Smart Manufacturing in Small and Medium Enterprises in the United States: Implementation, Drivers, Barriers, and Technologies

Partial fulfillment of DE-EE0006716

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Prepared for: Department of Energy, Energy Efficiency & Renewable Energy

Cite this report as:

Pixley, Joy E., Sabine Kunrath, Genoveva Paz, Richard Donovan, & G.P LI. 2021. Smart Manufacturing in Small and Medium Enterprises in the United States: Implementation, Drivers, Barriers, and Technologies. Prepared for the Department of Energy, DE-EE0006716: University of California, Irvine.

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Acknowledgements:

The authors would like to thank Gregg Profozich from CMTC for distributing the survey to the MEP network and Jennifer Rosa (NIST) for feedback on the recruitment materials.

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ABBREVIATIONS AND ACRONYMS

Term	Definition
AMO	Advanced Manufacturing Office
CESMII	Clean Energy Smart Manufacturing Innovation Institute/ The Smart Manufacturing Institute
CMTC	California Manufacturing Technology Consulting
CON	Survey subjects who are consultants working with SMMs
EERE	Office of Energy Efficiency and Renewable Energy
IAC	Industrial Assessment Center
ICT	Information and Communication Technologies
IND	Survey subjects who are individual representatives of SMMs
IoT	Internet of Things (IoT)
IIoT	Industrial Internet of Things
LM	Lean Management
ISO	International Organization for Standardization
MEP	Manufacturing Extension Partnership
M2M	Machine-to-machine
NAICS	North American Industry Classification System
NIST	National Institute of Standards and Technology
SEEM	Smart Energy-Efficient Manufacturing
SM	Smart manufacturing
SME	Small and medium enterprises
SMM	Small and medium manufacturers
UCI	University of California, Irvine

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Executive Summary

Introduction

Smart manufacturing is a framework for implementing smart technologies to optimize energy efficiency and productivity and to reduce waste, empowering workers and managers to improve decision-making. Research suggests that large manufacturing companies are more prepared to digitize their operations, while SMMs face greater challenges to realize the potential of SM. The large percentage of SMMs in the manufacturing industry and their importance to the economy encourages efforts to help SMMs succeed in becoming more productive and competitive in a changing environment. Understanding how US SMMs view SM and what their experiences have been with it is key to developing and implementing effective scaled-down solutions.

This research is part of the "Smart Connected Workers in Advanced Manufacturing" program, funded by the office of Energy Efficiency & Renewable Energy (EERE) of the US Department of Energy (DE-EE0006716). Under the leadership of researchers at University of California, Irvine (UCI), the program brought together various organizations from academic institutions, industry, and the Smart Manufacturing Institute (CESMII) with the goal of creating an affordable, scalable, and portable smart manufacturing (SM) solution for small and medium manufacturers (SMMs). The UCI research team worked with the National Institute of Standards and Technology (NIST) Manufacturing Extension Partnership (MEP) Centers to conduct a survey with SMMs to identify the current status of readiness for and adoption of SM solutions, major barriers and drivers, and experiences and opinions about specific SM technologies and strategies. The research team took a two-pronged approach: (1) review prior survey research on SM in SMMs and (2) develop a new, comprehensive survey to complement existing studies, focusing on SMMs in the US. This report presents the results of the literature review and the subsequent survey study.

Literature Review

An extensive literature review assessed key concepts and findings in the SM literature, focusing on SM in SMMs in the United States. However, much survey work on SM has focused on larger manufacturers or on SMMs in other countries, or has not separated the experience of SMMs from those of larger companies. The review showed significant gaps and weaknesses in the research assessing the state of SM for SMMs in the US. Specifically, more work is needed that addresses:

- which SM technologies and connected strategies are already being used,
- how prepared SMMs are to adopt these technologies,
- which specific barriers SMMs encounter to introduce this technology,
- what desired benefits do SMMs want from SM,
- which of these technologies are perceived to be the most promising to increase efficiency given the special constraints and needs of SMMs.

Survey

Based on an extensive review of prior findings, the team developed a survey addressing the following research questions: how ready are SMMS to adopt SM, what barriers and drivers do they perceive for SM adoption, and which SM technologies are used by SMMs or have been considered. The survey was designed to replicate key questions from prior studies when possible. It goes beyond generalizations to ask how twenty specific SM technologies have been tried in SMMs, which are still being used, and how workers respond to them. The survey was administered to a national sample of owners and employees of individual SMMs (IND) and consultants working with multiple SMMs (CON). This report presents findings for 54 owners and employees and 48 consultants.

Results

Results show that consultants tend to report lower levels of readiness for the SMMs they work with than individual subjects report for their own companies, and yet both groups tend to report somewhat higher levels of readiness –and adoption—than seen in previous studies. For instance, few subjects report that SMMs have fully implemented smart manufacturing (16% for IND and 17% for CON), but 56% of IND subjects claim to have developed a clear business case or even implemented first measures, compared to 36% of the SMMs consultants work with. Likewise, CON subjects report higher rates of being paper intensive (24% v. 11%) and lower rates of fully digital and automated (17% v 36%) than IND subjects do. More than one in four subjects (26% IND and 30% CON) report that current employees would find it difficult to adapt to new technology and new, more skilled workers would need to be hired.

Although 20-30% reported already using smart solutions for specific tasks, even more felt smart solutions would help with those tasks. However, a substantial minority of subjects reported being satisfied with how well low-tech solutions worked, particularly for assigning jobs or tasks (43% IND and 34% CON), communicating with third parties (41% IND), and internal communication (35% IND and 38% CON). This finding provides an important reminder that not all solutions should be sought simply because they are smart: SMMs need to concentrate their relatively limited resources on adopting only those solutions that solve their specific needs.

For IND subjects, the topmost reported drivers of adoption were reducing costs (24%) and following a conscious strategy (15%), while the topmost barriers were not having the time (26%) or money (22%) to invest. Since constructing a conscious internal strategy takes time and labor that most SMMs can't spare, these two findings illustrate the essential challenge faced by SMMs: they don't have the time and money they need to invest in order to make better use of their time and save more money. Results from CON subjects showed a slightly different story: although reducing costs was also their topmost driver (21% CON), they were more likely than IND subjects to rate customer requirements (17%) and requests from consultants (15%) as the topmost driver. More CON subjects listed the topmost barrier as insufficient management commitment (23%) or uncertainty about whether the investment would benefit profits (21%), which may reflect how and with whom they negotiate the adoption process

The technologies the most subjects reported using for SM are cybersecurity, tablets, and mobile phones with IND subjects also including IoT and big data and analytics in their top five and CON subjects including handheld scanners and cloud computing in their top five. However, many other technologies were currently used or had been considered by a smaller subset. For technology types not currently being used in the subjects' companies, 33% of IND subjects reported trying and discontinuing at least one of them, while 59% reported that their company seriously considered adopting at least one smart technology but decided against it because of anticipated problems. Many of the technologies considered and rejected were the same ones currently being used by many other subjects' companies, such as tablets, reflecting their ubiquity rather than their likelihood of rejection. More concerning are the technologies that companies tried and rejected, nine of which were reported by more than 5% of subjects (ranging from 6%-9%): mobile phones, additive manufacturing/3D printing, simulation, handhold scanners, system integration, artificial intelligence, headsets, VR headsets, and smart glasses. This is another important insight, that technologies that may work well for some companies (especially larger ones) may not work for SMMs. Indeed, the reasons most often given for discontinuing a smart solution were cost (56%) and complexity of using and maintaining the solution (50%).

Increased task completion speed was cited as the main "pro" by far of many of the most-used technologies by IND subjects, whereas CON subjects were more likely to cite easier implementation. This difference may reflect the fact that consultants are more involved at the planning and implementation stage whereas workers are directly involved in day-to-day task completion long afterward. There was more variation in the main "con" subjects cited for these technologies, with no single problem dominating across all types. IND subjects rated workers as having substantially more positive responses to specific technologies currently being used than CON subjects reported (38% v. 10% strongly positive, and 7% v. 33% somewhat or strongly negative), but even among IND subjects, many technologies received neutral, mixed, or negative responses from workers.

Conclusions

In summary, SMMs potentially benefit from smart technologies, but they face serious challenges when adopting this digital transition. Overall, these results support the idea that SMMs, even more so than larger companies with more flexible resources, should focus their decision-making on specific technologies for specific needs rather than attempting to embrace the full spectrum of smart manufacturing at once. The differences in perceptions by consultants, managers, experts, and workers on certain issues highlight the importance of addressing experiences, concerns, and insights at every level of the company. More research is needed to gain a better understanding of where US SMMS are in their transition to smart manufacturing and what problems they have that specific new technology can address. This study further adds to this research by asking about companies' experiences with specific technologies. These results will inform the development of technological solutions that are affordable and easily adaptable for SMMs.

INTRODUCTION

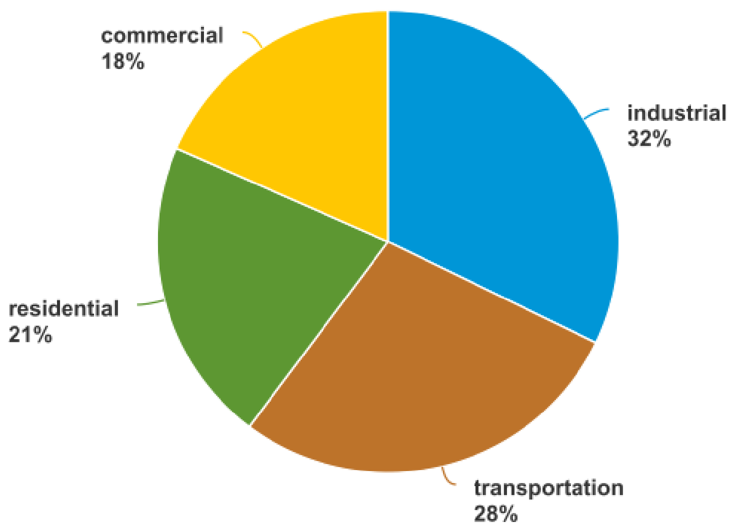
This research is part of the Advanced Manufacturing" program, funded by the office of Energy Efficiency & Renewable Energy (EERE) of the US Department of Energy (DE-EE0006716). Under the leadership of researchers at the University of California, Irvine, the program brought together various organizations from academic institutions (University of California, Los Angeles, California State University Northridge, San Diego Super Computing Center), industry (General Mills, Honeywell, The Aerospace Corporation, Atollogy), and the Smart Manufacturing Institute (CESMII) with the goal of creating an affordable, scalable, and portable smart manufacturing (SM) solution for small and medium manufacturers (SMMs). As part of the statement of project objectives, the leadership team worked with the National Institute of Standards and Technology (NIST) Manufacturing Extension Partnership (MEP) Centers to conduct a survey with SMMs to identify the current status of readiness for and adoption of SM solutions, major barriers and drivers, and experiences with specific SM technologies and strategies. The research team took a two-pronged approach: (1) review prior survey research on SM in SMMs and (2) develop a new, comprehensive survey to complement existing studies, focusing on SMMs in the US. This report presents the results of the literature review and the subsequent survey study.

LITERATURE REVIEW

The manufacturing industry in the United States provides an invaluable basis for research, development, innovation, productivity, and job creation, as it generates more economic activity than any other sector (Scott, 2015). Manufacturing is also highly energy intensive (Brueske, Sabouni, Zach, & Andres, 2012). In 2018, the industrial sector (which includes manufacturing and non-manufacturing industrial uses such as mining, construction, and agriculture) used about one third of the total energy consumed in the US (see Source: U.S. Energy Information Administration (2018); Note: total 101.3 quadrillion British thermal units

Figure 1) (U.S. Energy Information Administration, 2018). Most of this energy consumption went into manufacturing (Brueske et al., 2012). When accounting for both direct emissions from the manufacturing processes and indirect emissions from the associated electricity use, the industrial sector was the largest contributor of greenhouse gases of any sector, with almost 29% in 2018 (U.S. Environmental Protection Agency, 2020). This makes manufacturing a prime target to address unnecessary energy and process inefficiencies as they impact productivity, with consequences for companies' economic health and competitiveness, as well as the environment (Brueske et al., 2012; Nimbalkar et al., 2017). Emerging smart technologies can help to decrease production costs, enhance energy productivity, conserve finite energy resources, and reduce greenhouse gas emissions (Nimbalkar et al., 2017; Whitlock, Elliott, & Rightor, 2020)**.** For example, a factory that is enabled with smart technology can lower both its energy cost and greenhouse gas emissions by using electricity at the time of the day when an abundance of less expensive energy from renewable sources is available, and shifting consumption away from peak times. Also, using smart technologies can facilitate more efficient use of materials by reducing production errors and subsequent losses and optimizing workflow overall

(Intergovernmental Panel on Climate Change, 2014) which helps manufacturers to be more energy-efficient and cost-effective.



Source: U.S. Energy Information Administration (2018); Note: total 101.3 quadrillion British thermal units

Figure 1: Total Energy Consumption by End-Use Sector, 2018

However, there are indications that small and medium manufacturers (SMMs) face substantial barriers to the digitization of their manufacturing. This is important because SMMs make up a large proportion of manufacturers. In 2016, about 246,000 of the almost 250,000 US manufacturing firms employed fewer than 500 people; thus, SMMs made up about 98.5% of all manufacturing firms (United States Census Bureau, 2018). Of these, the biggest share (42%) employed fewer than five people. The relatively small number of large manufacturers employ more workers than all the SMMs combined, with 6.4 million versus 5.1 million employees (U.S Small Business Administration, 2018a; United States Census Bureau, 2018); still, 44% of manufacturing employees work for SMMs. The large share of small and medium-sized enterprises is similar across other regions and nations (Grube, Malik, & Bilberg, 2017; OECD, 2017). Small and medium businesses in general are often called the "backbone" of economies (Issa, Lucke, & Bauernhansl, 2017; Mittal et al., 2019; Trianni, Cagno, & Farné, 2016). Indeed, between 2000 and 2017, small businesses across all industries (e.g., health care, retail trade, manufacturing, construction) created 8.4 million of all net new jobs while large businesses created 4.4 million net new jobs (i.e., the difference between job gains and job losses) (U.S Small Business Administration, 2018b). Besides creating new jobs and providing opportunities for workers to develop skills, small and medium enterprises contribute to innovation and generate value added to existing products (OECD, 2017).

However, many new businesses fail, usually while they are still small- or medium-sized. In the US, only about half of new businesses survive at least five years and only about one in three survives ten years (U.S Small Business Administration, 2018b). Small and medium enterprises are vital to a healthy economy, and helping these companies retain a competitive edge can ensure financial success (Hughes

& Troy, 2020). Digitalization can help small and medium enterprises to compete in a global economy, but their ability to adopt more sophisticated technologies is limited, essentially slowing their progression (OECD, 2017).

Large manufacturers are more likely to use SM technologies and smart connected worker strategies than smaller companies (Schröder, 2017). Small and medium manufacturers (SMMs) can potentially also benefit from such technologies, but there are indications that SMMs face additional challenges when adopting this digital transition. They share many of the risks and problems of larger manufacturers, such as attracting and retaining a quality workforce (National Association of Manufacturers, 2020). At the same time, they also share the obstacles encountered by other small and medium enterprises, such as the lack of financial and human resources to tackle inefficiencies and innovate (Hughes & Troy, 2020). Even when a large manufacturer is spread across the country as numerous small or medium-sized factories, each one benefits from the stability of a large firm's resources, whereas SMMs have no such security net. As such, it is prudent to carefully consider which smart manufacturing approaches are most likely to be effective for SMMs, rather than assume the same approaches adopted by larger firms will work.

In the following section of the report we define key concepts related to SM and lay out how SM technologies can potentially benefit SMMs. We then examine survey studies that investigate the status of implementation of SM technologies and factors that influence adoption, again with a focus on SMMs, to obtain their perspective on SM.

Approach

To perform a thorough review of the literature, we developed a comprehensive search strategy. We conducted searches in Web of Science, Academic Search Complete, and Google Scholar, most recently updated in January 2021.[1] We also searched the reference lists of key publications and the table of contents of special editions of journals and recent books (e.g., special issues “Industry 4.0 for SMEs - Smart Manufacturing and Logistics for SMEs” in *Sustainability* and “Implementing and acceleration of industry 4.0” in *Journal of Manufacturing Technology Management*). Last, we searched web pages of

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[1] Search terms used for literature search (general concepts): [manufactur*] AND [SMMs OR SME OR small OR small and medium OR medium OR middle market] AND [Smart manufacturing OR Industry 4.0 OR Advanced Manufacturing OR ICT OR Information Communication Technology OR IoT OR Internet of Things OR Industrial Internet of Things OR IIoT].

Search terms used for literature search (survey studies): [manufactur*] AND [SMMs OR SME OR small OR small and medium OR medium OR middle market] AND [Smart manufacturing OR Industry 4.0 OR Advanced Manufacturing OR ICT OR Information Communication Technology OR IoT OR Internet of Things OR Industrial Internet of Things OR IIoT] AND [Survey studies OR survey OR questionnaire OR interview governmental organizations (e.g., NIST), industry groups (e.g., Plataine) and consulting firms (e.g., Boston Consulting Group) to retrieve survey reports. We focused on studies that were published in 2015 or more recently.

Our search identified literature about SM in general and SM in SMMs specifically but relatively little primary research, particularly for SMMs in the US. We retrieved 29 national and international survey studies about SM (see Appendix). We excluded 5 studies where SMMs were either not sampled or the ratio between SMMs and large manufacturers was not clear. Of the 24 remaining survey studies, seven contained US data, details of which are shown in Table 1 (for the other survey studies, see the Appendix). However, only five studies were entirely conducted in the US (Advanced Manufacturing Media, 2015; Bosman, Hartman, & Sutherland, 2020; Industry of Things World USA, 2017; Sikich, 2017; Wuest, Schmid, Lego, & Bowen, 2017). Of these, only two focused specifically on SMMs either by sampling only SMMs or by analyzing and discussing data separately for SMMs (Bosman et al., 2020; Wuest et al., 2017). The other two studies included US data among others (Morton, George, Ben-Bassat, Ben-Assa, & Books, 2020; Rauch, Stecher, Unterhofer, Dallasega, & Matt, 2019); one of these (Rauch et al., 2019) focused on SMMs. Notably, of these seven studies that contain US data, only three studies were conducted by independent academic institutions (Bosman et al., 2020; Rauch et al., 2019; Wuest et al., 2017). The other studies were conducted and published by consulting firms and interest groups (Mittal, Khan, Romero, & Wuest, 2018). Most of the other studies (13) were conducted in Europe, with one each in Canada, New Zealand, Asia, and South America. Of the 17 non-US-studies, 13 focused specifically on SMMs, the rest had a mix of small, medium, and large manufacturers.

The literature will be discussed in terms of:

- key concepts and definitions
- preparedness of SMMs to transition to a SM framework, including the current status of SM technologies diffusion,
- factors that drive SMMs towards adoption, and
- barriers that prevent SMMs for implementing SM technology

Although the focus is on the US, the review is supplemented with results from other countries.

Key Concepts

Smart Manufacturing and Related Concepts

Smart manufacturing (SM) is a framework for implementing smart technologies to optimize energy efficiency, productivity, and to reduce waste. It involves the use of data and the internet of things (IoT) to streamline operations (Kagermann, Wahlster, & Helbig, 2013).

