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What is Advanced Manufacturing? Exploring the Topography of Definitions

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Abstract

Global economists have cited advanced manufacturing (AM) as one of the fastest growing, dynamic, and economically instrumental industry sectors in the world. In response, many community colleges and undergraduate-serving institutions have established technician education programs to prepare future workers to support AM vitality and innovation. However, in the rush to couple market and training demands, stakeholders have not agreed upon a definition of the field. Without a central notion of AM, the competencies and professional identities of AM workers are likewise unclear. In an effort to address this consensus gap, we undertook an extensive systematic review of AM definitions to chart of sector's topography, in an effort to understand AM's breadth and depth. The goals of this study were to: 1) define AM as perceived by policymakers and 2) identify important concepts and contextual factors that comprise and shape our understanding of AM. In this study, we used systematic policy and literature review approach to analyze canonical and research-based publications pertaining to AM's origins, components, and operational definitions. We classified, compared, and synthesized definitions of AM depending by stakeholder, for example, professional organizations, government agencies, or educational program accreditors. Among our notable findings is that in the eyes of policymakers, manufacturers are advanced not because they make certain products, but because they have adopted sophisticated business models and production techniques. Advanced manufacturers typically use a combination of three factors to remain competitive: "advanced knowledge," "advanced processes," and "advanced business models." This study is both timely and important because in a dynamic field such as AM, educators and industry leaders must work together to meet workforce needs. Clear understanding of AM can inform competency models, bodies of knowledge, and empirical research that documents school-to-career pathways. Both our findings and our methods may shed light on the nature of related technical fields and offer industry and education strategies to ensure their alignment.

Overview

Having a strong domestic manufacturing base is vital to the United States innovation leadership. Technology-rich advanced manufacturing (AM) provides an important foundation for learning and developing process skills and capabilities that are increasingly intertwined with core research and development in industry sectors (e.g., health care, construction, automotive) most important to the country's economic future [1]. AM is essential to the U.S. economy because it is the main pipeline for new products and productivity-enhancing processes.

In response to the growing global competition, many manufacturing companies are in the process of adopting advanced manufacturing technologies to improve their business operations. Recent advances in machine learning, biotechnology and materials science are creating new opportunities for global competition in manufacturing based on scientific and technological innovation. Though the United States still leads the world in scientific and technological innovation and it must protect and leverage this strength to rapidly and efficiently develop and transition new manufacturing technologies into practice.

Where major challenges in the industry include finding ways to maintain the balance production with continuous innovation and skilled worker demands, some of the problems include that there is no set definition for AM and there are different perspectives to understand this field as a universal definition of Advanced Manufacturing does not exist. However, as the Editor-in-Chief of *IndustryWeek* noted:

> [W]e haven't agreed on what the term 'advanced manufacturing' means, let alone on how we should measure it…[H]aving a variety of definitions of 'advanced manufacturing' has contributed to over a decade of underinvestment in U.S. manufacturing—by both public policymakers and too many business leaders. Without strong agreement about what advanced manufacturing means, we've over-valued some segments of the manufacturing sector and under-valued others [2].

Defining and measuring "advanced manufacturing" is a critical step not only in driving public and private investment, but also signaling to potential workers the viability of AM as a professional path; before prospective workers, investors, and regulators can become involved in AM, they must understand the landscape of the field. Think of advanced manufacturing as a sea in which educational, industry, and governmental stakeholders exist, and lacking a settled AM definition, with uncertain proximity to an another. An AM definition provides boundaries and adjacencies that can yield crucial unity to all stakeholders.

In this study, we investigate different ways AM is defined among key stakeholders in government, industry, and education We will pursue this research through following question: RQ1. To what extent key policy documents define AM in ways that are compatible or in conflict?

Literature Review

AM is an industry sector, therefore preparation for AM employees must take place in the context of an academic discipline. In this section, we will address how AM has grown and evolved to become a distinct industry sector as well as the relationship between industry sectors and professional preparation. By examining the industry and educational perspectives, we provide important context for the importance of policy and demonstrate potential boundaries and boundary spanners [3-5] in AM's enactment.

