requisite workforce upskilling (at the technician *and* engineer level) to meet those needs and deliverables.

In applications (i)-(iv), an intimate systems-level partnership between fiber optics and PICs will guide an inevitable convergence of future workforce skills needs and learning methods.

Methods

To characterize workforce needs within the photonics industry we have relied primarily on surveying firms within that industry. Development and deployment of that survey followed a process involving four major steps. (See Figure 1.) These are to 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 survey to characterize the relative importance of those occupations and skills; and 4) analyze the survey results to identify workforce and skills gaps. The following sections summarize key elements of these steps for studying the photonics industry. More details of the research method are provided in the appendix to this report.

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

Discern emerging advanced manufacturing industries

Photonics is an manufacturing industry that is growing rapidly and is projected to reach a value of $836.8 B globally by 2025(PR Newswire 2021). Based on expert input, we elected to treat the industry as comprising two sectors, one focused on the construction of fiber optic cabling and related systems (referred to as fiber cabling) and another on the production of photonic components and systems (referred to as components).

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 photonics industry. These were in turn 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 photonics industry are listed in Table 12 and Table 13 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 21 relevant middle-skilled positions associated with the photonics industry. To facilitate survey data collection, these were grouped into eight representative positions, as shown in bold in Table 1. This set includes five types of engineering technicians – electrical / electronic, industrial, mechanical, chemical and photonic – as well as technical maintenance personnel (e.g., mechanics, electricians), computer-numerical-controlled machine operators, and machinists.

Additionally, five lower-skilled (i.e. positions where most workers highest level of education is high-school or less) were selected to better understand firm needs and trends. These were: electrical and electronic equipment assemblers, semiconductor processors, optical equipment operators, and ceramics equipment operators These lower-skilled positions were selected because they each were highly concentrated in some portion of the photonics supply chain.

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	
Electrical and electronics engineering technicians(representing)	
Electrical and electronics engineering technicians	17-3023
Electro-mechanical technicians	17-3024
Electrical and electronics drafters	17-3012
Industrial engineering technicians(representing)	
Industrial engineering technicians	17-3026
Aerospace engineering and operations technicians	17-3021
Mechanical engineering technicians(representing)	
Mechanical engineering technicians	17-3027
Mechanical drafters	17-3013
Photonics Technician	17-3029
Chemical technicians	19-4031
Industrial machinery mechanics(representing)	
Industrial machinery mechanics	49-9041
Maintenance workers, machinery	49-9043
Heating, air conditioning, and refrigeration mechanics and installers	49-9021
Mobile heavy equipment mechanics, except engines	49-3042
Electrical and electronics repairers, commercial and industrial equipment	49-2094
Avionics technicians	49-2091
Aircraft mechanics and service technicians	49-3011
Camera and photographic equipment repairers	49-9061
Computer-controlled machine tool operators(representing)	
Computer-controlled machine tool operators	51-4011
Computer numerically controlled machine tool programmers	51-4012
Machinists(representing)	
Machinists	51-4041
Tool and die makers	51-4111
Lower-skilled	
Electrical and electronic assemblers (representing)	
Electrical, electronic, and electromechanical assemblers	51-2028
Coil winders, tapers, and finishers	51-2021
Semiconductor processors	51-9141
Optical equipment operators	51-9083
Ceramics equipment operators	51-9195

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.

The research team selected six to ten technical skills for each occupation to better understand its importance. The specific skills explored are listed in the results plots and tables in the results section of the report.

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 photonics industry. Such programs themselves focus on technical skills and, therefore, require feedback on the same. Secondly, the survey tool applied in this research was already of a scale that taxed most respondents. As such, tradeoffs had to be made to limit its scope and content.

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 skills were the most commonly identified important human skill. This was followed by creativity, problem solving, teamwork and critical thinking. 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. Although not the focus of this study, where possible, we attempt to map survey results about technical skills onto the human skill categories they most complement.

Emerging Skills

While the O*NET database gives a sense of the current technical skills needed for these occupations, the research team also wanted to get a sense of what additional types of skills would be expected to become important within the photonics industry. Considerable work has been invested into exploring what might be the consequences of the changing technological composition of manufacturing work, and we sought to leverage some of that learning into devising a set of questions that would explore how the survey respondents imagined the skills required for these occupations would change.

The specific emerging skills evaluated within the survey were:

- Conducting (and assessing the results of) statistical process control analyses
- Evaluating and making use of process management analyses
- Collaborating with engineering and management staff
- Working with digital collaboration tools
- Knowing the science & engineering underlying the product
- Troubleshooting processing problems
- Working with CAD products

Table 18 in the Appendix illustrates one mapping of these abstractions to the "essential skills" framework that is used by the Canadian government(Government of Canada 2015).

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.

Develop and deploy survey

Survey design

The survey is structured into four main sections:

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

In the first section of the survey, respondents were asked to identify the primary role that their firm plays in the photonics 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 third section of the survey, respondents were asked to quantify how many individuals were employed at their firm for each type of relevant occupation.

In the final section of the survey, respondents were randomly assigned three relevant occupations. For each of these, they were asked to rank the importance of specific skills and tools for the future.

Survey Deployment

The survey was implemented in the Qualtrics online platform(Qualtrics XM 2021) and was sent out to members of the MIT Microphotonics Center[4], members of COMSET[5] (Center for Optical Materials Science and Engineering Technologies) – fiber industry focused group based out of Clemson University, and the Optical Society of America[6] and targeted at operations managers in the integrated photonics industry. Fifty responses where the respondent completed more than 50% of the survey were received and incorporated into the following results.

Results

Survey results are presented in two major sections. First, we detail responses about overall demand for and training challenges associated with all of the positions considered in this study. This section includes results for an analysis to estimate demand for those positions. Secondly, we explore in depth the changing importance of specific technical skills for these positions. In this section, recommendations for changes in training is also provided.

Demand for occupations

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

Our findings indicate a growing demand for technical workers, both middle- and lower-skilled, in the photonics industry. A breakdown of survey results is shown in and fiber firms (second row) and by general respondent trend of demand is expected to grow significantly (first column), grow (second column), hold (third), or be soft (fourth).

Considering the frequency of "grow significantly" and "grow" responses, these results indicate that demand growth for technical workers in the components sector is growing more rapidly than in the fiber sector. This result is not unexpected because the fiber industry is more mature, while the photonics component market continues to emerge.

[4] https://mphotonics.mit.edu/
[5] http://www.clemson.edu/centers-institutes/comset/
[6] https://www.osa.org/

The positions with the greatest expected demand growth in both the component and fiber sectors are Photonics Technicians and Optical Equipment Operators. This suggests that curricula focused on the skills required for these two positions could greatly aid in addressing workforce gaps in the photonics industry.

> *"The rate of growth for photonics technician graduates is increasing each year. There is 5X the demand for graduates compared to last year. Community colleges that currently have photonics technician programs are all trying to keep up with the demand and are not having success staying ahead of that demand."*
>
> Springfield Technical Community College, 2020 Faculty Member

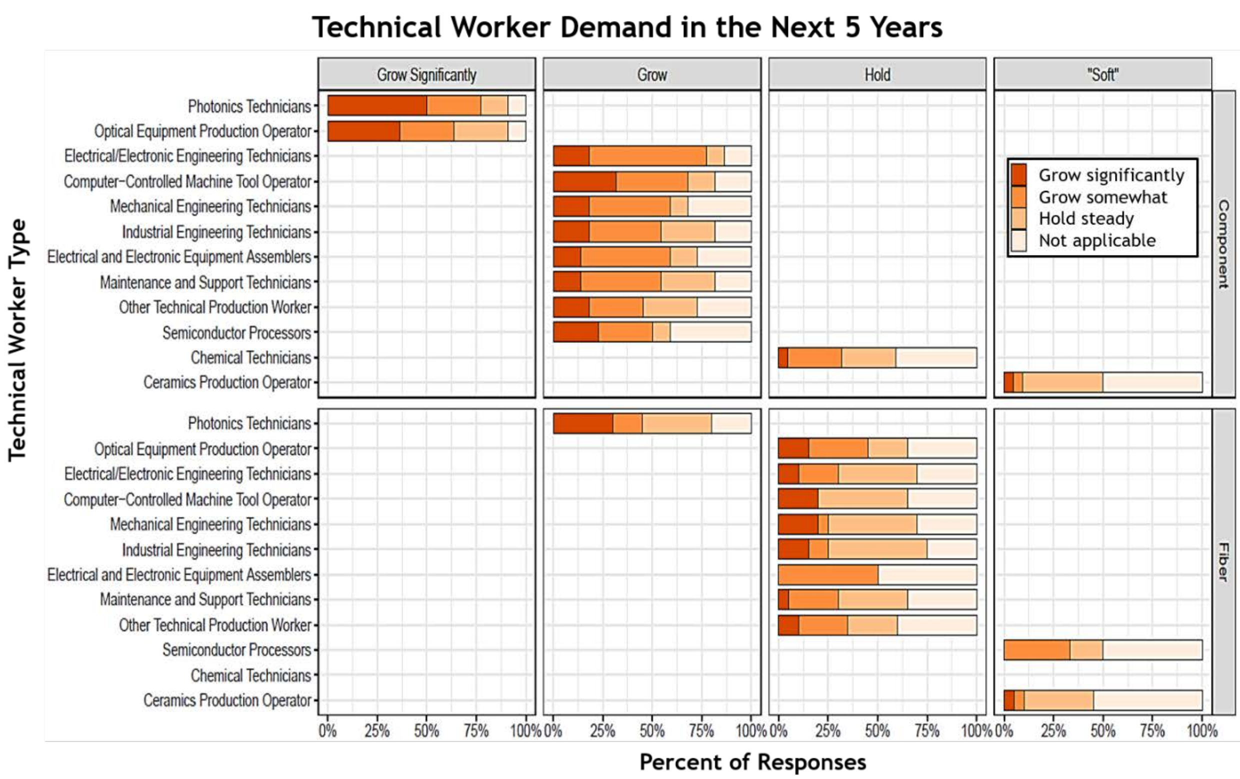


Figure 2. The technical worker occupations studied were classified according to future demand growth in the component and fiber sectors of the photonics industry. Number of respondents, n =47.

Because total demand for technical workers in this sector derives from both components and fiber firms, the researchers have attempted to identify an overall composite trend in demand. Considering responses from both types of firms the results indicate demand for the occupations can be categorized as follows:

Strong Growth	Moderate Growth	Hold	Soft
Photonics Technicians Optical Equipment Operators	Computer-controlled (CNC) Machine Tools Operators Electrical/Electronic Engineering Technicians Industrial Engineering Technicians Mechanical Engineering Technicians Electrical and Electronic Equipment Assemblers Maintenance and Support Technicians Semiconductor Processors Other Technical Production Worker	Chemical Technicians	Ceramics Production Operator

To better contextualize the growth trends implied by the survey, the research team developed a projection of expected positions and openings within the photonics industry. This projection was based on three sources of data: forecasts for the overall economic activity within the U.S. photonic industry, estimates of worker intensity per dollar of economic activity within the represented sectors, and survey responses about specific staffing levels and anticipated growth in demand for specific occupations.

Estimates of economic activity within the U.S. photonic industry were assembled from four sources of market intelligence(SPIE 2020; Lightcounting 2020; BCC Research 2017) including the SPIE[7] *Optics & Photonics Industry Report Fall 2020* and the *Optical Communication Market Forecast* produced by LightCounting. From these sources of information, we estimate the photonic industry within the United States currently generates approximately $65B of revenue and is projected to grow at a rate of approximately 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 half this rate of growth.) Of this total, photonic integrated circuits production in the United States represents about $0.5B in revenue. As such, for some time, demand for middle and lower-skilled positions will be driven by other photonics market segments. Estimates of workforce intensity (i.e. workers per dollar of revenue) are based on analysis of BLS data of the same for the hybrid industry that is used here to represent photonics.

Note: in the balance of this section, in the interest of simplicity, we refer to technical middle-skilled and lower-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. For lower-skilled occupations, we examine only four types of occupations that are particularly associated with this industry. As such, one would expect many additional lower-skilled openings beyond those we specifically analyze here.

[7] Formerly the Society of Photo-Optical Instrumentation Engineers

As shown in Figure 3, we estimate that currently there are ~58,000 technical middle-skilled and lower-skilled positions in the U.S. photonics industry with that figure growing to just under 85,000 positions by the end of the decade (Figure 3a). About 40% (~24,000) of these positions are associated with middle-skilled technical occupations. The expected growth coupled with expected departures from the existing workforce would lead to an emergence of over 100,000 openings over that same time period including around 42,000 middle-skilled and 61,000 lower-skilled technical openings. This analysis projects more than 22,500 openings for engineering technicians within the industry over the next decade. Demand for more generalized middle-skilled technical workers appears to remain strong as well, with more than 16,700 openings in maintenance technicians, other technical production workers (e.g., machinists), and CNC tool operators. The largest share of openings within the lower-skilled positions are found within the electrical and electronic equipment assembler and the semiconductor processor occupations.

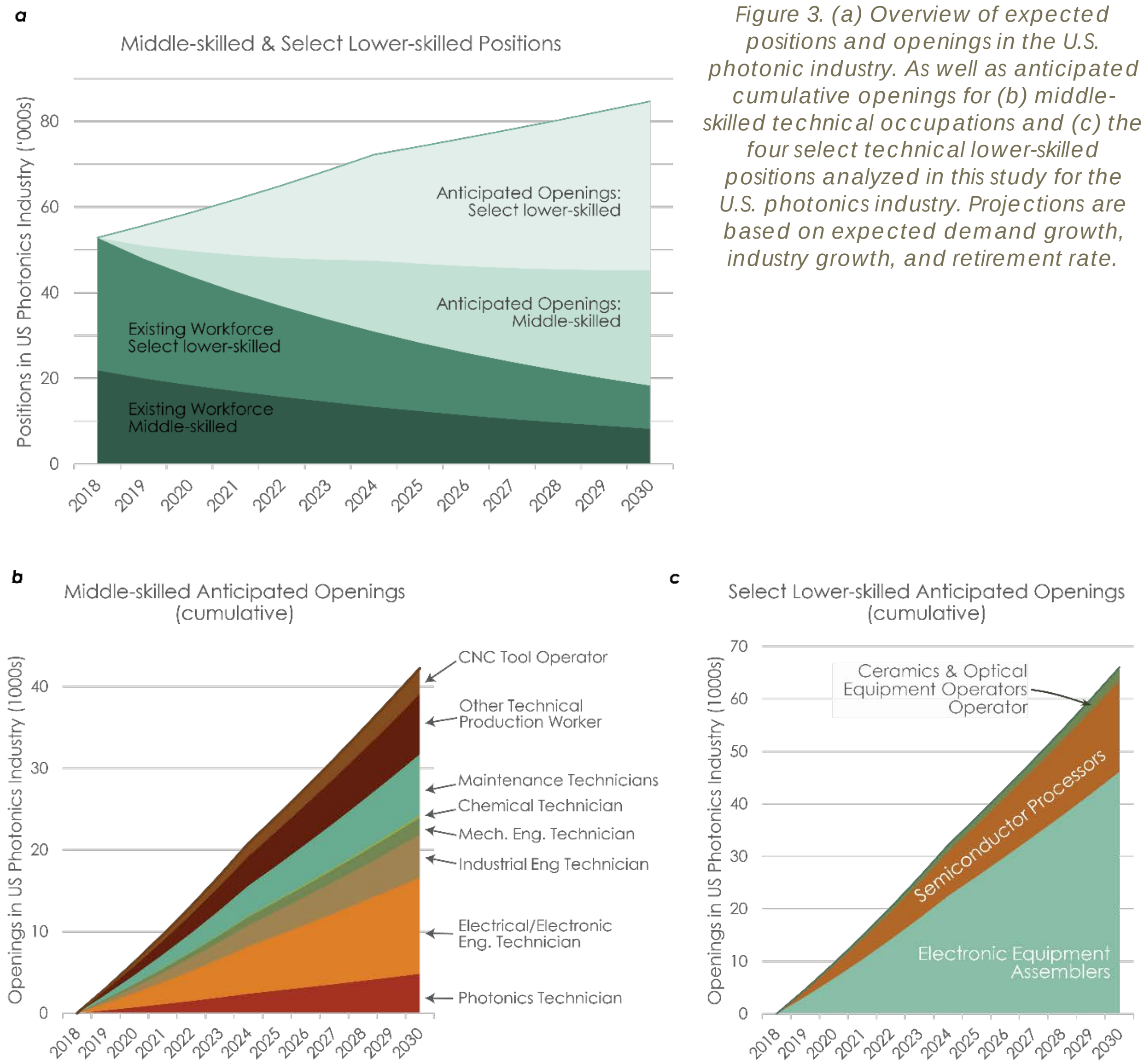


Figure 3. (a) Overview of expected positions and openings in the U.S. photonic industry. As well as anticipated cumulative openings for (b) middle-skilled technical occupations and (c) the four select technical lower-skilled positions analyzed in this study for the U.S. photonics industry. Projections are based on expected demand growth, industry growth, and retirement rate.

Considering all of the technical openings together, these estimates translate into a need of over 9,100 new workers per year including 3,500 middle-skilled (including 2,200 engineering technicians) and 5,500 lower-skilled workers. If a typical community college program graduates 15 middle-skilled learners with these skills per year, the country will need about 140 programs to meet the engineering technician needs of the photonics industry. Another clear recommendation that emerges from these numbers is the development of certificate or other short programs to provide the skills needed for the many lower-skilled workers that will be entering this industry. Assuming such programs could train 30 workers per year, at least 180 such programs would be needed nationally.

Mapping these number to a Massachusetts context, we estimate approximately 3,210 cumulative total openings in these positions for this sector within the state. This includes about 990 middle-skilled openings (including 730 engineering technician openings) and 2,200 lower-skilled openings within the state. Following the national trends, these values translate into around 90 middle-skilled (including 70 engineering technician) and 200 lower-skilled openings per year in the photonics industry, easily supporting five educational programs to train engineering technicians for the photonics industry in the state.

Hiring Challenges

Question
Filling this type of position is ....

In the survey, respondents were asked to identify the level of difficulty for hiring each of the studied middle- and lower-skilled positions. Hiring difficulty was classified as one of hard (>60 days to fill the position), average (30-60 days), or easy (<30 days). Results of survey responses are shown in Figure 4 segmented by sector (rows) and difficulty (columns). As with demand growth, the research team has grouped positions based on the overall set of responses into one of three levels of hiring difficulty labeled as considerable, moderate, or nominal.

In the component industry, Photonics Technicians and Semiconductor Processors were considered the most difficult to hire. Most positions presented some hiring difficulty with at least 25% of respondents indicating that a position was hard to fill. There was no position for which the majority of responses was easy to fill. These results show how there is a lower supply of more specialized technicians, especially for the component industry. It is likely that currently the more specialized roles (e.g. photonics technician) are filled by more common technician types with additional training upon hiring.