Table 1: Survey Study Overview: Surveys with US Data for SMMs

Author/Year/Publication Title	Type of publication	Country (Region)	SMM focus/ separate results	Sample size (% SMM)
Bosman, L., Hartman, N., & Sutherland, J. (2020). How manufacturing firm characteristics can influence decision making for investing in Industry 4.0 technologies.	Academic journal	USA (Indiana)	Yes	138 (100%)
Wuest, T., Schmid, P., Lego, B., & Bowen, E. (2017). Overview of Smart Manufacturing in West Virginia.	Report (academic institution)	USA (Virginia)	Yes	54 (70%)
Advanced Manufacturing Media. (2015). How Advanced Manufacturing is helping U.S Companies Compete Globally.	Report (industry/ interest group)	USA	No	618 (78%)
Industry of Things World USA. (2017). Survey Report 2018.	Report (industry/ interest group)	USA	No	221 (67% <50M annual revenue)
Sikich. (2017). 2017 Manufacturing Report. Trends and strategies to help manufacturers understand growth challenges and capture opportunities.	Report (consulting firm)	USA	No	"more than 250" (76% <50M annual revenue)
Rauch, E., Stecher, T., Unterhofer, M., Dallasega, P., & Matt, D. T. (2019). Suitability of Industry 4.0 concepts for small and medium sized enterprises: Comparison between an expert survey and a user survey.	Conference Proceedings	USA, Italy, Austria, Slovakia	Yes	28 companies (61% 10 - 249 employees); 12 experts
Morton, D., et al. (2020). Trends in Global Manufacturing. Implementing Industry 4.0 & Building the Digital Factory.	Report (consulting firm)	International, including the USA	No	"over 200" (46% <50M annual revenue)

Manufacturing processes have significantly transformed since the first industrial revolution in the 19th century. In the early 20th century, electrically powered mass-production revolutionized manufacturing, in the 1970s, electronics and computers enabled automated production., Now, the introduction of “smart” technologies has been called the Fourth Industrial Revolution, or Industry 4.0 (Erol, Schumacher, & Sihn, 2016; Kagermann et al., 2013; Xu, Xu, & Li, 2018). Industry 4.0, a term coined in German government initiatives, emphasizes the use and integration of intelligent machines, real-time data, embedded software and the internet to organize automated, streamlined operations (Erol et al., 2016; Grube et al., 2017; Kagermann et al., 2013; Liao, Deschamps, Loures, & Ramos, 2017; Müller & Däschle, 2018; Vaidya, Ambad, & Bhosle, 2018). The Industry 4.0 framework is being used worldwide under different names and trademarks. The German name is “Industrie 4.0”, in Japan it is called the “Industrial Value Chain Initiative” (Schuh, Anderl, Dumitrescu, Krüger, & Hompel, 2020a). China is pushing a similar initiative under the term “Made in China 2025” (Manufacturing Policy Initiative, 2019; Zhong, Xu, Klotz, & Newman, 2017). In the US, the digital tranformation of manufacturing is promoted by organisations such as the Smart Manufacturing Leadership Coalition (SMLC, 2021) and the the Industrial Internet Consortium (Industrial Internet Consortium, 2020). The Department of Energy and the National Institute for Standardization and Technology (NIST) support SM initiatives (NIST, 2019; U.S. Department of Energy, 2019); the Manufacturing Extension Partnership (MEP) program is tailored in particular to the needs of SMMs. There are local initiatives, such as “LA made 4.0” that also promote digitalization (Garcetti, 2019).

The terms “smart manufacturing” and “industrial internet of things" (IIoT) are often used interchangeably for Industry 4.0 (Ezell, Atkinson, Kim, & Cho, 2018). However, some scholars point out that Industry 4.0 differs from SM in that it is wider in scope: Industry 4.0 focuses on implementing connected virtual and physical systems throughout the entire manufacturing ecosystem whereas SM focuses on integrating one part of the supply chain or value creation network (Vaidya et al., 2018). Indeed, there are hundreds of definitions for “Industry 4.0” or “smart manufacturing” available (Moeuf, Pellerin, Lamouri, Tamayo-Giraldo, & Barbaray, 2018) but there is no generally accepted definition (Kusiak, 2018). For the remainder of the text, we will use the term “smart manufacturing” and follow the definitions brought forward by NIST, the California Manufacturing Technology Consulting (CMTC), and the American Council for an Energy-Efficient Economy (ACEEE).

NIST defines SM systems as “fully-integrated, collaborative manufacturing systems that respond in real time to meet changing demands and conditions in the factory, in the supply network, and in customer needs” (NIST, 2018). In other words, SM is the practice of using information about the manufacturing processes when and where it is needed, and in the form that it is needed, by people and machines (Davis et al., 2015; MEP National Network, 2018). The American Council for an Energy-Efficient Economy states that SM is defined by the integration of all aspects of manufacturing through Information and Communication Technologies (Rogers, 2014). The goal is to optimize performance and data-driven, “smart” decision-making by providing actionable information (Gallaher, Oliver, Reith, & O’Connor, 2016; MEP National Network, 2018; Nimbalkar et al., 2017).

The goal of SM is to increase the amount of value-added services to generate more revenue and to improve productvity and efficiency within an agile network (Bechtold, Kern, Lauenstein, & Bernhofer, 2014). Applying SM technologies can potentially decrease the cost for production, energy, and water, the equipment down-time, and the environmental impact of the operation overall; and they can increase energy productivity, energy efficiency, production flexibility, and product quality (Gallaher et al., 2016; MEP National Network, 2018; Nimbalkar et al., 2019). As previously mentioned, the introduction of SM has been equated with the fourth industrial revolution and is commonly seen as a means for manufacturers to stay competitive in a global market (Brune, 2019; Manufacturing Policy Initiative, 2019; National Science & Technology Council, 2018)

SM addresses issues of low productivity and inefficiencies through cyber-physical systems that expedite the workflow; these systems also provide a wealth of information that can be used to make data-informed decisions on allocation of resources or customer needs (Huang, Talla Chicoma, & Huang, 2019; Kagermann et al., 2013; Xu et al., 2018). This data-informed approach can result in better training and development modules, and can increase motivation and opportunities for growth within the industry (Bhoganadam, Rao, & Rao, 2017).

Intelligent technology can help develop workers' skills through augmented reality and virtual reality training, assist in expediting tedious or cumbersome processes, and create safer work environments by informing employees of potential threats and minimizing injury risk (Kagermann et al., 2013). SM also has the potential to allocate resources more efficiently, resulting in higher financial returns (Kagermann et al., 2013; Müller & Däschle, 2018). The expansive amount of data provided by cyber-physical decision systems can then inform more efficient day-to-day operations in terms of machine maintenance and product quality control (Accenture, 2016; Joerges & Müller, 1983; Xu et al., 2018). Data gathered across the supply chain about customer needs and preferences can also be used to enhance marketing strategies (Müller & Däschle, 2018). Moreover, smart connected manufacturing processes function to reduce energy waste and ensure product quality.

Smart Manufacturing in Small and Medium Manufacturing Enterprises

Definitions about what constitutes a small to medium enterprise differ across countries and regions (Kushnir, Mirmulstein, & Ramalho, 2010), which is important to keep in mind when comparing across studies (Centre for Strategy & Evaluation Services, 2012). Internationally, "small" or "small and medium" enterprises are most commonly defined as having fewer than 250 employees (Kushnir et al., 2010; OECD, 2017). The European Union employs a threshold of fewer than 250 employees for medium enterprises and sets limits on annual turnover (value of invoices no more than 50 million Euro) or the balance-sheet total (net worth no more than 43 million Euro) (Centre for Strategy & Evaluation Services, 2012). In the US, the US Small Business Administration (SBA) uses varied size standards to qualify as small (U.S Small Business Administration, 2019). For most manufacturers, the threshold to qualify as a small business is 500 employees (note that the SBA does not define medium-sized businesses). Specific industries, such as tobacco manufacturing, carpet and rug mills, or sanitary paper product manufacturing, are defined as small with up to 1,500 employees. The National Association of

Manufacturers labels manufacturers with fewer than 50 employees as small, those with 50 to 499 employees as medium, and those with 500 or more employees as large. Some definitions focus solely on the annual revenue of a business to determine its size. For example, the "middle market" in manufacturing (i.e., neither a small nor a large business) can be defined by an annual revenue of between $10 million and $1 billion (National Center for The Middle Market, 2018); however, thresholds vary greatly, for example BDO (2019) uses a threshold of $200 million and $3 billion revenue to define middle market. Other definitions add the energy intensity of a manufacturer as a criterion for the size (Trombley, 2014). For the purpose of this review, we defined the size for SMMs by the number of employees: manufacturers with fewer than 500 employees are considered SMMs and those with 500 or more employees are considered large, unless indicated otherwise.

It is generally recognized that SMMs are working under different conditions and constraints than large manufacturers. Mittal et al. (2018) compare some defining features for SMMs and large manufacturers based on the literature (see Table 2 for selected features). Typically, SMMs face specific financial, technical, and organizational constraints that may hinder the adoption of SM practices. Indeed, large manufacturing companies worldwide have been in the process of adopting this SM approach and have reimagined their business models to capitalize on the benefits of executing this manufacturing framework; as a result, they have gained a competitive advantage in the globalized market by improving productivity and product quality, reducing costs, and adding data-based services (Erol et al., 2016; Kagermann et al., 2013; Xu et al., 2018). Those emerging smart technologies and the internet of things may also be able to benefit small and medium manufacturers (SMMs) with a tailored approach (Xu et al., 2018). However, there is a concern that SMMs are not able to leverage SM technologies to the same extent as large companies (Sommer, 2015): SM technologies are mostly made for large manufacturers by large corporations, making this technology less applicable and too expensive for SMMs (Radziwon, Bilberg, Bogers, & Madsen, 2014). There is a concern not just about the implementation cost of IoT technologies (Rogers, 2014), but also about the energy cost of operating these devices and networks (Dwyer & Bassa, 2018), even more so for SMMs. To get a comprehensive picture of how US SMMs perceive the benefits and challenges of SM, what the current status of adoption is, and whether these SMMs are willing and feel ready to adopt these technologies, we reviewed all national survey studies published on the topic. Where appropriate, we also used insights of international studies to highlight some issues and results that may also be relevant for the US and to guide further research in the US.

Table 2: Comparison of SMMs and Large Enterprises on Selected Features

Feature	SMMs	Large Enterprise
Financial Resources	Low	High
Use of advanced manufacturing technologies	Low	(Very) High
IT (software) integration (incl. data analytics)	Low (often tailored solutions)	High (with more standardized solutions)
Research & Development	Low	High
Standards consideration (e.g., ISO)	Low	High
Organization culture/ Leadership flexibility	Low	High
Company Strategy	Dictated by instinct of leader (owner)	Market research & accurate analyses
Decision Making	Restricted to leader/few knowledge carriers	Board of Advisors & (internal/external) consultants
Human Resources Engagement	Multiple domains ("Jack of all trades")	Specialized workforce
Alliances with Universities/ Research Institutions	Low	High

Source: adapted from Mittal et al. (2018, page 197)

Prior Studies Summary

Readiness to Implement Smart Manufacturing

The implementation of smart manufacturing (SM) technologies is a complex endeavor that depends on the technological, cultural, and organizational circumstances of a given SMM. SMMs need to fulfill certain basic technological requirements that allow them to embark on the SM journey. SM technology builds on the information and automation technologies from the 3rd industrial revolution (Kagermann et al., 2013); a computerized and networked environment sets the stage for the introduction of SM technologies (Schuh et al., 2020a; Schuh, Anderl, Gausemeier, Hompel, & Wahlster, 2017). The existing technology infrastructure affects how easy it is for a given company to connect their systems and use the generated data to the benefit of the whole operation. For example, companies require a reliable Wi-

Fi network before installing a system that uses Wi-Fi to communicate between machines and sensors on the shopfloor (Mittal et al., 2018). Knowing which technologies are currently prevalent in SMMs helps gauge the readiness of these SMMs for SM technologies.

In addition to the technological capabilities, SMMs also benefit from an organizational culture that is open to change and innovations, and need the human resources to tackle the transformation. SMMs need to be aware about the new technical possibilities and think that this approach is relevant to them. Also, to make the task less daunting it helps if they are aware of any programs that may help them with transitioning. Depending on their existing capabilities and knowledge, SMMs can feel more or less prepared to implement SM technologies.

SM “readiness” and “maturity” are both concepts that assess the technological and organizational status of an enterprise in multiple dimensions. Some experts keep these similar concepts apart by defining “readiness” as the starting point state prior to adopting SM and “maturity” as the enterprise’s developmental stage towards implementation of SM once adoption is underway (Schumacher, Erol, & Sihn, 2016). Stentoft, Wickstrom, Philipsen, and Haug (2020) describe the following dimension of Industry 4.0 readiness (adapted from an IT readiness scale introduced by Haug, Graungaard Pedersen, and Stentoft Arlbjørn (2011)):

- a perceived pressure to change processes;
- willingness to take risks with the new technologies;
- sufficient knowledge about the technologies,
- employees with the right competencies and the right motivation to work with the technologies and
- top management support in terms of financial support and attitude

There are numerous models that describe the process of how manufacturers transition through different maturity stages, however, they are mostly applicable to large, often multinational enterprises; maturity models reflecting the situations of SMMs still need to be developed (Mittal et al., 2018). Case studies are used to exemplify how maturity assessments can guide manufacturers through the implementation of a SM system (e.g., Schuh, Anderl, Dumitrescu, Krüger, & Hompel, 2020b)

The survey studies included in this review mostly addressed “awareness”, “preparedness”, and “readiness”, discussing whether SMMs have a plan to implement these technologies. They spoke less of the maturity level of SMMs.

Awareness, Preparedness/Readiness, and Plans To Implement

In a 2017 industry survey, most respondents (83%) said that that only some or very few people that they meet understand what the IIoT is and how it can be applied (Industry of Things World USA, 2017). An academic survey of 54 West Virginia manufacturers (70% of which were SMMs with up to 499 employees) showed that overall, the surveyed manufacturers had little awareness of SM (Wuest et al., 2017). While almost 60% said that they had heard the term, there was little knowledge about SM technologies and applications. From accompanying interviews, the authors concluded that smaller companies have less awareness about this topic and that even those companies that are interested in the topic are still in the early phases to transition to smart manufacturing. Less than one fifth said that their company was dealing with concepts like SM or the (Industrial) Internet of Things, however, 80% thought that these concepts were relevant. Rauch et al. (2019) found in their survey of 28 manufacturers that how many and which SM concepts mattered to manufacturers varied by size. For both small (10 to 49 employees) and medium (50 - 249 employees) manufacturers, four concepts out of 42 emerged as relevant. Small manufacturers think that for them, agile manufacturing systems, digital and connected workstations, continuous material flow models, and the cultural transformation matter most while medium enterprises find digital real-time monitoring systems, ERP/MES systems, an Industry 4.0 roadmap, and also digital and connected workstations relevant. By contrast, large enterprises (250 or more employees) saw eleven concepts as fairly to very important. This result, which was also replicated when asking experts from academia, indicates that SMMs find smart technologies less applicable for their operations than large enterprises. However, it reasonable to assume that both awareness, knowledge, and relevancy increased in the most recent years and especially during the Covid-19 pandemic, where digitalization in general was greatly accelerated (Lund et al., 2021).

Prior surveys also show reluctance to implement SM technologies. According to a US industry survey with a majority of medium-sized (50 to 250 employees) manufacturers represented in the sample, 77% said that they did not have plans to implement IoT technologies (Sikich, 2017). In this study, the top three priorities reported by manufacturers were addressing workforce challenges, cutting operational costs, and seeking new markets, while utilizing the industrial internet of things had the lowest priority. In the Industry of Things World USA (2017) survey, 32% said that they were already using or about to use IIoT technologies; of the remaining 68% only 5% said that they didn't have a clear sense of what IIoT is and why it is important, 20% were monitoring the development, and the rest was either evaluating the potential or already sensed a commitment and understanding among colleagues. In a more recent survey, Morton et al. (2020) were able to compare 2020 data to 2018 data. It showed that 84% are currently implementing or evaluating solutions (up 57 percent points from 2018), 5% were planning to start within the next one or two years (down 12 percent points), and only 12% said that they were not interested in implementing digital strategies (down 43 percent points). Note that this is not longitudinal data, but assuming that the samples were comparable, the results suggest a trend towards higher acceptance and adoption. However, more recent studies of SMMs still show a low degree of readiness and implementation in their samples (for example Stentoft et al., 2020; Yu & Schweisfurth, 2020).

Existing Technology Infrastructure

There is a common assumption that most SMMs tend to utilize and prefer simpler, more basic technologies (Nimbalkar et al., 2017). There are also regional differences, for example, Ingaldi and Ulewicz (2020) noted that the level of automation and robotization of SMMs in Poland is lower than in similar enterprises in other countries of the European Union. Most survey studies reviewed here did not provide a detailed assessment of specific existing technologies, however, a few studies mention classes of technologies used by SMMs. Morton et al. (2020) found in their mixed sample that 58% used enterprise resource planning software, 20% customer relationship management, another 20%

manufacturing execution systems, 17% an enterprise quality management software, and 15% said that they were using an IIoT platform (multiple choice possible, 19% replied with "other"). Internationally, a survey of 43 small-to-medium manufacturers in New Zealand showed that almost all companies use Information Technology (IT) services with their accounting and finances (90%) and with procurement and inventory management (83%) (Hamzeh, Zhong, & Xu, 2018). IT technology was used less often for networked control of the production equipment (38%) and for managing or decreasing energy consumption (21%). However, the study also did not explore what specific types of IT or other technologies were used by these SMMs.

SM practices and the associated technologies are not widely adopted yet, however, there is an upward trend visible if comparing older and newer survey studies. In a 2018 survey repeated in 2020, the percentages of companies that described themselves as fully or mostly digital went from 26% to 41%, and only 16% described themselves as paper intensive (vs. 21% in 2018); the remainder are moving towards digitization (Morton et al., 2020). The 2017 West Virginia Study showed that only 14% of the respondents had adopted SM practices in their operations (Wuest et al., 2017). Similarly, 14% indicated in the Industry of Things World USA (2017) survey that their company is advanced in terms of applying the Internet of Things to both their business and manufacturing operations. The rest either already had islands of connectivity and collected data on key operations (40%), were on the way to adopting these technologies (21%), or were still getting informed (21%). Of those that were applying SM systems, 29% each were applying SM technologies either on the machine level or on enterprise/supply chain levels, 21% on the plant level and 17% percent used these systems integrated across all level. The percentages do not only depend on the time of the survey, but also on the sample. For example, 64% of the respondents of the Advanced Manufacturing Media (2015) survey said they were using advanced manufacturing equipment, 62% said they were using advanced software, 55% used advanced sensing, measurement, and process control, and 54% industrial robotics – all of which is comparatively high and likely not representative. Interestingly, Bosman et al. (2020) found that SMMs with less than 20 employees and/or less sales are prioritizing the implementation of digital technologies that impact directly the manufacturing process on the factory floor whereas larger SMMs prioritize enterprise support operations technologies .