Industry, Education, and Government in a Professional Discipline

Foucault identified that disciplines emerge and evolve "in response to particular needs" [6, p.138] as societies and economies change and grow. Foucault's work illuminates how these needs become academic disciplines through education and training; specialization; and stages through which individuals need to progress to become technically fluent in a subject [6]. Detailed characterization, classification and specialization develop firm foundations to embed disciplines as distinct knowledge bases [7] and communities of practice [8].

Figure 1 illustrates the intertwined evolution of a profession's preparation and practice [9]. As Figure 1 suggests, the enactment of a professional discipline is guided both by ethics and standards of practice; these activities define competencies, job roles, and ultimately career paths. Professional societies codify these elements by defining ethics and competencies, but also by

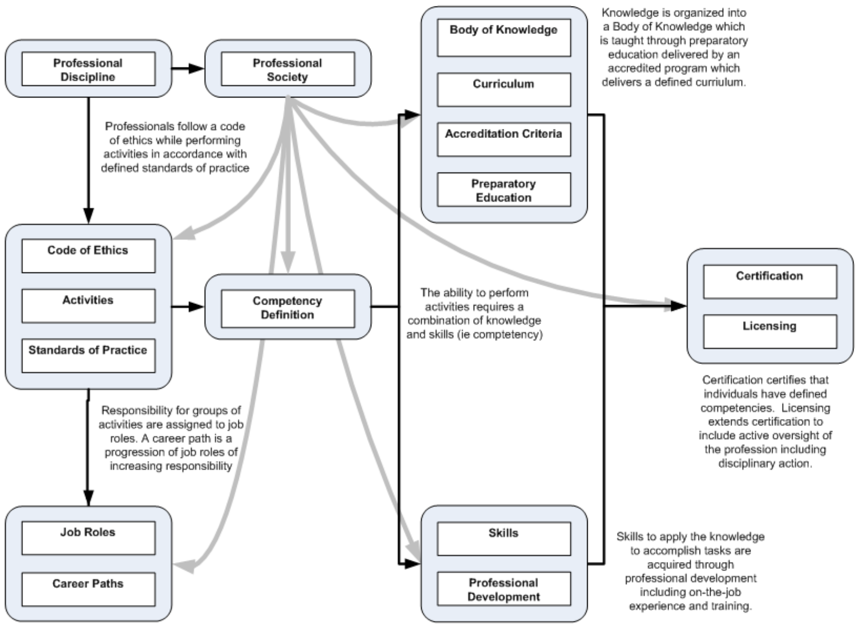

Figure 1. Model of a Professional Discipline [6]

reflecting professional performance. Professional societies span another boundary: governmental. By promoting and facilitating certification and licensure, professional societies legitimize and allow external bodies to monitor and enforce professional performance. In this way, government spans the boundaries of industry and education.

As a professional discipline evolves, stakeholders distill a body of accumulated specialist knowledge, expressed in standards curriculum, institutionalized through accreditation, and enculturated through preparatory education. Members of a professional discipline exercise and update their discipline through skills performance and professional development [10, 11]. Professional disciplines address needs which are not static, so they continue to evolve through technological and intellectual development; professionals are expected to keep abreast of and continually master their disciplinary knowledge [6, p.160-161]. Professional practice is a set of applications from a field of study; no field can develop without eventually facing technical or societal challenges, and practice is necessary for surmounting barriers [12]. To ensure consistency and ethical conduct, often government is involved in some way as a monitor or enforcer.

Practically oriented disciplines may in fact be multi-hybrid or multi-disciplinary, drawing on a number of different disciplines, which complicates the industry, educational, and governmental influences to which they must respond [10, 13]. For applied disciplines like technical work fields, strong links to a recognized career path can emphasize their distinctive nature through a feedback mechanism between the institutional development of a curriculum and the professionalization of the discipline. In these cases, the disciplinary knowledge focuses on relevant skills for employment outside of institutional education; while the coalescence of this knowledge into coherent theory, the methods and research to advance the knowledge and the curriculum developed to teach it, are internal to the academic domain of the educational institution. This feedback loop ensures that the discipline stays aligned to both the needs of the job market it feeds but also retains intellectual rigor, as show in in Figure 2 [14].

