International Journal of Engineering Education Vol. 39, No. 2, pp. 429–440, 2023
Printed in Great Britain

0949-149X/91 $3.00+0.00

Use of a Delphi Research Process for Designing, Developing, and Assessing the Importance of Contemporary Advanced Manufacturing Curriculum*

GISELE RAGUSA, SATYANDRA K. GUPTA, QIANG HUANG, YONG CHEN, AZAD M. MADNI and SVEN KOENIG, LILIAN LEUNG
Viterbi School of Engineering, University of Southern California, Viterbi School of Engineering 1042 Downey Way DRB 235.
Los Angeles, CA 90089, USA. E-mail: ragusa@usc.edu, guptask@usc.edu, yongchen@usc.edu, qiang.huang@usc.edu, skoenig@usc.edu, azad.madni@usc.edu, lilianl@usc.edu

The manuscript describes a study of the design and development of advanced manufacturing engineering curriculum and competencies. The study employed a Delphi research technique to explore and determine the contemporary competencies necessary to prepare and train current and future manufacturing workforces. A multi-step Delphi research approach was used with advanced manufacturing industry experts to determine and refine the needed professional competencies in the manufacturing engineering world now and in the future. Eighty-eight subject matter experts from diverse industries participated in the research together with university faculty in advance manufacturing. The resulting core competencies from this research inform creation of flexible, multi-level advanced manufacturing curriculum necessary to prepare both inservice and preservice engineers for current and future workforces.

Keywords: manufacturing; competencies; engineering education; preservice; inservice; Delphi; subject matter experts

1. Introduction

Advanced manufacturing is key to keeping manufacturing engineering industries competitive by reducing cost, improving quality, and realizing innovative products that leverage new technologies [1]. Maintaining a vital and vibrant manufacturing workforce is also critical from a national and global security perspective. The deployment of advanced manufacturing technologies is changing the nature of the field and has the potential of creating new production jobs. However, as new manufacturing technologies are deployed, large sectors of workers find themselves without the requisite skills for competing in advanced manufacturing job markets [2, 3]. Simultaneously, companies interested in deploying new manufacturing technologies are unable to find workers with contemporary requisite skills for such rapidly changing industries. Therefore, many available manufacturing positions are left unfilled or filled with underprepared workers. To meet this important workforce need and to address the gaps in advanced manufacturing knowledge and skills globally, this research team set out to identify the specific content and strategic needs in advance manufacturing training and education in an effort to design, deploy and test new curriculum and aligned pedagogies to meet contemporary advanced manufacturing needs in diverse industries. This particular research presents a study completed to develop specific content needed in preservice (university) and inservice (professional) engineering education to address contemporary challenges in advanced manufacturing. Accordingly, a Delphi process was employed to conduct this workforce relevant engineering education research.

1.1 Manufacturing Curriculum

Manufacturing curriculum has historically drawn upon select aspects of mechanical engineering (modeling of physical processes), material science (understanding of materials being processed), and industrial engineering (control and optimization of manufacturing operations). Contemporary manufacturing engineering utilizes sophisticated and complex systems with multiple interacting components. Specifically, individual machines are complex mechatronic systems that are networked together to create production lines and cells. These, in turn, interact with enterprise-wide information systems such as resource planning software. Global supply chains have become the lifeblood of production engineering in large manufacturing corporations. Interactions with suppliers further increase the complexity of manufacturing. Given these multiple sources of complexity, a systems approach is essential to design, model, and operate manufacturing systems with the requisite degree of resilience to sustain contemporary supply and demand [4–14]. In this regard, advanced systems engineering concepts such as model-based systems engineering and systems-of-systems modeling and integration are becoming foundational skills for the next genera-

* Accepted 18 November 2022.

tion of manufacturing engineers. Recent advances in artificial intelligence (AI) and machine learning (ML) are expected to become a source of competitive advantage for improving system performance in global markets. Current educational approaches that largely focus on single disciplines are inadequate for training the next generation of the advanced manufacturing workforce. Simply combining courses from different engineering disciplines is at best a partial solution to educating future and current professional manufacturing engineers. A critical need to create an intellectually coherent educational program that exploits modern systems engineering principles, with contemporary challenge-to-solution foci to provide a holistic view of manufacturing has emerged.

Developing an innovative advanced manufacturing engineering curriculum requires close interaction and a feedback loop with industry professionals to identify core competencies that are needed in the modern manufacturing workforce. It is for this reason that this research team employed an iterative Delphi research process to collect and analyze such core manufacturing competency information in advance of creating innovative manufacturing curriculum.

The manufacturing workforce is highly diverse, comprising of individuals with varying education levels [15]. Broadly speaking, this workforce can be categorized into the following levels: (1) people with advanced degrees, (2) people with bachelor's degree, and (3) people with associate's degrees or technical certifications. To adequately prepare people from these three levels, colleges and universities must ensure that manufacturing curriculum and associated pedagogy can be helpful to people at each of these three levels. For example, additive manufacturing curriculum should be helpful to machine operators so they are able to diagnose causes of defects in parts. It should also help the design engineer to create a structure to fully exploit the capabilities of the process. It should assist the manufacturing engineer in optimizing process parameters by using the most contemporary advances in machine learning. To address this multidimensional need, this research team of interdisciplinary engineering faculty partnered with industry using a Delphi research process to identify and prioritize the contemporary core competencies needed for current and future engineers in advanced manufacturing. The long term goal of this research is to develop a set of courses and learning modules that address the most contemporary needs in advanced manufacturing. To initiate this process, this Delphi study was conducted to determine the needs in the manufacturing industry. This study addresses this need and is described herein.

1.2 Manufacturing Engineering Education

Many engineering education studies have developed and experimented with new curriculum, learning modules, and collaborations within and outside of colleges and universities to drive changes in manufacturing engineering education to enhance students' engagement, learning effectiveness, and career readiness. One of the major objectives of manufacturing engineering education is requiring students to analyze, improve, and select manufacturing processes through product design [16]. Active experimentation strengthens students' outcomes and engages them to exercise underlying skills such as data analysis, problem-solving, communication, and evaluation, all of which are contemporary processes aligned with engineering education pedagogical research [17]. Additive manufacturing (AM) was introduced as an effective tool to advance engineering education and connect students' theoretical knowledge to the practical skills necessary for preparedness for the manufacturing workforce [18]. Online learning modules were developed to support distance education by allowing students to engage in hands-on activities and laboratory exercises virtually and in self-paced learning environments [19].