The (pre-pandemic) preference for simpler and more basic technologies by SMMs is corroborated by case study findings. A recent paper analyzed the level of sophistication of SM energy efficiency measures that were implemented in SMMs between 2000 and 2016 through the US Department of Energy's Industrial Assessment Centers (Nimbalkar et al., 2017). Most of the implemented technologies employed simple controls or sensor-based control systems; "smarter solutions" using controls with communication systems and linking the information with other data to allow for optimal decision making were rare. Similarly, Moeuf et al. (2018) reviewed 23 case studies published in academic papers which focused on SM to improve inefficiencies in energy consumption and workflow. The review found that the SMMs under consideration used less-expensive and more established SM technologies, whereas more costly and revolutionary technologies were not reported as being utilized. Research is lacking regarding implementation of fully autonomous processes that offer self-organization and selfdiagnosis within SMMs. Indeed, there are questions about whether SMMs would benefit from more complex technologies, such as collaborative robotics, the same way as a large manufacturer would (Moeuf et al., 2018). The preference for more basic technologies and more established applications can be tied back primarily to the lack of technological expertise and funding of such complex endeavors in SMMs (Moeuf et al., 2018; Rauch, Dallasega, & Matt, 2017). However, higher-level smart technologies may have the potential to increase energy savings and avoid the degradation of these savings (Nimbalkar et al., 2017; Rogers, Elliott, Kwatra, Trombley, & Nadadur, 2013).

Drivers for Adoption

SMMs can experience multiple benefits to adopting a SM approach, including a reduction in environmental and energy waste, additional value-added services based on real-time data, and improved connectedness (Grube et al., 2017; Müller & Däschle, 2018; Vaidya et al., 2018); expected benefits drive the adoption of innovative technologies. Two studies addressed the relative weight of these factors using regression models, and concluded that drivers exert an even stronger influence on SM adoption than barriers (Arnold & Voigt, 2019; Stentoft et al., 2020).

The perception that SM adds value helps drive adoption (Wuest et al., 2017); a more positive attitude towards SM leads to greater perceived benefits (Masood & Sonntag, 2020). Consistent with that notion, in a few recent studies the authors found that the knowledge about technology and the expected benefit of the new technology was significantly associated with the implementation of SM technologies (Arnold & Voigt, 2019; Yu & Schweisfurth, 2020; Zheng, Ardolino, Bacchetti, Perona, & Zanardini, 2020). Support from top management showed a significant positive effect on the decision to adopt SM (Arnold & Voigt, 2019). A long-term strategy to adopt a SM approach that is driven by customer requirements, the desire for cost reduction, the need to improve time-to-market, and by competitors adopting SM can also set the stage for the transition to smart technologies (Stentoft, Jensen, Philipsen, & Haug, 2019; Trianni et al., 2016). External/public advisors (such as the Manufacturing Extension Partnership National Network) also play a role to drive the advancement of new technologies (NIST, 2019; Stentoft et al., 2019; Trianni et al., 2016).

Other previous surveys showed that lowering production cost acts as a driver for about half of the respondents (Morton et al., 2020; Sikich, 2017). Survey respondents hoped to improve on-time delivery (chosen by 51% of the respondents), reduce quality risks (47%), increase manufacturing capacity (45%), improve visibility into production (40%), and predict machine or tool failure (39%) (Morton et al., 2020). Also, respondents want to solve issues between multiple business systems (Sikich, 2017) and increase supply chain collaboration (Morton et al., 2020). Moreover, SMMs may want to improve customer service. Improving service and response time was the top driver in one survey, surpassing the wish to reduce cost (Sikich, 2017).

Barriers for Adoption

Top Management Support and Mindset

Several barriers hinder SMMs from adopting SM technologies. First and foremost, SMMs need to be willing to consider SM technologies for their operation. Thus, a mind-set that does not embrace new technologies acts as a major barrier (Wuest et al., 2017), especially at the beginning of the transformation into a “smarter” enterprise (Mittal et al., 2018). Morton et al. (2020) found that 29% of their respondents said that the lack of management buy-in and support acts as a major hurdle to pursuing digital transformation. Similarly, in the Industry of Things report, about one quarter of respondents said that resistance from management was a challenge for implementing SM in their company (Industry of Things World USA, 2017). SMMs often lack long term strategies for investments, production, and equipment decisions, and are still using manual processes for planning and operations (Grube et al., 2017). Many SMMs require all their available labor time just to maintain day-to-day operations and other imminent tasks, and cannot focus on long-term strategy and company development (Stentoft et al., 2019; Türkeș et al., 2019; Wuest et al., 2017). This makes top management support and a mindset that embraces innovations even more crucial.

Financial Considerations

Cost emerges as one of the main challenges in several studies (Advanced Manufacturing Media, 2015; Masood & Sonntag, 2020; Morton et al., 2020; Wuest et al., 2017). Without a clear business case to introduce SM technologies and an uncertain return of investment (Morton et al., 2020), financially strapped SMMs are unlikely to take the risk of implementing new technologies. The West Virginia SM study pointed out that for those manufacturers who have decided to embark on the SM journey, the initial cost of these new technologies is the main barrier (Wuest et al., 2017). In the survey by Advanced Manufacturing Media (2015), the lack of funding was mentioned by 52% of the respondents as a main reason for withholding investments in SM, and 36% mentioned an insufficient return on investment. The study showed that 26% of the surveyed small manufacturers (defined as fewer than 50 employees) were not allocating any funds at all towards SM capabilities for the next two years. About half of small manufacturers planned on spending less than $300,000 and about another quarter planned to spend $300,000 or more. Medium-sized manufacturers planned to invest more. Only 4% of the medium-sized manufacturers (defined as 50 to 499 employees) said that they had not allocated any funds to expand their advanced manufacturing capabilities, a third of them were planning to spend less than $300,000, and 63% were planning to spend more than that. By contrast, only 1% of the large manufacturers said that they did not allocate any funds; almost 75% allocated more than $100,000 for SM, and almost one-quarter allocated $5 million or more. This finding highlights the financial constraints of SMMs relative to larger firms, and the need for low-cost solutions for these manufacturers.

Surveys conducted in Europe (Sevinç, Gür, & Eren, 2018), New Zealand (Hamzeh et al., 2018), and South America (Huang et al., 2019) identify one specific cost restricting adoption of smart technology for manufacturers in general and SMMs especially: the substantial financial investment necessary to implement cyber-physical systems.

Time and Personnel Resources

Another significant barrier is the amount of time it takes to research, select, implement, and maintain smart solutions (Hamzeh et al., 2018). Three quarters of all US SMMs employ fewer than 20 people; many SMMs lack the capacity to tackle the process of digitalization of their operations. SMMs often do not employ sufficient personnel with the skills or training needed to use these technologies (Hamzeh et al., 2018; Wuest et al., 2017); the lack of human resources is the most-cited barrier in the study by Morton et al. (2020), mentioned by 47% of the respondents, surpassing even high costs as a hurdle. The complexity of technology and anticipated technical problems can be off-putting for SMMs that lack specialized personnel to support the implementation and maintenance of smart infrastructure (Swamidass, 2003). Indeed, 32% of the respondents in the Advanced Manufacturing Media Survey (2015) mentioned a lack of technical skills as a barrier to invest in smart technologies. According to a recent study, companies have problems to find employees with the right competences to implement SM (Bosman et al., 2020). Most companies do not have dedicated financial and/or human resources to help with the transition, highlighting the needs for programs to support SMMs (Wuest et al., 2017).

Other Barriers

There are many more barriers that apply to both large and small manufacturers. These include data security concerns (Accenture, 2016) and cyber security risks (Morton et al., 2020; Sikich, 2017), the lack of common standards and protocols (Gallaher et al., 2016), interoperability issues between systems (BDO, 2019), and the potential complexity of system generation (Morton et al., 2020). In some cases, SMMs may not have access to the necessary infrastructure for digitalization (Industry of Things World USA, 2017). Other considerations are the stress that workers may experience from the connected technology (Körner et al., 2019; Oh & Park, 2016), and fears of employee pushback or resistance (BDO, 2019; Industry of Things World USA, 2017). However, as outlined above, compared to large manufacturers, SMMs encounter more challenges to introduce any technological and organizational innovations (Swamidass, 2003), including not only SM technologies, but related energy efficiency and information technologies.

Implications

The review of the current literature revealed important insights about smart manufacturing (SM) concepts and what issues SMMs face transitioning to an SM framework. Unfortunately, there is relatively little empirical research specifically for US SMMs that addresses the main issues that emerge: the uptake of SM technologies in those enterprises, the needs SM might address in SMMs, and the drivers toward versus barriers against adopting SM. In the US, most surveys have been conducted by consulting firms or interest groups, but these focus on larger and already engaged manufacturers (see for example Accenture, 2016; BSquare, 2017; Industry of Things World USA, 2017; Lorenz, Küpper, Rüßmann, Heidemann, & Bause, 2016); when they include smaller manufacturers, results are rarely presented stratified by enterprise size (see for example Advanced Manufacturing Media, 2015; Sikich, 2017). The US Manufacturing Energy Consumption Survey (MECS) is representative of the population, but it excludes manufacturers that have fewer than five employees; also, it focuses on energy efficiency technologies, not explicitly SM technologies (U.S. Energy Information Administration, 2002, 2014).

Academic research about SM implementation and barriers specifically in SMMs have been conducted in countries as diverse as Denmark (Stentoft et al., 2020), New Zealand (Hamzeh et al., 2018), Peru (Huang et al., 2019), Turkey (Sarı, Güleş, & Yiğitol, 2020; Sevinç et al., 2018), and Romania (Türkeș et al., 2019). Findings from these studies are consistent with expectations about barriers for smaller manufacturers. However, difference across countries in policy, law, and economics necessarily limits the conclusions that can be drawn for SMMs in the US. In the US one academic research project addressed the state of SM in West Virginia by surveying 54 manufacturers; the study results are consistent with previously described barriers, but it is not clear how the results generalize to a larger or different area of the US.

In sum, there are significant gaps and weaknesses in the research assessing the state of SM for SMMs across the US. Specifically, more work is needed that addresses:

- which SM technologies and connected strategies are already being used,
- how prepared SMMs are to adopt these technologies,
- which specific barriers SMMs encounter to introduce this technology,
- what desired benefits do SMMs want from SM,
- which of these technologies are perceived to be the most promising to increase efficiency given the special constraints and needs of SMMs.

The results from this literature review were used to design a survey that addressed these gaps. The survey data can be used to inform the development of technological solutions that are affordable and easily adaptable for SMMs.

METHODS

To get a comprehensive picture of how US SMMs perceive the benefits and challenges of smart manufacturing (SM), what the status of adoption is, and whether these SMMs are willing and feel ready to adopt these technologies, we first reviewed the questions and results of the prior surveys identified in the literature review to build upon. We then designed a survey based on key questions from prior surveys that replicated exact wording whenever appropriate.[2] In addition, we consulted with experts to construct a list of twenty specific SM technologies and designed questions to assess how they have been used or could be used in SMMs. To manage survey length, after the key questions were asked, subjects were thanked for completing the main survey and asked if they would be willing to answer some more questions.

One version of the question set was designed to capture the experiences and opinions of SMM owners and employees. A second version rephrased the questions to apply to consultants who work with multiple SMMs, either within the Manufacturing Extension Program (MEP) or independently. Questions were kept as similar as possible across the two versions, but the response options are necessarily different. Individual representatives of companies are reporting on whether something is true for their current company, whereas consultants are asked to think about all the SMMs they have worked with in the past two months. Thus, consultant questions were generally reframed to ask what proportion of those companies had a particular experience. For many questions there was no way to construct perfectly comparable response options, but some comparison is still possible.

All questions allow for “don’t know” and “prefer not to answer” responses to avoid forcing uninformed guesses. For the rare questions where more than a few subjects chose these responses, that is considered a finding and is discussed; otherwise they are omitted from analyses of that question and only the “valid” responses are included.

Subjects were recruited via the national MEP network between November 2020 and March 2021. The recruitment plan involved sending recruitment materials to regional MEP Center leaders across the country who were asked to include them in regular email newsletters. However, monitoring revealed that few of these networks actually sent regular email newsletters, and few of those that did complied with requests to include recruitment announcements despite repeated requests from MEP representatives. As a result, sample size was substantially smaller than expected, and heavily skewed toward California subjects, as the California MEP director assisted with recruitment efforts and effectively conveyed messages to California MEP members. The survey was conducted online on the Qualtrics survey platform. As an incentive, subjects were offered the chance to win one of three randomly selected lottery prizes: Visa gift cards worth $500, $300, and $200. Subjects were deemed eligible if they were 18 or older and owned, worked for, or were a consultant for SMMs. Statistical analyses were conducted using SAS 9.4.

[2] Survey instrument is available upon request.

RESULTS

Subject Characteristics

A total of 102 subjects completed the main questions, including 48 consultants (CON) and 54 individual owners and employees of SMMs (IND). Unless otherwise noted, demographics and other results refer to these 102 subjects. Of these, 32 CON subjects and 42 IND subjects continued on to answer all of the supplemental questions.

IND subjects are younger than representative samples of working adults, largely due to the presence of younger production workers. Of the 54 IND subjects, 48% are 25 to 34 years old, compared to 11-15% each in the categories of 18-24, 35-44, 45-54, and 55-64. By contrast, only 29% of CON subjects are 25 to 34, with almost as many in the 35 to 44 (27%) and 45 to 54 (21%) ranges.

IND subjects identified their current position in the company, which was collapsed into four categories to facilitate analyses. Management (n = 19; 35%) includes “owner”, “upper manager (president, CEO, VP)”, and “middle manager (supervise people and processes)”. Administrative (n = 7; 13%) includes “administrative worker (purchasing, marketing, clerical).” Expert (n = 14; 26%) includes “technical expert (engineer, scientist, IT, or R&D)” and “operations manager (manage facility, machines, operators).” Worker (n = 14; 26%) includes “production worker (operate machines, assemble product).” Given how few administrative workers were captured in the sample, they are not included in separate employment category analyses, although their answers are included in overall results. The rationale of the grouping was to separate management, who would presumably know more about executive decisions, major investments, and costs, from production workers, who would presumably know more about what technology is actually used (or needed) on the factory floor. Technical experts and operations managers offer a useful midline view, presumably knowing more about the technology being employed across the range of workers and manufacturing processes than either management or workers. Finally, employees in administrative positions may range widely in knowledge of the company’s operations and products, but are unlikely to have either the big picture view of management or the technical understanding of the experts and workers. Of course, assumptions about knowledge areas and expertise may not apply equally to all members of these groups, particularly given the small and nonrepresentative sample. As explained in the methods section, almost half (48%) of subjects are from California. The other subjects are scattered across 21 other states, with only one or two subjects from each state.

Manufacturing companies were defined as being “small to medium” if they had fewer than 500 employees. Of the individual companies represented by this sample, 17% have 1 to 19 employees, 57% have 20 to 99, and 26% have 100 to 499. Although only one IND subject gave a “don’t know” response for this question, CON subjects did not estimate a size for 14% of the companies they work with, on average. Of the valid responses, on average more CON companies are small than for IND subjects, with 32% having up to 19 employees, 43% having 20 to 99, and 25% having 100 to 499.

Industry type categories were drawn from the North American Industry Classification System (Office of Management and Budget, 2017); subjects vary widely across these types. For IND subjects, the largest groups are food manufacturing, with 10 subjects (19%), and textile and textile product mills (15%). Fifteen other categories include one to five subjects each, with the larger including apparel manufacturing, leather and allied products, wood products, fabricated metal products, and computer and electronic products. CON subjects were asked for up to three type of SMMs they had worked most with in the previous two years, resulting in higher percentages for any given industry type. Again, food manufacturing was mentioned most often (25%), followed by apparel manufacturing (19%) and fabricated metal products (17%).

Readiness to Implement Smart Manufacturing

One major question in this study, as with other studies of SMMs, is how prepared companies are to implement smart manufacturing (SM) solutions and the extent to which they have already adopted some measures. One measure of readiness uses seven items based on the Industry 4.0 Readiness Index (Stentoft et al., 2020) (see Table 3). The items were slightly modified to correspond to the rest of our survey. The question for IND subjects used a five-level Likert scale from strongly agree to strongly disagree (coded so that higher numbers indicate higher agreement). Results for IND subjects show a mean of 3.8 (s.d., 0.7), just below "somewhat agree." Average responses were similar across items. There were no differences in readiness score across employment categories. This level of perceived readiness is higher than the scale mean of 2.95 (s.d., 0.7) reported in the previous study (Stentoft et al., 2020). Additional readiness items are also shown in Table 3, and show similarly high perceptions of management's understanding of and willingness to implement SM technology. There was somewhat lower agreement that the company was already using that technology, however.

Table 3. Mean for Readiness Index and Individual Measures

	IND		CON	
	Mean[1]	s.d.	Mean[2]	s.d.
Readiness Index	3.82	0.77	2.72	0.90
Management pressured to work with SM	3.70	1.01	2.77	1.20
Management willing to take risks to experiment	3.87	1.03	2.72	1.09
Management has necessary knowledge about SM	3.91	1.10	2.67	1.15
Company has support from top management	3.98	1.08	2.70	1.13
Employees have right competencies	3.79	1.12	2.56	0.97
Employees have right motivation	3.74	1.01	2.91	1.14
Company has economic freedom	3.72	1.13	2.68	1.14
Management has clear concept of technology	3.81	0.98	2.78	1.21
Management has clear concept of potential	4.00	0.84	2.70	1.09
Management willing to implement near future	3.98	0.91	2.70	1.06
Company already using SM	3.61	1.19	2.70	1.09
N	53		44	

1 IND response options range from 1 "strongly disagree" to 5 "strongly agree" it is true for your company.
2 CON response options range from 1 "none" to 5 "all" for how many consulted companies this is true for.

Consultants were asked how many of the companies they worked with these statements were true for, with the response options of none, a few, about half, most, or all. The average readiness index across their companies is 2.72, or almost "about half." To compare this to the IND answers, we first posited that IND subjects' response of "somewhat agree" or "agree" for their company was the equivalent of "true" for each of the CON subjects' multiple client companies. Then IND subjects were divided based on whether their readiness index score was 4.0 or higher (averaging at least "somewhat agree" to the seven items) versus lower. Almost half (47%) of IND subjects met that criteria, indicating that the CON and IND subjects' average readiness scores are similar.

Two other measures of readiness level include a question on how prepared the company is to introduce new technologies, and whether the existing employees have sufficient skills to adapt to SM. Subjects report a wide range of preparation levels for their companies (see Table 4). Among IND subjects, about one in three (33%) say the company has a clear business case, with another third reporting that their companies are more prepared than this and about one in four reporting their companies are less prepared. The variation across employment categories is not statistically significant, although it is notable that managers appear more likely than other groups to report the extremes, both of being fully implemented and being not prepared. CON subjects range from reporting most of their consulted companies at early stages to most in higher stages of preparation; the averages are shown in Table 4. On average, CON subjects report lower levels of preparedness for SM than IND.

