Proposal for New Program

MS in Advanced and Intelligent Manufacturing (AIM)

Graduate School of Engineering

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EXECUTIVE SUMMARY

In the last five years, the United States has seen a resurgence in advanced manufacturing fueled in part by the creation of 14 National Network of Manufacturing Innovation Institutes. The US government and industry have invested several billion dollars to revitalize advanced manufacturing in the US. As a result, all stakeholders including industry, academia, research labs, and government agencies have been forming strong partnerships to rapidly transfer science and technology into manufacturing high-tech products and processes. To meet the current and projected demand for engineers, researchers, and scientists trained in advanced and smart manufacturing and leverage Northeastern's recognized research and development in nano and microscale manufacturing, smart manufacturing, and data analytics, the College of Engineering (COE) proposes to start a new graduate program, MS in Advanced and Intelligent Manufacturing (AIM). This program will enable students to acquire the necessary engineering, analytical and research skills to design, supervise, and manage advanced and manufacturing facilities and projects in industry, government or academia. Figure 1 depicts an infographic of advanced and smart manufacturing[1]. The program will address conventional manufacturing as well as advanced manufacturing. Conventional manufacturing covers topics such metal removal, forming, casting, and particulate processes. In contrast advanced manufacturing covers topics such as nanomanufacturing, fabrication and printing of micro and nano devices, additive 3D printing of parts, electronics, sensors, medical, materials and energy applications. The smart manufacturing focuses on advanced high-fidelity, models, networked data and computation for seamless interoperation of cyber and physical assets in manufacturing facilities, data analytics and industrial internet of things, and factory automation. While the core courses of the program come from the Department of Mechanical and Industrial Engineering, the elective courses will be provided by the College of Engineering, College of Computer and Information Science (CCIS), and D'Amore-McKim School of Business (DMSB). The program is built on existing well-established courses inside and outside the college. The program will also leverage the Northeastern University manufacturing infrastructure such as: George J. Kostas Nanoscale Technology and Manufacturing Research Center (www.kostas.neu.edu) and the NSF Center for high-rate Nanomanufacturing (www.nano.neu.edu) and Advanced Nanomanufacturing Cluster for Smart Sensors and Materials (www.neu.edu/CSSM).

[1] Karavan Advisory Enterprises: Digital Manufacturing, https://www.karavanenterprises.com/digital-manufacturing/

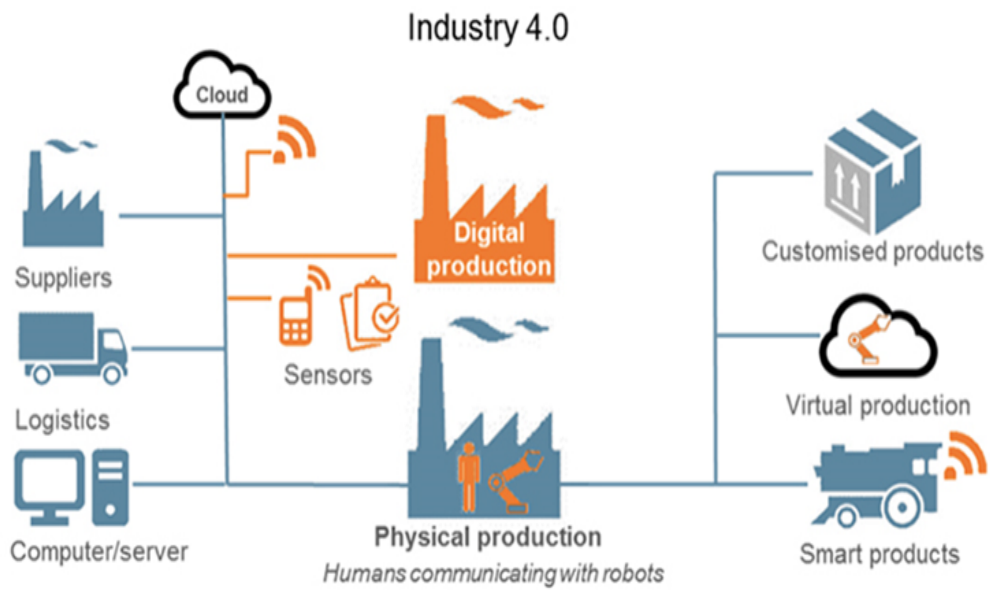

Figure 1. Infographic of advanced and intelligent manufacturing (AIM)

1. Program Description

In recent years, manufacturing has seen a renaissance. The advent of industrial internet of things, additive manufacturing (3D printing) of parts and electronics, new materials with unique properties, and efficient materials processing methods is leading to the emergence of a new generation of manufacturing, commonly known as *advanced manufacturing*. It focuses on developing innovative technologies to create existing and new products by leveraging nano science, additive methods, information, automation, computation, software, sensing, and networking. As recently as February 2018, the National Science and Technology Council's Subcommittee on Advanced Manufacturing (NSTC SAM) issued a solicitation seeking input from the public, industry, academia, and non-profits to chart out a National Strategic Plan for Advanced Manufacturing[2]. The main goal of the strategic plan is to improve US government coordination and direct federal programs to strengthen US manufacturing competitiveness and promote advanced manufacturing research and development over the next five to ten years.

[2] https://www.manufacturing.gov/news/announcements/2018/02/input-solicited-national-strategic-plan-advanced-manufacturing

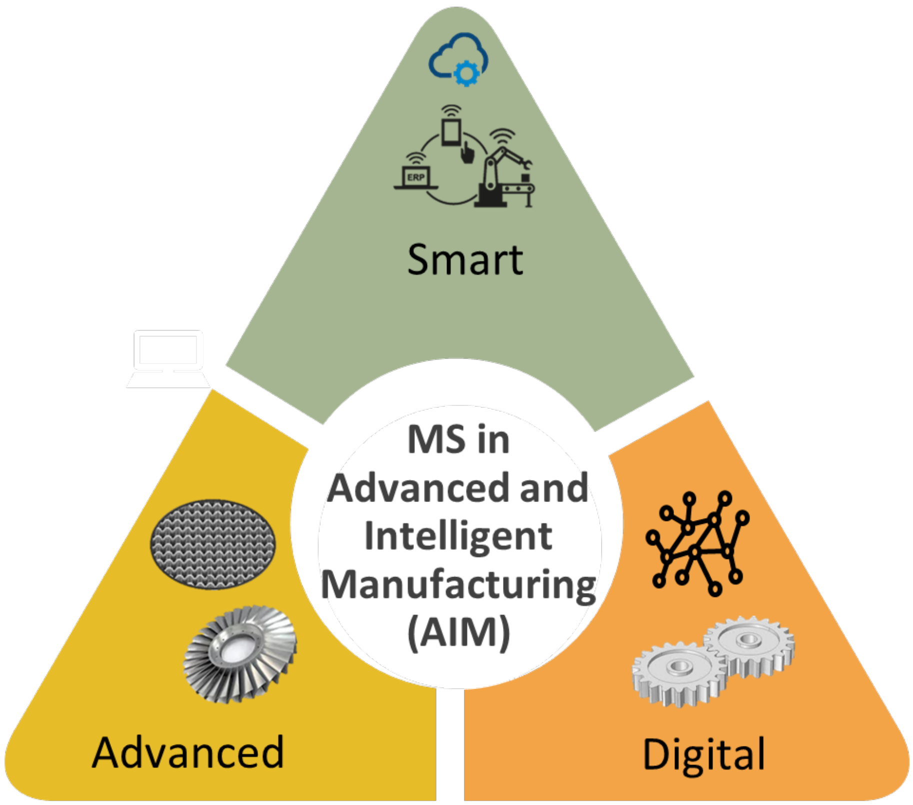

Figure 2. Key curriculum components of the MS in Advanced and Intelligent Manufacturing (AIM) program

Responding to the growing need for engineers, researchers, and scientists trained in advanced manufacturing, the College of Engineering (COE) at Northeastern University proposes to start a new program, MS in Advanced and Intelligent Manufacturing (AIM). Three key curriculum components of the AIM MS program are advanced, smart, and digital (Figure 2). Advanced manufacturing includes conventional manufacturing, additive manufacturing, and nanomanufacturing. The conventional manufacturing covers metal removal, forming, casting, and particulate processes. The additive manufacturing covers topics such as 3D printed of parts using different approaches. The nanomanufacturing covers conventional fabrication as well as printing of micro and nano devices and design and creation of multifunctional materials using automation and scalable processes. Smart manufacturing focuses on factory automation, prognostics and health management, dynamic scheduling, cloud enabled manufacturing, and industrial internet of things for manufacturing performance assurance. Digital manufacturing leverages real-time data analytics and control systems, advanced high-fidelity models, networked data and computation for seamless interoperation of cyber and physical assets in manufacturing facilities. In smart and digital manufacturing all entities included people, parts, products, equipment, systems, suppliers, and logistics and transportation system are connected to achieve enterprise level efficiency.

The three curriculum components of AIM MS program — advanced, smart and digital — are selected to leverage Northeastern strength and expertise in manufacturing, available courses, and research facilities at Northeastern. These three curriculum components are also among the top 10 most promising advanced technologies transforming the global manufacturing industry[3] (Figure 3).

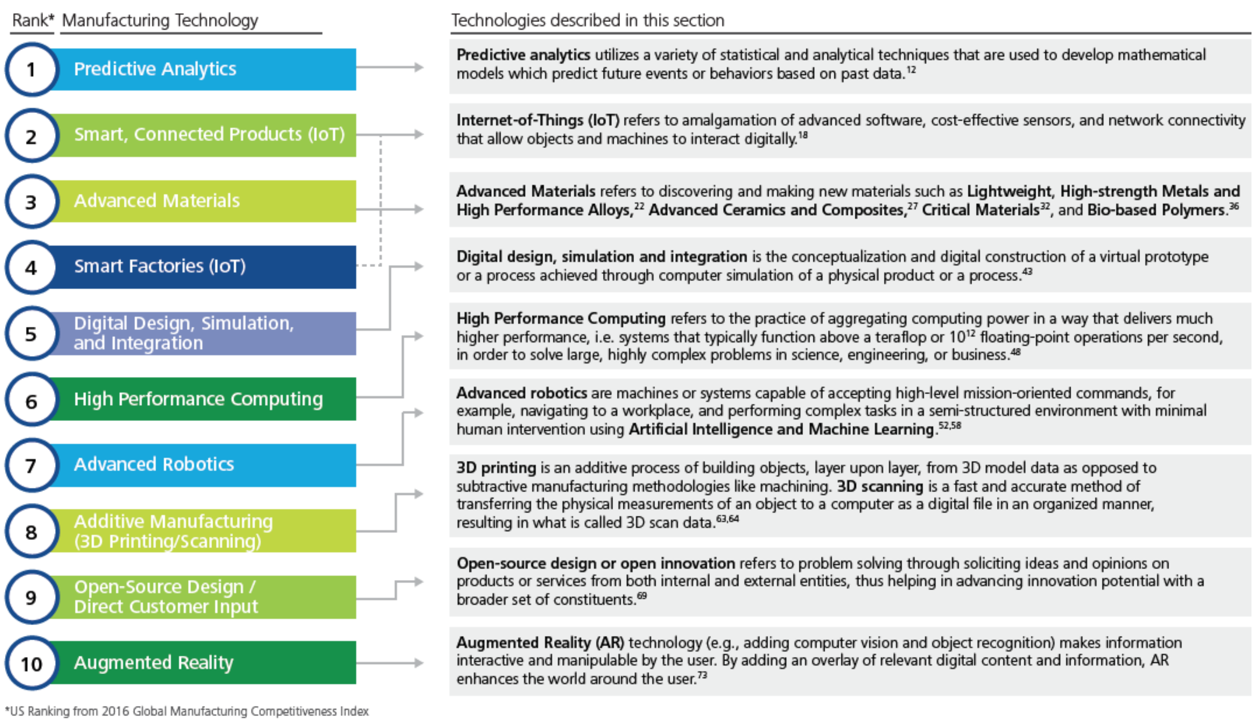

Figure 3. List of 10 of the most advanced technologies transforming the global manufacturing industry. The AIM MS curriculum components — advanced, smart, and digital — common themes in this list.

