Research Needs for Cyberphysical Systems in Machining and Machine Tools:

A Roadmap

September 23, 2024

Executive Summary

Rapid advances in artificial intelligence and computational capability have underscored the need for targeted government investment in research that advances new manufacturing capabilities to both boost national productivity and increase national security, but also assure the resilience of manufacturing supply chains to global disruption and unexpected events.

This report offers preliminary results of a roadmapping effort by the *Future of Manufacturing: A Network for Cybermanufacturing in Machining* project to uncover critical research needs that not only support industry initiatives to transform manufacturing and machining within their companies, but also inform consortium building efforts such as the open competition to establish a new Manufacturing USA institute focused on the use of AI to increase the resilience of US manufacturing, recently announced by the National Institute of Standards (NIST).

Funded by the National Science Foundation (NSF), this *Future of Manufacturing* project focuses on cyberphysical systems for machining and machine tools—leveraging the convergence of advances across artificial intelligence and computing to materials and metrology to identify research endeavors that would be transformative to the machining industry. Many of these same research needs and future advances are also critical to the goals of the NIST call for the new Manufacturing USA Institute on AI for resilient manufacturing.

The *Future of Manufacturing* project established a network of world-class industry and academic researchers and practitioners in cybermanufacturing to engage in a series of roadmapping events to create and mature a basic research roadmap for cyberphysical systems in machining and machine tools. Participants were trained in the roadmapping procedure developed at the National Center for Defense Machining and Manufacturing (NCDMM) and previously used by other Manufacturing USA Institutes and government agencies.

Machining is one of the most widely practiced of all manufacturing operations and supports virtually every economic sector and product family, either by direct manufacture of the product's critical elements, or through fabrication of the tooling and equipment used to manufacture and distribute the product. Machining technology is a critical contributor to the vitality of the entire U.S. manufacturing economy. The overall machine tool industry captures a growing $70 billion in annual capital expenditure and has both direct and indirect resources of over $2 trillion.

Conceived as a longitudinal study, roadmapping events have been held annually from 2021 to 2024 at the International Machine Tool Show (IMTS) and North American Manufacturing Research Conference (NAMRC) in alternating years. The first roadmapping event in June 2021 took place virtually, due to COVID. Subsequent events have been convened at IMTS in 2022, NAMRC/MSEC in 2023, and IMTS in 2024.

"Democratizing" of decision-making is the driver of the proposed roadmapping effort, gathering input of diverse research topics from a broad coalition of members and synthesizing these inputs into consistent themes that can be evaluated as to their difficulty and importance for prioritization. The roadmapping activity involves the following three broad phases.

1. **Ideation of Research Topics.** The starting point for the roadmapping process is the creation of a creative matrix defined by the intersection of research pillars and cross-cutting technologies. These creative matrices facilitate a modified brainstorming approach for identifying research topics that fall within the cells of the matrix. Allowing for flexibility, the creativity matrices that were developed for the various roadmapping events comprised some that were broad in their scope, while others allowed for "deep dives" on specific topics, notably artificial intelligence, and the scale of research projects (machine, cell, factory, globe).

2. **Affinity Clustering.** Similar research topics generated during ideation are grouped through affinity clustering, a graphical technique used to organize large amounts of data or creative ideas into logical topic areas or themes that allow collaborators to draw insights and new ideas out of otherwise

disparate pieces of information. The topic areas that emerge can be easily prioritized, and the data in the affinity clusters can be used to develop funding opportunity announcements (FOAs) or justify expenditures in different research topics.

3. **Difficulty/Importance Assessment.** Positioning of these topic areas on a difficulty/importance quad chart allows prioritization of research topics and provides guidance for the establishment of research institutes and the funding of larger programs. Difficulty/importance charts that resulted from the accumulated results of the four *Future of Manufacturing* roadmapping events to date are shown in Figs. 1 and 2. A unique feature of the difficulty/importance charts is that they are derived not by individuals or specific representatives from academia or industry, but instead represent a consensus of the participants who were drawn from all groups interested in machining.

This report contains selected results of the roadmapping events to date. These results are being shared now given their relevance to current efforts to build research entities around manufacturing and artificial intelligence, including the NIST competition for a new Manufacturing USA institute.

The results of roadmapping to date represent a consensus starting strategy for research investment, as reached by academic/industry/professional society involvement.

Work under this *Future of Manufacturing: A Network for Cybermanufacturing for Machining* project is continuing.

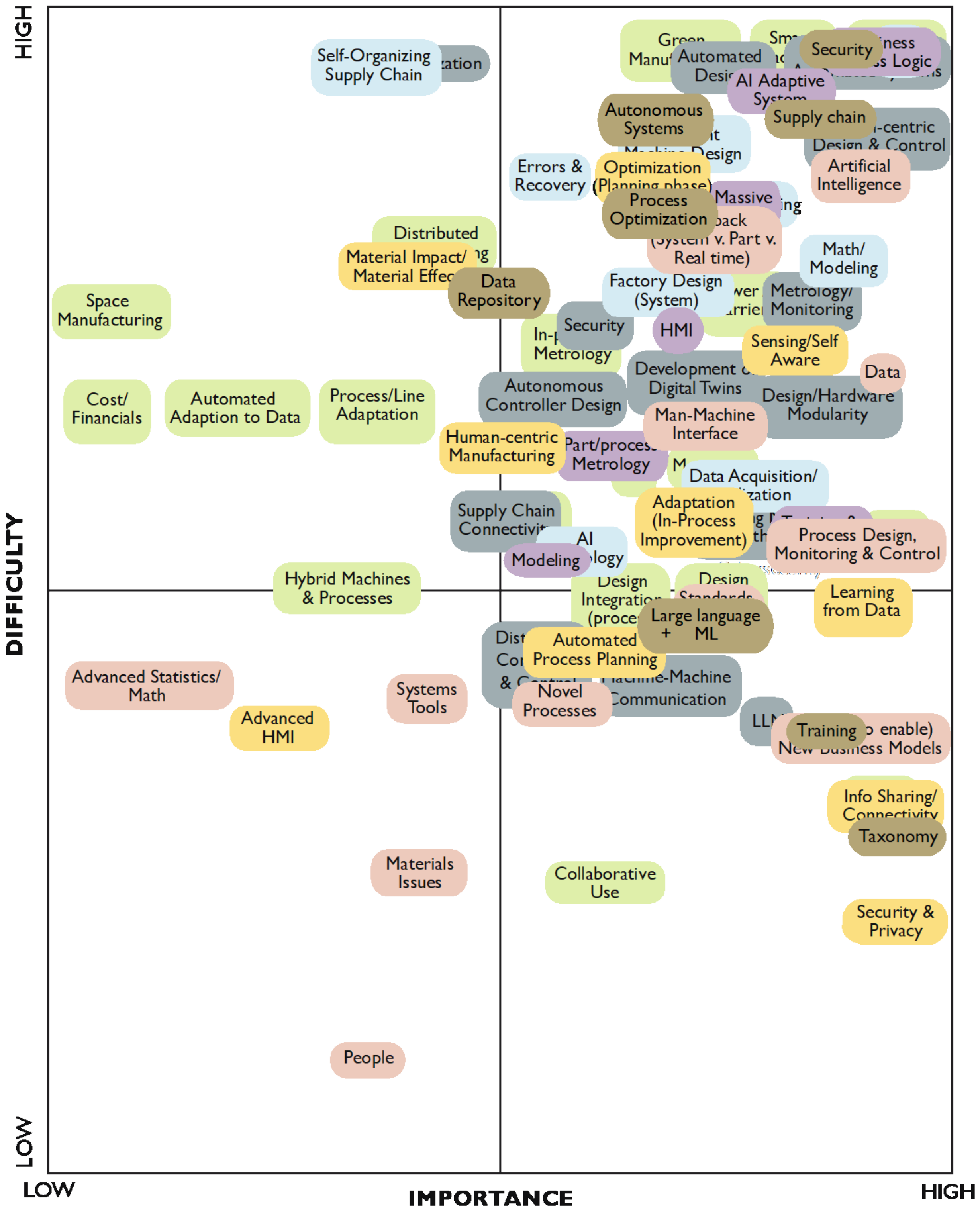

Figure 1: (a) Aggregation of all roadmapping results related to cyberphysical systems in machining and machine tools from 2021-2024. Results are color-coded consistent with Figs. 6-11

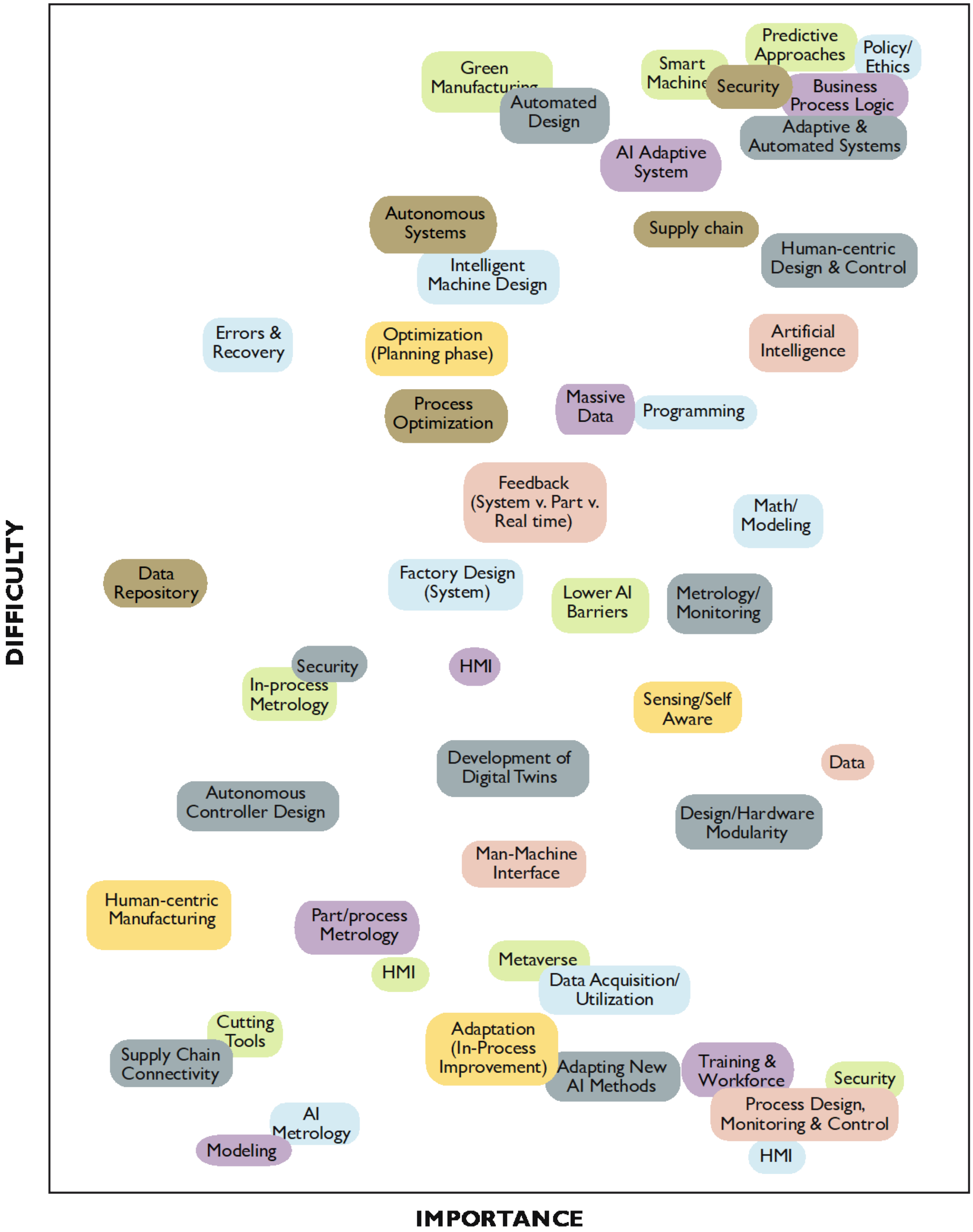

Figure 1: (b) Detail of the first quadrant of Fig. 1a, showing themes of high difficulty and high importance. These are useful candidates for consortium/center/Institute funding.

Figure 2: Repeated key words from the aggregate roadmap in Figure 1.

Glossary

(ref: Towards Resilient Manufacturng Ecosystems Through Artificial Intelligence – Symposium Report. (National Institute of Standards and Technology, Gaithersburg, MD, NIST Advanced Manufacturing Series (AMS) NIST AMS 100-47. https://doi.org/10.6028/NIST.AMS.100-47)

Artificial Intelligence (AI) in manufacturing refers to software systems that can recognize, simulate, predict and optimize situations, operating conditions, and material properties for human and machine action.

Machine Learning (ML, generally seen as a subset of AI) refers to algorithms that use prior data to accurately identify current state and predict future state, with the goal of improving productivity, precision, and performance.

Models are digital, software representations (quantitative, qualitative, pattern, causal, inference, etc.) of real-world events, systems, or behaviors, which can use data to simulate or predict future results.

Network Effects are the incremental benefits gained by existing users for each new connection that joins the network through expansion of available information and accessible knowledge.

Networking creates digital connections among devices, machines, equipment, databases, computer programs, and users, to exchange information, make decisions, and take actions.

Predictive Modeling is the use of data, AI, ML, simulation and digital twins to assess, predict, and anticipate process, product and operational behaviors for control, design, optimization, health, and failure prevention and mitigation.

Scale means readily accessible, easy to use, and cost effective for manufacturers of all sizes.

Standard Data Format refers to the organization of information (protocol) according to agreements on preset specifications that describe how data should be stored or shared for consistent collection and processing across different systems and users.

Tools refer to software platforms that support the availability of data, knowhow, and models for use in business and operations.

1. Background

Future prognostication, or futurism, is an error-prone activity. For every insight into future technologies (communicators in Star Trek [1], supercomputers [2], etc.) there are spectacular failures (flying cars, hovering skateboards, etc.). What has been certain is that technological progress is constant, but not steady; speed to market is more important than in previous decades; and the manufacturing sector has been, and continues to be, transformed by rapid technological developments. It is recognized that the filthy, loud, dangerous, smoke- and mist-filled and odorous factories of the past (and still in the imagination of most non-practitioners of modern manufacturing) have been replaced by what would have been called laboratories. Modern manufacturing increasingly takes place in clean environments, without bins of parts waiting at machines, but with agility, computer integration across the entire enterprise, and a highly skilled workforce.

It is not a daring assertion that the factories of today, while impressive, will seem archaic and inefficient in future years or decades. It is certain that computer integration will be even further advanced, that automation will drive further increases in productivity and competitiveness, workforce skills will change, and software data will be at the same time more important and more ubiquitous.

A strong manufacturing sector is essential for the economic welfare and national security of the United States. Recognizing this, Executive Order of the President (EO) 13806 focused on Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States [3]. The EO directed the Secretary of Defense to conduct a whole-of-government assessment of risks and to propose recommendations to support manufacturing. The unclassified response [4] identified a number of traditional sectors (aircraft, munitions and missiles, shipbuilding, ground systems, etc.) and cross-cutting topics (cybersecurity, machine tools and industrial controls, materials, software engineering, etc.). Machining was specifically identified as a topic of great importance.

Machining is one of the most widely practiced of all manufacturing operations and supports virtually every economic sector and product family, either by direct manufacture of the product's critical elements, or through fabrication of the tooling and equipment used to manufacture and distribute the product. It is well-established that no nation can be a global leader in manufacturing without also being a global leader in advanced machining. Machining technology is a critical contributor to the vitality of the entire US manufacturing economy. The overall machine tool industry captures a $70 billion, and growing, annual capital expenditure market globally. With direct and indirect resources factored in, the size of the machine-tool-related industry is estimated to be over $2 trillion, with the US presently appearing in 2nd place for the world's machine tool consumption and utilization and 6th place for production; the post-pandemic industrial expansion saw a dramatic increase in North American machining activity [5].

It is also recognized that continuous productivity improvements are essential to maintaining a healthy manufacturing sector in high-wage countries such as the United States. A recognized pathway to such productivity improvements involves widespread application of advanced tools such as artificial intelligence, Big Data, security conscience cloud platforms, stability lobes, surface engineering, sensor fusion, Industry 4.0, and precision engineering/metrology. These research themes can also revolutionize the man/machine interface to allow a more effortless interaction within or between machines, operators and managers.

Increased productivity also reduces the embedded energy in a product, and therefore can have dramatic impact on ecomanufacturing. Recognizing that the US manufacturing sector accounts for roughly one-quarter of energy demand, strategies that eliminate defects and that reduce energy expended in product manufacture are needed. It is well known that by the time a part is machined, the embedded energy has already been mostly established. That is, a metal has been refined, cast, annealed, cast/forged/rolled with associated handling before it is machined. Machining contributes to the embedded energy, but a catastrophe occurs if a defect is generated – all of the embedded energy is lost. For this reason, the infusion of physics into future controlling and simulation software that eliminates defects associated with chatter, residual stresses and tool deflection will drive down embedded energy. Hence, there is a strong ecomanufacturing motivation for pursuit of research in cyberphysical systems in machining and machine tools.

2. Objectives

The National Science Foundation funded this effort from the Future of Manufacturing Program; the objectives were to convene the community; develop a roadmap of basic research needs in cyberphysical systems for machining and machine tool, with a focus on leveraging American strengths in mechanical engineering, materials science and computer software; and to identify and prioritize research topics that can fundamentally transform American manufacturing. Given the reach of machining, this project provides direct and major impact on American economic welfare and national security.