Table 4. Preparation Level

	IND				CON	Valid only	
	All	Manager	Expert	Worker		IND	CON
Full concept in implementation	15%	21%	7%	7%	12%	16%	17%
Implemented first measures	19%	5%	29%	36%	14%	20%	18%
Developed clear business case	33%	26%	29%	36%	14%	36%	18%
Developed first concepts	15%	11%	29%	14%	18%	16%	23%
Not prepared	11%	21%	7%	0%	18%	12%	24%
Don't know	6%	11%	0%	7%	15%		
Prefer not to answer	2%	5%	0%	0%	9%		
N	54*	19	14	14	48	50*	35

** Total includes administrative category.*
Question: IND "How prepared is your company to introduce new technologies for smart manufacturing?"
CON, same wording, but prompted to give the percentage of companies they work with that are at each level.

Compared to other questions, a relatively large minority of subjects say they don't know or choose not to answer, which is especially surprising among the manager category for INDs (16%) and even more pronounced for CONs (24%). Comparing only those subjects with valid responses, IND and CON results are more similar, although consultants still report more companies in the lowest levels of preparedness.

Both IND and CON subjects report higher preparation level than a prior study using this question, although the sample there differed. A study of larger US and German manufacturers (annual revenue of more than 50 million) by the Boston Consulting Group (Lorenz et al., 2016) showed that about 5 years ago, only 3% of the sampled US manufacturers had the full Industry 4.0 concept in implementation and 41% identified their company as not yet prepared. The largest share (29%) had developed first concepts.

A frequent worry is that the skillset needed for SM cannot be met with the existing workforce. As shown in Table 5, few subjects believe their company's existing employees have the skills needed to adapt to SM technology. The majority of IND subjects (63%) think their company's workers could adapt if given a little training, but one in four believe the company would need to hire new workers. These perceptions are quite similar across employment categories. About one in four CON subjects (27%) gave a "don't know" or "prefer not to answer" response to this question, suggesting that consultants may not be as familiar with this important element of SM readiness as perhaps they should be. Among those who gave a valid answer, on average they reported more companies having employees with necessary skills than IND subjects, although an equally high number who would need to hire new employees.

Table 5. Skill Level of Workers

	IND				CON
	All	Manager	Expert	Worker	
Existing employees have enough skills to adapt to new technology	11%	11%	7%	14%	33%
Existing employees could adapt to new technology with a little training	63%	63%	57%	64%	37%
Existing employees would find it significantly difficult to adapt to new technology, so there would be a need to hire new people	26%	26%	36%	21%	30%
N	54*	19	14	14	35

** Total includes administrative category.*
Question: IND, "What best describes the skill level of the workers in your company?" CON, same wording, but prompted to give the percentage of companies they work with that are at each level.

Another aspect of readiness is the extent to which the company is already using digital processes. This question was asked in the supplementary section and thus has a smaller subsample size. Among IND subjects, only 11% called their companies paper intensive and 36% describe them as fully digital and automated. A trend is observed in which managers believe their companies are less digitalized than experts and workers, although these differences are not statistically significant. CON subjects report more companies as paper intensive and fewer as fully digitized than IND subjects.

As with previous questions, this study's subjects report higher rates of digitization than a previous survey using the same question. Morton et al. (2020) report the results for this question from a 2018 and 2020 survey conducted with a mix of small, medium, and large manufacturers. In 2018, 21% of the surveyed manufacturers called themselves paper intensive, while in the 2020 sample the share had decreased to 16% (note that this was not a longitudinal study and thus the proportions are not directly comparable). The proportion claiming to be fully digital did not increase greatly from 2018 to 2020 (from 2% to 6%) but the proportion who said they were mostly digital increased from 24% to 35%.

Table 6. Digitization Level of Company

	IND				CON	
Level	All	Manager	Expert	Worker	All	Valid only
Paper intensive	11%	13%	17%	8%	24%	29%
Moving toward digitization	33%	47%	25%	25%	27%	32%
Mostly digital	16%	13%	8%	8%	16%	18%
Fully digital and automated	36%	20%	50%	58%	17%	20%
Don't know	4%	7%	0%	0%	7%	
No answer	0%	0%	0%	0%	10%	
N	45*	15	12	12	35	28

** Total includes administrative category.*
Question: Ind, "Which of the following best describes your company's digitization level?" CON, same wording, but prompted to give the percentage of companies they work with that are at each level.

Problems that Smart Manufacturing Could Solve

A related question is the extent to which companies have sufficient incentive to upgrade to smart technologies for any specific tasks or processes. Lower-tech approaches can be effective, especially at the smaller scale of SMMs. If companies are not experiencing productivity problems that would be noticeably improved by new technology, the investment of time and money would not be worth it.

Subjects were asked whether they thought smart technology would help with specific tasks or whether they thought that traditional, lower-tech solutions, such as paperwork on clipboards, would work equally fine. The tasks are listed Figure 2 for IND subjects, and the same order in Figure 3 for CON subjects. Results are fairly similar across IND and CON subjects. Both groups reported smart solutions already being used for specific tasks in about 20% to 35% companies, although there is a slight trend for CON subjects to report higher rates of current usage (e.g., for timesheets, managing stock, and communicating with third parties). The top three tasks most IND subjects thought would benefit from SM are analyzing data (60%), accessing job and/or task information (54%), and managing stock (50%). The top three tasks CON subjects thought would benefit also include analyzing data (50%), along with accessing data (53%) and inputting information into forms (53%); inputting information onto forms (48%) is a close fourth place. Another way to approach this question is which tasks subjects think work fine with lower-tech solutions. For IND subjects, the top three are assigning jobs and tasks (43%), communicating with third parties (41%) and internal communication (35%), suggesting a preference for direct interpersonal communication rather than mediated methods. Two of these are the same for CON subjects, whose top three are internal communication (38%), assigning jobs and tasks (34%) and analyzing data (33%). That last result is surprising, given that analyzing data is also seen as most likely to benefit from smart solutions; it is possible that subjects are picturing different types of analyses that lend themselves to varied methods, such as computer-based statistics versus on-the-spot personal diagnoses of problems.

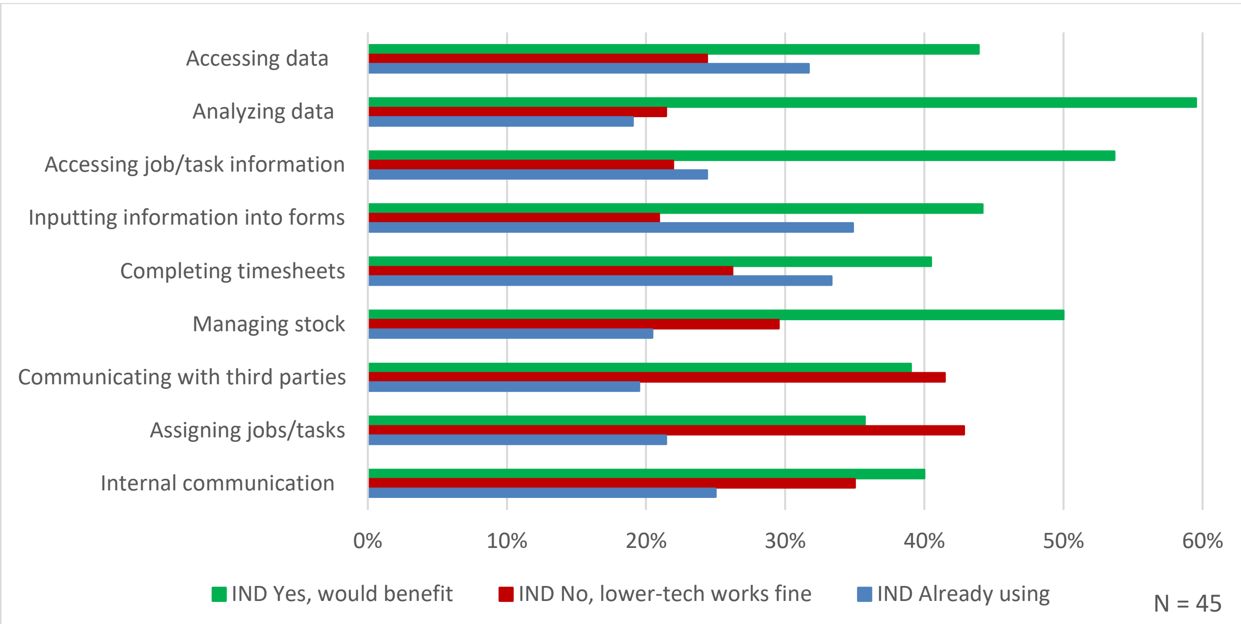


Figure 2. Tasks that Could Benefit from Smart Manufacturing Solutions, Individual Subjects

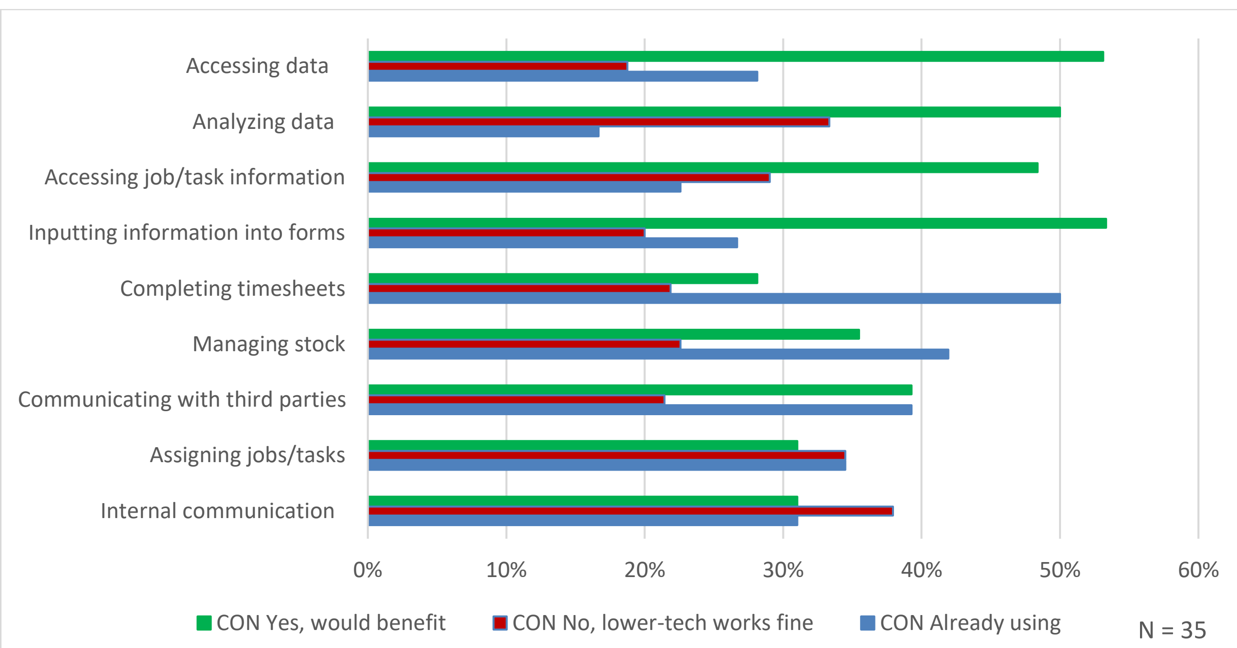


Figure 3. Tasks that Could Benefit from Smart Manufacturing Solutions, Consultant Subjects

The productivity problems that a company faces provide a key incentive to adopting new solutions for those tasks or issues. One way of looking at productivity problems that might be solved with new technology is to assess where inefficient outcomes are observed in the production process. Based on the productivity ("waste") problems identified in lean management (Caldera, Desha, & Dawes, 2019), subjects were asked which waste stream issues have the strongest negative impact on productivity for their company (or for CON subjects, for the companies they have worked with in the past two years). They were allowed to select up to three. Among IND subjects, 9% said they didn't know or chose to give no answer. Of those who gave valid answers, one said "none", 37% marked one issue, 10% marked two, and 51% marked the maximum of three. Likewise, among CON subjects who gave valid answers, 64% marked the maximum of three waste stream issues, 9% gave two, 25% gave one, and one person said none. Results were fairly similar across IND and CON subjects, although CON subjects reported more issues overall (and thus generally higher rates for each one), except for non-utilization of talent (e.g., trained workers doing less-skilled tasks), which IND subjects were somewhat more concerned about.

Results are shown in Figure 4. As subjects could choose up to three options, the percentages add up to more than 100%. Lack of training (e.g., delays while waiting for skilled worker) was cited most frequently by both IND (37%) and CON (42%) subjects, and substantially more often than the next-highest ranked for both groups. The next top three for IND subjects are non-utilized talent (26%), delays while waiting for earlier processes to complete (22%), and losing batches due to defects (20%). For CON, the next top three also include waiting (27%) and defects (27%), along with waste due to overproduction (e.g., machines cooling product longer than necessary) (25%).

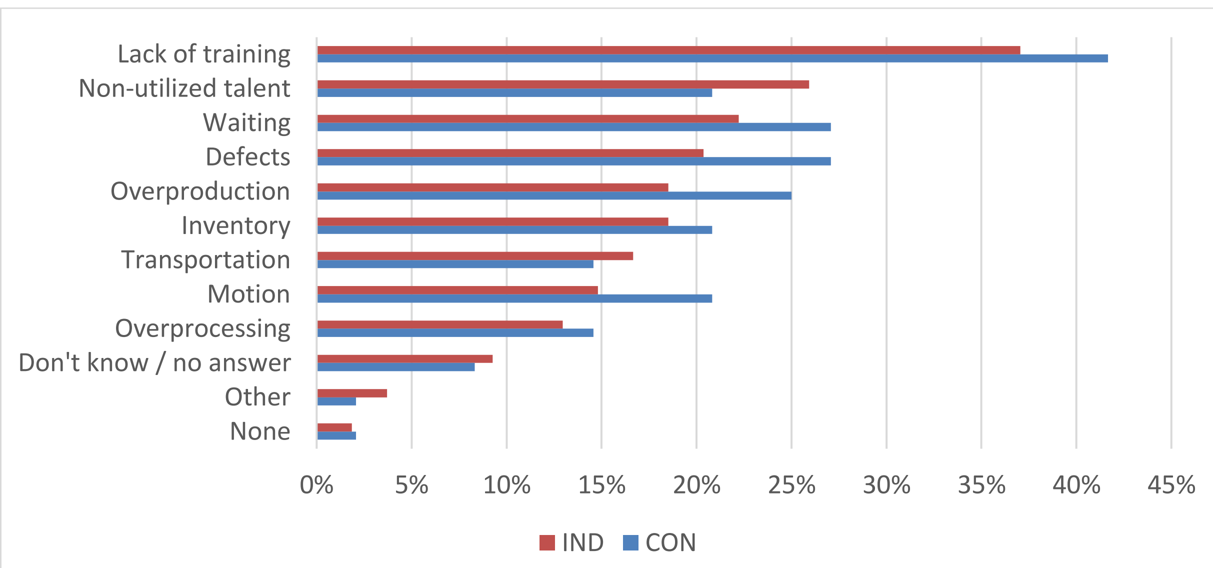
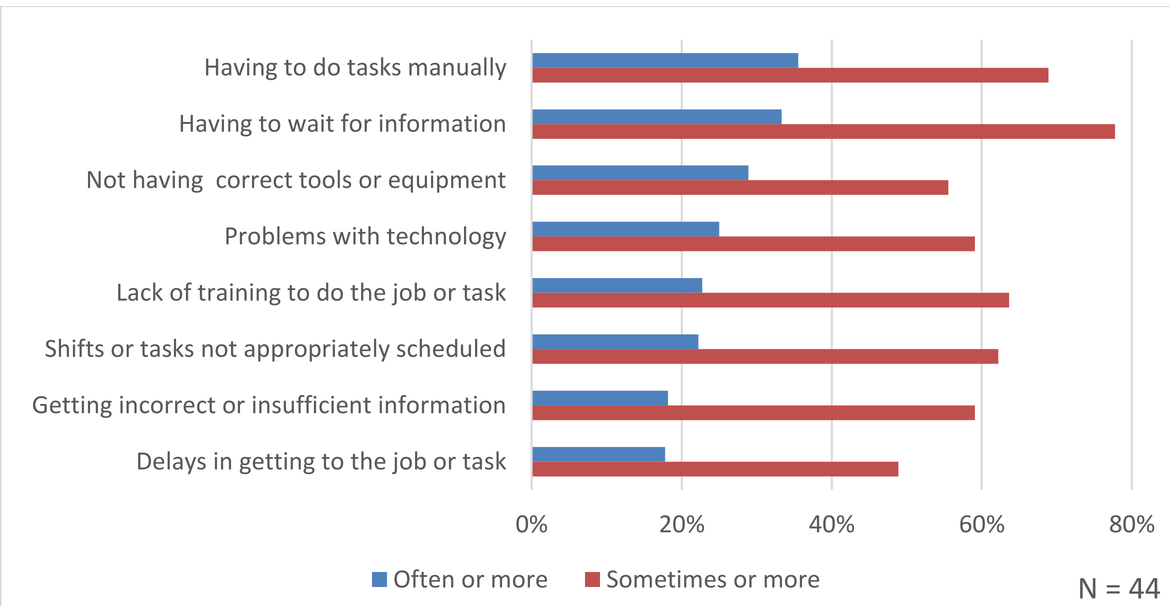


Figure 4. Waste Stream Issues with the Strongest Negative Impact on Productivity

Subjects were asked in the supplementary part of the survey about whether SMMs faced "significant productivity issues" due to a list of problems with how tasks are done, such as sharing information or using tools (see Question, IND: How often does your company face significant productivity issues due to the following problems?

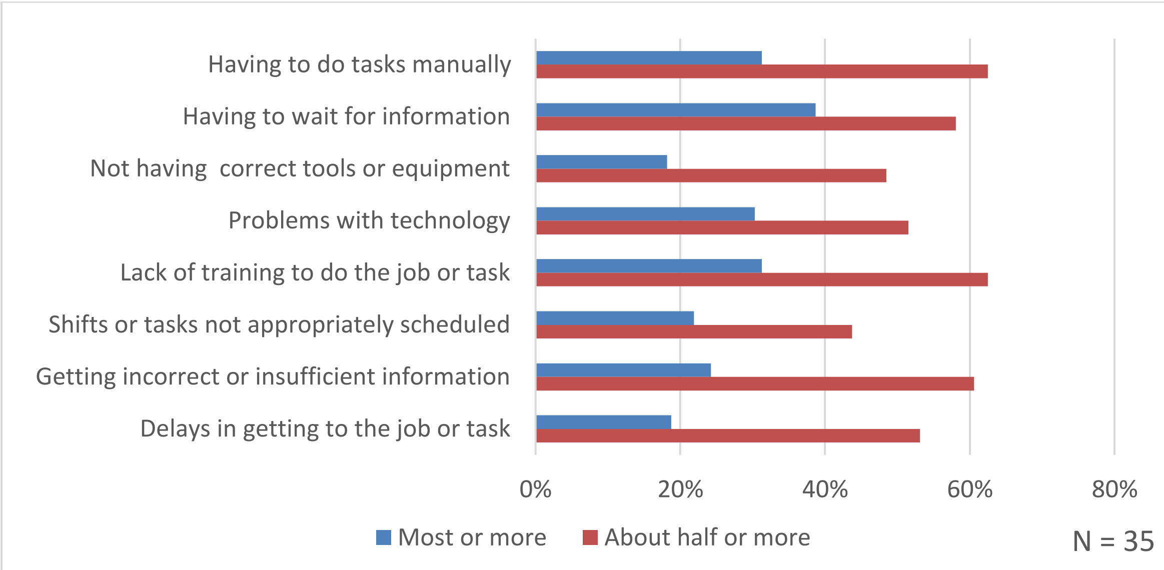
Figure 5 for IND and Question, CON: How many of these SMMs face significant productivity issues due to the following problems?