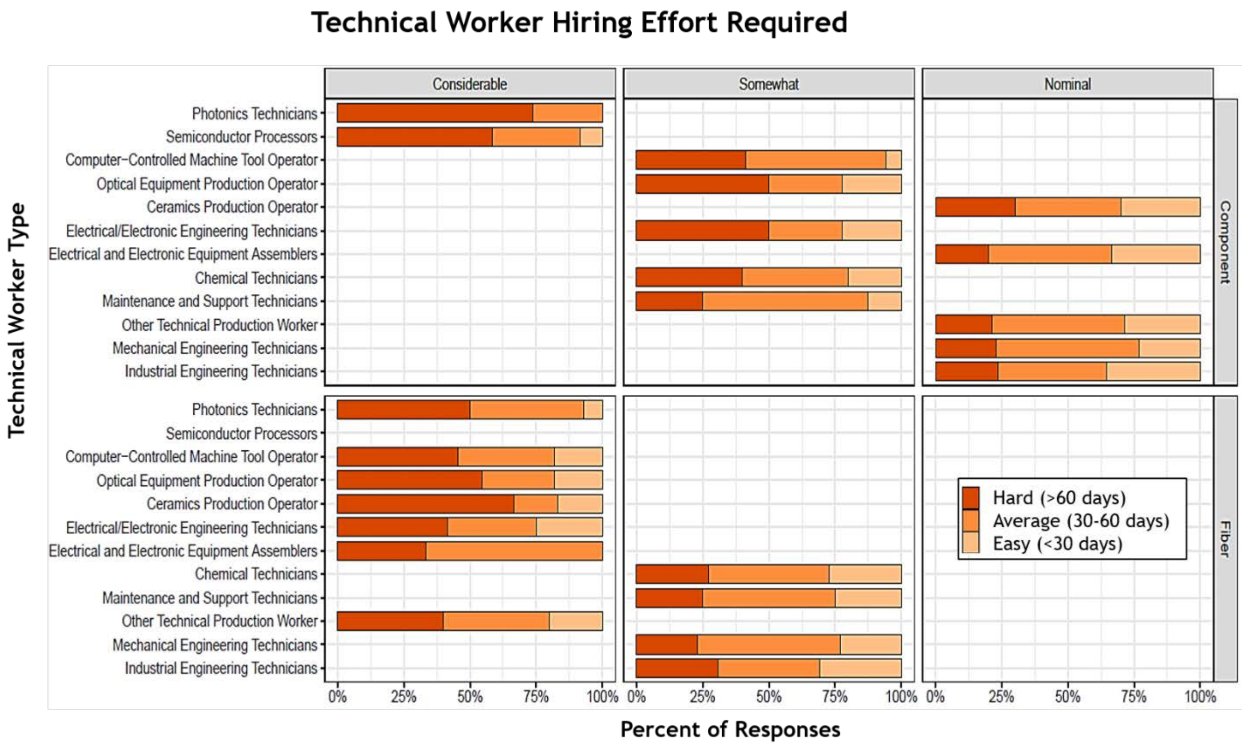


Figure 4. The difficulty of hiring various technician positions was assessed for the component and fiber industries (n=47). Photonics Technicians and Semiconductor Processers were found to be significantly difficult to hire for component companies. In the fiber industry, a majority of the positions are considerably or moderately difficult to hire.

In the fiber industry, however, a majority of occupations were classified as difficult to fill (see Figure 4), suggesting a more pervasive challenge of attracting technical workers.

Considering both sectors together the research team assembled the following composite trend for hiring effort.

- Considerable hiring effort
  - Photonics Technicians
  - Semiconductor Processors
  - CNC Machine Tool Operators
  - Ceramics Production Operators
  - Optical Equipment Production Operator
  - Electrical Engineering Technicians
- Moderate
  - Chemical Technicians
  - Maintenance and Support Technicians
  - Other Technical Production Workers
- Nominal
  - Mechanical Engineering Technicians
  - Industrial Engineering Technicians
  - Electrical and Electronic Equipment Assemblers

Training Effort Required

Question
New hires typically require training that is ...

To understand the type of training involved for each of the occupations, survey respondents were asked to assess the amount of on-the-job training required for each position. The training required for new hires was categorized as extensive, some, or basic orientation only for new hires. Results of survey responses are shown in Figure 5 segmented by sector (rows) and extent of training required (columns).

In the components industry, many of the positions, including photonic technician, semiconductor processor, CNC tool operator, optical equipment operator, and electrical/electronic engineering technicians, require extensive on-the-job training. In the fiber industry, only photonic technicians were identified as requiring extensive training, the remaining positions are classified as only some training or basic training only. The results suggest that the more specialized roles require additional on-the-job training, which could be due to the low supply of specialized workers with adequate trainings. Curricula focused on these specialized positions could reduce the number of hiring days as well as the on-the-job training required.

Considering result from both the components and fiber sectors, these results suggest a composite trend in training challenges for the photonics industry as follows:

- Extensive training required
    - Photonics Technicians
    - Semiconductor Processors
    - CNC Machine Tool Operators
    - Electrical Engineering Technicians
    - Optical Equipment Production Operator
- Moderate training required
    - Mechanical Engineering Technicians
    - Maintenance and Support Technicians
    - Industrial Engineering Technicians
    - Electrical and Electronic Equipment Assemblers
- Nominal training required
    - Chemical Technicians
    - Ceramics Production Operators
    - Other Technical Production Workers

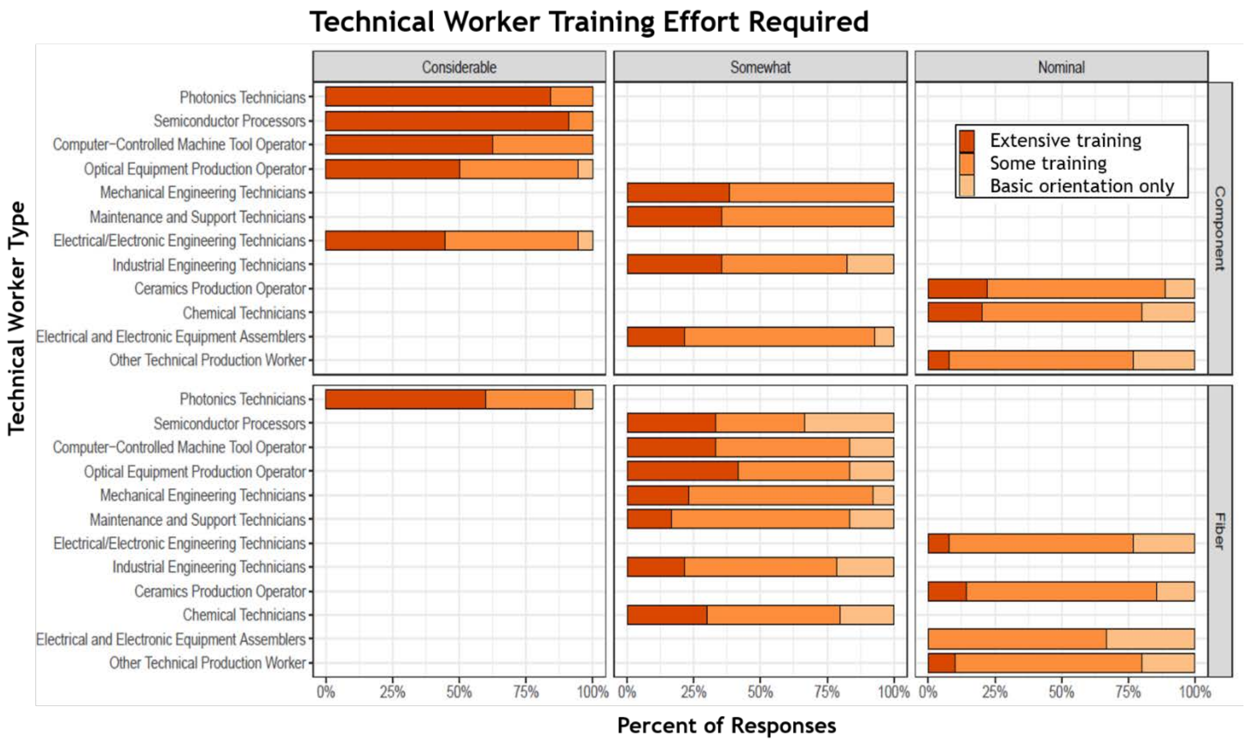


Figure 5. The training required for each position was assessed as extensive, some training, or basic orientation only (n=47). Several positions require extensive on-the-job training and most require at least some training.

Skills required for In-Demand Positions

Survey results clearly suggest both a significant demand growth for middle-skilled and lower-skilled workers and a training gap for these same workers within the U.S. photonics industry. As such, it is critical to investigate and identify the specific skills and tools required for these positions. To accomplish this, survey respondents were asked to evaluate which skills and technologies and tools are becoming more (or less) important over the next five years.

In each case, survey respondents evaluated the expected importance of various work activities and tools and technologies (software) for three randomly selected, relevant occupations. Expected importance was classified as grow significantly, grow somewhat, hold constant, or not important. The research team used the overall set of responses to classify future importance for each work activities and each tool and technology as tending to grow significantly, grow, hold, diminish or diminish/regionally specific. The first four categories are generally self-explanatory. The final category "diminish/regionally-specific" was applied to items where many responses indicated a diminishing trend, but at least some responses were "grow" or "grow significantly." For these cases, the researchers felt that it was important to highlight that there are clearly some firms where this skill is important. As such, training programs should explore this topic with the firms that they serve locally to better understand its role for those firms.

There were a sufficient number of responses (n>=5) to characterize six positions including four middle-skilled positions and two lower-skilled positions. Significant training gaps exist for these workers and therefore there is an opportunity to improve future training and curricula to address workforce needs.

Table 2 Occupation descriptions for the six positions with a sufficient number of responses with four middle-skilled workers (red) and two lower-skilled positions (green).

Occupation Title	**Description**
Photonics Technicians (SOC Code 17-3029.08)	Build, install, test, or maintain optical or fiber optic equipment (e.g. lasers, lenses or mirrors, using spectrometers, interferometers, or related equipment)
Mechanical Engineering Technicians (SOC Code 17-3027.00)	Apply theory and principles of mechanical engineering to modify, develop, test, or calibrate machinery and equipment
Electronics Engineering Technicians (SOC Code 17-3023.01)	Lay out, build, test, troubleshoot, repair, and modify developmental and production electronic components, parts, equipment, and systems (e.g. computer equipment, electron tubes, machine tool numerical controls, etc.). Apply principles and theories of electronics, electrical circuitry, engineering, mathematics, electronic and electrical testing, and physics
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
Optical Equipment Operator (SOC Code 51-9083.00)	Cut, grind, and polish lenses or other precision optical elements. Assemble and mount or otherwise process optical elements (e.g. precision lens polishers or grinders, centerer-edgers, and lens mounters)
Ceramics Production Operator (SOC Code 51-9195.05)	Operate production machines such as pug mill, jigger machine, or other processing equipment in the manufacture of ceramic products

Middle-Skilled Workers

Photonics Technician

Survey responses for photonic technicians are shown in Figure 6. Recommendations for training of Photonics Technicians based on these results are summarized in Table 3.

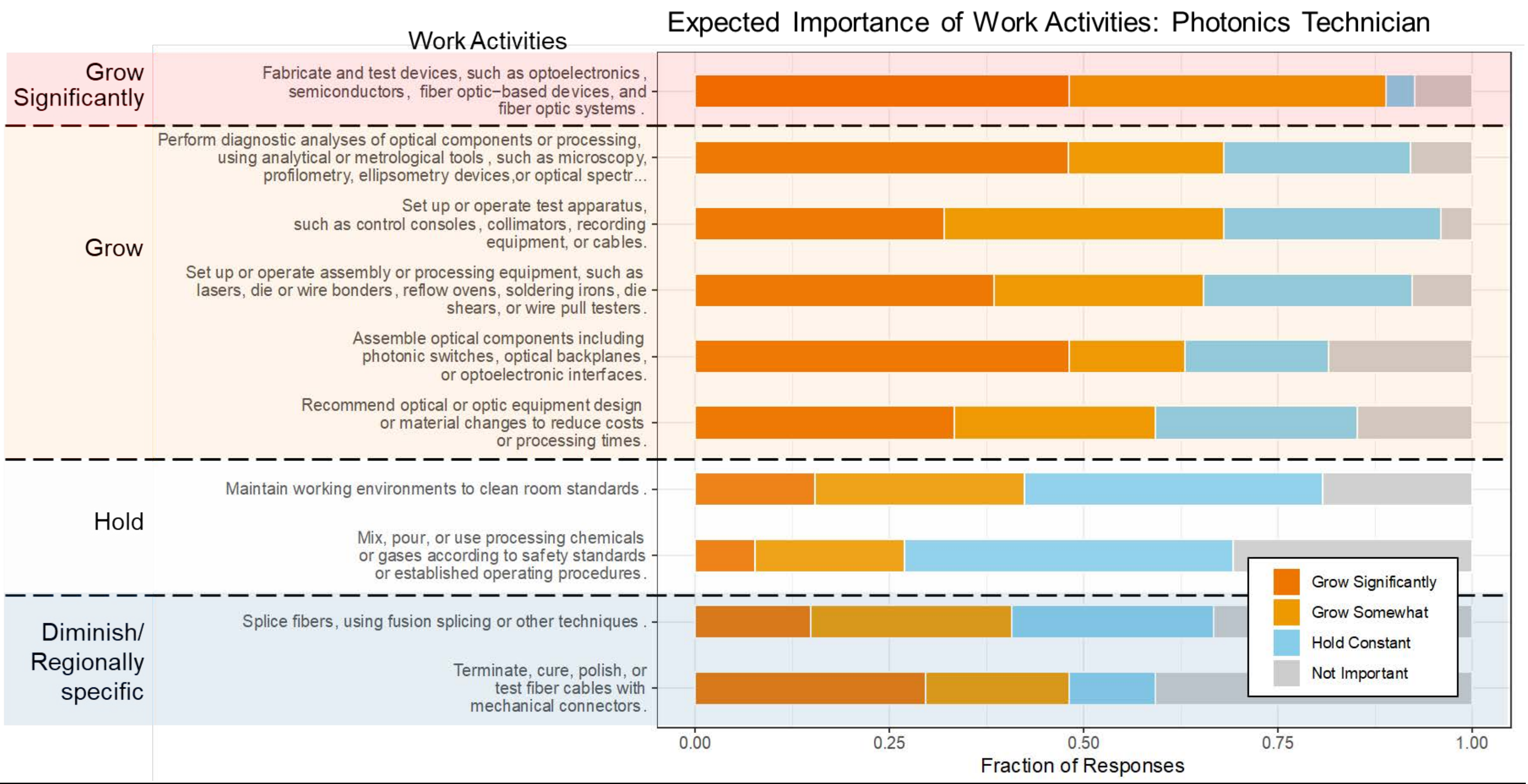


Figure 6. The expected importance of the work activities for photonics technicians are ranked from grow significantly to diminish and evaluate regionally.

Table 3. Recommended changes in the training of Photonics Technicians for the photonics industry.

Recommendation	Skill	Full Skill Description
Increase emphasis on...	Fabrication and assemble optical systems	Fabricate & test devices, such as optoelectronics, semiconductors, fiber optic-based devices, ...
		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.
		Assemble optical components including photonic switches, optical backplanes, ...
	Diagnose and resolve process or product problems	Perform diagnostic analyses of optical components or processing, using analytical or metrological tools, ...
	Design and execute testing	Set up or operate test apparatus, such as control consoles, collimators, ...
		Fabricate & test devices, such as optoelectronics, semiconductors, fiber optic-based devices, ...
	Recommend design changes	Recommend equipment design or material changes to reduce costs or processing times.
Maintain training on...	Clean room standards	Maintain working environments to clean room standards.
	Safety	Mix, pour, or use processing chemicals or gases according to safety standards ...
Evaluate with their local industry the importance of...	Fiber handling	Splice fibers, using fusion splicing or other techniques. Terminate, cure, polish, or test fiber cables with mechanical connectors.

Survey responses about expected importance of various tools and technologies for Photonics Technicians are summarized in Figure 7.

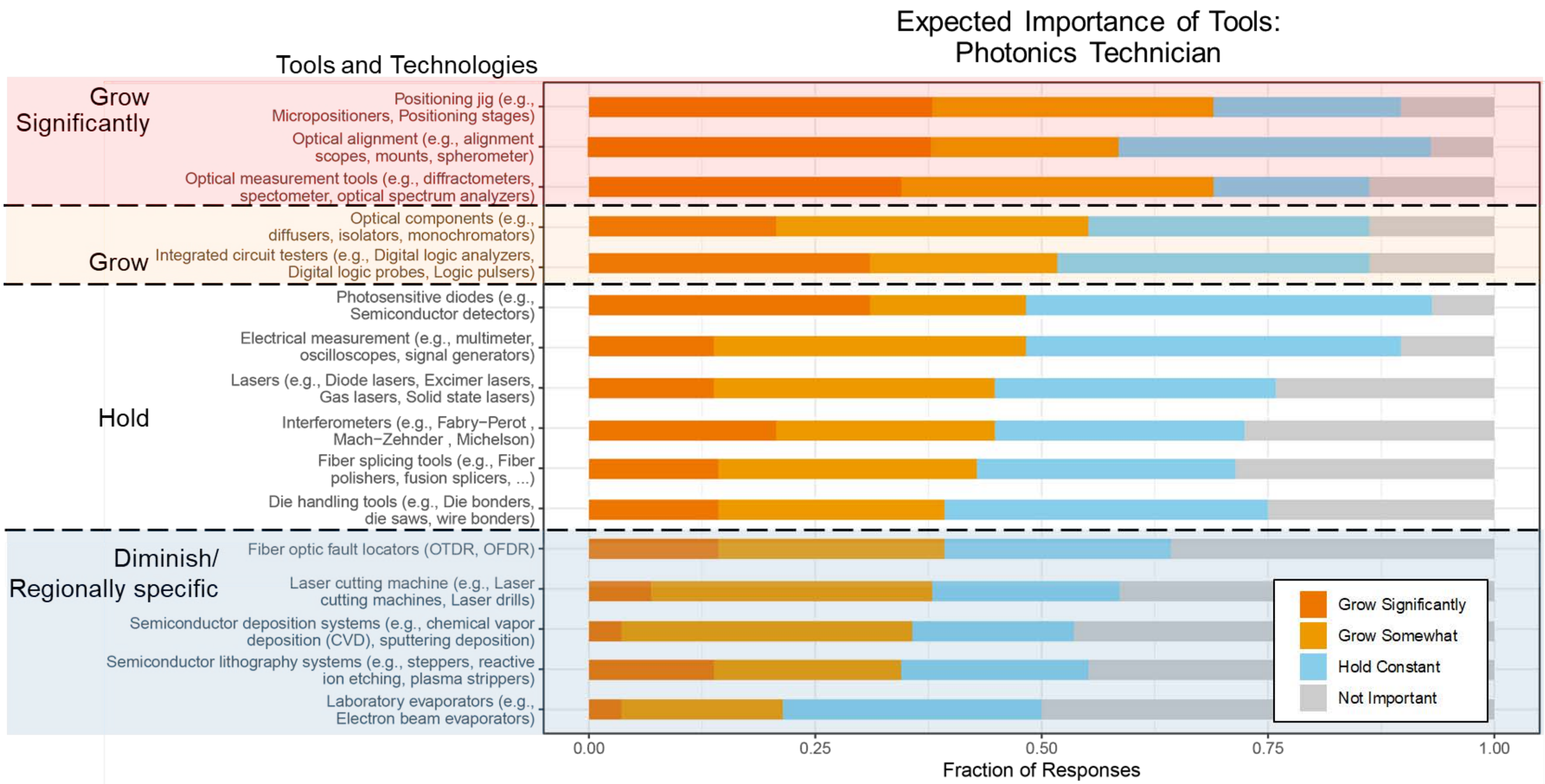


Figure 7. The expected importance of the tools and technologies for photonics technicians are ranked from grow significantly to diminish and evaluate regionally.

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 4.

