



The Digital Manufacturing Institute

MxD Final Report Project 17-01-01

Digitally Enabling the Supply Chain: Integrating Existing Tools and Capabilities to Guide Application	
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I. EXECUTIVE SUMMARY

At the outset of this project the concept for the final deliverable was a set of document style playbooks for Original Equipment Manufacturers (OEMs) and Small and Medium Manufacturers (SMMs) to use in developing understanding of the need for becoming digitally enabled to participate in the supply chains of today and into the future and provide guidance on what and how to get started. The intent of the document-based deliverable was to provide MxD- the Digital Manufacturing Institute (formerly the Digital Manufacturing and Design Innovation Institute (DMDII)) with a resource that could be widely distributed to industry. After award, and delving into the research, the research team came to the realization that the deliverable in document form would have a limited shelf life and may not produce the desired outcome envisioned for the project.

The research team discussed the options available to make the deliverable more robust and extend the value-added life of the playbooks. To this end the team determined that it was possible to make the playbooks “wiki-like” so the digital manufacturing and supply chain community could continue to contribute and update the playbooks, adding value and increasing the shelf life of the project outcomes. It was later determined that the ‘Community Contribution’ or ‘wiki-like’ capability was too much of a reach for this project. Additionally, the team determined that the deliverables should be web based and interactive, allowing users of the playbooks to make inquiries of the topics and make their way through the resource to find the particular capability in which they are interested.

Other insights found in the execution of the research portion of this project have indicated that what the digital manufacturing and supply chain community believed to be the current state of industry may not be accurate. At the outset the team held the belief that perhaps up to 50% of industry was in a position to further increase their existing digital capability to a connected and integrated level. Interviews with tiered supply chain partners indicated that industry is not as far along the digital capability maturation scale as the team originally thought. This discovery caused the team to pause and think about whether this effort was a “how to” playbook effort or did it have more of an education and awareness purpose?

Further literature review supported the conclusion that industry is not as ready for implementing digital capabilities as the team had originally anticipated. The research team decided to modify the approach from writing playbooks to developing a digital manufacturing guide to overcome the lack of awareness of what digital manufacturing is and the components and technologies that are associated with it. The guide that has been created is a resource for manufacturers to learn about what digital manufacturing is, why it is valuable and necessary, and how to do it with examples from other successful digital transformations.

ORIGINAL PROBLEM STATEMENT

The longer a product is in the act of manufacture, and the more it is moved around, the greater is its ultimate cost. That was true in the 1920s and is still true today. Anything that hinders the flow of product through a manufacturing system slows product down and increases the ultimate cost. The flow of information through the product realization system is just as important and can be just as costly as the physical impedances of product. If the right information is not in the right place at the right time in the right format to allow for the best decision to be made, the cost of the product will increase due to delays in the information system. Reduction in lead time (from customer order

to customer receipt) has long been a goal of manufacturers, and great strides have been made through the application of continuous process improvement and a culture of innovation. But, interoperability between systems in the design/manufacture/deliver/sustain product realization process is a significant source of delay and increased costs. Information flow in the supply chain is an additional level of complexity placed upon the product realization system.

There continues to be a significant amount of manual intervention in the supply chain to adapt to a 3-D model and associated production information Model-Based Enterprise (MBE) environment (Fischer, 2016). Companies have provided anecdotal evidence of the benefits of MBE and connecting the major nodes within the digital thread (Hedberg, 2016). Some areas in which there has been evidence of improvement in the product realization include:

- The elimination or reduction in the need to re-create downstream models,
- Reduction in cycle time and costs,
- Reduction in the risks of introducing downstream errors,
- Increases in part yield,
- Production of parts that meet customer requirements and expectations [1].

With some understanding of the benefits available through MBE and a digitally enabled supply chain, industry has attempted to embrace MBE on an ad-hoc basis which has generated some islands of excellence amid a sea of unclaimed opportunity. But there are significant issues with accomplishing the implementation of the complete digital thread. Interoperability is an irritation that constantly hinders the effort to clearly and quickly exchange technical data between supply chain partners. Efforts have been made to navigate through this interoperability by the development of standards such as STEP AP242, STEP AP203, STEP AP214, Mil-Std-31000A, JT, and QIF that may affect how data is created, transferred and consumed by entities within the supply chain, but these efforts have not been completely realized by the software and service providers in the MBE community. The research team has found no comparable effort to address the implementation of MBE and the digitally enabled supply chain from the full product lifecycle and enterprise perspective. Various OEMs have implemented unique solutions with various degrees of success. But, no one has addressed all of industry, nor the full supply chain from both the OEM and SMM perspectives.