Mirkouei and colleagues' research [17] found that students perceived the framework of active experimentation with hands-on learning as being more useful than traditional written assignments in engineering education. In this research, learning modules were developed through four frameworks: (1) define learning outcomes, (2) create instructional resources, (3) create active learning resources, and (4) create summative assessment. The hands-on activities for the modules provided students with active learning through phases: reflective observation to active experimentation and real-time data analytics. Compared to traditional pedagogical approaches, students were encouraged to innovate, think beyond traditions, and work with both their hands and minds. This approach also enabled students to practice communication through small group discussions. Although active learning and direct participation of students with project-based learning are ideal, they are often absent from current engineering classrooms.

In Motyl and Filippi's [18] systematic review of engineering education literature, a trend of advocation to improve manufacturing engineering education was noted, especially in courses dedicated to Industry 4.0 subjects – AM and manufacturing improvement. This change required the effort of providing cross institutional training. Including AM and 3D printing (3DP) as new skill sets related to product design were found to be fundamental in preparing young engineers for the manufacturing workforce. The courses incorporating AM and 3DP in Motyl and Filippi's review were found to facilitate students' deeper understanding, improve their design and visualization skills, and stimulated independent student learning.

The integration of design for additive manufacturing (DfAM) into engineering curriculum in Prabhu and colleagues' research [20] demonstrated change in students' DfAM self-efficacy in two paradigms – opportunistic and restrictive. Opportunistic DfAM centers on the capabilities of AM whereas restrictive DfAM accommodates the limitation of AM processes. Participating students in this research who received restrictive DfAM education demonstrated a significant change in their restrictive DfAM self-efficacy. Although DfAM did not affect participants' technical abilities of their AM design outcome in Prabhu and colleagues' research, it demonstrated that there is a need to emphasize the use of AM and opportunistic DfAM in manufacturing engineering educational interventions to stimulate active learning in preparing the next generation of the advance manufacturing engineering workforce.

In addition to active learning, meaningful learning is another important component of impactful engineering education. In Ullah's [16] study of incorporating e-learning in manufacturing engineering education, concept map e-learning was implemented in college classrooms to foster meaningful learning by relating new information to existing student knowledge. Often manufacturing engineering education is structured as academic discipline-based education. The objective of concept map based pedagogy is to accommodate both academic discipline-based learning and near-future employment needs by building knowledge around focus questions and integrating the aspects of educational outcomes, universe, and context. In Ullah's research, after student participants experienced an e-learning module with a concept map, they demonstrated meaningful learning behaviors by associating a concept with other related and unrelated concepts. Accordingly, incorporating concept maps which connect acquired knowledge with new materials can lead to better prepared workforces in engineering [19]. This approach requires contemporary content to be blended with acquired content to be effective. It is precisely from this research that the present study authors set out to determine which competencies and associated content are most needed to advance a new manufacturing curriculum in engineering education with interdisciplinary foci.

To narrow the gap between academics and industry, Melikyan and colleagues [21] initiated change in an engineer education model through a collaboration between the industry, Synopsys, and universities, with the goal of producing well-trained engineers for the current global industry. The Synopsys Armenia Educational Department (SAED) had as its goal for "Universities to go to Industries". Accordingly, the SAED partnered with five universities to support universities and students with degree completion including Bachelor's, Master's, and Ph.D.s in the fields of finance, computer software and hardware, with training for professors, and installation of classroom and laboratories within the company to prepare students for industry. This became a highly successful multi-university-industry partnership in which many of the SAED participants graduated with employment in a high-leading position at Synopsys, thereby underscoring the need for of partnerships between universities and industries to create a better engineering education environment which matches industry needs with university learning environments. This can better prepare students for the next generation of engineering workforces, especially those that involve advanced manufacturing.

2. Methodological Approach

This study posited to gather information via Delphi research that was employed to collect, study and understand the needs of contemporary manufacturing industries. Traditionally, the Delphi process is used to build consensus of ideas among diverse experts in fields. This research methodology builds upon the National Academy of Engineering (NAE)'s recognized team science, which leads to development of common vocabulary and consensus perspectives on subject matter that prior to employing Delphi strategies were often disparate and disconnected.

2.1 Study Sample and Recruitment

The study participants for this Delphi study were senior level industry leaders in diverse globally focused manufacturing engineering companies. Eighty-eight participants were recruited to participate in the study using a level of convenience sampling from those who the research team had some familiarization with and their colleagues. A subset of the participants (N = 12) were a part of the researchers' industry advisory boards. This recruitment process was deliberate as the research team intended to access information from what is referred to in Delphi style research as subject matter experts (SMEs). The participants represented such expertise in that they came from diverse engineering and computer science backgrounds and also were at advanced enough levels within their respective companies to fully understand the contemporary needs both of pre-employment engineers, (college and university students), and practicing engineers (professionals) in advanced manufacturing fields.

2.2 Research Questions

This research responded to several important questions:

- What are the most contemporary core competencies necessary to fully prepare students and practicing engineers for advanced manufacturing workforces?
- What are areas of advanced and precursing knowledge that practitioners in advance manufacturing need?
- In what ways can universities and industries work together to prepare the next generation of manufacturing engineering professionals?

To best respond to these important research questions, the research team identified a process by which they could gather comprehensive and contemporary information from subject matter experts using a well-defined, researched, and iterative process, thereby turning to a Delphi research process for their work.

2.3 Overview of the Delphi Process

The Delphi process is a research approach used to develop themes, needs, directions, and consensus about a topic or set of topics through a series of surveys and meetings, where information and results are fed back to subject matter experts (SMEs) between each data collection experience. This research methodology has been presented in various ways, including as a survey, procedure, method, and technique [22–24]. It was first used in technology forecasting studies initiated by the RAND Corporation and was used as an approach to solving complex issues in education. It has become a ubiquitous way of eliciting opinions from people with expertise, although the method itself and the purposes for which it has been used have been extensively modified by research across time [25].