The AIM MS program is built on the principles and body of knowledge drawn from materials science and engineering, mechanical engineering, industrial engineering, computer science, robotics and controls engineering, electrical and computer engineering, environmental engineering, and business administration (Figure 4). However, a major share of the program curriculum comes from the courses and research projects offered by the Department of Mechanical and Industrial Engineering (MIE).

[3] Deloitte's Advanced Technologies Initiative: Manufacturing & Innovation, https://www2.deloitte.com/us/en/pages/manufacturing/articles/advanced-manufacturing-technologies-report.html

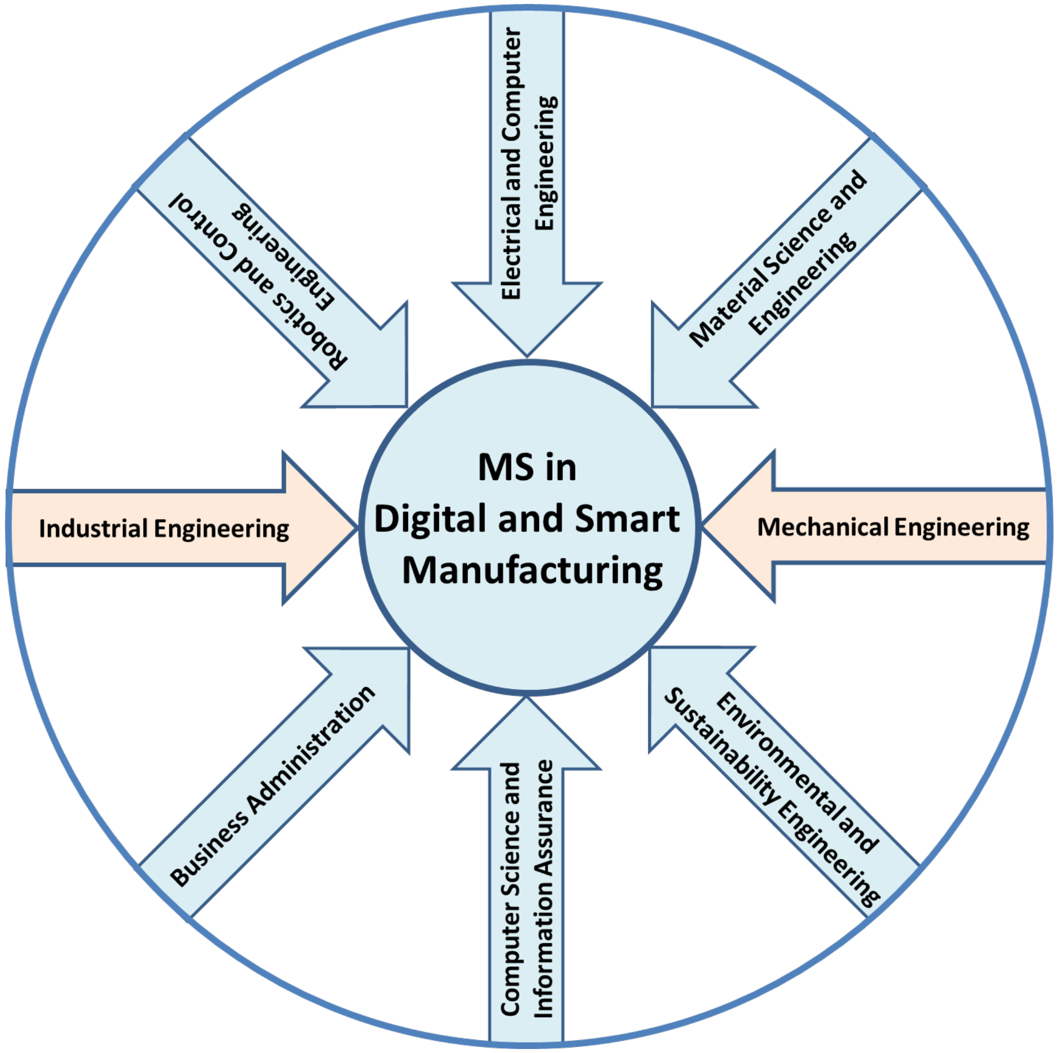

Figure 4. Convergence of different disciplines at Northeastern to support the AIM MS program. A major share of the program curriculum is covered by courses and research projects offered by the Department of MIE.

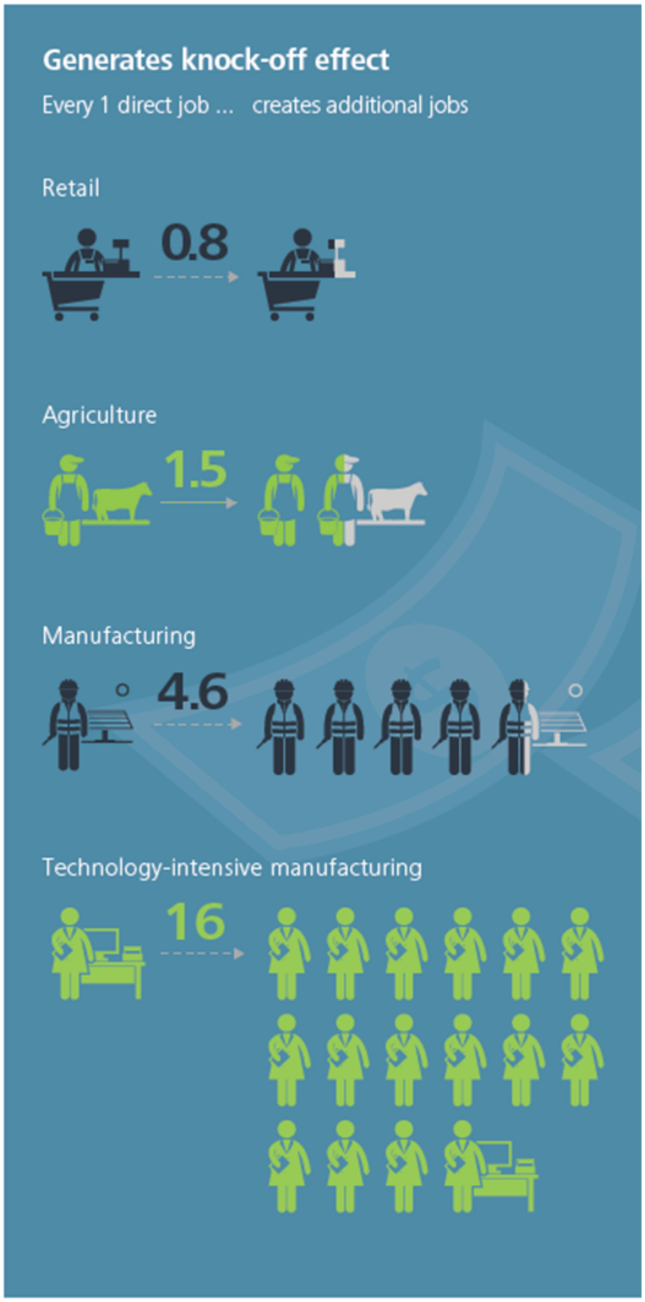

Figure 5. Advanced manufacturing strengthens economies. Each technology-intensive manufacturing job creates 16 other jobs in the industry.

The US innovation system responsible for keeping America at the forefront of cutting-edge science, technology, and innovation is supported by an educational system that fosters creative thinking, superior talent, excellent research infrastructure, solid venture capitalist presence, and strong support for regional innovation clusters. In this innovation ecosystem, advanced manufacturing technologies will create high-value jobs, and each high-value job, in turn, will create about 16 more other jobs in the industry[4,5] (Figure 5). The AIM MS program contributes to this innovation ecosystem's excellent education for sustaining the nation's global manufacturing competitiveness. The vision of the AIM MS program is to produce researchers for development of advanced manufacturing technologies and leaders for managing advanced manufacturing enterprises. The MS program produces graduates who can join as engineers at high-tech companies, become managers at government agencies, or pursue PhD degrees and advanced manufacturing US universities. The graduates coming from this program can work in key sectors such as aerospace, automotive, computers, chemical processes, electronics, materials, controls, instruments, and power

[4] Employment multipliers, Content First and US Bureau of Economic Analysis, http://www.contentfirst.com/multiplier.shtml, last accessed on March 2015; "Ask Bill Clinton: How important is manufacturing to US job growth?", Bloomberg, http://www.bloomberg.com/bw/articles/2013-06-13/bill-clinton-on-manufacturings-importance-to-u-dot-s-dot-job-growth, June 2013.

[5] Deloitte's Advanced Technologies Initiative: Manufacturing & Innovation, https://www2.deloitte.com/us/en/pages/manufacturing/articles/advanced-manufacturing-technologies-report.html

systems. Proposal AIM MS program has potential touch a wide range of Industry 4.0 technologies to boost efficiency and respond to new market opportunities[6] (Figure 6)

Figure 6. Advanced and smart manufacturing is key to Industry 4.0 technologies designed to boost efficiency and respond to new market opportunities

[6] https://www.mckinsey.com/~/media/McKinsey/Global%20Themes/Americas/Making%20it%20in%20America%20Revitalizing%20US%20manufacturing/Making-it-in-America-Revitalizing-US-manufacturing-Full-report.ashx

Digital manufacturing offers several benefits to the US economy[7] (Figure 7). Globally nine out of ten industrial companies are investing in digital factories[8] (Figure 8)

