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The Future of Manufacturing: A New Perspective

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ABSTRACT

Many articles have been published on intelligent manufacturing, most of which focus on hardware, software, additive manufacturing, robotics, the Internet of Things, and Industry 4.0. This paper provides a different perspective by examining relevant challenges and providing examples of some less-talked-about yet essential topics, such as hybrid systems, redefining advanced manufacturing, basic building blocks of new manufacturing, ecosystem readiness, and technology scalability. The first major challenge is to (re-)define what the manufacturing of the future will be, if we wish to: ① raise public awareness of new manufacturing's economic and societal impacts, and ② garner the unequivocal support of policy-makers. The second major challenge is to recognize that manufacturing in the future will consist of systems of hybrid systems of human and robotic operators; additive and subtractive processes; metal and composite materials; and cyber and physical systems. Therefore, studying the interfaces between constituencies and standards becomes important and essential. The third challenge is to develop a common framework in which the technology, manufacturing business case, and ecosystem readiness can be evaluated concurrently in order to shorten the time it takes for products to reach customers. Integral to this is having accepted measures of "scalability" of non-information technologies. The last, but not least, challenge is to examine successful modalities of industry–academia–government collaborations through public–private partnerships. This article discusses these challenges in detail.

1. Introduction

A wealth of information has been published on intelligent manufacturing, Industry 4.0, cyber-physical systems, and topics related to the future of manufacturing [1–9]. The intent of this article is to lend perspective to other less-talked-about topics that are essential for the successful implementation of the future of manufacturing. These topics include: a system of hybrid systems; advanced manufacturing building blocks; concurrent maturation of technology, manufacturing, the business case, and ecosystem readiness [10]; technology scalability; and industry-academic-government collaboration.

2. Redefining manufacturing

The contributions of manufacturing to the national economy are far-reaching and broad, and include the gross domestic product (GDP), exports, high-paying jobs, meaningful return on investment, the symbiotic relationship between manufacturing and innovation, science, technology, engineering, and mathematics (STEM) education, and national security. It is critical that policy-makers and the general public understand the impact of advanced manufacturing on the economy, society, and the nation's economic portfolio. However, it is not always an easy task to raise public awareness and garner the support of policy-makers. A major challenge is that the "image" of manufacturing in the minds of most people is entirely outdated. Most people envision manufacturing today as still being similar to the factories and mills of the past.

The first major challenge is to (re-)define what the manufacturing of the future will be, if we wish to: ① inform the general public about how manufacturing impacts our economy and society, and ② garner the unequivocal support of policy-makers. New manufacturing processes, innovative materials, and disruptive business models will drastically affect our knowledge base and evolve what we consider to be grand challenges.

One good example is the use of biological cells in manufacturing, whether cells are part of the manufacturing ingredients or whether they are the product itself. As an example of the former

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case, monoclonal antibodies are made with cultured cells. This involves immunizing mouse spleen cells with the desired antigen and then fusing these cells with myeloma cells [11]. On the other hand, cells are increasingly being developed and cultured as therapeutic products and potential medicine for cardiovascular diseases, cancers, neurological diseases, and inflammation. A recent example is the National Cell Manufacturing Consortium that the Georgia Institute of Technology (Georgia Tech) led in developing a roadmap in 2014–2017 [12,13]. Cell-based therapeutic products were rare or unheard of 10 years ago, but they are quickly becoming a viable medical paradigm because of their clinical, societal, and economic impact.

With respect to processing techniques, additive manufacturing is gaining broader acceptance as a "direct production" process due to improved material selection, material property, efficiency, and quality. However, additive manufacturing should not be viewed as a mere manufacturing process. In addition to changing how products are made, additive manufacturing changes how products are distributed (i.e., supply chain and logistic implications [14]) as well as how products are designed (e.g., topology optimization or part consolidation [15,16]). A well-known and successful contribution of additive manufacturing to part consolidation is exemplified by the GE90 jet engine fuel nozzle. Using an additive manufacturing process, the fuel nozzle not only combines all 20 parts of the old design into a single unit, but also weighs 25% less and is more than five times as strong [17]. The nozzle exceeded the team's wildest expectations. Additive manufacturing makes the unit cost far less sensitive to production lot sizes. It isolates unit cost from lot size considerations, which have been a manufacturer's dilemma since the beginning of the profession. As a result, it is possible that one day parts will be made in lot sizes of a few or even one—anywhere, anytime, and at a reasonable cost. This notion of integration across the stack for a lot size of a single product—anywhere, anytime—will disrupt many existing business models as well as create newer, more evolved ones.

