Journal of Integrated Design and Process Science 26 (2022) 415–441
DOI 10.3233/JID-220007
IOS Press

Prioritizing actions and outcomes for community-based future manufacturing workforce development and education

Karl R. Haapala[a,*], Kamyar Raoufi[a], Kyoung-Yun Kim[b], Peter F. Orazem[c], Christopher S. Houck[a], Michael D. Johnson[d], Gül E. Okudan Kremer[e], Jeremy L. Rickli[b], Federico M. Sciammarella[f] and Kris Ward[g]

[a]*School of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, Corvallis, OR, USA*
[b]*Department of Industrial and Systems Engineering, Wayne State University, Detroit, MI, USA*
[c]*Department of Economics, Iowa State University, Ames, IA, USA*
[d]*Department of Engineering Technology and Industrial Distribution, Texas A&M University, College Station, TX, USA*
[e]*School of Engineering, University of Dayton, Dayton, OH, USA*
[f]*MxD, Chicago, IL, USA*
[g]*Tooling U-SME, Cleveland, OH, USA*

Abstract. Rapid innovations in manufacturing process technology, information technology, and systems technology have led to simultaneous concerns about labor displacements and skills shortages. To address these concerns, the key challenges for educating and training the current and future workforce should be identified and the specific activities leading to the design of new manufacturing career pathways should be defined. Thus, the objective of this article is to define and prioritize the necessary activities and short- to long-term outcomes that will aid in developing high-skill career pathways that will positively impact children and families, students and teachers, and future workers. Expert perspectives from industry and academia have been analysed through two lenses: education (primary/secondary, technical, and university levels) and policy/innovation. The nominal group technique (NGT) is applied in this research to capture these perspectives, which enabled the generation of ideas followed by discussion and ranking by the experts. This approach encourages participation and avoids the associated drawbacks of typical group interactions. As a result, prioritized activities, short-term outcomes, and policy ideas to introduce children and families, students and teachers, and future workers to careers in advanced manufacturing are presented for each lens of focus. In addition, inputs from experts were captured to discuss desired medium- to long-term outcomes. In conclusion, this article summarizes the key findings from the study.

Keywords: Future manufacturing, workforce development, communities, education and research, policy

1. Introduction

Concerns that technology will displace labor date back to the beginning of the Industrial Revolution, when machined textiles replaced hand weaving. However, the long history of technological change has raised worker incomes and employment prospects. For example, taking data from Bolt (2018) for Great Britain, labor productivity rose only 0.02% per year and the population hovered at or below

*Corresponding author: Karl R. Haapala, School of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, Corvallis, OR, USA. Tel.: +1 541 737 3122; E-mail: Karl.Haapala@oregonstate.edu.

ISSN 1092-0617/$35.00

subsistence from year 0 to 1700. Between 1700–2000, labor productivity rose 4.1% per year and per capita GDP rose over 13 times. Focusing on the U.S., since 1947, labor productivity has risen 356%, labor hours increased 143%, and real hourly compensation rose 290% (Fig. 1). While labor has benefited from technological changes, this is not universally true for all sectors. For instance, agriculture accounted for 41% of the workforce in 1900, but only 2% today. The migration out of agriculture was slow, however, and accomplished by outmigration from rural to urban markets by the young and most mobile. Moreover, new technologies tended to make labor more productive. Thus, the new jobs created through technological change dominated the jobs that were replaced.

Rapid innovations in information technologies have led to increasing concerns about labor displacements. As presented in Fig. 1, it appears working hours stopped increasing after 2000 as productivity increased. Moreover, real compensation has grown more slowly, after closely tracking productivity before 2000. The U.S. Bureau of Labor Statistics (2008) defines labor productivity as the ratio of output to hours of labor input; compensation per hour as the compensation of employees and the self-employed divided by hours worked by all persons engaged in the sector; and hours include hours worked by employees, proprietors, and unpaid family workers. Researchers have argued that information technologies and automation have atypically displaced workers in the middle of the skill distribution (Acemoglu & Restrepo, 2018a). These displaced workers have generally moved into lower-skill jobs, leading to depressed wages for workers at the lower tail of the skill distribution. To better understand why, each occupation can be defined by its associated tasks. Tasks can be routine or nonroutine. Automation can replace only routine tasks. Hence, the occupations that are most likely to be replaced by automation are the ones comprised of a high share of routine tasks.

Autor et al. (2003) developed a method to measure the share of tasks that are automatable for each occupation, and recently reported what happened to employment by occupation since 1979 as a function of the occupation's share of routine tasks (Autor, 2015). They found employment rose for occupations with nonroutine tasks and fell for those involving tasks that could be most easily replaced by information technologies. As shown in Fig. 2, the largest employment declines were for production and construction workers, clerical or administrative support workers, and sales staff. These jobs tended

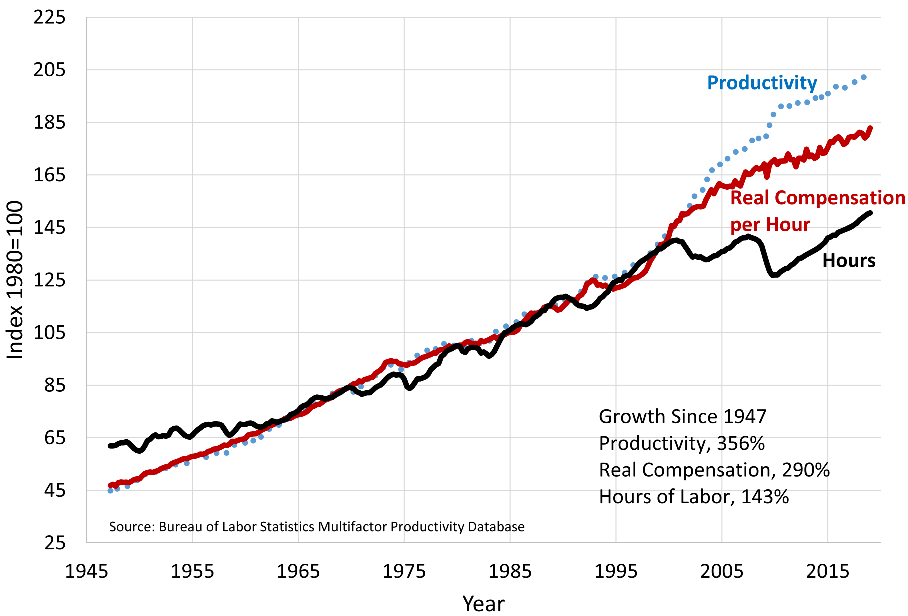

Fig. 1. Comparison of productivity, real compensation, and hours worked (1947–2019) (Bureau of Labor Statistics, 2021b).

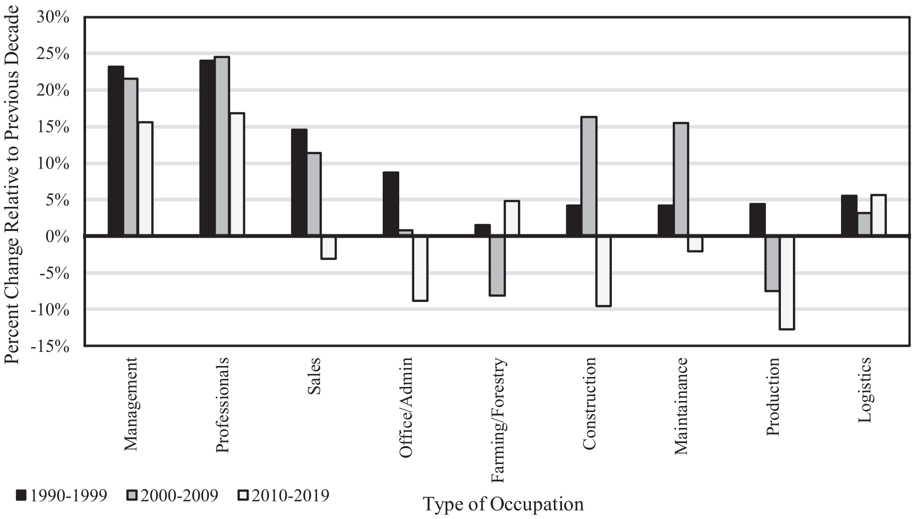

Fig. 2. Percent change from previous decade by occupation (Bureau of Labor Statistics, 2021a).

to be in the middle of the wage distribution. Employment rose for jobs at the lower tail of the wage distribution (personal service, food service, and security workers), and for workers at the upper tail of the wage distribution (managers, professionals, and technical workers). Autor (2015) showed the same patterns occur in all the Organization for Economic Co-operation and Development (OECD) countries.

Nonroutine tasks can be divided into abstract and manual tasks (Autor et al., 2003). Abstract tasks are found in the most highly-educated occupations and include jobs that require creativity, judgment, innovation, experimentation, and analytical skills. Manual tasks are found in the least-educated occupations and involve customer interactions and/or physical exertion. The occupations replaced by automation tended to be in the middle of the skill distribution. Lacking the education to compete for higher-skill jobs, the displaced workers largely entered jobs in the lower tail of the skill distribution. This tended to depress wages for those jobs, even as wages were rising for jobs at the upper tail of the skill distribution. The resulting increase in income inequality has been experienced to varying degrees in all the industrialized economies.

Autor and Salomons (2018) showed that automation has increased aggregate employment and hours worked. However, labor's share of output has declined as capital's share has risen. The implication is that labor will get a smaller share of revenue generated by production, slowing wage growth. In fact, the pace of average wage gains has declined noticeably since 1979. Acemoglu and Restrepo (2018a) evaluated the impact of one specific type of automated machine, the robot, which replaces tasks completely. While their importance on overall employment is small, robots have large effects on specific sectors of the economy, especially durable goods manufacturing. Further, Acemoglu and Restrepo (2018b) provided details on the demographic groups most affected by competition with robots. Job losses were nearly uniform across education groups with moderately larger impacts on the group with between 12–16 years of schooling; those with graduate degrees saw negligible effects. However, the greatest impacts were on workers in their middle years, ages 36–55, the group that is normally in the most stable employment stage of life.

The policy challenge that automation and information technologies present is that they atypically displace workers with intermediate skills and intermediate ages. Workers in these groups are at or near the peak of their earnings profiles, but their earnings and productivity are tied to skills that are no longer desired in the labor market. During the Great Recession, workers in these groups who lost their jobs faced significantly long job searches before finding new jobs, and they absorbed large pay cuts upon reemployment (Farber, 2017). It is important to note that displaced workers have skills that were in high demand just a few years earlier. In Becker's (1994) terminology, these workers had firm- or process-specific skills that did not have value outside the firm or production process. However, they do have other skills that are valued more generally, e.g., noncognitive skills such as reliability, stability, and dependability. There should be ways to retain their productivity in new settings, while providing new skills through retraining to replace the lost specific skills. Policies that combine targeted training with job search assistance present a plausible strategy. More intriguing, but more controversial, are policies that incentivize capital investment aimed at repurposing existing human capital and physical plant so immobile workers may find new careers in the same location.