Figure 6 for CON). Response options for IND were always, often, sometimes, rarely, and never. For ease of analyses, these were collapsed into two binary variables, one comparing “always or often” versus less frequent and one comparing “always, often, or sometimes” versus less frequent. Response options for CON were all, most, about half, a few, and none. These were likewise collapsed into two variables, for “most or more” and “about half or more.” The tasks listed here were at least sometimes a problem for 49% to 78% percent of IND subjects, and often or always a problem for 18% to 36%. Having to do tasks manually (e.g., on paper) and having to wait for information needed for the job or task were reported most frequently as problematic. The tasks are shown in the same order for the CON subjects, for ease of comparison. Overall, the productivity issues that CON subjects reported more SMMs having roughly corresponds to the frequency with which IND subjects reported having the same productivity problems; having to do tasks manually and having to wait for information were again the top two issues.



Question, IND: How often does your company face significant productivity issues due to the following problems?

Figure 5. Productivity Problems Reported by Individual Subjects



Question, CON: How many of these SMMs face significant productivity issues due to the following problems?

Figure 6. Productivity Problems Reported by Consultant Subjects

Perceived Drivers and Barriers

One driver for adopting SM is the perceived benefits. Subjects were offered ten potential drivers and asked what they saw as the most critical factors driving their company (or for CON subjects, the SMMs they work with) to implement smart technologies. They were allowed to select up to three, and could write their own answers into an "other" category. Subjects who chose more than one driver were then asked to narrow down the top-most factor. Three IND subjects and four CON subjects marked no drivers, while 48% of IND subjects and 46% of CON subjects chose the maximum of three.

Results are shown in Figure 7 for IND subjects and Figure 8 for CON subjects, sorted by the topmost driver reported. The most frequently cited of these drivers for both IND and CON was to reduce costs. It is notable that having a conscious strategy about SM was mentioned frequently by both groups in their top three – second-most for IND (33%) and third-most for CON (29%) – it was the second topmost driver for IND subjects (15%) and the lowest rated topmost driver by CON subjects (2%). Customer requirements and competitors who practice SM were also major drivers for both IND and CON subjects, while consultants were more likely to mention the influence of consultants as being an important driver for SMMs.

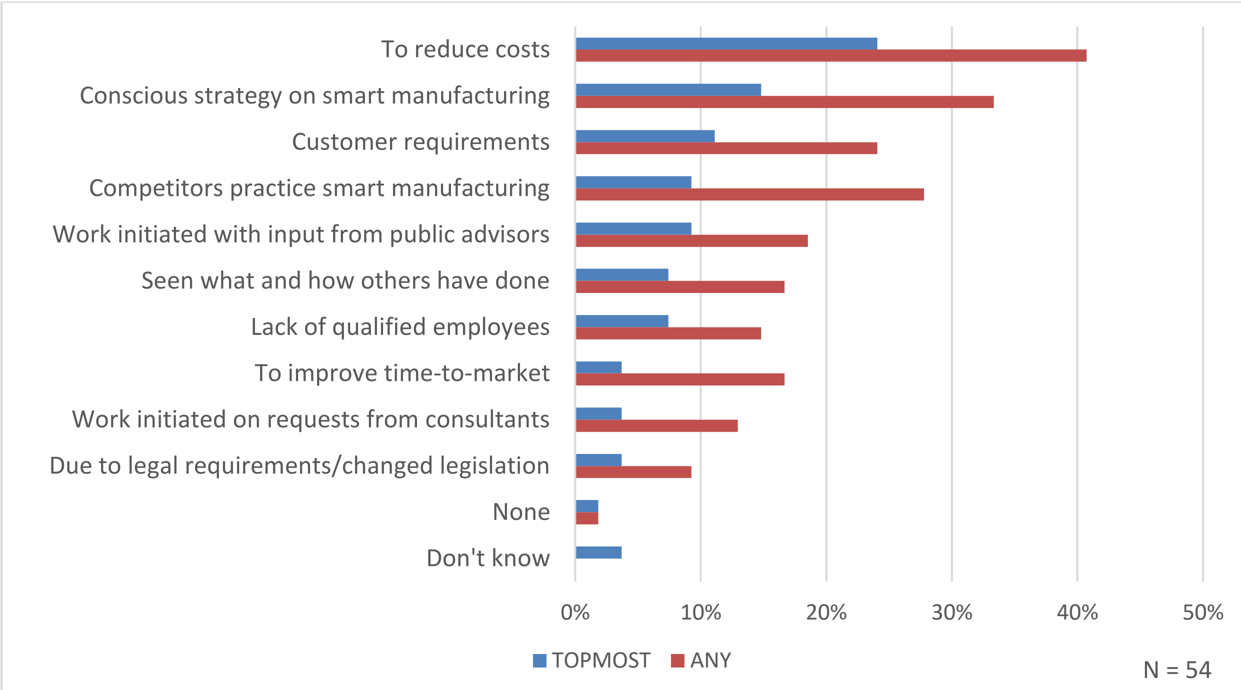


Figure 7. Perceived Drivers for Subject's SMM to Adopt Smart Manufacturing from Individual Subjects

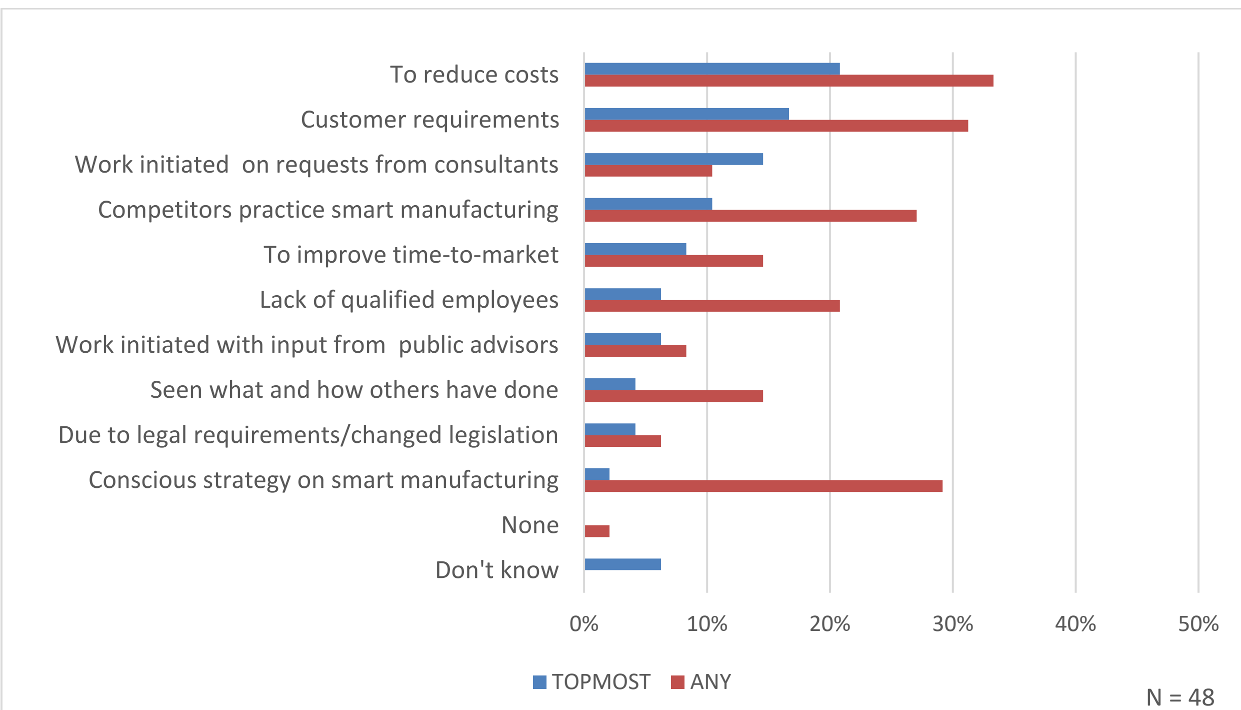


Figure 8. Perceived Drivers for SMMs to Adopt Smart Manufacturing from Consultant Subjects

These results are largely consistent with past research. Lowering costs emerges consistently as the top driver in numerous other survey studies (Hamzeh et al., 2018; Morton et al., 2020; Stentoft et al., 2020; Türkeș et al., 2019). The relative importance of other drivers varies across studies and may be influenced by how choices are presented to the respondents. In two European studies that used mostly the same categories as the authors, the desire to improve time-to-market (Stentoft et al., 2020; Türkeș et al., 2019), and having a conscious strategy on SM (Stentoft et al., 2020) were the top drivers.

As with drivers, barriers are influenced by perceptions of anticipated problems, such as the difficulty or costs of the solution. Subjects were offered eleven potential barriers and asked what they saw as the most critical barriers to implementing SM for their company or for the SMMs they consulted with. Subjects were allowed to select up to three options and to write their own answers into an "other" category. Subjects who chose more than one barrier were then asked to narrow down the top-most critical barrier. One IND subject and one CON subjects marked no drivers, while 56% of both and CON subjects chose the maximum of three

Results are shown in Figure 9 for IND subjects and Figure 10 for CON subjects, sorted by the topmost barrier reported. For IND subjects, the most frequently cited of these barriers is the additional investment of funds needed to adopt SM technologies: this is cited in the top three barriers by 43% of IND subjects and listed as the top-most barrier by 26%. A close second, and related issue, is the uncertainty about the implications of investment on the company's operating profits, cited in the top three by 30% of IND subjects and top-most for 22%. These are by far the two most important barriers for IND subjects. Third place for top-most barrier drops to 9%, and is tied between lack of qualified employees and concerns about data security. For CON subjects, uncertainty about whether the investment will positively affect profits is also a key barrier, mentioned by 31% in their top three and cited as top-most barrier by 21%. However, slightly more CON subjects cite low prioritization or insufficient management commitment as being a barrier (33% in top three and 23% top-most). As with IND subjects, the next most-cited top-most barrier for CON subjects is substantially lower rated, with investments of time and of funding tied at 10%. With such a small sample, it is unwise to overinterpret slight differences in percentages caused by only a few people. However, it is interesting that IND and CON subjects ranked certain barriers so differently. In particular, while management commitment was cited by more CON subjects as the top-most barrier than any other, it was almost the lowest-cited barrier for IND subjects (4%). Also, lack of qualified employees was tied for third-most important barrier for IND subjects and tied for least important barrier for CON subjects. Put together, this suggests that consultants may not be as aware of staff training issues as individuals working in these SMMs, while consultants are more aware of the role of management support for SM initiatives. It's notable that for both IND and CON subjects, employee pushback was mentioned by the fewest subjects as a barrier of concern.

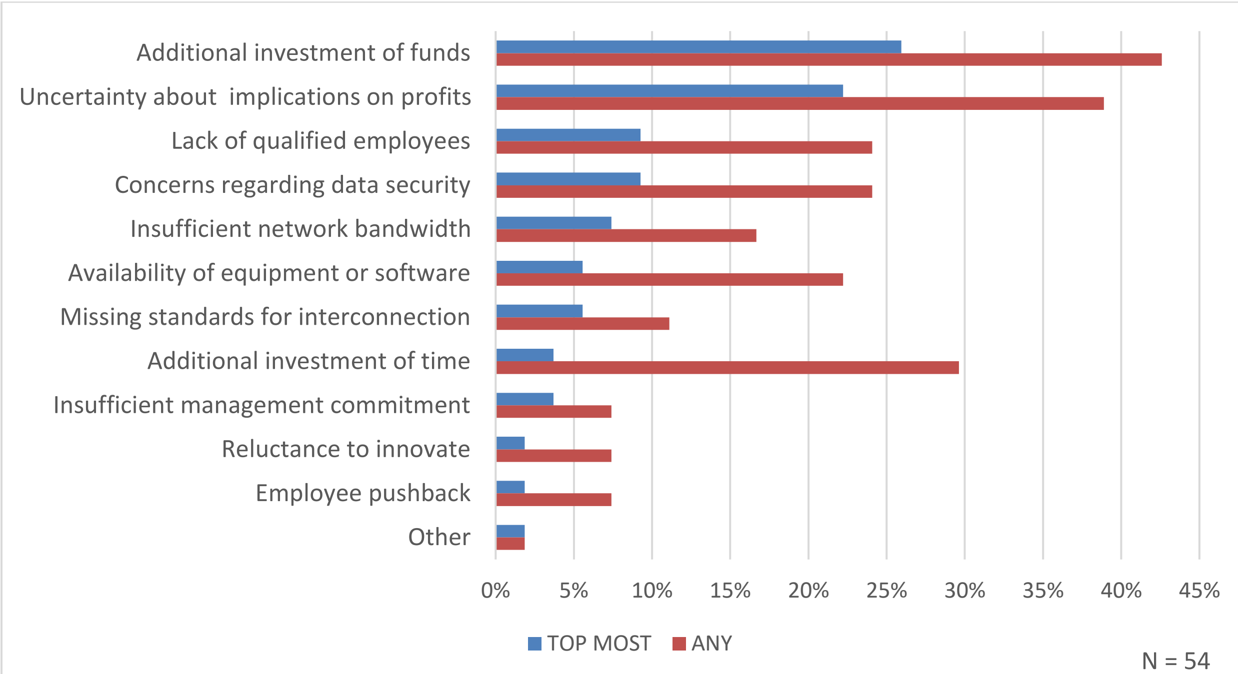


Figure 9. Perceived Barriers to Adopting Smart Manufacturing from Individual Subjects

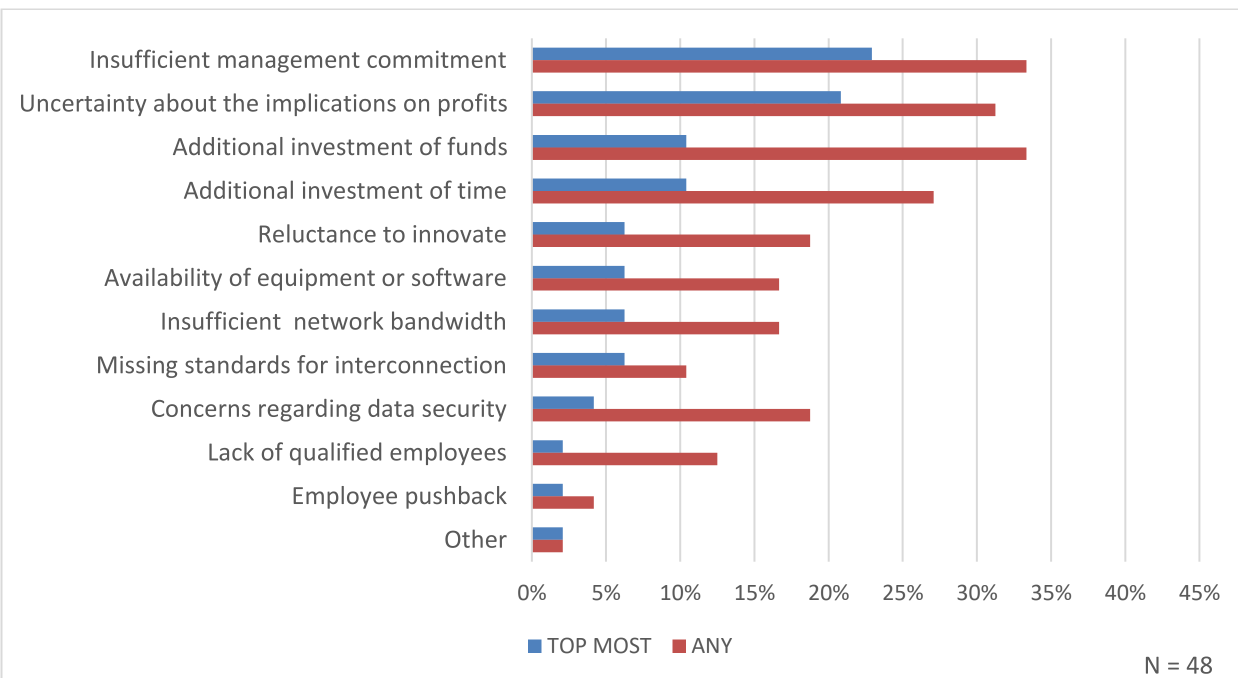


Figure 10. Perceived Barriers to Adopting Smart Manufacturing from Consultant Subjects

Specific Smart Manufacturing Technology Types

One of the main purposes of this study was to determine which specific SM solutions SMMs already had deployed, as well as which ones they had tried or considered and decided against, and what the pros and cons of each type are perceived to be.

Currently Used Technologies

The survey offered a choice of twenty technologies that might be used in SMMs "as part of a SM solution." IND subjects are asked whether the technologies are currently being used in their companies. CON subjects are asked how many of the SMMs they've worked with in the previous two years are using them, with the response options of all, most, about half, a few, and none.

Looking first at overall averages, IND subjects reported an average of 8 smart technology types being used in their companies. This differed by employment category, with management reporting an average of 4.7 types, experts reporting 7.9, and workers and administrative employees reporting 11.1 and 11.3, respectively.[3] CON subjects reported that at least "a few" of the companies they worked with used many more than this (average of 14.6 across types), compared to "almost half" or more (7.5), at least "most" of them (3.5), or all of the SMMs (1.2).

Figure 11 shows the percentage of IND subjects reporting that these technologies are currently being used in their companies, overall and separately for the three main employee categories. The primary take-away is which technologies are most common: not surprisingly, cyber-security, big data and analytics, and tablets are in the lead, with IoT sensors (and machine-to-machine communications) and mobile phones close behind. The results do not indicate a clear division between one group of popular solutions and another group of less-used solutions, but rather a gradual decline from almost two-thirds in use to only about one in five for the lowest ranked, including VR headsets, smart glasses, and radio-frequency identification (RFID) and/or real-time locating system (RTLS) technologies. Cybersecurity also emerged as the most-applied technology in other survey studies (Sarı et al., 2020; Stentoft et al., 2020; Yu & Schweisfurth, 2020); for other technologies the order differed, which may also indicate the sampling of different industries or geographical differences. Another interesting finding is the pattern of differences by employment category. For every technology, workers are more likely to report it being used than managers, and for most of them, technical experts and operations managers are in the middle of these two groups. This is one of the few clear differences found across employee categories for IND subjects, and it is a surprisingly robust one, spanning across all twenty technologies from the most often to the least often used. It is difficult to discern from the current data which subjects are more likely to be correct; the implications are explored more thoroughly in the discussion section, below.

[3] The lower rate for managers is significantly different from workers at $p < .001$, from administrative employees at $p < .01$, and from experts at the trend level of $p < .10$.