As far as the business model is concerned, manufacturing-enabled service is becoming the main driving force for defining value. In these cases, manufacturing initiates value creation, and technology enables it. Many manufacturing companies have realized that manufacturing and service are converging because economics has switched from product delivery to continuing interaction with the customer. Advanced and profitable services that are enabled by intelligent sensors and communications are gradually becoming the business model of choice for many manufacturers [18,19]. There are increasing numbers of successful blended manufacturing-service business models. For example, in order to better monitor performance and detect problems, Rolls-Royce uses sensors in its jet engines. In fact, this company turned its product into a service by charging its customers for engine usage rather than having customers purchase an engine outright. As another example, Babolat makes tennis racquets with sensors that can generate data to analyze the player's tennis strokes, which subsequently allows the enterprise to offer coaching services. Some John Deere equipment can receive and send data on weather and soil conditions in order to advise customers on when and where to sow seeds.

3. Hybrid manufacturing

About three decades ago, when innovation led to the high use of robotics in factories, many people predicted that within 10 years all factories would be filled with robots, and there would be no human operators. Decades later, human operators are still present in factories and will continue to be there in the foreseeable future. Today, people are predicting that additive manufacturing will replace all machining processes. It will not. The factory of the future will be a system of hybrid systems of robots and humans, additive and subtractive manufacturing, composites and metals, digital and analog processes, cyber and physical systems, nano and macro scales, and so on. Robots will not completely replace humans, just as additive manufacturing will not completely replace subtractive manufacturing. Rather, they will work collaboratively with a balanced distribution of responsibility. The study of individual systems is obviously important. Equally or even more important is the study of the interface and the technical and financial balance between different systems—that is, the interface between robots and humans, between additive and subtractive manufacturing, and between composites and metals. Standards will also be essential for the system of hybrid systems to function efficiently and effectively.

Forming, machining (subtractive), and additive manufacturing are three major classes of fabrication. Fig. 1 is a notional chart that shows the relationships between unit cost and build quantity (or lot size). Obviously, forming is best suited for very large lot size production in order to reach a low unit cost by amortizing high initial capital investment in tooling and machinery over a huge number of parts. Compared with forming, the lot size for machining can be lower, but it is still relatively higher than that of additive manufacturing.

It is important to note that as additive manufacturing becomes more mature as a direct production technique, the break-even point between subtractive and additive manufacturing will shift to the right of the chart in Fig. 1. This makes additive manufacturing more cost effective for additional applications. Similar technical and economic analyses can and should be done for human–robot integration, composite–metal integration, and many other scenarios in the future of manufacturing.

4. Building blocks of the future of manufacturing enterprises

Each of the previous industrial revolutions took at least 80 years to complete, so it is still early to define exactly what Industry 4.0 is. However, based on what we have witnessed so far, it is reasonable to speculate that the future of successful manufacturing enterprises will include the following essential building blocks:

(1) **Digital twins and digital threads.** The notions of digital twins and digital threads were initially developed by the defense community and are now being adopted far beyond the original developer community [20]. A digital twin is a digital representation of a physical asset. Digital twins provide information on the workings of the asset, such as design specifications, engineering models, and the as-built and operational data that are unique to that asset. The digital thread is the communication framework that connects data from all areas of the asset and provides a combined