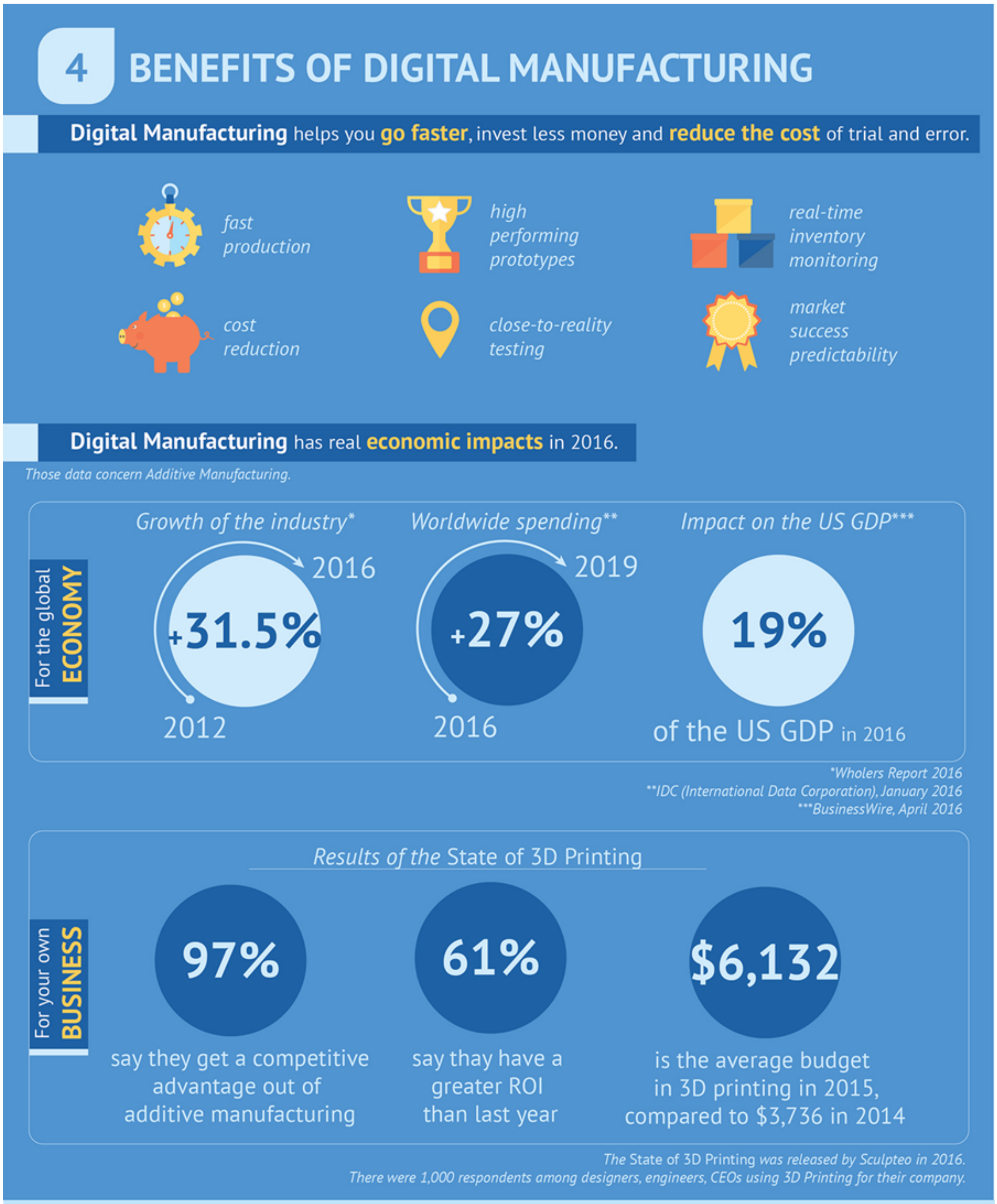

Figure 7. Benefits of digital manufacturing to the US economy

[7] http://www.industryweek.com/technology/digital-manufacturing-factory-future-here-today

[8] Digital Factories 2020: Shaping the future of manufacturing, https://www.pwc.com/gx/en/industries/industrial-manufacturing/publications/digital-factories-2020.html

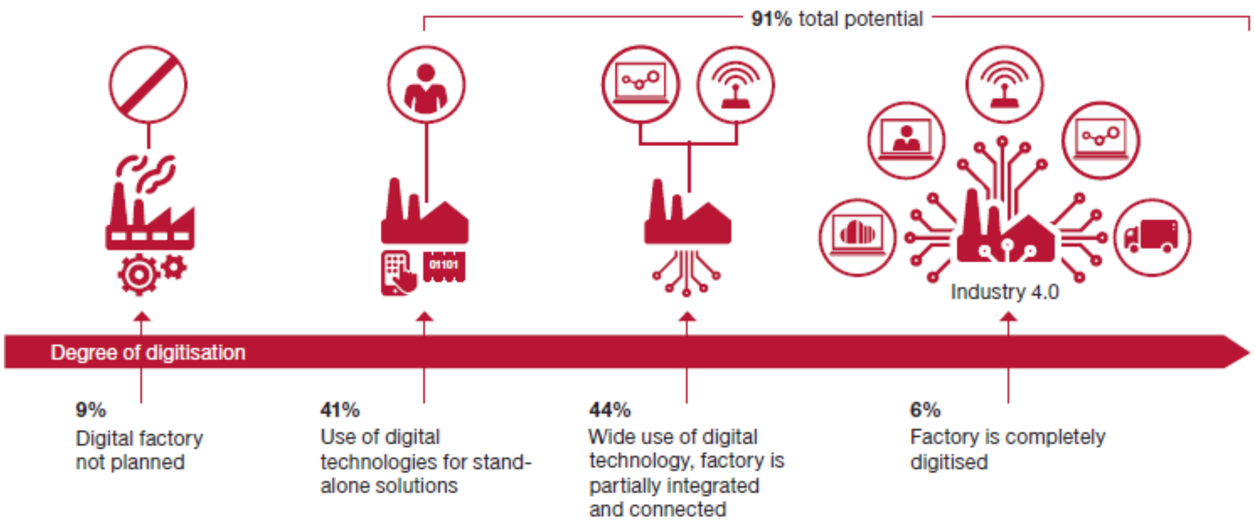

Figure 8. Globally nine out of ten companies are investing in digital factories

2. Contribution to the University's Mission

The proposed AIM MS program contributes significantly to Northeastern's emphasis on experiential education and translational and interdisciplinary research. The program produces professionals who can apply the fundamental knowledge of materials, manufacturing processes, manufacturing systems, industrial internet of things, and cyber security to design and operate fully automated cyber manufacturing systems. The program not only can attract graduate students from many countries it can also provide another attractive option for Northeastern's BS students to pursue for their MS. The AIM MS program opens additional avenues for university-industry collaborative projects and new opportunities for graduate co-op positions. The AIM MS program brings Northeastern into the national network created by the National Network Manufacturing Innovation Institutes, which is commonly referred as *Manufacturing USA*.

As of FY 2016, the Manufacturing USA public-private partnership model included 548 manufacturing firms (66%); 177 educational institutions (21%), and 105 other entities (13%), including federal, state, and local government, Federal laboratories, and not-for-profit organizations. Figure 9 gives a picture of the network of stakeholders in Manufacturing USA, which includes over 1,200 organizations and 9,000 substantive relationships[9]. It is imperative that Northeastern be part of this network to attract major manufacturing research funding and be known for producing high-quality manufacturing engineers, researchers, and scientists.

[9] https://www.manufacturingusa.com/sites/prod/files/Manufacturing%20USA-Annual%20Report-FY%202016-web.pdf

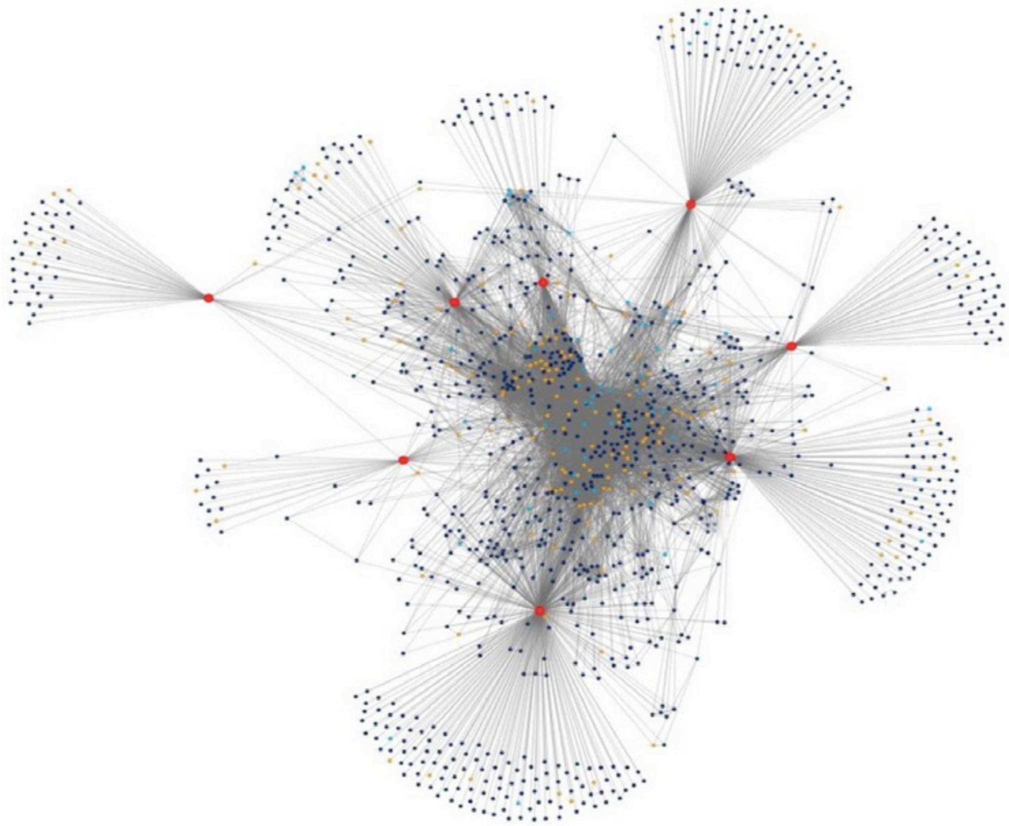

Figure 9. Network of industries, academic institutions, federal research labs, and government agencies enabled by the Manufacturing USA initiative, including over 1,200 organizations and 9,000 substantive relationships. Northeastern would significantly benefit by joining this network.

3. PROGRAM CLIENTELE ANALYSIS

The manufacturing sector contributes to over 12% of American GDP. This sector, which provides employment to over 12 million Americans, is critical to US global economic competitiveness.[10] The technology-based productivity improvements in manufacturing have been promoting continuous job growth.[11] Every dollar spent in manufacturing is generating $1.35 in additional economic activity.[12] Manufacturing USA, in partnership with private and public stakeholders, promotes innovative advanced manufacturing technologies to improve US competitiveness, reducing costs and saving energy[13]. As such, there is an urgent need to train the new workforce to support enormous growth we

[10] Department of Labor, Bureau of Labor Statistics (2015) http://www.bls.gov/iag/tgs/iag31-33.htm#workforce

[11] National Science and Technology Council. "A National Strategic Plan for Advanced Manufacturing." Web. February 2012. http://www.whitehouse.gov/sites/default/files/microsites/ostp/iam_advancedmanufacturing_strategicplan_2012.pdf

[12] President's Council of Advisors on Science and Technology. "Report to the President on Capturing Domestic Competitive Advantage in Advanced Manufacturing." Web. July 2012. http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_17_2012.pdf

[13] US Department of Energy. Quadrennial Technology Review. Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. http://www.doe.gov/qtr

are seeing in advanced manufacturing. Business leaders are concerned that we will have much difficulty sustaining manufacturing workforce needs[14]. Over the past 25 years, US manufactured goods exports have quadrupled[15], and approximately 3 million manufacturing jobs are expected to be created in the next 10 years[16]. The Bureau of Economic Analysis and Bureau of Labor Statistics[17] report that the average worker in the industry earns $81,289, compared to $63,830 earned by the average worker in all non-farm industries.

Shortage of Engineers, Researchers and Scientists

Currently, there is a serious shortage of people trained in advanced manufacturing. Talent Board reports that 50 to 75% of the people who apply to a job are unqualified for it[18]. Figure 10 presents the distribution of skill shortage in manufacturing sectors Currently, the manufacturing sector is experiencing over 28% shortage of engineers, researchers, and scientists. If the issue is not addressed, the shortage is likely to grow beyond 37% by 2020. Figure 11 identifies the factors contributing to talent shortage in the manufacturing sector in future.