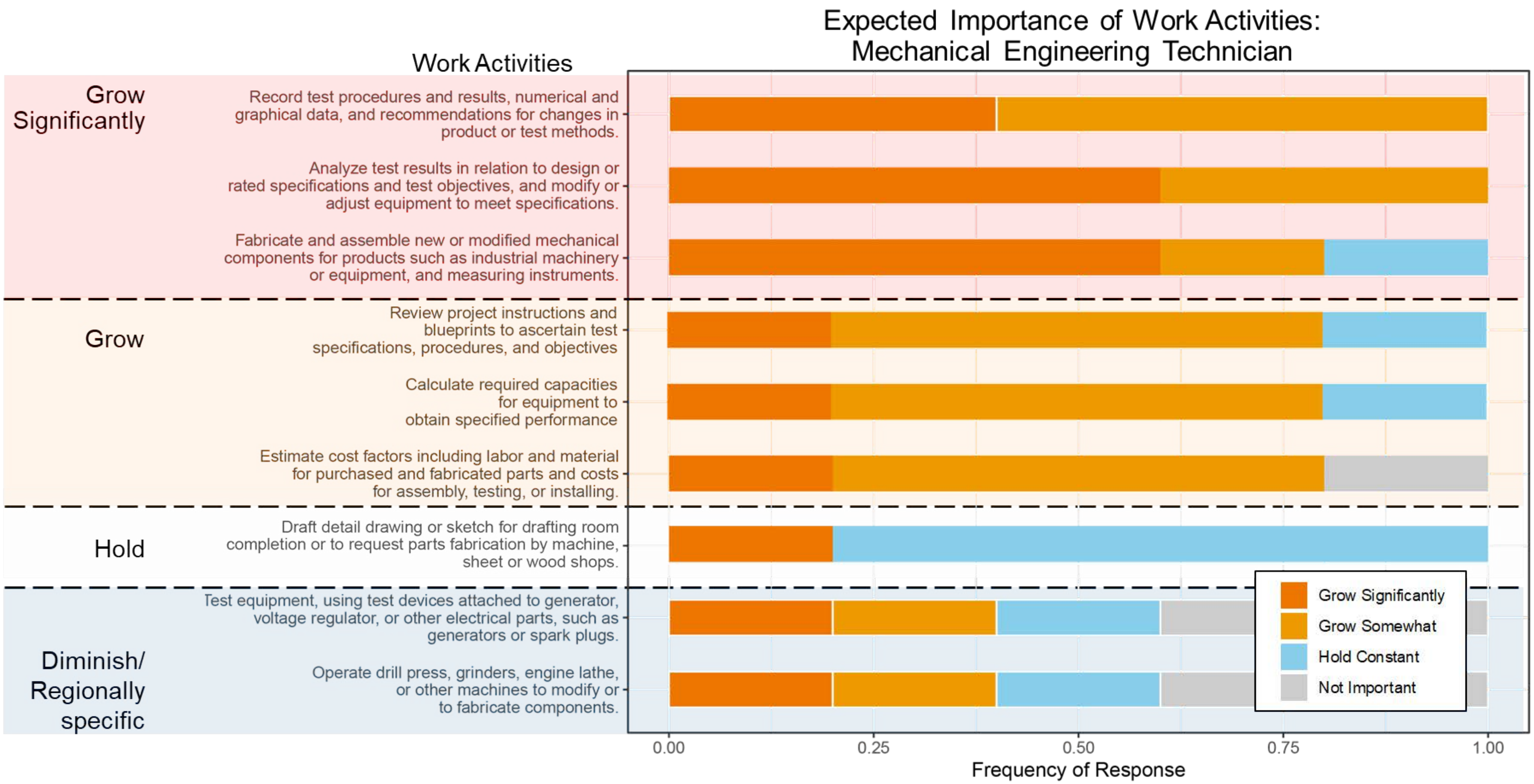


Figure 8. The expected importance of the work activities for mechanical engineering technicians are ranked from grow significantly to diminish or evaluate regionally.

Table 4. Recommended changes in the training of Mechanical Engineering Technicians for the photonics industry.

Recommendation	Skill	Full Skill Description
Increase emphasis on...	Analyze and respond to test data***	Analyze test results in relation to design or rated specifications and test objectives, and modify or adjust equipment to meet specifications.
	Fabrication methods ***	Fabricate and assemble new or modified mechanical components for products such as industrial machinery or equipment, and measuring instruments.
	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.
	Interpret process or test requirements	Review project instructions and blueprints to ascertain test specifications, procedures, and objectives
	Estimate equipment capabilities	Calculate required capacities for equipment to obtain specified performance
	Estimate process cost	Estimate cost factors including labor and material for purchased and fabricated parts and costs for assembly, testing, or installing.
Maintain 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.
Evaluate with their local industry the importance of...	Electrical testing	Test equipment, using test devices attached to generator, voltage regulator, or other electrical parts, such as generators or spark plugs.
	Operate specific equipment	Operate drill press, grinders, engine lathe, or other machines to modify parts tested or to fabricate experimental parts for testing.

Survey responses about expected importance of various tools and technologies for Mechanical Engineering Technicians are summarized in Figure 9.

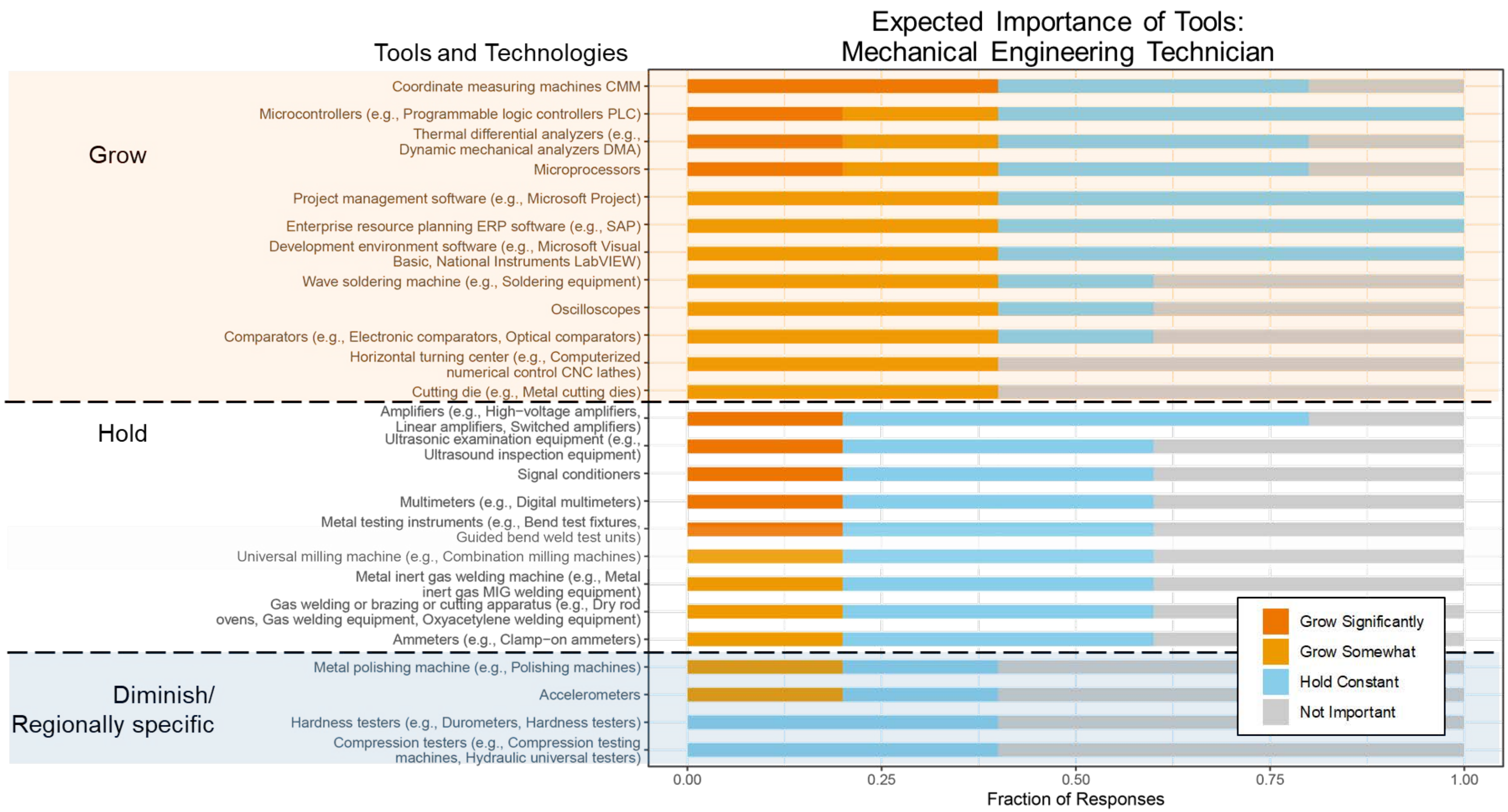


Figure 9 The expected importance of the tools and technologies for mechanical engineering technicians are ranked from grow significantly to diminish and evaluate regionally.

Electrical Engineering Technician

Survey responses for electrical engineering technicians are shown in Figure 10. Recommendations for training of electrical engineering technicians based on these results are summarized in Table 5.

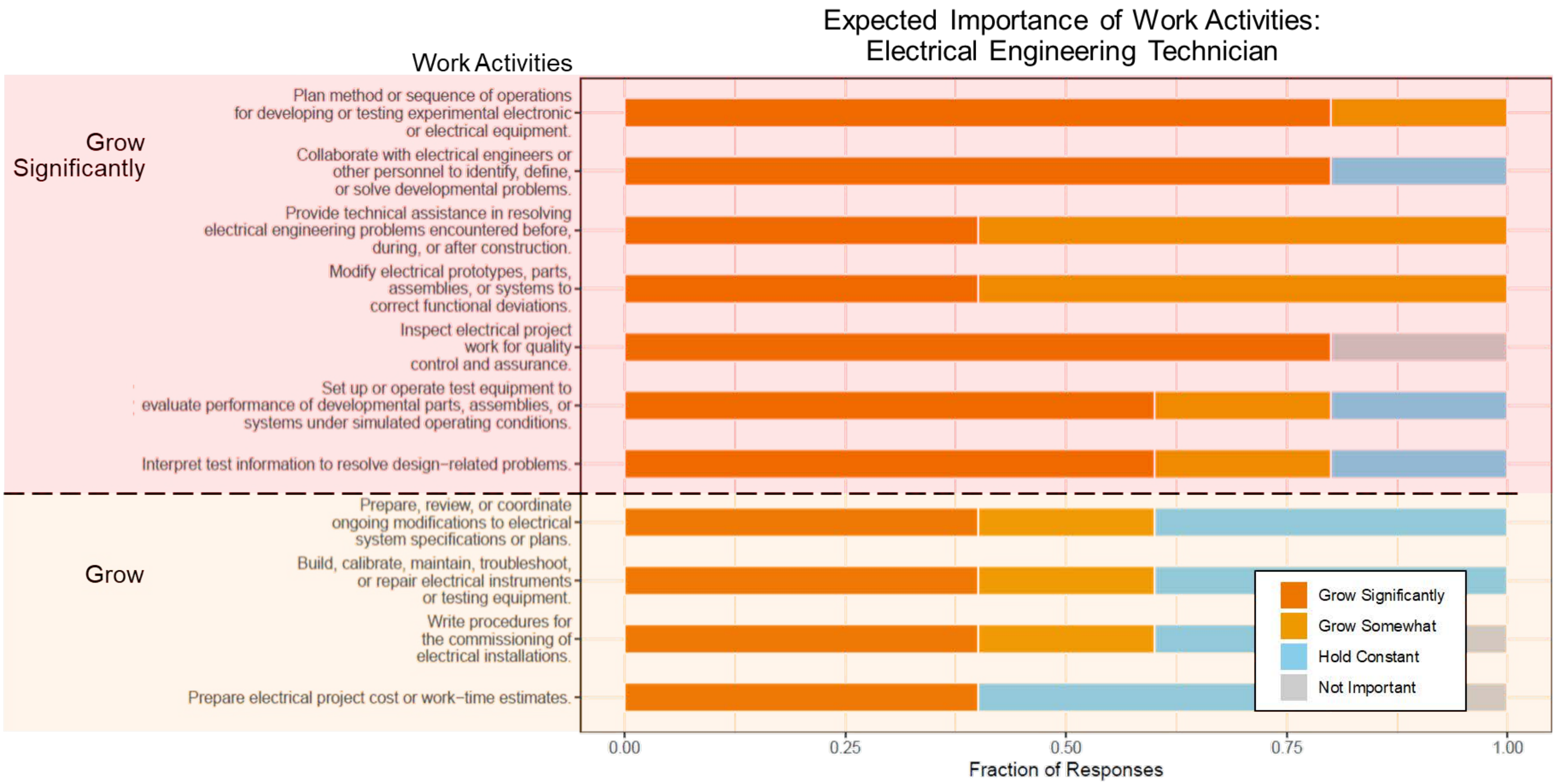


Figure 10. The expected importance of the work activities for electrical engineering technicians are ranked from grow significantly to grow.

Table 5. Recommended changes in the training of Electrical Engineering Technicians for the photonics industry.

Recommendation	Skill	Full Skill Description
Increase emphasis on...	Develop and execute standard testing procedures	Plan method or sequence of operations for developing or testing experimental electronic or electrical equipment.
		Set up or operate test equipment to evaluate performance of developmental parts, assemblies, or systems under simulated operating conditions.
	Collaborate to improve design or troubleshoot problems	Collaborate with electrical engineers or other personnel to identify, define, or solve developmental problems.
		Provide technical assistance in resolving electrical engineering problems encountered before, during, or after construction.
	Diagnose and resolve process or product problems	Inspect electrical project work for quality control and assurance.
		Modify electrical prototypes, parts, assemblies, or systems to correct functional deviations.
	Analyze and respond to test data	Interpret test information to resolve design-related problems.
Maintain training on ...	Manage electrical system specifications	Prepare, review, or coordinate ongoing modifications to contract specifications or plans.
	Build and maintain electrical instruments or testing equipment	Build, calibrate, maintain, troubleshoot, or repair electrical instruments or testing equipment.
	Write installation procedures	Write procedures for the commissioning of electrical installations.
	Estimate project or process cost	Prepare electrical project cost or work-time estimates.

Survey responses about expected importance of various tools and technologies for Electrical Engineering Technicians are summarized in Figure 11.

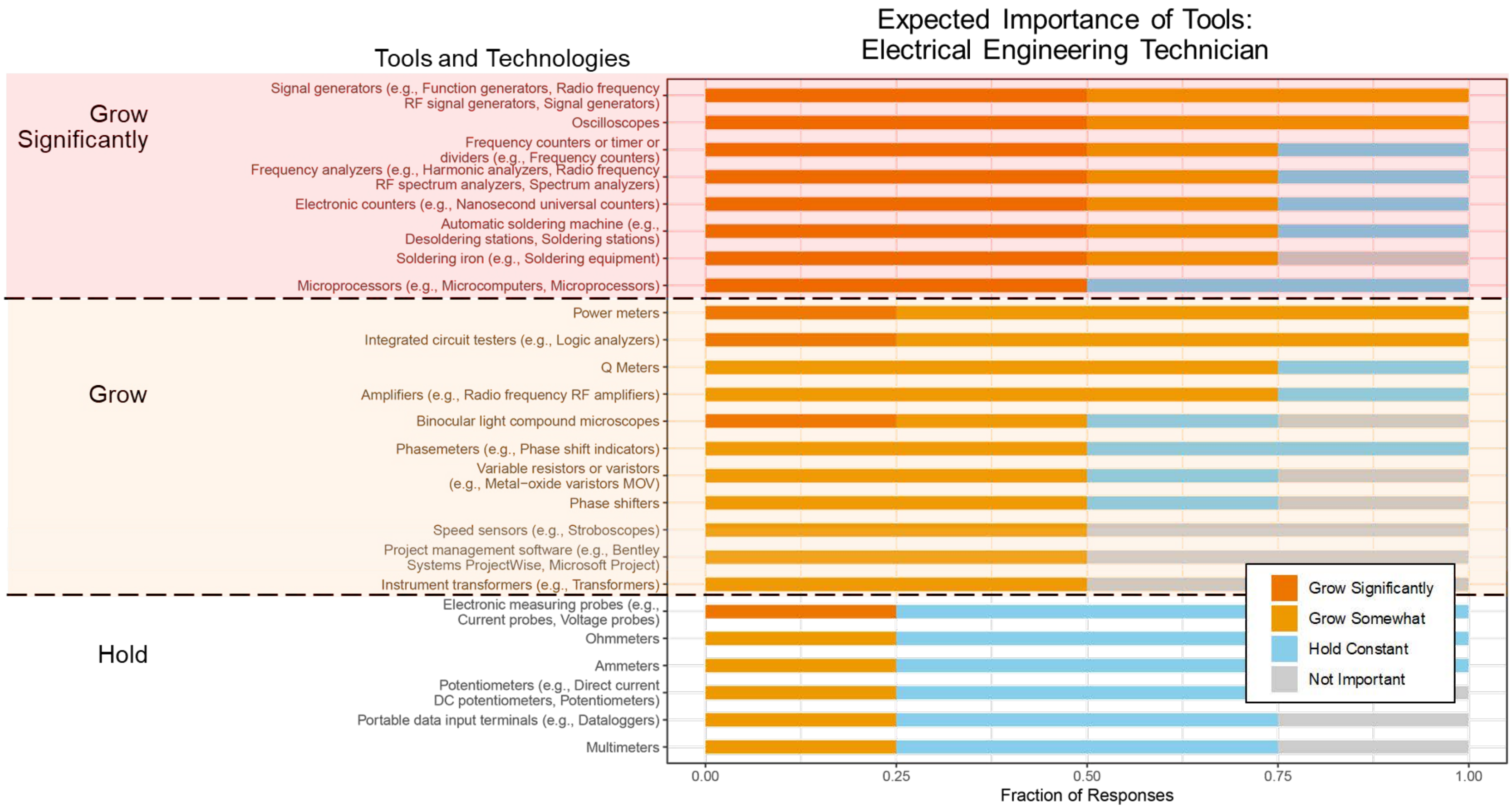


Figure 11 The expected importance of the tools and technologies for electrical engineering technicians are ranked from grow significantly to diminish and evaluate regionally.

Industrial Engineering Technician

Survey responses for industrial engineering technicians are shown in Figure 12Figure 6. Recommendations for training of industrial engineering technicians based on these results are summarized in Table 6.