In order to address these future workforce concerns more holistically, the objective of the article herein is to define and prioritize the required activities and short- to long-term outcomes that will aid in developing high-skill career pathways positively impacting children and families, students and teachers, and workers. Thus, industry and academic perspectives are captured and analysed. In tackling this work, we are informed by and experienced in engineering design and user-centered design processes (Ogot & Kremer, 2004); hence, we put the users (e.g., faculty and industrial companies) of the eventual system as part of the requirements analysis. Broadly, educational design starts with identifying the needs and analyzing the problem followed by designing and developing prototype solutions (i.e., educational interventions), and finally, evaluating and refining the solutions in practice (van den Akker et al., 2013). Educational design is a foundation for educators and educational designers play a key role in creating innovative educational interventions (e.g., teaching materials, learning environments, and programs). While this research does not directly define educational design requirements, findings from this work can support future educational design efforts. A number of prior studies have examined the application of educational design for introducing students and educators to advanced technologies such as augmented reality (Garzón et al., 2020; Gerup et al., 2020), virtual reality (Radianti et al., 2020; Soliman et al., 2021), additive manufacturing (Motyl & Filippi, 2021; Pei et al., 2019), digital twins (Keaveney et al., 2021; Toivonen et al., 2018), and cyberlearning (Ma et al., 2022; Raoufi, 2020).

The remainder of this paper is organized as follows. The identified focus areas for the discussed activities and outcomes are described in Section 2. In Section 3, the methodology applied is presented. Next, prioritized actions and outcomes from the work are provided in Section 4. Finally, a summary of the results along with recommendations for future community-based manufacturing workforce development are discussed in Section 5.

2. Focus areas

Wheeler (2007) showed that in an ideal job market the creation and destruction of jobs happens without any losses of employment. However, decreases in demand for a product leads to the destruction of jobs in an industry related to that product, while the creation of jobs for higher demand products allows an industry to become a more efficient producer (Caballero & Hammour, 1991). Most of the resulting unemployment is due to the time and resources required for workers and employers to find a job-match (Merz, 1999). We posit that an effective solution to this problem is to retrain the workforce to be able to more effectively make the transition between jobs, thus retaining a larger portion of the manufacturing workforce and lowering overall unemployment. At the same time, we need to consider new workers entering the job market. If we are to have a strong future manufacturing workforce, we need to educate students at all levels about emerging technologies in manufacturing and develop a positive image of manufacturing (Wang, 2018).

2.1. Education

Several educational levels are considered in this research, and include primary, secondary, and post-secondary (technical and university). All three levels of education involve elements of formal and informal learning. Each type of education is necessary for developing a skilled workforce, with each having its own specific goals. Prior to the start of their career, workers need to build up basic knowledge and skills, such as reading and logical thinking, accomplished by following any number of different educational pathways.

Primary education involves teaching the next generation who have not yet started their career the foundational skills for their future careers. In the U.S., these are primarily students in the public K-12 school system. Unlike the technical and university education, primary education is not directly committed to supporting future manufacturing careers. Recently, Career and Technical Education (CTE) programs in K-12 schools have received increasing support as states have recognized the need for a stronger manufacturing workforce (National Academies of Sciences, Engineering, and Medicine, 2017). The goal of primary education is to find ways to instill interest in future workers, opposed to giving them the exact skills required for their career. To instill an interest in the next generation of workers, the development of a "science literacy" around manufacturing is necessary. Science literacy is a way of describing how much the general population understands about science and technology (National Academies of Sciences, Engineering, and Medicine, 2016). Similar to Ryder's (2001) conclusion that children need to study science to actively engage in the subject, they also need to study science, technology, engineering, and mathematics (STEM) subjects to support future careers in manufacturing. While the interest of this work is in building a future manufacturing workforce, it is acknowledged that simply building a love of learning has positive effects later in life. In a report about 21st century skills, the National Research Council (2012) concluded people with higher education will gain more knowledge on the job and will be better at transferring their knowledge between jobs throughout their career. Thus, while a well-rounded education is important for any career, general education (i.e., math, science, language, and arts) is not within the scope of this work.

As children grow and move into careers as adults in the manufacturing workforce, it is imperative to maintain their engagement and to find ways to sustain career growth. Technical education supports the sustainment of the workforce through formal and informal training and retraining programs (National Academies of Sciences, Engineering, and Medicine, 2017). While junior colleges, community colleges, and technical schools prepare adults for the manufacturing workforce, technical education is an informal process that takes place throughout the working career. Although technical education is crucial for maintaining workforce productivity, it receives the least public attention and funding. It may be noted, in 2020, the U.S. Department of Labor received a total budget of $10.9 billion (U.S. Department of Labor, 2020a), while the U.S. Department of Education received a budget of $64 billion (U.S. Department of Education, 2019). Of the $64 billion allocated, about 2% ($1.3 billion) was spent in CTE programs.

Figure 3 presents a distribution of education levels for manufacturing workers based on data from the U.S. Bureau of Labor Statistics, showing about 40% of manufacturing workers have some level of college education. The National Student Clearinghouse Research Center (2019) identified nearly 36 million people who had some college education, but left before they finished a degree. Of these students, only 10% were identified as potentially able to complete a degree. Many courses are geared toward full-time students who started at a university and have been taking the recommended curriculum. Professionals who have learned the requisite technical skills in the work environment may lack training in other related skills that are expected to complete the course. For example, someone who has work experience in production scheduling may not be able to fulfill the requirements of a project management course because they lack technical writing experience. Classes are often taught in-person and only

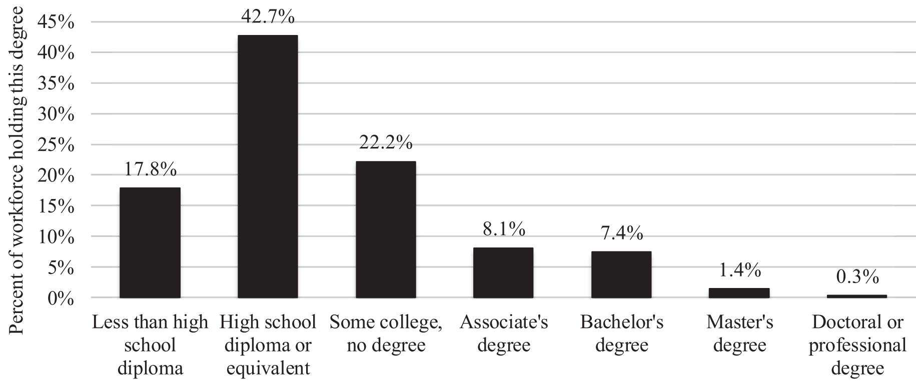

Fig. 3. Education level of the production workforce (U.S. Bureau of Labor Statistics, 2020).

offered during the workday, which prevents workers from enrolling in and completing formal education programs.

A challenge of maintaining a strong technical education program is the need to keep up with changes in the work environment. New manufacturing systems require many of the same technical skills (Campbell et al., 2014; National Research Council, 2012); however, workers who have spent many years working in a specific system find it difficult to learn the skills needed to be productive in a new system (Carrillo-Tudela et al., 2016). As shown in Fig. 2, the number of jobs in manufacturing has decreased since the year 2000, with many skilled workers not able to utilize their skillset being compelled to seek careers in different fields (Dahlin, 2019). Concerningly, 52.7% of skilled manufacturing jobs were unfilled in 2018, with growing shortages expected across all areas from skilled production to engineering (Giffi et al., 2018). Most US manufacturers defined a "shifting skill set due to the introduction of new advanced technology and automation" as the cause. While the loss of manufacturing jobs is a symptom of automation and outsourcing, the root cause of this decline appears to be the lack of trained workers with the skills to enter, or reenter, the manufacturing workforce. Simply retraining workers is not sufficient to sustain workforce productivity. As automation becomes more prevalent, so does the knowledge required to work with manufacturing equipment. In some cases, the skilled operator takes on the role of a technician who services the machine, while more highly skilled engineers take responsibility for automation and control of the process.

Thus, exploring novel university education pathways is essential to overcome the barriers that prevent many current and prospective students from learning the skills that support the manufacturing industry. In addition to the problems presented above that prevent non-traditional students from returning to the classroom, there are also challenges that impede students from finishing their degrees. For many students who were interested in manufacturing at a young age, perhaps no programs were available that offered them engaging experiences, causing a shift in their attention to other career paths that piqued their interests.

2.2. *Policy and innovation*

In order to implement education reforms that support manufacturing careers, policy and other systemic innovations are needed. Investigation of policy changes should be centered on delivering training and education to a broader audience. Meanwhile, educators and educational systems should focus on specific means of delivering appropriate education and training programs. As discussed above, technical education programs have the best potential to benefit from policy changes because they are directly related to growing a productive workforce. For instance, policy mechanisms could be used to establish a network to unify disjointed manufacturing education and training programs. Such a network would reach a larger audience, establish new training centers based on successful programs, and reveal ways to reach out to students, educators, industry, and other stakeholders who would benefit. Policy changes would be needed to allow workers to receive tailored assistance while enrolled in education and training programs (Becker, 1994).

University policy improvements may include finding ways to partner with established organizations to provide more and higher quality education and training opportunities for a broad range of students. For example, Oregon State University provides a unique industry internship program for senior engineering students who work at two different companies for six months each while receiving pay equal to 70% of a similar entry level position (MECOP, 2021; Shea & West, 1999). However, positions are limited and available to high-achieving students, which further disadvantages students that may be balancing other responsibilities such as families and non-career-related work. National organizations like Manufacturing USA (Gayle et al., 2021) could facilitate student internships and trainings that would ease transitions to the workforce. Similarly, innovative opportunities could be created for workers to return to university studies to pursue education while working – facilitated by a growing number of online STEM programs (Palvia et al., 2018). Many states in the U.S. have established postsecondary education attainment goals (National Student Clearinghouse Research Center, 2019; Texas Higher Education Coordinating Board (THECB), 2015) and are investing in returning "potential completers" to university. These types of initiatives are especially important for states where the number of people with some college education outweighs the number of students currently enrolled.

At the K-12 level, schools have faced challenges engaging students in STEM subjects (Stocklmayer et al., 2010). With new technologies often reaching industry years before becoming more broadly available, schools could benefit by engaging students in these technologies through manufacturing partners. Engaging students in occupational-related learning would not only benefit them in the manufacturing industries, but better prepare them for other career paths they may choose. For example, "a practical introduction to working life" through occupational training is a requirement of comprehensive school in Finland and Sweden (Skovhus & Thomsen, 2020). In addition to helping 60% of students decide their next steps in their careers, these programs "can lead students to consider options that they were not previously familiar with or had written off due to negative preconceptions or to re-evaluate their original plans as the reality did not match their expectations." Such opportunities can be crucial for students to gain exposure to manufacturing industries, regardless of their chosen career.

While these educational and policy innovations offer initial ideas for addressing worker and skills gaps facing the manufacturing industry, it is important to solicit input from multiple perspectives in order to define specific actions, and desired short-, medium-, and long-term outcomes to address these needs. The process undertaken to do so is presented in the next section, followed by a discussion of the study results.

3. Method of study

The objective of the interrogative research presented herein was focused on answering the following primary questions posed to experts representing the industrial and educational perspectives:

- How do we define new mobility pathways that will enable cross-generational career growth in advanced manufacturing technologies?