A research roadmap serves as a valuable document for identifying and prioritizing research opportunities and imperatives, leading to improved machine tool design with respect to machining speed and precision, reduced machining cost, and elimination of chatter and defects through advanced dynamics and controls. Focusing on cybermanufacturing required attracting researchers and practitioners in the areas of mechanics, dynamics and control, precision metrology, tribology, and materials science as well as computer science specialists in Big Data, artificial intelligence, IT communication and machine learning. It is felt that a path to increased productivity and capability consists of merging and applying these disparate disciplines (Fig. 3). The project's focus on cyberphysical systems allowed consideration of next-generation developments in artificial intelligence, communication, man-machine interface tools, etc., which can have a direct influence on the sector's future productivity.

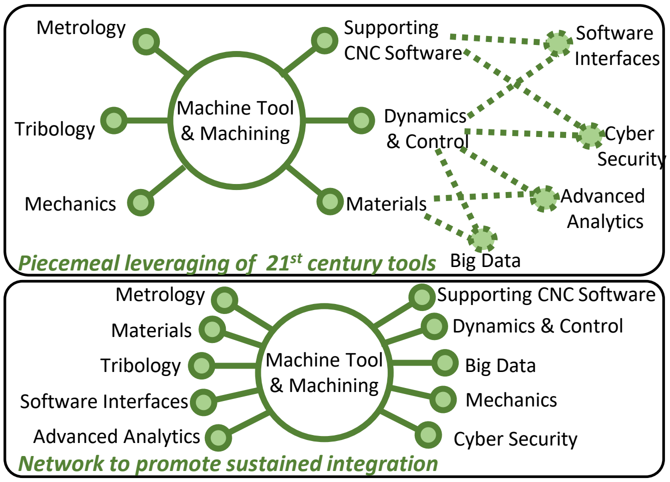

Figure 3: To overcome the current status (top), the proposed network (bottom) will provide a platform for peripheral expertise to engage with the machining community to accelerate the next generation of machining and manufacturing.

The roadmap also identifies emerging areas that are not yet deployed, thereby providing guidance for training and workforce development efforts. Through reimagining training programs and curricula for machinists and machining center operators, this effort is expected to have an important influence on economic welfare.

3. Participants

Value of the roadmapping effort is assured through attraction of broad representation from academia, government, and industry. The roadmapping events have consistently attracted a broad cross-section of disciplines and sectors related to machining and manufacturing. The graph shown in Fig. 4 shows the representation of each group in the first roadmaping event, which has been maintained since. The large industry representation was a very welcome development. Companies, universities and government agencies that have participated in roadmapping events to date are listed in Table 1.

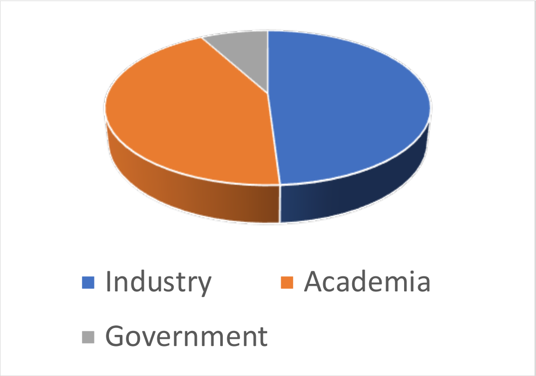

Fig. 4: Breakdown of roadmapping event attendees by employer.

Table 1: Represented organizations.

Industry

- 3DCERAM Sinto Inc.
- Acclaim Aerospace
- AISune
- ANSER
- Arthrex
- Boeing
- Carl Zeiss Industrial Metrology
- Caterpillar
- DMG Mori USA
- Domaille Companies
- Ford
- GE
- General Motors
- Haas Automation
- HendTech
- Honda
- Hybrid Manufacturing Technologies
- IBM
- Ingalls Ship Building
- Innovia
- ITAMCO
- John Deere
- Johnson & Johnson
- JTEKT
- KB Science
- Kennametal
- Lockheed-Martin
- Manufacturing Technology Deployment Group
- Micro-LAM Inc.
- Mitsui Seiki USA
- Moog
- MSC Industrial Supply
- Niagara Cutter
- Okuma
- Oshkosh Corporation
- Perfect Planner
- Praemo Inc.
- REM Surface Engineering
- Renishaw Inc.
- Rolls Royce
- Sandvik Coromant
- Siemens
- Stanley Black & Decker
- Stryker
- The Knudsen Institute
- Tech Manufacturing
- Third Wave Systems
- Timken
- Zeiss USA
- Zimmer Biomet

Academia

- Auburn University
- Carnegie Mellon University
- Central Alabama Community College
- Clemson University
- Fayetteville State University
- Georgia Tech
- Greenville Technical College
- Harvard University
- Navajo Institute of Technology
- North Carolina State University
- Notre Dame
- Ohio State University
- Oregon Institute of Technology
- Oregon State University
- Purdue
- Texas A&M University
- University of Colorado Boulder
- University of Florida
- University of Maryland
- University of Michigan
- University of North Carolina at Charlotte
- University of Notre Dame
- University of Tennessee
- University of West Virginia
- University of Wisconsin
- Virginia Tech

Government/Other

- AMT
- Blue Forge Alliance
- Department of Defense
- MPIF
- MT Connect Institute
- NASA
- NCDMM
- NIST
- NSF
- Oak Ridge National Laboratory
- SME
- TechSolve Inc.

4. Roadmapping Approach

The roadmapping approach utilized here was developed by the National Center for Defense Machining and Manufacturing (NCDMM) and refined over time by America Makes, the Manufacturing USA Institute focused on Additive Manufacturing. The basic steps in the roadmapping program are described below:

1. **Engagement of Participants**. Before roadmapping activities can commence, careful selection of participants is required to ensure representation of and engagement by industry (large and small companies), academic and government/professional organizations. Industry buy-in is especially important at this stage. In meetings held before the roadmapping events, a preliminary creativity matrix (described below) is developed, reviewed and approved by all partners.
2. **Creativity Matrix** The creativity matrix provides both structure and guidance for the brainstorming exercise by framing the challenges and transitioning the discussion to focus on achievable manufacturing goals. As shown in Fig. 5, the creativity matrix is described by column and row labels that represent general thrust areas for future research. Typically, the columns describe so-called research pillars or core research foci, while the rows represent "cross-cutting" technologies that can impact all of the research pillars. However, departure from these normal practices can be beneficial. For example, in Fig. 5, the main "cyber" topics are rows, while "physical" topics are columns. To allow for topic consideration outside the named rows and columns, a "wild card" label is included, which accommodates any answer. The benefits of a creativity matrix include generation of wide-ranging ideas in a short period of time and also stimulation of cross-talk by providing a template for ideation. It avoids the pitfalls of conventional brainstorming by engaging all participants. Indeed, The "democratizing" of the decision making is the driver of the described roadmapping effort.
3. **Affinity Clustering**. The resulting creative matric entries are sorted according to similarities through affinity clustering, a graphical technique used to organize large amounts of data or creative ideas into logical topic areas. This effort involves involves identification of focus areas from the creative matrix that allow collaborators to draw insights and new ideas out of otherwise disparate pieces of informationCollaborators develop specific details, identifying existing barriers to implementation, future solutions and impacts, metrics, and developing a path forward. Affinitiy clustering is a group effort, involving significant negotiation and discussion to reach concensus.
4. **Difficulty/Importance Chart**. The results from affinity clustering are plotted relative to each other on a separate difficulty/importance quad chart. This again depends on crowdsourcing to rate projects according to these two variables. The topic areas from the affinity clustering are arranged along the lower boundary of the difficulty/importance chart, according to perceived difficulty. Each topic is then considered separately, and its importance rated to complete the difficulty/importance chart. The most provocative topics are grouped along a band from lower left to top right.

The difficulty/importance chart is a useful tool for the design of funding initiatives in government, consortia focus or as a strategy for Manufacturing USA Institutes. The difficulty/importance matrix includes a prioritization of research thrusts, in turn identifying legitimate thrust areas for a center or institute. The projects suitable for institute, consortia, center or other research programs are focused in the (upper right) first quadrant. These have high difficulty and importance, benefit from shared resources and collaboration, or and cannot usually be justified by a single company.

In the second and third quadrants, project importance is low; these projects are generally avoided. In some cases, the second quadrant can include research themes that could be addressed by an institute/industry/academia partnership, and the third quadrant can be the source of "quick wins" when such goals are desired. The fourth quadrant is the classic "low hanging fruit" with low difficulty but high importance. These projects generally are best targeted by industry.

Therefore, an institute, center or program properly focuses on the first quadrant. However, sometimes exceptions can be identified, since participants tend to propose only highly regarded research topics or themes. Regardless, a prioritization arises from consideration of the matrix diagonal; the further a topic lies on the diagonal (i.e., high difficulty and high importance), the greater the research priority for a consortium or program. For a Manufacturing USA Institute, the topics in the first quadrant represent research priorities for funding and attention.

Physical

Cyber

	Dynamics & Control	Metrology	Machine Design	Materials	Wild Card
Artificial Intelligence					
Big Data					
Networking					
Man/Machine Interface					
Wild Card					

(a)

Research Pillar

Scale

	Artificial Intelligence	Big Data	Networking	Man/Machine Interface	Wild Card
Machine Level					
System Level					
Plant Level					
Enterprise Level					
Wild Card					

(b)

Research Pillars

Cross-cuts

	Machine Monitoring	Sensor & sensor fusion	Digital Twins	Pattern recognition	Wild Card
Software Design					
Open-source controller					
Machine Design					
System Integration					
Wild Card					

(c)

Research Pillars

Cross-cuts

	Self-aware Factories	Natural language interface	Closed-loop Control	(Efficient) machine learning	Wild Card
Software Design					
Real-time metrology					
Machine Design					
Open-source controller					
Wild Card					

(d)

Research Pillars

Cross-cuts

	Supply Chain	Language Models	Circular Economy	(Efficient) machine learning	Wild Card
Software Design					
Data Access					
Communication/ Security					
Workforce & Education					
Wild Card					

(e)

Figure 5: Creativity matrices considered for cyberphysical systems in machining to date. (a) General creativity matrix; (b) Application scale matrix; (c) AI control of machinery matrix; (d) Artificial intelligence deep-dive matrix; (e) Artificial intelligence for resilient supply chains in manufacturing matrix.

5. Results

Documentation of roadmapping activities from the creative matrix to affinity clustering stages is contained in the Appendices. This section summarizes the difficulty/importance charts from the roadmapping sessions.

Figures 6-11 show the difficulty/importance charts from the roadmapping events conducted to date. However, the creative matrices varied across events, as noted earlier, to focus upon specific concerns. The creativity chart themes (Fig. 3) influence the difficulty-importance chart results. The themes identified are as follows:

- The first roadmapping event used the creativity matrix of Fig. 3a, which sought to address the general landscape of cyberphysical systems in machining and machine tools. Since this is inherently collaborative, the research pillars were defined by the physical and the rows by computer science or cyber concerns. The results are shown in Fig. 6, where the color codes correspond to the two different breakout groups involved. The general matrix was revisited in 2023, with results shown in Fig. 9.
- There is significant interest in artificial intelligence, especially since a funding opportunity announcement was developed by NIST for a Manufacturing USA Institute for AI for Resilient Manufacturing[1]. The roadmapping in this effort found the general topic of artificial intelligence to be highly rates (see Fig. 1). However, since AI is both a specific field of study in computer science and a general over-arching term, a number of focused roadmaps were developed. The roadmapping events and the Difficulty-Importance diagrams produced each represent a consensus of research needs as reached by the industry/academia/government consortia.
    - This community noted that artificial intelligence finds application in all areas and scales of manufacturing, but takes different forms. For example, when used to monitor machine operation, an AI routine can have physical models from dynamics or tribology incorporated to make it more effective; however, supply chain monitoring does not require embedded physics. It has been common in the literature to ignore these differences; recommendations therefore are difficulty to evaluate. The creative matrix of Fig. 5b was designed to differentiate scale of application, as seen by the row labels starting from machine level to multiple-factory level. The resulting difficulty/importance matrix is shown in Fig. 7.
    - Artificial intelligence used to control machinery operations was a specific concern of the community involved in this effort. The creative matrix of 5c was intended to roadmap control of machines, resulting in Fig. 8.
    - Figures 5d and e represent "deep dives" on AI. In Fig. 6, the term "Artificial Intelligence" was identified as the top research priority. However, the term has numerous meanings, and the creative matrix of Fig, 5d was designed to allow infuse some specificity in the difficulty/importance matrix, with results shown in Fig. 10.
- Figure 5e was designed to be of direct relevance to the upcoming NIST Manufacuring USA Institute on Artificial Intelligence for Resilient Supply Chains in Manufacturing. The Institute competition has since been renamed Artificial Intelligence for Resilient Manufacturing, but the results are still directly applicable. The resulting difficulty/importance chart is shown in Fig. 11.

An overlay of all results to date is shown in Fig. 1. This figure is difficult to interpret directly, since a consistent creativity matrix was not used for each of the difficulty/importance matrices. However, there are trends regarding the topics resulting from affinity clustering. For clarity, related entries are shown in Fig. 2 if they appeared in a majority of the affinity matrices.

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[1] https://www.nist.gov/oam/ai-resilient-manufacturing-institute-competition

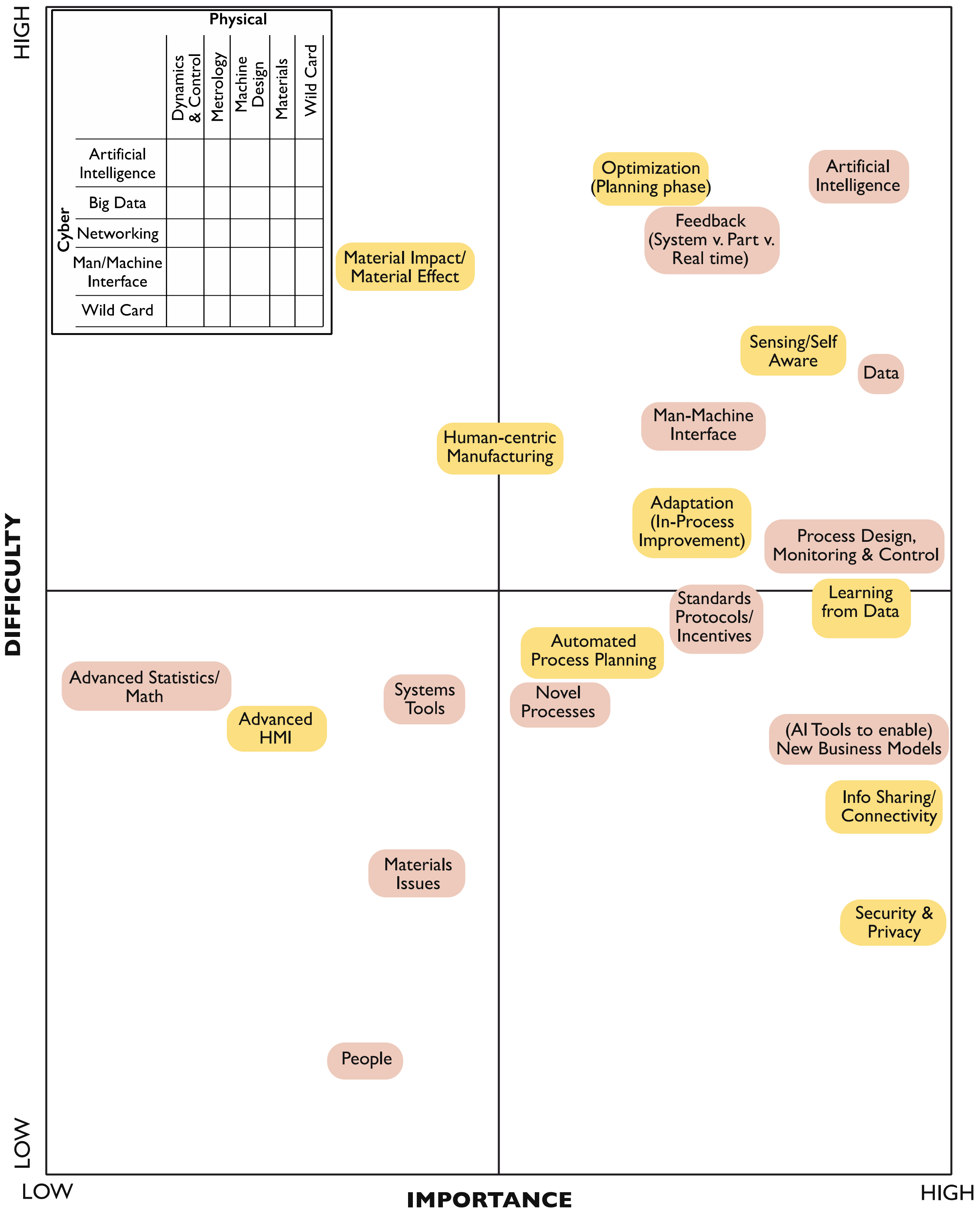


Figure 6: Difficulty/Importance results from the 2021 roadmapping event, using the general creativity matrix of Fig. 5(a). The creativity matrix is reproduced in the top-left corner for reference purposes.