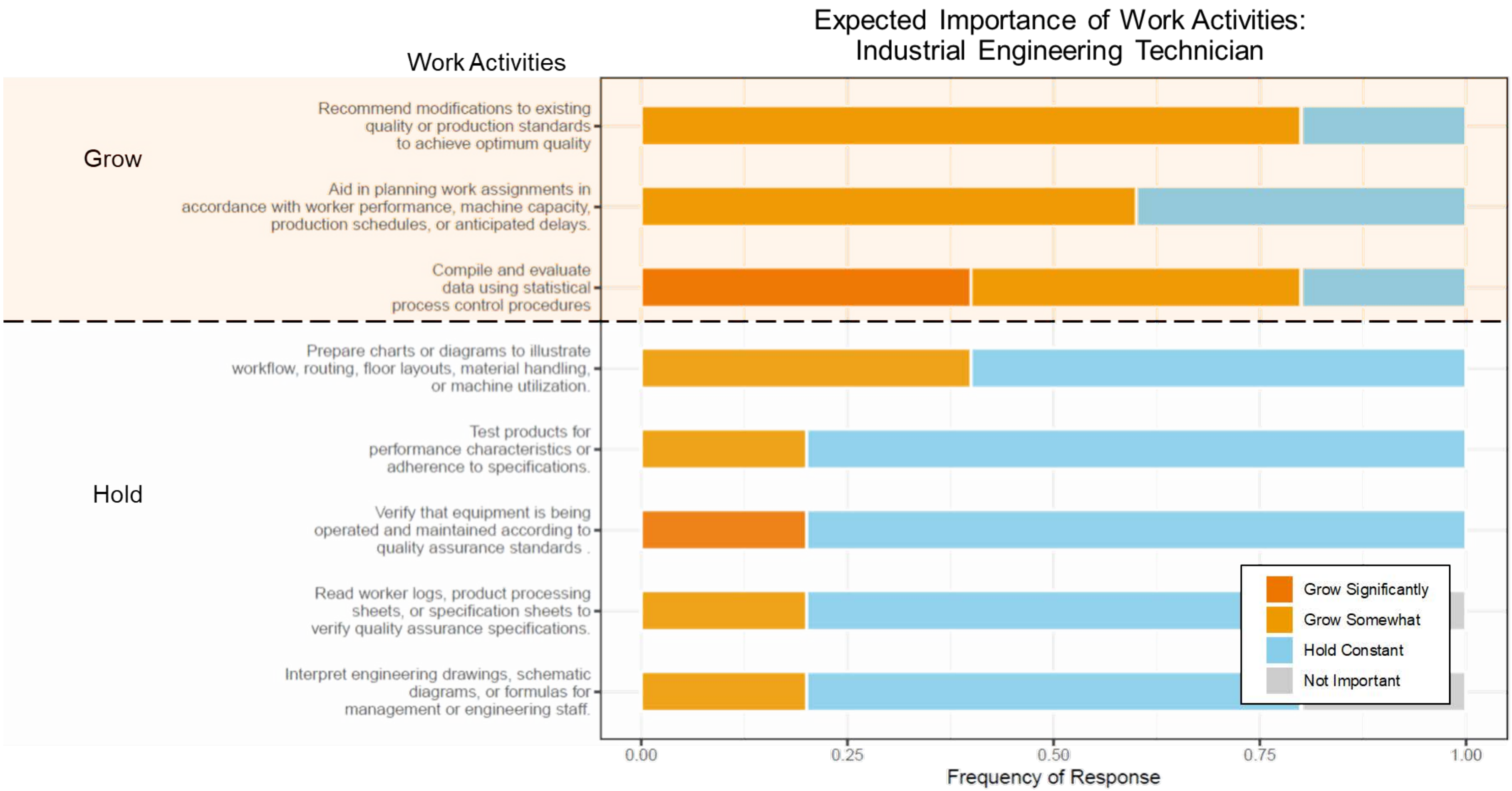


Figure 12. The expected importance of the work activities for industrial engineering technicians are ranked from grow to maintain.

Table 6. Recommended changes in the training of Industrial Engineering Technicians for the photonics industry

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

Survey responses about expected importance of various tools and technologies for Industrial Engineering Technicians are summarized in Figure 13.

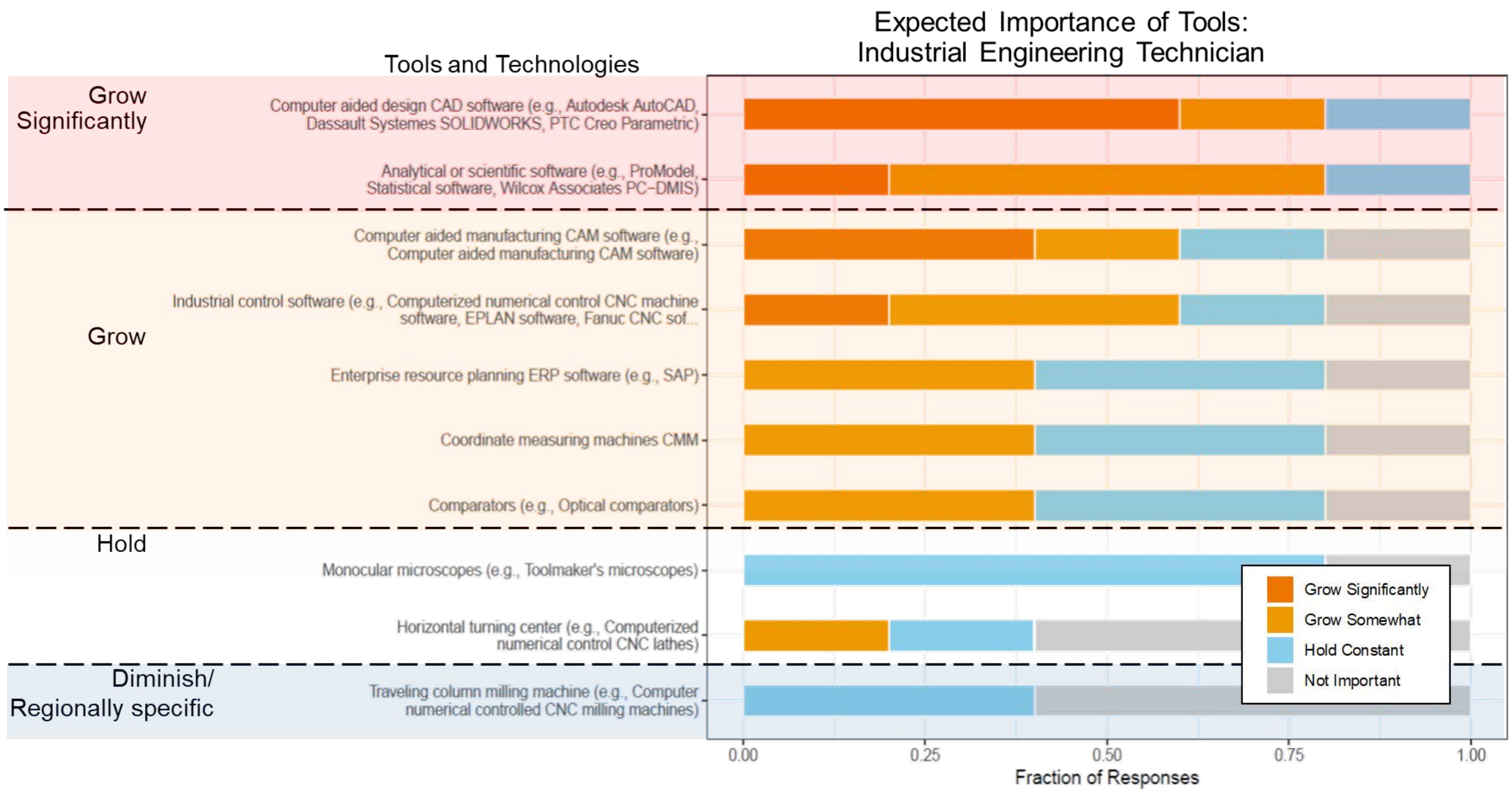


Figure 13. The expected importance of tools for industrial engineering technicians are ranked from grow significantly to diminish or evaluate regionally.

Lower-Skilled Workers

Optical Equipment Operator

Survey responses for optical equipment operators are shown in Figure 14Figure 6. Recommendations for training of optical equipment operators based on these results are summarized in Table *7*.

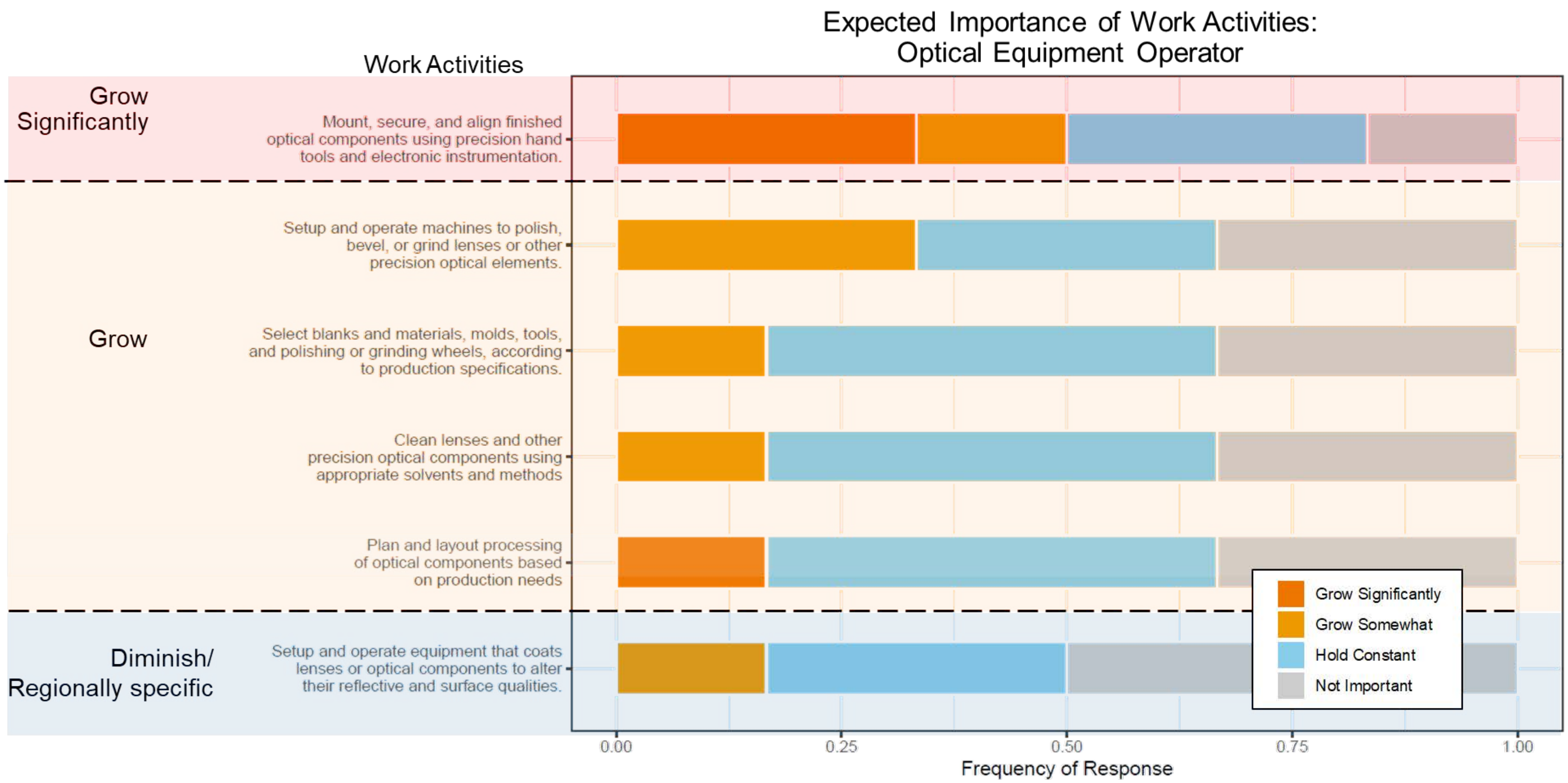


Figure 14. The expected importance of the work activities for optical equipment operators are ranked from grow significantly to diminish or evaluate regionally.

Table 7. Recommended changes in the training of Optical Equipment Operators for the photonics industry

Recommendation	Skill	Full Skill Description
Increase emphasis on...	Setup and operate precision optical machines	Mount, secure, and align finished optical components using precision hand tools and electronic instrumentation.
		Setup and operate machines to polish, bevel, or grind lenses or other precision optical elements.
	Select appropriate materials and processes	Select blanks and materials, molds, tools, and polishing or grinding wheels, according to production specifications.
	Design processing plan	Plan and layout processing of optical components based on production needs
	Optical component handling	Clean lenses and other precision optical components using appropriate solvents and methods
Evaluate with their local industry the importance of...	Setup and operate coating equipment	Setup and operate machines to polish, bevel, or grind lenses or other precision optical elements.

Survey responses about expected importance of various tools and technologies for Optical Equipment Operators are summarized in Figure 15.

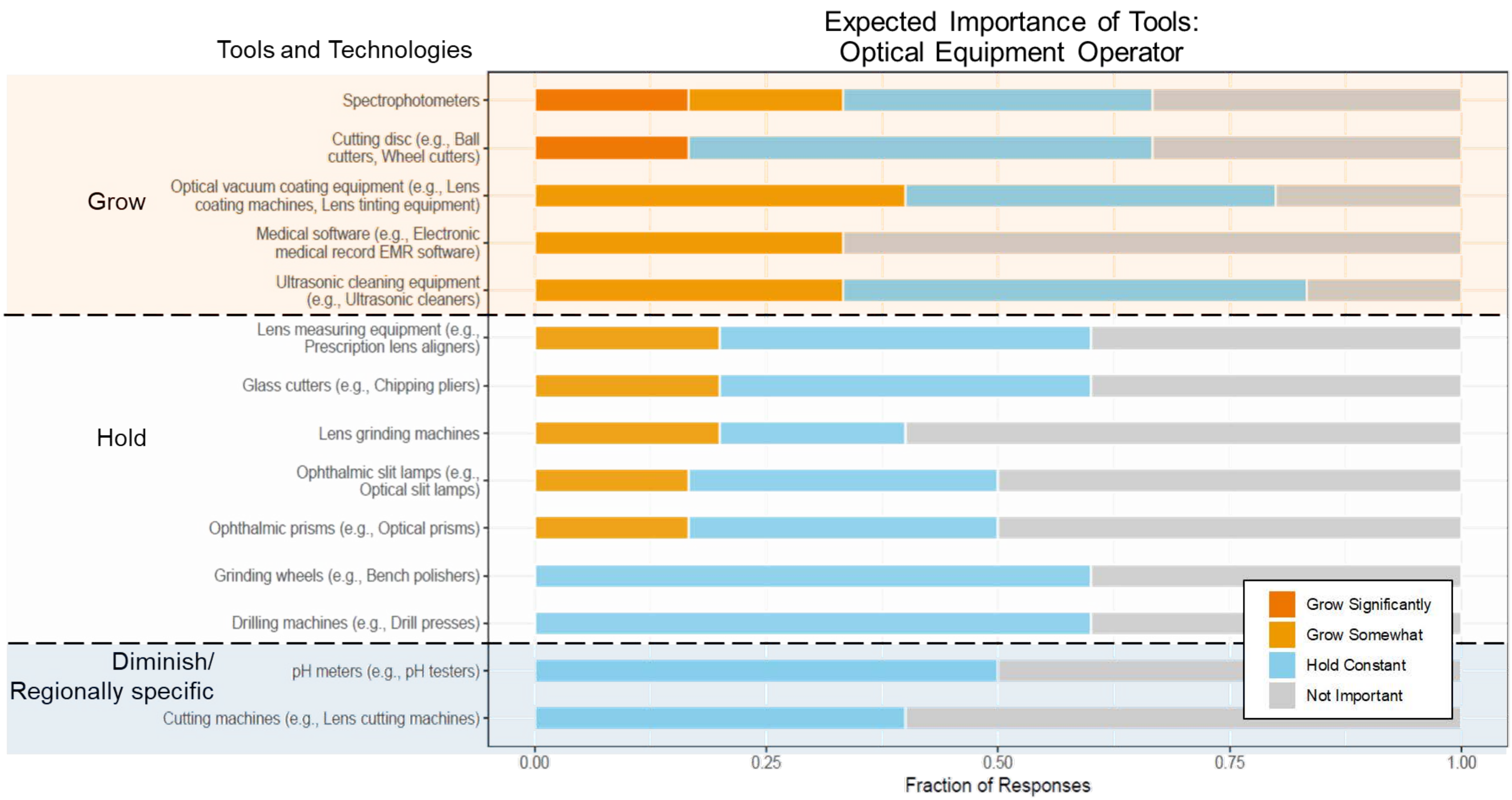


Figure 15. The expected importance of tools for optical equipment operators ranked from grow to diminish or evaluate regionally.

Ceramics Production Operator

Survey responses for ceramics production operators are shown in Figure 16. Recommendations for training of ceramics production operators based on these results are summarized in Table 8

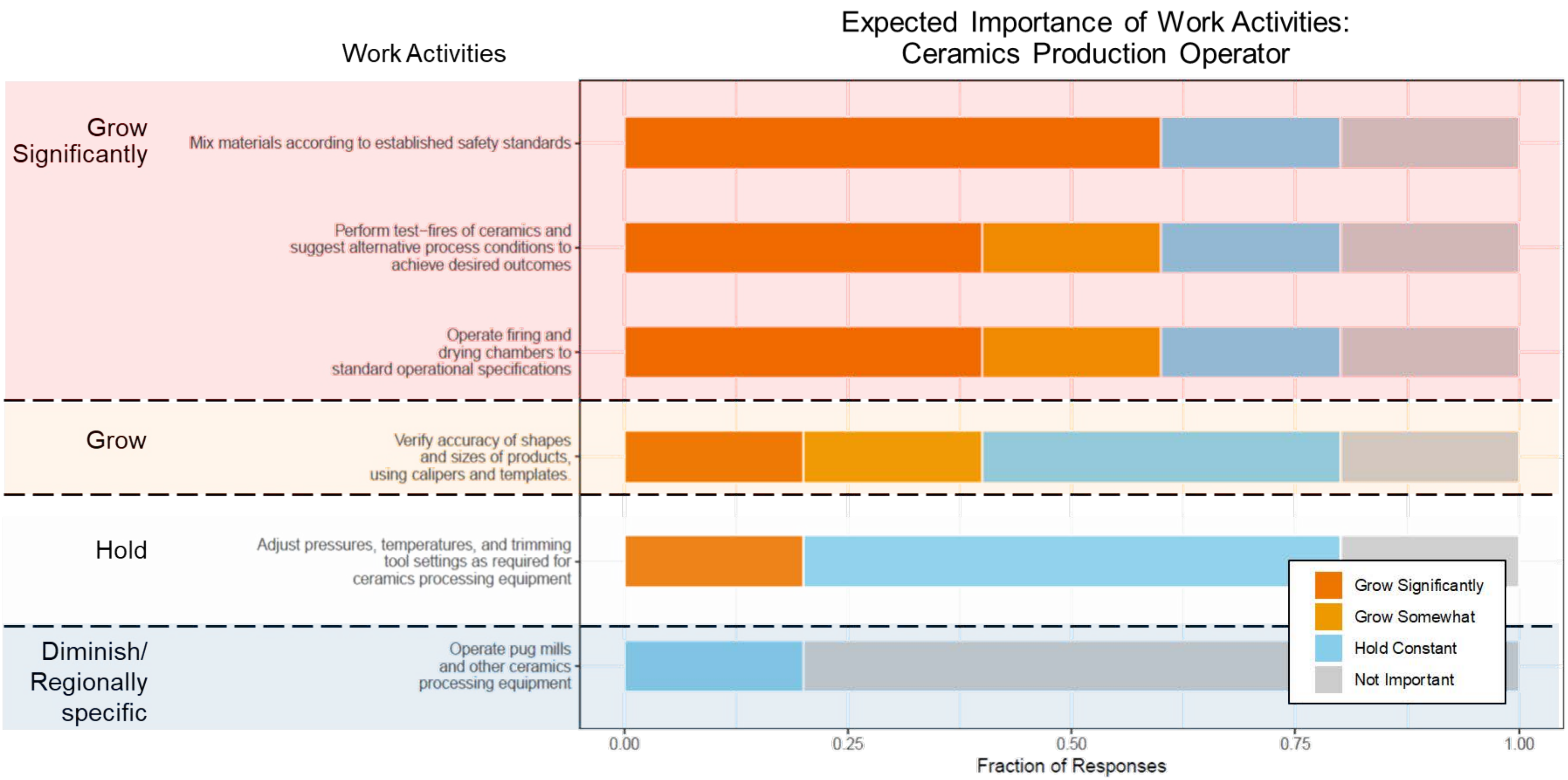


Figure 16. The expected importance of work activities for ceramics production operators are ranked from grow significantly to diminish or evaluate regionally.