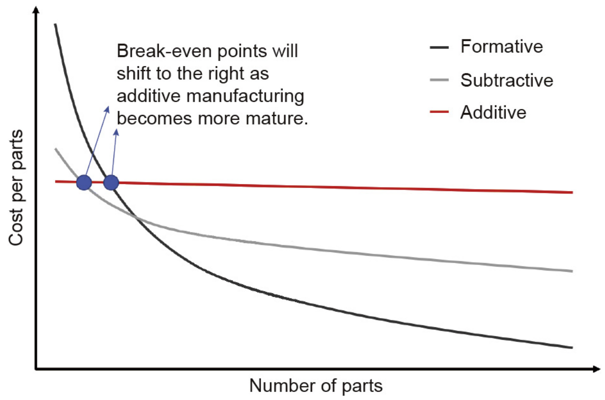

Fig. 1. Plot of unit cost versus lot size.

view of the data for the asset's entire life cycle. Similar to what just in time, manufacturing was intended to achieve by delivering the "right components to the right place at the right time," the digital thread concept is meant to deliver the right information to the right place at the right time.

(2) **Total supply chain transparency and visibility.** The concept of system engineering has been gaining acceptance. It goes beyond the notion of optimizing the operation of a production location or a distribution center, to advocate the optimization of the entire supply chain or the entire supplier base. With the Internet of Things and digital threads, we are one major step closer to total supply chain transparency and visibility.

(3) **Hybrid manufacturing.** This has been discussed in earlier sections; the future of manufacturing will be based on embedded systems of hybrid systems.

(4) **Innovative materials.** Major periods of human civilization have been largely defined by the new material being used to make the necessary tools of the time: stone, bronze, iron, and so forth. Material innovation will continue to be an important topic for science, technology, and economic policy. Manufacturing and materials are inseparable. Materials provide the "work" for manufacturing, whereas manufacturing adds value to raw materials. According to a report [21], it takes an average of 20–25 years to mature a material from the laboratory benchtop to the marketplace. In order to accelerate the research/development/deployment process, serious work on a number of fronts must be done quickly, including advanced manufacturing and integrated computational materials engineering.

(5) **Advanced metrology.** As a general rule of thumb, the accuracy of measuring should be at least an order of magnitude higher than what it is meant to measure. As nano-processing is becoming a routine technique in certain sectors, the demand for more advanced metrology will increase accordingly.

(6) **A skilled workforce for intelligent manufacturing.** Lack of a skilled manufacturing workforce is perhaps the greatest threat to next-generation intelligent manufacturing around the world. This shortage comes in at least two dimensions. First, there are not enough people with the necessary skills to fill manufacturing positions. That is to say, the quantity and quality of the workforce carrying out the manufacturing of the future are insufficient. In the United States alone, there will be a shortage of 3.5 million manufacturing operators by 2030 [22]. Second, even though apprenticeship has been recognized as a good method for developing a skilled workforce, most apprenticeship programs are simply not scalable.

(7) **New business models such as convergent manufacturing and high-end service.** As discussed earlier in this article, we see a trend of manufacturing and service converging in many sectors.

5. Transformations from Industry 2.0/3.0 to Industry 4.0

A quick examination of the history of industrial revolutions reveals that each stage lasted 80–100 years. In other words, a revolution does not happen overnight; rather, a revolution is the culmination of continuous evolutions and improvements. We are at the beginning of the Fourth Industrial Revolution, which is likely to last at least 50 years.

The factors characterizing each stage of industrialization are described below.

Industry 2.0 is characterized by standardization and simple hard-wired automation, including standardization of the foundation of mass production and automation. Standardization comes in a number of different dimensions: standardized parts, standardized manufacturing steps, standardized inspection and quality control, and so forth. Examples of simple hard-wired automation include simple pick-and-place devices and vibration-based part feeders. The intent of hard-wired automation is to increase the speed of automation with process repeatability in mind. Process flexibility is not much of a concern during process design.

Industry 3.0 is characterized by sophisticated automation, digitization, and networking. This phase has much more sophisticated automation that introduces speed, quality, and processing flexibility. Advanced robotics and programming are in a quintessential class of flexible automation. With flexible automation, the manufacturer can accommodate product variety and lot size fluctuation with reasonable responsiveness and precision. Another hallmark that is characteristic of Industry 3.0 is the instrumentation of machine tools (computer numerical control machines, three-dimensional (3D) printers, and robots) with sensors to collect data for the purpose of process monitoring, control, and management. The last characteristic that separates Industry 3.0 from Industry 2.0 is that Industry 3.0 is supported by networks of different technologies. With the network of sub-networks, machine with machine, factory with factory, and enterprise with enterprise are able to communicate with one another in real time. Sensors, data sharing, and networking provide unprecedented power to industrial and manufacturing companies. However, they also put these companies at risk for unprecedented cybersecurity issues. There are articles on this important and timely topic, so we will not discuss it further in this paper.