The goal of employing a Delphi research process is to achieve consensus or 'general agreement' through a process of iteration. Group interaction in research is generally underpinned by an assumption that an individual's attitudes and beliefs do not form in a vacuum and that people listen to others' attitudes and understandings so that they can focus on their own understanding [26]. The main purpose of adopting a Delphi research process is to provide a structured approach to collecting data in situations where the only available alternatives are anecdotal or other entirely subjective approaches to data collection and analyses [22]. The features of anonymity, iteration with controlled feedback, statistical group response and expert input can facilitate consensus where there is contradictory or insufficient information to conclude informed results. There are many other group approaches to reaching consensus, including nominal working groups, brainstorming, and focus groups, but these have been found to be less appropriate to the development of a model for advancing training around new competencies [27]. The disadvantage with each of those techniques is their risk of accounting only for the perceptions of the most outspoken or opinionated members of a particular group or of focusing solely on interesting or controversial elements.

The Delphi research process has been found to be particularly useful for situations where a problem does not permit the application of precise analytical techniques, but can benefit from judgments on a collective basis; where the relevant specialists are in different but related fields and occupations and not in direct communication; where the number of specialists is too large to effectively interact in a face-to-face meeting exchange longitudinally [23, 25]. In particular, the Delphi process has been found to be an appropriate mechanism for ensuring that emergent differences between and within key stakeholder groups can be accounted for in a systematic way. The most obvious benefit in using the Delphi research process is that by guaranteeing anonymity in responses to individual items or topics, it is encouraged to provide opinions that are free of influences from others and therefore are more likely to be 'true' [24]. Anonymity encourages subject matter experts to make statements on the basis of their own professional knowledge and experience, rather than a more cautious institutional position [25]. By adopting this iterative research approach to data collection, the 'collective human intelligence capability' found in groups of people with expertise can be more appropriately harnessed [23]. In this research team's particular Delphi process, the researchers first convened a panel of subject matter experts to engage in a "group think" to identify an initial sent of advanced manufacturing competencies and then from that listing of competencies, a larger group of subject matter experts were sent a survey in which they could weigh in on and rate the relative importance of competencies to the manufacturing world from their professional perspective with anonymity.

2.4 Delphi Process Reliability and Validity

As with survey type methodology, researchers must ensure that processes have both high reliability and validity. The Delphi process differs from traditional survey data collection and analyses in two ways.

First, participant panel members are not selected randomly, but instead are deliberately selected because of their knowledge and experience – that is, due to their specific expertise, in the case with this research in diverse manufacturing companies [28]. Second, the number of participating members in a Delphi study may be much smaller than what is traditionally thought to be sufficient to guarantee the reliability of a survey [29].

Delphi research is an expert method [28, 29] as it is an approach used to collect experts' opinions, knowledge, and experiences concerning a certain problem or research question set. The reliability of the Delphi process is based on (1) selection of the experts, (2) size of the participant panels, and (3) conducting of the process, including constructing the prompts to which participants will respond and the process for establishing research consensus. In a Delphi study, an expert is defined as a person with excellent and recognized knowledge in the field, a wide interest in knowledge outside their own discipline, longitudinal experience, and willingness to create something new without being tied to traditional viewpoints [29]. It is also recommended that the participant panel should be as heterogeneous as possible to ensure discourse and an iterative achievement of consensus. With regard to the panel size, researchers also keep in mind that, even when research uses a randomized sampling method for surveys, the research questions also limit the population. The size of traditional survey type studies is often large, however size itself is not significant for reliability. Rather, the representativeness of the sample is an indicator of reliability. The literature related to Delphi research indicates that the number of panelists is primarily set at between 15 and 30 [28], the minimum is often set at twelve [30], but smaller and larger panels have been observed and have been quite effective. Typically, validity of the responses are primarily in the researchers' hands. How well have the prompts been formed to which participants have responded and set, does the panel consist of precisely those experts who have the best knowledge and experience, and are the responses accurately collected and analyzed become elements of research validity in a Delphi study [31].

With this in mind, for this advanced manufacturing engineering education research, the research team engaged in iterative planning strategies to ensure proper validity and reliability of this Delphi process. The reliability of this study is based on four arguments:

1. Robust subject matter expert participant group – The number of subject matter experts (SMEs) was adequate (12 + 76 = 88) vs the minimum in the Delphi literature, which varies from ten to fifteen SMEs.
2. The iterative nature of the process – a panel precursed sampling with the larger group of research participants.
3. The anonymity of the process – none of the SMEs knew who had said what during their process of completing their surveys, except for during the brainstorming process and associated initial draft core competency generation with a 12 member face-to-face panel. Thus, there was no fear of losing face or being identified as a representative of a certain stakeholder group.
4. The quality of the SMEs – The research team selected advanced manufacturing experts according to experience and knowledge, and all of the perceived stakeholders of developing advanced manufacturing curriculum were involved, making the study's participant group diverse in terms of expertise and knowledge of the manufacturing world.

In the study, the logic and the applicability of the results were recognized by the SMEs. The results of the Delphi process helped address the study's research questions and also produced more information and data than originally anticipated, thereby fully informing the competencies that needed to be addressed in creating advanced manufacturing curriculum and eventual aligned pedagogy to train and educate current and future manufacturing workforce members.

2.5 A Delphi Process in Advanced Manufacturing Engineering Education

The Delphi research process has not been a primary research method in the engineering education community thus far. However, a handful of researchers have used different variations of the Delphi process to identify important concepts in a variety of engineering educational contexts, including thermal and transport sciences [32], industrial engineering [33], engineering computing [34], engineering technology education [35], distance education [36], and engineering ethics [37]. The Delphi process has also been used to develop and improve engineering education policy [38].

There is yet to be research that employs a Delphi research process in an advanced manufacturing engineering context with a global focus [39]. The research team drew upon pivotal research and the literature above to extend the application and utility of the Delphi process to engineering education contexts, specifically to the conceptualization and development of contemporary, multi-leveled and multifaceted advanced manufacturing curriculum.