Table 8 Recommended changes in the training of Ceramics Production Operators for the photonics industry

Recommendation	Skill	Full Skill Description
Increase emphasis on...	Recommend process design changes	Perform test-fires of ceramics and suggest alternative process conditions to achieve desired outcomes
		Adjust pressures, temperatures, and trimming tool settings as required for ceramics processing equipment
	Materials handling	Mix materials according to established safety standards
	Operate firing and drying chambers	Operate firing and drying chambers to standard operational specifications
	Testing and quality assurance methods	Verify accuracy of shapes and sizes of products using calipers and templates
Evaluate with their local industry the importance of...	Operate specific processing equipment	Operate pug mills and other ceramics processing equipment

Survey responses about expected importance of various tools and technologies for Ceramics Production Operators are summarized in Figure 17.

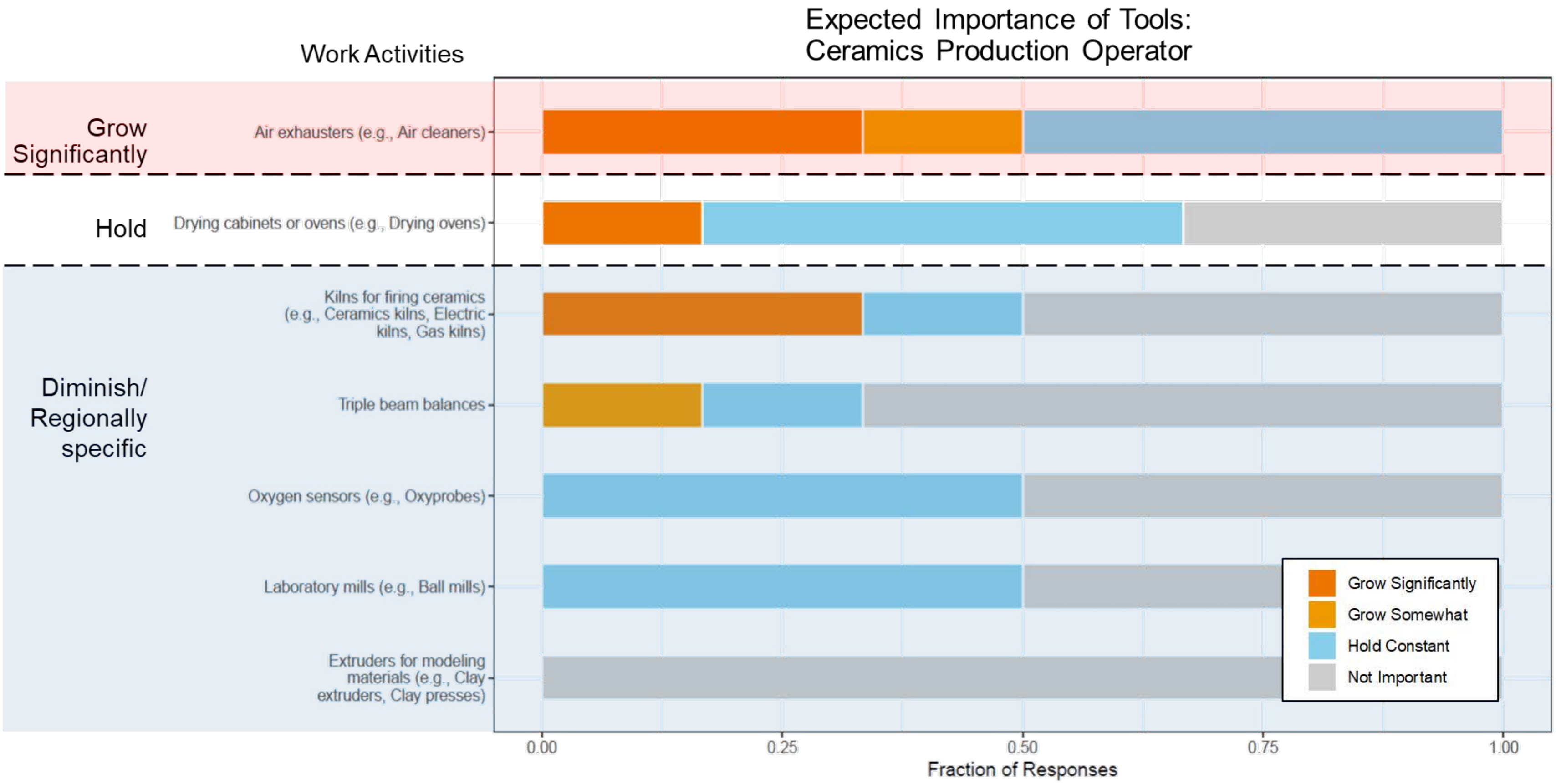


Figure 17. The expected importance of tools is ranked from grow significantly to diminish or evaluate regionally.

Emerging skill needs

In addition to technical skills to each occupation, survey respondents also assessed how more general emerging skills are growing in importance for these occupations. This same set of skills was presented to respondents for each of technical occupations that they were asked about in detail. The importance of these emerging skills is ranked below in Figure 18 for both the lower-skilled, operator positions and the middle-skilled, technician positions.

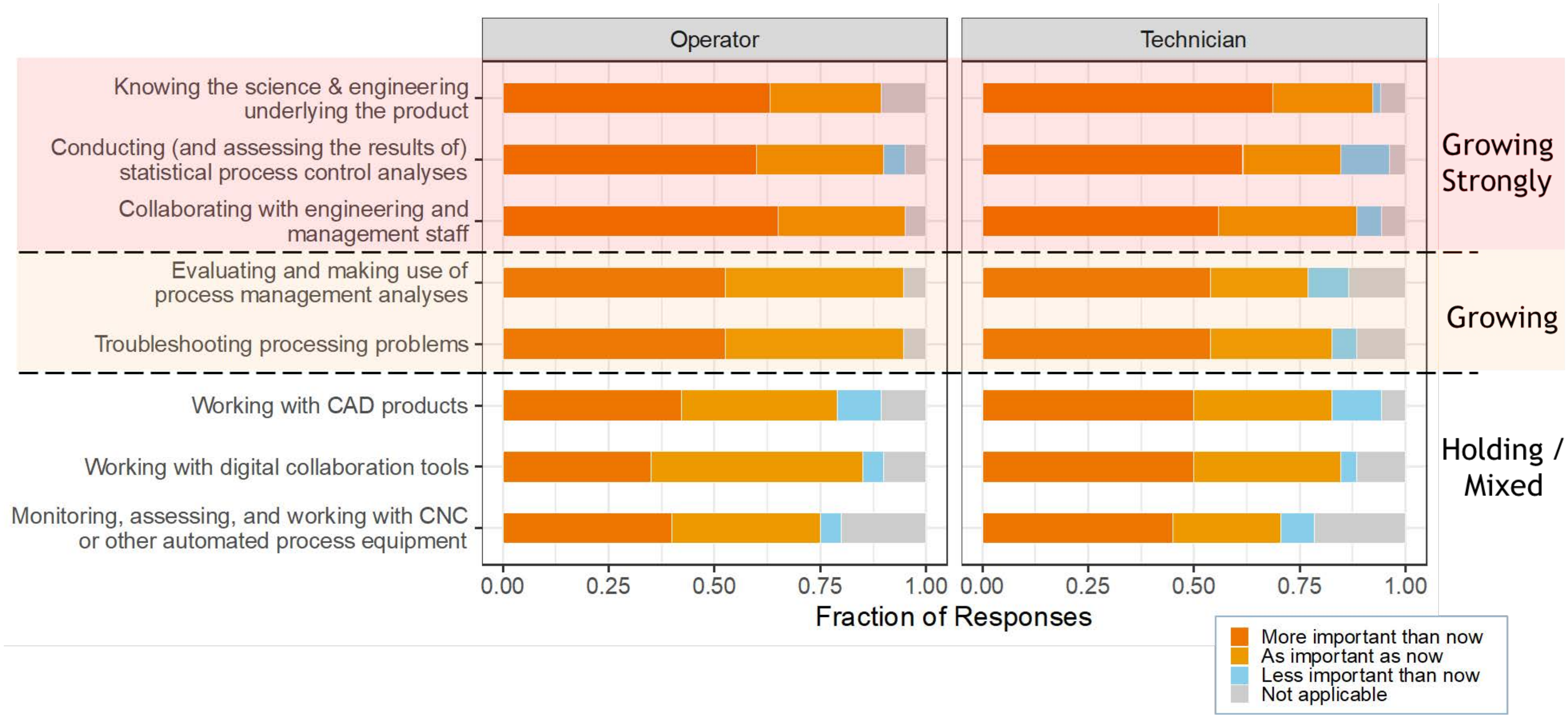


Figure 18 The expected importance of emerging skills is ranked as more important than now, as important as now, less important than now, and not applicable. The following skills are expected to grow strongly: 1) underlying science and engineering; 2) statistical process control; and 3) collaboration skills with engineering and management.

Overall, these results indicate that these types of skills are growing in importance for most technical workers, but there is a greater expectation of such skills in technicians than operators. Based on these results, the research team strongly recommends that training programs for technical workers, particularly technicians, put additional emphasis on:

1) underlying science and engineering; 2) statistical process control; and 3) collaboration skills with engineering and management. Results indicate some growing importance of skills in evaluation and troubleshooting. It would appear that digital tools such as CAD, CNC, and digital collaboration tools are already important and will likely remain so.

As shown in Figure 19, the three skills that are expected to grow significantly in importance over the next five years map to 8 of the 10 essential skills as defined by Employment and Social Development Canada (Government of Canada 2015). While improvements in technical training skills and tools have been underscored in the previous results, interpersonal, soft skills such as communication and critical thinking should also be emphasized in training programs to help develop the most valuable employees.

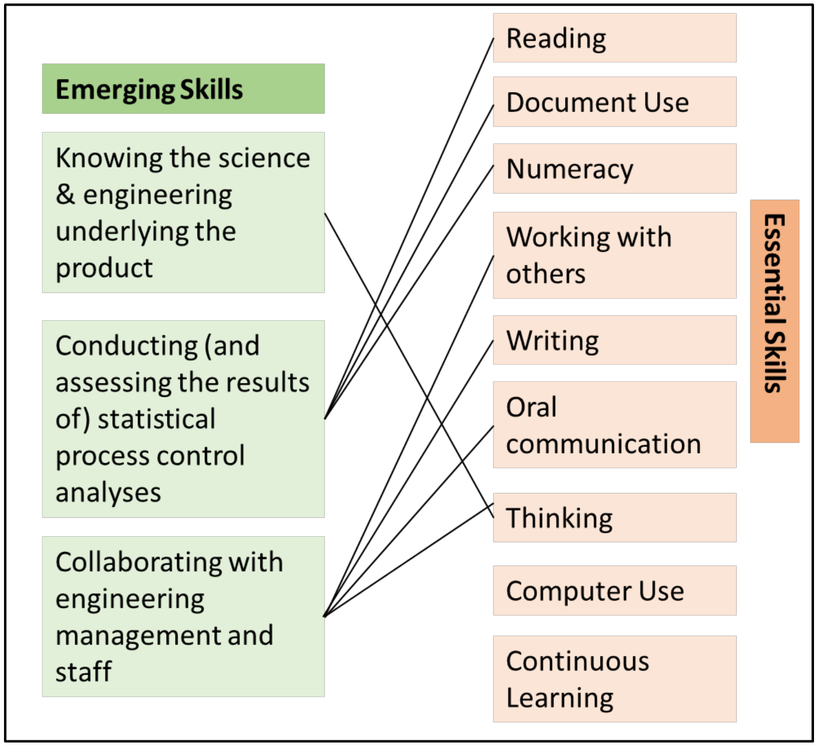


Figure 19 A mapping of the highest rank future skills to the essential skills list demonstrates the growing need for training in interpersonal, soft skills in the photonics industry.

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.

Figure 20 shows the ten common GTS level skills associated with middle-skilled positions in photonics ranked from highest to lowest weighted average importance. Notably, the five highest ranked common skills – thinking & making creatively, analyzing data or information, making decisions & troubleshooting problems, estimating & judging characteristics of products or process, and providing consultation & advice to others – involve critical thinking skills. Table 9 to Table 11 provide details on the underlying specific skills associated with the top four GTS. Details for all GTS are provided in the appendix.

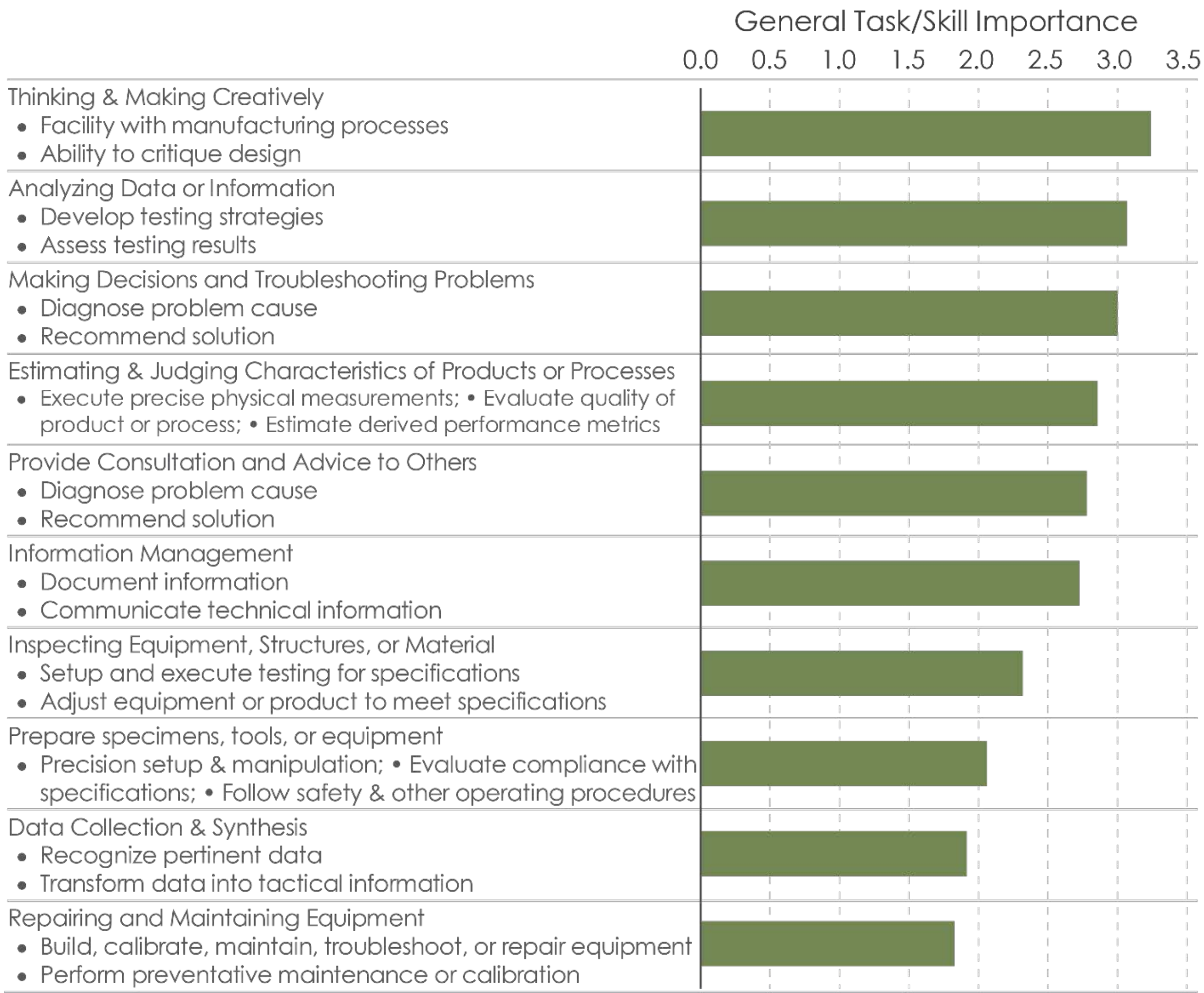


Figure 20. General Task or Skill ranked by weighted average importance of the skills within that class. Only GTS that are shared across at least three occupations are labeled as common and, therefore, included in this figure.

Table 9 shows the underlying categorization and score detail for the first ranked GTS, thinking and making creatively. While the first specific skill within this category "Plan method or sequence of operations…" is a wholly cognitive activity, many (including the next three) of the other specific skills in this class involve a combination of both critical thinking and physical craftsmanship. The importance of these skills were identified for every one of the technician positions except chemical technicians. The most common action described in this category is skill in fabrication.

Table 9. Details of skill importance for General Task/Skill "Thinking Creatively" 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	CNC Oper
Thinking & Making Creatively	3.2	Develop research plans or methodologies.	4.6	Plan method or sequence of operations for developing or testing experimental electronic or electrical equipment.	4.6			X			
		Design industrial systems or equipment.	3.8	Fabricate and assemble new or modified mechanical components for products such as industrial machinery or equipment, and measuring instruments.	3.8					X	
		Design electrical or electronic systems or equipment.	3.7	Modify electrical prototypes, parts, assemblies, or systems to correct functional deviations.	3.8			X			
				Fabricate and test devices, such as optoelectronics, semiconductors, fiber optic-based devices, and fiber optic systems .	3.7	X					
		Create visual designs or displays.	1.8	Prepare charts or diagrams to illustrate workflow, routing, floor layouts, material handling, or machine utilization.	1.8		X				
				Draft detail drawing or sketch for drafting room completion or to request parts fabrication by machine, sheet or wood shops.	1.8					X	
				Design basic circuitry and design documentation under engineers' direction, using drafting instruments or computer-aided design (CAD) equipment.	-nr-			X			
		Develop models of systems, processes, or products.	1.7	Build prototypes from rough sketches or plans.	-nr-			X			

Table 10 shows the details of the scoring for the second highest ranked GTS, analyzing data or information. All six technician types had skills of this type included in the survey. In all cases, these skills involve both executing diagnostic tests, analyzing the data that comes from those, and interpreting that data to guide some product or process decision.

Table 10. Details of skill importance for General Task/Skill "Analyzing Data or Information" and its sub classes and skills.

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	CNC Oper
Analyzing Data or Information	3.1	Analyze performance of systems or equipment.	3.8	Analyze test results in relation to design or rated specifications and test objectives, and modify or adjust equipment to meet specifications.	4.2					X	
				Interpret test information to resolve design-related problems.	3.8			X			
				Compile and evaluate data using statistical process control procedures	3.4		X				
		Analyze data to improve operations.	3.1	Perform diagnostic analyses of optical components or processing, using analytical or metrological tools, such as microscopy, profilometry, ellipsometry devices,or optical spectrum analyzers.	3.2	X					
				Set up or operate test apparatus, such as control consoles, collimators, recording equipment, or cables.	3.0	X					
		Analyze biological or chemical substances or related data.	1.5	Conduct chemical or physical laboratory tests to assist scientists in making qualitative or quantitative analyses of solids, liquids, or gaseous materials.	1.8				X		
				Set up and conduct chemical experiments, tests, and analyses, using techniques such as chromatography, spectroscopy, physical or chemical separation techniques, or microscopy.	1.3				X		

Table 11. Details of skill importance for General Task/Skills "Provide Consultation and Advice to Others" and "Documenting / Recording Information" and their sub classes and skills.