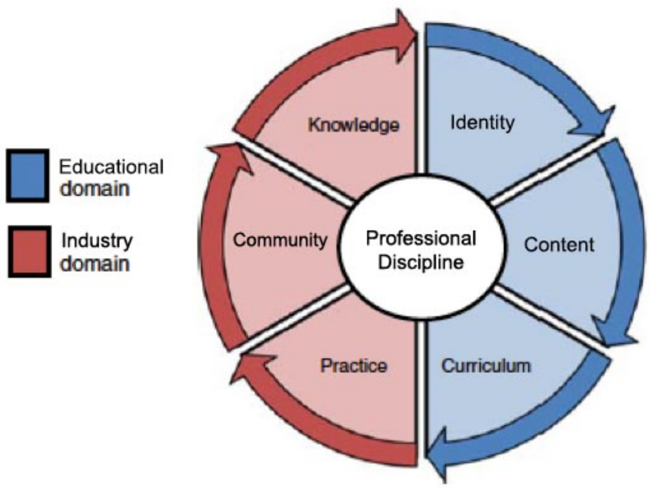

Figure 2. Professional Discipline Enactment Cycle [11]

Figure 2 illustrates that a professional discipline has two main elements, education and industry. As learners identify themselves as professionals in a field, they embody content through curriculum, which they then practice at work. Workers in an industry form a community which shares and encodes knowledge, forming the basis for an identity that can be seen and understood by future professionals. Professional societies have an important boundary spanning role to play in this cycle since they promote identity to prospective members and provide community support for existing professionals.

The Evolution of AM as a Discipline and a Profession

AM's bears many hallmarks of prevailing theories [e.g., 7, 14, 15] of disciplinary and professional evolution from engineering and engineering technology (ET). Since mid-1900s, engineering has evolved in its technical as well as conceptual aspects. Figure 3 provides an overview timeline of engineering technology.

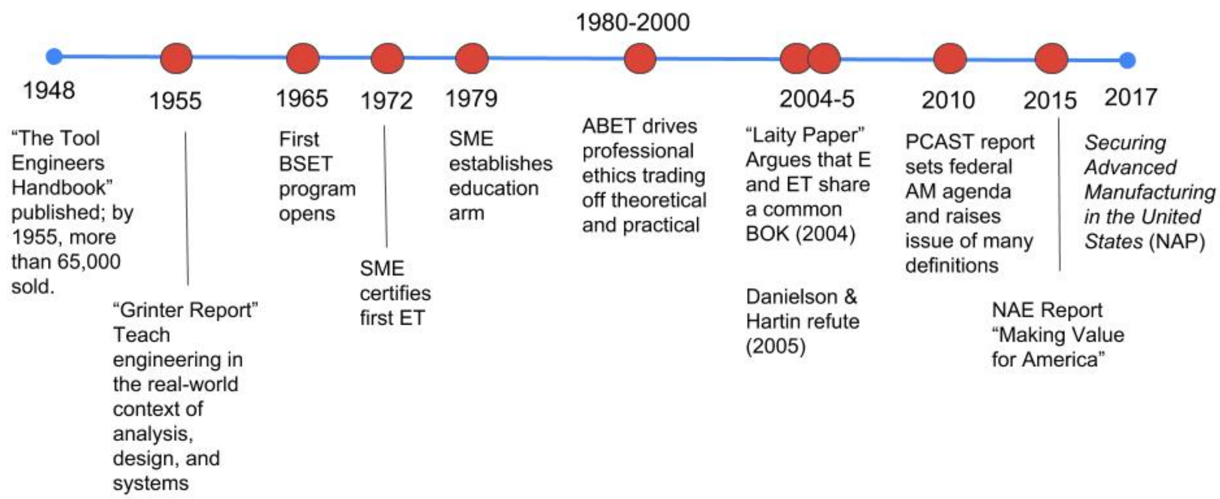

Figure 3. Engineering Technology Evolution Timeline

As Figure 3 shows, "The Tool Engineers Handbook" was published in 1948. As a reference for all phases of planning, controlling and designing of manufacturing industries, by 1955, over 65,000 engineering professionals purchased the book. Reflecting strong interest in practical, standard application of engineering principles, the book had subsequent editions published in 1959 and 1976. These editions were expanded to reflect the latest in the manufacturing industry seeing the continuing advances and significant diversification of informational needs of the modern manufacturing engineering. Also in 1955, the "Report on Evaluation of Engineering Education," or commonly, "Grinter Report" explained the importance of real-world context for analysis, design and systems in engineering. This report established applied engineering as an independent professional background, calling for traditional engineering programs to embrace curricular flexibility and strengthen humanities and social science content in their programs.