2.6 Iterations in the Delphi Research

The Delphi research process in this study involved three Delphi iteration steps of equal importance. Step one involved a focused session with twelve advanced manufacturing subject matter experts in which the research team explained the intent of the research and its ultimate curricular and workforce goals. During this step, small groups of three members each were convened to brainstorm on contemporary needs in the manufacturing field. This initial brainstorm was followed by a group report out and then, in step two, formulation of an initial set of core competencies in advanced manufacturing. Consensus building occurred during step two as all twelve SMEs weighed in on the listing and refinement of the competency list in advanced manufacturing. This step culminated with a consensus list of thirty core advance manufacturing competencies. In preparation for the third step in the Delphi research process, the research team first ended the consensus building meeting, charging the twelve SMEs to contemplate the list of core competencies in preparation for rating them by importance to the field using an e-survey sent only to the 12 initial SMEs. Resulting from this rating of the initial SME panel, the research team then expanded the list of SMEs to a broader industrial group of 76 participants, to be certain that the team had broad feedback and weigh-in on an adapted and adjusted set of thirty core competencies (resulting from the initial SME panel rating) from diverse industries all of which were deeply involved in advanced manufacturing. For step four in the Delphi process, the group of 76 SME participants + plus the 12 original SMEs was sent the listing of core competencies in the form of a second electronic survey. In this survey, the SMEs were asked to rate the core competencies on a 4-point Likert-type scale in accordance with degree of importance to the global world of advanced manufacturing. This process was intended to narrow the listing of core competencies so that the competencies could serve as curriculum topics, manufacturing skills and strategies that would be taught both to next generation and current practicing engineers in advanced manufacturing. In addition to asking the SMEs to rate the competencies, the researchers also asked the larger SME group to suggest edits to the descriptions of any core competencies that they believed did not accurately represent what they intended to describe.

Fig. 1 illustrates this multilevel, Delphi research process for this work. It underscores the importance of an iterative process for development of advanced manufacturing engineering education research to meet the diverse needs of inservice and preservice engineers.

3. Results

The results of this multi-step Delphi research are presented by the various iterative steps required to complete the full Delphi process. As previously described and illustrated in Fig. 1, step one and two of the process consisted of convening a small group (N = 12) of SMEs to brainstorm and create a listing of core competencies in advanced manufacturing. This resulted in a draft of 30 core competencies contained in Table 1.

Upon completion of creating and vetting this listing of competencies, the researchers recognized that the listing was too extensive and broad to

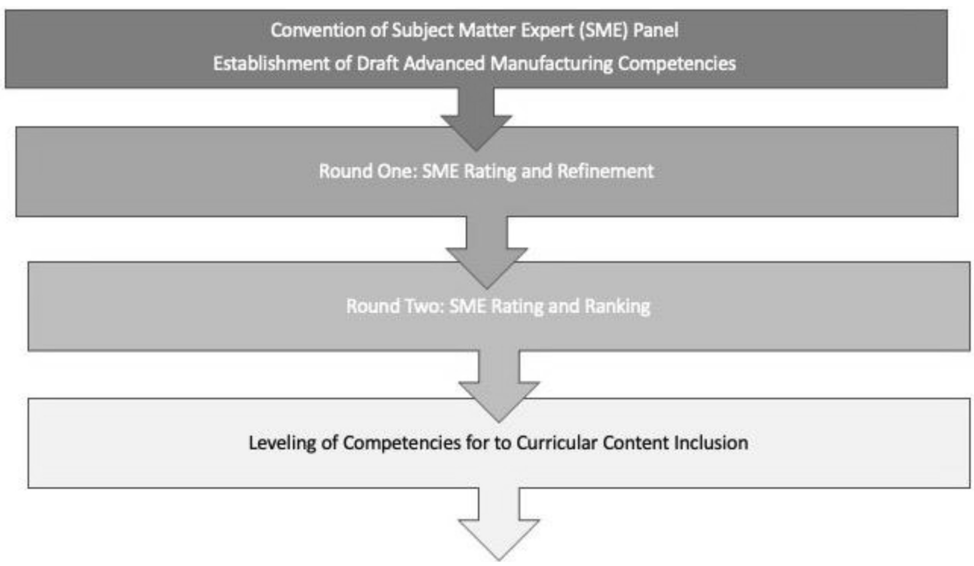

Fig. 1. Advanced manufacturing engineering iterative Delphi research model.

Table 1. Initial core competencies in advanced manufacturing engineering

• Engineers will identify opportunities for utilizing additive manufacturing to improve performance. • Engineers will exploit the capabilities of additive manufacturing by incorporating process constraints during the design stage. • Engineers will be able to use virtual prototyping to optimize product design. • Engineers will select the correct materials and processes for parts based on requirements. • Engineers will design parts by applying appropriate design rules for the selected process and material. • Engineers will design products for ease of assembly and manufacturing. • Engineers will estimate manufacturing costs using digital product models. • Engineers will create a digital twin for a given manufacturing process. • Engineers will select the right automation technology based on product requirements. • Engineers will develop system architecture based on system requirements. • Engineers will design an automated manufacturing cell with appropriate human interfaces. • Engineers will design integrated and secure cyber-physical (mechatronic) systems. • Engineers will verify systems using formal methods. • Engineers will select system features using trade-off analysis based on requirements. • Engineers will use analytics tools to diagnose problems. • Engineers will use machine learning to build process models. • Engineers will use resilience methods for coping with known-unknowns and unknown-unknowns to design manufacturing systems.	• Engineers will use artificial intelligence to optimize system operation. • Engineers will design products to ensure the feasibility of cost-effective manufacturing automation. • Engineers will determine the main cost drivers for the selected materials and process and be able to explain how product design influences cost. • Engineers will determine the advantages and limitations of various additive manufacturing technologies. • Engineers will use the application context to determine and utilize the system modeling and simulation approaches, and languages. • Engineers will use appropriate analysis tools for different life cycle phases of a system engineering project. • Engineers will use appropriate computational methods, including state machines, as well as deterministic and probabilistic modeling approaches to model the system. • Engineers will use verification and validation methods ranging from inspection, simulation-based analysis, demonstration, and testing. • Engineers will develop adaptive architectures that facilitate the introduction of cyber-secure, resilience methods, and measures. • Engineers will develop approaches to handle key integration challenges associated with legacy integration, human-system integration, and system of systems integration. • Engineers will understand the current advantages and limitations of a variety of AI methods and determine when and how to integrate them into intelligent systems. • Engineers will select, model, and analyze components of modern mechatronics systems. • Engineers will use appropriate software libraries for implementing machine learning approaches.

incorporate into one set of modules in advanced manufacturing. Accordingly, they set out to obtain additional feedback and expertise in determining which competencies were of highest priority for industries in advanced manufacturing. This resulted in the need for expanding the number of and diversity in expertise of SMEs from which they could obtain information. Resulting from this desire, eighty-eight SMEs were included in step three of the Delphi process. These SMEs were sent an electronic survey containing the listing contain in Table 1 and were asked to rate the core competencies by level of importance to the global manufacturing field. The results of this rating process are illustrated in Table 2(a and b). Table 2a addresses competencies associated with analytical foci while Table 2b are focused on design elements. The competencies are listed in order of rated importance by the SMEs.