So, what separates Industry 4.0 from Industry 3.0? What do we expect Industry 4.0 to attain above and beyond Industry 3.0? Below are some thoughts:

(1) **Beyond optimization.** Optimal resource allocation is important to industrial and manufacturing companies in order to maximize the output/input ratios. In Industry 4.0, optimization is essential but insufficient. In other words, optimization alone is not enough to be a business differentiator.

(2) **Situational awareness.** All production units—machine tools, robots, and 3D printers—must have the ability to "scan" the environment and make certain decisions. Many decisions are made based on prior knowledge and historical data, just as they are in Industry 3.0. However, an Industry 4.0 company should have the ability to: ① recognize an unknown scenario, ② break down the problem into pieces, ③ apply knowledge to solve the pieces of the problem that it can solve, and ④ look for data or knowledge outside its data base for solutions to other pieces, or simply ask for human intervention. Once the "new" or "unknown" problem is solved, the manufacturing company becomes more "intelligent" than it was before, because lessons have been learned by the system. These situational awareness and learning capabilities are perhaps the most defining characteristics of Industry 4.0.

(3) **Structured and unstructured data.** Extensive use of both structured and unstructured data is the norm for Industry 4.0. Solutions are no longer confined to the domain of structured data. Unstructured datasets such as images, natural language, and even messages in social media and market updates anywhere in the world become an integral part of intelligent solutions.

(4) **Performance metrics.** The performance metrics for Industry 4.0 include those for Industry 3.0—such as productivity, quality, repeatability, cost, and risk—along with, more importantly, new metrics such as flexibility, adaptability, and the ability to learn from failure or human intervention.

6. The integrated readiness level framework: Concurrent maturation of technology, maturation, business cases, and ecosystems

Policy-makers and politicians are increasingly aware that a robust manufacturing sector must be an integral component of a sustainable and resilient national economic policy. By making use of innovative processes to accelerate the rate at which new technologies or materials are commercialized, the ability to strengthen manufacturing competitiveness can be greatly enhanced. To better describe the process, the Georgia Tech Manufacturing Institute (GTMI) proposes an innovative framework, the integrated readiness level (xRL), to analyze the process. The xRL framework addresses readiness levels across multiple aspects of the concurrent maturation of technology, manufacturing, and business case, and supports ecosystem development. This section describes an emerging xRL model and explains why it matters to manufacturing policy making.

GTMI researchers are developing this framework to accelerate the commercialization of research being conducted at the university level. The technical and manufacturing measures are based upon the technology readiness level (TRL) and manufacturing readiness level (MRL) frameworks that were developed primarily by the National Aeronautics and Space Administration [23] and the US Department of Defense [24], respectively, and that are widely used in industry. The business case readiness level (BcRL) and ecosystem readiness level (EcRL) are new GTMI initiatives in preliminary development stages [10]. Tables 1–4 and the accompanying discussion below briefly describe the underlying characteristics of the TRL, MRL, BcRL, and EcRL system, and the challenge of expanding and implementing them in the real world.

6.1. Business case readiness level

No matter how innovative a product or process may be, if a firm cannot see the financial benefit, then the new technology will likely be filed away. While engineers and researchers work within the realms of technology and manufacturing readiness—that is, TRL and MRL—corporate decision-makers work within the realms of profits and earnings. Incorporating BcRL into the equation provides the financial data that corporate decision-makers need in order to advocate for moving forward with a new technology.

This is where BcRL comes in. Along with data from TRL and MRL analyses, BcRL captures business considerations, and thus provides a complete look at the positioning of a technology or manufacturing process. BcRL shortens the time to market by methodically building a business case and "market pull" as a technology matures.