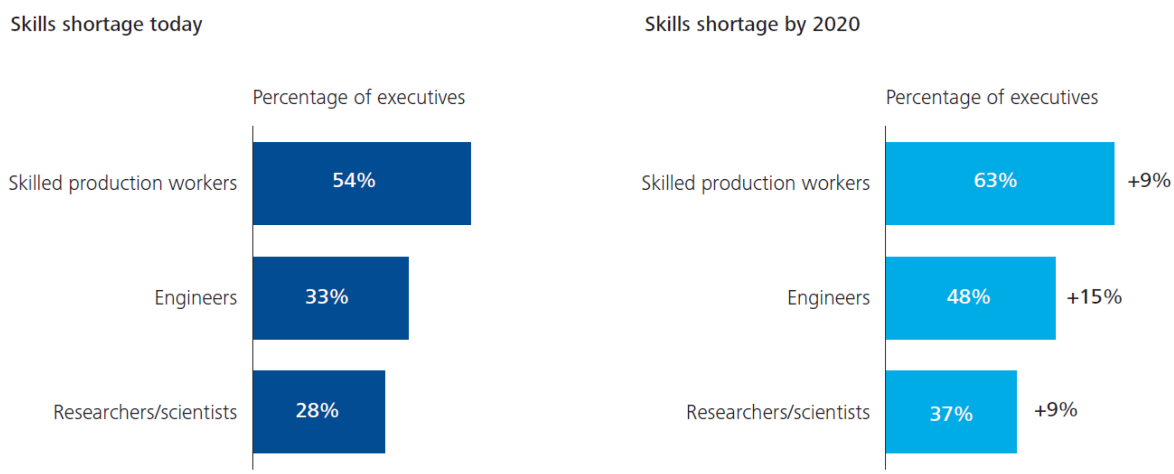

Figure 10. Current and predicted shortage of skills in the manufacturing

[14] White paper on "7 insights to grow your manufacturing workforce, faster," iCIMS Inc.
[15] . Commerce Department
[16] Deloitte and the Manufacturing Institute.
[17] Bureau of Economic Analysis and Bureau of Labor Statistics.
[18] Screening Matters, Talent Board.

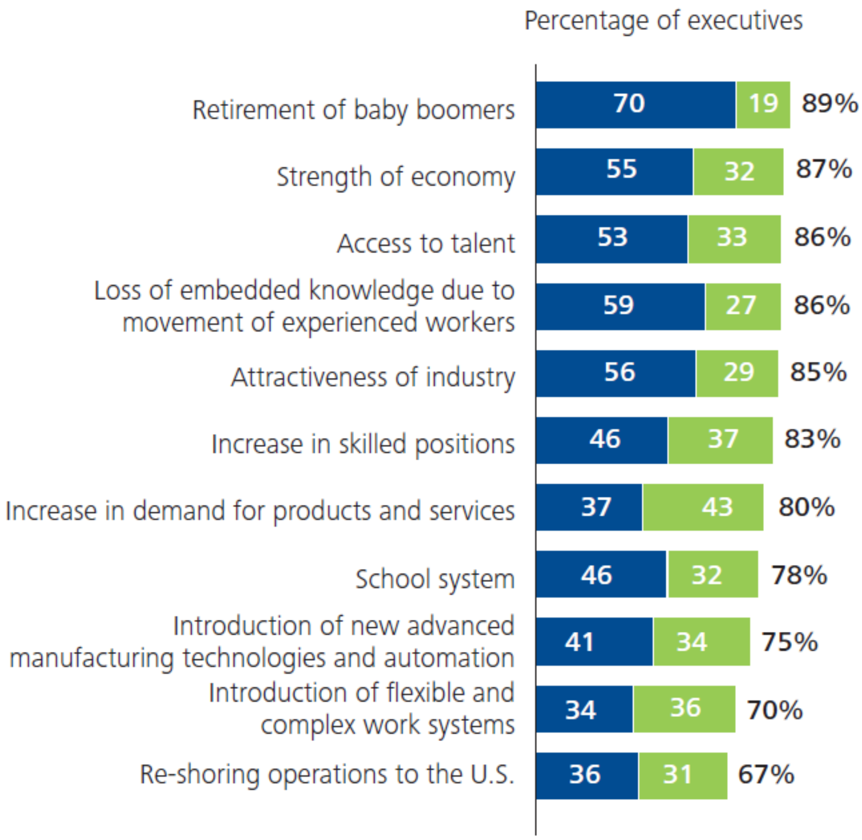

Figure 11. Factors contributing to shortage of skills in the manufacturing sector in future

Importance of Manufacturing

A McKinsey[19] report on manufacturing in the US discusses the next decade of projections of manufacturing growth under three different scenarios. The "low end" of the projections points out to a $350 billion increase in manufacturing GDP, where a trend of decline continues across most industries. A "new normal" situation where the decline is arrested and the US maintains the current level of domestic content in finished goods in most industries, a value add across the manufacturing industry is expected to reach $2.8 trillion by 2025. In the "stretch" situation, manufacturing GDP is expected to reach $3 trillion in 2025—an increase of $530 billion (20%) above the current trend. The "new normal" or "stretch" scenario is expected to add 1.3 to 2.3 million jobs by 2025 (see Figure 12).

[19] https://www.mckinsey.com/~/media/McKinsey/Global%20Themes/Americas/Making%20it%20in%20America%20Revitalizing%20US%20manufacturing/Making-it-in-America-Revitalizing-US-manufacturing-Full-report.ashx

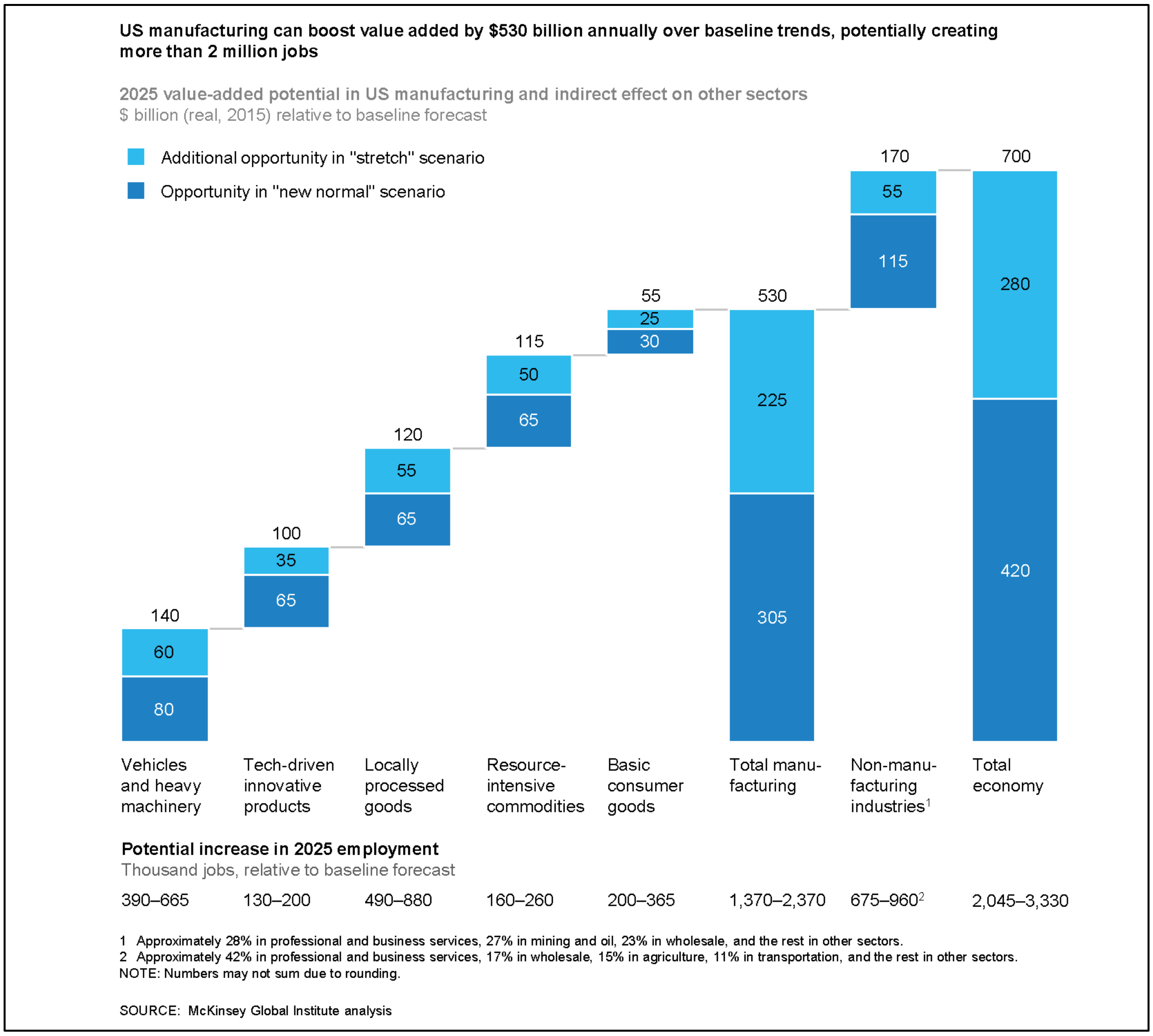

Figure 12. US manufacturing can boost value added by $530 billion annually over baseline trends, potentially creating more than 2 million jobs.

The Era of National Network of Manufacturing Innovation Institutes

In the last 5 years, various US federal agencies have collectively created the National Network for Manufacturing Innovation Institutes (NNMII)[20]. Federal NNMII partners include the Departments of Energy, Defense, and Commerce, as well as NASA and the National Science Foundation. To date, fourteen (14) institutes have been established, and more are underway, all working to create globally competitive products and advanced manufacturing technologies. This set of institutes collectively referred to as *Manufacturing USA*[21] is an interagency initiative made up of public/private partnerships devoted to manufacturing excellence. Each institute in Manufacturing USA brings together innovative manufacturers, university engineering schools, community colleges, federal

[20] https://www.manufacturingusa.com/institutes

[21] https://www.manufacturing.gov/

agencies, non-profits, and regional and state organizations to invest in unique, but industrially relevant, manufacturing technologies with broad applications. The innovation institutes in Manufacturing USA, each with over $150M budget, provides funding to conduct applied research and carry out demonstration projects that reduce the cost and risk of commercializing new technologies, solve generic industrial problems, provide education and training at all levels, develop innovative methodologies and practices for supply-chain integration, and engage with small and medium-sized manufacturing enterprises. Table 1 presents the list of NNMIIs that provide funding opportunities for advanced manufacturing research.

Table 1. List of manufacturing innovation institutes. Each institute has an operating budget of over $150M to rejuvenate advanced manufacturing.