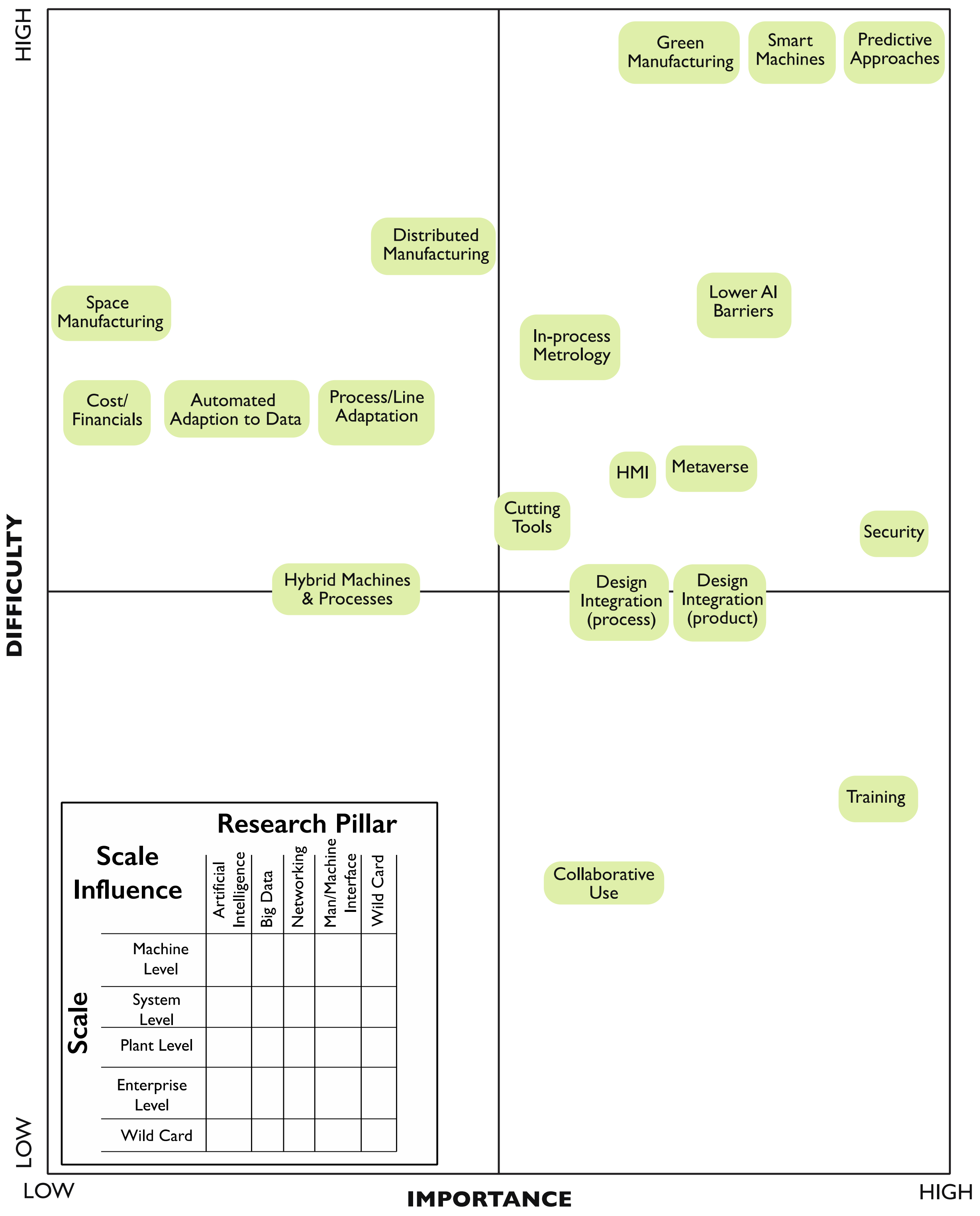


Figure 7: Difficulty/importance results from the 2022 roadmapping event, using the scale-specific creativity matrix of Fig. 5(b). Some roadmaps or technical documents treat all AI approaches the same, whether it is applied on a machine, cell, factory, or global scale. The intent of this chart was to segregate AI technologies by scale and provide guidance regarding prioritization of efforts. The creativity matrix is reproduced in the bottom-left corner for reference purposes.

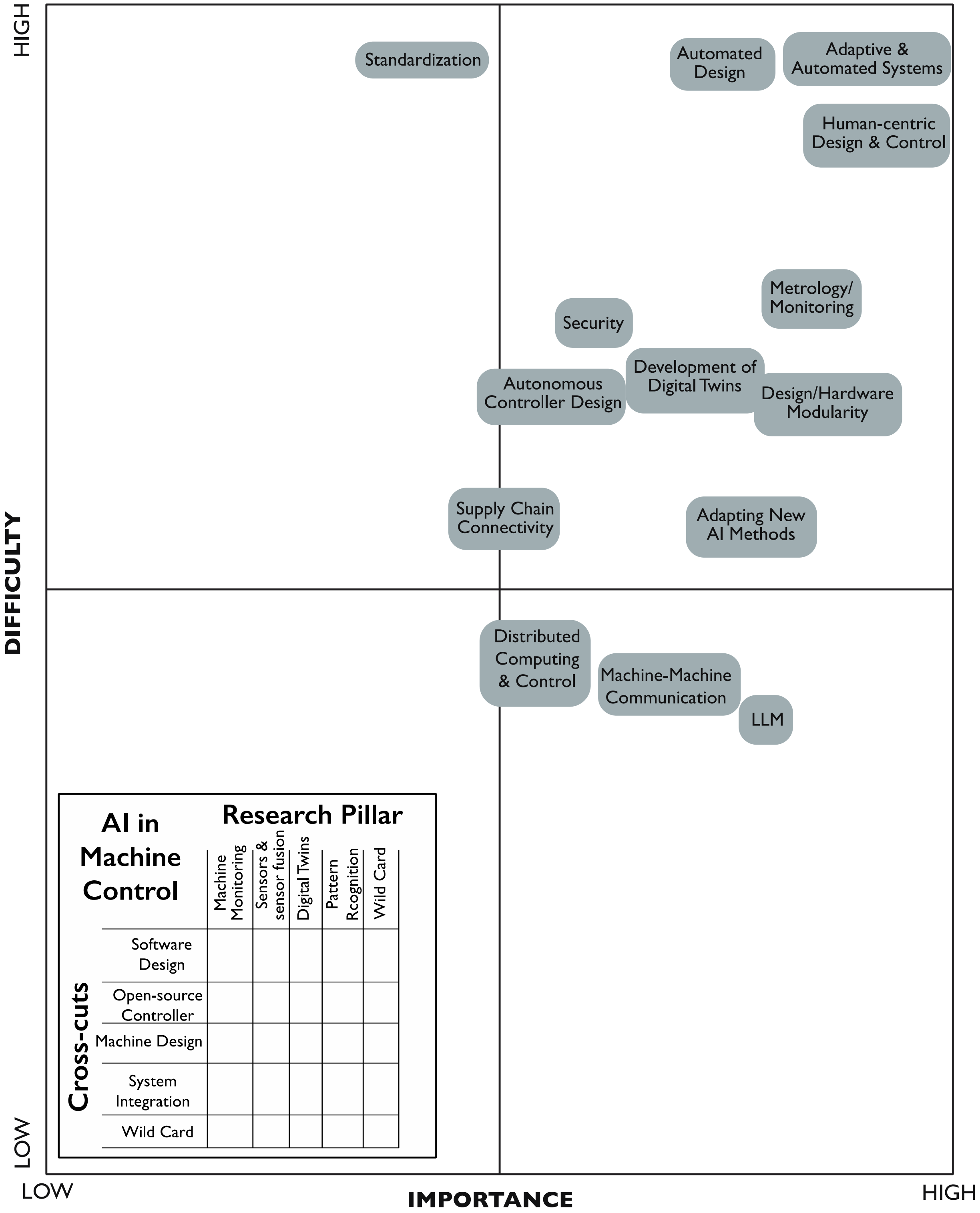


Figure 8: Difficulty/importance results from the 2023 roadmapping event focused on topics pertaining to AI control of machinery. Since AI has many meanings and can refer to a specific computer science topic or an overarching theme, this chart focused on the use of AI in machine control. The creativity matrix is reproduced in the bottom-left corner for reference purposes.

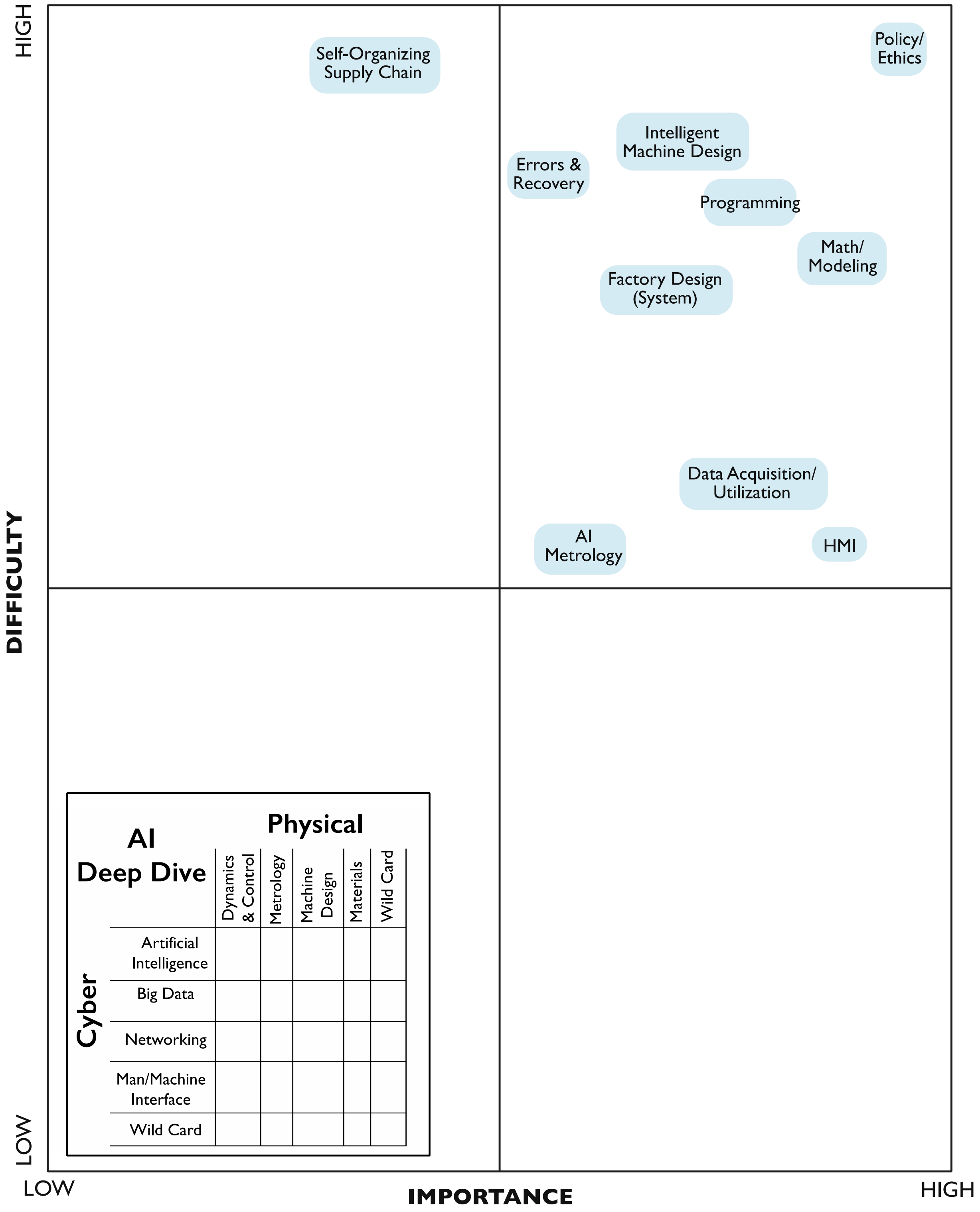


Figure 9: Difficulty/importance results from the 2023 roadmapping event, focused on an AI “deep dive”, where AI-specific topics were identified. This should be compared to Figs. 1 and 6, where AI takes a prominent role in the figure, but some AI technologies are of much less interest. The creativity matrix is reproduced in the bottom-left corner for reference purposes.

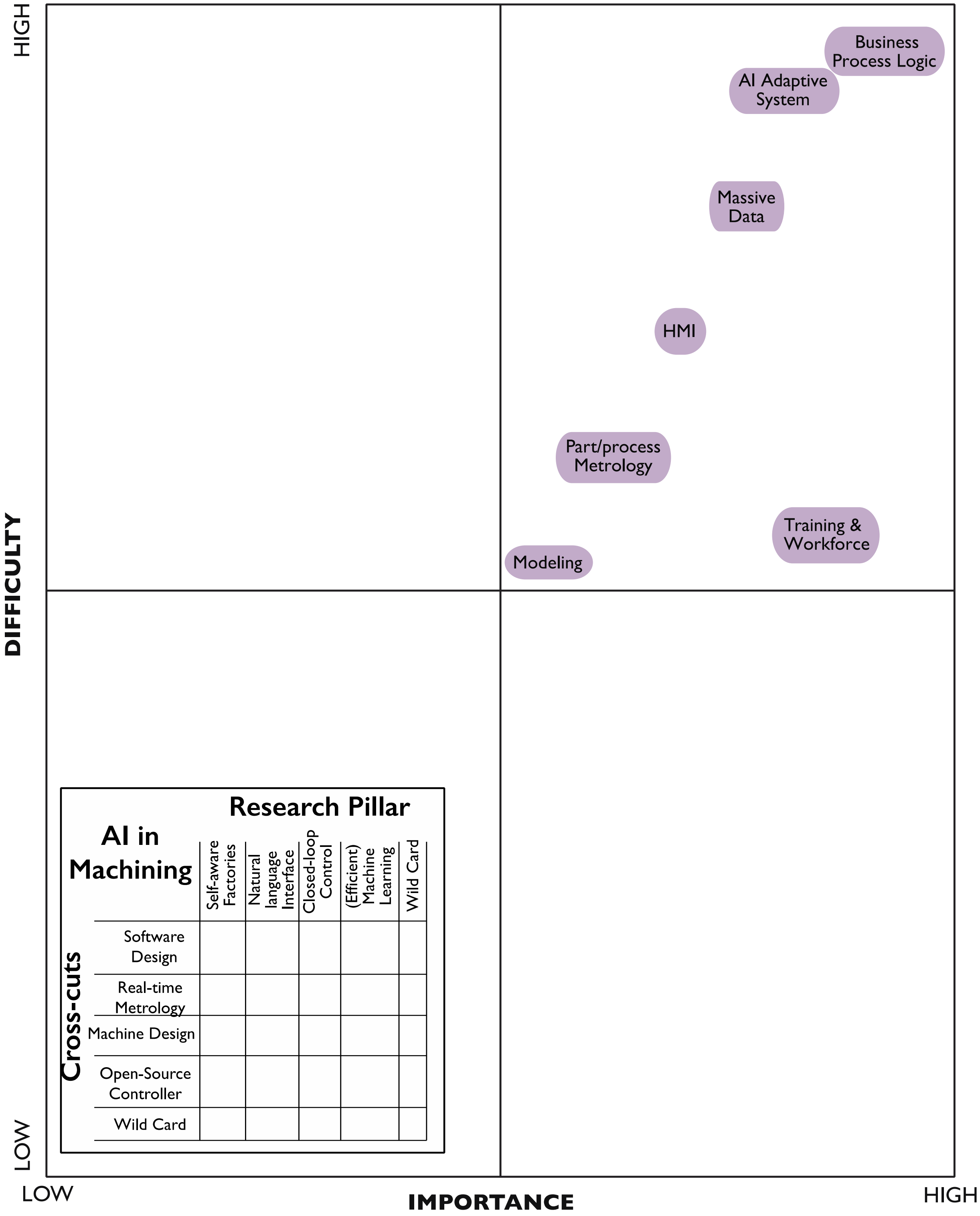


Figure 10: Difficulty/importance results from the 2024 roadmapping event, focused on a "deep dive" for AI in machining, as in Fig. 9. The creativity matrix is reproduced in the bottom-left corner for reference purposes.