BcRL analysis provides plans for inserting the technology into the marketplace, data on what the market looks like for the technology, a timeline or roadmap for insertion, a strategy for capturing a greater market share, and a description of financial benefits the company might enjoy.

Table 1
Underlying characteristics of the TRL system.

TRL	Brief description
TRL 9	Actual application of the technology in its final form and under mission conditions
TRL 8	Technology has been proven to work in its final form and under expected conditions
TRL 7	Prototype exists having all key functionality available for demonstration and testing
TRL 6	Representative model or prototype system is tested
TRL 5	Fidelity of breadboard technology increases significantly
TRL 4	Basic technological components are integrated to establish that they will work together
TRL 3	Analytical and laboratory studies to physically validate analytical predictions of separate elements of the technology
TRL 2	Practical applications are identified but are speculative; no experimental proof or detailed analysis is available
TRL 1	Scientific research begins to be translated into applied research and development

Table 2
Underlying characteristics of the MRL system.

MRL	Brief description
MRL 10	Full rate production demonstrated and lean production practices in place
MRL 9	Low rate production demonstrated; capability in place to begin full rate production
MRL 8	Pilot line capability demonstrated; ready to begin low rate production
MRL 7	Capability to produce systems, subsystems, or components in a production-representative environment
MRL 6	Capability to produce a prototype system or subsystem in a production-relevant environment
MRL 5	Capability to produce prototype components in a production-relevant environment
MRL 4	Capability to produce the technology in a laboratory environment
MRL 3	Manufacturing concepts identified

Table 3
Underlying characteristics of the BcRL system.

BcRL	Brief description
BcRL 9	Full rate production into national markets; future product improvements planned
BcRL 8	Full rate production into local market; confirmation of financial metrics estimate
BcRL 7	Product insertion into one target market; positive market focus group response
BcRL 6	Market-ready research prototype vetted to outside entity and key customers
BcRL 5	Financial issues defined; return on investment required; margin, funding source (internal, external, or both)
BcRL 4	Research concept/target markets presented to industrial partners; fit to strategic plan goals
BcRL 3	Research concept vetted to outside entity (incubator management, venture capital investors, etc.) for review
BcRL 2	University team review and validation of potential research concept market insertion
BcRL 1	Research concept proven in laboratory; principle investigator defines usage of potential market value

Table 4
Underlying characteristics of the EcRL system.

EcRL	Brief description
Macroeconomic environment	Aggregated indicators: GDP, unemployment rate, and price indexes Major factors: national income, output, consumption, unemployment, inflation, savings, investment, trade, and finance Government policies: monetary policy and fiscal policy
Local market attractiveness and efficiency	Market size and purchasing power
Talent-driven innovation	Applied research and product development
Business sophistication	Pool of entrepreneurs, pool of advisors and experts, champions and community support, tacit knowledge availability
Financial market efficiency	Access to capital, cost of capital, and robustness of capital market
Climate and natural disasters	–
Cost and availability of workforce	Cost of workforce, availability of workforce, and efficiency of labor market
Quality of life	Cost of living, healthcare system, public school system, and choice of activities
Legal, regulatory, and admin systems	Legal systems, regulatory systems, and administrative systems
Economic, trade, financial, and tax systems	Economics, trade, financial aspects, and taxes
Government investment in manufacturing and innovation	–
Energy cost and policies	Energy cost, energy availability and robustness, energy policies
Physical and cyber infrastructure	Electricity, water, transportation, communications, and cyber infrastructure

BcRL is organized at the same readiness levels as TRL and MRL, as shown in Table 3 [10]. Technology development reaches a tipping point at the critical phases of BcRL 3–7, where the analysis points out the new technology's potential business value and the justification to move it forward. The tipping point can be thought of as the point during test market evaluation at which a product reaches a sufficiently large mass demand to indicate commercial success.

6.2. Ecosystem readiness level

The EcRL is a tool to examine the compatibility between a region and the manufacturing of a new product or family of similar products. Once a new product reaches maturity and goes to market, it needs a supportive production environment or "manufacturing ecosystem" [25]. Important aspects of the ecosystem are local businesses that can support manufacturing the new product with design services, production capabilities, distribution centers, investment avenues, and more.