Institute Name	Technology Focus	Description of Institute
Advanced Functional Fabrics of America (AFFOA)*	Materials, Material Processing, Sensors, Electronics	AFFOA is working to enable a manufacturing-based revolution by transforming traditional fibers, yarns, and fabrics into highly sophisticated, integrated and networked devices and systems. http://www.rle.mit.edu/fabric/
American Institute for Manufacturing Integrated Photonics (AIM Photonics)	Sensors, Optics and Photonics, Electronics	AIM Photonics is working to accelerate the transition of integrated photonic solutions from innovation to manufacturing-ready deployment in systems spanning commercial and defense applications. http://www.aimphotonics.com/
National Additive Manufacturing Innovation Institute (America Makes)	Materials, Material Processing, Lightweighting	America Makes is a national accelerator and the nation's leading collaborative partner for technology research, discovery, creation, and innovation in additive manufacturing and 3D printing. https://americamakes.us/
Advanced Robotics Manufacturing (ARM)*	Artificial Intelligence, Robotics, Sensors Modeling and Simulation, Automation, Digital Electronics, Materials	ARM Institute's mission is to create and then deploy robotic technology by integrating the diverse collection of industry practices and institutional knowledge across many disciplines – sensor technologies, end-effector development, software and artificial intelligence, materials science, human and machine behavior modeling, and quality

		assurance. http://www.arminstitute.org/
Advanced Regenerative Manufacturing Institute opens its doors to the future (BioFabUSA)	Biofabrication, Robotics, Biotechnology, Materials	BioFabUSA program looks to bridge the gap between early scientific research and later-stage product development by advancing critical technologies to enable large-scale biological manufacturing efforts. http://www.armiusa.org/
Clean Energy Smart Manufacturing Innovation Institute (CESMII)*	Sensors, Modeling and Simulation, Digital	CESMII works to spur advances in smart sensors and digital process controls that can radically improve the efficiency of US advanced manufacturing. https://cesmii.org/
Digital Manufacturing and Design Innovation Institute (DMDII)*	Design, Automation, Digital	DMDII encourages factories across the United States to deploy digital manufacturing and design technologies, so those factories can become more efficient and cost-competitive. http://dmdii.uilabs.org/
Institute for Advanced Composites Manufacturing Innovation (IACMI)	Materials, Material Processing, Lightweighting	IACMI is committed to accelerating development and adoption of cutting-edge manufacturing technologies for low-cost, energy-efficient manufacturing of advanced polymer composites for vehicles, wind turbines, and compressed gas storage. http://iacmi.org/
Lightweight Innovations For Tomorrow (LIFT)	Modeling and Simulation, Metrology, Design, Materials, Material Processing, Lightweighting	LIFT is working to develop and deploy advanced lightweight materials manufacturing technologies. http://lift.technology/
America's Flexible Hybrid Electronics Manufacturing Institute (NextFlex)*	Sensors, Digital Electronics	NextFlex takes key steps toward futhering US development and adoption of the flexible hybrid electronics that will revolutionize the way we live, work and play. http://www.nextflex.us/
National Institute for Innovation in Manufacturing	Metrology, Biotechnology,	IIMBL is working to enable more efficient and flexible manufacturing capabilities for existing and emerging biopharmaceutical products,

Biopharmaceuticals (NIIMBL)	Materials, Material Processing	and develop a world-leading biopharmaceutical manufacturing workforce. http://www.niimbl.us/
Advancing Wide Bandgap Power Electronics (Power America)	Electronics Materials	Power America is accelerating the adoption of advanced semiconductor components made with silicon carbide and gallium nitride into a wide range of products and systems. http://www.poweramericainstitute.org/
Rapid Advancement in Process Intensification Deployment Institute (RAPID) Chemical	Chemical Processing, Material Processing	RAPID Institute serves as an American manufacturing leader convening companies, universities, industrial research organizations and national laboratories to focus on new technologies that maximize processes at the molecular level to save energy with every chemical reaction—adding up to big savings on the manufacturing floor. http://processintensification.org/
Reducing EMbodied-energy And Decreasing Emissions (REMADE)	Recycling, Reuse, Sustainable Manufacturing	REMADE Institute enables early stage applied research and development of technologies that could dramatically reduce the embodied energy and carbon emissions associated with industrial-scale materials production and processing. https://remadeinstitute.org/
* Northeastern University is an active member of these Institutes		

As of now Northeastern University is a member of five NNMIIs: Advanced Functional Fabrics of America (AFFOA), Advanced Robotics Manufacturing (ARM), Clean Energy Smart Manufacturing Innovation Institute (CESMII), Digital Manufacturing and Design Innovation Institute (DMDII), and America's Flexible Hybrid Electronics Manufacturing Institute (NextFlex).

In addition to NNMIIs, two other important federal agencies, National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST), support advanced manufacturing research. The manufacturing cluster is the largest program in the division of Civil and Mechanical and Manufacturing Innovation division. Table 2 presents the details of manufacturing programs at NSF and NIST.

Table 2. List of advanced manufacturing programs at NSF and NIST.

Institute	Technology Focus	Description
Advanced Manufacturing Cluster at the National Science Foundations	Cyber manufacturing Systems, Manufacturing Machines and Equipment, Materials Engineering and Processing, Nanomanufacturing	NSF's The Advanced Manufacturing Cluster supports fundamental research leading to transformative advances in manufacturing and building technologies across size scales from nanometers to kilometers, with emphases on efficiency, economy, and minimal environmental footprint. https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503287
National Institute of Standards and Technology	Materials Genome Initiative, Emerging Technologies, Smart Manufacturing	NIST Laboratory Programs collaborate with industry, academia, and other government agencies to develop the measurement and standards solutions to accelerate the development of the next generation of manufacturing technologies. https://www.nist.gov/topics/manufacturing

It is also pertinent to note that several national research laboratories are active in advanced manufacturing. *Oak Ridge National Lab* develops new manufacturing technologies that are needed to enable companies to rapidly produce energy-efficient, competitively priced, high-quality products that will rejuvenate US manufacturing[22]. *National Renewable Energy Laboratory* focuses on scientific and engineering research in advanced manufacturing to identify and develop advanced materials and advanced processes that drive the impact of new energy technologies[23]. *Sandia National Laboratory*'s the Manufacturing Science and Technology Center develops and applies advanced manufacturing processes for realization of products to ensure that the nation's nuclear weapons stockpile is safe, secure, and reliable[24].

Northeastern's Advanced Sustainable Nano and Micro Manufacturing

Over the past two decades the cost of commercial electronics manufacturing continues to increase, with fabrication facilities costing up to $17 billion (Taiwan Semiconductor Manufacturing Company, TSMC, announced last year that their next plant will cost $20 billion), and requiring massive quantities of water and power. This high cost of entry barrier completely shuts out small and medium size businesses. Currently, there are only four companies in the world that are capable of building such plants. These conventional

[22] https://www.ornl.gov/research-area/advanced-manufacturing
[23] https://www.nrel.gov/manufacturing/
[24] http://www.sandia.gov/mst/

nanofabrication technologies, although responsible for all of the technological progress we experienced during the last three decades, have not been able to take advantage of many of the novel and superior properties of nanomaterials such as 0D nanomaterials (e.g., quantum dots, other conductive, semiconducting, or insulating nanoparticles); 1D nanomaterials (e.g., carbon nanotubes or nanowires); 2D nanomaterials (e.g., molybdenum disulfide [MoS2], graphene, etc.) that were discovered during the last two decades.

The Internet of Things (IoT) or Industry 4.0 is the network of physical objects embedded with sensors, electronics, software and connectivity with a total potential impact of up to $11 trillion per year in 2025 that will affect every industry and community on earth. However, these IoT market projections can only succeed if low cost ubiquitous sensors and electronics are made available. Printing of electronics offers significant savings over similar conventional silicon or gallium nitride based electronics fabrication. Over the past decade, there has been a new interest in manufacturing of low-end electronic devices using printing technologies. Inkjet, screen-printing, and gravure printing are technologies that are commercially used for printing electronics, flexible displays, and RFID tags. The cost of printed circuits is 10-100 times less than the cost of conventionally made devices. Current printing, however, scale-wise is 40 years old. Printed features using inkjets is about 20 microns, which was silicon electronics' line width in1975.

The next generation of printed devices requires a technology leap to print features at today's silicon electronics line width, which is 20 nm or less—some 1000 times smaller than current inkjet capability. There is a need for a nanoscale high-throughput printing technology that is high-rate, that can utilize a variety of nanomaterials, and that is capable of printing heterogeneous structures. The directed assembly-based printing processes, was developed by the NSF Science and Engineering Center for High-rate Nanomanufacturing (CHN) at Northeastern University, meet these requirements. The processes were specifically developed to be scalable, high-throughput, sustainable, yet show precise and repeatable control printing of various nanomaterials. The high-rate offset nanoscale printing technology using reusable Damascene templates utilizing electrophoretic directed assembly (inking) and transfer (printing) processes. These efforts have resulted in over 80 patent applications that cover the directed assembly-based printing and printed devices. The Museum of Science Boston (MOS) produced a 21-minute film about the transition of university nanoscience and engineering research to commercial success that featured NanoOPS and a nanotube company. The film was directed by Emmy-Award winning NOVA producer, Lawrence Klein. From Lab to Fab: Pioneers in Nano-Manufacturing https://www.youtube.com/watch?v=tZeO9I1KEec. Also, the National Science Foundation made a 5-minute video Nanoscale Offset Printing System. https://www.youtube.com/watch?v=2iEjIcog774

Unique opportunity for Northeastern

Northeastern is uniquely positioned to offer AIM MS program. Northeastern University was one of few universities that were awarded a National Science Foundation Nanoscale Science and Engineering Center that focuses on High-rate manufacturing (CHN) that resulted in more than 80 patents (25 granted) and over a thousand journal articles. It also partnered with over 40 small, medium and large corporation. The newly established Advanced Nanomanufacturing Cluster for Smart Sensors and Materials established in 2016 at the Burlington campus also has partnerships with major corporation interested in 3D printing of nano and micro electronics, sensors and materials applications. In addition, many MIE faculty are working on research projects that address issues in additive, nano, and smart manufacturing. For example, faculty members who are working in powder and material model, nano process development, nano device fabrication, process monitoring and control, data analytics, optimization, and simulation can directly support the courses and research projects for AIM MS program. In addition, faculty in Electrical and Computer Engineering and Computer Science can bring their expertise in sensor networks, wireless communication, cyber security, and machine learning to the MS program. Faculty in D'Amore-McKim School of Business can support courses and projects for managing manufacturing operations and supply chain. The program would significantly benefit from the Center for High Rate Nanomanufacturing (CHN) and Institute of Information Assurance (IIA). Northeastern's partnerships with many small and medium scale manufacturing companies and strong collaboration with big companies such as GE, IBM, Raytheon, EMC, Flex, Northrop and Grumman, and Analog Devices strengthen the program with co-op positions, translational research projects, and employment opportunities. About 60% of manufacturing industry executives believe that using internship programs and partnerships with universities is a means to address the issue of skills shortage for engineers, researchers, and scientists. The executives also report that internship programs and university recruitment are their top sources for recruiting engineers, researchers, and scientist[25]. The proposed AIM MS program enables Northeastern to supply a highly skilled talent pool for advanced manufacturing.

Evidence for program demand for ability to attract high quality students

The College of Engineering at Northeastern, historically and more so in the past five years, has attracted highly qualified applicants for their MS programs. The Graduate School of Engineering received more than 8,800 applications for their graduate programs for the fall 2017 admission cycle. Riding on the brand name of Northeastern's College of Engineering, one can confidently expect a sizable pool of highly qualified applicants for

[25] http://www.themanufacturinginstitute.org/~/media/827DBC76533942679A15EF7067A704CD.ashx

the AIM MS program. By offering three tracks in the AIM MS program, we are catering to a broad range of applicants. This application pool will likely come both from international and domestic students. Empirically, this is already evident from the exponential rise in the number of NU engineering grad and undergrad students enrolling into COE's MS and PhD programs.

Competition from other programs

Even though the demand for students with degrees in advanced manufacturing is growing, US universities have not kept up with the job market trend. Most of them still focus on traditional manufacturing curricula. Nationwide, there are around 42 or so graduate programs in manufacturing[26]. Out them, 25 prominent programs are listed in Table 3. These universities offer Master of Science (MS) or Master of Engineering (ME) programs in manufacturing. Most of them are companion programs for PhD in manufacturing. Table 3 summarizes these manufacturing MS/ME programs. Among them, most of the programs focus on traditional manufacturing that include CAD/CAM and production systems. A few programs cover additive manufacturing and robotics and automation. None of the programs have yet included courses on internet of things, intelligent manufacturing, and data analytics engineering. It is clear from the review of these MS/ME programs that there are no other universities that are offing MS programs that cover digital, smart, and connected aspects of manufacturing.