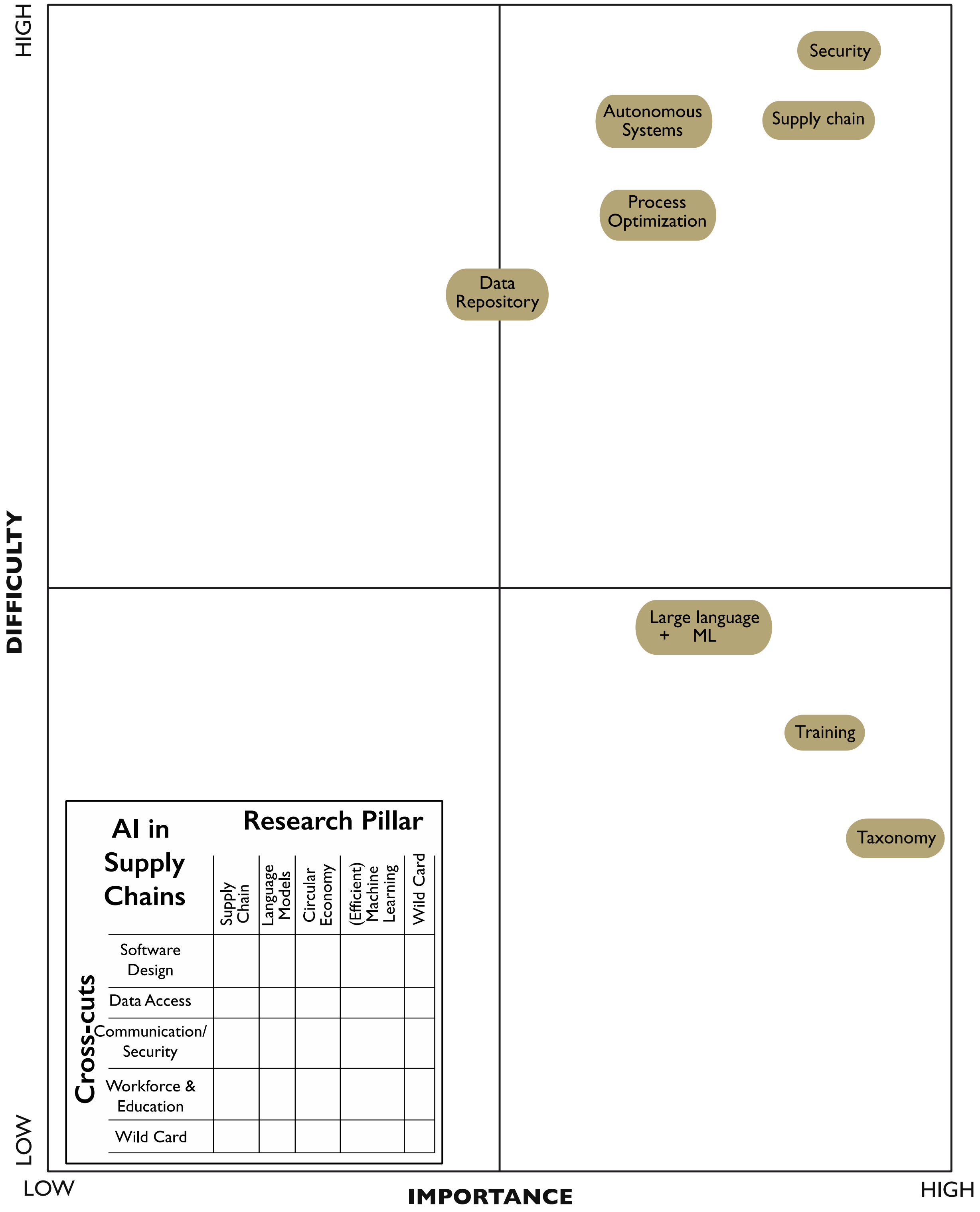


Figure 11: Difficulty/importance results from the 2024 roadmapping event, focused on an AI “deep dive” for supply chains. Supply chains are unique in that the process models that are incorporated into AI approaches are absent. The creativity matrix is reproduced in the bottom-left corner for reference purposes.

6. User's Guide

The collection of difficulty/importance matrices should be of benefit to anyone planning a research initiative on AI in manufacturing. The matrices presented in this document have been developed through combined influence of industry and academia. An exemplar program manager would use these matrices using the following steps:

1. The particular roadmap can be selected that aligns with current interest (AI in control of machinery, AI for supply chains, deep dive in AI, etc.). The combined roadmap of Fig. 1 can be used for planning of larger program. Using the appropriate creative matrix, the resulting difficulty/importance matrix represents the prioritization of research topics as already confirmed by leaders from industry and academia.
2. The program manager can then decide whether the roadmap should be further separated into swim lanes. For example, the recommendations in Fig. 1 could have a "Man Machine Interface" swim lane, consisting of projects involving interface devices, natural language processing, human-centered manufacturing, and secure communications. A number of swimlanes could be defined, if desired.
3. Using the theme or themes, a program director can review the projects that formed the basis for the high rating given by the roadmapping teams.
4. A funding opportunity announcement (FOA), or equivalent, can then be prepared based on the theme and exemplar projects.

The FOA is then quickly produced, as it leverages the significant time invested by the roadmapping teams.

7. Conclusions

Roadmapping efforts conducted to date have resulted in a prioritization of research efforts that should be the focus of an industry/university partnership. In the difficulty/importance charts, those topics that are furthest to the top and right of the chart should be prioritized. Prioritized topics to date include topics like ethics and environmental issues (such as safety of AI, reducing coolant use, etc.), general AI applications in manufacturing, design issues (such as design of next generation machine tools, but also AI tools that can be applied to product design activities), etc. These prioritized results from industry and university participants were generated without bias towards a particular product or researchers' "pet" research focus. Roadmaps should be updated periodically; this roadmapping effort accurately reflects the results through September, 2024.

References

[1] Space.com, available: https://www.space.com/9705-top-10-star-trek-technologies.html. [Accessed 27 September 2024].

[2] Heinlein, R.A., The Moon is a Harsh Mistress, Mass Market Paperback, 1966.

[3] "Presidential Executive Order on Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States," available: https://www.govinfo.gov/app/details/DCPD-201700489. [Accessed 27 September 2024].

[4] "Assessing and Strengthening the Manufacturing and Defense Industrial Base and Supply Chain Resiliency of the United States," available: https://media.defense.gov/2018/Oct/05/2002048904/-1/-1/1/ASSESSING-AND-STRENGTHENING-THE-MANUFACTURING-AND%20DEFENSE-INDUSTRIAL-BASE-AND-SUPPLY-CHAIN-RESILIENCY.PDF [Accessed 27 September 2024].

[5] World Machine Tool Report Shows Manufacturing Shift to North America, available https://www.mmsonline.com/blog/post/world-machine-tool-report-shows-manufacturing-shift-to-north-america [Accessed 27 September 2024].

Appendix A: Creativity Matrix and Affinity Clustering Results, June 17-18, 2021

A.1 Creativity Matrix

The first annual roadmapping workshop in 2021 was held virtually, facilitated by the National Center for Defense Manufacturing and Machining (NCDMM). The NCDMM roadmapping approach is tailored to specific topics and, for this project, was specifically designed for cyberphysical systems in machining and manufacturing. The creativity matrix was created and the cells were populated in a modified brainstorming approach. This process is often referred to as an "ideation phase" since the goal is to collect or harvest a wide range of research topics. The creativity matrix is used to focus and classify research ideas produced. To guide discussions and to encourage less constrained responses, research ideas were also characterized as Rose (current strength), Bud (topic of high potential), or Thorn (current weakness).

The resulting creativity matrix contents for the two breakout groups are organized according to the row and column headers as follows:

Artificial Intelligence / Dynamics and Control		
Rose	**Bud**	**Thorn**
• Machine responds to data collected from prior cycles • Machines • AI for real time process improvement	• On-line adaptation • Perturbations introduced in manufacturing • Network introspection to determine parameter importance. • Efficient Machine Learning • Optimization • Cloud Control • Closed-loop control of process state (e.g., cutting temperature) • Develop ML process for machine / tool / material • Use AI to predict tool tip dynamics • Holonic manufacturing on factory scale • A/I is ultimate vision. Still value in analytic steps:.descriptive, diagnostic, predictive, prescriptive	• Stochastic perturbations introduced in manufacturing • High mix low volume versus low mix high volume • Systems • Current adaptive control is not reliable--too many false stops
Artificial Intelligence / Metrology		
Rose	**Bud**	**Thorn**
• Hands off	• Real-time automated feedback loops that inspect, analyze and adjust controls to never make a defective part • Add readable tolerances to all CAD/CAM programs • Real-time inspection and analysis of key part parameters • Data-driven inspection sampling • Automate inspection procedure • Closed-loop control of process state (e.g., cutting temperature) • Opportunity for reinforcement learning • Simple cases would be doable. practically; too many options • Integrate sensors at the machine design stage • Open access to sensors etc.	• Trust • Uncertainty in AI • accuracy/uncertainty associated with AI

Artificial Intelligence / Machine Design

Rose	Bud	Thorn
• Design optimization • Use alternative materials for machine structures based on AI design feedback • Ultraprecision machines and automation	• Generative design • Self-aware machines • Standard digital twin (data structure) of machine • Integrate sensors at the machine design stage • Standardization of digital twin component • Open access to sensors etc. • Getting better at this with more reusable models • Predict machine state (e.g. temperature, stress) and compensate	•

Artificial Intelligence / Materials

Rose	Bud	Thorn
	• Fast evaluation of material through contact before machining • Extract material properties quickly during cut • Workpiece-specific adaptation • Tie material properties to work piece for ML • Quantifying material property/variability from the first few seconds via tool-workpiece interaction, and adapting the rest of the cut • Identify workpiece material from machining sensors • Virtual material certification (i.e. ndt) • Account for all pre-machining processing effects • Material DNA • Optimization / discovery of new materials	• Everything is experience-based and too slow! • Dynamic coolant mix adjustment based on material and application • Propose tool/material substitutions • Cluster alternative material/machining combinations • Too complicated

Artificial Intelligence / WILD CARD

Rose	Bud	Thorn
• Automated CAM • Sharing enables learning, undermines privacy.	• Design for manufacturing, learning from previous best practices • Process optimization • Compressive inference: sparse sampling for efficiency, maintain accuracy. • PHM • Preventative maintenance • Few-shot learning for "small data" problem • Automated cutting parameter selection • Machine (brain and nervous system) • Tools for discovery of capabilities and solutions. • Software tools that will automatically (and with intelligence) pick the tooling and process parameters for a given CAD model • Process/Data, Talent, Trust • CAD system can automatically generate PMI/drawing from solid model (true MBD)	• Machining for desired (not specified) surface finish • AI is conflated with NN-ML. Other areas, like ontology and Markovian for FMEA • Bayesian methods are not capable of handling causality

Big Data / Dynamics and Control

Rose	Bud	Thorn
• Data on the structural dynamics of the machine tools is available • Machines	• Share compact knowledge representations. May help privacy, but proofs hard. • Extensive pool of process parameters for the specific case • Data is coming • Self-monitoring machine analysis and adjustment • Holonic manufacturing on a factory scale • It's not about the data. It's about the context/analytics	• Too much raw data • Storage space and speed of accessibility/utilization • Manual data labeling • Significant cost to SMMs to bridge big data volumes to useable forms for AI. Standardized data models from data source through to AI Input is needed. • Taking real-time assessment data and informing real time machine settings • Machines

Big Data / Metrology

Rose	Bud	Thorn
• Capture on-machine data • Typically, the data quality is good	• Integrate sensors at the machine design stage • Open access to sensors etc. • Tools with integrated sensors • High resolution measurements • Digital thread	• Metrology sampling vs. 100% • Still cannot get right to the tool-workpiece interface - so how good is data? • Comparability and transferability between individuals/machines • Open access to databases • Real-time analysis of key part parameters • Transmission • Real-time analysis of inspection data • Approaches to featurize the large amount of data collected by metrology is not available

Big Data / Machine Design

Rose	Bud	Thorn
• Sensor tech and network speed explosion	• Compare machine state (e.g. temperature, stress) from precious case and compensate • Develop biologic strategies for being Intentional • If you have a value to what the part should feel like and the machine knows what it should feel like. • Integrate sensors at the machine design stage • Comment open access to sensors etc. • Vibration sensors built into machine • Integrate health and maintenance data	• Common architecture to handle internal and external data acquisition • Machines are only REACTIVE • Machine tool designers don't typically consider data availability in their list of priorities. No standard to comply with or adhere to.

Big Data / Materials

Rose	Bud	Thorn
• Looking for more domain models • Material databases and material genome approaches	• ICME frameworks • Large design database to quickly suggest solutions • Large material database with properties and potential applications • Actual material composition is not readily available prior to machining • Create means to predict tool performance in any material • How to share data safely	• Predict machinability of new materials • Linking data from multiple supply chain • Part distortion • ICME needs to be grander!

Big Data / WILD CARD

Rose	Bud	Thorn
•	• Machining strategy/process development reliant on tribal knowledge • Machine (brain and nervous system) • PHM • Big Data needs semantics, CEP and interval calcs to be effective • Application to drive improvements to process	• Benefiting from the experiences of other manufacturers • Cybersecurity • Businesses don't like sharing THEIR data • Trust • Proprietary hurdles

Networking / Dynamics and Control

Rose	Bud	Thorn
•	• Vulnerability for Cyber Attacks • Need to support Air Gap unless 100% security and connectivity is assured. • Cloud-to-Edge architecture resiliency. Connection dropout. • Remote Process Control • Next Generation MTConnect for control?	• Cybersecurity • Speed of networking (thinking IIoT) • Machines are only REACTIVE • Cybersecurity affecting manufacturing uptime

Networking / Metrology

Rose	Bud	Thorn
• Opportunity for Feedback or Feed forward • Instruments are networked to reduce data recording errors • Data collection and analytics	• Process quality metrics • Process effort metrics • Shared performance/ uncertainty knowledge between systems - build consistency	• Visual Metrology data - profile traces into database

Networking / Machine Design		
Rose	**Bud**	**Thorn**
• Many industrial standards for machine connectivity	• Linked to marketplaces, i.e. McMaster • Learning machines (from one another) • 5G? 10G? ∞G? What is enabled by the fastest possible network?	• No standard protocol or data structure • Controller architecture is 20 years out of date • Dynamic self-scheduling by the machines • Lack common protocol for machine networking/ interface

Networking / Materials		
Rose	**Bud**	**Thorn**
•	• Student exchange? • Possible internship at machining companies? • Sharing processing parameters for various materials and machining processes • Tracking technologies for product traceability	• Material databases are not shared and are out of date • Early-stage data-sharing between Materials Scientists and Machining Engineers

Networking / WILD CARD		
Rose	**Bud**	**Thorn**
•	• PHM • Are there any potential (big) industries that are missing from this?	• Ontology for inter-communication • Benefiting from the experiences of other manufacturers • Plant infrastructure

Man Machine Interface / Dynamics and Control		
Rose	**Bud**	**Thorn**
• Machine-human communication loop, lack of measurement and connected dynamic control of what the human and machine are doing that affect each other. • Machine for Dummies	• Use haptics in control • Hololens for Manufacturing! • Ergonomics and work-design talent needed • Mistake-proofing - machine reviews operator input against solid model • Training tools • Voice control • AR / Wearable technologies for operator interface • Specification languages evaluated via user studies for speed and correctness rate. • Automated Tool Path Planning (Art-to-Part) • Capture "tribal knowledge"	• Gathering the FRF from existing machine tools • Machine will believe everything the operator tells it • Still operating as if it was 1990 • Still one-way communication • No significant connection

Man Machine Interface / Metrology

Rose	Bud	Thorn
• Extensive activity on ease of use • GUI	• Mixed reality visualization • Tool wear condition • Automatic feed/speed/doc selection to maintain forces, temperature, vibration. • Automatic tool setting and work coordinate setting • Training tools • Real-time measurement and communication to operator	• Not many opportunities for real-time feedback on part quality • How to present the information that an operator can should respond to [difference in reaction times] • 5-Axis Tool Tip Accuracy • Notes/Attaching tolerance deviation to models

Man Machine Interface / Machine Design

Rose	Bud	Thorn
• Worker safety • Crowd-Problem Solve Strategies (chemE)	• "Lane-keep assist" for preventing bad choices and programming • Self-diagnosing • Mixed-reality visualization • More intuitive interfaces – multi-media system inputs • Automated fabrication of strong parts by non-experts w/ inexpensive infrastructure. • Automatic tool setting and work coordinate setting • Gamification/Alternate visualization • Should we move past G-code? STL? etc. • Natural Language Interface • Training tools • Hololens for Manufacturing!	• Don't know when we will exceed autoignition temperature • How to present the information that an operator can should respond to [difference in reaction times] • Counterintuit Interface could be like gaming headgear? (intuitive) • Too many faults, not enough solutions!

Man Machine Interface / MAterials

Rose	Bud	Thorn
•	• Machine verified workpiece material • AR/VR technologies • A whole generation of people with abstraction skill • Training tools	• Operator insights into process performance • ProcEngr feedback on how their process works

Man Machine Interface / WILD CARD

Rose	Bud	Thorn
•	• Behavioral Psychology to drive desired behaviors • Capture knowledge from skilled operators • Integrate system dynamics directly with Programming • Create JARVIS • Need more cell phone app versions to support all mfg. • Create FREE video game for learning machining • Virtual reality/augmented reality	• Operator job description • Global nonstandard line • Technology acceptance by the workforce

WILD CARD / Dynamics and Control

Rose	Bud	Thorn
•	• Add Machining Dynamics as critical course for machinists	• Eliminate need for Frozen Processes

WILD CARD / Metrology

Rose	Bud	Thorn
•	• Functional performance feedback • Workpiece recognition • OMM and automatic compensation	• Designs that focus on 100s of characteristics • Tie process reaction to product performance

WILD CARD / Machine Design

Rose	Bud	Thorn
• Retrofitting legacy machines for data acquisition	• More Speed! • Add functionality - assembly, welding, insert molding, etc. Not just AM + Machining • New machine designs and materials to address supply chain (e.g., components made outside US) • Multi-axis robotics and automation for part design	• Cybersecurity affecting manufacturing uptime • Retrofitting legacy machines for closed-loop control

WILD CARD / Materials

Rose	Bud	Thorn
• E-Chem people (batteries) need to be leveraged • Machining newly developed additive materials is a crapshoot • Lasers have BLOWN UP via AM Tech	• Some processes don't care how hard the materials are	• We are focused on milling only • Local sourcing/sustainability

WILD CARD / WILD CARD		
Rose	**Bud**	**Thorn**
•	• Operators assigned to machine(s) instead of tasks • Tool ID including cutting edges • Industry-wide adoption of ISO13399 • Create and/or adopt more logical programming language	• Technology acceptance by organizations • Organizational attitude toward technology

A.2 Affinity Clustering

Affinity clustering was the next roadmapping activity. This allowed for the identification of greater patterns, priorities and associations within the topics produced in the creativity matrices. Group A organized the Roses, Buds and Thorns into the following clusters:

- Human Centric Manufacturing
- Advanced HMI
- Automated Processes
- Security and Privacy
- Sensing/Self Aware
- Material Impact/Material Effect
- Learning From Data
- Adaptation (in process improvement)
- Optimization (Planning Phase)
- Info Sharing/Connectivity.

Group B organized their creativity matrix into the following clusters:

- Data
- Advanced Statistics/Math
- Material Issues
- People
- System Tools
- Man/Machine Interface
- Feedback (System v Part v Realtime)
- Artificial Intelligence
- Novel Processes
- Process Design
- Monitoring & Control
- Standards/Protocols
- Incentives,
- AI as an Enabler of New Business Models.