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	CNC Oper
Making Decisions and Troubleshooting Problems	3.0	Determine operational methods or procedures.	4.6	Plan method or sequence of operations for developing or testing experimental electronic or electrical equipment.	4.6			X			
		Determine resource needs of projects or operations.	2.4	Calculate required capacities for equipment to obtain specified performance	3.0					X	
				Prepare electrical project cost or work-time estimates.	2.4			X			
				Calculate machine speed and feed ratios and the size and position of cuts.	1.8						X
Estimating and Judging the Characteristics of Products or Processes	2.9	Evaluate production inputs or outputs.	3.5	Monitor product quality to ensure compliance with standards and specifications.	3.5				X		
		Estimate project development or operational costs.	2.6	Estimate cost factors including labor and material for purchased and fabricated parts and costs for assembly, testing, or installing.	2.8					X	
				Prepare electrical project cost or work-time estimates.	2.4			X			

The next two important common skills, "Making Decisions and Troubleshooting Problems" and "Estimating and Judging the Characteristics of Products or Processes", are detailed in Table 11. Both of these skills involve critical thinking skills on the part of the worker. In particular, they depend on being able to know what information is needed in a particular context and how to act on that information.

Results Summary

Overall, interviews and survey results indicate that there is strong and growing demand for technical workers in the US photonics industry. Specifically, we project middle-skilled and our focal lower-skilled positions within this industry to grow from around 58,000 today to nearly 85,000 by the end of the decade. Accounting for expected retirement and separations, this translates into around 42,000 cumulative middle-skilled openings over that time period or a need for around 3,500 new middle-skilled workers per year. This includes a cumulative of over 22,500 engineering technician openings averaging over 2,200 per year. These numbers suggest the country needs about 140 training programs to meet the engineering technician needs of the photonics industry. We also estimate over 61,000 cumulative openings or around 5,500 openings per year for the selected lower-skilled occupations that were evaluated as part of this study. This level of demand may support over 180 certificate programs nationally to train lower-skilled workers for the photonics industry

Training for technical workers in integrated photonics should increase emphasis on

- Fabrication processes and methods
- Design of tests (for product or process quality) and interpretation of test data
- Diagnosis and troubleshooting of processing issues
- Collaboration and communications with other parts of the firm
- Fundamental science and engineering underlying photonic technologies

Mapping these number to a Massachusetts context, we estimate about 90 middle-skilled (including 70 engineering technician) and 200 lower-skilled openings per year in the photonics industry in the state; easily supporting five educational programs for training middle-skilled engineering technician workers.

Additionally, firms identified strong, growing demand and / or hiring challenges for every type of technical occupation that was evaluated in this study. Of the occupations studied, five were notable as experiencing both strong or moderate growth in demand and representing moderate to challenging hiring effort to the firm. Those occupations were:

- Photonics Technicians
- Electrical/Electronic Engineering Technicians
- Computer-controlled (CNC) Machine Tools Operators
- Optical Equipment Operators
- Semiconductor Processors

Interestingly, survey respondents identified these same five positions as requiring extensive on-the-job training for new hires. Together, these results make it clear that there are both real opportunities for technical careers within the photonics industry and for improved training for these occupations.

Because of specific implementation decisions, we did not receive sufficient responses to comment on the technical skill needs for all five of these critical positions. We did receive feedback on the importance of specific technical skills for photonic technicians, electrical/electronic engineering technicians, and optical equipment operators. Across these three, there is a clear trend to increasing importance of skills in

- Fabrication processes and methods
- Design of tests (for product or process quality) and interpretation of test data
- Diagnosis and troubleshooting of processing issues
- Collaboration and communications with other parts of the firm

In this study, the focus was on understanding and evaluating technical skills gaps. We explicitly did not ask respondents to evaluate soft skills; however, we acknowledge the significance of these skills in addressing workforce challenges and worker employability.

The increasing importance of these specific skills is consistent with survey responses about the importance of generalized skills. Specifically, we found that survey respondents expect increasing importance for technical workers to be skilled in

- Fundamental science and engineering of the firm's technology
- Statistical methods to interpret data
- Collaboration

In the end, it is clear that there are many opportunities for technical careers in the photonics industry for both middle-skilled and lower-skilled workers. Correspondingly, there are key opportunities to improve the training for persons pursuing those careers.

Appendix:

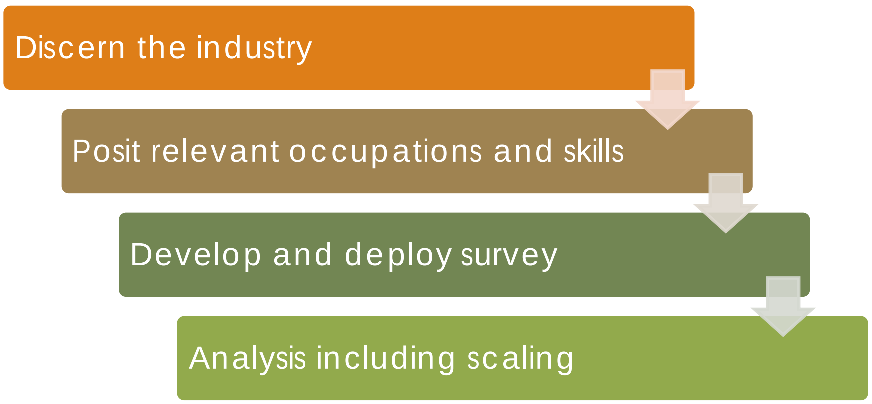
Literature review and gap analysis

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 photonics curricula and matriculate more competitive technician candidates, for targeted hiring in photonics 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 the photonics industry we have relied primarily on surveying firms within that industry. Development and deployment of that survey 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 photonics industry, archetype firms were identified through a number of methods, including querying member listing from relevant professional associations[8], consulting market intelligence reports (Ross 2020a), and expert elicitation. Once archetypes were identified, they were queried within the discernment system. The

[8] In this case, we specifically queried the membership roster of AIM Photonics (American Institute for Manufacturing Integrated Photonics) a Manufacturing USA institute based in Rochester, NY and the *Photonics Marketplace*, and online database of photonics companies maintained by *Photonics Spectra* a publication of Laurin Publishing Company, Inc. in Pittsfield, MA, United States. (Available at: https://www.photonics.com/BuyersGuide.aspx last accessed July 1, 2020

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.

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.

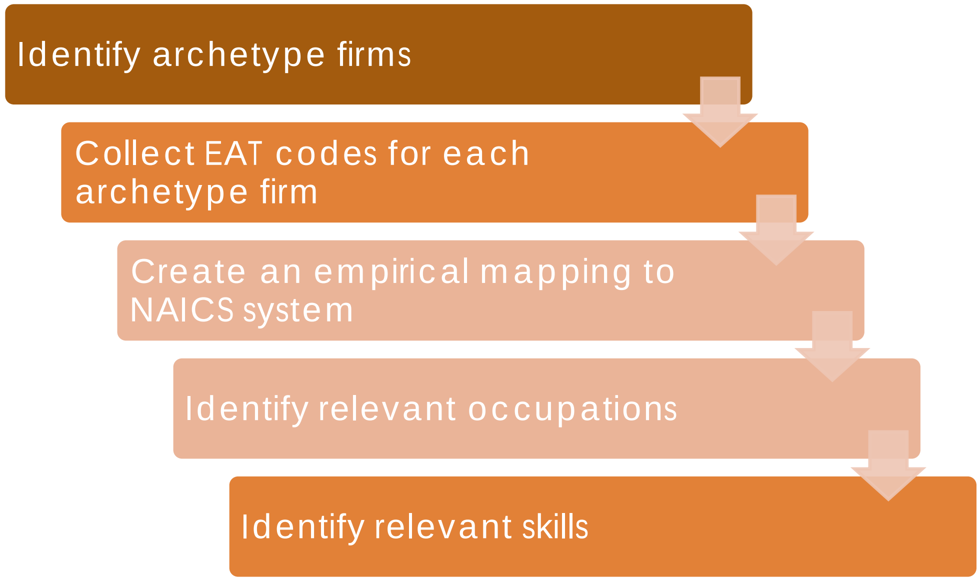


Figure 21 5-step process for discerning emerging advanced manufacturing industries.

Photonics is an advanced manufacturing industry that is rapidly growing and is projected to reach a value of $836.8 B by 2025(PR Newswire 2021). Based on expert input, we elected to treat the industry as comprising two sectors, one focused on the construction of fiber optic cabling and related systems (referred to as fiber cabling) and one focused on the production of photonic components and systems (referred to as components). Because ultimately both cables and components are integrated to provide overall system solutions. There are naturally some firms that sit at the boundary between these two sectors. Table 12lists the four companies that were identified as archetypes for the fiber cabling sector within the photonics industry. Together, these firms produce more than half of the supply of fiber cabling in the United States (Ross 2020b).

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 photonics industry. Table 1 shows the SIC8 and NAICS EAT codes for the fiber cabling industry 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. In the SIC8 system, three of the four firms are classified as code 33570102 (Fiber optic cable (insulated)) with one firm classified as 32290401 (Fiber optics strands).

Table 12 Fiber cabling industry classification archetype examples

Company	US Standard Industrial Classification – DB Hoovers Expanded Version (SIC8)	North American Industrial Classification System (NAICS)
AFL Telecommunications	32290401 Fiber optics strands	517911 Telecommunications Resellers
Corning Inc	32290400 Glass fiber products (Primary) 33570102 Fiber optic cable (insulated)	327212 Other pressed and blown glass and glassware manufacturing
OFS Fitel LLC	33570102 Fiber optic cable (insulated)	327212 Other pressed and blown glass and glassware manufacturing
Optical Cable Corporation	33570102 Fiber optic cable (insulated)	335921 Fiber optic cable manufacturing

Using the D&B Hoovers companies database, we identified the 105 unique firms with more than 20 employees that are classified by one or both SIC8 code 33570102 or 32290401. These firms are classified into 24 different NAICS economic activities. Fortunately, 90% (91) of these firms are classified into one of ten NAICS codes. These ten codes are listed in Table 13. 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 13 also lists the six BLS equivalent codes that capture this same scope for the optical cabling industry.

Table 13. Most common NAICS codes for firms identified as in the optical fiber cabling industry. These codes capture 90% of firms identified.

NAICS Code	NAICS Description	BLS Equivalent Code
327212	Other Pressed and Blown Glass and Glassware Manufacturing	327000
327215	Glass Product Manufacturing Made of Purchased Glass	”
333314	Optical Instrument and Lens Manufacturing	333300
334210	Telephone Apparatus Manufacturing	334200
334220	Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing	”
334417	Electronic Connector Manufacturing	334400
334419	Other Electronic Component Manufacturing	
335313	Switchgear and Switchboard Apparatus Manufacturing	335300
335921	Fiber Optic Cable Manufacturing	335900
335999	All Other Miscellaneous Electrical Equipment and Component Manufacturing	”

In summary, we discern the optical cabling industry as firms classified as either 33570102 or 32290401 within the SIC8 system which maps to the six BLS equivalent industrial classification codes 327000, 333300, 334200, 334400, 335300, and 335900. Effectively, we are defining the industry of interest as a hybrid of these six industries. This hybrid industry description, will be used to identify relevant occupations.

An equivalent process was followed for discerning firms engaged in photonics component fabrication and/or packaging and assembly. The archetype firms of those types were associated with a rather broad range of SIC8 EAT codes as listed in Table 14.

Table 14 US Standard Industrial Classification – DB Hoovers Expanded Version (SIC8) associated with archetype firms engaged in photonics component and system manufacturing and firms engaged in assembly and packaging of integrated photonic component assembly and packaging

US Standard Industrial Classification – DB Hoovers Expanded Version (SIC8)

Integrated Photonic Component Fabrication Firms	
35599927	Semiconductor manufacturing machinery
36619908	Fiber optics communications equipment
36639901	Antennas, transmitting and communications
36740000	Semiconductors and related devices
36740103	Light emitting diodes
36740200	Integrated circuits, semiconductor networks, etc.
38250226	Semiconductor test equipment
38269909	Laser scientific and engineering instruments
38270100	Optical instruments and apparatus
50650309	Semiconductor devices
35599927	Semiconductor manufacturing machinery
Integrated Photonic Packaging and Assembly Firms	
35599927	Semiconductor manufacturing machinery
36619908	Fiber optics communications equipment
36740000	Semiconductors and related devices
36740202	Hybrid integrated circuits
36740206	Microcircuits, integrated (semiconductor)
36749905	Modules, solid state
38270000	Optical instruments and lenses
38270100	Optical instruments and apparatus

Using the D&B Hoovers companies database, we identified more than 1,800 unique manufacturing firms with more than 20 employees that are classified by one of the SIC8 codes listed in Table 14. These firms are classified into 150 different NAICS economic activities. Fortunately, more than 85% (1,565) of these firms are classified into one of ten NAICS codes. These ten codes along with the BLS equivalent codes are listed in Table 15. These codes were used to define the industry of interest.

Table 15. Most common NAICS codes for firms identified as in the integrated photonic component fabrication, packaging, and assembly industries. These codes capture 85% of firms identified.

NAICS Code	NAICS Description	BLS Equivalent Code
334413	Semiconductor and Related Device Manufacturing	334400
334417	Electronic Connector Manufacturing	"
334418	Printed Circuit Assembly (Electronic Assembly) Manufacturing	"
334419	Other Electronic Component Manufacturing	"
334515	Instrument Manufacturing for Measuring and Testing Electricity and Electrical Signals	334500
334516	Analytical Laboratory Instrument Manufacturing	"
333314	Optical Instrument and Lens Manufacturing	333300
333242	Semiconductor Machinery Manufacturing	3330A1
334210	Telephone Apparatus Manufacturing	334200
334220	Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing	"

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 inTable 16. 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 16. 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 21 relevant middle-skilled positions associated with the photonics industry. To facilitate survey data collection, these were grouped into eight representative positions, as shown in bold in Table 17. Additionally, five lower-skilled (i.e. positions where most workers highest level of education is high-school or less) were selected to better understand firm needs and trends. These positions were selected because they each were highly concentrated in some portion of the photonics supply chain.

Table 17. 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	
Electrical and electronics engineering technicians(representing)	
Electrical and electronics engineering technicians	17-3023
Electro-mechanical technicians	17-3024
Electrical and electronics drafters	17-3012
Industrial engineering technicians(representing)	
Industrial engineering technicians	17-3026
Aerospace engineering and operations technicians	17-3021
Mechanical engineering technicians(representing)	
Mechanical engineering technicians	17-3027
Mechanical drafters	17-3013
Photonics Technician	17-3029
Chemical technicians	19-4031
Industrial machinery mechanics(representing)	
Industrial machinery mechanics	49-9041
Maintenance workers, machinery	49-9043
Heating, air conditioning, and refrigeration mechanics and installers	49-9021
Mobile heavy equipment mechanics, except engines	49-3042
Electrical and electronics repairers, commercial and industrial equipment	49-2094
Avionics technicians	49-2091
Aircraft mechanics and service technicians	49-3011
Camera and photographic equipment repairers	49-9061
Computer-controlled machine tool operators(representing)	
Computer-controlled machine tool operators	51-4011
Computer numerically controlled machine tool programmers	51-4012
Machinists(representing)	
Machinists	51-4041
Tool and die makers	51-4111
Lower-skilled	
Electrical and electronic assemblers (representing)	
Electrical, electronic, and electromechanical assemblers	51-2028
Coil winders, tapers, and finishers	51-2021
Semiconductor processors	51-9141
Optical equipment operators	51-9083
Ceramics equipment operators	51-9195

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 2 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 22 Competencies and tools associated with the job title electrical engineering technician.

> **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 photonics industry. Such programs themselves focus on technical skills and, therefore, require feedback on the same. Secondly, the survey tool applied in this research was already of a scale that taxed most respondents. As such, tradeoffs had to be made to limit its scope and content.

Emerging Skills

While the O*NET database gives a sense of the current skills needed for these occupations, we also wanted to get a sense of what kinds of skills would be expected to become important in the coming years. Considerable work has been invested into exploring what might be the consequences of the changing technological composition of manufacturing work, and we sought to leverage some of that learning into devising a set of questions that would explore how the survey respondents imagined the skills required for these occupations would change.

Much of the work in this area has centered upon the ways in which occupations will increasingly require extended problem-solving skills, building upon increased basic technological knowledge and more interpersonal, soft skills (see, for example, Weaver and Osterman 2017). These skills are also sometimes referred to as essential skills (Government of Canada 2015), skills that are necessary to be successful in the workplace and community. For instance, as manufacturing jobs become much less solitary than before, collaborative skills are increasingly important (Yoo, Boland, and Lyytinen 2006) . Similarly, the concurrent rise of technologically-centered and technologically-enabled production environments require problem-solving and process evaluating skills that require new kinds of competencies and tools.

Because the literature speaks in terms of relatively high levels of abstraction when speaking of these emerging skills, we elected to construct a set of job skills for the survey that would reflect the ideas of these emerging skills. The expectation was that a more concrete set of skills would be less taxing for the survey respondents to evaluate in terms of their future importance. Table 18illustrates one such mapping of these abstractions to the “essential skills” framework that is used by the Canadian government. This table is illustrative of the kinds of abstract skills whose importance we were trying to understand better.

Table 18 The essential skills framework maps essential skill types to specific emerging skills identified for the photonics industry.

Essential Skill Types	Survey Skills Inquiry	Comment
• Reading • Document Use • Numeracy	• Conducting (and assessing the results of statistical process control analyses) • Evaluating and making use of process management analyses	With increased computer control comes increased opportunity to measure and track process performance, hence a rise in the importance of SPC and related tools. Such evaluations depend upon numerical literacy and problem-solving skills
• Working with Others • Writing • Oral Communication	• Collaborating with engineering and management staff • Working with digital collaboration tools	While collaboration, per se, is not a particularly novel skill, the ability to employ emerging digital tools will lead to
• Thinking	• Knowing the science & engineering underlying the product • Troubleshooting processing problems	General problem-solving skills will depend upon employees able to frame their understanding of process / product problems within a commonly-held scientific and technological context, particularly since collaboration will be key
• Computer Use	• Working with CAD products • Monitoring, assessing, and working with CNC or other automated process equipment	Formal ability to work with advanced engineering programming, as well as process control tools
• Continuous Learning	-	-

Realistically, of course, there are many ways of mapping these statements to the emerging skills. This family of skills were tested with subjects before wider deployment to ensure that they met our goals of being future-looking as well as approachable by the survey respondents.

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.

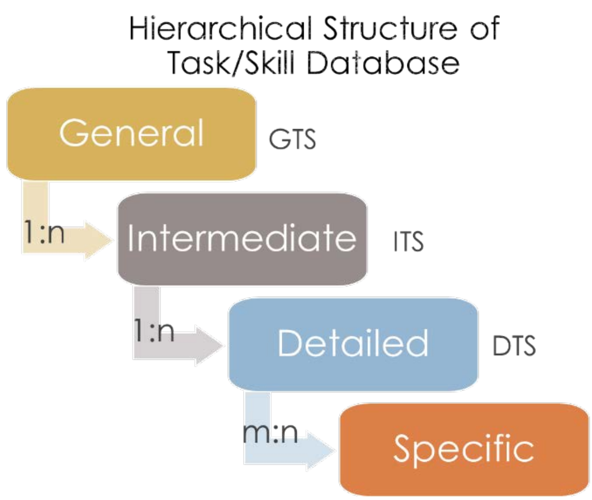


*Figure 23. Hierarchical structure of the task/skill database used in this study. Survey respondents were asked about occupation specific (orange level) tasks or skill. 1:n indicates a one (parent) to many (child) relationship. m:n indicates a many to many relationship. The hierarchies are defined within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

Develop and deploy survey

Survey design

The survey is structured into four main sections:

1) firm characterization,
2) Hiring and training challenges
3) Workforce scaling, and
4) Emerging skill needs.