It is important to note, however, that maintenance of the existing ecosystem is critical because, unlike other readiness level tools, the EcRL may change at certain levels. If any of the sustainability supports deteriorate, then the EcRL will evolve accordingly. Table 4 shows the components of the EcRL.

Previous frameworks have been used to address specific areas of interest (i.e., technology or manufacturing); however, xRL addresses the meta-view of product readiness by providing a comprehensive view of product readiness status. It makes use of well-established sub-frameworks such as TRL and MRL and extends the overall readiness level analysis by addressing BcRL and EcRL.

7. Scalability of technology

Scalability is discussed extensively in information technology (IT), particularly the scalability of software and computing. Scalability in computing performance or software is referred to as the ability of a system, network, or process to grow and evolve to handle a growing amount of work [26].

Scalability of non-IT technology is discussed much less, relatively speaking, but requires full attention. Without proper study and, more importantly, without an accepted method to measure the scalability of non-IT technology, the flow from benchtop to marketplace will not be coordinated and synchronized among collaborating stakeholders.

We look at technology scalability from the following perspectives:

(1) Quantity: the capability of a system (process, machine, etc.) to facilitate more orders. Example: A chemical vapor deposition process can produce 2 g of carbon nanotubes in the laboratory. Can the process be scaled to produce kilograms or tons of carbon nanotubes with the same quality?

(2) Size: the capability of a system (process, machine, etc.) to fabricate similar products with much larger size.

(3) Complexity, particularly geometric complexity: the capability of a system (process, machine, etc.) to produce products that are much more complex in their geometric features than the current products.

(4) Functionality: the capability of a system (process, machine, etc.) to make products that have much more functionality than the current ones.

(5) Flexibility: the capability of a system (process, machine, etc.) to handle the variety of products that it can produce.

(6) Cost: the capability of a system (process, machine, etc.) with quantity, size, complexity, functionality, and flexibility scalability to produce similar objects at a reasonably similar cost.

Research into various aspects of scalability of new non-IT and connecting it with accelerating technology development and commercialization success is needed.

8. Industry–academia–government collaboration modalities

Industry–academia–government collaboration from benchtop to marketplace is increasingly important in order to bring each stakeholder's best strengths to the partnership and avoid breakdowns along the innovation value chain. Any breakdown means more cost, more delay, and more frustration for all.

Based on our experience, companies come to a university for the following primary reasons (not listed in any particular order):

- To gain access to next-generation technical talent, and to recruit employees.
- To gain access to breakthrough/transforming technology for strategic positioning in growing markets.
- To gain a window on evolving/competitive technology.
- To obtain complementary technology to internal core research.
- To reposition a current product/process using next-generation technology.
- To develop a virtual research and development center by leveraging partner assets.
- To accelerate commercialization via partnering in order to gain skill or market access; and
- To achieve critical technical problem resolution.

Not all companies use all eight principles in selecting an academic partner, but most companies use a subset of the above eight principles, according to our experience.

Continuing with the xRL technology value creation spectrum discussed in the previous section, the following core leadership competencies (Fig. 2) are necessary in order to have complete coverage of the entire value-creation chain: intellectual leadership, translational leadership, and development leadership. Academia is in charge of the intellectual leadership, whereas industry is the primary party for development leadership. It is the mid-section of the xRL spectrum that has been ignored, and which lacks a clearly responsible stakeholder. In other words, there has been no clear "owner" of translational leadership.

As the Advanced Manufacturing Partnership (AMP) report pointed out [21], effective public–private partnership (PPP) models are needed to accelerate technology development and time to market. One recommendation was to create a National Network for Manufacturing Innovation (NNMI) of 15 Manufacturing Innovation Institutes (MIIs). The primary intent of these MIIs is three-fold: ① a shared facility for all participating members; ② translational development of new technologies; and ③ a training ground to develop a skilled workforce. At the time of writing this article, 14 MIIs have been established (Table 5).

In terms of technology clusters, there are three MIIs in electronics, three in materials, two in bio-manufacturing, three in energy usage/environmental impact, and three in digital automation. This coverage of technologies is comprehensive and strategic.