These round 3 Delphi results indicate that eight of the thirty core competencies were rated highly important to the advanced manufacturing field by the majority of the eighty-eight subject matter experts. Furthermore, an additional six of the thirty core competencies sere highly rated by at least 40% of the SMEs. Of the core competencies that were not rated as highly important to the field by the majority of SMEs (50% or above) only two core competencies were rated as moderately important to the field by the majority of the SMEs (50% or above). Importantly, very few of the core competencies were rated as not important to the advanced manufacturing field by any SME. Across all competencies, no more than 2 SMEs of the eight-eight rated any competency as unimportant. This underscores the depth of thought that was enabled by the Delphi research process in determining the competencies necessary in advanced manufacturing. While each of the identified core competencies were rated highly by the SMEs, it is interesting to note that taken together, the design focused competencies were rated higher than the analytically focused competencies with some design focused competencies rated as much as 20% higher than analytically focused competencies. The researchers believe may be attributed to the ongoing practical approach that continues to be of focused in advanced manufacturing in industries.

As a final step in the Delphi process, the SMEs had an opportunity to suggest additional or revised core competencies and to provide written rationale for their selection or ratings. Interestingly, rather

Table 2a. Rated core competencies- analytical foci *(ordered by rated importance)*

Core Competency	Not Important	Somewhat Important	Moderately Important	Highly Important
Engineers will use verification and validation methods ranging from inspection, simulation-based analysis, demonstration, and testing.	0.00%	17.74%	22.58%	59.68%
Engineers will use analytics tools to diagnose problems.	1.61%	14.52%	29.03%	54.84%
Engineers will identify opportunities for utilizing additive manufacturing to improve performance.	0.00%	11.84%	34.21%	53.95%
Engineers will select system features using trade-off analysis based on requirements.	1.61%	19.35%	33.87%	45.16%
Engineers will understand the current advantages and limitations of a variety of AI methods and determine when and how to integrate them into intelligent systems.	4.84%	16.13%	38.71%	40.32%
Engineers will select, model, and analyze components of modern mechatronics systems.	1.61%	16.13%	43.55%	38.71%
Engineers will use machine learning to build process models.	1.61%	37.10%	24.19%	37.10%
Engineers will use appropriate analysis tools for different life cycle phases of a system engineering project.	1.61%	22.58%	40.32%	35.48%
Engineers will use appropriate computational methods, including state machines, as well as deterministic and probabilistic modeling approaches to model the system.	0.00%	27.42%	37.10%	35.48%
Engineers will estimate manufacturing costs using digital product models.	0.00%	21.62%	44.59%	33.78%
Engineers will use artificial intelligence to optimize system operation.	6.45%	27.42%	33.87%	32.26%
Engineers will use the application context to determine and utilize the system modeling and simulation approaches, and languages.	1.61%	33.87%	35.48%	29.03%
Engineers will use appropriate software libraries for implementing machine learning approaches.	3.23%	20.97%	50.00%	25.81%
Engineers will verify systems using formal methods.	6.56%	26.23%	44.26%	22.95%

Table 2b. Rated core competencies- design foci *(ordered by rated importance)*

Core Competency	Not Important	Somewhat Important	Moderately Important	Highly Important
Engineers will select the correct materials and processes for parts based on requirements.	0.00%	8.11%	20.27%	76.62%
Engineers will design products for ease of assembly and manufacturing.	0.00%	1.33%	31.51%	63.01%
Engineers will be able to use virtual prototyping to optimize product design.	0.00%	6.76%	32.43%	60.81%
Engineers will design parts by applying appropriate design rules for the selected process and material.	1.37%	9.59%	28.77%	60.27%
Engineers will determine the main cost drivers for the selected materials and process and be able to explain how product design influences cost.	1.61%	11.29%	37.10%	50.00%
Engineers will exploit the capabilities of additive manufacturing by incorporating process constraints during the design stage.	0.00%	13.51%	40.54%	45.95%
Engineers will design products to ensure the feasibility of cost-effective manufacturing automation.	1.64%	14.75%	37.70%	45.90%
Engineers will determine the advantages and limitations of various additive manufacturing technologies.	0.00%	12.90%	41.94%	45.16%
Engineers will select the right automation technology based on product requirements.	0.00%	18.92%	39.19%	41.89%
Engineers will develop approaches to handle key integration challenges associated with legacy integration, human-system integration, and system of systems integration.	1.61%	24.19%	37.10%	37.10%
Engineers will design an automated manufacturing cells with appropriate human interfaces.	1.61%	30.65%	32.26%	35.48%
Engineers will design integrated and secure cyber-physical (mechatronic) systems.	4.84%	19.35%	40.32%	35.48%
Engineers will create a digital twin for a given manufacturing process.	2.70%	20.27%	43.24%	33.78%
Engineers will develop system architecture based on system requirements.	2.70%	20.27%	44.59%	32.43%
Engineers will develop adaptive architectures that facilitate the introduction of cyber-secure, resilience methods, and measures.	8.06%	30.65%	33.87%	27.42%
Engineers will use resilience methods for coping with known-unknowns and unknown-unknowns to design manufacturing systems.	4.84%	17.74%	54.84%	22.58%

than revise the competencies or suggest additional competencies for the core list, the SMEs chose to discuss the relative importance of competencies to varying fields within manufacturing in their rationale. They considered the core competencies listing an "exhaustive" one, also cited the role of interdisciplinarity in making it difficult to rate and narrow the core competency listing. Some SMEs did list additional elements of potential core competencies, however, upon close qualitative review of these suggestions, the research team recognized how such elements actually were contained in one or more of the existing core competencies that the SMEs were asked to rate. Additionally, some SMEs suggested "simpler" wording of the competencies to enable engineers at diverse levels of training to understand the content. This finding spoke to the importance of leveling the curriculum that would result from the core competencies to meet diverse student learning needs in engineering education programs. Other SMEs indicated that the "manufacturing market had not yet caught up with" areas including artificial intelligence and machine learning in their company or firm, and therefore these areas would require a great deal of professional training for practicing engineers. This finding highlighted the importance of providing training and engineering education for practicing engineers in addition to preservice engineers that would be flexible to meet their diverse needs. As such, the research team considered the potential flexibility that could be exploited using a modular approach to curriculum design and development for such in-service engineers. Other SMEs indicated that the technologies in small to mid-sized companies may make it difficult for engineers to practice what they learned in potential course modules. This further underscored the need for flexibility and in-course practice for those who may already be in engineering employment when accessing future course content. This finding was supported by the reviewed research in engineering education presented in this manuscript.