In the first section of the survey, respondents were asked to identify the primary role that their firm plays in the photonics 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 third section of the survey, respondents were asked to quantify how many individuals were employed at their firm for each type of relevant occupation.

In the final section of the survey, respondents were randomly assigned three relevant occupations. For each of these, they were asked to rank the importance of specific skills and tools for the future.

Survey Deployment

The survey was implemented in the Qualtrics online platform (Qualtrics XM 2021) and was sent out to members of the MIT Microphotonics Center[9], members of COMSET[10] (Center for Optical Materials Science and Engineering Technologies) – fiber industry focused group based out of Clemson University, and the Optical Society of America[11] and targeted at operations managers in the photonics industry. Fifty responses where the respondent completed more than 50% of the survey were received and incorporated into the following results.

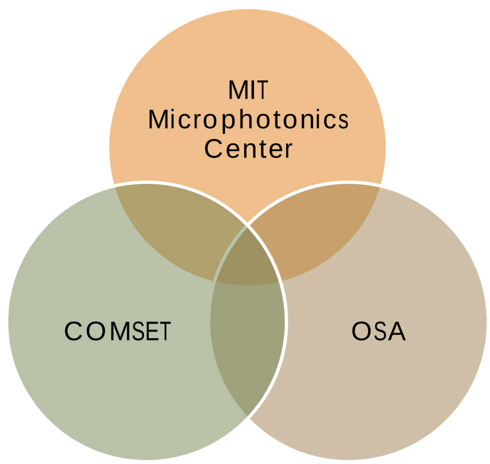


Figure 24. Survey was distributed by three organizations in the photonics industry

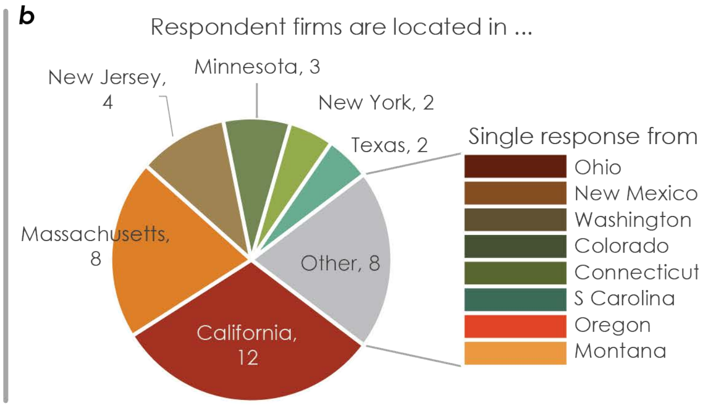
9 https://mphotonics.mit.edu/
10 http://www.clemson.edu/centers-institutes/comset/
11 https://www.osa.org/

Respondent Demographics

Survey respondents came from a broad array of firms. As shown in Figure 25a, firms ranged in size from as few as four employees to as many as 10,000. The median firm size was 70 employees. Annual revenue ranged from $33M to nearly $32B with a median of $2B per year. Most respondents came from firms in California, Massachusetts, or New Jersey, but there were responses for all parts of the United States (See Figure 25b).

a

	Annual Revenue (million USD)	Size of Frim (Headcount)
Median	$33.5	70
Mean	$1,900	1090
Min	$0.5	4
Max	$32,000	10,000



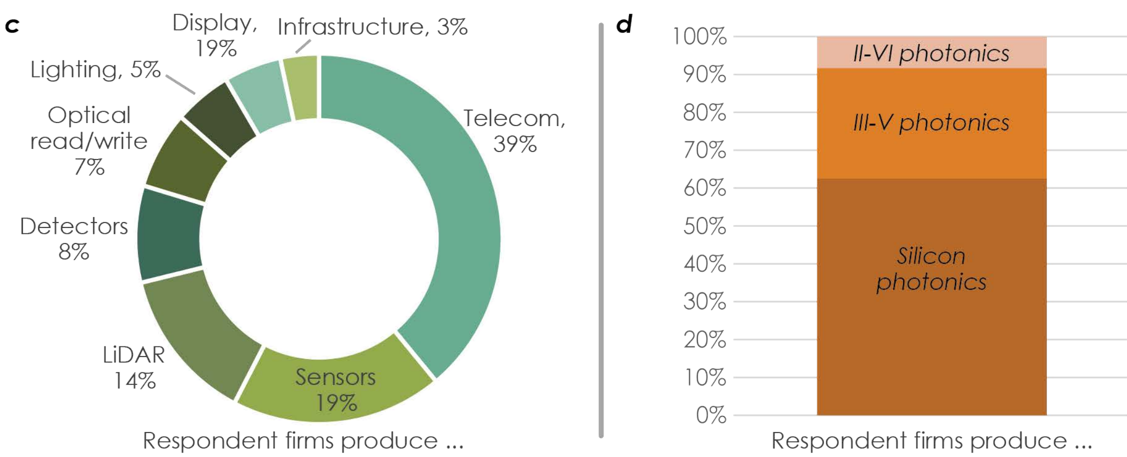


Figure 25. Distribution of respondent location for those that provided a location.

Respondent firms produced a range of products (see Figure 25c), but more than two-thirds were concentrated in the telecom/datacom, sensors, or LiDAR markets. The majority of respondent firms produce products from silicon (see Figure 25d) with about 1/3 producing III-V devices.

Finally, firms were asked to identify their role within the photonics supply chain. Responses about the firms primary activity in the supply chain are reported in Figure 26. Specifically, firms were asked if they primarily participated in the fiber cabling supply chain (blue bars) or the planar components supply chain (brown bars).

As Figure 26 makes clear, most respondents were primarily associated with the component supply chain and had a primary role in component fabrication or assembly, packaging, and test.

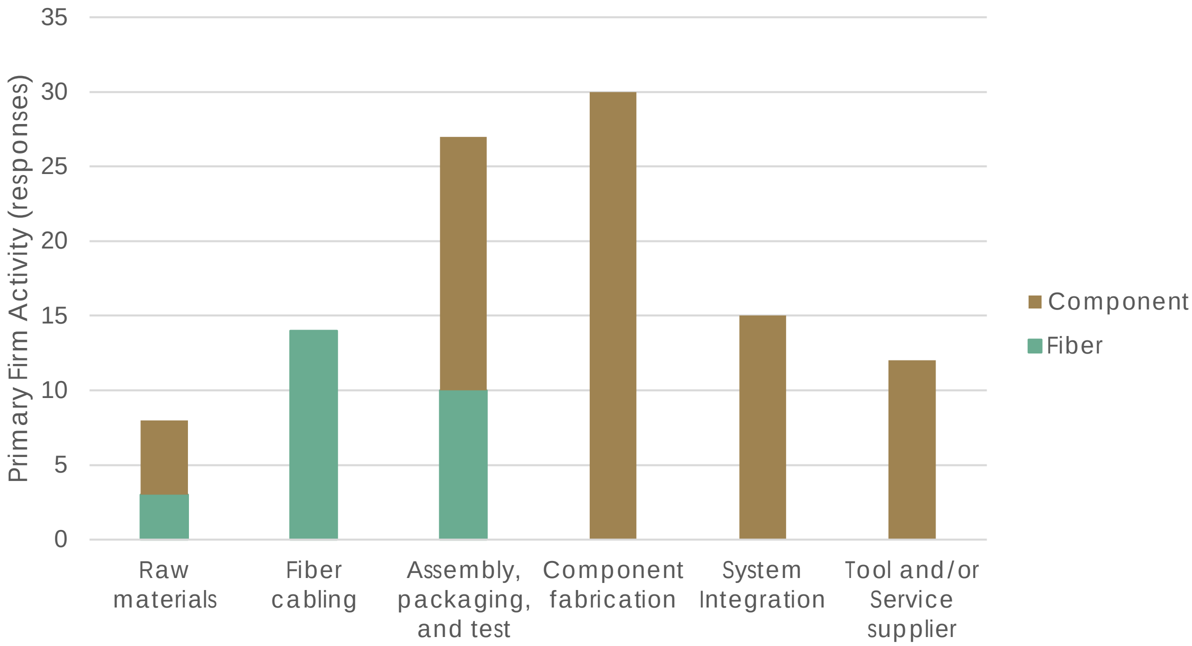


Figure 26. Distribution of responses of firm primary activity within the photonics supply chain. Firms could indicate more than one primary activity. Firms also indicated whether they were engaged primarily with the fiber cabling supply chain (blue) or the planar components supply chain (brown).

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 19.

Table 19. Focal occupations that were evaluated in this study and abbreviated title used in GTS / ITS tables

Occupation	Abbreviation
Electrical and electronics engineering technicians	ElecEng T
Industrial engineering technicians	Ind Eng T
Mechanical engineering technicians	MechEng T
Photonics Technician	Photonic T
Chemical technicians	Chemical T
Computer-controlled machine tool operators	CNC Oper
Electrical and electronic assemblers	Elect Assm
Semiconductor processors	Semi Proc
Optical equipment operators	Opt Eq Op
Ceramics equipment operators	Cer Pr Op

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	CNC Oper
Thinking & Making Creatively	3.2	Develop research plans or methodologies.	4.6	Plan method or sequence of operations for developing or testing experimental electronic or electrical equipment.	4.6			X			
		Design industrial systems or equipment.	3.8	Fabricate and assemble new or modified mechanical components for products such as industrial machinery or equipment, and measuring instruments.	3.8					X	
		Design electrical or electronic systems or equipment.	3.7	Modify electrical prototypes, parts, assemblies, or systems to correct functional deviations.	3.8			X			
				Fabricate and test devices, such as optoelectronics, semiconductors, fiber optic-based devices, and fiber optic systems .	3.7	X					
		Create visual designs or displays.	1.8	Prepare charts or diagrams to illustrate workflow, routing, floor layouts, material handling, or machine utilization.	1.8		X				
				Draft detail drawing or sketch for drafting room completion or to request parts fabrication by machine, sheet or wood shops.	1.8					X	
				Design basic circuitry and design documentation under engineers' direction, using drafting instruments or computer-aided design (CAD) equipment.	-nr-			X			
		Develop models of systems, processes, or products.	1.7	Build prototypes from rough sketches or plans.	-nr-			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	CNC Oper
Analyzing Data or Information	3.1	Analyze performance of systems or equipment.	3.8	Analyze test results in relation to design or rated specifications and test objectives, and modify or adjust equipment to meet specifications.	4.2					X	
				Interpret test information to resolve design-related problems.	3.8			X			
				Compile and evaluate data using statistical process control procedures	3.4		X				
		Analyze data to improve operations.	3.1	Perform diagnostic analyses of optical components or processing, using analytical or metrological tools, such as microscopy, profilometry, ellipsometry devices,or optical spectrum analyzers.	3.2	X					
				Set up or operate test apparatus, such as control consoles, collimators, recording equipment, or cables.	3.0	X					
		Analyze biological or chemical substances or related data.	1.5	Conduct chemical or physical laboratory tests to assist scientists in making qualitative or quantitative analyses of solids, liquids, or gaseous materials.	1.8				X		
				Set up and conduct chemical experiments, tests, and analyses, using techniques such as chromatography, spectroscopy, physical or chemical separation techniques, or microscopy.	1.3				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	CNC Oper
Making Decisions and Troubleshooting Problems	3.0	Determine operational methods or procedures.	4.6	Plan method or sequence of operations for developing or testing experimental electronic or electrical equipment.	4.6			X			
		Determine resource needs of projects or operations.	2.4	Calculate required capacities for equipment to obtain specified performance	3.0					X	
				Prepare electrical project cost or work-time estimates.	2.4			X			
				Calculate machine speed and feed ratios and the size and position of cuts.	1.8						X
Estimating and Judging the Characteristics of Products or Processes	2.9	Evaluate production inputs or outputs.	3.5	Monitor product quality to ensure compliance with standards and specifications.	3.5				X		
		Estimate project development or operational costs.	2.6	Estimate cost factors including labor and material for purchased and fabricated parts and costs for assembly, testing, or installing.	2.8					X	
				Prepare electrical project cost or work-time estimates.	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	CNC Oper
Provide Consultation and Advice to Others	2.8	Coordinate with others to resolve problems.	4.2	Collaborate with electrical engineers or other personnel to identify, define, or solve developmental problems.	4.2			X			
		Advise others on the design or use of technologies.	3.8	Provide technical assistance in resolving electrical engineering problems encountered before, during, or after construction.	3.8			X			
		Advise others on business or operational matters.	2.7	Recommend optical or optic equipment design or material changes to reduce costs or processing times.	2.7	X					
				Recommend modifications to existing quality or production standards to achieve optimum quality	2.6		X				
		Advise others on products or services.	2.3	Provide user applications or engineering support or recommendations for new or existing equipment with regard to installation, upgrades, or enhancements.	-nr-			X			
		Explain technical details of products or services.	1.2	Interpret engineering drawings, schematic diagrams, or formulas for management or engineering staff.	1.2		X				
Information Management	2.7	Document technical designs, procedures, or activities.	3.1	Record test procedures and results, numerical and graphical data, and recommendations for changes in product or test methods.	3.8					X	
				Write procedures for the commissioning of electrical installations.	2.8			X			
				Write reports or record data on testing techniques, laboratory equipment, or specifications to assist engineers.	-nr-			X			
		Prepare documentation for contracts, applications, or permits.	3.0	Prepare, review, or coordinate ongoing modifications to electrical system specifications or plans.	3.0			X			
		Present research or technical information.	1.3	Write technical reports or prepare graphs or charts to document experimental results.	1.3				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	CNC Oper
Inspecting Equipment, Structures, or Material	2.3	Inspect completed work or finished products.	4.0	Inspect electrical project work for quality control and assurance.	4.0			X			
		Test performance of equipment or systems.	2.2	Set up or operate test equipment to evaluate performance of developmental parts, assemblies, or systems under simulated operating conditions.	3.8			X			
				Terminate, cure, polish, or test fiber cables with mechanical connectors.	2.1	X					
				Test equipment, using test devices attached to generator, voltage regulator, or other electrical parts, such as generators or spark plugs.	1.8					X	
				Test electronics units, using standard test equipment, and analyze results to evaluate performance and determine need for adjustment.	-nr-			X			
		Test characteristics of materials or products.	1.4	Test products for performance characteristics or adherence to specifications.	1.4		X				
Prepare specimens, tools, or equipment	2.1	Assemble equipment or components.	3.0	Assemble optical components including photonic switches, optical backplanes, or optoelectronic interfaces.	3.0	X					
				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.	3.0	X					
				Build, calibrate, maintain, troubleshoot, or repair electrical instruments or testing equipment.	3.0			X			
		Adjust equipment to ensure adequate performance.	2.5	Perform preventative maintenance or calibration of electronic equipment or systems.	-nr-			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	CNC Oper
Prepare specimens, tools, or equipment (cont)		Clean tools, equipment, facilities, or work areas.	1.9	Maintain working environments to clean room standards.	2.0	X					
				Clean machines, tooling, or parts, using solvents or solutions and rags.	1.3						X
		Install commercial or production equipment.	1.8	Splice fibers, using fusion splicing or other techniques.	1.8	X					
		Disassemble equipment.	1.8	Maintain machines and remove and replace broken or worn machine tools, using hand tools.	1.8						X
		Prepare industrial materials for processing or use.	1.4	Mix, pour, or use processing chemicals or gases according to safety standards or established operating procedures.	1.4	X					
		Clean workpieces, finished products, or other objects.	1.3	Maintain, clean, or sterilize laboratory instruments or equipment.	1.3				X		
		Prepare specimens or materials for testing.	1.0	Prepare chemical solutions for products or processes, following standardized formulas, or create experimental formulas.	1.0				X		
		Set up equipment.	1.0	Set up and conduct chemical experiments, tests, and analyses, using techniques such as chromatography, spectroscopy, physical or chemical separation techniques, or microscopy.	1.3				X		
				Mount, install, align, and secure tools, attachments, fixtures, and workpieces on machines, using hand tools and precision measuring instruments.	0.8						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	CNC Oper
Data Collection & Synthesis	1.9	Read documents or materials to inform work processes.	1.9	Review project instructions and blueprints to ascertain test specifications, procedures, and objectives	3.0					X	
				Review program specifications or blueprints to determine and set machine operations and sequencing, finished workpiece dimensions, or numerical control sequences.	1.3						X
				Read blueprints, wiring diagrams, schematic drawings, or engineering instructions for assembling electronics units, applying knowledge of electronic theory and components.	-nr-			X			
Repairing and Maintaining Equipment	1.8	Maintain electronic, computer, or other technical equipment.	1.9	Build, calibrate, maintain, troubleshoot, or repair electrical instruments or testing equipment.	3.0			X			
				Maintain, clean, or sterilize laboratory instruments or equipment.	1.3				X		
				Perform preventative maintenance or calibration of electronic equipment or systems.	-nr-			X			
				Adjust or replace defective or improperly functioning circuitry or electronics components, using hand tools or soldering iron.	-nr-			X			
		Maintain tools or equipment.	1.8	Maintain machines and remove and replace broken or worn machine tools, using hand tools.	1.8						X
Controlling Machines and Processes	3.3	Fabricate devices or components.	3.4	Fabricate and assemble new or modified mechanical components for products such as industrial machinery or equipment, and measuring instruments.	3.8					X	
				Fabricate and test devices, such as optoelectronics, semiconductors, fiber optic-based devices, and fiber optic systems .	3.7	X					
				Operate drill press, grinders, engine lathe, or other machines to modify or to fabricate components.	1.8					X	
		Operate industrial processing or production equipment.	3.1	Set up or operate test apparatus, such as control consoles, collimators, recording equipment, or cables.	3.0	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	CNC Oper
Organizing, Planning, and Prioritizing Work	2.3	Develop operational or technical procedures or standards.	2.3	Develop or upgrade preventative maintenance procedures for components, equipment, parts, or systems.	-nr-			X			
		Plan work activities.	2.2	Aid in planning work assignments in accordance with worker performance, machine capacity, production schedules, or anticipated delays.	2.2		X				
Interacting With Computers	1.6	Program computer systems or production equipment.	1.6	Set up and operate computer-controlled machines or robots to perform one or more machine functions on metal or plastic workpieces.	1.8						X
				Input machine control programs	1.8						X
				Modify cutting programs to account for problems encountered during operation	1.0						X
Monitor Processes, Materials, or Surroundings	1.5	Monitor operations to ensure adequate performance.	1.8	Verify that equipment is being operated and maintained according to quality assurance standards .	1.8		X				
		Monitor equipment operation.	1.5	Monitor machine operation and control panel displays, and compare readings to specifications to detect malfunctions.	1.8						X
				Check to ensure that workpieces are properly lubricated and cooled during machine operation.	1.3						X
		Monitor operations to ensure compliance with regulations or standards.	1.2	Read worker logs, product processing sheets, or specification sheets to verify quality assurance specifications.	1.2		X				