Table 3: MS/ME programs in manufacturing in major US universities

	University	Program	Description
1	**Arizona State University**	MS in Manufacturing Engineering	https://poly.engineering.asu.edu/engineering/ms-manufacturing-engineering/
2	**Boston University**	ME in Manufacturing Engineering	https://www.bu.edu/academics/eng/programs/manufacturing-engineering/meng/
3	**Massachusetts Institute of Technology**	ME in Advanced Manufacturing and Design	https://manufacturing.mit.edu/
4	**New Jersey Institute of Technology**	MS in Manufacturing Systems Engineering	http://catalog.njit.edu/graduate/newark-college-engineering/mechanical-industrial/manufacturing-systems-ms/

[26] https://www.hotcoursesabroad.com/study/training-degrees/us-usa/postgraduate/manufacturing-engineering-courses/loc/211/slevel/3/cgory/wa.6-4/sin/ct/programs.html#search&catCode=WA.6-4&countryId=211&parentQualId=3&nationCode=211&nationCntryCode=211&studyAbroad=N&studyOnline=N&studyCross=N&studyDomestic=N&studyPartTime=N&restRefineFlag=Y&pageNo=1

5	**Pennsylvania State University**	MS with Manufacturing	http://www.ime.psu.edu/students/resources/academic-plans/ms-manufacturing-option.aspx
6	**University of Michigan**	ME in Manufacturing	http://isd.engin.umich.edu/degree-programs/manufacturing-engineering/courses.htm
7	**University of New Mexico**	ME in Manufacturing Engineering	http://www.mfg.unm.edu/programs-and-degrees/program-overview.html
8	**University of Wisconsin Madison**	MS in Manufacturing Systems Engineering	https://www.engr.wisc.edu/app/uploads/2016/02/MSE_Program_Guide_10-27-2013.pdf
9	**Virginia Tech**	MS in Manufacturing Systems Engineering	http://catalog.njit.edu/graduate/newark-college-engineering/mechanical-industrial/manufacturing-systems-ms/
10	**Western Michigan University**	MS in Manufacturing	https://wmich.edu/extended/academics/manufacturing-engineering
11	**Worcester Poly Technique Institute**	MS in Manufacturing Engineering	https://www.wpi.edu/academics/departments/manufacturing-engineering
12	**University of Texas Rio Grande Valley**	MS in Manufacturing Engineering	http://www.utrgv.edu/graduate/for-future-students/graduate-programs/program-requirements/manufacturing-engineering-mse/index.htm#item4
13	**University of Texas at El Paso**	MS in Manufacturing Engineering	https://www.utep.edu/engineering/imse/academic-programs/ms-manufacturing.html
14	**Tennessee State University**	MS in Mechanical and Manufacturing Engineering	http://www.tnstate.edu/me/degrees.aspx
15	**Rochester Institute of Technology**	MS in Manufacturing and Mechanical Systems Integration	https://www.rit.edu/cast/mmet/graduate-programs/ms-in-manufacturing-and-mechanical-systems-integration
16	**Wayne State University**	MS in manufacturing engineering	https://engineering.wayne.edu/ise/ms/manufacturing-engineering.php
17	**University of Michigan - Dearbon**	MSE in manufacturing systems engineering	https://umdearborn.edu/cecs/departments/industrial-and-manufacturing-systems-engineering/graduate-programs/mse-manufacturing-systems-engineering

18	**Minnesota State University - Mankato**	MS in Manufacturing Engineering Technology	https://grad.mnsu.edu/programs/bulletin/met.html
19	**Western Illinois University**	MS in Manufacturing Engineering Systems	http://www.wiu.edu/grad/0506catalog/manuf.shtml
20	**Illinois Institute of Technology**	MS in manufacturing engineering	https://engineering.iit.edu/programs/graduate/master-science-manufacturing-engineering
21	**University of Southern California**	MS in Manufacturing Engineering	http://catalogue.usc.edu/preview_program.php?catoid=7&poid=6743&returnto=2081
22	**University of Wisconsin - Milwaukee**	MS in Manufacturing Engineering	https://uwm.edu/engineering/academics-2/departments/industrial-manufacturing-engineering/
23	**Ohio State University**	MS in Manufacturing Engineering	https://engineering.osu.edu/graduate/ise
24	**University of Texas San Antonio**	Advanced Manufacturing and Enterprise Engineering	http://graduateschool.utsa.edu/programs/advanced-manufacturing-and-enterprise-engineering-m.s
25	**University of California - Los Angeles**	MS in manufacturing engineering	https://grad.ucla.edu/programs/school-of-engineering-and-applied-science/mechanical-aerospace-engineering-department/manufacturing-engineering/

Figure 13 presents a SWOT analysis chart for the proposed AIM MS program. The main strength of Northeastern is its excellent faculty and industry collaborations that can support teaching and research in digital and smart manufacturing. In addition, the students of this program can benefit from experiential learning model and co-op experience in hi-tech manufacturing companies.

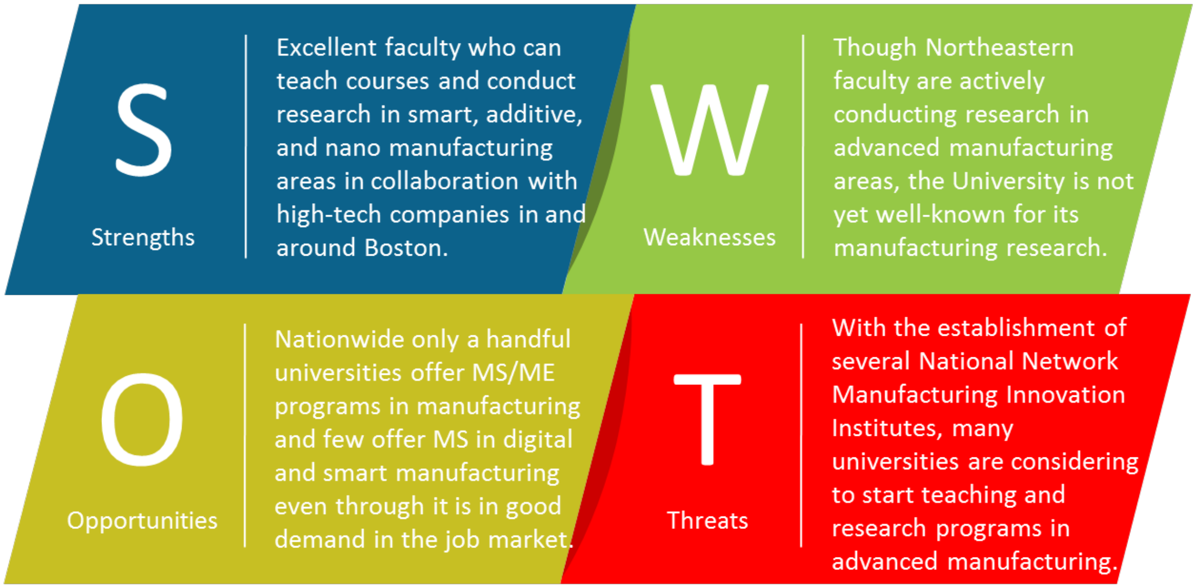

Figure 13. SWOT analysis of the proposed AIM MS program

In the absence of MS programs in digital and smart manufacturing in the US, Northeastern has an excellent opportunity to establish the program and become well-known internationally for manufacturing education and research in advanced manufacturing, particularly in industry 4.0. Though Northeastern faculty are conducting cutting-edge research in areas related to advanced manufacturing, the University has not yet commanded matching recognition for contributions to manufacturing. This is in part due to lack of integration of research being conducted in isolated pockets. The proposed program has potential threat from other leading universities. The recently established 14 NNMIIs are channeling significant amounts of federal dollars for translational research in advanced manufacturing. In the light of these opportunities, many universities, including Georgia Tech, MIT, Purdue, and Texas A&M, are likely to consider starting teaching and research programs in digital and smart manufacturing. So, the proposed AIM MS program will put Northeastern at the forefront of the industry 4.0 wave to gain competitive advantage. With its emphasis on digital, smart and connected, the proposed AIM MS program at Northeastern distinguishes itself from other MS programs. Table 4 compares different MS/ME manufacturing programs in the US.

Northeastern's AIM MS program can expect to experience overwhelming demand from applicants and industry partners, considering that Boston is a hub of defense, information technology, bio-pharma, and robotics, and high-tech manufacturing industries. Northeastern’s AIM MS program should also stand apart due to its graduate co-op opportunities, experiential learning model, and translational research.

Table 4. Comparison of MS/ME programs in manufacturing in major US universities

University	CAD/CAM	Production Systems	Additive Manufacturing	Robotics and Automation	Digital & Smart Manufacturing
Northeastern University	✓	✓	✓	✓	✓
Boston University	✓	✓	✗	✗	✗
Massachusetts Institute of Technology	✓	✓	✓	✗	✗
New Jersey Institute of Technology	✓	✓	✗	✗	✗
Pennsylvania State University	✓	✓	✓	✗	✗
University of Michigan	✗	✗	✗	✗	✗
University of New Mexico	✓	✓	✗	✗	✗
University of Wisconsin Madison	✓	✓	✓	✓	✗
Virginia Tech	✓	✓	✗	✓	✗
Western Michigan University	✓	✓	✗	✗	✗
Worcester Poly Technique Institute	✓	✓	✗	✗	✗
University of Texas Rio Grande Valley	✗	✓	✗	✓	✗
University of Texas at El Paso	✗	✓	✗	✗	✗
Tennessee State University	✓	✓	✗	✓	✗
Rochester Institute of Technology	✗	✓	✗	✓	✗
Wayne State University	✓	✓	✗	✗	✗
University of Michigan - Dearborn	✓	✓	✗	✗	✗

Minnesota State University - Mankato	✓	✓	✗	✗	✗
Western Illinois University	✓	✓	✗	✓	✗
Illinois Institute of Technology	✓	✓	✗	✓	✗
University of Southern California	✓	✓	✗	✓	✗
University of Wisconsin - Milwaukee	✗	✓	✗	✗	✗
Ohio State University	✓	✓	✗	✗	✗
University of Texas San Antonio	✓	✓	✗	✓	✗
University of California - Los Angeles	✓	✓	✗		✗

Impact on existing programs at Northeastern

The AIM MS program will have a positive and synergistic impact on existing graduate and undergraduate programs. It draws its core and elective courses from the existing pool of courses offered by several departments and colleges at Northeastern. The majority of these courses come from COE, and only a few specialty courses come the College of Computer and Information Science and D'Amore-McKim School of Business. The AIM MS program creates demand rather than competition for these existing courses. For example, the program can increase demand for courses that are typically taken by students from graduate programs in Mechanical Engineering, Industrial Engineering, and Electrical and Computer Engineering. The program could also open many research opportunities for undergraduate students.

4. Educational Objectives and Curriculum

This section discusses educational objectives, course curriculum, admission criteria, and other requirements of the proposed AIM MS program.