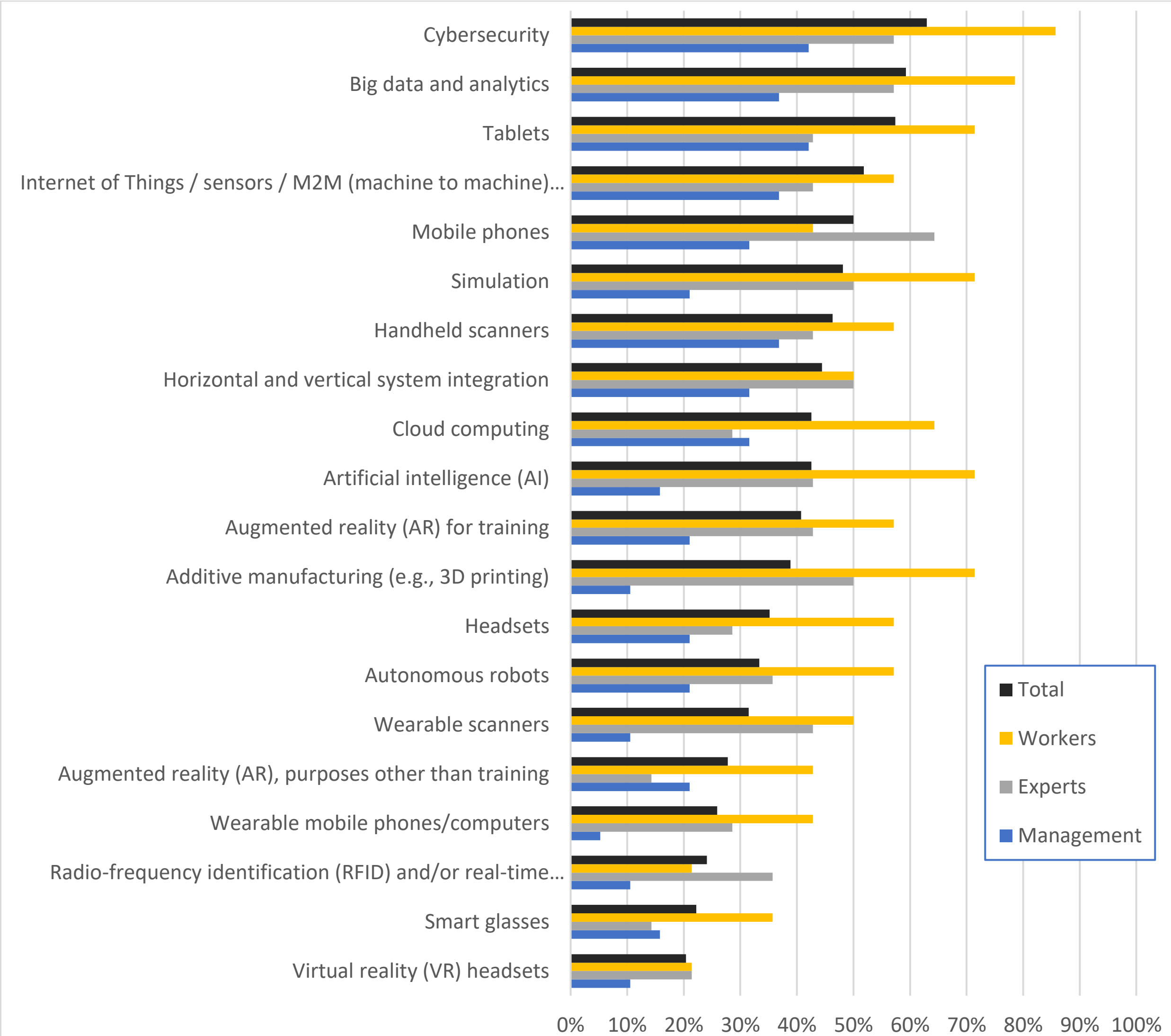


Figure 11. Technology Types Currently Implemented in Individual Subjects' Companies by Employee Type

CON subjects reported on how many of the SMMs they worked with used each of the technology types. These results are shown in Figure 12. These results are complicated to present, as the technology types most often reported being used by "all" the SMMs are not necessarily the ones also more likely to be used by "most" or least likely to be used by "none" of the SMMs. The results are shown sorted in two of the possible ways, for ease of interpretation: by which types are used by at least half the SMMs that these consultants work with (Panel A) and by none of them (Panel B). Based on use by at least half of the SMMs, the top five types are cybersecurity (61%), mobile phones (58%), tablets (48%), handheld scanners (47%), and cloud computing (47%). However, relative to the other four, cybersecurity ranks lower among devices used by all or even most of the SMMs. Mobile phones have the highest ranking there, with 19% of CON subjects reporting them being used for SM purposes in all of the SMMs they work with, and 33% saying all or most.

Note: Panel A is sorted by "half or more" and Panel B is sorted by "none".

Figure 12. Consultant Reports of How Many SMMs Use Each Technology Type

Turning to the other end of the spectrum, the technology types most CON subjects report being used by *none* of the SMMs are smart glasses (40%), artificial intelligence (39%), virtual reality headsets (38%), augmented reality (AR) for purposes other than training (36%) and AR for training (33%). These are key technologies in current trends toward SM for larger companies, but they are also relatively expensive solutions, and may not be as clearly linked to productivity and profitability for SMMs as simpler, more flexible solutions.

Reports of usage differ across subjects. For IND subjects, the top five most used technologies are cybersecurity, big data and analytics, tablets, IoT, and mobile phones. For CON subjects, the top five (used by at least half of their clients) are cybersecurity, mobile phones, tablets, handheld scanners, and cloud computing. CON and IND subjects are generally in agreement on cybersecurity, tablets, and mobile phones, and somewhat on handheld scanners (number 7 on the IND list) but have very different rankings for the other four types.

Technology Types Rejected or Discontinued

Subjects who reported that a given technology type was not currently used in their companies were asked whether that technology had ever been implemented but was later discontinued due to problems with it, or if the company had seriously considered implementing the technology but decided against it based on expected problems. As this is strongly affected by whether the IND subject's company is already using the technology, the combined results of these two questions for IND subjects are shown in Figure 13. Several technologies had been discontinued by more than 5% of the companies represented, led by artificial intelligence and mobile phones (used specifically for SM solutions). The technology most often considered for use in SM but later rejected was additive manufacturing/3D printing (21%), with tablets, AR and VR types, autonomous robots, and RFID close behind. In total, 33% of subjects reported their companies discontinued at least one SM solution (with half of these reporting at least two) and 59% reported seriously considering but rejecting at least one solution (with half of these reporting at least three). No significant differences were observed by employment category.

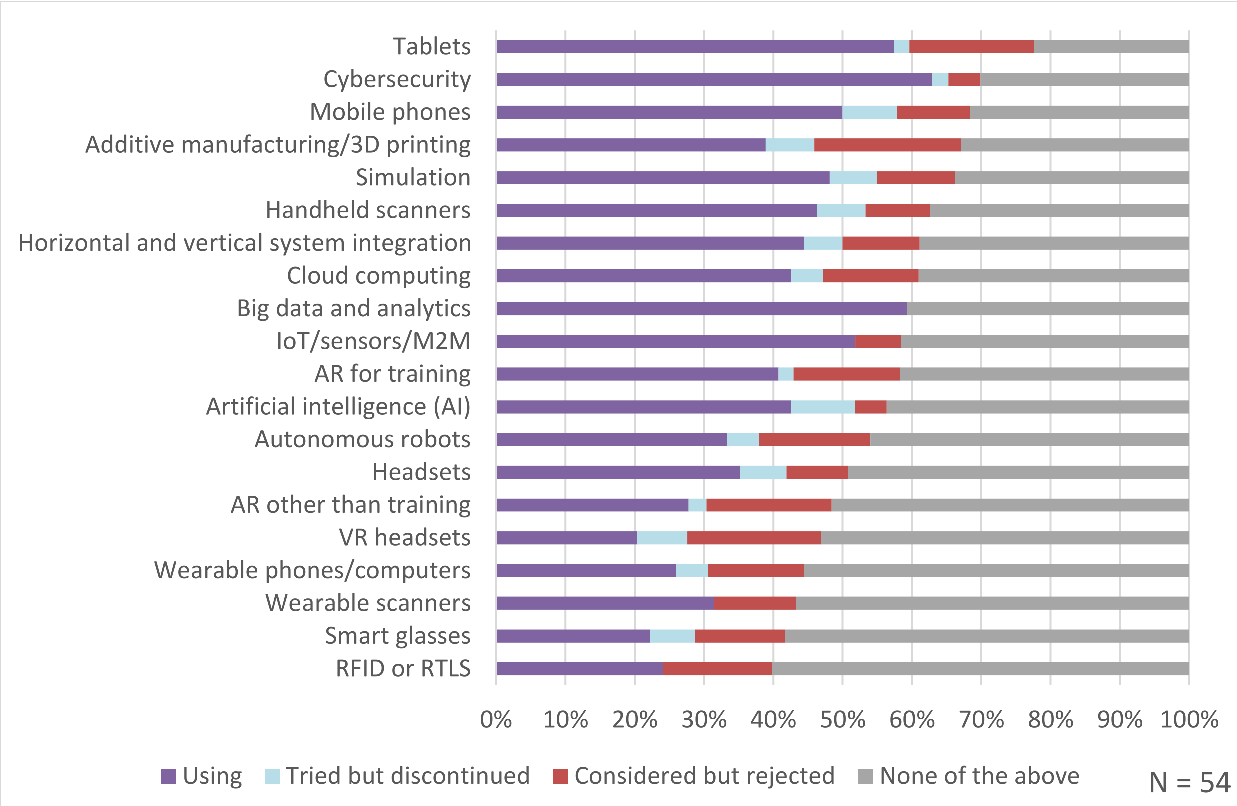


Figure 13. Current and Past Use of Technology Types Reported by Individual Subjects

This question was asked for CON subjects as well. Unfortunately an error in the programmed skip pattern meant that only CON subjects who said that none of their SMMs used a technology type were asked this follow-up (rather than those who did not say "all"), producing results of questionable quality.

For each technology that subjects reported their company either discontinuing or rejecting, they were asked to select the main reason for that among those listed in Table 7 (or a write-in "other" category). Given the small number of subjects responding for each specific technology type, the responses were grouped and are presented as the proportion of subjects who selected that reason at least once (among those who reported discontinuing or rejecting any technology). Results show that cost is mentioned most often, followed by how complex the technology is to use and maintain. Difficulty of implementation is mentioned more often for rejecting a technology than for discontinuing it, which may suggest that by the time implementation problems manifest, the worst of the implementation is already be over and discontinuation is not warranted. Privacy and security threats were least often mentioned as the main reason for either rejecting or discontinuing a technology; such concerns may still be important, but are ranked lower than other issues.

Table 7. Reasons for Discontinuing or Rejecting Any Technology Types

Reasons	Tried but discontinued	Considered but rejected
Cost	56%	66%
Complexity of usage and maintenance	50%	47%
Difficulty of implementation	28%	41%
Privacy and security threats	17%	19%
N	18	32

Pros and Cons of Specific Technologies

For each SM technology type IND subjects reported using in their company, they were asked for the most significant "pro" and "con" of that technology, based on their experience with it. CON subjects were asked the same question for every technology they reported any of their SMM companies using.

Five types of advantages or pros were listed, and subjects could write in their own "other" category as well. The percentages of subjects who reported each pro for each technology are shown for IND subjects in Figure 14 and for CON subjects in Figure 15. For IND subjects, the technology types are sorted by how many subjects reported using them in their companies (see Figure 11) from lowest to highest. For CON subjects, the technology types are sorted by the percentage who reported that half of ore of their SMMs used it. Note that the subsample answering for each technology is limited to those who reported that their companies, or the SMMs they work with, use the technology. For each group, the overall average for each "pro" is shown at the far right of the figure.

Increased task completion speed is endorsed by more IND subjects than other options for most of the technologies, including all of the most-often used ones (to the right of the figure). Better ergonomics also does well for several technologies, including smart glasses, AR, and autonomous robots. It does less well for VR headsets and wearable mobile phones/computers, although this doesn't mean they don't also provide better ergonomics, only that task completion speed is more important. Reduced task complexity was the most often mentioned pro for wearable scanners, and second-most for headsets, AR for training, and tablets. Easier implementation was selected as the main pro by a small minority of subjects for every technology type, and mentioned somewhat more often for the most used technologies, such as cybersecurity, tablets, big data and analysis. Reducing 'management by walking around' was cited as the primary pro only 5% of the time on average, but cited by more than 40% of IND subjects for wearable scanners.

CON subjects did not show as much agreement about what the pros are for each technology, but several types showed 30% or even 40% of consultants agreeing on the most significant pro. For instance, easier implementation was considered most important for several types, including more commonly used solutions such as mobile phones, tablets, cloud computing, handheld scanners, and headsets, including VR headsets. Increased task completion speed was endorsed by over 20% of CON subjects on average, much fewer than for IND subjects, and only reached top place for RFID and/or RTLS solutions.

Cybersecurity had an unusual number of "other" responses, the majority of which mentioned improved data security, privacy, or compliance with security protocols; this pro was not included in the original list and not as relevant for other technology types, but is clearly an important element for future research.

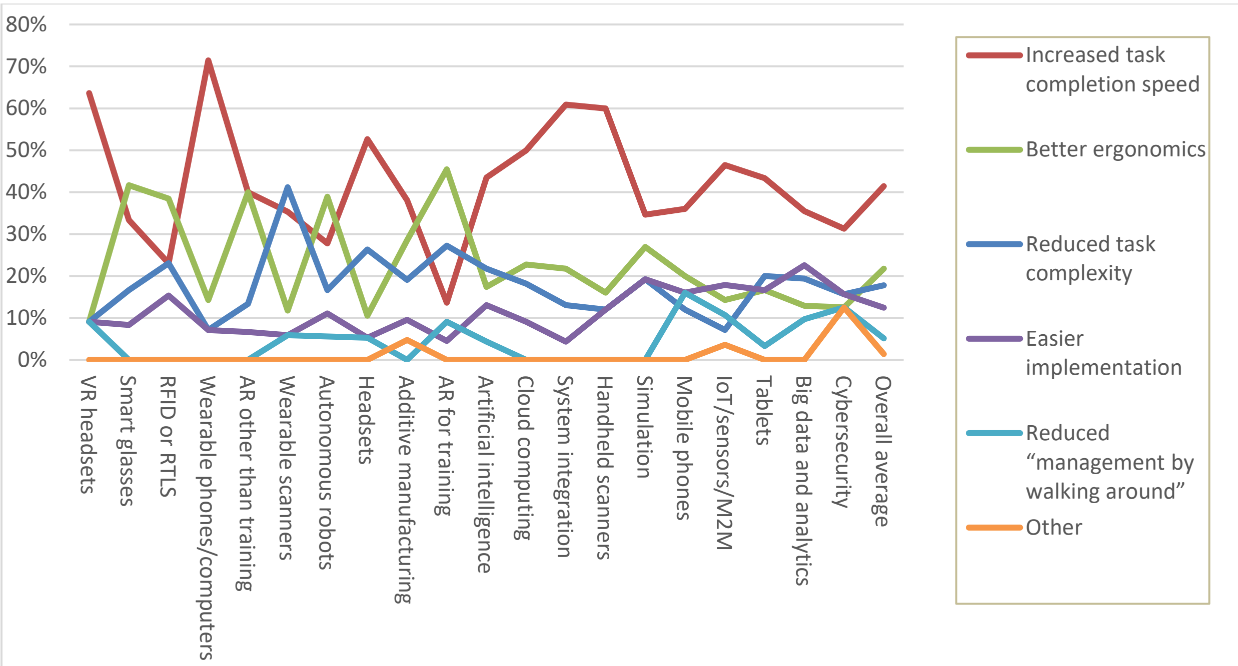


Figure 14. Perceived Pros of Specific Technology Types for Individual Subjects

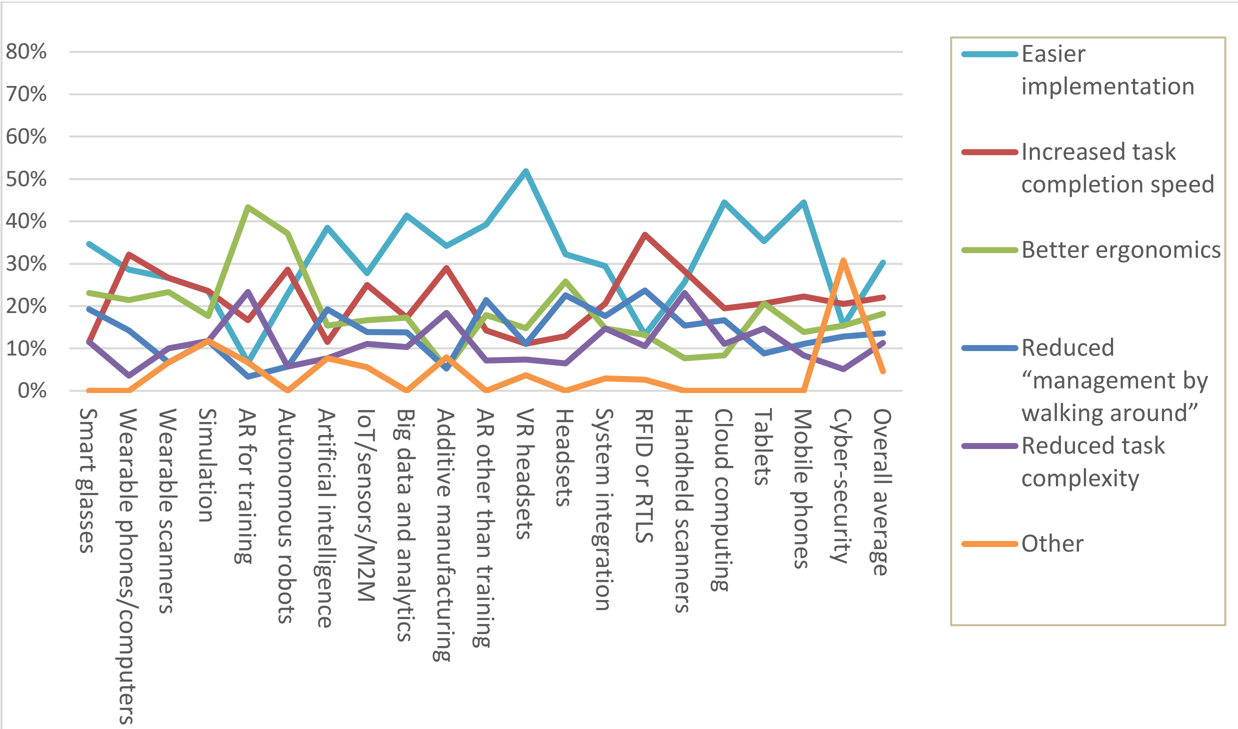


Figure 15. Perceived Pros of Specific Technology Types for Consultant Subjects

Parallel questions in the survey asked for the most significant "con" for each task from a list of four. Results are shown in Figure 16 for IND subjects and in Figure 17 for CON subjects; again, the technology types are sorted with more commonly used types to the right of the figure (which differ by IND versus CON groups). Despite having fewer cons to choose from, for most tasks, IND subjects were less unified in which cons were most important than they were on which pros were most important. Difficulty of implementation is mentioned least often for almost all solutions, which corresponds to how few IND subjects endorsed easier implementation as a pro for these same solutions. Cost was seen by many more IND subjects as a problem for certain technologies, including handheld scanners, cloud computing, artificial intelligence, and autonomous robots. However, for most of these technology types, cost, complexity of use and maintenance, and privacy and security threats were each endorsed as most significant by a substantial minority.