4. Discussion of Results

The results of this Delphi study has informed significant curriculum content themes in the areas connected to the highly rated core competencies from this Delphi study on advanced manufacturing engineering education. This has guided the research team in creating a thematic approach to course module development that will lead to more contemporarily informed future and current engineers involved in global manufacturing industries. It is important to note that the rated competencies, when divided into the two categories of design focused competencies, and analytically focused competencies, the competencies rated of highest importance fell within the design category. As previously noted, this speaks to the SMEs' perceived need for advanced design. It is of critical importance, however, that some of the competencies blended both design and analytical elements thereby underscoring the increasing need for competence in applied analysis that informs manufacturing design. This is particularly relevant when advanced technologies are paired with machine learning and artificial intelligence. Accordingly, these most contemporary needs rose to the top during the SME competency ratings.

4.1 Study Limitations

This study is limited solely by the number of SMEs who participated in the research. While the sample size is robust, especially for a Delphi study, the SMEs are practitioner leaders in the field associated with advanced manufacturing, so therefore their focus in not solely on research. The goal of the research is to identify contemporary practitioner needs in advanced manufacturing so therefore, the research has both practical and research significance.

4.2 Future Work

Currently and in the near future, curriculum in advanced manufacturing resulting from this Delphi research is under development. Accordingly, as a final analytical step after the four step Delphi research process, the research team has categorized the highest rated core competencies into thematic curricular content areas to which they will group the final core competencies and formulate course modules that can be used both in university degree programs and also leveled according to students' and practicing engineers' competency needs and skill levels and infused into courses and professional education for use nationally and globally. This research team is now in the process of taking the competencies developed during the Delphi research process and developing and piloting multi-leveled modular curriculum that will be ongoingly tested, evaluated, revised and utilized in colleges, universities and for inservice engineering professional development globally to inform and prepare the next generation of engineers with the necessary interdisciplinary skills, knowledge and strategies in advanced manufacturing.

5. Conclusions

The need for leveled curriculum to meet the diverse entry level skill set needs of undergraduate students was reinforced from this Delphi research. This is of particular importance for students who may have access to curriculum resulting from this research from two-year colleges. Furthermore, some of the suggestions made by the SMEs further underscored the importance of creating maximal flexibility in topic areas generated by the core competencies so that practicing engineers with varying backgrounds in terms of technology expertise could gain competence in the areas that they or their supervisors determined most important for their current workplace. Additionally, the fact that the design focused competencies were rated highest by the SMEs identified the need for new designs in advanced manufacturing. Some of the identified competencies combined both design and analytical approaches often to the degree that the analytical approaches could inform the design of new manufacturing technologies. This provides information that can inform both university curriculum and support the professional development needs that engineers and computer scientists in the manufacturing field currently have and will use in the not too distant future.

Acknowledgements – This research is based upon work supported by the National Science Foundation under Grant #1935712. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

References

1. National Academy of Engineering, *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work*, The National Academies Press, Washington, DC, USA, 2015.
2. Addressing America's Reskilling Challenge, https://trumpwhitehouse.archives.gov/wp-content/uploads/2018/07/Addressing-Americas-Reskilling-Challenge.pdf, Accessed 13 July 2022.
3. Reskilling America's Workforce Workshop, http://www.bhef.com/news-events/events/reskilling-americas-workforce-workshop, Accessed 13 July 2022.
4. T. J. Bayer, S. Chung, B. Cole, B. Cooke, F. Dekens, C. Delp, I. Gontijo, K. Lewis, M. Moshir, Rasmussen and D. Wagner, Model based systems engineering on the Europa mission concept study, *INCOSE International Symposium*, **23**(1), pp. 694–709, 2012.
5. E. A. Bjorkman, S. Sarkani and T. A. Mazzuchi, Using model-based systems engineering as a framework for improving test and evaluation activities, *Systems Engineering*, **16**(3), pp. 346–362, 2012.
6. J. A. Estefan, Methodology and metrics activity: Overview, update, and breakout agenda, *INCOSE International Workshop*, Phoenix, AZ, USA, January 2011.
7. S. Friedenthal and C. Oster, *Architecting Spacecraft with SysML: A Model-based Systems Engineering Approach*, CreateSpace Independent Publishing Platform, Scotts Valley, CA, USA, 2017.
8. E. Fosse, A. Devereaux, C. Harmon and M. Lefland, Inheriting curiosity: Leveraging MBSE to build Mars 2020, *AIAA SPACE 2015 Conference and Exposition*, Pasadena, CA, USA, September 2015.
9. E. A. Lee, Constructive models of discrete and continuous physical phenomena, *IEEE Access*, **2**, pp. 797–821, 2014.
10. D. W. Orellana and A. M. Madni, Human system integration ontology: Enhancing model based systems engineering to evaluate human-system performance, *Procedia Computer Science*, **28**, pp. 19–25, 2014.
11. A. Qamar, C. Paredis, J. Vikander and C. During, Dependency modeling and model management in mechatronic design, *Journal of Computing and Information Science in Engineering*, **12**(4), pp. 1–10, 2012.
12. M. Schluse, L. Atorf and J. Rossmann, Experimentable digital twins for model-based systems engineering and simulation-based development, *IEEE International Systems Conference*, Québec, Canada, April 2017.
13. J. D'Ambrosio and G. Soremekun, Systems engineering challenges and MBSE opportunities for automotive system design*, 2017 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Banff, Canada, October 2017.
14. A. M. Madni, Transdisciplinary systems engineering: Exploiting disciplinary convergence to address grand challenges, *IEEE SMC Magazine*, **5**(2), pp. 6–11, 2019.
15. K. S. Campbell, *Manufacturing Workforce Development Playbook*, Summit Media Group, New York, NY, USA, 2014.
16. A. S. Ullah, On the interplay of manufacturing engineering education and e-learning, *International Journal of Mechanical Engineering Education*, **44**(3), pp. 233–254, 2016.
17. A. Mirkouei, R. Bhinge, C. McCoy, K. R. Haapala and D. A. Dornfeld, A pedagogical module framework to improve scaffolded active learning in manufacturing engineering education, *Procedia Manufacturing*, **5**, pp. 1128–1142. 2016.
18. B. Motyl and S. Filippi, Trends in engineering education for additive manufacturing in the industry 4.0 era: a systematic literature review*, International Journal on Interactive Design and Manufacturing*, **15**(1), pp. 103–106, 2020.
19. C. Saygin and F. Kahraman, A web-based programmable logic controller laboratory for manufacturing engineering education, *International Journal of Advanced Manufacturing Technology*, **24**(7), pp. 590–598, 2004.
20. R. Prabhu, S. R. Miller, T. W. Simpson and N. A. Meisel, Exploring the effects of additive manufacturing education on students' engineering design process and its outcomes, *Journal of Mechanical Des*ign, **142**(4), 2020.
21. V. Melikyan, H. Musayelyan, G. Markosyan, K. Bartleson, W. Wood and R. Goldman, An experience of industry/ University collaboration in microelectronics education, *Proceedings of the 7 European Workshop on Microelectronics Education*, pp. 148–149, 2008.
22. D. Broomfield and G. M. Humphris, Using the Delphi technique to identify the cancer education requirements of general practitioners, *Medical Education*, **35**(10), pp. 928–937, 2011.
23. H. A. Linstone and M. Turoff, *The Delphi method: Techniques and applications*, Addison-Wesley, Boston, MA, USA, 1975
24. R. Snyder-Halpern, Indicators of organizational readiness for clinical information technology/ systems innovation: a Delphi study, *International Journal of Medical Informatics*, **63**(3), pp. 179–204, 2011.
25. U. G. Gupta and R. E. Clarke, Theory and applications of the Delphi technique: A bibliography (1974–1994), *Technological Forecasting and Social Change*, **53**(2), pp. 185–211, 1996.
26. J. Reed and V. R. Payton, Focus groups: Issues of analysis and interpretation, *Journal of Advanced Nursing*, **26**(4), pp. 765–771, 1997.