With these series of engineering education publications, engineering technology emerged from a convergence of several key aspects of the United States technological and educational development. Junior and community college programs in technical education and the consistent movement of US engineering education toward curricula containing more emphasis on science knowledge/theory yielded the first Bachelor's of Science in Engineering Technology (BSET) degree program in 1965. The program focused on the study of engineering devices and their applications; by 1976, many digital and computer courses were added to the curriculum.

Industry professional organizations claimed a role on the movement with the Society for Manufacturing Engineers (SME) certification of the first ET professional in 1972, soon followed by the establishment of their education arm in 1979. SME spanned industry and education by providing both industry certification and educational content [16]. SME's educational efforts were soon joined by in 1980 by Accreditation Board for Engineering and Technology (ABET) in the organization's efforts to promote professional ethics by honoring theoretical and practical approaches to engineering. This focus on what is learned rather than what is taught, affirmed the importance of institutions establishing clear objectives and assessment processes to ensure that each program provides graduates with the technical and professional skills employers demand [17].

By 2004, AM's ET's independent identity as a discipline was distinct enough to be in dispute. On behalf of the American Society of Manufacturing Engineers (ASME), Laity [18] argued that engineering and ET were similar enough to share a Body of Knowledge, a taxonomy of core competencies. However, engineering educators objected to this position, pointing out that the numerous specializations and applications of engineering in technological domains deserved separate consideration [19]. Though the conflict over professional identity and practice played out through professional societies, engineering educators were doing the arguing—and not achieving resolution. Educators variously focused on the technology and processes of AM. For example, De Weck, a professor of Aeronautics and Astronautics and Engineering Systems at the Massachusetts Institute of Technology, defined AM as "the creation of integrated solutions that require the production of physical artifacts coupled with valued-added services and software, while exploiting custom-designed and recycled materials and using ultra-efficient processes" [20] " although Gunawardana [21], another educator, defined AM by its operational components: 'soft' manufacturing process technologies such as just-in-time (JIT) manufacturing, total quality management (TQM), and supply chain management. Even divorced from engineering or separate from engineering technology, the educational domain has lacked a consistent AM definition.

Governmental policymakers reflected the disparities seen in industry professional and educational organizations. The President's Council of Advisors on Science and Technology setting federal AM agenda and raised the issue of many definitions of AM. Since the field has a broad set of aspects, it is almost impossible to find a definition of the term that covers all the aspects.

Method

In order to address the gaps in the definitions, we decided this research should focus on identifying themes within the different definitions and understanding of advanced manufacturing. The approach used for this qualitative study is thematic analysis, where we identified, analyzed and reported themes within the data collected.

Data Collection

For the purposes of this study, we focused on reports that were produced by predominant governmental AM stakeholders. We excluded websites, blog posts, and other non-report documents.

Governmental Stakeholders

- Executive Branch: National Science and Technology Council (NSTC); President's Council of Advisors on Science and Technology (PCAST)
- Agencies: Department of Commerce; Department of Energy (DOE); Department of Labor (DOL);

- Independent Governmental Organization: National Science Foundation (NSF); National Academies of Engineering (NAE)

Educational Stakeholders

- Accreditation Board for Engineering and Technology (ABET)
- American Society for Engineering Educators (ASEE)
- IEEE Technology & Engineering Manufacturing Society (IEEE-TEMS)

Industry Professional Stakeholders

- American Society of Manufacturing Engineers (ASME)
- Association for Manufacturing Technology (AMT)
- National Council for Advanced Manufacturing (NACFAM)
- Society of Manufacturing Engineers (SME)

We chose 2010 as our start date not only to align with the release of the PCAST report, but also to reflect the highly dynamic nature of AM. We then reviewed each of the selected publications for definitions of AM and compiled those in tables by stakeholder group.