Educational Objectives

The Department of Mechanical and Industrial Engineering (MIE) offers the Master of Science in Advanced and Intelligent Manufacturing (MS in AIM) to meet the growing demand for engineers, researchers, and scientists trained in advanced manufacturing and Industry 4.0 technologies. This degree program offers students an opportunity to either train for industry jobs with coursework and co-op experience or prepare for a doctoral program through coursework and research experience. MIE Department offers both core courses and elective courses required to complete the program. Students can take MS Project or MS Thesis under any MIE faculty. This program is designed for engineering and science students planning to pursue careers in advanced and smart manufacturing. The key sectors that require manufacturing professionals include automotive, aerospace, defense, appliances, computing machines, smart phones, and communication equipment. The MS in AIM program helps students acquire knowledge and skills to:

- Build digital (CAD) models of parts and products to support manual and computer-aided manufacturing.
- Design, develop, and analyze traditional and advanced manufacturing processes.
- Utilize additive manufacturing to produce complex parts with ease and efficiency.
- Select manufacturing processes to fabricate parts and products for quality and cost.
- Configure and analyze manufacturing systems for efficiency, responsiveness, and high throughput.
- Understand the characteristics and challenges of nano manufacturing processes.
- Leverage Industry 4.0 technologies including internet of things, cloud computing, sensor analytics for advanced manufacturing.
- Adopt condition-based maintenance strategies to achieve high resource utilization.
- Apply automation, robotics, and artificial intelligence to make manufacturing smart and self-operational.
- Use human-machine interaction tools such as augmented reality and virtual realty.
- Analyze human performance in sociotechnical systems such as supply chains.
- Apply data analytics methods to gain insights from design and manufacturing data.

In the context of this program, the traditional manufacturing covers metal removal, forming, casting, and particulate processes. The additive manufacturing covers topics such as 3D printed of parts using different approaches. The nanomanufacturing covers fabrication as well as printing of micro and nano devices and design and creation of multifunctional materials. Intelligent manufacturing focuses on factory automation, prognostics and health management, dynamic scheduling, cloud enabled manufacturing, and industrial internet of things for manufacturing performance assurance. It also leverages real-time data analytics and control systems, advanced high-fidelity models, networked data, and computation for seamless interoperation of cyber and physical assets in manufacturing facilities.

Admissions criteria and process

To be eligible for admission to MS in AIM program, a prospective student must hold a Bachelor of Science degree in engineering, science, mathematics, or equivalent field. Applications to the MS in AIM program will be processed by the Graduate School of Engineering. The program director will review the applications and offer admission to applicants that meet the admission standards defined in terms of GPA, GRE and TOEFL scores, recommendation letters, and manufacturing-related work experience. The Program Director will communicate his or her decision to the Graduate School of Engineering for a final review and follow through the admission process. The admissions requirements of the program will be defined within the framework of policies and guidelines set forth by the College of Engineering and the University Graduate Council.

Degree requirements

This section gives details about the credit requirements, core courses, elective courses, MS project and MS thesis

Credit hour requirements

To graduate from the program students are required to complete a total of 32 SH. Students take 24 SH of core courses and 8 SH of elective courses or 8 SH MS-thesis. In addition, 4 SH elective(s) can be replaced by a 4 SH project.

Degree Requirements	With Thesis	With Project	Course Work Only
Core courses	16 SH	16 SH	16 SH
Electives courses	8 SH	12 SH	16 SH
MS Project	-	4 SH	-
MS Thesis	8 SH	-	-
Minimum semester hours required	**32 SH**	**32 SH**	**32 SH**

Core Courses

Students are required to take 4 core courses (16 SH) listed below:

IE 6300 Manufacturing Methods and Processes (4 SH)
IE 7270 Intelligent Manufacturing (4 SH)
ME 5240 Computer Aided Design and Manufacturing (4 SH)
ME 5640 Additive Manufacturing (4 SH) [new course to be developed]

These core courses are designed to give students a solid foundation in manufacturing processes, manufacturing systems, digital and smart manufacturing, and materials processing. Description of core courses is presented in Appendix A.

Restricted Elective Courses

Students are required to take 1 course from the restricted elective courses (4 SH) listed below:

CSYE 6510 Fundamentals of the Internet of Things (4 SH)
IE 6500 Human Performance in Sociotechnical Systems (4 SH)
ME 7374 Nano and Microscale Manufacturing (4 SH)

These restricted elective courses are designed to add to the foundational core in manufacturing processes, manufacturing systems, digital and smart manufacturing, and materials processing. Descriptions for these courses are presented in Appendix A.

Elective courses

Students are typically required to complete 2 or 3 courses, for a total of 8-credits, from the following elective course list. These courses provide students with knowledge and understanding of digital and smart manufacturing related topics such as robotics and automation, control systems, mechatronics, composite materials, additive manufacturing, statistical quality control, reliability analysis, mass customization, and supply chain engineering. Or students can select their electives to prepare themselves for a doctoral program by taking advanced courses in mathematics, statistics, machine learning, and pattern recognition. The following is the list of approved elective courses offered by different academic units distributed across different colleges. Students must select these courses in consultation with AIM MS program advisor.

AIM Elective Course List:

Industrial Engineering
IE 5617 Lean Concepts and Applications
IE 6200 Engineering Probability and Statistics
IE 7200 Supply Chain Engineering
IE 7215 Simulation Analysis
IE 7255 Manufacturing Processes
IE 7270 Intelligent Manufacturing
IE 7275 Data Mining in Engineering
IE 7280 Statistical Methods in Engineering
IE 7285 Statistical Quality Control

IE 7290 Reliability Analysis and Risk Assessment
IE 7315 Human Factors Engineering
IE 7615 Neural Networks in Engineering

Operations Research
OR 7230 Probabilistic Operation Research
OR 7235 Inventory Theory
OR 7240 Integer and Nonlinear Optimization
OR 7245 Network Analysis and Advanced Optimization
OR 7310 Logistics, Warehousing, and Scheduling

Materials Engineering
MATL 6270 Principles, Devices, and Materials for Energy Storage and Energy Harvesting
MATL 6285 Structure, Properties, and Processing of Polymeric Materials
MATL 7365 Properties and Processing of Electronic Materials

Mechanical Engineering
ME 5XXX Additive Manufacturing (4 SH) [new course to be developed]
ME 5245 Mechatronic Systems
ME 5250 Robot Mechanics and Control
ME 5645 Environmental Issues in Manufacturing and Product Use
ME 5650 Advanced Mechanics of Materials
ME 5659 Control Systems Engineering
ME 7247 Advanced Control Engineering

Engineering Management
EMGT 5220 Engineering Project Management
EMGT 6225 Economic Decision Making
EMGT 6305 Financial Management for Engineers

Project

In place of an elective course, students can undertake a 4-credit hour digital/smart manufacturing project under the supervision of a faculty member from the College of Engineering at Northeastern University. The project should involve a digital and smart manufacturing related topics such as robotics and automation, control systems, mechatronics, composite materials, additive manufacturing, mass customization, statistical quality control, reliability analysis, and supply chain engineering. The project could be either sponsored by industry or defined by a faculty advisor.

MS Thesis

In lieu of elective courses, students can undertake an 8-credit MS thesis under the supervision of a faculty member from the College of Engineering, Northeastern University. The project should address a research problem in digital and smart manufacturing related areas such as robotics and automation, control systems, mechatronics, composite materials, additive manufacturing, statistical quality control, reliability analysis, mass customization, and supply chain engineering. The thesis should train students for a doctoral program in advanced manufacturing.

Minimum academic standards

There are no academic standards required in addition to the university requirements.

Requirements as applicable

All AIM MS program students with thesis or project options, must complete the 0 SH MEIE 6800 Technical Writing and MEIE 6850 Research Seminar courses in Mechanical and Industrial Engineering, preferably during their first year of full-time study. If appropriate, part-time students may petition the graduate affairs committee to waive these requirements. Students who receive financial support from the university in the form of a research, teaching, or tuition assistantship must complete an 8-semester-hour thesis. Students who complete the thesis option must make a presentation at a thesis defense before approval by the department. All students in the program must complete a minimum of 32 semester hours of approved course work (exclusive of any preparatory courses) with a minimum GPA of 3.000.

Audiences

The AIM MS program is designed for audiences who have the educational background necessary to enter a graduate program in engineering. This program is also designed to make it attractive to BS/MS students enrolled in Northeastern's undergraduate engineering programs. Students seeking admission into the AIM MS program with insufficient background, who otherwise meet the admission standards, will be required to take remedial courses in calculus, differential equations, linear algebra, and statistics offered by the Graduate School of Engineering.

Minimum academic standards

There are no academic standards required in addition to the university requirements.

Curriculum requirements

The curriculum documentation checklist, new programs curriculum requirements form, and pattern of attendance form have been completed and are included with this proposal package.

Curriculum requirements for completion

These requirements were described above.

New elective courses to be developed

ME 5640 Additive Manufacturing (4 SH) [new course to be developed]

Program assessment

The learning outcomes for the program are listed at the beginning of Section 4. The program director and advisory committee will develop a rubric of metrics for key performance indicators of the course and program objectives. Using this rubric, the program director and the advisory committee will assess course and program activities and experiences.

Once the students are admitted into the program, core outcomes of each course will be assessed through direct and indirect assessment methods. The program director will develop survey instruments to get anonymous student feedback on completed courses. These surveys will be conducted for all core courses and for a random sample of elective courses. In addition, the outcomes for the courses will be assessed through TRACE evaluations. The survey results will be summarized in an outcome rubric for each course to assess the core outcomes of the course. This assessment will be conducted each year until the program reaches maturity and stability, expectedly by the end of the fifth year of the program.

The overall program outcomes will be assessed through many standard graduate program metrics such as application volume, acceptance rate, yield, graduate rate, placement statistics, and competency match between curriculum and industry needs. The program will also monitor the students' co-op positions and co-op employers' feedback to gauge the program outcomes. Furthermore, the program will conduct surveys for graduating students and the employed alumni in the field to get their feedback on the program performance. This feedback from the graduating students and employed alumni will be translated into recommendations for the program improvement. This assessment will be conducted annually to address curricular issues and co-op and employment issues. A comprehensive program review will be conducted at the end of the fifth year of the program.

The program director and the advisory committee will conduct a comprehensive curriculum assessment at the end of the fifth year of the program. By reviewing formative course evaluations and program evaluations, the program director and advisory committee will identify and address issues related to knowledge and skill gaps, course prerequisites, course sequences, and other barriers to student learning. The assessment methods and schedule are summarized in Table 7.

Table 7. Assessment methods and schedule.

Assessment Method	Year 1 (AY 19/20) Formative Assessment	Year 2 (AY 20/21) Formative Assessment	Year 3 (AY 21/22) Formative Assessment	Year 4 (AY 22/23) Formative Assessment	Year 5 (AY 23/24) Summative Assessment
Admission Data Review	Spring	Spring	Spring	Spring	Spring
Student Feedback on Courses	Summer	Summer	Summer	Summer	Summer
TRACE Evaluations	Summer	Summer	Summer	Summer	Summer
Co-Op Student Survey	Fall	Fall	Fall	Fall	Fall
Co-Op Employer Survey	Fall	Fall	Fall	Fall	Fall
Graduate Student Exit Survey	Spring	Spring	Spring	Spring	Spring
Employed Alumni Survey	Fall	Fall	Fall	Fall	Fall
Curriculum assessment	Summer	Summer	Summer	Summer	Summer
Overall Program Performance Evaluation	Summer	Summer	Summer	Summer	Summer

5. RESOURCES

No additional resources are required to implement and run the proposed AIM MS program. The program is built on existing, well-established courses. An additional elective course, ME xxxx Additive Manufacturing, will be developed by one MIE faculty member. No additional cost and effort will be required to offer core and elective courses of the program. Coincidentally, the MIE Department is planning to hire one or two new faculty members in the manufacturing area this academic year to establish a compressive research program in advanced manufacturing. The arrival of new advanced manufacturing faculty will also strengthen the AIM MS program in terms of courses, projects, and dissertation theses.

Faculty resources

The following is the list of faculty members within the Department Mechanical and Industrial Engineering, Chemical Engineering, Electrical and Computer Engineering, and Civil and Environmental Engineering that could potentially serve as core and/or affiliated members for the AIM MS program. These faculty members will teach core and elective courses for the AIM MS program. Also identified below are faculty members from CCIS and DMSB who could serve as affiliate members for the AIM MS program. All these faculty members will be able to serve research advisors for students enrolled in AIM MS program. Faculty resources are listed in Tables 8 and 9.