Of these topics, there are numerous common themes, although the language is slightly different between the groups. The following topics were shared across both groups:

- Human/Machine Interface
- Automated Processes/Process Design/Novel Processes
- Materials Issues
- Data Science
- Adaptation/Feedback

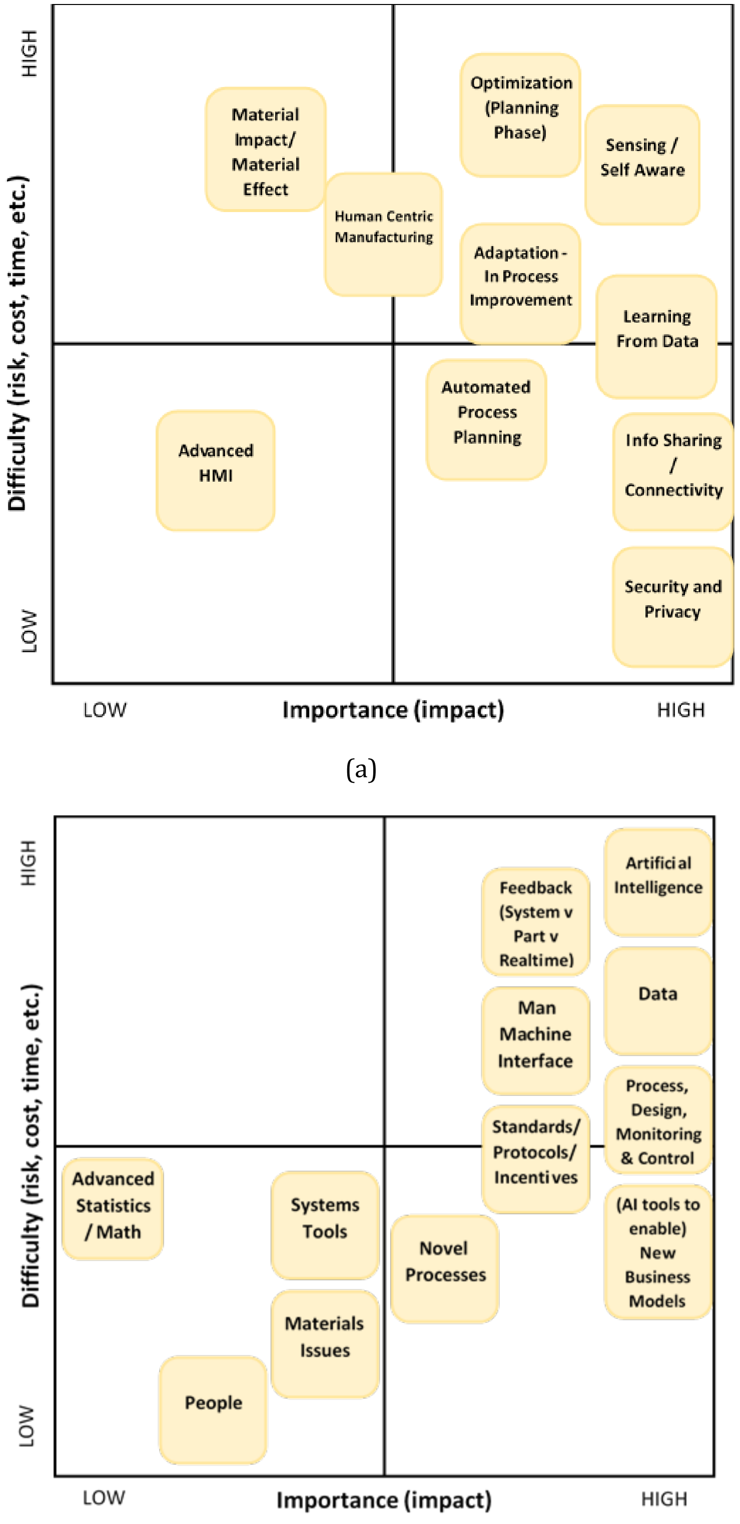
A.3 Difficulty/Importance Charts

Creating the difficulty/importance chartenabled the participants to position the affinity clustering topics on a importance versus difficultyquad chart. This exercise allows attendees to prioritize main ideas, identifying those ideas that have the best balance of importance and difficulty to be considered for further research. The significance of a difficulty/importance chart is that projects suitable for institute or center focus are in the first quadrant. These have high difficulty and high importance, and benefit from shared resources and collaboration.

In the second quadrant, project importance is low while difficulty is high. These projects are generally avoided. The third quadrant projects are rated low in difficulty and low in importance, and therefore represent "quick wins" when such goals are desired. The fourth quadrant is the classic "low hanging fruit" with low difficulty but high importance. These projects generally are best targeted by industry.

A prioritization arises from consideration of the matrix diagonal. The further to the right that a topic lies on the diagonal (i.e., high difficulty and high importance), the greater the research priority. For a Manufacturing USA Institute, the topics in the first quadrant represent topics that should receive attention.

The difficulty/importance chart for the two breakout groups are shown in Fig. A.1.



(a)

(b)

Figure A.1: Difficulty/importance chart: (a) First breakout group; (b) Second breakout group.

Appendix B: Creativity Matrix and Affinity Clustering Results, September 14, 2022

B.1 Creative Matrices

The 2022 roadmapping event took place at the International Machine Tool Show in Chicago and used the application scale matrix shown in Figs. 5(a) and 5(b). Matrix 5(a) was identical to the creativity matrix used in 2021; matrix 5(b) was modified prior to the roadmapping session to clarify the role of application scale to the research topics. For example, it has been widely noted in literature and other roadmaps that the need to embed physical models into AI is essential. However, this observation is demonstrably false. Certainly, the incorporation of physical models such as stability lobes or wear laws into AI can be beneficial on a machine scale, but the presence of physics models in AI routines that manage supply chains is not necessary. For this reason, the rows of the creativity matrix represent the scale of application, as seen in Fig. 5(b).

Results for the scale-specific creativity matrix shown in Fig. 5(b) are organized according to the row and column headers as follows:

Artificial Intelligence / Machine Scale

- AI-informed operating parameters
- Inference on-machine, not in cloud
- Adaptive workpiece-specific machining
- Closing the sensing-inference-activation loop. (Death to static tool paths)
- Natural language conversation with the machines
- Self-aware machine that uses a STEP file and machines without intervention
- General fault identification/prediction
- Ball screw AI degradation monitor
- On-board, AI-based process controls
- One machine to assess with other machines in the plant
- Machine intelligence to accept/reject job based on tolerances/part design request
- Digital twins for machines
- Material DNA
- Spindle degradation monitoring
- AI Machining Database of machining parameters
- Cost/efficiency parameters
- Environmental parameters (temperature, vibration, humidity, etc.)
- Automated material identification at the point of machining
- Real-time estimation of cutting force coefficients

Artificial Intelligence/System Level

- Automatic coordination
- Robust Model (OOD)
- Diagnosis tools
- Link intended part characteristics to the manufactured properties

Artificial Intelligence / Plant Level

- Bid and Cost Estimate generation
- Plant optimization based on internal and external data
- Health and safety data presentation (vibration, sound, etc.)
- Machine-machine interaction involving communication, learning, deciphering important features, etc.
- Autonomous self-healing systems
- Human-AI teaming

Artificial Intelligence / Enterprise level

- Subcontractor identification
- Multi-plant ERP access

- Contract generation
- UI/UX improved by recommended systems
- Subcontractor identification
- Multi-plant ERP access
- Contract generation
- UI/UX improved by recommended systems
- Workflow automation AI
- Supply chain fault prediction

Artificial Intelligence / WILD CARD

- Connect manufacturing insights to design

Big Data/ Machine Scale

- Big data for machine level
- Define doppelganger for machine and parts
- On-machine tap test w/ adaptive parameters
- Manufacturing database collective
- Process parameter optimization
- Sharable data
- Data aggregation, with daily performance correlation

Big Data/System Level

- Big data for system level
- Small data (minimize data to allow real-time work)
- Data on actual machine
- Data-driven labeling, lineage, sensitivity, governance
- Software for automated machining process plan development
- Process engineering tools: "Entitlement v. Actual", that is, what can be done

Big Data/Plant Level

- Big data for plant level
- Predictive plant maintenance
- Predictive task scheduling and management
- Process parameter database for sharing and leveraging cell-to-cell and site-to-site
- Auto-spec (materials data v. process corrections)

Big Data/Enterprise Level

- Big Data for Enterprise level
- Encrypted data for sharing
- Data exploration, discovery and analysis
- Component traceability
- Data sharing for process optimization
- Real-time state and status of supply chains
- Database of feature process plans to advise designer
- Blockchain for traceability
- Determine when data is obsolete
- Process parameter database for sharing company-to-company lessons (remove competition, promote teamwork)

Big Data/WILD CARD

Big data for other applications

Networking/ Machine Scale

- Network sensors and machines
- Interface protocol standardization
- Wireless communication

Networking / System Level

- Real time stock and material property ID and communication
- Automated information models
- Further expansion of MT Connect
- Standardization for plug-and-play, perhaps MTConnect

Networking /Plant Level

- Plant-level communication among manufacturing machines
- Security between physical plants
- Security for shop floor and machine
- Adaptice parameter changes for real-tiome flow balance

Networking /Enterprise Level

- Time “Distributed manufacturing” with total visibility and control
- Cybersecurity
- Optimization strategies for factory networks
- Orchestration of collaborative and independent manufacturers
- Database of providers and capab ilities
- Touchless exchange of data

Networking /WILD CARD

- Talent sharing programs between companies and industries
- Virtual factory tours for Junior High and High School Students

Man/Machine Interface/ Machine Scale

- Virtual reality representation of assembly operations
- Gamification UI and interaction
- Verbal command input/Natural language interface
- Interpretation of command capabilities
- “Machine Tools for Dummies”/Simplified training
- Machine guided human repeated operations (Machine and human initiated)
- Virtual reality for training
- Understanding operator intent via natural language
- Machine verbal suggestions for part machining
- Adaptive control for different operators
- AI to detect part/events in time to auto-correct adjustments
- Augmented reality for machine operators and maintenance personnel
- Virtual human interface – no buttons!

Man/Machine Interface/System Level

- Video guided setup and maintenance
- Hololens for multiple machines
- Virtual reality for machining precess and data visualization
- System level digital twin presentation
- Decision models to recommend course of action

Man/Machine Interface/Plant Level

- Hololens or Meta 3 for plant operations
- Integrate/bridge different data types with warning to operator

Man/Machine Interface/Enterprise Level

- Haptic feedback for process planning
- Virtual reality for process plan visualization
- Devise "Need to Know" training for common processes
- Low-cost interface for legacy machines

Man/Machine Interface/WILD CARD

- Talent sharing programs between companies and industries
- Virtual factory tours for Junior High and High School Students

WILD CARD/ Machine Scale

- Programming software that determines tool path strategy based on shape, material and blueprint dimensions
- Smart cutting inserts (force, temperature measurement)

WILD CARD /System Level

- New uses for metal cutting chips
- Security for OS/Legacy machines

WILD CARD /Plant Level

- Minimum quantity lubrication/eco-friendly fluids
- Dynamic library of energy usage
- Collaborative marketplace of machine skills
- Matching of environmental requirements to local machining capability

WILD CARD /Enterprise Level

- Haptic feedback for process planning
- Virtual reality for process plan visualization
- Devise "Need to Know" training for common processes
- Low-cost interface for legacy machines

WILD CARD /WILD CARD

- Getting young professionals from historically marginalized groups
- Colonization of space/manufacturing in space
- Accelerate adoption of new technologies
- New business models
- Standardization for Machine Capabilities and maintenance
- Take advantage of NSF INTERN program
- Establish universal income

B.2 Affinity Clusters

The scale-specific creativity matrix of Fig. 5(b) resulted in the affinity clusters as follows:

Predictive Approaches

- Real time estimate of cutting force coefficients
- Process monitoring, query other machines if adjustments are needed
- Predictive asset maintenance
- Ball screw AI degradation model
- Predictive task scheduling
- Supply chain fault predictions
- Real time status of supply chains
- Decision models to recommend course of action
- Spindle degradation monitoring
- Prognosis
- Data generation for training AI systems
- Thermal control (even temperature distribution)
- Hubrid modeling (physics & phenomenological)
- Real time inspection and correction feedback
- Digital twins for machines
- Defining doppelgangers for machines and parts
- Robust model out-of-distribution

Smart Machines

- Self-evaluate with machine peers
- Haptic feedback simulation for process planning
- Intelligent systems with automated integration of process planning and ancillary functions
- Feature/function parameters for metrology
- One machine to self-assess with respect to other machines in the plant
- Monitoring and predicting human actions for safety
- Self-aware machine that gets the step file and the workpiece and machines without human intervention
- Machine intelligence to accept/reject job based on tolerances, etc.
- Data aggregation which updates performance daily
- Smart video-based assembly and training
- Understanding operator intent/natural language
- Real time monitoring of process signature
- Live chatter detection and response system
- Autonomous process selection and control
- Health/Safety monitoring (visual, vibration, sound, structural)
- Tool break prediction before the break
- Automated conditional adjustment of machine foundational setup

Lower AI Barriers

- Build Jarvis
- AI tool standards in machine tools
- Ethical point of divergence in AI and human decision making
- Workflow automation AI
- Autonomous AI
- Human-AI teaming
- Methods of accelerating adoption of new technologies

In-Process Metrology

-

HMI

- Natural language interface
- Los-cost HMI for legacy machines
- NLP and voice inputs to MT control
- Interpretation of command work capabilities
- Machine verbal suggestions for part drawing
- Virtual human interface – no buttons
- UI/UX improved by recommended systems
- NLP conversations with the machines

Industrial Metaverse

- Augmented reality machine operation and maintenance
- Virtual reality for training
- Augmented reality for machine-operator collaboration
- AR/VR machine tools for training and troubleshooting
- Hololens for plant
- Virtual reality verification of assembly processes
- VT for instant machining process data visualization
- Subcontractor identification when parts can't be made or to save cost
- Hololens for multiple machines

Cutting Tools

- On-machine tool edge reconditioning
- Smart cutting inserts
- Active tools to avoid pocketing
- Sensor embedded cutting tools
- Sensor embedded workholding

Design Integration (process)

- Data sharing for process optimization
- Process parameter database for sharing and leveraging cell-to-cell and site-to-site
- AI influenced operating parameters
- Process engineering tools: Entitlement vs. Acutal; what can be done?
- Process planning for hybrid processes
- Process parameter database for sharing company-to-company
- AI machining database of parameters
- Virtual reality for visualizing process plans
- Heterogeneous material processing
- Link inspected part characteristics to the manufacturing processes that created them to support SPC
- Software that determines toolpath strategy and tool/tool parameter selection based on shape, material and blueprint
- Machine-machine collaboration
- Complete state and stalls of processes
- Software for automating process plan development and optimization

Design Integration (product)

- Connect manufacturing inputs to design
- Automated DFM
- Database of feature process plans to advise engineer
- Use production data to measure producibility of product
- Use production data to recommend producibility improvements in design
- Component traceability/blockchain for traceability
- On-demand search of design and manufacturing models

- Industry wide standards for machine capabilities and maintenance
- Intelligent CAD to select optimum processes and their order
- System level digital twin

Training

- Devise “need to know” training for common machining practices
- Machine initiated training
- Human initated training at machine
- Video guided setup and maintenance
- Machine Tools For Dummies
- Gamify user interface and interaction to upskill workers
- Education on manufacturing-related perceptions
- Getting young people from historically marginalized groups interested in machining/manufacturing.

Cost/Financials

- Bid/cost estimates; e-contract generation
- Software to determine when additive and when machining are needed
- Machine tools as a service
- Offer tax benefits to encourage adoption
- Optimization software to select type and number of machines
- New business models to improve revenue
- Unconditional universal income
- Data on actual cost by process/parameter/machine, etc.

Automated Adaptation to Data

- Adaptation of process to measured data
- Edge device issues: Power; Latency
- Hard inference on machine (not in cloud)
- Adaptive workpiece-specific machining
- Closing the sensing-inference-automation loop
- On-board AI-based Process Controls
- Environmental parameters-based control: Temperature, Vibrations, Humidity
- Automatic compensation
- Automated learning for process optimization
- Adaptive parameter changes for real-time line flow balance
- Automaterial identification at point of machining
- Adaptive control for different operators
- Adaptive/Live process optimization
- Autonomous and self-healing systems
- Automated adaptive machining and control
- On-machine tap test with adaptive parameters
- Relational digital twin with bi-directional data flow

Process/Line Adaptation

- Use production data to assess weak link in manufacturing system
- Closed loop control of manufacturing system/line
- Gather process & intervention to assess process health
- Automatic compensation
- Ability to change tools based on availability (process-line level)
- Connect insights from material variations by analyzing process using AI.

B.3: Difficulty-Importance Charts

The general creativity matrix shown in Fig. 5(a) led to the difficulty/importance chart shown below in Fig. B.1; the scale-specific creativity matrixshown in Fig 5(b) resulted in the difficulty/importance chart shown in Fig. B.2.