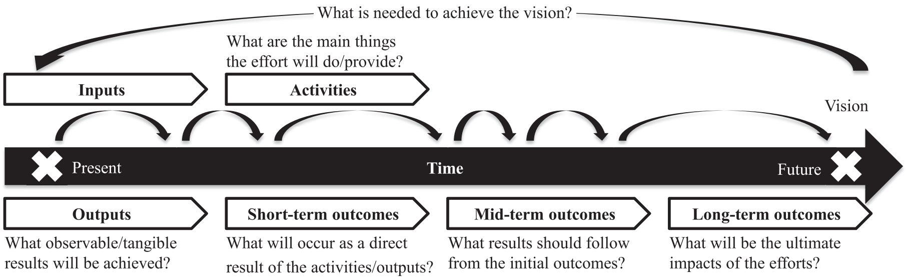

Fig. 4. Backcasting process.

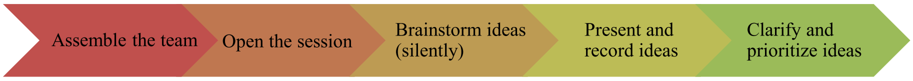

Fig. 5. Nominal group technique process (after Gallagher et al., 1993).

- How do we define, develop, and deploy new pathways for upskilling production workers through formal and informal education, training, and credentialing?
- How do we increase youth awareness of careers in advanced manufacturing including STEM requirements to prepare them for multiple career trajectories?

To achieve this research objective, a logic model is applied and supported with a backcasting process (Fig. 4). A logic model defines the relationships between the resource inputs used to support a project, the activities planned to be undertaken, and the outputs and outcomes to be achieved. Backcasting was originally developed for the energy sector (Robinson, 1982), and related scenarios are used to examine paths to futures that vary according to their desirability, e.g., either preferable and optimistic, or disagreeable and pessimistic (Kok et al., 2011). It is particularly used to translate the achievement of long-term futures to a series of short-term actions, which can help articulate the education design requirements.

The three questions posed above were examined in this research using the nominal group technique (NGT) process (Fig. 5) from four perspectives, i.e., informal and primary education, technical education, university education, and policy/innovation. The NGT process captures information about a specific subject from a group of experts in that area (Gallagher et al., 1993). It enables the generation of ideas followed by discussion and ranking by the experts. NGT encourages participation of the full group and avoids drawbacks associated with typical group interactions, such as domination of the discussion by certain personalities. As such, NGT provides an environment where participants are ensured their voices and viewpoints are effectively heard and captured. The assembled experts form a nominal group, which is able to discuss thoughts and ideas in the later stages of the process.

The NGT process begins by assembling the group, first by defining the criteria for selecting the participants. In this study, the group needed to represent (1) the perspectives of industry and different levels of formal and informal education, (2) the perspectives of various industries and U.S. geographic regions, and (3) the perspectives of different educational, trade, and industry organizations. A list of potential participants was generated by the organizing team from their professional networks and from relevant educational, trade, and industry organizations. Next, the team invited potential participants to join the group by providing an invitation message that briefly described the meeting format and motivation, possible topics to be discussed, and a draft agenda. The team asked those unable to join to recommend other potential participants. The nominal group was comprised of three university engineering faculty and four individuals from industry trade organizations primarily responsible for professional education, also maintaining high school, college, and university education partnership programs. They represented perspectives from the U.S. Midwestern, Plains, West Coast, and Southern regions.

Once the meeting date, time, and location is set, the nominal group is assembled and the meeting begins with an opening session. For this study, due to COVID-19 pandemic restrictions, the meeting was organized as a virtual conference workshop, entitled Democratization through Digitalization: Prospects for Flexibly Redeploying the Future Manufacturing Workforce (Haapala et al., 2020). This three-hour workshop was held using videoconferencing technology on November 18, 2020 as a part of the 25th Anniversary – First Online Conference sponsored by the Society for Design and Process Science (SDPS). Since it was held virtually and open to all conference attendees, the organizing team designed the workshop to be flexible to accommodate potential participants in addition to the nominal group (who served as session panelists). The workshop agenda included an Opening Session (welcome and overview, keynote presentation, and introduction to the brainstorming process); Topic 1: Medium- and long-term outcomes (introduction, expert perspectives, breakout brainstorm, and report out); Topic 2: Needed activities and short-term outcomes (introduction, expert perspectives, breakout brainstorm, and report out), and Closing Session (summary and workshop closing). After the organizing team presented the welcome and overview, a keynote talk was presented by Dr. Peter Orazem (Iowa State University), who focused his talk on the impacts of advanced manufacturing technologies and automation on the workforce. The talk stimulated much discussion, leading to a modification of the backcasting process, which focused only on Topic 2. Brainstorming of Topic 1 outcomes was then reserved as a post-workshop activity. In addition, rather than using breakout rooms to facilitate brainstorming, it was decided to maintain all attendees in the main workshop room. Over the course of the virtual workshop, the number of attendees from the general conference varied from about 15–20. While not by design, these attendees acted as observers and listeners to the discussion.

The third step of the methodology involves a silent brainstorm of ideas. It was planned to explore the four perspectives mentioned above in breakout brainstorming. However, since the number of workshop attendees was manageable, the plan was modified as noted above. Thus, the organizing team invited all participants to reflect on the discussion and generate their own ideas for needed activities and short-term outcomes to aid in developing high-skill career pathways for impacting children and families, students and teachers, and workers. Ten minutes were allotted for the silent brainstorm. Next, in the fourth step, an online visual collaborative whiteboard platform, Miro (Miro, 2021), was used to present and record ideas generated in the silent brainstorm. Participants were able to write short descriptions for their ideas and post them for the whole group to see. In addition, participants were able to show support for and expand on the ideas presented in an open forum. Participants were allowed to post as many ideas as they desired in a simultaneous or synchronous fashion, which facilitated the nominal nature of this group technique. To assist with categorization of ideas, the whiteboard was divided into four quadrants: (1) primary education, (2) technical education, (3) university education, and (4) policy/innovation.

The last step of the methodology is to clarify and prioritize the ideas. Typically, this step is completed as part of the nominal group meeting; however, the workshop time was limited, so prioritization was completed using a workshop follow-on survey completed by the nominal group and organizing team. Due to the nature of the whiteboard activity, which was accompanied by discussion among the participants, ideas generated did not require further clarification for the survey respondents. The survey presented each of the four workshop categories along with the associated brainstorming ideas. A five-point scale was used to rank each idea from 1 (lowest importance) to 5 (highest importance). To ensure all ideas were ranked consistently, respondents were required to use all of the ranking values. Further, each ranking value had to be assigned to a defined number of ideas based on the total number of ideas generated under each category. The results of the brainstorming and the prioritization activities are presented in the next section, in addition to the brainstormed ideas and discussion surrounding future outcomes. It should be noted that specific activities, outputs, and outcomes will need to be continuously refined and validated by experts from each of the industrial, educational, and policy domains representing the future manufacturing workforce. Development of metrics, assessment scales, and means to evaluate outcomes is out of the scope of this research. However, such assessment will be needed to demonstrate the effectiveness and efficiency of future interventions, e.g., educational program design and implementation.

4. Prioritized actions and outcomes

As discussed above, the research herein aims to define and prioritize the necessary activities and short-, medium-, and long-term outcomes to lead to high-skill career pathways for positively impacting children and families, students and teachers, and workers. The focus of this study considers informal and formal education at the primary/secondary, technical, and university levels. In addition, policy mechanisms and other innovations are considered. The prioritized ideas for activities and short-term outcomes generated by the nominal group for each focus area are first presented in the following subsections. Thereafter, the authors discuss several key expected medium- and long-term outcomes of these activities for each area of focus in more detail.

4.1. Primary/secondary education

4.1.1. Needed activities and short-term outcomes

Based on discussions among the group, a list of 19 activities and short-term outcomes were captured for introducing children and families to careers in advanced manufacturing. These ideas were categorized into potential opportunities for informal and formal education for learners and educators. Based on the ideas generated by the nominal group for primary/secondary education, survey responses were requested from the group following the workshop. Respondents were asked to classify three to four of the identified ideas into each of five ranking values by assigning each of the 19 ideas a discrete ranking value (1 = Lowest Importance to 5 = Highest Importance). The overall score for each idea was then determined by summing the associated ranking values assigned by each expert. In this case, summed scores ranged from 11 to 33. Next, this range was divided to form five categories: 33-29 as highest, 28-24 as higher, 23-20 as medium, 19-15 as lower, and 14-11 as lowest importance. The prioritized activities and short-term outcomes are presented in Table 1, and medium- to long-term outcomes are discussed in the section that follows.

4.1.2. Desired medium- and long-term outcomes

In the medium- and long-term, we posit that carefully thought out plans should be put in place that leverage 1) the current knowledge on identity development and career choices, 2) the natural connection of manufacturing to engineering design, and 3) workforce needs and state/federal investments.

Introducing youth to manufacturing careers during the formative years of primary and secondary education is important. Current knowledge on student identity development affirms that such experiences are important in determining career choices. Student identity develops through experiences, nurturing of interests, and engagement with role models, and can be seen as increased and sustained interest in a career where the student develops self-efficacy, or the belief in one's ability to achieve a desired outcome (Bandura, 1986). This identity development coincides with middle school years, or between the ages of 10 and 14 years (Archer et al., 2010; Maltese & Tai, 2010). Having parents or

Table 1
Prioritized ideas to introduce children and families to careers in advanced manufacturing

Category	Activities and Short-term Outcomes	Importance
Informal education for learners	Leveraging existing programs (e.g., SME PRIME and Tooling U-SME)	Highest
	Educating parents about manufacturing careers	Higher
	Create an interactive module that can be taken to children's museum or other places that highlights manufacturing & advanced manufacturing	Medium
	Micro-credentialing/Badging to recognize incremental learning	Medium
	Benchmark existing informal learning infrastructure (e.g., Milwaukee Museum of Science and Technology – manufacturing line)	Lower
	Working with local museums/libraries to develop hands-on resources or activities	Lowest
	Citizen science and museum installations	Lowest
Informal education for educators	Develop learning materials to assist teachers	Highest
	Educating educators and other non-manufacturers about manufacturing	Higher
	Paid externships with local employers for STEM teachers to learn about manufacturing	Higher
	STEM skills seem directed at College prep today not towards trade	Lower
Formal education for learners	Create fun hands-on options for technical skills at high school level. Replace the old mechanic shop with the new high-tech boot manufacturing camp.	Higher
	Exposure programs that teach a few basic mfg. skills with application through AR/VR experiences at the middle school level	Lower
	Create 3D or virtual tours of manufacturing facilities so that young people can see what it is like to work for a manufacturer	Lower
Formal education for educators	Participate in Manufacturing Day	Lower
	Manufacturing Day tours and events to promote manufacturing to students	Lower
	Summer camps focused on advanced manufacturing education	Lower
	STEM Camps focused on emerging mfg. technologies	Lower
	Enable COVID supply chain impacts to be used as a learning opportunity	Lower

other role models who are manufacturing workers can have a positive influence on a youth's identity development and related career choices. Interactions with close role models can improve motivation and familiarity with a field (Chakraverty & Tai, 2013). These interactions often allow for enriching out-of-class learning activities (e.g., trips to museums or industry). Therefore, it is important for manufacturing professionals to inform youth in their extended family, in the community, and as they engage with schools as volunteers. In thinking about youth who will not have access to such role models, another key medium- and long-term outcome is to invest in those that enable a STEM/manufacturing career pipeline, namely teachers and counselors. This investment can materialize in several different ways, starting with manufacturing professionals assisting teachers to think through appropriate curricular material for various age groups and monetary and equipment donations to enable them to cover the curriculum to a high level. Informing career counselors appropriately and attending career days as ambassadors of manufacturing are also important.