27. D. K. Deardorff, Identification and assessment of intercultural competence as a student outcome of internationalization, *Journal of Studies in International Education*, **10**(3), pp. 241–266, 2006.
28. R. Loo, The Delphi method: a powerful tool for strategic management, *Policing: An International Journal of Police Strategies & Management*, **25**(4), pp. 762–769, 2002.
29. C. Powell, The Delphi technique: Myths and realities, *Journal of Advanced Nursing*, **41**(4), pp. 376–382, 2003.
30. P. Buriak and G. C. Shinn, Mission, Initiatives, and obstacles to research in agricultural education: A national Delphi using external decision-makers, *Journal of Agriculture Education*, **30**(4), pp. 14–23, 1987.
31. F. Hasson, S. Keeney and H. McKenna, Research guidelines for the Delphi survey technique, *Journal of Advanced Nursing*, **32**(4), pp. 1008–1015, 2000.
32. R. A. Streveler, B. M. Olds, R. L. Miller and M. A. Nelson, Using a Delphi study to identify the most difficult concepts for students to master thermal and transport science, *American Society for Engineering Education Annual Conference & Exposition*, Nashville, TN, USA, June 2003.
33. H. Eskandari, S. Sala-Diakanda, S. Furterer, L. Rabelo, L. Crumpton-Young and K. Williams, Enhancing the undergraduate industrial engineering curriculum: Defining desired characteristics and emerging topics, *Education + Training*, **49**(1), pp. 45–55, 2007.
34. K. Goldman, P. Gross, C. Heeren, G. Herman, L. Kaczmarczky, M. C. Loui and C. Zilles, Identifying important and difficult concepts in introductory computing courses using a Delphi process, *SIGCSE' 08: The 39th ACM Technical Symposium on Computer Science Education*, Portland, OR, USA, March 2008, pp. 256–160, 2008.
35. A. Rossouw, M. Hacker and M. K. de Vries, Concepts and contexts in engineering and technology education: An international and interdisciplinary Delphi study, *International Journal of Technology and Design Education*, **21**(4), pp. 409–424, 2010.
36. T. Williams, The reflective model of intercultural competency: A multidimensional, qualitative approach to study abroad assessment, *The Interdisciplinary Journal of Study Abroad*, **18**(1), pp. 289–306, 2007.
37. J. Li and S. Fu, A systematic approach to engineering ethics education, *Science and Engineering Ethics*, **18**(2), pp. 339–349, 2012.
38. K. Korhonen-Yrjänheikki, T. Tukiainen and M. Takala, New challenging approaches to engineering education: Enhancing University-Industry co-operation, *European Journal of Engineering Education*, **32**(2), pp. 167–179, 2007.
39. G. Ragusa, Engineering Global Preparedness: Parallel Pedagogies, Experientially Focused Instructional Practice, *International Journal of Engineering Education.* **30**(2), pp. 1–12, 2014.

Gisele Ragusa is a professor at the University of Southern California (USC) in the Viterbi School of Engineering's Division of Engineering Education. She chairs USC's STEM Education and Research Consortium. Her research interests and areas of expertise include: engineering education, college access, STEM mentorship, STEM teacher education and retention, literacy education, content literacy, early childhood, special education and deaf education as well as assessment and measurement in STEM education. She teaches courses in engineering design, research design, measurement theory, engineering ethics, critical pedagogy in STEM and courses in learning and instructional theory. She has extensive expertise in assessment, psychometrics, advanced quantitative analyses, and multimodal research design. Prior to joining USC, Dr. Ragusa held an appointment as an assistant professor in special education and bilingual education at California State University, Northridge in addition to a faculty position at Pacific Oaks College. She is active in many professional associations in engineering education. She has been the principal investigator on several federal grants through the US Department of Education, the National Institute of Health, and the National Science Foundation.