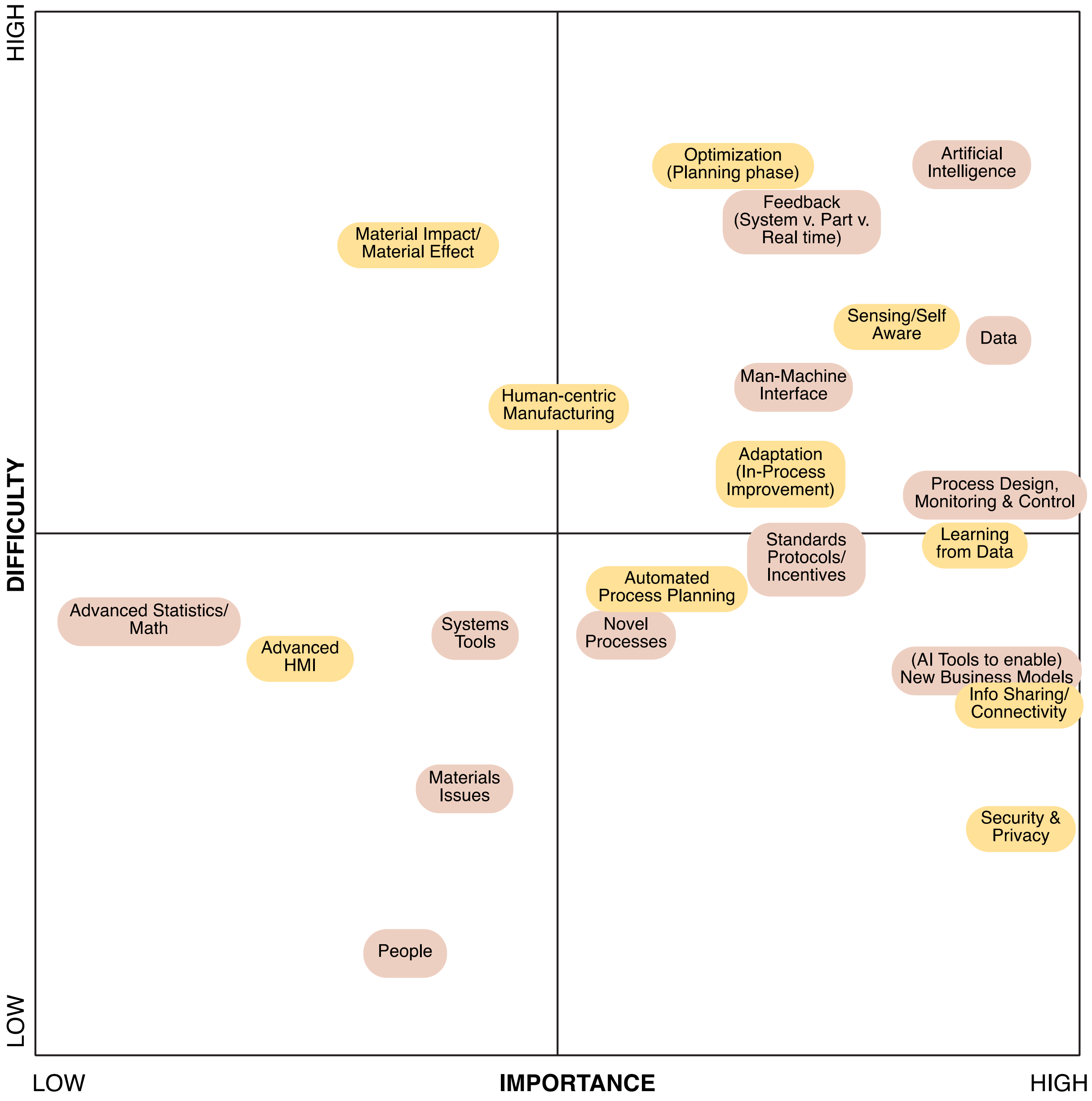


Figure B.1: Difficulty/importance results from the 2021 roadmapping event, using the general creativity matrix of Fig. 5(a).

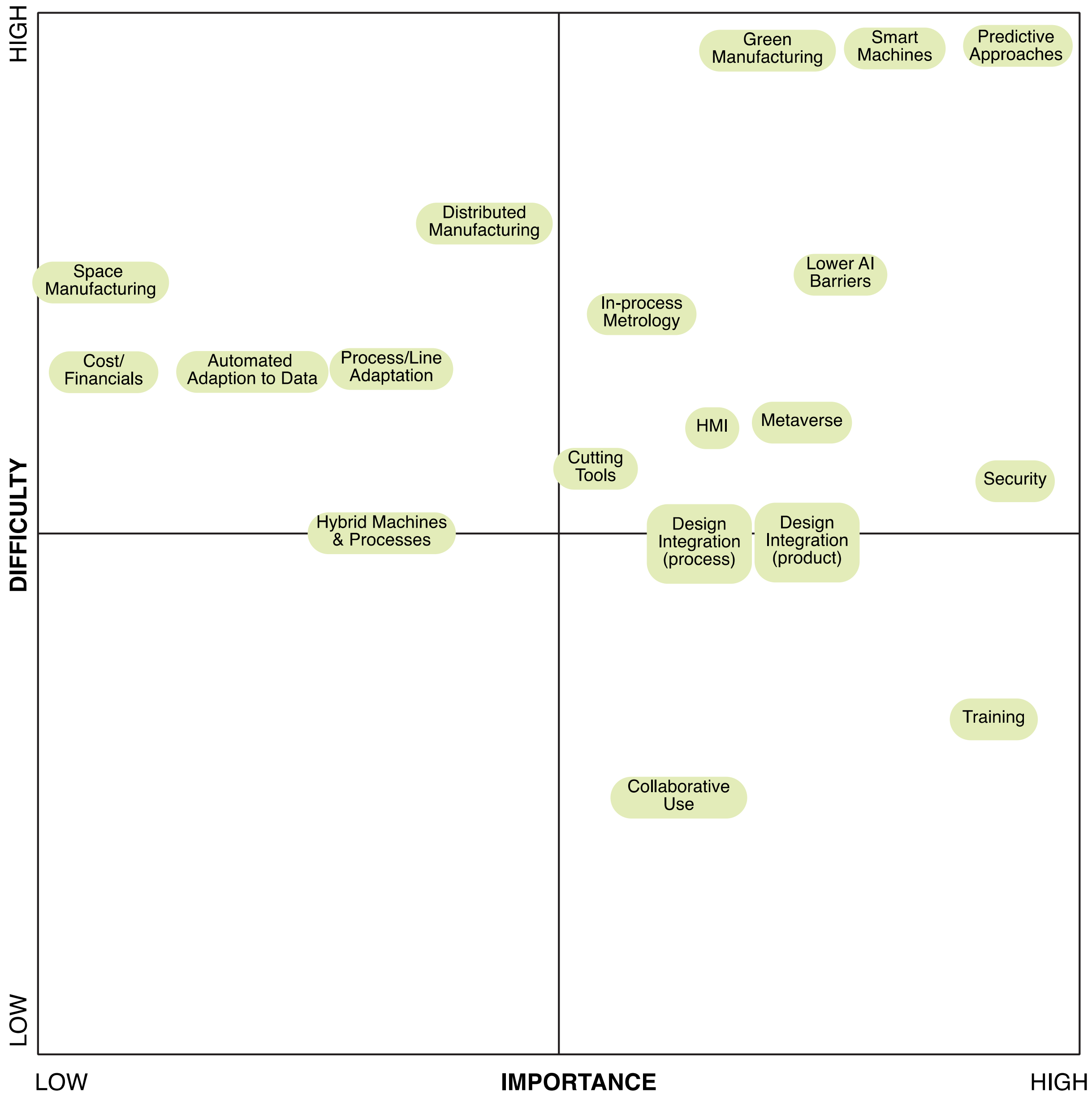


Figure B.2: Difficulty/importance results from the 2022 roadmapping event, using the scale-specific creativity matrix of Fig. 5(b).

Appendix C: Creativity Matrix and Affinity Clustering Results, June 10, 2023

The 2023 roadmapping event took place at the North American Manufacturing Research Conference (NAMRC) at Rutgers University. Two breakout groups were formed and addressed two different creativity matrix topics. The first group considered AI control of machinery shown in Fig 5(c); the second considered a "deep dive" of AI topics shown in Fig 5(d)

C.1 AI Control of Machinery Breakout Session

The AI control of machinery creativity matrix is given in Fig. 5(c). When populated, the creativity matrix had the following contents:

Machine Monitoring / Software Design

- Parameter recommendations
- Software for fast data transfer
- Edge computing; AI; smart sensors
- Predictive maintenance
- Self-learning machine/process state monitoring
- Virus control for machine tools

Machine Monitoring / Controller

- Standardization
- Compute power at the edge
- Controller to provide all necessary parameters

Machine Monitoring/Machine Design

- Design for cybersecurity
- Embedded robust sensing from design stage
- Integrated machine and robot system
- Adaptive, self-adjusting machine tools
- New machine design concepts

Machine Monitoring / System Integration

- Machine-machine communication
- Automatic compensation
- Intelligent thermal control (volumetric errors)
- Machine to machine scheduling
- Build/generate database of abnormal machine conditions
- Closed-loop monitoring using tool with embedded sensors

Machine Monitoring / WILD CARD

- Anomaly, manipulation, attack detection

Sensor and Sensor Fusion / Software Design

- Mathematically integrate structural sensor network to machine error compensation
- App development for portable devices

Sensor and Sensor Fusion / Controller

- Measurement of process signature (state variables)
- Connectivity standards
- Edge vs. Cloud data processing
- Data standards

Sensor and Sensor Fusion / Machine Design

- Sensors embedded in machine design
- Predictive maintenance
- Structurally integrated sensing network
- Additive manufacturing of sensors for intelligent tooling
- “Biologicalization” of MD sensing – as in nervous system to level of all subsystems
- Fully integrated and AI-enabled sensors

Sensor and Sensor Fusion / System Integration

- Micro/nano sensors integrated in tools
- Awareness of environment (humans, AMRs, etc.)

Sensor and Sensor Fusion / WILD CARD

- NIST hardware standard to train image-based AI
- Better data tools
- AI for carrying machine and process dynamics
- Cost-effective fabrication and sensors and sensor materials
- New sensor design

Digital Twins / Software Design

- Machine twins, not just products
- Virtual certification/validation
- Reduce costs – modularization of digital twins
- Codeless quick setup factory sim model
- Automatic generation of models

Digital Twins / Controller

- Measurements plus estimation of state variables that cannot be measured
- Standardization like ROS for robots
- Flexible CNC and machine control
- Hierarchical digital twins that build/connect to each other

Digital Twins / Machine Design

- Accurate 5-axis mill vibration/stiffness model
- Virtual machine and system dynamics
- Process monitoring and control
- Verification of modeling
- Connecting micro scale modeling with macro scale prediction
- Feedback to supply chain (i.e., material shortage due to weather)
- Design for digital twins

Digital Twins / System Integration

- Collaboration for digital twins
- Part design recommendations (DFM, cost improvement, etc.)
- Languages for digital twins
- Self-learning cascade drive control
- Legacy components to new manufacturing routing tool based on drawing and old loading
- Languages for digital twin communication

Digital Twins / WILD CARD

- Digital twin of entire process chain
- Modular with intent, i.e., KPI that change
- Real time component progress and AI schedule modification
- Digital twins for legacy equipment

Pattern Recognition / Software Design

- From pattern recognition to reasoning
- Physics informed pattern recognition
- Recognizing patterns – failure modes beyond those experienced before

Pattern Recognition / Controller

- Controller adaptive to tool state (wear, temperature, etc.)
- Controller adaptive to people state (operator, program, planning)
- Controller adaptive to market or production conditions
- Cloud-based data storage and analysis

Pattern Recognition / Machine Design

- Predictive maintenance
- Leverage pattern recognition to improve machine design based on history of performance breakdowns
- AI-enabled machine design

Pattern Recognition / System Integration

- In-situ geometric error analysis and automated corrective algorithms
- In-process AI enabled visual inspeciton

Pattern Recognition / WILD CARD

- AI for new process physics identification
- Work with any data

WILD CARD / Software Design

- OpenAI, ChatGPT code generation
- Natural language machine instructions and response
- Human UI design
- ChatGPT for machine tools

WILD CARD / Controller

- Cloud driven controller (see past Blue Sky)
- Controller beyond G&M codes – AI driven
- Voice controlled HMI/controller
- Quantum computer controller

WILD CARD / Machine Design

- Modular and standardized machine components for plug & play
- Reconfigurable machines – plug & play hardware addons
- Generative machine design
- Human-machine collaboration

WILD CARD / System Integration

- Energy augmented machining (laser, electrical power, vibration, etc.)
- Automated process design

WILD CARD / WILD CARD

- Decision modeling
- Automated fixture/workholding design
- Autogenerated tooling design and manufacturing routing
- Los-cost modular machine tool
- Self-configuring machine tool
- Ability to master human element
- Autonomous systems

The contents of the AI control of machinery creative matrix resulted in the affinity clusters as follows:

Standardization

- Data standards
- Standardization
- Connectivity standards
- Standard integration APIs for DTs
- Standardization like ROS for robots
- Reduce costs – modularization of digital twins
- NIST hardware standard to train image-based AI
- Languages for digital twin communication

Language Models

- Chat GPT for machine tools
- Natural language machine instruction
- Open AI Chat GPT code generation

New AI Methods

- Physics informed pattern recognition
- Better data cleanup tools
- Recognize patterns failure modes beyond those experienced before
- Work with any data
- From pattern recognition to reasoning
- AI for new process physics identification

Collaboration for Digital Twins

- Digital twins for legacy equipment
- Hierarchical digital twins that build/connect to each other
- Machine twins not just products
- Digital twin of entire process chain
- Connecting microscale modeling with macroscale prediction
- Design for digital twins
- Automatic DT generation of models

Human-centric Design & Control

- Human – machine collaboration
- Human UI design
- Decision modeling
- Controller adaptive to people state (operator, program, planning)
- Voice control HMI/controller
- App development for portable devices
- Ability to measure human element
- Parameter recommendations

Security and Anti-Counterfeiting

- Anomaly, manipulation, attack detection
- Design for cybersecurity
- Virus control for machine tools

Hardware Modularity and New Design

- AI-enabled machine design
- Modular and standardized machine components
- Adaptive, self-adjusting machine tools
- Reconfigurable machines plug-and-play hardware addons
- Integrated machine + robot system

- Low-cost modular machine tool
- Self-configuring machine tool
- New machine design concepts
- Energy-augmented machining (laser, electrical power, vibration, etc.)

Measuring/Monitoring

- Measurement of process signature (state variables)
- Estimation of state variables that cannot be measured
- Embedded robust sensing from design stage
- Fully integrated and AI-enabled sensors
- Micro/nano sensors integrated in tools
- Sensors embedded in machine design
- Closed-loop monitoring using tool with embedded sensors
- Build/generate database of abnormal machine conditions/states
- In-situ geometric error analysis and automated corrective action
- In-process AI enabled visual inspection
- Structurally integrated Sensing Network
- Mathematically integrate structural sensor network to error compensation
- “Biologicalization” of machine design; sensing as in nervous system to level of all subsystems
- Automatic compensation
- Self-learning machine/process state monitoring
- Additive manufacturing of sensors for intelligent tooling
- New sensors
- Cost-effective fabrication of sensors and sensor materials.

Automated Design

- Automated fixture/workholding design
- Autogenerated tooling design and manufacturing routing
- Automated process design
- Codeless quick setup factory sim model
- Part design recommendations (DFM, cost improved, etc)
- Generative machine design
- Virtual certification (validation)

Mchine-machine Communication

- Machine to machine scheduling
- Optimize usage based on demand or opportunity
- Machine-machine communication
- Awareness of environment (humans, AMRs, etc.)

Autonomous Controller Design

- Controller to provide “all” necessary parameters
- Intelligent thermal control (volumetric errors)
- Verification of modeling & prediction
- Accurate 5 axis mill vibration/stiffness model
- Controller beyond G&M codes
- Virtual machine and system dynamics

Adaptive and Autonomous Systems

- Self-learning cascade drive control
- Controller adaptive to tool state (wear, temperature, etc.)
- AI for varying machine and process dynamics
- Flexible CNC and machine control
- Controller adaptive to market of production conditions
- Autonomous systems

C.3 AI Deep Dive Breakout Session

The AI deep dive creativity matrix is shown in Fig. 5(d). When populated, the creativity matrix had the following contents:

Self-Aware Factories / Software Design

- Real-time cyber bidding and contracting
- Communication among machines
- AI driven tool selection with optimal operating parameters
- Software design to enable plug-and-play sensing
- Integrated part design and shop floor optimization
- Pro-active action of machine tool
- Integrate new dimensions to problems

Self-Aware Factories / Real-time Metrology

- 5G enabled pyrometry
- Identification and analysis of machine data to predict issues very early
- Vibration detection and AI resolution

Self-Aware Factories / Machine Design

- Error detection (defect)
- Hybrid machines of all types
- Holonic manufacturing

Self-Aware Factories / Open-Source Controller

- Machine adapts itself to IT/OT (existing) infrastructure

Self-Aware Factories / / WILD CARD

- Automated contextualization of data models using AI/ML
- Create Jarvis
- Self-organizing production lines
- Machine performance AI
- Where do you put the furniture?