When tasked with integrating new content into the curriculum, teachers report many challenges: shortage of funds and equipment; lack of clear, concise, and unrestricting curriculum; and lack of knowledge and time for professional development. These challenges exist even for engineering design, which has been a part of the U.S. National Science Education standards since the late 1990s (Kelley & Wicklein, 2009). Manufacturing professionals and organizations should approach teachers having this knowledge of the challenges they face, and adjust their expectations from teachers and be prepared to fully support these needs to produce lasting, impactful results. A possible point of entry, for instance, might be to add manufacturing engineering as a natural extension to the design engineering curriculum (Raoufi et al., 2018). Programs such as Project Lead the Way, Engineering by Design, and Project ProBase could present curricular options to further enhance manufacturing content. Constraints on time, space, and preparation needs should be carefully considered not to burden teachers further.

Critically, a teacher shortage in STEM programs is a key crisis in education reported by the U.S. National Academy of Engineering and National Research Council (Hansen et al., 2019; National Academy of Engineering & National Research Council, 2012). Accordingly, this shortage exists in CTE programs, which include the STEM and manufacturing clusters. Logically, it is not possible to create the workforce of the future without qualified instructors. To develop a potential manufacturing and engineering talent pipeline, qualified teachers with experience in the field through previous job roles or externships is essential. Incentivizing those seeking teaching careers to pursue STEM and/or CTE areas of focus is critical. Once they enter academia, they should be provided with industry-driven resources and professional development opportunities to ensure effectiveness in the classroom and bringing real-world manufacturing and engineering experiences to students. This also applies to career counselors in education, who are frequently overwhelmed as their duties are blended with general guidance counselling, with a high counselor to student ratio (Tate, 2019). It is critical to provide resources for career counselors to help guide students into fields of study preparing them for success in future manufacturing or engineering careers.

In addition to support of teachers and counselors, another medium- to long-term outcome is engagement of industry in the development of curriculum standards for STEM and CTE that lead to jobs after high school. In manufacturing, a strong supply chain is essential for successful delivery of products. The end customer provides clear requirements and detailed plans to suppliers, so they are able to deliver the appropriate parts to the next step of the manufacturing process. This concept equally applies to education; the education system is delivering a student, over time, for potential employment. In the context of primary and secondary education, engaging the potential employers of students in the development of standards and curriculum design will enable a deeper education-employer partnership. This involvement can provide insight to competencies needed in gainful employment after high school for students who do not want to immediately pursue post-secondary education. It will also provide support for experiential learning opportunities for students and teachers to broaden exposure to future manufacturing and engineering careers. Engaging employers, educators, students, parents and the greater community with programs and competitions such as the SME Partnership Response in Manufacturing Education (PRIME), First Robotics, FIRST Lego League, Vex Robotics, SkillsUSA, and other CTE and CTE exposure programs, has been effective at local levels. A holistic community approach for early exposure to manufacturing and STEM exposes students and parents to modern manufacturing. It also provides progressive opportunities for applied learning that may lead to interest in STEM or CTE pathways at the secondary level, and further engagement with employers may lead to secondary-level internships and/or employment opportunities.

Finally, as students prepare to graduate from secondary school, they can be further incentivized to enter a manufacturing or engineering pipeline. In the early 1900s, the U.S. attempted to promote free college education (Judd, 1921). However, the experiment ultimately failed due to lack of planning and unified goals. Recently, better educational structure, clearer goals, and better planning capacity led to states (e.g., Tennessee and Oregon) experimenting with free community college or post-secondary tuition (Nguyen, 2020). To address the pipeline needs in manufacturing and other STEM fields experiencing a shortage of workers, focusing tuition-free options for training and education on careers in-demand may steer students to pathways to complete their education debt-free, and improve their opportunities to obtain meaningful employment. The next section explores these post-secondary educational opportunities in a more detail.

Table 2

Prioritized ideas to introduce workers to technical careers in advanced manufacturing

Category	Activities and Short-term Outcomes	Importance
Student recruitment	Investment to continue to develop employer/education partnerships to establish and evolve manufacturing CTE (e.g., SME PRIME) – possible development of a light middle school manufacturing program as part of the exploratory/elective portion of the curriculum	Highest
	Developing/leveraging joint programs with high schools and universities to ease the transition through the pipeline	Higher
	Connect manufacturers with CTE and pre-apprenticeship programs	Medium
	Train/educate parents on understanding the importance of technical training	Lower
	Summer internship and CTE projects hosted at R&D/training centers	Lower
Student retention	Clearly defining career pathways, earning potential, and the education & competency requirements to get into 1) entry level and 2) progress within the career	Highest
	Create pathways of industry sectors (e.g., cybersecurity roles)	Medium
	Partnering between innovators and educators for upscaling workforce	Lowest
Transition to workforce	Portal that can list technical education availability with demands in areas that correspond to those. Could be virtual as well for training and finish off with hands on if needed.	Lower
	Fund creation of virtual factories for education purposes that can be used nationally	Lowest
Worker retention / sustaining workforce	Sustainability models that incorporate maintenance and continuous improvement of grant funded training resources potentially in perpetuity – through partnerships with organizations with operational and distribution models that can ensure this will happen independent of funding	Higher
	Guarantees for wage increases if program is completed	Lower
	There are many participants in robotics and other STEM-related competitions that may not make the transition into manufacturing. Develop programs & resources to recruit and encourage those students during and after those competitions.	Lowest

4.2. Technical education

4.2.1. Needed activities and short-term outcomes

Thirteen activities and short-term outcomes were generated by the nominal group as ideas to introduce post-secondary students and workers to technical careers in advanced manufacturing. These ideas were further categorized into opportunities for student recruitment and retention, transitioning to the workforce, and worker retention and workforce sustainment. As described above, each expert assigned each idea a discrete ranking value from 1 to 5, where each rank could only be assigned to two to three of the ideas. The overall score for each idea was determined by summing the associated ranking values assigned by each expert, and ranged from 14 to 32. This range was evenly divided to form five categories: 32-28 as highest, 27-25 as higher, 24-21 as medium, 20-18 as lower, and 17-14 as lowest importance. The prioritized activities and short-term outcomes are shown in Table 2, and medium- to long-term outcomes are discussed in the section that follows.

4.2.2. Desired medium- and long-term outcomes

To aid manufacturers in meeting the skills gaps highlighted above, medium- and long-term technical education outcomes should focus on attracting and empowering the manufacturing workforce with skills and abilities that will meet the needs of the future, including an ability to lead through ambiguity and apply strong collaboration skills. The importance of developing and training the technical workforce cannot be understated. However, concrete actions must be taken to ensure meaningful impact, as highlighted in the U.S. Advanced Manufacturing Partnership 2.0 (AMP 2.0) report (PCAST, 2014). In particular, a flexible and skilled workforce can address the ever-changing technology challenges in manufacturing and can assist industry in achieving lasting products and processes (Raoufi, Park, et al., 2019).

While technical skills are important, educators must take a variety of approaches in engaging students and their parents. For example, they can be connected with professional and industry organizations, e.g., the American Society of Mechanical Engineers, American Welding Society, Society of Manufacturing Engineers, and Manufacturing USA Institutes, which are developing resources to support the educational community, students, and families. The 2019-2020 Manufacturing USA highlights report (Gayle et al., 2021) presents ways to attract and engage students, for example by participating in research and development projects, technical certifications, and field-based apprenticeships. Moreover, considering the hands-on nature of manufacturing and engineering education, more effective pedagogical methods can be developed to expand upon traditional learning experiences (Raoufi, Manoharan, et al., 2019).

Such an effort by MxD (Manufacturing times Digital), a Manufacturing USA institute, the National Center of Digital Manufacturing, and the National Center for Cybersecurity in Manufacturing aims to develop the talent pipeline needed to meet the demands of cybersecurity and digital manufacturing. Through collaborative efforts within its ecosystem, MxD has created two key documents that highlight the future needs in digital manufacturing. In 2017, MxD released a jobs taxonomy identifying 165 current and future digital roles for manufacturing, showing the rapid change in industry (MxD, 2017).

In 2020, MxD published a hiring guide that defined 247 manufacturing cybersecurity roles and recommended how to train and upskill workers to handle these jobs (MxD, 2020). As a result of this document developed in partnership with the University of Maryland Baltimore County, MxD launched its first course for upskilling workers in cybersecurity, called Cybersecurity for Manufacturing Operational Technology, or CyMOT (https://www.mxdusa.org/cymot/). This course addresses one of the 247 roles defined in the hiring guide and enables people to obtain this in-demand skillset. Thus, both documents can provide pathways and highlight critical skillsets that are required in future manufacturing careers. Further, this effort is stimulating discussions across academia, industry, and professional organizations on how to best meet the needs of the growing and changing future manufacturing workforce and leveraging these documents to do so. Next, ideas are explored for post-secondary education at the university level.

4.3. University education

4.3.1. Needed activities and short-term outcomes

Twelve activities and short-term outcomes were generated by the nominal group for university-level education in advanced manufacturing. These ideas were further categorized into opportunities for internal and external partnering, as well as programmatic change. Each expert assigned ideas a discrete ranking value from 1 to 5, where each rank could only be assigned to two to three of the ideas. The overall score for each idea was determined by summing the associated ranking values assigned by each expert. Summed scores ranged from 15 to 33, evenly divided to form five categories: 30–27 as highest, 26–24 as higher, 23–21 as medium, 20–18 as lower, and 17–15 as lowest importance. The prioritized activities and short-term outcomes are reported in Table 3, and medium- to long-term outcomes are discussed in the next section.

4.3.2. Desired medium- and long-term outcomes

Kolb characterized the key to experiential learning as the creation of knowledge “through the transformation of experience” (Kolb, 1984). Manufacturing is a discipline that offers students the ability

Table 3
Prioritized ideas to introduce undergraduates to careers in advanced manufacturing

Category	Activities and Short-term Outcomes	Importance
Within university partnering	Work with industry to develop hands-on labs; funding is a perennial challenge	Highest
	"Easy" manufacturing electives for those across the university community (e.g., liberal arts majors)	Highest
	Encourage more options for cross-discipline education at undergraduate level	Higher
	Joint projects between 4-year and 2-year students to break down barriers	Medium
Programmatic changes	Develop online courses/modules, certificates and programs catering to working professionals	Higher
	Need to break down credit hours into something more manageable	Medium
	Modularize the learning contents	Medium
	Expand pathways for students to reach university (articulation with community colleges or other training organizations)	Lower
	System level programs not dependent on individual faculty member or university silo	Lower
External Partnering	Industry internships for faculty	Medium
	Imbeds of faculty at innovation institutes and or other organizations like MEPs, SME, etc.	Lowest
	More plant visits and opportunities for industry exposure	Lowest

to observe, reflect, conceptualize, and experiment. These acts of reflection and conceptualization are the non-routine aspects of manufacturing education that should be emphasized. At the beginning of an undergraduate education, these aspects can be used to teach students about manufacturing and related careers as well as to emphasize physical and mathematical concepts and provide grounding and application for abstract ideas. For instance, the clamping forces required for injection-molded components of various cross-sectional dimensions can be used to demonstrate the importance of process settings in addition to the mechanics principles in physics. Experimentation with manual machining process settings (e.g., speeds and feeds) produces visual (e.g., component surface finish), auditory, and tactile feedback, as well as providing a platform for teaching students about vibration and natural frequency. Such experiences provide a basis for reflection and an understanding of impacts of process variables on product quality, while also providing a basis for conceptualization and a desire to further understand the mechanics of manufacturing processes.