Occupation Descriptions

Occupation Title	Description	Alternative Titles
Ceramics Production Operator (SOC Code 51-9195.05)	Operate production machines such as pug mill, jigger machine, or other processing equipment in the manufacture of ceramic products	Glazer, Jigger Artisan, Jigger Machine Operator, Manufacturing Potter, Model and Mold Maker, Model Maker, Pot Maker, Potter, Potters Manufacturer
Chemical Technicians (SOC Code 19-4031.00)	Conduct chemical and physical laboratory tests to assist scientists in making qualitative and quantitative analyses of solids, liquids, and gaseous materials. Inform research and development of new products or processes, quality control, maintenance of environmental standards	Analysis Tester, Analytical Tech, Chemical Assistant, Color Consultant, Control Analyst, Cosmetic Chemist, Dye Lab Tech, Fiber Analyst, Formulation Tech, Inventory Tech, Lab Analyst, Lab Cureman, Operations Tech, Paint Tech, Plastic Tech, Pyrotechnist, Research Tech, Spectrograph Operator, Water Analyst
Computer-Controlled Machine Tool Operator (SOC Code 51-4011.00)	Operate computer-controlled machines or robots to perform one or more machine.	Automation Machine Operator, CNC Laser Operator, CNC Machine Operator, Machinist, Manufacturing Assistant, Numerical Control Machine Operator, Robotic Machine Operator
Electrical and Electronic Equipment Assemblers (SOC Code 51-2022.00)	Assemble or modify electrical or electronic equipment (e.g. computers, test equipment telemetering systems, electric motors, batteries	Assembler, Battery Assembler, Cable Wirer, Capacitor Assembler, Circuit Board Assembler, Computer Builder, Connector, Electric Motor Assembler, Electric Wirer, Electrical Accessories Assembler, Electrical Mechanical Fabrication Tech, Industrial Equipment

Occupation Title	Description	Alternative Titles
		Assembler and Wirer, Semiconductor Assembler, Production Worker, Subassembler, Wiring Tech
Electronics Engineering Technicians (SOC Code 17-3023.01)	Lay out, build, test, troubleshoot, repair, and modify developmental and production electronic components, parts, equipment, and systems (e.g. computer equipment, electron tubes, machine tool numerical controls, etc.). Apply principles and theories of electronics, electrical circuitry, engineering, mathematics, electronic and electrical testing, and physics	Automation Tech, Calibration Tech, CNC Programmer, Computer Engineering Tech, Controls Tech, Digital Tech, Electrical Tech, Failure Analysis Tech, Instrument Mechanic, Low Voltage Tech, Test Technician
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	Analysis Tester, Engineering Tech, Manufacturing Tech, Methods Engineer, Motion Study Engineer, Plant Facilities Tech, Process Engineer, Production Analyst, Quality Assurance Manager
Mechanical Engineering Technicians (SOC Code 17-3027.00)	Apply theory and principles of mechanical engineering to modify, develop, test, or calibrate machinery and equipment	Automation Design Checker, Certified Control Systems Tech, Development Tech, Engineering Lab Tech, Experimental Tech, Mechanical Designer, Maintenance Tech, Process Engineering Tech, Proof Tech,

Occupation Title	Description	Alternative Titles
Optical Equipment Operator (SOC Code 51-9083.00)	Cut, grind, and polish lenses or other precision optical elements. Assemble and mount or otherwise process optical elements (e.g. precision lens polishers or grinders, centerer-edgers, and lens mounters)	Benchroom Shop Optician, Beveler, Lens Tech, Edger Tech, Glass Cutter, Layout Tech, Lens Generator, Ophthalmic Tech, Optical Coating Tech, Precision Lens Generator
Photonics Technicians (SOC Code 17-3029.08)	Build, install, test, or maintain optical or fiber optic equipment (e.g. lasers, lenses or mirrors, using spectrometers, interferometers, or related equipment)	Certified Laser Tech, Coating Manager, Engineering Tech, Fiber Optic Tech, Fiber Optics Design Tech, Optical Engineering Tech, Optical Fabrication Tech, Optical Manufacturing Tech, Optomechanical Tech, Precision Optics Tech
Semiconductor Processors (SOC Code 51-9141.00)	Perform any of the following functions in the manufacture of electronic semiconductors: □load semiconductor material into furnace; saw formed ingots into segments; load individual segment into crystal growing chamber and monitor controls; locate crystal axis in ingot using x-ray equipment and saw ingots into wafers; and clean, polish, and load wafers into series of special purpose furnaces, chemical baths, and equipment used to form circuitry and change conductive properties	Charge Preparation Tech, Chemical Etch Operator, Crystal Finisher, Crystal Grower, Device Processing Engineer, Electronic Component Processor, Electronic Semiconductor Processor, Etcher, Fabrication Operator, Integrated Circuit Fabricator, Microelectronics Tech, Process Tech, Semiconductor Assembler, Wafer Fabrication Tech

References

Ainslie, B. James, and Clive R. Day. 1986. "A Review of Single-Mode Fibers with Modified Dispersion Characteristics." *Journal of Lightwave Technology* 4 (8): 967–79. https://doi.org/10.1109/JLT.1986.1074843.

Alwayn, Vivek. 2004. *Optical Network Design and Implementation | Cisco Press*. https://www.ciscopress.com/store/optical-network-design-and-implementation-9781587051050?w_ptgrevartcl=Fiber-Optic+Technologies_170740.

Atabaki, Amir H., Sajjad Moazeni, Fabio Pavanello, Hayk Gevorgyan, Jelena Notaros, Luca Alloatti, Mark T. Wade, et al. 2018. "Integrating Photonics with Silicon Nanoelectronics for the next Generation of Systems on a Chip." *Nature* 556 (7701): 349–53. https://doi.org/10.1038/s41586-018-0028-z.

Barley, S. R. 1986. "Technology as an Occasion for Structuring: Evidence from Observations of CT Scanners and the Social Order of Radiology Departments." *Administrative Science Quarterly* 31 (1): 78–108. https://doi.org/10.2307/2392767.

BCC Research. 2017. "Silicon Photonics Market Research Report ." https://www.bccresearch.com/market-research/photonics/silicon-photonics-technologies-and-global-markets.html.

Blumenthal, Daniel J., Hitesh Ballani, Ryan O. Behunin, John E. Bowers, Paolo Costa, Daniel Lenoski, Paul A. Morton, Scott B. Papp, and Peter T. Rakich. 2020. "Frequency-Stabilized Links for Coherent WDM Fiber Interconnects in the Datacenter." *Journal of Lightwave Technology* 38 (13): 3376–86. https://doi.org/10.1109/JLT.2020.2985275.

Braud, Tristan, Farshid Hassani Bijarbooneh, Dimitris Chatzopoulos, and Pan Hui. 2017. "Future Networking Challenges: The Case of Mobile Augmented Reality." In *Proceedings - International Conference on Distributed Computing Systems*, 1796–1807. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ICDCS.2017.48.

Carroll, Lee, Jun-Su Lee, Carmelo Scarcella, Kamil Gradkowski, Matthieu Duperron, Huihui Lu, Yan Zhao, et al. 2016. "Photonic Packaging: Transforming Silicon Photonic Integrated Circuits into Photonic Devices." *Applied Sciences* 6 (12): 426. https://doi.org/10.3390/app6120426.

Chen, Na, and Minoru Okada. 2020. "Towards 6G Internet of Things and the Convergence with RoF System." *IEEE Internet of Things Journal*. https://doi.org/10.1109/JIOT.2020.3047613.

Christensen, C. M., M. Verlinden, and G. Westerman. 2002. "Disruption, Disintegration and the Dissipation of Differentiability." *Industrial and Corporate Change* 11 (5): 955–93. https://doi.org/10.1093/icc/11.5.955.

Combemale, Christophe, and Erica Fuchs. 2020. "Embedded Knowledge on the Production Line: How 'Sorcery' at the Technical Frontier Can Give Workers a Role in Innovation."

Combemale, Christophe, Kate Whitefoot, Laurence Ales, and Erica Fuchs. 2021. "Not All

Technological Change Is Equal: Disentangling Labor Demand Effects of Automation and Parts Consolidation." *Industrial and Corporate Change*, no. In Press.

Combemale, Christophe, Kate S. Whitefoot, Laurence Ales, and Erica R.H. Fuchs. 2019. "Not All Technological Change Is Equal: Disentangling Labor Demand Effects of Simultaneous Changes." *Academy of Management Proceedings* 2019 (1): 10715. https://doi.org/10.5465/ambpp.2019.10715abstract.

Cramer, Jonathan. 2017. "D&B Increases Confidence Across SIC Code Databases with AI." 2017. https://www.dnb.com/perspectives/master-data/how-dnb-improves-sic-classification-ai.html.

Dalziel, Margaret. 2007. "A Systems-Based Approach to Industry Classification." *Research Policy* 36 (10): 1559–74. https://doi.org/10.1016/j.respol.2007.06.008.

Dandridge, Anthony, and Gary B. Cogdell. 1991. "Fiber Optic Sensors for Navy Applications." *IEEE LCS* 2 (1): 81–89. https://doi.org/10.1109/73.80443.

Dobbelaere, P. De, A. Dahl, A. Mekis, B. Chase, B. Weber, B. Welch, D. Foltz, et al. 2018. "Advanced Silicon Photonics Technology Platform Leveraging a Semiconductor Supply Chain." In *Technical Digest - International Electron Devices Meeting, IEDM*, 34.1.1-34.1.4. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/IEDM.2017.8268493.

Dun and Bradstreet, Inc. 2020. "Company Search." 2020. https://www.dnb.com/business-directory/company-search.html.

Foy, F. Pat, and George Iwaszek. 1996. "Workforce Development - Building the Public Education Pipeline to Meet Manufacturing Technician Hiring Needs." In *IEEE/SEMI Advanced Semiconductor Manufacturing Conference and Workshop*, 451–54. IEEE. https://doi.org/10.1109/asmc.1996.558117.

Fujimoto, Daiki, Hai Han Lu, Kazuo Kumamoto, Song En Tsai, Qi Ping Huang, and Jing Yan Xie. 2019. "Phase-Modulated Hybrid High-Speed Internet/WiFi/Pre-5G In-Building Networks over SMF and PCF with GI-POF/IVLLC Transport." *IEEE Access* 7: 90620–29. https://doi.org/10.1109/ACCESS.2019.2926709.

Fuller, J, and M Raman. 2017. "Dismissed by Degrees."

Giffi, Craig A, Joseph Vitale, Thomas Schiller, and Ryan Robinson. 2018. "A Reality Check on Advanced Vehicle Technologies Evaluating the Big Bets Being Made on Autonomous and Electric Vehicles."

Government of Canada. 2015. "What Are Essential Skills? - Canada.Ca." 2015. https://www.canada.ca/en/employment-social-development/programs/essential-skills/tools/what-aresential-skills.html.

Gupta, Mool, and John Ballato. 2007. *The Handbook of Photonics - Google Books*. 2nd ed. https://books.google.com/books?hl=en&lr=&id=j4XMBQAAQBAJ&oi=fnd&pg=PP1&dq=innovations+photonics+industry&ots=4lVW_dh1mA&sig=Jm7FofN2BxPptXCsZS5vFFQGvSw#v=onepage&q=innovations photonics industry&f=false.

Hallacher, Paul M, Douglas E Fenwick, and Stephen J Fonash. 2002. "The Pennsylvania Nanofabrication Manufacturing Technology Partnership: Resource Sharing for Nanotechnology Workforce Development*."

Hardcastle, Alan, and Stacey Waterman-Hoey. 2010. "Advanced Materials Manufacturing Sustainability and Workforce Development: Pilot Study." https://research.libraries.wsu.edu:8443/xmlui/handle/2376/5951.

Hecht, Jeff. 2020. "The Breakthrough Birth of Low-Loss Fiber Optics." *Optics and Photonics News* 31 (3): 26. https://doi.org/10.1364/opn.31.3.000026.

Huang, Yong, Ming C. Leu, Jyoti Mazumder, and Alkan Donmez. 2015. "Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations." *Journal of Manufacturing Science and Engineering, Transactions of the ASME* 137 (1). https://doi.org/10.1115/1.4028725.

Jhoja, Jaspreet, Jackson Klein, Xu Wang, Amy Liu, Jonas Flueckiger, James Pond, Lukas Chrostowski, et al. 2014. "Design Challenges in Silicon Photonics." *IEEE J. Sel. Top. Quantum Electron* 20: 1–8. https://doi.org/10.1364/OE.25.009712.

Kahn, Joseph M., and Keang Po Ho. 2004. "Spectral Efficiency Limits and Modulation/Detection Techniques for DWDM Systems." *IEEE Journal on Selected Topics in Quantum Electronics*. https://doi.org/10.1109/JSTQE.2004.826575.

Kile, Charles O, and Mary E Phillips. 2009. "Using Industry Classification Codes to Sample High-Technology Firms: Analysis and Recommendations." *Journal of Accounting, Auditing & Finance* 24 (1): 35–58. https://doi.org/10.1177/0148558X0902400104.

Kobayashi, Kohroh, and Ikuo Mito. 1988. "Single Frequency and Tunable Laser Diodes." *Journal of Lightwave Technology*. https://doi.org/10.1109/50.9978.

Koch, Thomas L., and Uziel Koren. 1990. "Semiconductor Lasers for Coherent Optical Fiber Communications." *Journal of Lightwave Technology* 8 (3): 274–93. https://doi.org/10.1109/50.50725.

Kumar, Sanjeev, and J. Kent Hsiao. 2007. "Engineers Learn 'Soft Skills the Hard Way': Planting a Seed of Leadership in Engineering Classes." *Leadership and Management in Engineering* 7 (1): 18–23. https://doi.org/10.1061/(ASCE)1532-6748(2007)7:1(18).

Lightcounting. 2020. "October 2020 Market Forecast Report." https://www.lightcounting.com/products/forecastoct/.

Marpaung, David, Jianping Yao, and José Capmany. 2019. "Integrated Microwave Photonics." *Nature Photonics*. Nature Publishing Group. https://doi.org/10.1038/s41566-018-0310-5.

Mears, R.J. 2003. "The EDFA: Past, Present and Future." In , 1332 vol.2. Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/apcc.1999.820510.

Pant, Mihir, Don Towsley, Dirk Englund, and Saikat Guha. 2019. "Percolation Thresholds for Photonic Quantum Computing." *Nature Communications* 10 (1): 1–11. https://doi.org/10.1038/s41467-019-08948-x.

Pérez, Daniel, Ivana Gasulla, Lee Crudgington, David J. Thomson, Ali Z. Khokhar, Ke Li, Wei Cao, Goran Z. Mashanovich, and José Capmany. 2017. "Multipurpose Silicon Photonics Signal Processor Core." *Nature Communications* 8 (1): 1–9. https://doi.org/10.1038/s41467-017-00714-1.

Peterson, NORMAN G., MICHAEL D. MUMFORD, WALTER C. BORMAN, P. RICHARD JEANNERET, EDWIN A. FLEISHMAN, KERRY Y. LEVIN, MICHAEL A. CAMPION, et al. 2001. "UNDERSTANDING WORK USING THE OCCUPATIONAL INFORMATION NETWORK (O*NET): IMPLICATIONS FOR PRACTICE AND RESEARCH." *Personnel Psychology* 54 (2): 451–92. https://doi.org/10.1111/j.1744-6570.2001.tb00100.x.

PR Newswire. 2021. "Photonics Market Worth $837.8 Billion by 2025 - Exclusive Report by MarketsandMarkets™." 2021. https://www.prnewswire.com/news-releases/photonics-market-worth-837-8-billion-by-2025--exclusive-report-by-marketsandmarkets-301221003.html.

Qualtrics XM. 2021. "The Leading Experience Management Software." 2021. https://www.qualtrics.com/.

Rao, M. S. 2014. "Enhancing Employability in Engineering and Management Students through Soft Skills." *Industrial and Commercial Training* 46 (1): 42–48. https://doi.org/10.1108/ICT-04-2013-0023.

Ross, Gavin. 2020a. "Fiber-Optic Cable Manufacturing." Los Angeles, CA, USA.

———. 2020b. "OD5660 Fiber-Optic Cable Manufacturing - MyIBISWorld." 2020. https://my.ibisworld.com/us/en/industry-specialized/od5660/about.

Sanders, Glen A., Bogdan Szafraniec, Ren-Young Liu, Clarence L. Laskoskie, Lee K. Strandjord, and George Weed. 1996. "Fiber Optic Gyros for Space, Marine, and Aviation Applications." In *Fiber Optic Gyros: 20th Anniversary Conference*, edited by Eric Udd, Herve C. Lefevre, and Kazuo Hotate, 2837:61–71. SPIE. https://doi.org/10.1117/12.258208.

Schmidtke, Katharine. 2019. "Hyperscale Data Center Applications of Optoelectronics." In *Metro and Data Center Optical Networks and Short-Reach Links II*, edited by Madeleine Glick, Atul K. Srivastava, and Youichi Akasaka, 10946:201. SPIE. https://doi.org/10.1117/12.2518569.

Schulz, Bernd. 2008. "The Importance of Soft Skills: Education beyond Academic Knowledge." *NAWA Journal of Language and Communication*.

Shastri, Bhavin J., Alexander N. Tait, T. Ferreira de Lima, Wolfram H.P. Pernice, Harish Bhaskaran, C. D. Wright, and Paul R. Prucnal. 2021. "Photonics for Artificial Intelligence and Neuromorphic Computing." *Nature Photonics*. Nature Research. https://doi.org/10.1038/s41566-020-00754-y.

Shumate, Paul W. 2008. "Fiber-to-the-Home: 1977-2007." *Journal of Lightwave Technology* 26 (9): 1093–1103. https://doi.org/10.1109/JLT.2008.923601.

Slussarenko, Sergei, and Geoff J. Pryde. 2019. "Photonic Quantum Information Processing: A Concise Review." *Applied Physics Reviews*. American Institute of Physics Inc.

https://doi.org/10.1063/1.5115814.

SPIE. 2020. “2020 Optics and Photonics Industry Report (Fall Update).” https://spie.org/news/2020-optics-and-photonics-industry-report?SSO=1.

Stump, Glenda, George Westerman, and Katherine Hall. 2020. “Human Skills: Critical Components of Future Work - The EvoLLLution The EvoLLLution.” March 2020. https://evolllution.com/revenue-streams/workforce_development/human-skills-critical-components-of-future-work/.

Sun, Jie, Erman Timurdogan, Ami Yaacobi, Ehsan Shah Hosseini, and Michael R. Watts. 2013. “Large-Scale Nanophotonic Phased Array.” *Nature* 493 (7431): 195–99. https://doi.org/10.1038/nature11727.

Thomas, Gordon A., Boris I. Shraiman, Paul F. Glodls, and Michael J. Stephen. 2000. “Towards the Clarity Limit in Optical Fibre.” *Nature* 404 (6775): 262–64. https://doi.org/10.1038/35005034.

U.S. Bureau of Labor Statistics. 2018. “National Employment Matrix.” 2018. https://www.bls.gov/emp/ind-occ-matrix/.

U.S. Department of Labor. 2020. “O*NET 25.1 Database.” 2020. https://www.onetcenter.org/database.html.

Washburn, Adam L., and Ryan C. Bailey. 2011. “Photonics-on-a-Chip: Recent Advances in Integrated Waveguides as Enabling Detection Elements for Real-World, Lab-on-a-Chip Biosensing Applications.” *Analyst*. Royal Society of Chemistry. https://doi.org/10.1039/c0an00449a.

Weaver, Andrew, and Paul Osterman. 2017. “Skill Demands and Mismatch in U.S. Manufacturing.” *Industrial and Labor Relations Review* 70 (2): 275–307. https://doi.org/10.1177/0019793916660067.

Yoo, Youngjin, Richard J. Boland, and Kalle Lyytinen. 2006. “From Organization Design to Organization Designing.” *Organization Science* 17 (2): 215–29. https://doi.org/10.1287/orsc.1050.0168.

Yu, Jianjun, and Xiang Zhou. 2010. “Ultra-High-Capacity DWDM Transmission System for 100G and Beyond.” *IEEE Communications Magazine* 48 (3). https://doi.org/10.1109/MCOM.2010.5434379.

Zhou, Minqi, Rong Zhang, Dadan Zeng, and Weining Qian. 2010. “Services in the Cloud Computing Era: A Survey.” In *2010 4th International Universal Communication Symposium, IUCS 2010 - Proceedings*, 40–46. https://doi.org/10.1109/IUCS.2010.5666772.