Natural Language Interface / Software Design

- Machine/Machine interface
- ChatGPT for machine tools
- Adapt to different languages
- Automatic generation of part programs on voice/text command

Natural Language Interface / Real-time Metrology

- Immediate feedback on measurement and cause
- Real-time part 3D scanning for geometric accuracy
- Interface for real time updated process control
- Rosetta stone for feature names

Natural Language Interface / Machine Design

- Wearable electronics (Oculus/Google Glass/Headsets)
- Interactive guidance from AI
- Talking and listening machines

Natural Language Interface / Open-Source Controller

- Human-in-the-loop control

Natural Language Interface / / WILD CARD

- Generative design
- FMRI for thought control
- NCP/voice in loud environments

Closed-Loop Control / Software Design

- Tribology models influence parameters
- Incorporation of multiple constraints, eg., minimum cost, maximum speed, minimum tools use combined to set parameters

Closed-Loop Control / Real-time Metrology

- Generative modification to machine code from measurement
- Measure thermal stresses and deflections, as well as due to force and residual stress
- Tool condition monitoring and AI

Closed-Loop Control / Machine Design

- Sensor fusion and retrofits
- Self aware machines making decisions based on actual data

Closed-Loop Control / Open-Source Controller

- AI-enabled error recovery (autonomous)
- Intelligence to augment human operator capabilities

Closed-Loop Control / / WILD CARD

- Incorporate uncertainty/decision theory into control theory

(Efficient) Machine Learning / Software Design

- ChatGPT for G code
- AI using models and data to go FAST
- UI adapts to user to optimally support
- Learning across systems
- Forecasting failure of machine tools

(Efficient) Machine Learning / Real-time Metrology

- Part quality machine and CMM
- AI powered dynamics and feed/speed adjustments
- Measurement outcomes and cause
- Edge deployed module
- Image-based AI for metrology and corrective algorithms
- Performance of machine for process control

(Efficient) Machine Learning / Machine Design

- High volume data acquisition

(Efficient) Machine Learning / Open-Source Controller

- Machine learning related to cutting tools
- AI for process control related to part quality
- Learning from small/imbalanced data sets
- Process control
- Real time learning from data/process model updating
- Sustems of machines AI

(Efficient) Machine Learning / WILD CARD

- Truly generalizable learning

WILD CARD / Software Design

- Integrated no-code and to-end solutions (including repositioning)
- Automated G-code generation
- AI programming using feature recognition
- System design for IIOT of machine-machine connectivity

WILD CARD / Real-time Metrology

- Automatic machine adjustment based on measured part dimensions

WILD CARD / Machine Design

- Disposable single-use or purpose machines developed from part model
- Anticipate (forecast) future applications over lifecycle
- Generative design of hybrid machines
- Self-reconfigurable machine tools
- Trusted layer to share data from different sources to allow for training
- Machine designing itself
- Adaptable/modular machine tools

WILD CARD / Open-Source Controller

- Open-source controller simulations/ease software integration
- AI layer for non-connected heterogeneous machine controls for a system view

WILD CARD / / WILD CARD

- AI Ethics in manufacturing
- Supply chain management for small lot manufacturing
- Get rid of requirements – replace with preferences
- Optimize tolerances
- More rigorous treatment of uncertainty
- Manage IP/competitive info
- Supplier-buyer algorithm/market place

The AI control of machinery creative matrix resulted in the affinity clustering as follows:

Policy/Ethics

- AI ethics in manufacturing
- Manage IP/competitive info

Self-organizing supply network

- Supply chain management for small lot manufacturing
- Supplier-buyer algorithm/marketplace
- Real time cyber bidding and contracting

Errors/Recovery

- Error detection (defect)
- AI-enabled error recovery (autonomous)
- Integrate new dimension to problems
- Quality assurance

Math

- Get rid of requirements – replace with preferences
- AI using models and data to go FAST
- Optimize tolerances
- On-tool correction based on metrology
- More rigorous treatment of uncertainty
- Incorporate uncertainty/decision theory into control theory
- Incorporation of multiple constraints
- Learning from small/imbalanced data sets

- Truly generalizable learning
- Minimizing constraints

Factory Design (System)

- Self-organizing production lines
- Where do you put the furniture?
- Machine adapts itself to IT/OT infrastructure
- Software design to enable plug-and-play sensing
- Automated contextualization of data models using AI/ML
- System design for IIOT of machine-machine connectivity
- Adaptable/modular machine tools
- Holonic manufacturing
- Generative design

Data Acquisition and Utilization

- High volume data acquisition
- Vibration detection and AI resolution
- Data repository
- 5G enables pyrometry
- Automatic machine adjustment based on measured part dimensions
- Data standards
- Tool condition monitoring and AI
- Trusted layer to share data from different sources for training
- Sensor fusion (built-in sensors) and retrofits
- Self-aware machines making decisions based on actual data.

Human-Machine Interaction

- Adapt to different languages
- ChatGPT for machine tools
- Intelligence to augment human operator capabilities
- Human-in-the-loop control
- Interactive guidance from AI to operator
- Natural language processing / voice in loud environments
- fMRI for thought control
- Automatic generation of part programs on voice/text command
- UI adapts to user
- Wearable electronics: Oculus/Google Glass/other headset
- Create Jarvis
- Gamify UI

C.3 Importance/Difficulty Charts

The difficulty/importance chart for the AI Control of machinery creativity matrix is given in Fig. C.1, while that for a “deep dive” on artificial intelligence for machining and machine tools is given in Fig. C.2.

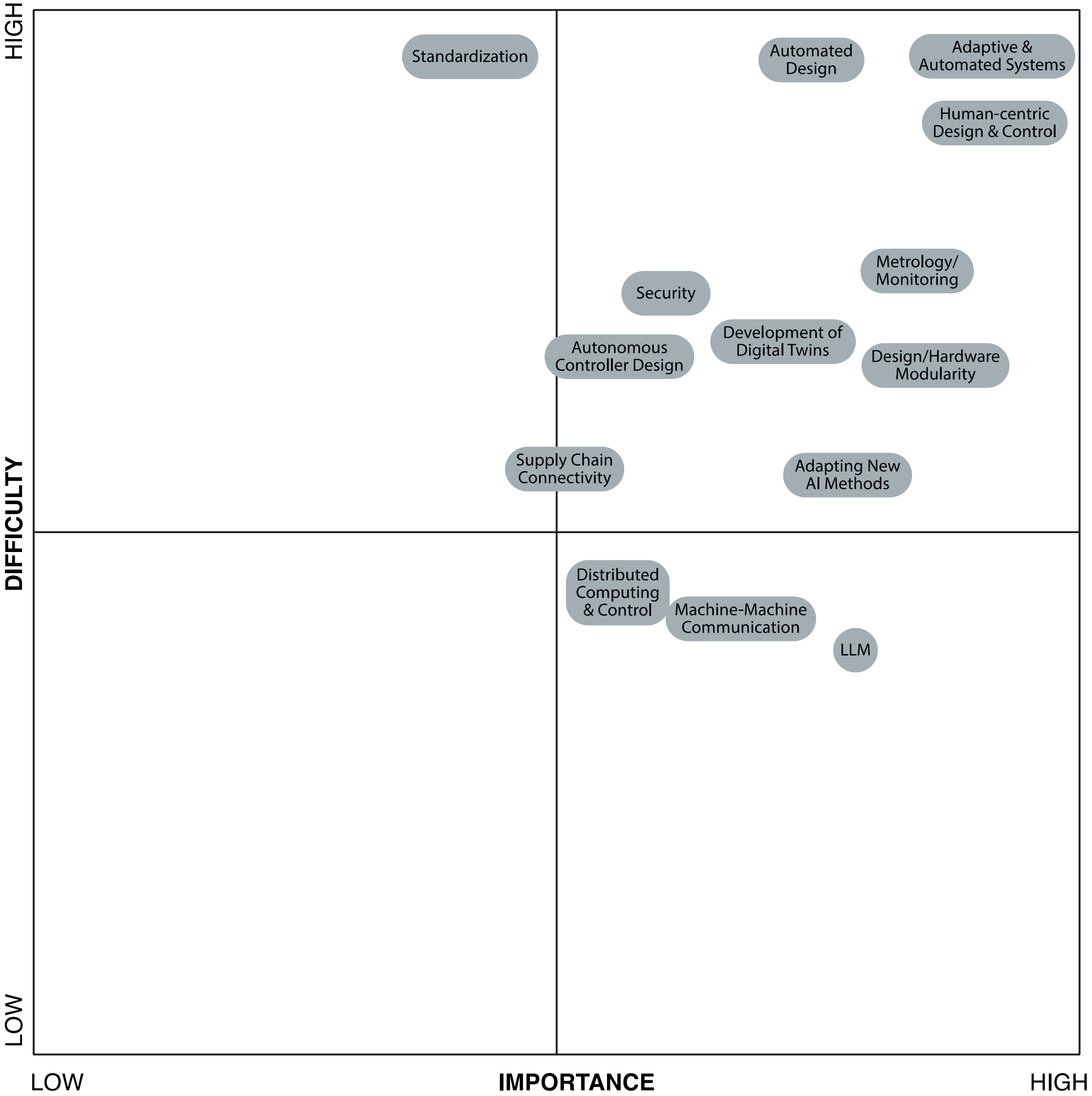


Figure C.1: Difficulty/importance results from the 2023 roadmapping event, focused on topics on AI control of machinery.

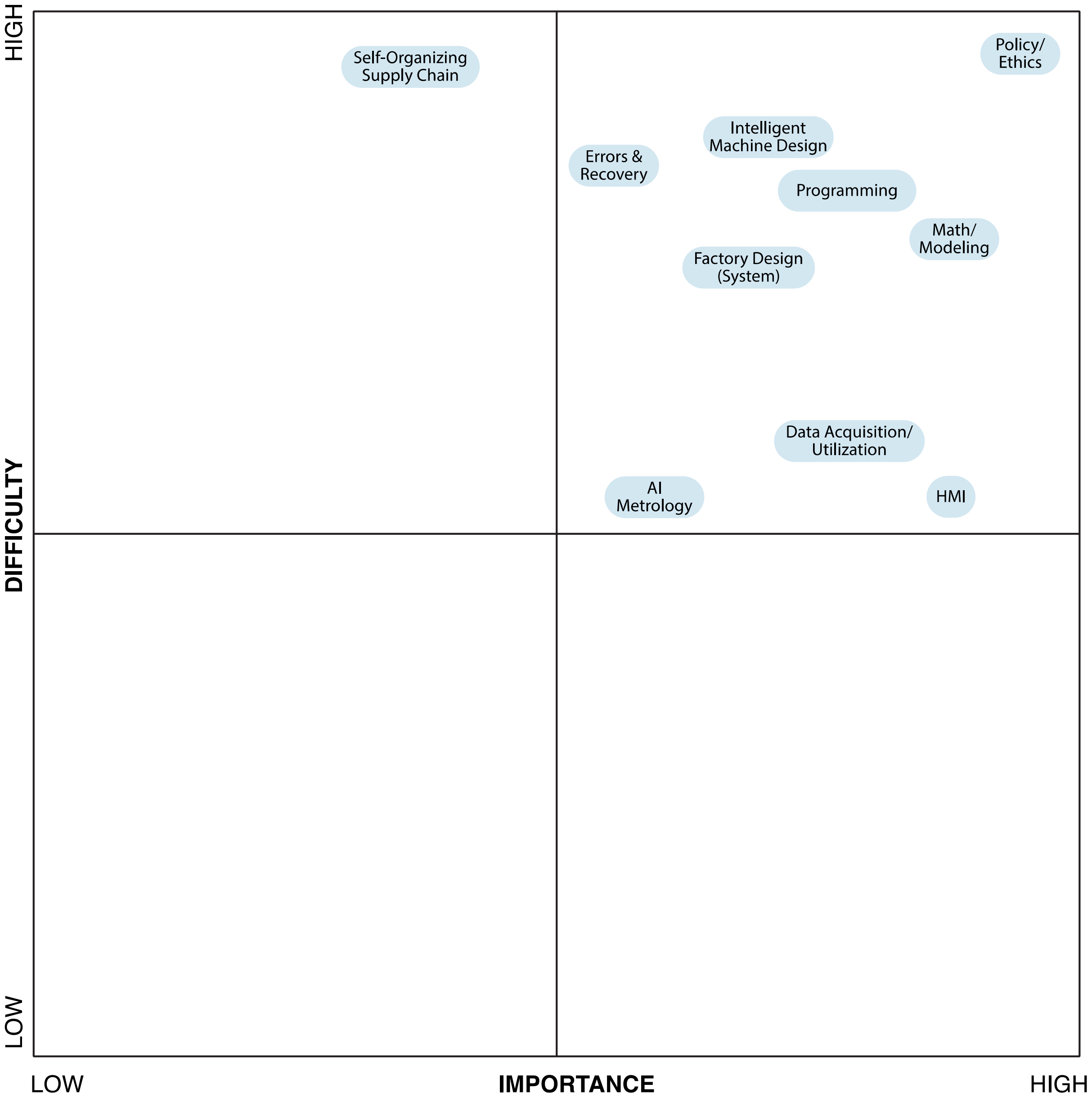


Figure C.2: Difficulty/-mportance results from the 2023 roadmapping event, focused on an AI “deep dive”.

Appendix D: Creativity Matrix and Affinity Clustering Results, September 13, 2024

The 2024 event highlighted artificial intelligence, especially as relates to reliance of supply chains in manufacturing. The AI "deep dive" creative chart from 2023 shown in Fig. (d) was applied, and a creativity matrix for AI applications in supply chains shown in Fig. 5(e) was developed.

D.1 AI Deep Dive Breakout Session

The AI deep dive creativity matrix is is shown in Fig 5(d).. When populated, the creativity matrix had the following contents:

Self-Aware Factories / Software Design

- Real-time cyber bidding and contracting
- Machine/ERP integration
- Self-aware control
- Automatic PO generation and contracting
- Holonomic manufacturing

Self-Aware Factories / Real-time Metrology

- Real time awareness of OEE/In factory and supply chain
- Automated multi-system data analysis in real time
- Self-reporting metrology
- Real time assessment and knowledge base of machine capabilities

Self-Aware Factories / Machine Design

- Plug & Play smart integration
- Machine design for self-aware factories
- Mobile machines
- Leverage tools to visualize information for operator

Self-Aware Factories / Open-Source Controller

- Sensor fusion everywhere and networked
- Plug and Play / Upgradable
- Secure communications

Self-Aware Factories / / WILD CARD

- Generate daily reports to management

Natural Language Interface / Software Design

- No training – speak and listen to machine
- AI/NLP to automatically generate programs
- Low learning curve solutions
- Training plus physics for operator

Natural Language Interface / Real-time Metrology

- Provide part dimensions on voice command
- Toll speaks to operator when metrology system triggers discussion
- Easy to understand for operators
- Machine communicates values or warnings.

Natural Language Interface / Machine Design

- Conversational machine control
- No more G-code
- NLP to GenAI to Real time machine design

Natural Language Interface / Open-Source Controller

- User voice recognition for access level
- Human machine interface devices

Natural Language Interface / / WILD CARD

- NLI and Training

Closed-Loop Control / Software Design

- Adaptive machining and control in real time
- HMI for operator to amplify/NTE
- Self-adaptive software configuration based on incoming job.

Closed-Loop Control / Real-time Metrology

- Tooling and part metrology and feedback
- Fast enough on-machine metrology
- Temperature and vibration monitoring
- Composite present and feedback
- Real time interface process
- In machine scanning for full 3D reconstruction

Closed-Loop Control / Machine Design

- Sensor fusion and retrofits
- Leverage cloud computing for closed loop control

Closed-Loop Control / Open-Source Controller

- Open-source geometry kernel
- Feed forward and feedback of process monitors

Closed-Loop Control / / WILD CARD

(Efficient) Machine Learning / Software Design

- Affordable edge analysis
- Open-source database
- Have access to other plants and users
- Massive data set redux and manipulation tools
- Convert old physical drawing to 3D model

(Efficient) Machine Learning / Real-time Metrology

- Fast metrology
- Machine learning enabled virtual metrology twin
- Exception capture to HMI presentation
- Neuroscience model to support HMI
- Data/Discover strategies to manage global problems
- Process parameter-based ML inspection
- Metrology for preventative maintenance
- ML-based heat index monitoring to reduce porosity in metal 3D

(Efficient) Machine Learning / Machine Design

- Alloy DNA automatic detection of material
- Digital twins of machines (not for maintenance)
- Old or aging machine Comp + Control
- The part is the digital twin (lots of info. On part that can be retrieved)
- Gen. AI using DT for machine design

(Efficient) Machine Learning / Open-Source Controller

- Controller self-evolution
- Open source but integrates with others (swappable controllers)

(Efficient) Machine Learning / WILD CARD

- ID then rank process method alternatives to design intent
- Optionality under raw material/tooling constraint environment
- (Graph) reduce cost at low production quantities

WILD CARD / Software Design

- Integrated no-code and to-end solutions (including repositioning)
- Automated G-code generation
- AI programming using feature recognition
- System design for IIOT of machine-machine connectivity

WILD CARD / Real-time Metrology

- Automatic machine adjustment based on measured part dimensions

WILD CARD / Machine Design

- Design for security
- Extra sensing adaptation of machine/process interface
- Retrofitting legacy equipment
- Robot plug and play ready

WILD CARD / Open-Source Controller

WILD CARD / / WILD CARD

- Education in an evolving manufacturing era
- Process recognition of requirements for obsolete parts

The AI deep dive creativity matrix resulted in the affinity clustering as follows:

Modelling

- Digital twins of machines (not for maintenance)
- The part is the digital twin (lots of info. On part that can be retrieved)
- Alloy DNA automatic detection of material

Part/Process Metrology

- Automated multi-system data analysis in real time
- Self-reporting metrology
- Process parameter-based ML inspection
- Metrology for preventative maintenance
- ML-based heat index monitoring to reduce porosity in metal 3D
- Automated magnetic particle inspection using computer vision
- Calibration and Classification tracking of metrology devices
- Fast Metrology
- Temperature and vibration monitoring
- Machine learning-enabled virtual metrology
- Tooling & part metrology and feedback
- In machine scanning for full 3D reconstruction

  - Sensor fusion everywhere and networked
  - Composite preset and feedback to PE & DE