Communications inefficiencies in engineering-centric manufacturing supply chains increase costs and time while stymying innovation. While this has been documented in numerous studies, an important finding from National Institute of Standards and Technology (NIST) research indicated that these challenges contribute to a \$5 billion per year cost to the U.S. automotive supply chain (Brunnermeier & Martin, 1999).

Reduction in lead time and error rate have long been goals of manufacturers. Information flows necessary in the supply chain adds an additional level of complexity on the product realization system. Many of the collaborative exchanges around technical data are executed via unstructured communications, such as email, phone calls, and fax. This unstructured data does not easily allow for capture, analysis and re-use. A comprehensive guide or playbook does not exist for an organization to utilize during the adoption and employment of digital manufacturing and design capabilities, provide insight into how to utilize these tools and capabilities in the global supply chain, nor how to assure the integrity and protection of information.

To date there has not been a comprehensive effort to pull together and integrate the previous work performed by Department of Defense (DoD), Manufacturing Technology Program (ManTech), NIST, MxD and industry that produced information for providing a step by step approach to developing digital capability for supply chain engagement. Also, there has never been a true implementation guide created and shared with all of industry, especially one that targets the SMMs. This project attempted to pull together the previous work performed and create a picture of the digital thread designed to accelerate the depth and breadth of adoption.

ORIGINAL SOLUTION APPROACH

The goal of this project was to deliver a comprehensive roadmap and playbook for OEMs and SMMs to the best practices and technologies available for adoption to become a digitally enabled, value adding member of the industrial supply chain. This project attempted to utilize existing best practices and technologies, such as research projects and work performed by DoD, ManTech, NIST, MxD and industry, to develop a roadmap that identifies the next gaps and obstacles to overcome in this digital journey. The development of a guide to the adoption and application of digital and model based capabilities in OEMs and SMMs will substantially improve supply chain compatibility, interoperability and competitiveness of U.S. manufacturers.

By leveraging existing work, the research team built upon proven technology solutions, enhancing and multiplying the benefits already identified, and achieving benefits that come only from the multiplicative effect of building on a solid foundation. By reducing the amount of manual intervention in the development, use and exchange of models and production information, an organization will realize positive impacts upon performance through the elimination of the time required for human input and the potential for errors leading to rework. The elimination of unnecessary rework and churn is brought about through improved communications. The implementation of digital capability in the supply chain allows for the strategic use of efficient real-time feedback loops instead of the open-ended communications involving status reporting, which is common today.

Semantic representation of Product-and-Manufacturing Information (PMI) can be utilized to enable effective and efficient identification and recovery of appropriate information to the operation needing access and eliminate searching for the correct data. The MBD will be communicated to the supplier like drawings and 3D geometry is today, but the MBD will contain all required information embedded in the MBD itself and not in separate files that can be lost, misplaced or corrupted. With the information embedded in the MBD, digital maps can be used to find opportunities for data reuse and the processes required to use the data.

The research portion of this project was partitioned into several major components. Initially the direction of the team for the Research function was to perform a literary review then supplement that work with interviews with suppliers to either validate or contradict the literary review. Additionally, the team would review previously performed projects to identify where work has been done in identified gaps and technologies matured to help usher in the digital thread, and the industry partners were asked to provide input on the supplier relationship arrangements they have for the exchange of technical data.

Supply chain processes and activities were identified and researched. Industry partners were asked to provide supplier contacts for the interview team and to identify suppliers that the industry partners would interview. The interview team developed a set of questions for suppliers to be

used by the interview team and a second, very similar, set of questions to be used by the industry partners.

All industries and companies and individuals that desire to engage in the supply chain of the future were targets for the deliverables of this project and the return on investment opportunity is significant. The OEMs, SMMs, and organizations wishing to adopt digital supply chain capabilities and establish a model based enterprise have access to the framework and guidance in the playbooks through several venues.

TEAM MAKEUP

The research team is made up of a diverse set of experts in the fields of digital enterprise and supply chain. Table 1 shows the partners and their category of contribution.