Just as university students are exposed to the natural sciences, mathematics, and literature, they should also be exposed to manufacturing as a cornerstone of modern society and a vehicle for the application of fundamental physical sciences. The production of food, clothing, and consumer goods is necessary to ensuring a good quality of life; thus, all students would have improved awareness of the effects their purchasing decisions can have on life-cycle social and environmental impacts. Further, while manufacturing topics might be part of a technology survey course, understanding how raw materials are transformed into products should be foundational to higher education. The popularity and impact of maker spaces (Hilton et al., 2020; Namasivayam et al., 2020) demonstrate the appeal of creating things and highlight the benefits that manufacturing experiences produce in advancing student perceptions of the world around them. Coupling this appeal with experiential learning will help generate the necessary "science literacy" around manufacturing, and engender excitement in students, families, and communities.

Continuous innovations in manufacturing process technology and information technology mean that advanced manufacturing education is ever-evolving. Computer-numerically controlled lathes and milling machines, manual welders, and coordinate measuring machines were once cutting edge in manufacturing, but are now being displaced by applications of additive manufacturing, collaborative robotic welding, friction stir welding, and laser line or computed tomography scanners. In the next three, five, or ten years, these new technologies will continue to be augmented with manufacturing technologies being developed in university, industry, and governmental research labs. While transformative, the pace of innovation is a challenge for university educational laboratories, which strive to teach students both the theoretical foundation and hands-on knowledge of various manufacturing technologies. Manufacturing education systems – to borrow a term from the manufacturing lexicon – must be "agile." Agility is not characteristic of manufacturing education laboratories due to the high costs of materials, tools, and equipment. However, virtual- and augmented-reality learning, industry-university cooperative planning, and strategic outlooks can aid in developing advanced manufacturing education programs. Such environments can evolve with innovations in manufacturing and broaden the appeal of advanced manufacturing to student populations that may not have considered manufacturing as a career path.

In this way, medium-term outcomes can build on university manufacturing education infrastructure and bridge between short-term and long-term outcomes. This infrastructure includes manufacturing engineering courses and laboratories as well as connections with local industry. One student-focused outcome would focus on manufacturing process and systems coursework for first- to third-year students, and could target students across engineering to demonstrate the relationship between advanced manufacturing and the engineering or computer science disciplines. A second outcome would focus on developing coordinated internship opportunities for upper-level undergraduate and graduate students that align with advanced manufacturing needs. These internships require industry-university collaboration to direct students to the application of advanced manufacturing concepts, rather than broader engineering or general tasks.

In addition to these student-focused outcomes, medium-term laboratory-focused outcomes include environment and learning content development for virtual advanced manufacturing laboratories. Virtual and augmented reality environments, while not providing a 1:1 experience of hands-on interaction, are more easily adaptable to advanced manufacturing innovations and new manufacturing technologies. In addition, existing manufacturing educational lab equipment should be investigated for integration with advanced manufacturing technologies. Industry 4.0 and Industrial Internet of Things (IIoT) technologies can support advanced manufacturing education targeting the intersection of information and operational technology. Such education-based efforts can be directly translated to industry partners as they evaluate how to integrate existing assets into future advanced manufacturing systems.

In addition to student-focused and lab-focused outcomes, a third category of medium-term outcomes focuses on the educational program content and delivery. For example, advanced manufacturing technologies should be assessed in terms of what can be taught at the undergraduate level. This effort requires investigating the prerequisite knowledge required for various advanced manufacturing technologies and the logistics of integrating such new requirements into existing undergraduate curricula. In addition, it requires establishing an outlook of critical advanced manufacturing technologies with industry input. This outlook would lay the foundation to design curricula that adapt to the shifting needs and innovations in advanced manufacturing (Raoufi et al., 2020).

Thus, building upon the identified short- and medium-term outcomes, long-term outcomes should target development of deep partnerships with external organizations, in addition to institutional or infrastructure changes. Three categories of long-term outcomes can be defined, i.e., student-, laboratory-, and program-focused outcomes. To facilitate students transitioning from technical programs to undergraduate programs, interfacing curricula should be developed between two- and four-year institutions. This effort would move beyond articulated agreements to the development of courses and curricula that are designed, from the ground up, to be a natural pathway from community colleges to universities. For example, Wayne State University (Detroit, MI) is collaborating with Oakland Community College to collaborate on the design of collaborative robotic (cobot) manufacturing and programs (Djuric et al., 2018). The courses developed have naturally demonstrated engineering careers and encouraged two-year students to continue on to advanced manufacturing engineering education.

From a long-term perspective, laboratory- and program-focused outcomes should involve transitioning manufacturing laboratory designs from being single machine-/process-centric (e.g., individual lathes or milling machines) to more integrated designs (e.g., multiple interconnected machines utilizing Industry 4.0 technology). It is expected that this infrastructure will require a system design approach to accommodate multiple interacting advanced manufacturing components (i.e., machines, sensors, and computers) that students interact with and learn from across different courses and levels. Another long-term outcome involves securing commitments and sustained funding to keep courses and programs future-focused by continuously evaluating, refining, and replacing manufacturing curricula as well as relevant manufacturing equipment, process, and system innovations. Such an effort critically requires national-scale, long-term collaborations among industry (those that use new manufacturing machines and those that develop new manufacturing machines), colleges, universities, and national labs, as discussed in the next section.

4.4. Policy/innovation

4.4.1. Needed activities and short-term outcomes

To introduce students, families, and communities to careers in advanced manufacturing through policy-driven approaches, 18 activities and short-term outcomes were generated by the nominal group. These ideas were categorized into opportunities for workforce retraining and across the informal and formal educational spectrum. Each expert assigned each of the generated ideas a discrete ranking value from 1 to 5, where each rank could only be assigned to three to four of the ideas. The overall score for each idea was determined by summing the associated ranking values assigned by each expert. Summed scores ranged from 12 to 30, and divided to form five categories: 30-27 as highest, 26-24 as higher, 23-19 as medium, 18-16 as lower, and 15-12 as lowest importance. The prioritized activities and short-term outcomes are presented in Table 4, and medium- to long-term outcomes are discussed in the section that follows.

4.4.2. Desired medium- and long-term outcomes

For much of the 20th century, manufacturing provided a reliable path to the middle class for those with some high school or vocational training. These jobs helped to lessen income inequality from the 1930s through the 1970s. Since then, the forces of international competition and automation have destabilized the labor market for middle-skilled workers at the midpoints of their careers at ages where they are too young to retire and too old for traditional training programs. Nevertheless, these workers have many of the non-cognitive skills that firms say they desire, i.e., reliability, loyalty, self-reliance, even-temperament, and determination. At the same time, manufacturing firms complain that they are unable to fill all their vacancies from the ranks of the young market entrants. For these workers and firms, replacing tasks that face obsolescence with new tasks and training that build on these non-cognitive skills would stabilize work careers and provide an added source of reliable manufacturing workers. Thus, policies need to identify workers facing future task obsolescence and provide training before they face layoffs and income losses. Such intervention would reduce income inequality and stabilize household incomes for a large subset of U.S. middle-class workers.

Programs are in place that target workers who are displaced since their skills have become obsolete due to international trade. The Trade Adjustment Assistance Program, for instance, provides income assistance and training to workers who face import competition (U.S. Department of Labor, 2020b).

Table 4
Prioritized policy ideas to introduce future workers to careers in advanced manufacturing

Category	Activities and Short-term Outcomes	Importance
Workforce retraining	Hire displaced workers to use their skills to teach and train while they are getting re-skilled themselves	Highest
	Greater coordination of manufacturing workforce & training program priorities & funding across all federal agencies/cross-agency task force	Highest
	Use accessible technologies for remote training of production employees (i.e., online, cloud based, AR, VR, tablets)	Higher
	Need to coordinate training for displaced workers across states	Higher
	Leverage resources that exist in industry and industry consortia, as well as community colleges	Medium
	Use projected exposure to automation to identify workers who will need to be retrained before they are displaced	Medium
	Add creativity to retraining	Lowest
Informal education	Think about how we can do micro credentials/badges across different institutions with different focus areas	Higher
	How can we recognize on-the-job training in education?	Medium
	Germany style coordinated training for scarce skills across firms in the same sector	Lower
K-12 education	Create incentives for industry and/or other professionals to be involved in education in K-12 in innovative technologies	Medium
	Use of AR/VR technology to bring the student into the industry world	Lowest
Technical education	Propose active labor market policies that assist unemployed workers to find new skills and jobs	Highest
	Wage replacement during CTE training for displaced workers	Higher
	Partnering among educators and talent pool services to upskill and move laid off and force early retired into contingent workforce	Lower
University education	National clearinghouse to identify needed skills in short supply. Use that information to recruit students or experienced workers willing to fill slots	Medium
	Work with Manufacturing USA Institutes to connect across institutions and organizations	Medium
	Take learning innovations that have happened as a result of COVID-19 restrictions (remote learning, etc.)	Lower

However, the program has not been universally successful (Hummels et al., 2018). It has had a small positive impact on earnings and a larger impact on reemployment (Giordano, 2017). Better earning results occur when the link between the training and the subsequent job is well-defined, and trained workers have better retention rates (Park, 2012). However, as Baicker and Rehavi (2004) argued, there is no reason why these retraining programs should be focused only on workers displaced by international trade. Retraining and income support would have similar benefits to workers displaced for any reason. As noted above, automation threatens the employment of as many or more workers as international trade, especially for those in the middle of their careers. One issue with training programs for displaced workers is that they are not tailored to the career plans of the worker. Baiker and Rehavi (2004) suggested creating more flexibility by providing transfers equal to the cost of the training plus income support. Workers could then allocate the funds toward their preferred job training, income support, or a combination in a manner to best fit their needs. However, the other aspect of the training is the link to the future job. Manufacturers have faced difficulty finding sufficient quality workers.

Thus, a partnership between manufacturing firms and federal training programs to pair retraining with rehiring would greatly improve existing policy effectiveness.

Related opportunities for reinforcing the manufacturing workforce are in retraining veterans at the time of discharge from the military. In a recent study by the Pew Research Center (Parker et al., 2019), only 52% of 1,284 veterans surveyed indicated satisfaction for the military's training to transition to civilian life. While most veterans reported the military experience gave them marketable skills, over half felt they were a poor fit for their first job – 42% said they were overqualified and 12% said they were underqualified. This suggests that veterans could use enhanced job search training or assistance in finding better job skill matches, a need also identified for Trade Adjustment Assistance training programs. As with workers displaced by automation, veterans have non-cognitive skills that manufacturing firms value, including discipline, loyalty, and work effort. It would be useful to identify firms that place high weight on these behavioral skills, while also defining additional task-specific skills to prepare these workers for future manufacturing industry.