The mid-section of the xRL spectrum has always been ignored for a number of reasons. The lack of ownership has led to numerous challenges. We believe that the xRL framework is a good model for the MIIs or for any large-scale PPP whose focus is on bridging the "valley of death" or the "missing middle."

Translational leadership must be shared and owned by key stakeholders from academia, industry, or government, and sometimes by not-for-profit, nongovernmental organizations. The distribution of responsibility varies from project to project, and thus requires mutual trust and time for members to truly engage with one another. The primary model that the AMP NNMI uses is for an existing or purpose-formed not-for-profit organization—a

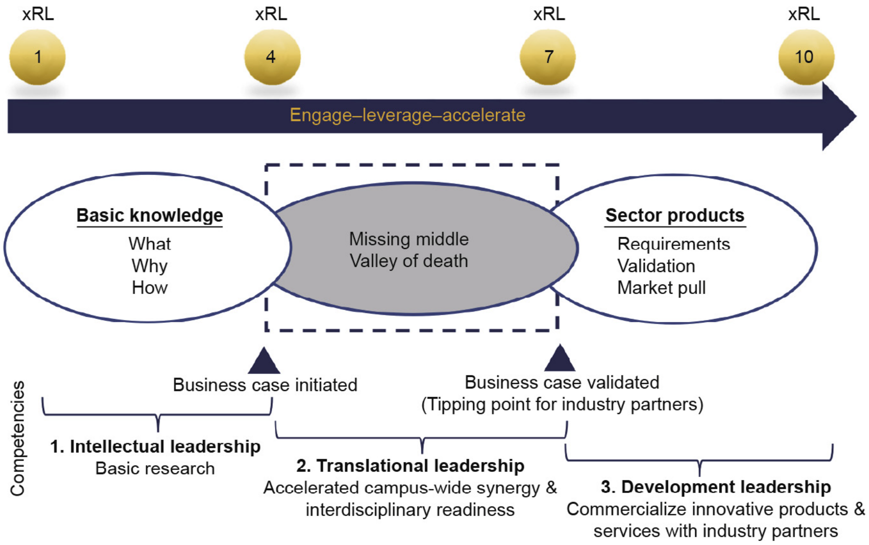

Fig. 2. Three core competencies.

Table 5
Established MIIs.

MIIs	Research field
America Makes	Additive manufacturing and 3D printing
The Digital Manufacturing and Design Innovation Institute	Digital manufacturing and design technologies
Lightweight Innovations for Tomorrow	Lightweight materials manufacturing
NextFlex	Flexible hybrid electronics
American Institute for Manufacturing Integrated Photonics	Integrated photonics
The Institute for Advanced Composites Manufacturing Innovation	Cutting-edge manufacturing technologies
PowerAmerica	Wide bandgap semiconductors
BioFabUSA	Regenerative manufacturing
The National Institute for Innovation in Manufacturing Biopharmaceuticals	Biopharmaceutical manufacturing
Clean Energy Smart Manufacturing Innovation Institute	Smart sensors and digital process control
Advanced Functional Fabrics of America	Advanced fibers and textiles
Rapid Advancement in Process Intensification Deployment Institute	Modular chemical process intensification
Reducing EMbodied-Energy and Decreasing Emissions	Sustainable manufacturing
Advanced Robotics Manufacturing	Advanced robotics

501(c)(3)[†] organization—to be a managing entity that works as an "unbiased broker" for all stakeholders. Obviously, this is only one model and the question of whether it is a sustainable model remains to be seen.

9. Conclusion

This article discussed several important topics that are often ignored in papers on intelligent or advanced manufacturing. These topics include: the future of manufacturing consisting of systems of hybrid systems; building blocks of future manufacturing enterprises; concurrent development of technology readiness, manufacturing readiness, business case readiness, and ecosystem readiness; and technology scalability. These topics are essential for academicians, business people, and policy-makers to study and consider as we usher in a new manufacturing renaissance.

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[†] An organization that is exempt from US federal income tax as per section 501(c)(3) of the tax code.

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