Satyandra K. Gupta is Smith International Professor in the Department of Aerospace and Mechanical Engineering at the University of Southern California. He is the founding Director of the Center for Advanced Manufacturing at the University of Southern California. He served as a program director for the National Robotics Initiative at the National Science Foundation from September 2012 to September 2014. Dr. Gupta's interest is in the area of physics-aware decision making to facilitate automation. He is specifically interested in automation challenges related to Engineering Design, Manufacturing, and Robotics. He has published more than three hundred technical articles. He is a fellow of the American Society of Mechanical Engineers (ASME) and editor of ASME Journal of Computing and Information Science in Engineering. Dr. Gupta has received several honors and awards for his research contributions. Representative examples include: Young Investigator Award from the Office of Naval Research in 2000, Robert W. Galvin Outstanding Young Manufacturing Engineer Award from the Society of Manufacturing Engineers in 2001, CAREER Award from the National Science Foundation in 2001, Presidential Early Career Award for Scientists and Engineers (PECASE) in 2001, Invention of the Year Award at the University of Maryland in 2007, Kos Ishii-Toshiba Award from ASME Design for Manufacturing and the Life Cycle Committee in 2011, Excellence in Research Award from ASME Computers and Information in Engineering Division in 2013, and Distinguished Alumnus Award from Indian Institute of Technology, Roorkee in 2014.

Yong Chen is a professor of Aerospace and Mechanical Engineering and Industrial and Systems Engineering at the University of Southern California. His research focuses on additive manufacturing (3D printing) in micro- and meso-scales, especially modeling, analyzing, synthesizing, and optimizing digital design and manufacturing. Dr. Chen has published more than 180 publications in refereed journals and conferences. He received over ten Best/Outstanding Paper Awards in major design and manufacturing journals and conferences. Other major awards he received include the National Science Foundation Faculty Early Career Development (CAREER) Award in 2012, the Outstanding Young Manufacturing Engineer Award from the Society of Manufacturing Engineers (SME) in 2008, and a Leadership and Service Award from the ASME CIE division in 2010. He was invited to the National Academy of Engineering (NAE) Frontiers of Engineering Symposium in 2009, 2013, and 2015, respectively. Dr. Chen is a Fellow of American Society of

Mechanical Engineers (ASME). He has served as conference/program chairs as well as keynote speakers in several international conferences, including the Conference Chair of the 2017 International Manufacturing Research Conference (NAMRC/MSEC/ICM&P), the Program Co-Chair of the 2019 International Design Engineering Technical Conferences (IDETC), and the Program Co-Chair of the 2021 and 2022 Manufacturing Science and Engineering Conference (MSEC). At USC, Dr. Chen teaches design and manufacturing related courses to undergraduate and graduate students. He also helped students and collaborators create five startup companies related to 3D printing.

Qiang Huang is a professor of Industrial and Systems Engineering at the University of Southern California. He conducts research that focuses on engineering-informed machine learning and data analytics for advanced manufacturing systems, with special emphasis on Integrated Nanomanufacturing and Nanoinformatics (INN) and Machine Learning for Additive Manufacturing (ML4AM). His research has been supported by National Science Foundation (NSF) (including NSF CAREER award) and Office of Naval Research. He was the holder of Gordon S. Marshall Early Career Chair in Engineering at USC from 2012 to 2016. Prof. Huang received 2013 IEEE Transactions on Automation Science and Engineering Best Paper Award. He is Department Editor for IISE Transactions and Associate Editor for ASME Transactions, Journal of Manufacturing Science and Engineering. He also served an Associate Editor for IEEE Transactions on Automation Science and Engineering and for IEEE Robotics and Automation Letters.

Sven Koenig is Dean's Professor of Computer Science at the University of Southern California. His research centers around techniques for decision making (planning and learning) that enable single situated agents (such as robots or decision-support systems) and teams of agents to act intelligently in their environments and exhibit goal-directed behavior in real-time, even if they have only incomplete knowledge of their environment, imperfect abilities to manipulate it, limited or noisy perception or insufficient reasoning speed. Sven is a fellow of the Association for the Advancement of Artificial Intelligence (AAAI), the Association for Computing Machinery (ACM), the Institute of Electrical and Electronics Engineers (IEEE), and the American Association for the Advancement of Science (AAAS). Additional information about Sven can be found on his webpages: idm-lab.org.

Azad M. Madni is University Professor of Astronautical Engineering, holder of the Northrop Grumman Fred O'Green Chair in Engineering, and Executive Director of the Systems Architecting and Engineering Program in University of Southern California's Viterbi School of Engineering. He has joint courtesy appointments in the Rossier School of Education and Keck School of Medicine. He is the founding director of the Distributed Autonomy and Intelligent Systems Laboratory, and faculty affiliate of USC's Ginsburg Institute of Biomedical Therapeutics in the Keck School of Medicine. A member of the Academy of Engineering, he is the recipient of the 2023 *NAE Gordon Prize for Innovation in Engineering and Technology Education.* A Life Fellow of IEEE, he is the recipient of the 2023 *IEEE Simon Ramo Medal* for exceptional achievement in systems engineering and systems science. He is also a Life Fellow/Fellow of AAAS, AIAA, INCOSE, IISE, IETE, AIMBE, AAIA, WAS, and SDPS. He has more than 400 publications comprising journal papers, book chapters, peer-reviewed conference publications, and research reports. He is the author of *Transdisciplinary Systems Engineering: Exploiting Convergence in a Hyperconnected World* (Springer, 2018), co-author of *Tradeoff Decisions in Systems Design* (Springer, 2016), and co-author of *Deep Learning Networks – Design, Development and Deployment* (Springer, expected 2023). He is the Co-EIC of Conference on Systems Engineering Research Series (Springer) and co-founder and chair of IEEE SMC Technical Committee on Model Based Systems Engineering. Since 2008, he has been serving as the General Chair and Organizer of the Conference on Systems Engineering Research when it is hosted by USC. He received his PhD, MS and BS degrees in Engineering from UCLA. He is a graduate of the AEA/Stanford Executive Institute Program for Senior Executives.

Lilian Leung is a program specialist at the University of Southern California (USC) in the Viterbi School of Engineering's Division of Engineering Education. She specializes in program management, professional development, data-driven decision making, interpersonal communication, and professional leadership. She focuses on initiating changes and closing the equity gap in the culture of Science, Technology, Engineering, and Mathematics (STEM) education and Community College students. Lilian received a Bachelor of art (BA) degree in Applied Mathematics and a Minor in Science and Math Education from the University of California, Berkeley in 2018. He received a Master of Science in Education (MS Ed.) and a graduate certification in Leadership in Technology Integration in 2020 from the Johns Hopkins University.