Data Analysis

We reviewed the definitions for themes within each stakeholder group (to answer RQ1) and among the three stakeholder groups (to answer RQ2).

Limitations of the Method

This method faces limitations. Basing our work on canonical documents meant that we had to make subjective judgments about which documents to include and which to leave out.

Findings and Discussion

Our findings are compiled in Table 1.

Table 1. Governmental Stakeholders' Definitions of Advanced Manufacturing

Source	Definition
	Governmental Organizations
NSTC	"Advanced manufacturing is a family of activities that (a) depend on the use and coordination of information, automation, computation, software, sensing, and networking, and/or (b) make use of cutting-edge materials and emerging capabilities enabled by the physical and biological sciences, for example nanotechnology, chemistry, and biology. It involves both new ways to manufacture existing products, and the manufacture of new products emerging from new advanced technologies" [22] "Advanced manufacturing includes both new manufacturing methods and production of new products enabled by innovation" [23]

	"Advanced manufacturing is the manufacture of conventional or novel products through processes that depend on the coordination of information, automation, computation, software, sensing, and networking, and/or make use of cutting-edge materials and emerging scientific capabilities" [24]
PCAST	"Advanced manufacturing is not limited to emerging technologies; rather, it is composed of efficient, productive, highly integrated, tightly controlled processes across a spectrum of globally competitive U.S. manufacturers and suppliers" [25] Advanced manufacturing includes "all aspects of manufacturing, including the ability to quickly respond to customer needs, through innovations in production processes and innovations in the supply chain," which are increasingly "knowledge intensive, relying on information technologies, modeling, and simulation" [25]
Industry Organizations	
SME	"In AM, an object is built from a digital design file by printing one layer of material at a time. But even within 3D printing, a wide range of processes are used to build objects, such as selective laser sintering, electron beam melting, and fused deposition modeling, just to name a few. Each of these technologies has a number of limitations and challenges that must be overcome in order to make AM more marketable. This research requires advanced knowledge about materials, lasers, software and more. The field of advanced manufacturing also consists of older technologies that have grown very sophisticated over time, with the help of software and other developments." [26]

As Table 1 indicates, of the 13 organizations we searched for reports, we located 5 total reports. The Department of Commerce, DOE, DOL, NSF, NAE, ABET, ASEE, IEEE-TEMS, ASME, AMT, and NACFAM did not produce reports in which AM was specifically defined.

In relation to the first research question, "To what extent key policy documents define AM in ways that are compatible or in conflict," many descriptions of a profession have suggested that educational, industry, and governmental stakeholders all have a role is defining a professional discipline and ensuring that its function and expectations are understandable to existing and prospective participants [27]. However, our analysis showed that educational, professional, and governmental organizations rarely defined AM and, in fact, appeared to proceed from an assumption that all readers of their publications would immediately understand AM and its components. For the documents that did define AM, the definitions almost exclusively focused on AM technologies, processes, and industry sectors and did not address the role of the AM professional, perhaps because industry professionals, not educators, served on the committees and organizations that produced the report.

This depersonalized description of the field does little to address "a key challenge [which] is to educate students and workers about what manufacturing looks like today. 'The next generation of shop-floors…doesn't look like [it] did 20 years ago' " [28]. Solely focusing on technology when discussing AM does little to help a prospective professional envision his or her work possibilities in the field or enable an existing community member to see his or her integral role.