Table 8. List of COE faculty working in mechanical, materials, industrial engineering, and sensors areas that could potentially serve as core and/or affiliated members for the AIM MS program.

MIE		CHE	ECE	CEE
Md Noor E Alam	Yang Liu	Edgar Goluch	Kaushik Chowdhury	Matt Eckelman
Teiichi Ando	Yongmin Liu	Francisco Hung	Hui Fang	Auroop Ganguly
Mehdi Behroozi	Yingzi Lin	Carolyn L.-Parsons	Yunsi Fei	Michael Kane
Ahmed Busnaina	Craig Maloney	Laura Lewis	Vincent Harris	Haris Koutsopoulos
Mohammad Dehghani	E. Melachrinoudis	Ming Su	Nicol McGruer	Amy Mueller
Chun-An Chou	Marilyn Minus		Taskin Padir	
Randall Erb	Mohsen Moghadam		Matteo Rinaldi	
Ozlem Ergun	Sinan Muftu		Hanumant Singh	
Nasser Fard	Hamid N.-Hashimi		Nian Sun	
Andrew Gouldstone	Himlona Palikhe		Srinivas Tadigadapa	
Jackie Griffin	Jinxiang Pei			
Surendra Gupta	Sri Radhakrishnan			
Babak Heydari	Manish Ranjit			
Jackie Isaacs	Sandra Shefelbine			
Safa Jamali	Rifat Sipahi			
Xiaoning Jin	Moneesh Upmanyu			
Yung Joon Jung	John Whitney			
Sagar Kamarthi	Wei Xie			
Laurent Lessard	Ibrahim Zeid			
Yaning Li	Jie Zhang			
	Hongli Zhu			

Table 9. List CCIS and DMSB faculty that could potentially serve as affiliated members for the AIM MS program.

CCIS	DMSB
Standardize Open Software and Communication Platforms	Matin Dias
Karl Lieberherr	Cuneyt Eroglu
Chrisina Nita-Rotaru	Richard Kesner
Guevara Noubir	Yang Lee
Pete Manolios	Robert Lieb
William Robertson	Tucker Marion
Ravi Sundaram	Robert Murray
Olga Vitek	Gilbert Nyaga
	Nada Sanders
Real-Time Data Analytics	Frederick Wiseman
David Choffnes	
Ehsan Elhamifar	
Javed Aslam	
Rajamohan Rajaraman	
Mirek Riedewald	
Advanced High-Fidelity Modeling	
Albert-Laszlo Barabasi	
Christoph Riedl	
David Lazer	
Alessandro Vespignani	
Robert Platt	

There are no space needs for the program. There are sufficient library resources already in place for the program.

Manufacturing Facilities Resources

Northeastern University three key manufacturing facilities that support the proposed AIM program: (1) Cyber Physical Factory Lab (approve and under constuction), (2) George J. Kostas Nanoscale Technology and Manufacturing Research Center, (3) Advanced Nanomanufacturing Cluster for Smart Centers and Materials (CSSM), and (4) Kostas Advanced Nano-Characterization Facility (KANCF).

Cyber Physical Factory Lab

COE is building a multi-use Cyber-Physical (CP) Factory laboratory to support undergraduate and graduate education, and to conduct translational research in emerging Industry 4.0 technologies such as internet of things, cyber security, robotics / automation, machine learning / artificial intelligence, augmented / virtual reality, and smart and sustainable manufacturing. Figure 14 gives a schematic of the lab, which is under building phase now. The university already allocated space (800 sqft) and funds to build this lab. This lab will be used as a testbed to demonstrate the research projects in thrust areas. As a leading experiential learning institution, education of our students on Industry 4.0 concepts and technologies is paramount to tackle the critical skills gap in the U.S. workforce. This lab is an essential part of proposed MS in AIM.

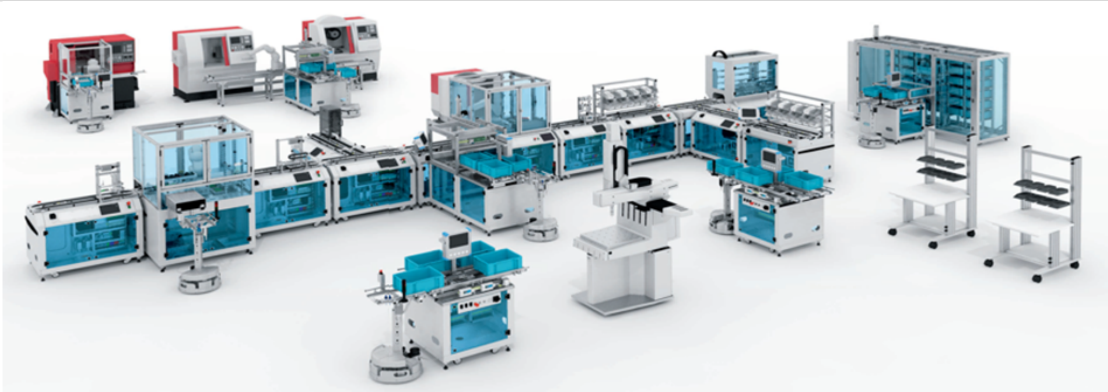

Figure 14. Schematic of the Cyber Physical Factory lab for demonstrating research projects in research thrusts

George J. Kostas Nanoscale Technology and Manufacturing Research Center

The George J. Kostas Nanoscale Technology and Manufacturing Research Center, is the primary user facility for micro and nanofabrication at Northeastern University. The 7,000 sq. ft. user facility includes cleanroom space down to Class 10 and houses instruments for micro and nanofabrication processes and characterization studies, including metrology. Non-cleanroom lab space includes chemical hoods; device-testing areas with a full range of electrical test instruments and design areas. The facility is open to faculty, students, researchers, coop students, and *external users with easy scheduling and access*. The facility provides support and materials based on user fees and have capabilities for processing 3, 4, and 6-inch wafers as well as smaller parts at lower cost. Applications range from nanoelectronics, nanodevices, sensors, energy storage, and NEMs to exploration studies in fundamental science and engineering. The facility is supported by highly trained and talented staff with a combined 75 years of fabrication and characterization experience who will assist the users with their process development. We welcome new researchers from all disciplines who wish to explore the use of micro and nano fabrication and characterization tools in expanding their research portfolio.

Homepage: www.kostas.neu.edu
Access: http://kostas.aeroweb.net/getting-started/
Use Fees: http://kostas.aeroweb.net/user-fees/
Staff: http://kostas.aeroweb.net/staff/

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Advanced Nanomanufacturing Cluster for Smart Centers and Materials (CSSM)
The CSSM cluster was established by funding from the Massachusetts Technology Collaborative's to establish an Advanced Nanomanufacturing printing facility and a Cluster for Smart Sensors and Mate-rials.

Advanced Nanomanufacturing has vast potential to advance con-nected technologies, known as the internet of things, and revolutionize the sensing industry. This includes potential commercial applications such as high-precision miniature wireless sensors used to monitor premature babies in hospital neonatal units, wearable sensors for health and fitness that tracks biomarkers such as glucose, lactate or other biometrics, and sensors that track water quality. The cluster leverages Northeastern's innovative Nanoscale Offset Printing System, or NanoOPS, a manufacturing technology pioneered by the College's NSF Center for High-Rate Nanomanufacturing (CHN). NanoOPS can print nanoscale sensors and devices as small as 20 nanometers—more than 10,000 times thinner than a human hair—on a variety of surfaces, and 100 to 1,000 times faster than current ink jet-based elec-tronic and 3-D printing. The cluster also includes infrastructure for materials characterization and testing smart sensor prototypes, and to build generation 2 and generation 3 NanoOPS with enhanced capabilities to the insti-tute, including the ability print on any surface.

Kostas Advanced Nano-Characterization Facility (KANCF)

The Kostas Advanced Nano-Characterization Facility(KANCF) is a multidisciplinary research and educational core facility within the Kostas Research Institute(KRI) at Northeastern University. It houses two state-of-the-art electron microscopes including a Cs-corrected TEM/STEM-FEI Titan Themis 300, and a high-resolution SEM/FIB-FEI Scios DualBeam system. The KANCF facility supports educational and research needs for students and faculty within Northeastern University community as well as provides electron microscopy related services for other universities, institutes and industry.

Homepage: https://web.northeastern.edu/kancf/
User Fees: https://web.northeastern.edu/kancf/?page_id=50

6. BUDGET [This section is under preparation]

There is no budget required for this program because all courses currently exist, except for one new course on additive manufacturing that need to be developed. The program expects to enroll 25 new students a year within the first 3 years.

APPENDIX A: Course Description of Core Courses

CSYE 6510 Fundamentals of the Internet of Things (4 SH)
Explores the foundations and technologies involved in the Internet of Things (IoT). Topics include machine-to-machine (M2M) communication and its relationship with IoT as well as their evolution. Examines fundamental components of the IoT architecture and presents a large array of real-life applications and case studies. Focuses on different wireless technologies that are relevant to the IoT including WiFi, Bluetooth Low Energy, and ZigBee, as well as several network layer protocols that are instrumental to the deployment of these networks. Discusses the most common IoT application technologies with special emphasis on MQTT, CoAP, and AMQP. Also explores special issues that affect IoT networks, including security and privacy considerations as well as reliability mechanisms intended to overcome network impairments.

IE 6300 Manufacturing Methods and Processes (4 SH)
Focuses on manufacturing and its relationship to design and computers. Examines the relationship between design and various aspects of manufacturing. Covers manufacturing systems, manufacturing processes, bill of materials, group technology, mechanical tolerancing, QC, SPC, QPC, TQM, process planning and CAPP, NC part programming, supply chain management, production scheduling, JIT, lean manufacturing, flexible manufacturing systems, CIM cells, and manufacturing control via, say, programmable logic controllers.

ME 5240 Computer Aided Design and Manufacturing (4 SH)
Covers basic aspects of computer graphics and CAD/CAM. Topics include hardware and software concepts, generic structure of CAD/CAM software and its modules, and CAD/CAM database structure. Also covers the parametric representations of curves, surfaces, solids, and features that are widely used in existing commercial CAD/CAM systems. Discusses geometrical transformations, CAD/CAM data exchange formats, prototyping techniques, and PDM. Presents applications such as mass properties calculations, assemblies, mechanical tolerancing, simulation, finite element mesh generation, process planning and CAPP, CNC part programming, and Web-based CAD/CAM.

IE 7270 Intelligent Manufacturing. 4 Hours (4 SH)
Covers several advanced and contemporary topics in manufacturing. Includes applications of computational methods including expert systems, neural networks, and multiagents in manufacturing. Discusses the methods related to distributed and web-enabled manufacturing.

ME ???? Additive Manufacturing (4 SH)

It cover comprehensive study of fundamentals, process characteristics and practical applications of various Additive Manufacturing processes. Students learn the basic process steps of the Digital Work Flow from Design to Manufactured AM parts; understand the various software tools, processes and techniques that enable advanced/additive manufacturing; learn the fundamentals of various additive manufacturing (AM) processes using polymers, metals, and other material and understand the operating principles, capabilities, and limitations of AM processes; gain hands-on experience with AM machines and understand the complete process steps through design, fabrication, and measurement of example parts; study the range of applications of AM across the spectrum of industries (e.g. aerospace/automotive, medical devices, and consumer products) while developing the understanding of the requirements, constraints, and business case for the applications; be able to evaluate and select appropriate AM technologies for specific applications; and AM role in the future of manufacturing and digital transformation of manufacturing.