In addition to training programs, new technology adoption by small, medium, and large manufacturers plays a key role in addressing workforce challenges. The U.S. National Institute of Standards and Technology (NIST) Manufacturing Extension Partnership (MEP) is a national program with centers in every state in the U.S. and Puerto Rico (National Institute of Standards and Technology, 2014). MEP centers assist small- to medium-sized manufacturers with access to resources they need to be successful. Key strategic goals for the network include championing manufacturing, empowering manufacturers, leveraging partnerships, and transforming the network. The MEP strategy focuses on manufacturers embracing productivity-enhancing innovation, advanced manufacturing technologies, navigating technology solutions, and recruiting and retaining a skilled and diverse workforce. Creating a workforce pipeline able to support these goals is critical. Ensuring K-12, technical, and university programs teach advanced technologies will be crucial to driving achievement of the national goals outlined above.

In particular, advanced manufacturing technologies (e.g., IIoT, cloud computing, AI, augmented reality, and additive manufacturing) are revolutionizing how products are made and how factories are operated. While these technologies have been adopted by large manufacturing companies, smaller manufacturers are lagging in the integration of these new capabilities. For example, Oregon MEP (OMEP) data shows the vast majority of Oregon manufacturers are small, 93% employ fewer than 100 employees. While new technologies promise huge productivity gains that would enhance the global competitiveness and resiliency of small and medium size manufacturers, investing in new technology is risky for smaller businesses operating on thin margins. They cannot afford disruption to their production lines, lack internal capabilities to select and integrate technologies, and do not have access to viable training for their employees to make use of these new technologies. It will be critical to equip manufacturers, particularly small- and medium-sized firms, with the capability to develop and integrate advanced manufacturing technology strategies in order to bolster their economic resilience and long-term competitiveness through innovative partnerships.

5. Summary and future outlook

This study focused on primary, secondary, and post-secondary (technical and university-level) training and education to define and prioritize relevant required activities and outcomes and to suggest career pathways needed to address emerging industrial needs in the United States. This work adds to ongoing global efforts toward development of the future advanced manufacturing workforce. In Japan, for instance, advanced manufacturing has been identified as one of four primary economic sectors, influencing one-third of its economic potential, and comprised of automotive, industrial machinery, and electronics industries (Desvaux et al., 2015). They have highlighted the need to create a more dynamic workforce with the skills required in a fast-changing environment. Moreover, it was suggested the

Japanese education system needs to instill critical thinking skills, promote a global mindset, and create a true education-to-employment pipeline to build talent and capabilities over the longer term.

Similarly, the European Commission highlighted advanced manufacturing as an enabler of industrial process improvement, reduction of energy and materials consumption, and enhanced waste management (European Commission, 2014). They discussed skills needed to strengthen Europe's position in advanced manufacturing as well as to respond in a flexible manner to new market opportunities and the increasingly complex nature of products and manufacturing processes. These skills include technical competency at craft and operative levels, leadership and management, market assessment, supply chain management, and R&D and design. As reported for the U.S, shortages in skills and competence deficits are reported as barriers to wider uptake of advanced manufacturing in Europe. It has been reported that 25% of the workers in Europe have no or low digital skills (Berger & Frey, 2016). Proper vocational training, certificate programs, and college education are required to close the skills gap in advanced manufacturing industry. It has been reported that workers with technical credentials experience higher rates of employment under technology shocks, e.g., automation (Andrew et al., 2020). This does not mean education/training guarantees economic security for a worker, but instead, it implies that technical credentials need further consideration across educational levels.

While educational and policy innovations offer initial ideas for addressing worker and skills gaps facing the manufacturing industry, it is important to solicit input from multiple perspectives in order to define specific actions, and desired short-, medium-, and long-term outcomes to address these pressing needs. The NGT-based study reported herein identifies multiple barriers and prioritizes actions and outcomes for different stakeholder groups, focusing on children and families, students and teachers, and workers. Key findings from the study include the following:

- Policies should incentivize investment aimed at repurposing existing human capital and physical plant so immobile workers may find new careers in the same location.
- Policies should expand education, training, and wage replacement programs to help displaced workers identify, prepare for, and build impactful careers in manufacturing.
- Policy mechanisms should be used to establish a network that unifies disjointed manufacturing education and training programs.
- Simply retraining workers is not sufficient to sustain workforce productivity; a holistic approach is needed to connect workers with education, training, and career support programs.
- Manufacturing professionals and organizations should engage teachers with emerging challenges they face, but also adjust their expectations of teachers and be prepared to support their needs.
- Qualified teachers with experience in STEM and manufacturing fields through previous job roles or externships will be essential to develop the manufacturing and engineering talent pipeline.
- Introducing youth to manufacturing careers during the formative years of primary and secondary education is important, and can be done using a number of innovative and existing mechanisms.
- For many students interested in manufacturing at a young age, programs are often unavailable that offer them engaging experiences, causing a shift in their attention to other career paths.
- Engagement of industry in the development of curriculum standards for STEM and CTE can lead to meaningful jobs for youth after graduation from high school.
- Virtual- and augmented-reality learning, industry-university cooperative planning, and strategic outlooks can aid in developing advanced manufacturing education programs.

The complex challenges highlighted in this article must be addressed through a theory of change that will engage families, educators, and industry leaders in identifying the key challenges facing students and future workers; in defining specific activities leading to the design of new manufacturing and engineering career pathways; and in implementing a cycle of deploying, testing, and iterating programs toward universal worker mobility within manufacturing industries of today and in the future.

For example, a transdisciplinary research program of educators, employers, and policy makers could be formed with a primary objective of defining core worker skills that will support medium- and long-term industry needs for a range of job roles. Such skills include technical and non-technical skills, which can be obtained through formal and informal mechanisms. The necessary skills required by future manufacturing workers could be defined both through observation of workers completing their job tasks and by querying them using interviews and survey instruments.

Another key function of such research program would be to define worker education and training mechanisms, including extracurricular activities for youth and families and corresponding volunteering opportunities for educators and manufacturing workers. Lab- and classroom-based learning activities can be developed through collaborations between industry professionals and educators for use across K-12, college, and university education programs. Critically, as manufacturing moves toward Industry 4.0, workers must be versed in a variety of technological (IIoT, robotics, additive manufacturing, etc.), programming (computational, modeling/simulation, coding, etc.), and other (data analytics, cloud computing, cybersecurity, etc.) technical skills (Maisiri et al., 2019). Non-technical skills such as analytical thinking, collaboration (machine-human and human-human), professional ethics, understanding of diversity and intercultural relationships, social responsibility, lifelong learning, and flexibility and adaptability, will be even more important as industry becomes increasingly global and interconnected.

Acknowledgments

The authors gratefully acknowledge the nominal group participants for generously contributing their input and feedback in support of this research. We also wish to thank Aaron Fox and Linda Wechsler of the Oregon Manufacturing Extension Partnership (OMEP) for their insights. Finally, we would like to thank Tom and Carmen West for their generous support of Chris Houck through their faculty endowment fund at Oregon State University.

References

Acemoglu, D., & Restrepo, P. (2018a). Demographics and Automation (No. w24421). National Bureau of Economic Research. https://doi.org/10.3386/w24421

Acemoglu, D., & Restrepo, P. (2018b). The race between man and machine: Implications of technology for growth, factor shares, and employment. *American Economic Review*, *108*(6), 1488-1542. https://doi.org/10.1257/aer.20160696

Andrew, M., Marler, T., Lastunen, J., Acheson-Field, H., & Popper, S.W. (2020). An Analysis of Education and Training Programs in Advanced Manufacturing Using Robotics. RAND.

Archer, L., DeWitt, J., Osborne, J., Dillon, J., Willis, B., & Wong, B. (2010). "Doing" science versus "being" a scientist: Examining 10/11-year-old schoolchildren's constructions of science through the lens of identity. *Science Education*, *94*(4), 617-639. https://doi.org/10.1002/sce.20399

Autor, D.H. (2015). Why are there still so many jobs? The history and future of workplace automation. *Journal of Economic Perspectives*, *29*(3), 3-30. https://doi.org/10.1257/jep.29.3.3

Autor, D.H., Levy, F., & Murnane, R.J. (2003). The skill content of recent technological change: An empirical exploration. *The Quarterly Journal of Economics*, *118*(4), 1279-1333. https://doi.org/10.1162/003355303322552801

Autor, D.H., & Salomons, A. (2018). Is automation labor-displacing? Productivity growth, employment, and the labor share (No. w24871). National Bureau of Economic Research. https://doi.org/10.3386/w24871

Baicker, K., & Rehavi, M.M. (2004). Policy watch: Trade adjustment assistance. *Journal of Economic Perspectives*, *18*(2), 239-255. https://doi.org/10.1257/0895330041371196

Bandura, A. (1986). Social foundations of thought and action: A social cognitive theory (pp. xiii, 617). Prentice-Hall, Inc.

Becker, G.S. (1994). Human Capital: A Theoretical and Empirical Analysis with Special Reference to Education, Third Edition (No. beck94-1). National Bureau of Economic Research. https://www.nber.org/books-and-chapters/human-capital-theoretical-and-empirical-analysis-special-reference-education-third-edition

Berger, T., & Frey, B. (2016). Digitalisation, jobs and convergence in Europe: Strategies for closing the skills gap (Vol. 50). Oxford Martin School Oxford.

Bolt, J., Inklaar, R., Jong, H., & Zanden, J L. (2018). Rebasing "Maddison": New income comparisons and the shape of long-run economic development. Undefined. /paper/Rebasing-%27Maddison%27-%3A-new-income-comparisons-and-of-Inklaar-Jong/64e22ebd3a4c59fb263b2aa5df99d9f280be6968

Bureau of Labor Statistics. (2021a). Labor Force Statistics. https://www.bls.gov/webapps/legacy/cpsatab13.htm

Bureau of Labor Statistics. (2021b). Division of Major Sector Productivity. Bureau of Labor Statistics. https://www.bls.gov/lpc/special_requests/msp_dataset.zip

Caballero, R., & Hammour, M. (1991). The Cleansing Effect of Recessions (No. w3922; p. w3922). National Bureau of Economic Research. https://doi.org/10.3386/w3922

Campbell, K.S., Adukaitis, C., Aroney, M., Bupp, M., Campbell, K.S., Carrick, G.A., Craig, K., DeVere, J., Evans, E., Ferrante, M., Fleming, K.J., Fogarty, D.W., George, J., Latif, N., Lipsky, K., McCann, E.J., Nance, S., Paynter, C., ... Symonds, W.C. (2014). Manufacturing workforce development playbook: Preparing for the manufacturing renaissance in America. Summit Media Group, Inc.

Carrillo-Tudela, C., Hobijn, B., She, P., & Visschers, L. (2016). The extent and cyclicality of career changes: Evidence for the U.K. *European Economic Review*, *84*, 18-41. https://doi.org/10.1016/j.euroecorev.2015.09.008

Chakraverty, D., & Tai, R.H. (2013). Parental occupation inspiring science interest: Perspectives from physical scientists. *Bulletin of Science, Technology & Society*, *33*(1–2), 44-52. https://doi.org/10.1177/0270467613509367

Dahlin, E. (2019). Are robots stealing our jobs? *Socius*, *5*, 2378023119846249. https://doi.org/10.1177/2378023119846249

Desvaux, G., Woetzel, J., Kuwabara, T., Chui, M., Fjeldsted, A., & Guzman-Herrera, S. (2015). The future of japan: Reigniting productivity and growth. McKinsey & Company: New York, NY, USA. http://www.google.com/logos/doodles/2017/oskar-fischingers-117th-birthday-5635181101711360-2xa.gif

Djuric, A., Rickli, J., Sefcovic, J., Hutchison, D., & Goldin, M.M. (2018). Integrating Collaborative Robots in Engineering and Engineering Technology Programs. *ASME 2018 International Mechanical Engineering Congress and Exposition*, Pittsburgh, PA. https://doi.org/10.1115/IMECE2018-88147

European Commission. (2014). Advancing Manufacturing—Advancing Europe'—Report of the Task Force on Advanced Manufacturing for Clean Production. https://ec.europa.eu/digital-single-market/en/news/advancing-manufacturing-advancing-europe-report-task-force-advanced-manufacturing-clean

Farber, H.S. (2017). Employment, hours, and earnings consequences of job loss: US evidence from the displaced workers survey. *Journal of Labor Economics*, *35*(S1), S235-S272.