CON subjects were likewise divided among themselves about which cons were most significant for most of these technology types. Privacy and security threats were endorsed by a substantial number of CON subjects for only a few solutions, but these include some of the most often used: mobile phones, tablets, and cloud computing. Cost was on average the most often endorsed, but only by slightly more CON subjects for most types, such as cyber-security, VR headsets, AR (other than for training), additive manufacturing (3D printing), wearable scanners, and smart glasses.

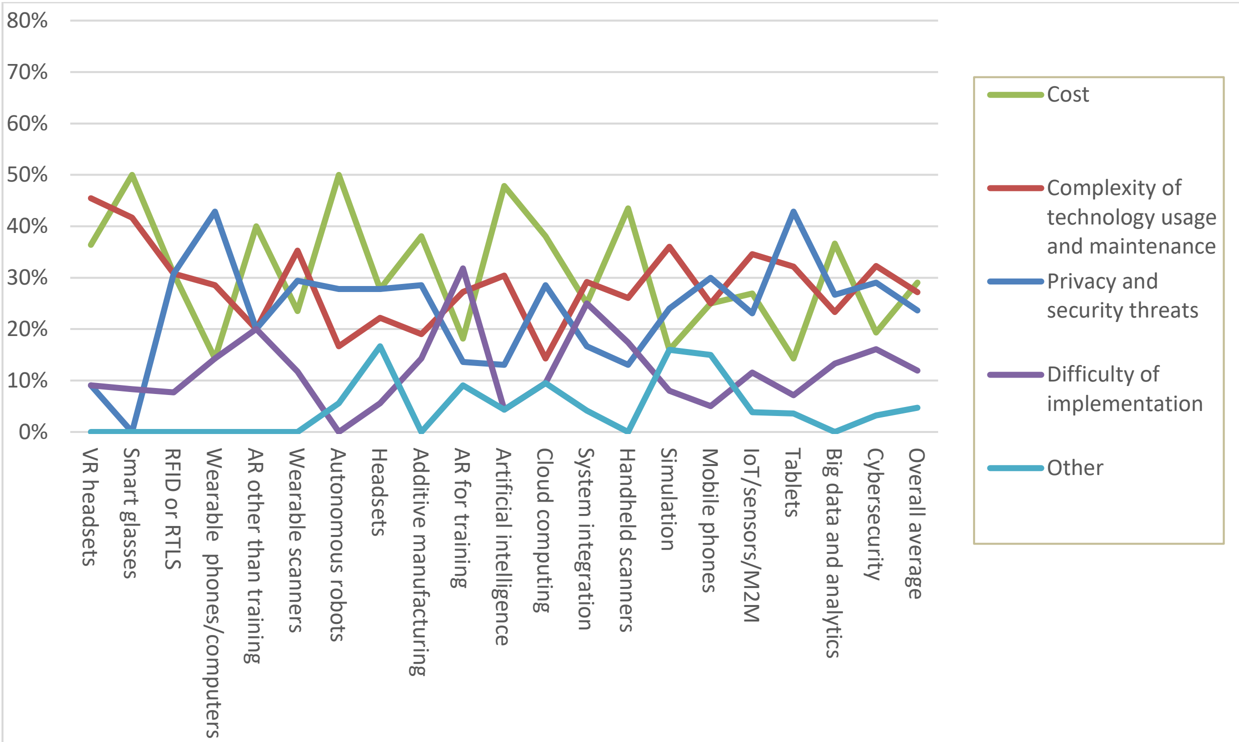


Figure 16. Perceived Cons of Specific Technology Types for Individual Subjects

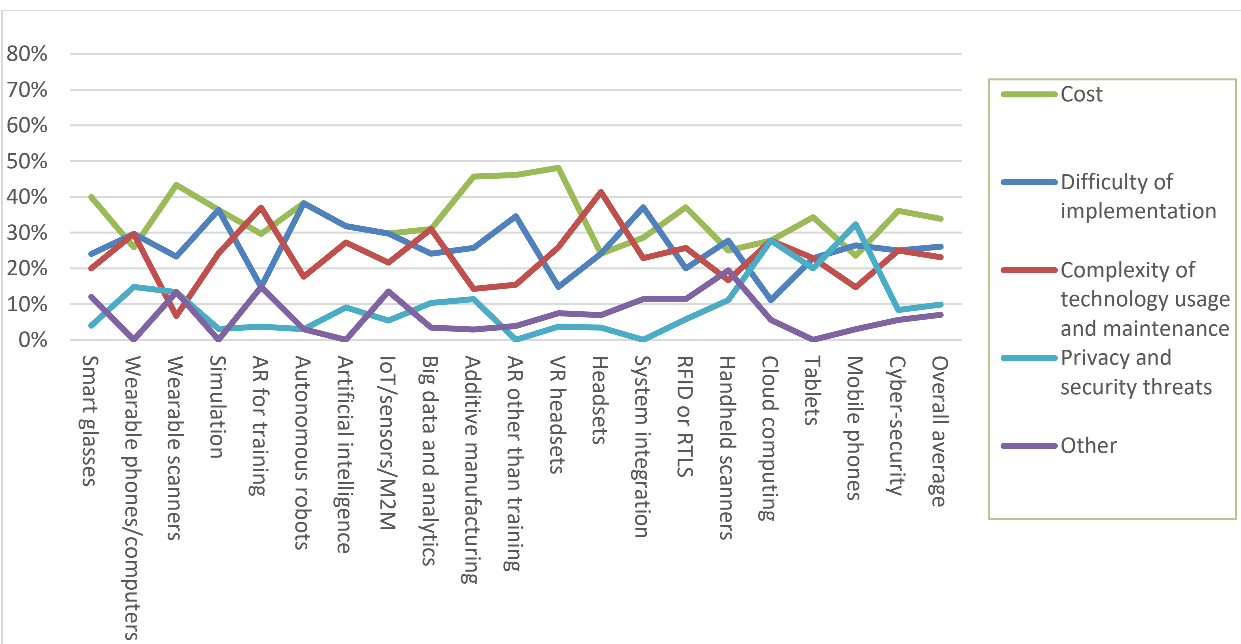


Figure 17. Perceived Cons of Specific Technology Types for Consultant Subjects

Worker Reactions

In the supplemental questions section, subjects who reported that their companies had implemented specific new technologies were asked how most workers reacted, overall. Responses from CON subjects, for the SMMs they worked with in the previous two years, were substantially more negative for both of these questions than those from IND subjects.

Individual owners and employees of SMMs reported strongly negative worker reactions for only one technology type: autonomous robots (see Figure 18).[4] For all these technology types, over half the IND subjects reported at least somewhat positive worker reactions, with many types reaching two-thirds positive reaction. Still, many types of technology received somewhat negative or mixed or neutral reactions and the only technologies that reached 50% strong positive support were mobile phones, tablets, smart glasses, and cyber-security. This lack of support is potentially problematic, given the importance of worker buy-in to the success of implementing any new solutions. Moreover, lack of positive reaction may signal problems in human–machine interactions, which can result in work-related stress (Körner et al., 2019).

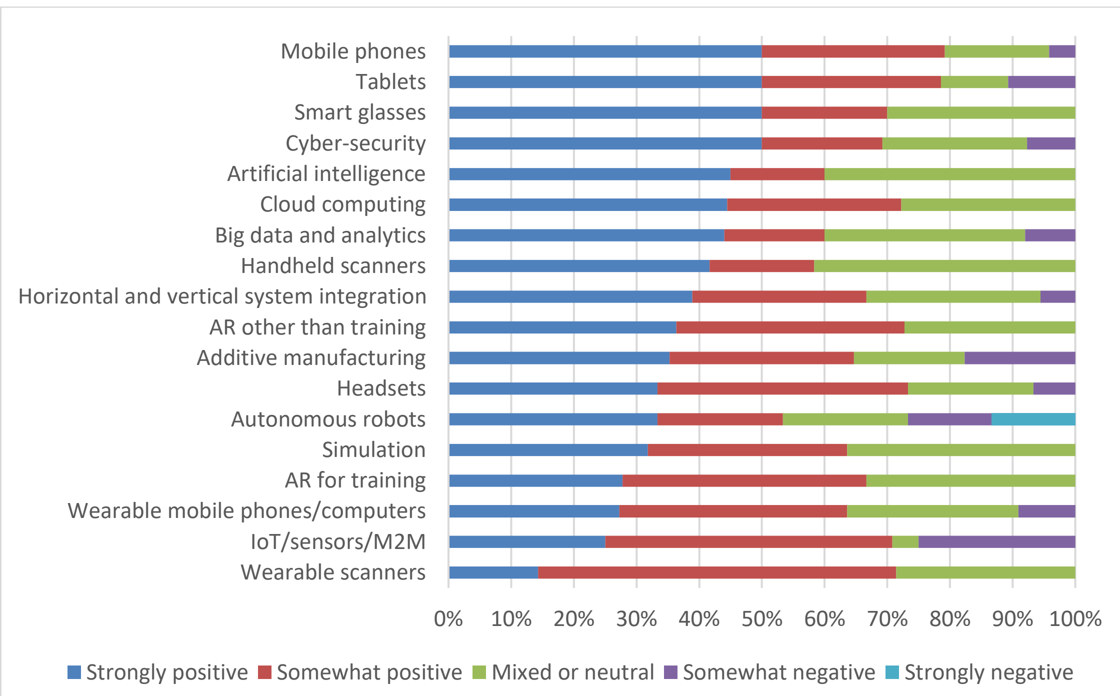


Figure 18. Individual Subjects' Perception of Workers' Reactions when Smart Manufacturing Technology was Implemented

By contrast, CON subjects rated worker reactions at their client SMMs substantially more negatively across the board (see Figure 19). Only one technology type garnered more than half positive responses:

[4] Results are not shown for two technology types, VR headsets and RFID and/or RTLS, for which fewer than ten IND subjects gave valid answers to this question.

the category including internet of things (IoT), sensors, and machine to machine (M2M) communication; this was one of only two technology types, along with RFID and/or RTLS, to receive more than 20% strongly positive responses. All technology types were seen as receiving negative worker responses at a substantial minority of companies (at least one in four), including but not led by the autonomous robots that the IND subjects reported perceiving negative worker responses to.

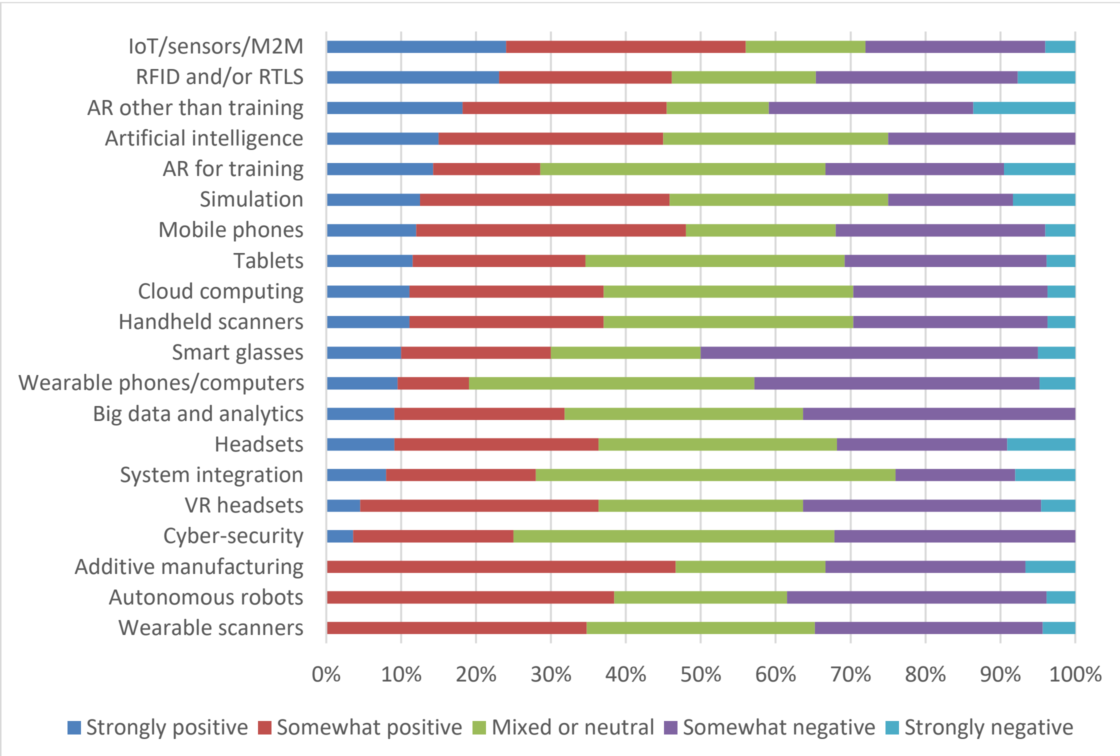


Figure 19. Consultant Subjects' Perception of Workers' Reactions when Smart Manufacturing Technology was Implemented

Another way to present this is the average perceptions of worker responses across all technology types, as shown in Figure 20. This illustrates the difference in CON and IND reports, with many more CON subjects reporting somewhat negative reactions on average and many more IND subjects reporting strongly positive reactions. Expressed as a mean score, where higher numbers mean more negative responses, this is statistically significant even with the small sample size (IND 2.13 [s.d., 0.78] v. CON 2.84 [s.d. .84], F = 11.54, p = .0012). This difference between groups might be an artifact of the small and nonrepresentative sample, reflecting unmeasured differences across the companies that subjects have experience with. However, It could plausibly be due to differences in what people at different levels of a company experience.

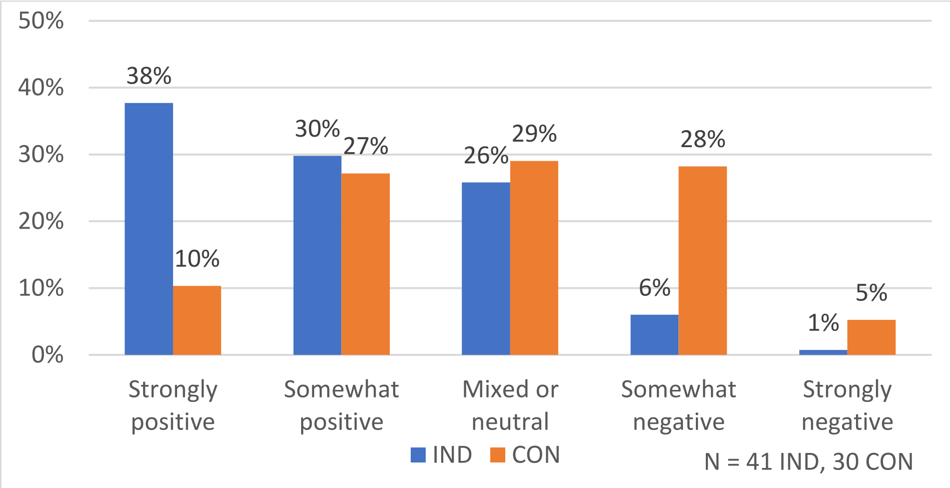


Figure 20. Average Worker Reactions to Smart Manufacturing Technology by Subject Type

Another question in the supplemental section asked how worried subjects thought workers in their company (or in the SMMs consultants worked with) were about sharing data about themselves, which may contribute to workers' worries about SM solutions. Five type of data sharing were asked about. As shown in Figure 21, IND subjects perceive, on average, that more than half of workers are at least a little worried about all these types of data sharing, but relatively few report workers being very worried. There is not much distinction in perceived level of concern across the types of data sharing.

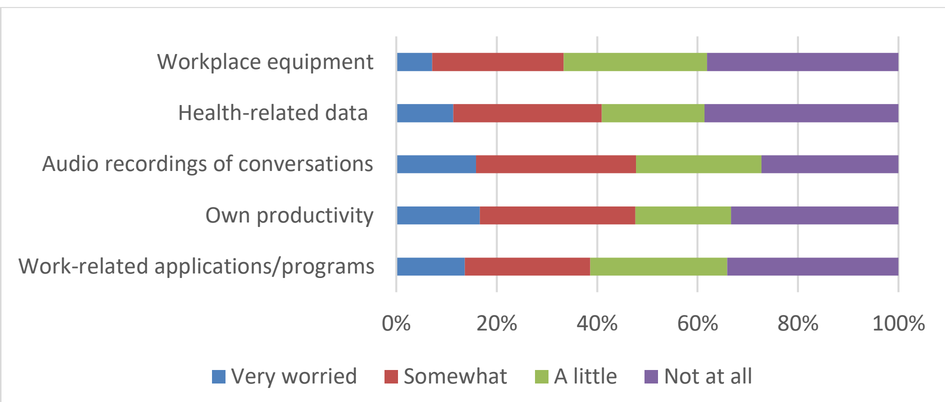


Figure 21. Perceptions of Workers' Worries about Data, Individual Subjects

As shown in Figure 22, CON subjects report at least three out of four workers being at least a little concerned about four types of data: health data, work-related applications and software program, audio recordings of conversations, and data measuring the workers' productivity. However, CON subjects report lower worker concerns about data shared about workplace equipment.

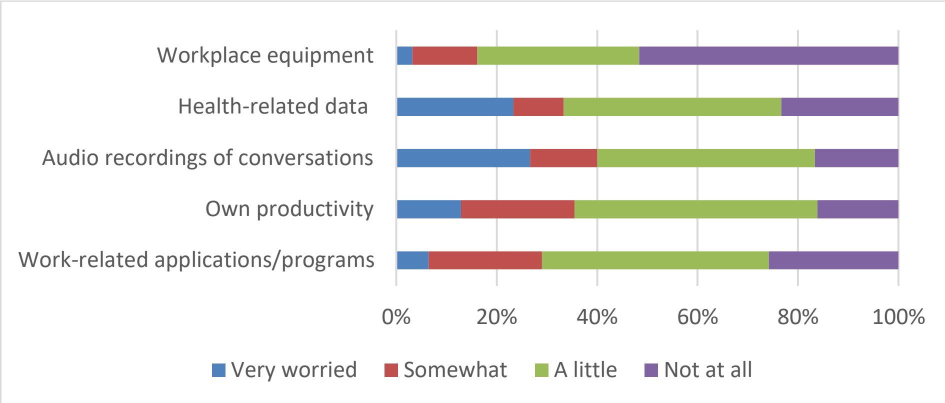


Figure 22. Perceptions of Workers' Worries about Data, Consultant Subjects

CONCLUSIONS

The results presented here replicate key findings of other studies as well as add new findings. Although the sample size is not large, it is still one of the largest quantitative surveys of small and medium manufacturers (SMMs) in the United States. It thus helps to quantify previously generalized knowledge and also give insights into how small and medium American manufacturers compare to prior studies of large American manufacturers and smaller European manufacturers. These results also shed light on how consultants and other outside experts who work with SMMs may have different perspectives than owners and employees within those companies.

The study contained multiple measures of readiness and preparation for smart manufacturing drawn from various prior surveys. One take-away is that questions that seem to be capturing related aspects of readiness are not necessarily aligned with one another, which could explain some of the variation across prior studies. Another take-away is that consultants tend to report lower levels of readiness for the SMMs they work with than individual subjects report for their own companies, and yet both groups tend to report somewhat higher levels of readiness –and adoption—than seen in previous studies. Specifically, as expected, few subjects report that SMMs have fully implemented smart manufacturing (16% for IND and 17% for CON). However, they are moving in that direction. IND subjects report higher readiness than CON subjects, with 56% claiming to have developed a clear business case or even implemented first measures, compared to 36% of the SMMs consultants work with. A seven-item Readiness Index focused on management skills and motivation is also optimistic, with IND subjects scoring 3.82 on average (close to “somewhat agreeing” that their company is ready). Almost half of IND subjects averaged at least 4 (“somewhat agree”) to these items; this matches well with the CON subjects giving an average score of 2.7 (where 3 is “about half”) indicating how many of their companies fit the readiness items.