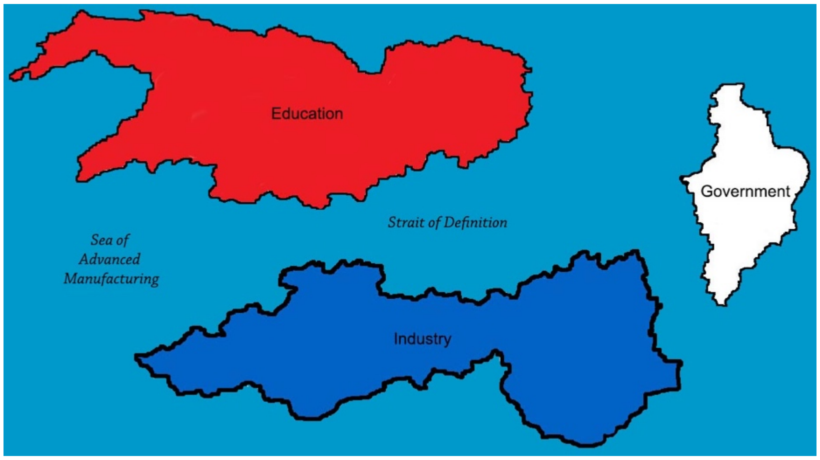

Figure 4. AM Stakeholders as Discrete Entities

As Figure 4 suggests, as far as setting an AM definition is concerned, educational stakeholders appear to be disconnected from industry and governmental entities. As SME's *Workforce Imperative* report noted, industry, government, and education must be an integrated solution to the question of what manufacturing is and what content needs to be taught in a competent manufacturing program so that individuals can be certified. They also set important standards for accreditation of educational programs. Certifications and degrees that come from accredited programs are necessary for industry to verify and trust the level of skills and knowledge that certain individuals bring to the workforce [29].

Figure 5 depicts how this integrated solution would look in contrast to the separation shown in Figure 4.

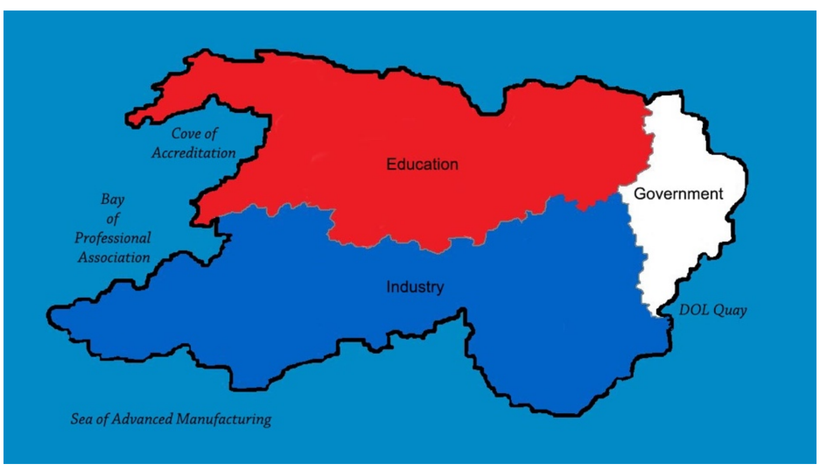

Figure 5. Unified "Continent" of AM Stakeholders

As Figure 5 suggests, there is room for optimism because professional organizations are so closely linked with AM competency definitions that they are the sole sources for the Department of Labor's Advanced Manufacturing competency model, though neither the model nor its accompanying documentation actually define the field [27]. If educational stakeholders center their content and curriculum development on the competency model, then their work will be in line with governmental expectations and industry needs—an alignment that will surely enable the creation of a settled AM definition.

Conclusion

"How interested students are in manufacturing is strongly dependent not only on how they perceive the discipline but how well prepared they are to succeed in a manufacturing career," [29] and this perception cannot accurately occur without a clear definition of the field. This study presented initial efforts to establish a common understanding of the definition of AM. Our primary goal was to offer insights into how AM is defined and understood by policy makers. By capturing different definitions of AM and exploring through the concept and context of these definitions, we found that when governmental and industry stakeholders directly defined AM, they do not define it very differently; their definitions centered on technologies, processes, and industry sectors and did not focus on the competencies and activities performed by AM professionals. In analyzing the selected reports for implicit and explicit definitions of advanced manufacturing, one of the most striking features is that there are more similarities than differences. Despite the commonalities, the need to address personological issues suggests that governmental, industry, and educational stakeholders need to address the issue of a clearly stated, commonly used definition of AM to attract investors, recruit workforce participants, and guide effective educational opportunities.

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