Gallagher, M., Hares, T., Spencer, J., Bradshaw, C., & Webb, I. (1993). The nominal group technique: A research tool for general practice? *Family Practice*, *10*(1), 76-81. https://doi.org/10.1093/fampra/10.1.76

Garzón, J., Kinshuk, Baldiris, S., Gutiérrez, J., & Pavón, J. (2020). How do pedagogical approaches affect the impact of augmented reality on education? A meta-analysis and research synthesis. *Educational Research Review*, *31*, 100334. https://doi.org/10.1016/j.edurev.2020.100334

Gayle, F., Molnar, M., Roth, J., & Brunner, Z. (2021). Manufacturing USA highlights report. *National Institute of Standards and Technology*. https://doi.org/10.6028/NIST.AMS.600-6

Gerup, J., Soerensen, C.B., & Dieckmann, P. (2020). Augmented reality and mixed reality for healthcare education beyond surgery: An integrative review. *International Journal of Medical Education*, *11*, 1. https://doi.org/10.5116/ijme.5e01.eb1a

Giffi, C., Wellener, P., Dollar, B., Manolian, H.A., Monck, L., & Moutray, C. (2018). 2018 Deloitte and The Manufacturing Institute skills gap and future of work study (Deloitte Insights, p. 20). *Deloitte Development LLC*. http://www.themanufacturinginstitute.org/ /media/E323C4D8F75A470E8C96D7A07F0A14FB/DI_2018_Deloitte_MFI_skills_gap_FoW_study.pdf

Giordano, J.N. (2017). Job Training subsidies, reemployment and earnings in the trade adjustment assistance program. *International Advances in Economic Research*, *23*(3), 283-293.

Haapala, K.R., Kim, K., & Raoufi, K. (2020). Democratization through digitalization: Prospects for flexibly redeploying the future manufacturing workforce [Online (due to the COVID-19 pandemy)]. https://sdpsnet.org/sdps-2020/ws3.html

Hansen, M., Breazeale, G., & Blankenship, M. (2019). STEM teachers are most in need of additional pay. *Brookings*. https://www.brookings.edu/blog/brown-center-chalkboard/2019/06/17/stem-teachers-are-most-in-need-of-additional-pay/

Hilton, E.C., Talley, K.G., Smith, S.F., Nagel, R.L., & Linsey, J.S. (2020). Report on Engineering design self-efficacy and demographics of makerspace participants across three universities. *Journal of Mechanical Design*, *142*(10). https://doi.org/10.1115/1.4046649

Hummels, D., Munch, J.R., & Xiang, C. (2018). Offshoring and labor markets. *Journal of Economic Literature*, *56*(3), 981-1028. https://doi.org/10.1257/jel.20161150

Judd, C.H. (1921). The American experiment of free higher education. *The School Review*, *29*(2), 94-105.

Keaveney, S., Athanasopoulou, L., Siatras, V., Stavropoulos, P., Mourtzis, D., & Dowling, D.P. (2021). Development and implementation of a digital manufacturing demonstrator for engineering education. *Procedia CIRP*, *104*, 1674-1679. https://doi.org/10.1016/j.procir.2021.11.282

Kelley, T.R., & Wicklein, R.C. (2009). Teacher challenges to implement engineering design in secondary technology education. *Journal of Industrial Teacher Education*, *46*(3), 34-50.

Kok, K., van Vliet, M., Bärlund, I., Dubel, A., & Sendzimir, J. (2011). Combining participative backcasting and exploratory scenario development: Experiences from the SCENES project. *Technological Forecasting and Social Change*, *78*(5), 835-851. https://doi.org/10.1016/j.techfore.2011.01.004

Kolb, D.A. (1984). Experiential Learning: Experience as the Source of Learning and Development. New Jersey: Prentice-Hall.

Ma, L., Wang, Y., Xu, C., & Li, X. (2022). Online robotics technology course design by balancing workload and affect. *Journal of Integrated Design and Process Science*, *Preprint*(Preprint), 1-29. https://doi.org/10.3233/JID-210026

Maisiri, W., Darwish, H., & van Dyk, L. (2019). An investigation of industry 4.0 skills requirements. *South African Journal of Industrial Engineering*, *30*(3), 90-105. https://doi.org/10.7166/30-3-2230

Maltese, A.V., & Tai, R.H. (2010). Eyeballs in the Fridge: Sources of early interest in science. *International Journal of Science Education*, *32*(5), 669-685. https://doi.org/10.1080/09500690902792385

MECOP. (2021). http://www.mecopinc.org/about

Merz, M. (1999). Heterogeneous job-matches and the cyclical behavior of labor turnover. *Journal of Monetary Economics*, *43*(1), 91-124. https://doi.org/10.1016/S0304-3932(98)00043-9

Miro. (2021). An Online Visual Collaboration Platform for Teamwork. https://miro.com/

Motyl, B., & Filippi, S. (2021). Trends in engineering education for additive manufacturing in the industry 4.0 era: A systematic literature review. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *15*(1), 103-106. https://doi.org/10.1007/s12008-020-00733-1

MxD. (2017). Jobs Taxonomy: Defining Manufacturing Jobs of the Future. https://www.mxdusa.org/taxonomy/

MxD. (2020). The Hiring Guide. MxD. https://www.mxdusa.org/hiringguide/

Namasivayam, S., Fouladi, M.H., Sivanesan, S., & Noum, S.Y.E. (2020). The role of makerspaces in enhancing the student learning experience. *International Journal of Engineering Education*, *36*(4). https://researchportal.hw.ac.uk/en/publications/the-role-of-makerspaces-in-enhancing-the-student-learning-experie

National Academies of Sciences, Engineering, and Medicine. (2016). Science Literacy: Concepts, Contexts, and Consequences (C. E. Snow & K. A. Dibner, Eds.; p. 23595). National Academies Press. https://doi.org/10.17226/23595

National Academies of Sciences, Engineering, and Medicine. (2017). Building America's Skilled Technical Workforce (p. 23472). National Academies Press. https://doi.org/10.17226/23472

National Academy of Engineering & National Research Council. (2012). Report of a Workshop on Science, Technology, Engineering, and Mathematics (STEM) Workforce Needs for the U.S. Department of Defense and the U.S. Defense Industrial Base. The National Academies Press. https://doi.org/10.17226/13318

National Institute of Standards and Technology. (2014). About NIST MEP [Text]. NIST. https://www.nist.gov/mep/about-nist-mep

National Research Council. (2012). Education for Life and Work: Developing Transferable Knowledge and Skills in the 21st Century. https://doi.org/10.17226/13398

National Student Clearinghouse Research Center. (2019). Some College, No Degree—2019. National Student Clearinghouse Research Center. https://nscresearchcenter.org/some-college-no-degree-2019/

Nguyen, H. (2020). Free college? Assessing enrollment responses to the Tennessee Promise program. *Labour Economics*, *66*, 101882. https://doi.org/10.1016/j.labeco.2020.101882

Palvia, S., Aeron, P., Gupta, P., Mahapatra, D., Parida, R., Rosner, R., & Sindhi, S. (2018). Online education: Worldwide status, challenges, trends, and implications. *Journal of Global Information Technology Management*, *21*(4), 233-241. https://doi.org/10.1080/1097198X.2018.1542262

Park, J. (2012). Does occupational training by the trade adjustment assistance program really help reemployment? Success measured as occupation matching. *Review of International Economics*, *20*(5), 999-1016. https://doi.org/10.1111/roie.12009

Parker, K., Igielnik, R., Barrosos, A., & Cilluffo, A. (2019). Views of Post-9/11 military veterans. *Pew Research Center*'s *Social & Demographic Trends Project*. https://www.pewresearch.org/social-trends/2019/09/10/the-american-veteran-experience-and-the-post-9-11-generation/

PCAST. (2014). Report to the President: Accelerating U.S. Advanced Manufacturing (p. 108). President's Council of Advisors on Science and Technology, Executive Office of the President. https://web.archive.org/web/20200122030413/https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/amp20_report_final.pdf

Pei, E., Monzón, M., & Bernard, A. (2019). Additive manufacturing-Developments in training and education. Springer.

Radianti, J., Majchrzak, T.A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers* & *Education*, *147*, 103778. https://doi.org/10.1016/j.compedu.2019.103778

Raoufi, K. (2020). Integrated Manufacturing Process and System Analysis to Assist Sustainable Product Design [Doctoral Dissertation, Oregon State University]. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/0c483s07g

Raoufi, K., Manoharan, S., & Haapala, K.R. (2019). Synergizing product design information and unit manufacturing process analysis to support sustainable engineering education. *Journal of Manufacturing Science and Engineering*, *141*(2), 021018-021032. https://doi.org/10.1115/1.4042077

Raoufi, K., Park, K., Hasan Khan, Md.T., Haapala, K.R., Psenka, C.E., Jackson, K.L., Kremer, G.E.O., & Kim, K.-Y. (2019). A cyberlearning platform for enhancing undergraduate engineering education in sustainable product design. *Journal of Cleaner Production*, *211*, 730-741. https://doi.org/10.1016/j.jclepro.2018.11.085

Raoufi, K., Paul, B.K., & Haapala, K.R. (2020). Development and implementation of a framework for adaptive undergraduate curricula in manufacturing engineering. *Smart and Sustainable Manufacturing Systems*, *5*(2). https://doi.org/10.1520/SSMS20200008

Raoufi, K., Shankar Raman, A., Haapala, K.R., & Paul, B.K. (2018). Benchmarking undergraduate manufacturing engineering curricula in the united states. *Procedia Manufacturing*, *26*, 1378-1387. https://doi.org/10.1016/j.promfg.2018.07.114

Robinson, J.B. (1982). Energy backcasting A proposed method of policy analysis. *Energy Policy*, *10*(4), 337-344.