Table 1. Project Partners

Partner	Category
Auburn University - Lead	Academic and Research
Rockwell Collins	Industry
Rolls-Royce	Industry
Raytheon	Industry
International TechneGroup Incorporated (ITI)	Software and Data Translation
The Lucrum Group	Supply Chain Research and Consulting
MBD360, LLC	Model Based Enterprise Consulting
National Institute of Standards and Technology (NIST)	Government Research

Unique Team Qualifications

The team is led by Auburn University with capabilities in Advanced Manufacturing, Digital Manufacturing and Systems Engineering. Dr. Gregory Harris is the Project Lead and has a long history of working in the Supply Chain, Digital Manufacturing and Design, and manufacturing operations space. Dr. Harris has more than 30 years of experience in the design, development and management of manufacturing and enterprise operations. He also was the co-author of the original white paper and Program Manager for the establishment of the Digital Manufacturing and Design Innovation Institute. His doctoral research was performed on the alignment of supply chain strategy with product characteristics. Since coming to Auburn University, he has established a research stream in the application of digitally enabled operations in supply chain and manufacturing operations researching the application of Lean Manufacturing principles to information flows and creating methods to appropriately generate a return on investment on digital initiatives.

David A. Umphress, Ph.D., is COLSA Professor of Cyber Security and Information Assurance in Auburn University's Department of Computer Science and Software Engineering. He is also Director of the Auburn Cyber Research Center. He has worked over the past 35 years in software and system engineering capacities in military, industry, and academia settings. His areas of expertise include general software engineering, systems engineering, secure software development, software vulnerability analysis, malware reverse engineering, and intrusion analysis. Dr. Umphress is a retired Air Force officer. He holds the Institute of Electrical and Electronics Engineers (IEEE) Software Engineering Master Certification.

Kevin Fischer was the Principle Engineering Manager in the Advanced Manufacturing Technology organization at Rockwell Collins (now Collins Aerospace). Mr. Fischer has over 30 years of experience in engineering design and manufacturing leadership. This includes mechanical design and manufacture of electronics equipment; leading engineering design services and tool support organizations; and leading advanced manufacturing technology pursuits and integration. During that time, he has provided strategic vision and leadership to teams that support multiple domains of engineering computer-based tools and product lifecycle management (PLM) systems, as well as for model-based manufacturing (MBm) and computer integrated manufacturing (CIM) solutions. Mr. Fischer has been involved in cross-industry standards-based data interoperability development and application, including PDES, Inc., CAX-IF, LOTAR, and the Purdue PLM Center. He served for many years as the National Defense Industrial Association (NDIA) Manufacturing Division Technology committee chairman. Mr. Fischer's education includes a Bachelor of Science Degree in Mechanical Engineering and a Master's Degree in Business Administration. During the course of this research Mr. Fischer retired from Collins Aerospace.

Gregory Pollari is a Systems & Process Engineer at Collins Aerospace. He has worked in product design and development and in manufacturing for over 30 years. Mr. Pollari is a co-lead for the MBSE (Model-Based Systems Engineering) track at the Global Product Data Interoperability Summit, has contributed to the Aerospace Vehicle Systems Institute (AVSI) Systems Architecture Virtual Integration (SAVI) project, and has led the PDES team working on MBSE standards. He is supporting the INCOSE (International Council on Systems Engineering) challenge team that is developing the DELS (Discrete Event Logistics Systems) interoperability data model. In support of the "digital thread," Mr. Pollari has also contributed to NDIA reports on Model Based Engineering and Identification of Modeling and Simulation Capabilities by Acquisition Life Cycle Phase. In these roles he has advocated for data exchange research and solutions that drive efficiencies across an enterprise and up and down the supply chain.

Ethel Salter is a certified Raytheon Six Sigma™ Expert and a member of the Raytheon Space and Airborne Systems business unit. Ethel Salter has an international business experience and has more than 20 years of experience working with cross-functional organizations and their business leaders in leading and driving continuous improvements that have resulted in cost avoidance, cost saving, cycle time improvements and risk mitigations. Ethel also leads and supports Supplier Engagement efforts to achieve improved Supplier performance. In addition, Ethel Salter provides coaching, mentoring, and training to employees while providing on-demand subject matter expertise.