AI Adaptive Soft/Hard ware system

- Plug & Play/upgradable
- Process recognition of requirements for obsolete parts
- ID then rank process method alternatives to design intent
- Controller self-evolution
- Generative AI using DT for machine design
- Plug & Play smart integration
- Machine design commons for self-aware factories
- Instant sub-process identification on CAD
- AI/NLP to automatically generate programs
- Self-adapting software configuration based on incoming jon
- Adaptive machining and control real time
- Open source but integrates with others (swappable controllers)
- Affordable edge analytics
- Mobile machines
- Retrofitting legacy equipment
- Robot plug & Play ready
- NLP to generative AI to real time machine design
- Old or aging machine comp + control
- Self-aware control
- Optionality under raw material / tooling constraint environment
- Leverage cloud computing for closed look control
- Sensor fusion built into machines

Training and Workforce Development

- Education in an evolving manufacturing era
- Natural language and training
- Conversational machine control
- Leverage AR tools to visualize information for operator
- Train + Physics interface for operator
- No training – speak and listen to software
- Neuro-science model to support HMI
- RT interface process quality
- Low learning curve solutions
- HMI for operators to amplify/NTE

Human Machine Interface

- Easy to understand for operators
- Provide part dimensions on voice command
- Tool speaks to operator when metrology triggers discussion
- Machine communicates values or warnings
- HMI devices
- User voice recognition for access level
- No more G-code Natural language CNC operation

Massive Data (Massive Process Data Monitoring and Utilization)

- Data/discover strategies to manage global problems
- Exception capture to HMI presentation
- Open-source database
- Real time awareness of OEEE in factory and supply chain
- Massive data set reduce and manipulation tools
- Feed forward and feed backward of process monitors

- Real time assessment and knowledge base update of machine's capabilities
- Extra sensory adaptation of machine/process interface
- Quantum optimization
- Decentralized IIOT selection across SMM ecosystem
- Machines teaching machines
- (Graph) reduce cost at low production quantities

Business Process Logic

- Bidding/Contracting
- Automatic PO Generation and contracting
- Holonomic manufacturing
- Secure communication
- Google for machines
- Open-source geometry kernel
- Generative daily reports to management
- Convert old physical drawing to 3D model
- Machine ERP/Internet integration
- Design for security
- Lightweight basic quoting/ERP for SMMs
- Have access to other plants and users

D.2 AI Global Supply Chain Breakout

The AI global supply chain matrix isshown in Figure 5(e). When populated, the creativity matrix had the following contents:

Supply Chain / Software Design

- Redesign inventory MRP AI Analysis
- Collaborative software agents for resilient SC
- Extensibility to other sectors and uses
- Autonomous agent network
- MITRE NC Schneider Boeing LMCO Der Sec Ops
- SBOM SSCA
- Supply chain digital twins
- Open marketplace of autonomous agents

Supply Chain / Data Access

- Data fusion across modes of transport
- Real-time awareness of part availability across supply chain
- Supply chain visibility for RT decision making
- Supply chains are interwoven
- Remove access side channel
- Software supply chain assurance
- Software bill of material
- Interoperability of data/software for SC
- Open marketplace of autonomous agents

Supply Chain / Communication/Security

- Resilient encryption
- User identification on behavior
- Blind trust protocols and security for SC operators – encryption tools
- SBOM x BOM

- RASC Remote Access Side Channel

Supply Chain / Workforce and Education

- Talent pipeline
- Unified training and QC standard throughout supply chain

Supply Chain / / WILD CARD

- Real time part and component tracking using RFID tags and ML

Language Models / Software Design

- Create code from voice commands and interactive communication
- Translation tools for global commerce and supply chains
- Compensating for non-determinism when mistakes are very costly
- Distribute language model inferences

Language Models / Data Access

- LLMs for training modes with limited data points
- Less common language datasets (e.g. Turkish, Welsh, Korean, etc.)
- Automated summaries of all information highly relevant to machining processes or specific problems encountered in processes
- Edge computing with agents

Language Models / Communication/Security

- Real time questions on data changes – your spindle torque is growing – need to respond?
- Language model output tagging IP tracking

Language Models Workforce & Education

- Machine training the operator
- Multimodal conversational deduction and on-the-job monitoring system
- Work instructions and manuals in multiple languages
- LLMs for feedback loop for new trainees to improve processes
- CNC operation without G-code but natural language
- Critical thinking – true/false detection

Language Models / WILD CARD

- LLM for new product feasibility study.
- Standardized testing relevant to industry

Circular Economy / Software Design

- Inclusion and alternative material types in design packages
- Design of bi-directional supply chains for circular supply chains
- Supply chain decision tools for recycle/manufacturing reuse

Circular Economy / Data Access

- Include "by products" or "waste" in inventory system
- Recycled material physical properties
- Cross industry sector data
- Shared data access for circular economy

Circular Economy / Communication/Security

- Avoid use of circularity data for other purposes
- Trust in data or greenwashing will occur

Circular Economy / Workforce & Education

- Sense of purpose to motivate next generation
- Training on material and energy use and regarding K-12, processes and recycling

Circular Economy/ WILD CARD

- CAD Tool circular economy evaluator
- Supply chain incentives for traceability
- Built-in validation and verification
- Circular economy product accreditation / Mark

(Efficient) Machine Learning / Software Design

- Efficiency of ML algorithm for Large SC problems
- Federated learning
- Optimized ML algorithms that can be trained with limited computational resources and easy to display
- Include ability to easily assess where it failed
- Adaptive machining based on real-time measurements, informed modeling and simulation

(Efficient) Machine Learning / Data Access

- Data storage for manufacturing processes; experimental, simulated, labeled
- Large scale data clearing house for ML applications
- Edge computing
- Differential privacy

(Efficient) Machine Learning / Communication & Security

- Information sharing for process optimization without revealing secrets
- Florida Institute of National Security

(Efficient) Machine Learning / Workforce & Education

- Training by AR with motion detection
- Education of machinists on most effective ways to use ML for process optimization
- Training how it works, assessment of failure modes/trustworthiness

(Efficient) Machine Learning / WILD CARD

- Adaptive machining focused on in-process automated measurement and inference about per part variation

WILD CARD / Software Design

WILD CARD / Data Access

- Shared data sources for manufacturing Close
- The bad factory physical examples of defects

WILD CARD / Communication & Sectурity

- Design for security
- Extra sensing adaptation of machine/process interface
- Retrofitting legacy equipment
- Robot plug and play ready

WILD CARD / Workforce & Education

WILD CARD / WILD CARD

- Education in an evolving manufacturing era
- Process recognition of requirements for obsolete parts

The AI global supply chain creativity matrix resulted in the affinity clustering as follows:

Data Repository

- The bad factory physical examples of defects
- Data storage for manufacturing processes; experimental, simulated, labeled
- Large scale data clearing house for ML applications
- Shared data sources for manufacturing data
- Shared data access for circular economy
- Large scale data clearing house

Large Language and ML

- Less common language datasets (e.g. Turkish, etc.)
- LLMs for training models with limited data points
- Translation tools for global commerce and supply chains
- Compensating for non-determinism when mistakes are very costly
- Create code from voice commands
- LLMs for feedback loop for new trainees to improce processes
- Real time questions on data changes. Your spindle torque is growing – need to respond?
- Efficiency of ML algorithm for Large supply chain problems
- Machine training the operator
- Interactive chat for manufacturing processes.
- Standardized LLM testing relevant to industry
- LLMs for new product feasibility study.

Training (Accelerated Training and Curriculum / Workfore & Machine Learning)

- Training by AR with motion detection
- Education of machinists on most effective ways to use ML for process optimization
- Training how it works, assessment of failure modes/trustworthiness
- Multimodal conversational education and on-the-job monitoring system
- Visual/VR learning
- Sense of purpose – motivates next generation
- NSPE/NICET AI ethics systems software integration
- AI ethics good and bad AI uses
- Student support models (economics – who pays?)
- Work instruction and manuals translation
- Critical thinking true/false detection

Supply Chain (Data Visibility and Integration)

- Automated summaries of all information highly relevant to machining processes or specific problems encountered in processes
- Data fusion across modes of transport
- Software bill of material
- Collaborative software agents for resilient SC
- Mitre NG Schneider Boeing LMCO Der Sec OPS
- Redesign inventory MRP AI/Analyses
- Software supply chain assurance
- Extensibility to other sectors and uses
- SBOM (Software bill of material) SSCA (software supply chain assurance)
- Supply chain digital twin
- Supply chain visibility for RT decision making
- Real-time parts component tracking using RFID tags and ML
- Interoperability of data/software for SC
- Supply chain incentives for traceability
- Supply chain decision tools for recycle, re-manufacture, reuse
- Design of bi-directional supply chains for circular supply chain

- Supply chains are interwoven. So is the data

Process Optimization

- Adaptive machining based on in-process automated measurement and inference about per part variation
- Information sharing
- Optimized ML Algorithms that can be trained with limited computational resources and easy to deploy.
- Include the ability to easily assess where it failed
- Avoid use of circularity data for other purposes
- Adaptive machining based on real-time measurement-informed modeling and simulation
- CNC operation without G-code but natural language

Taxonomy (Standardization in Recycled Materials Taxonomy for Better Reutilization)

- Include by products or waste in inventory streams
- Cross industry sector data
- Recycled material physical properties
- Built-in validation and verification
- Circular economy product accreditation/mark
- Inclusion of alternative material types in design packages
- Training on material and energy use and recycling in manufacturing
- CAD Tool circular economy evaluator

Security

- RASC Remote access side channel
- AI resilient encryption
- Differential privacy
- Florida institute of national security
- Blind trust protocols security for supply chain partners – encryption tools
- User identification on behavior
- Cleared talent pipleline
- Language model output tagging IP tracking

Autonomous Systems (Self-organizing and Autonomous Systems)

- Distribute language model inference
- Open marketplace of autonomous agents
- Autonomous agent network
- Edge computing
- Edge computing with agents
- Federated learning

D.3 Difficulty/Importance Charts

The difficulty/importance chart for AI deep dive is given in Fig. D.1, while that for AI for supply chains is given in Fig. D.2.

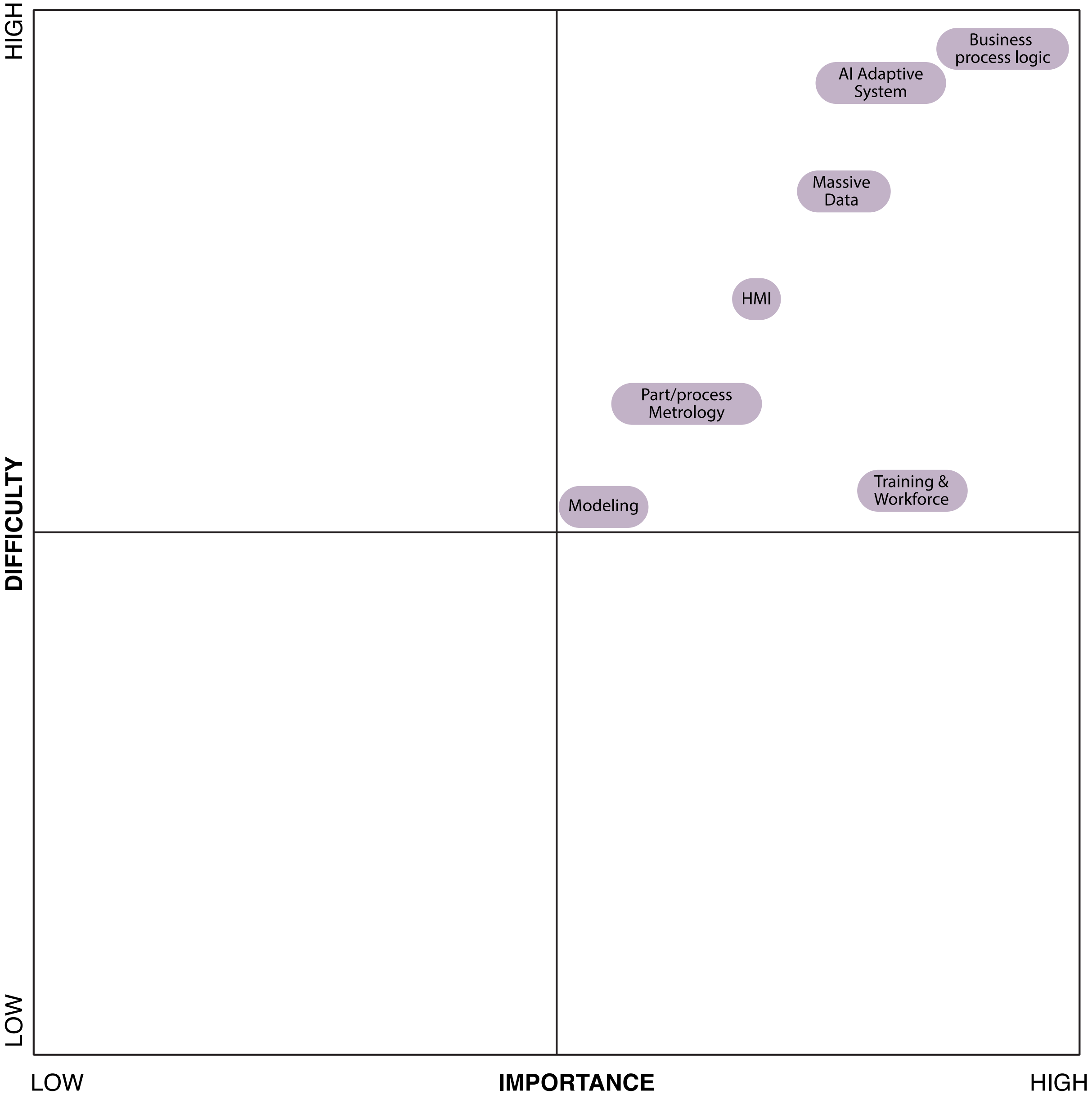


Figure D.1: Importance-Difficulty results from the 2023 roadmapping event, focused on a deep dive for AI in machining

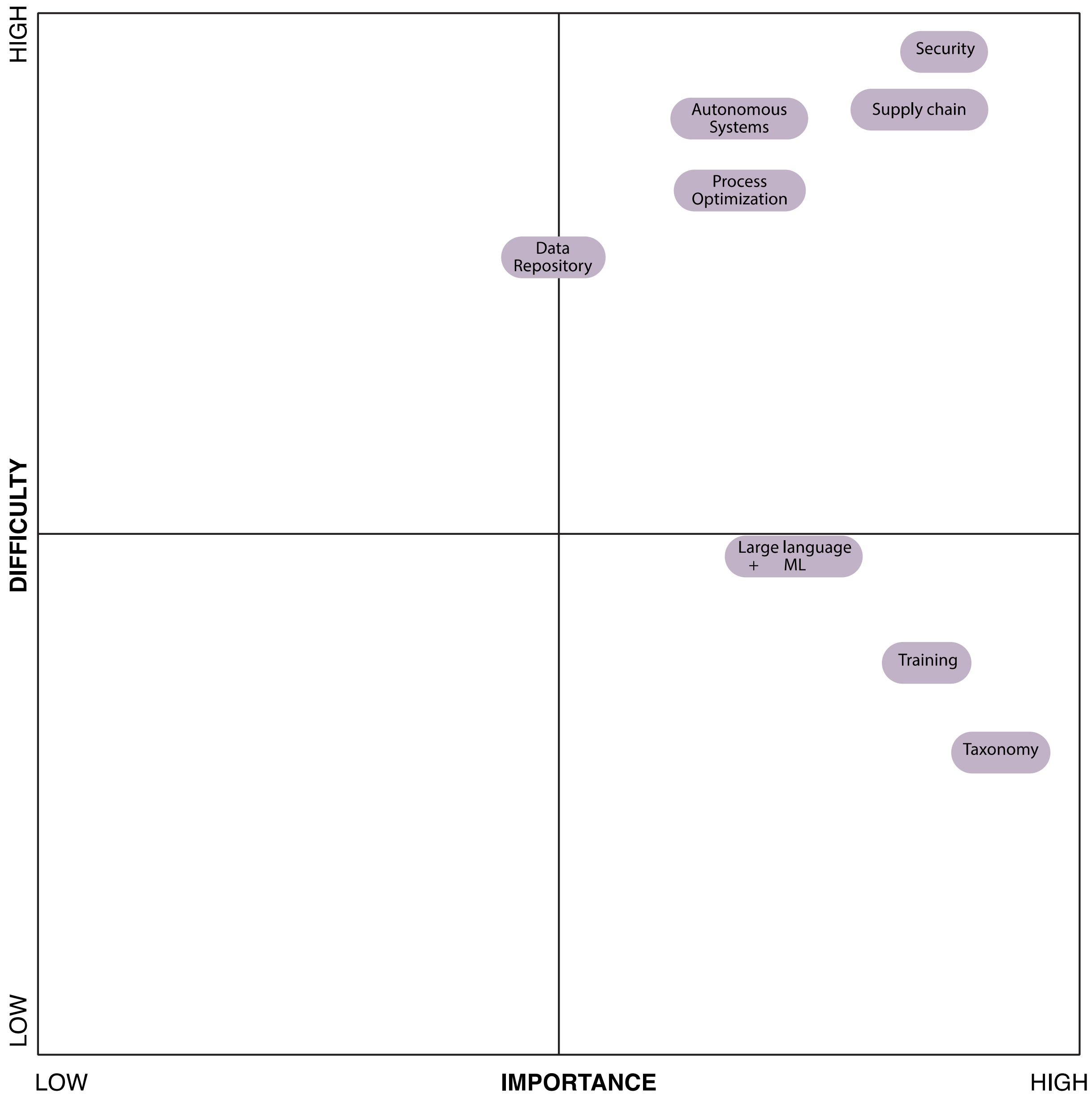


Figure D.2: Difficulty/importance results from the 2023 roadmapping event, focused on an AI deep dive for supply chains.