Ryder, J. (2001). Identifying science understanding for functional scientific literacy. *Studies in Science Education*, *36*(1), 1-44. https://doi.org/10.1080/03057260108560166

Shea, J.E., & West, T.M. (1999). Evolution of an industrial engineering curriculum. 4.246.1-4.246.8. https://peer.asee.org/evolution-of-an-industrial-engineering-curriculum

Skovhus, R.B., & Thomsen, R. (2020). From career choice to career learning: Taster programs and students' meaning-making processes. *Career and Career Guidance in the Nordic Countries*, 251-263. https://doi.org/10.1163/9789004428096_017

Soliman, M., Pesyridis, A., Dalaymani-Zad, D., Gronfula, M., & Kourmpetis, M. (2021). The application of virtual reality in engineering education. *Applied Sciences*, *11*(6), 2879. https://doi.org/10.3390/app11062879

Stocklmayer, S.M., Rennie, L.J., & Gilbert, J.K. (2010). The roles of the formal and informal sectors in the provision of effective science education. *Studies in Science Education*, *46*(1), 1-44. https://doi.org/10.1080/03057260903562284

Tate, E. (2019). Student-to-counselor ratios are dangerously high. *Here's How Two Districts Are Tackling It*. EdSurge. https://www.edsurge.com/news/2019-09-19-counselor-to-student-ratios-are-dangerously-high-here-s-how-two-districts-are-tackling-it

Texas Higher Education Coordinating Board (THECB). (2015). Texas Higher Education Strategic Plan: 2015–2030 (60x30TX Plan) (p. 44). Texas Higher Education Coordinating Board (THECB). http://reportcenter.highered.texas.gov/agency-publication/miscellaneous/60x30tx-strategic-plan-for-higher-education/

Toivonen, V., Lanz, M., Nylund, H., & Nieminen, H. (2018). The FMS Training Center—A versatile learning environment for engineering education. *Procedia Manufacturing*, *23*, 135-140. https://doi.org/10.1016/j.promfg.2018.04.006

U.S. Bureau of Labor Statistics. (2008). Technical Information About the BLS Major Sector Productivity and Costs Measures. Bureau of Labor Statistics. https://www.bls.gov/lpc/lpcmethods.pdf

U.S. Bureau of Labor Statistics. (2020). Educational attainment for workers 25 years and older by detailed occupation: U.S. Bureau of Labor Statistics. https://www.bls.gov/emp/tables/educational-attainment.htm

U.S. Department of Education. (2019). President's FY 2020 Budget Request for the U.S. Department of Education [Budget Materials]. US Department of Education (ED). https://www2.ed.gov/about/overview/budget/budget20/index.html

U.S. Department of Labor. (2020a). FY 2020 Budget. https://www.dol.gov/general/budget/index-2020

U.S. Department of Labor. (2020b). Trade Act Programs | U.S. Department of Labor. https://www.dol.gov/general/topic/training/tradeact

van den Akker, J., Bannan, B., Kelly, A. E., Nieveen, N., & Plomp, T. (2013). Educational Design Research: Part A: An Introduction (T. Plomp & N. Nieveen, Eds.). Netherlands Institute for Curriculum Development (SLO).

Wang, B. (2018). The future of manufacturing: A new perspective. *Engineering*, *4*(5), 722-728. https://doi.org/10.1016/j.eng.2018.07.020

Wheeler, C. H. (2007). Job flows and productivity dynamics: Evidence from U.S. manufacturing. *Macroeconomic Dynamics*, *11*(2), 175-201. https://doi.org/10.1017/S1365100507060026

Zeng, Y. (2011). Environment-based design (EBD). *ASME Conference Proceedings*, *2011*(54860), 237-250. doi: 10.1115/DETC2011-48263

Author Biographies

Karl R. Haapala is an associate professor in the School of Mechanical, Industrial, and Manufacturing Engineering at Oregon State University. His research addresses sustainable manufacturing challenges, including life cycle engineering methods, manufacturing process performance modeling, and engineering education. His research has been funded by DOE, NIST, NSF, and a number industry partners. He serves as Director of OSU's DOE Industrial Assessment Center and leads northwestern activities of the CESMII Western Smart Manufacturing Innovation Center. He served as Chair of the Design for Manufacturing and Life Cycle Technical Committee of the ASME Design Engineering Division and the Chair of the Life Cycle Engineering Technical Committee of the ASME Manufacturing Engineering Division. He has been recognized by the NAE (2015 Frontiers of Engineering) and SME (2014 Outstanding Young Manufacturing Engineer Award and 2012 & 2015 Distinguished Faculty Advisor Awards), and received Best Paper Awards from ASME (2015 & 2016 DFMLC), CIRP (2012 LCE), and ISSS (2017). Dr. Haapala served as a Fulbright-Tampere University Faculty Scholar in 2019-2020, and conducted research and teaching at the intersection of smart and sustainable manufacturing as applied to additive manufacturing processes.

Kamyar Raoufi is a researcher in the School of Mechanical, Industrial, and Manufacturing Engineering at Oregon State University. He was a graduate assistant under a multi-university research project funded by the U.S. National Science Foundation (NSF), where he collaborated with undergraduate/graduate students and researchers from Oregon State University, Iowa State University, Pennsylvania State University, and Wayne State University. Kamyar participated in an NSF INTERN supplement project from Aug.-Dec. 2018 at EarthShift Global, LLC, a sustainability consultancy in Maine. In 2019, he led research under an OSU-HP research seed fund project to characterize the sustainability performance of competing conventional and additive processes, and a new HP 3D printing technology. He received the 2019-2020 College of Engineering Outstanding Graduate Research Assistant Award at Oregon State University and completed his Ph.D. in Industrial Engineering in 2020.

Kyoung-Yun Kim is a professor in the Department of Industrial & Systems Engineering at Wayne State University, where he directs the Computational Intelligence and Design Informatics (CInDI) Laboratory. Dr. Kim's research focuses on design science; design informatics; semantic assembly design; welding and joining; and smart manufacturing. He has received external funding from federal agencies including NSF, DMDII, NIDRR, VA-CASE, DOD, and DOE, and several industry partners. He is Director of the Smart Manufacturing Demonstration Center (SMDC) and a Site Director for the NSF Industry and University Cooperative Research Center (I/UCRC) for e-Design. Dr. Kim is a Fellow of the Society of Design and Process Science and currently serves as Editor-in-Chief of the Journal of Integrated Design and Process Science. He received the top-cited article award (2005–2010) from Journal CAD and 2003 IIE Transactions Best Paper Award. Dr. Kim was an invited professor at Université de Technologie de Belfort-Montbéliard (UTBM), France, 2017 and was a visiting professor at Kyung Hee University, South Korea, 2014.

Christopher S. Houck is a student at Oregon State University working towards a master's in industrial engineering. He earned his B.S. in industrial engineering from OSU in 2020. During his undergraduate program, Chris worked for Tektronix where he received the Inspire Award for dedication to implementing an efficient workstation auditing system. He is currently a graduate teaching assistant supporting the new Engineering+ introductory engineering curriculum in the OSU College of Engineering, and has conducted graduate research in industrial energy efficiency and labor resource allocation.

Peter F. Orazem is a University Professor of Economics at Iowa State University. He serves as director of ISU's Program for the Study of Midwest Markets and Entrepreneurship that researches how firms develop human capital, input suppliers, customers, and venture capital sources in thin markets.

He is a graduate in economics at the University of Kansas and received his Ph.D. in economics from Yale University. He is a past member of the Ames City Council, Ames Convention and Visitors Bureau, and Ames Economic Development Commission. In 2018, he served as a Fulbright Fellow at the Univerza na Primorskem in Slovenia. His research deals with labor markets in the United States and in developing countries, and has coauthored chapters in the Handbook of Development Economics and the Handbook of Agricultural Economics. He served on the core team for the World Bank's 2007 World Development Report and wrote papers for the 2008, 2012 and post-2015 editions of the Copenhagen Consensus. He is coeditor of the book, Child Labor and Education in Latin America, 2009.

Michael D. Johnson is a professor in the Department of Engineering Technology and Industrial Distribution at Texas A&M University. He also serves as the Associate Dean for Inclusion and Faculty Success in the College of Engineering. Prior to joining Texas A&M, he was a senior product development engineer at the 3M Corporate Research Laboratory in St. Paul, Minnesota. He received his B.S. in mechanical engineering from Michigan State University and his M.S. and Ph.D. from the Massachusetts Institute of Technology. Dr. Johnson's research focuses on engineering education, production economics, and design tools. He has over 90 peer-reviewed publications and several patents. His research has been funded by the DOE, NSF, and industry. He is a member of the American Society for Engineering Education, the American Society of Mechanical Engineers, SME, and a senior member of IEEE. He served as president of the Tau Alpha Pi Engineering Technology Honor Society national board (2014–2018) and is past chair of the Mechanical Engineering Technology Leadership Committee. He is a member of the Engineering Technology Accreditation Commission of ABET. Dr. Johnson has won departmental and college awards, the ASEE National Engineering Technology Teaching Award, and Fredrick J. Berger Award.

Gül E. Okudan Kremer is Dean of Engineering at University of Dayton. Kremer served as chair of the Department of Industrial and Manufacturing Systems Engineering (2016–2021) and Senior Director Presidential Projects (2021-2022) at Iowa State University, in addition to past leadership roles at Penn State. Dr. Kremer has degrees in industrial engineering from Yildiz Technical University, a masters in business from Istanbul University, and a PhD in Engineering Management from Missouri University of Science and Technology. She was a National Research Council-US AFRL Summer Faculty Fellow in the Human Effectiveness Directorate (2002–2004), a Fulbright Scholar (2010-2011), and Program Director in NSF's Division of Undergraduate Education (2013–2016). Dr. Kremer's research interests include applied decision analysis to improve complex products and systems, and engineering education. Her research has appeared in 3 books and over 360 refereed publications. She is a Fellow of the American Society for Mechanical Engineers and senior member of the Institute of Industrial Systems Engineers. She served as Chair of Design Education and Design for Manufacturing and Lifecycle Technical Committees of the ASME Design Engineering Division. In addition, she has significant contributions to research efforts that are directed toward improving engineering education.

Jeremy L. Rickli is an associate professor in Industrial and Systems Engineering at Wayne State University. He received his B.S. and M.S. in Mechanical Engineering from Michigan Technological University and Ph.D. in Industrial and Systems Engineering from Virginia Tech. He is director of the Manufacturing and Remanufacturing Systems Laboratory (MaRSLab) and co-director of the Smart Manufacturing Demonstration Center. His research includes uncertainty management in remanufacturing; leveraging data for decision making in digital manufacturing; and collaborative robotic automation. Dr. Rickli is director of the NSF REU Site: Summer Academy in Sustainable Manufacturing which offered summer undergraduate research programs in 2016–2018 and was renewed for 2021–2023. This site exposes students to sustainable manufacturing research; develops a sustainable manufacturing community of students, faculty, and industry; and encourages students to pursue sustainable manufacturing research. He is also Co-PI of an NSF Advanced Technology Education project that has developed collaborative robot based learning modules and curriculums for community college and four year university students.

Federico M. Sciammarella serves as the President & CTO of MxD, where he is in charge of developing and implementing the technology vision for the institute and established the "Emerging Tech" program that focusses on early stage research from academic partners that transitions to industry. Dr. Sciammarella was previously an associate professor at Northern Illinois University where he directed the Advanced Research in Materials and Manufacturing for more than 10 years which generated over $2.5 million dollars in funding and created a launch pad for many students and technologies in advanced manufacturing. He has a long list of publications and patents for applications in laser assisted machining and additive manufacturing. His experience in creating research which always focused on applications for industry fits well with the MxD mission. Dr. Sciammarella received his B.S., M.S. and Ph.D. in Metallurgy and Material Science Engineering from the Illinois institute of Technology.

Kris Ward leads market intelligence and research efforts supporting Tooling U-SME sales, product, and marketing initiatives. She works to advance Tooling U-SME's understanding of the manufacturing industry and its unmet workforce development needs. In this capacity, Ward helps shape business development opportunities and informs the development of strategy and direction for learning and development products, services, and markets served. Ward started her career with SME in 1996, holding various positions over the years in marketing, product development, and product management. She received an MBA from Wayne State University and a Bachelor's in Business from Eastern Michigan University.