Given the infrastructure requirements of many smart solutions, it is promising that many IND subjects consider their companies either fully or mostly digitalized, with only 11% described as still paper intensive and 33% as moving toward digitalization. CON subjects report lower readiness here as well, with more companies paper intensive (24%) and fewer full digitized (17%).

An important aspect of readiness is the skill level of the current employees. A similar proportion of IND (26%) and CON (30%) subjects believe current employees would find it difficult to adapt to new technology and new, more skilled workers would need to be hired. However, only 11% of IND subjects believe current workers have sufficient skills compared to 33% of CON subjects.

For these overall measures, the current study indicates a higher level of readiness to adopt smart manufacturing technologies than was found in earlier studies of SMMs (Stentoft et al., 2020). For instance, a West Virginia study showed that only 14% of the respondents were working to adopt smart manufacturing practices in their operations (Wuest et al., 2017). This could suggest recent advances in awareness about smart manufacturing, and that SMMs have taken more steps towards implementation since earlier studies. However, it could also be due to varying ideas of what counts as smart manufacturing, digitization, and related terms. Another possibility is that the sample is biased toward SMMs that are more advanced than others, possibly due to being recruited through the NIST Manufacturing Extension Partnership (MEP) centers, which may indicate a higher level of engagement with new initiatives for these manufacturers. However, smart manufacturing is not yet a major initiative of the MEP network, which was a major impetus for conducting the current study. Also, it is worth noting that although about half the sample is from California and California is known for technology leadership, subjects from California did not express significantly higher readiness than others.

This study goes beyond general readiness level measures and gives insight into specific applications for smart manufacturing. Between 20% and 30% of IND subjects and a slightly higher percentage of CON subjects reported their companies as already using smart manufacturing solutions for specific tasks such as assigning jobs or tasks, internal communication, timesheets, inputting information into forms, managing stock, and accessing task information. For all the tasks asked about, the majority of subjects felt that smart manufacturing was either a current or possible benefit. However, a substantial minority of subjects reported being satisfied with how well low-tech solutions worked, particularly for assigning jobs or tasks (43% IND and 34% CON), communicating with third parties (41% IND), and internal communication (35% IND and 38% CON). This finding provides an important reminder that not all solutions should be sought simply because they are smart: SMMs need to concentrate their relatively limited resources on adopting only those solutions that solve their specific needs.

To help determine those special needs, the survey asked about productivity problems. The two tasks that most IND and CON subjects said they faced significant productivity issues “often” or “always” were having to do tasks manually and having to wait for information. Lack of training caused productivity issues for over half of both IND and CON at least “sometimes” and in another question, lack of training was mentioned most often by both IND and CON subjects (37% and 42%) as a waste stream issue having the strongest negative impact on productivity. Non-utilized talent (trained workers doing less skilled work) was the second most mentioned waste stream issue or IND subjects (26%). Both were much higher than production line problems, highlighting the importance of coordinating human resources in any smart manufacturing solution. On the other hand for CON subjects, waiting (e.g., for earlier processes to complete) and defects (e.g., leading to dumping whole batches) tied for second worst waste stream issue (27%).

Another way of approaching how smart manufacturing can benefit SMMs and also understand the slow adoption rates is to study drivers and barriers to SM. The differing perceptions from within the SMMS versus from consultants are again notable here. The driver most IND subjects identified as “topmost” for adopting smart manufacturing was reducing costs (24% IND), and the next most important was a conscious internal strategy that supported smart manufacturing (15%). The corollary is that the topmost perceived barriers to adopting smart manufacturing were the additional investment of time (26%) and money (22%). Since constructing a conscious internal strategy takes time and labor that most SMMs can’t spare, these two findings illustrate the essential challenge faced by SMMs: they don’t have the time and money they need to invest in order to make better use of their time and save more money. Results from CON subjects showed a slightly different story: although reducing costs was also their topmost driver (21% CON), they were more likely to rate customer requirements (17%) and requests of consultants (15%) as the topmost driver. More CON subjects listed the topmost barrier as insufficient management commitment (23%) or uncertainty about whether the investment would benefit profits (21%), which may reflect how and with whom they negotiate the adoption process.

The study makes another unique contribution by addressing experiences with and attitudes toward twenty major smart manufacturing technology types that SMMs might use. The technologies IND subjects most often reported using are cybersecurity, big data and analytics, tablets, IoT, and mobile phones, but many other technology types are used by at least a third of the subjects’ companies. For CON subjects, cybersecurity, tablets, and mobile phones also appeared in the top five for use among half or more of their client companies, but they also included handheld scanners and cloud computing, with big data and analytics and IoT less often mentioned.

The pattern of differences in reported technology use by employment category for the IND subjects is striking. On average, managers report that their companies use significantly fewer technology types than workers and administrative employees do (and somewhat less than experts, as well). In fact, for every individual technology, workers are more likely to report it being used than managers, and for most of them, technical experts and operations managers are in the middle. For some of these technologies, it would seem logical for workers to be more aware because they are the ones interacting with those devices on a daily basis, in which case the workers’ higher reported rates are more correct. For other technologies, it would seem logical for managers to be more aware of their presence because floor workers would not necessary interact with such solutions or be trained to understand them, such as cyber-security, cloud computing, or simulation tools. Technical experts and operations managers are better suited to understand and recognize the use of smart technologies, and probably have more accurate representations of their use. It should be noted that the survey subjects are from different companies all across the country: as with any of the questions in this survey, it cannot be inferred that workers and managers in the same company would disagree (or for other questions, that they would agree). It is possible that the workers’ companies differ from those represented by the managers.

However, this pattern is suspiciously consistent to be due to sampling bias: we would have to assume that the survey oversampled workers from companies with unusually high investments in SM technologies while oversampling managers from companies with relatively low adoption rates, and that this was consistent across all twenty of these types. Instead, we interpret the current pattern to suggest that managers (a category that includes owners and supervisors who don't work directly with manufacturing processes) tend to underestimate or be unaware of the use of SM solutions whereas production workers tend to overestimate the likelihood that such solutions are being used (perhaps elsewhere in the facility, or in ways that they can't perceive). This reinforces the importance of surveying a wide range of representatives from SMMs, and comparing the perspectives of different groups, while focusing on experts for specific factual answers.

For technology types not currently being used in the subjects' companies, 33% of IND subjects reported trying and discontinuing at least one of them, while 59% reported that their company seriously considered adopting at least one smart technology but decided against it because of anticipated problems. Many of the technologies considered and rejected were the same ones currently being used by many other subjects' companies, such as tablets, reflecting their ubiquity rather than their likelihood of rejection. More concerning are the technologies that companies tried and rejected, nine of which were reported by more than 5% of subjects (ranging from 6%-9%): mobile phones, additive manufacturing/3D printing, simulation, handhold scanners, system integration, artificial intelligence, headsets, VR headsets, and smart glasses. This is another important insight, that technologies that may work well for some companies (especially larger ones) may not work for SMMs. Indeed, the reasons most often given for discontinuing a smart solution were cost (56%) and complexity of using and maintaining the solution (50%). (Due to a survey error, responses are not available for CON subjects.)

Subjects were also asked about the pros and cons they have experienced with the technology types currently being used in their companies. This is another issue that reveals differences between consultants working with multiple SMMs and the owners and employees of individual SMMs. For IND subjects, increased task completion speed was by far the most commonly mentioned main pro, especially for the technologies used by the most companies. Reduced complexity and improved ergonomics were also highly rated for certain technologies. By contrast, CON subjects were most likely to cite easier implementation as the main pro for the listed technology types (which ranked fourth of five for IND subjects). It is interesting that consultants appear more focused on how easy smart solutions are to implement while owners and employees are more focused on how they speed up tasks; this may reflect the fact that consultants' role with these companies is generally at the planning and implementation stage whereas workers at those companies continue to be directly involved at the day-to-day task completion level long after implementation. There was even more variation in the main cons subjects cited for these technologies, with no single problem dominating across all types. On average across technology types, IND subjects were less likely to cite difficulty of implementation as the most significant con and CON subjects were less likely to cite privacy and security threats and most likely to cite cost. However, all the cons were cited by a substantial minority of subjects for at least some technologies. As an initial attempt to identify the most significant factors to focus on for improving each technology type, these questions produced more useful responses for some types than others. For those that showed little agreement across subjects about their most significant “pro” and especially their most significant “con”, more research is needed to determine whether subjects are unfamiliar with the technology or are legitimately divided on the qualities of the technology, and if so, what varied circumstances could lead to those impressions.

Another challenge for adopting new technology is engaging workers. For technologies used by IND subjects’ companies or CON subjects’ SMM clients, they were asked how negative or positive workers’ reactions were, overall. This is another topic that CON and IND subjects provided very different perspectives on. For IND subjects, only one technology type received a strongly negative reaction from more than 10% of workers: autonomous robots. On average, IND subjects reported that half or even two-thirds of workers were at least somewhat positive for most technologies. By contrast, CON subjects rated worker reactions at their client SMMs substantially more negatively across the board. Only one technology type garnered more than half positive responses: the category including internet of things (IoT), sensors, and machine to machine (M2M) communication. This was one of only two technology types, along with RFID and/or RTLS, to receive more than 20% strongly positive responses. All technology types were seen as receiving negative worker responses at a substantial minority of companies (at least one in four), including but not led by the autonomous robots that IND subjects reported negative worker responses to. A question on workers’ concerns about sharing data of various types produced mixed results and did not illuminate the differences for technology types. Both IND and CON subjects report workers having a little (or more) concern about the types of data sharing common for SM solutions, although CON subjects believe workers are much less concerned about data shared about workplace equipment.

The source of the differences in CON and IND views on worker reactions to SM technology is unclear. It may suggest a survivor effect: that is, that consultants work with a wide range of SMMs, including those who fail and those with negative experiences of SM who may drop out of groups such as the MEP network, whereas the companies represented by the IND subjects are still involved in the MEP network and perhaps are more successful at adopting SM. It is encouraging that owners and employees on the ground have such positive perceptions of worker reactions. However, given the importance of enthusiastic worker buy-in, the low levels of strongly positive reactions for many of these technologies and the substantial minorities of mixed or somewhat negative reactions raise concerns. These findings reinforce the importance of bringing workers to the table in discussions of technology development, both to educate and learn from them, and of considering how new solutions will affect employees at all levels.

In summary, SMMs potentially benefit from smart technologies, but they face serious challenges when adopting this digital transition. Overall, these results support the idea that SMMs, even more so than larger companies with more flexible resources, should focus their decision-making on specific technologies for specific needs rather than attempting to embrace the full spectrum of smart manufacturing at once. The differences in perceptions by consultants, managers, experts, and workers on certain issues highlight the importance of addressing experiences, concerns, and insights at every level of the company. More research is needed to gain a better understanding of where US SMMS are in their transition to smart manufacturing and what problems they have that specific new technology can address. This study further adds to this research by asking about companies' experiences with specific technologies. These results will inform the development of technological solutions that are affordable and easily adaptable for SMMs.

APPENDIX

	Title	Type of Publication	Authoring Institution	Number of respondents	Country of survey	Region coded	SME focus
1	Bosman, L., Hartman, N., & Sutherland, J. (2020). How manufacturing firm characteristics can influence decision making for investing in Industry 4.0 technologies. Journal of Manufacturing Technology Management, 31(5), 1117-1141.	Journal	University	138 manufacturing companies	USA (Indiana; cooperation with MEP centers)	USA	Y
2	Wuest, T., Schmid, P., Lego, B., & Bowen, E. (2017). Overview of Smart Manufacturing in West Virginia: Bureau of Business & Economic Research and West Virginia University.	Report	University	Online survey: 64 total respondents, 54 associated with manufacturing and included in analyses. Of these 16 respondents came from enterprises with 500 or more, rest SMMs n=38. 14 in-depth interviews with company representatives (n=9) and 5 experts from academia, associations, or state agencies.	USA (West Virginia)	USA	Y

	Title	Type of Publication	Authoring Institution	Number of respondents	Country of survey	Region coded	SME focus
3	Advanced Manufacturing Media. (2015). How Advanced Manufacturing is helping U.S Companies Compete Globally. [Online]: SME.	Pamphlet (Report)	Interest group	618 of 37,730	USA	USA	N
4	Industry of Things World USA. (2017). Survey Report 2018. [Online]: Author.	Report	Interest group//large annual conference of SM specialists	221	USA	USA	N
5	Sikich. (2017). 2017 Manufacturing Report. Trends and strategies to help manufacturers understand growth challenges and capture opportunities. [Online]: Sikich.	Report	Consulting firm	"More than 250"	USA	USA	N
6	Rauch, E., Stecher, T., Unterhofer, M., Dallasega, P., & Matt, D. T. (2019). Suitability of Industry 4.0 concepts for small and medium sized enterprises: Comparison between an expert survey and a user survey. In Proceedings of the International Conference on Industrial	Conference Proceedings	University	28 companies (users); 12 experts (professors/researchers)	USA Italy Austria Slovakia	INT-USA	Y

	Title	Type of Publication	Authoring Institution	Number of respondents	Country of survey	Region coded	SME focus
	Engineering and Operations Management.						
7	Morton, D., et al. (2020). Trends in Global Manufacturing. Implementing Industry 4.0 & Building the Digital Factory. [Online], SME and Plataine.	Report	Consulting firm and interest group	"over 200"	81% of respondents from North America, rest from Europe, Asia, and Latin America	INT-USA	N
8	Buer, S. V., Strandhagen, J. W., Semini, M., & Strandhagen, J. O. (2020). The digitalization of manufacturing: investigating the impact of production environment and company size. Journal of Manufacturing Technology Management.	Journal	University	76 (from 212 approached firms)	Europe (Norway)	Europe	Y

	Title	Type of Publication	Authoring Institution	Number of respondents	Country of survey	Region coded	SME focus
9	Ingaldi, M., & Ulewicz, R. (2020). Problems with the Implementation of Industry 4.0 in Enterprises from the SME Sector. Sustainability, 12(1), 217.	Journal	University	187 (194 minus 7 rejected) for first and second round of the survey supplemented with expert interviews (no number given)	Poland	Europe	Y
10	Jäger, J., Schöllhammer, O., Lickefett, M., & Bauernhansl, T. (2016). Advanced Complexity Management Strategic Recommendations of Handling the "Industrie 4.0" Complexity for Small and Medium Enterprises. Procedia CIRP, 57, 116-121.	Journal	University	161	Germany	Europe	Y
11	Masood, T., & Sonntag, P. (2020). Industry 4.0: Adoption challenges and benefits for SMEs. Computers in Industry, 121.	Journal	University	271 (238 completed)	UK	Europe	Y
12	Rauch, E., Dallasega, P., & Matt, D. T. (2017). Critical Factors for Introducing Lean Product Development to Small and Medium sized Enterprises in Italy. Procedia CIRP, 60, 362-367.	Journal	University	54	Italy	Europe	Y

	Title	Type of Publication	Authoring Institution	Number of respondents	Country of survey	Region coded	SME focus
13	Sevinç, A., Gür, Ş., & Eren, T. (2018). Analysis of the Difficulties of SMEs in Industry 4.0 Applications by Analytical Hierarchy Process and Analytical Network Process. Processes, 6(12), 264	Journal	Interest Group	N/A but consulted 15 experts	Turkey	Europe	Y
14	Stentoft, J., Wickstrom, K. A., Philipsen, K., & Haug, A. (2020). Drivers and barriers for Industry 4.0 readiness and practice: empirical evidence from small and medium-sized manufacturers. Production Planning & Control. doi:10.1080/09537287.2020.1768318	Journal	University	190 SMEs	Denmark	Europe	Y
15	Türkeș, M. C., Oncioiu, I., Aslam, H. D., Marin-Pantelescu, A., Topor, D. I., & Căpușneanu, S. (2019). Drivers and Barriers in Using Industry 4.0: A Perspective of SMEs in Romania. Processes, 7(3), 153.	Journal	University	176 of 604 managers; answer rate is 29.1%	Romania	Europe	Y
16	Arnold, C., & Voigt, K.-I. (2019). Determinants of Industrial Internet of Things Adoption in German Manufacturing Companies. International Journal of Innovation and Technology Management, 16(6). doi:10.1142/s021987701950038x	Journal	University	197	Germany	Europe	N

	Title	Type of Publication	Authoring Institution	Number of respondents	Country of survey	Region coded	SME focus
17	Sarı, T., Güleş, H. K., & Yiğitol, B. (2020). Awareness and readiness of Industry 4.0: The case of Turkish manufacturing industry. Advances in Production Engineering & Management, 15(1), 57-68.	Journal	University	427 manufacturing companies	Turkey	Europe	N
18	Zheng, T., Ardolino, M., Bacchetti, A., Perona, M., & Zanardini, M. (2020). The impacts of Industry 4.0: a descriptive survey in the Italian manufacturing sector. Journal of Manufacturing Technology Management, 31(5), 1085-1115.	Journal	University	103	Italy	Europe	N
19	Agostini, L., & Nosella, A. (2019). The adoption of Industry 4.0 technologies in SMEs: results of an international study. Management Decision, 58(4), 625-643.	Journal	University	163 SMEs	6 European regions in 5 countries (Italy - 2 regions, Poland, Germany, Austria, Hungary)	INT-EU	Y

	Title	Type of Publication	Authoring Institution	Number of respondents	Country of survey	Region coded	SME focus
20	Yu, F., & Schweisfurth, T. (2020). Industry 4.0 technology implementation in SMEs – A survey in the Danish-German border region. International Journal of Innovation Studies,	Journal	University	59	Denmark and Germany	INT-EU	Y
21	Gamache, S., Abdul-Nour, G., & Baril, C. (2020). Evaluation of the influence parameters of Industry 4.0 and their impact on the Quebec manufacturing SMEs: The first findings. Cogent Engineering, 7(1).	Journal	University	14	Canada (Quebec)	Canada	Y
22	Hamzeh, R., Zhong, R., & Xu, X. W. (2018). A Survey Study on Industry 4.0 for New Zealand Manufacturing. Procedia Manufacturing.	Journal	University	43 of 50	New Zealand	NZ	Y
23	Huang, C.-J., Talla Chicoma, E. D., & Huang, Y.-H. (2019). Evaluating the Factors that are Affecting the Implementation of Industry 4.0 Technologies in Manufacturing MSMEs, the Case of Peru. Processes, 7(3), 161.	Journal	University	49 of 70	Peru	South America	Y

	Title	Type of Publication	Authoring Institution	Number of respondents	Country of survey	Region coded	SME focus
24	Ratnasingam, J., Yi, L. Y., Azim, A. A. A., Halis, R., Liat, L. C., Khoo, A., . . . Amin, M. (2020). Assessing the Awareness and Readiness of the Malaysian Furniture Industry for Industry 4.0. BioResources, 15(3), 4866-4885	Journal	University	778	Malaysia	Asia	N

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