From Rolls-Royce, Dan Hartman provided the team with Digital Manufacturing expertise and the OEM perspective in Supply Chain. Dan has over 30 years of experience in developing and implementing Computer Automated and Digital Manufacturing systems across wide range of Aerospace and Defense businesses. He was the Digital Manufacturing Manager for Rolls-Royce North America and Rolls-Royce's Program Lead in the Digital Manufacturing and Design Innovation Institute (DMDII). Dan was Rolls-Royce's manufacturing representative on the UI LABS DMDII Proposal Team. After award, Rolls-Royce loaned Dan to UI LABS as their Director of Manufacturing R&D to assist in the launch of the Institute and build out the facility in Chicago. Dan accepted the position of Director of Global Digital Manufacturing Initiatives at Oshkosh, Inc. toward the end of the project period of performance.

ITI is an industry leader in data translation and validation software. Rendell Hughes is part of ITI's advanced manufacturing solutions team. Mr. Hughes has expertise in CAD/CAM/CAE tool integration development and deployment; management of DoD and Government funded projects; and development and deployment of engineering software for improving design and manufacturing processes. Mr. Hughes' industry experience includes 14 years at Lockheed Aerospace, where his responsibilities included engineering liaison to manufacturing; structural design, composites development center engineering interface, materials and process management. Mr. Hughes experience includes engineering and manufacturing for F-111, F-16, P-3, F-22, F-35 and support on programs including C-5, C-141 and C-130. Mr. Hughes has supported Lockheed in efforts to streamline interaction with suppliers, co-producers and between Lockheed business units. Experience at ITI includes, commercial product development for 3D model based enterprise based on CAD system interfaces, product development consulting, process automation, and model healing and repair.

MBD360 is a consulting company with experience in assessing, developing and implementing digital enterprises. Roy Whittenburg of MBD360 LLC provides the team with Model-Based Enterprise and Standards expertise. Roy has worked with both the DoD and Industry over the last decade to develop many of the foundational principles of MBE. One example of this is the MBE Capability Index which he acted as project lead during its development. He was also awarded 2012 Defense Manufacturing Technology Achievement Award for his work on the 3D Technical Data Package & Certification of 3D Models as the Product Master Program Team. Finally, he currently chairs the ASME Y14.47 Model Organization standard and founding member of the new ASME MBE Standards Steering Committee.

The Lucrum Group is a well-known supply chain company with many years of experience in advanced concepts. Christopher Peters, CEO, has an extensive background in driving the innovation and adoption of manufacturing supply chain solutions. He was co-founder of the world's first industry-backed manufacturing supply chain hub, backed by five of the country's largest metals producers. He went on to create similar hubs in 20 industries throughout North America, Europe and Asia. These hubs fundamentally changed the way that supply chain partners interact, and Mr. Peters' work in this area has been documented in several books and in publications ranging from The Wall Street Journal to BusinessWeek and IndustryWeek. Today Mr. Peters is a contributor on smart manufacturing to NIST and his clients include the DoD, Fortune 500 manufacturers and start-ups. His work ranges from developing supply chain solutions and defense industrial base insights to cybersecurity for manufacturing.

The National Institute of Standards and Technology contributes their expertise and facilities for both research and demonstration. Dr. Thomas Hedberg, Jr. is a member of the Systems Engineering group in the Systems Integration Division (SID) of the Engineering Laboratory (EL) at NIST. At NIST, Dr. Hedberg is the Project Leader of the Digital Thread for Smart Manufacturing project in the Smart Manufacturing Operations Planning and Control program and the Co-Leader of the Smart Manufacturing Systems Test Bed. Dr. Hedberg is also a Voting Member of the American Society of Mechanical Engineers (ASME) Y14.37, Y14.41, and Y14.41.1 subcommittees from the ASME Y14 suite of standards and Co-Chair and Americas Lead for the Visualization Working Group for LOTAR International. Prior to joining NIST, Dr. Hedberg was a Senior Mechanical Engineer and Technical Lead in the Model-Based Enterprise (MBE) group for the Product-Lifecycle-Management department in Honeywell's Engineering-Operations office. In

this role, Dr. Hedberg was instrumental in developing a strategy and implementation for Model-Based Enterprise at Honeywell.

II. PROJECT DELIVERABLES

The following list includes all deliverables created through this project. These deliverables will be referenced throughout this final report and can be accessed on the membership portal in accordance with the rights defined in the Membership Agreement.

#	Deliverable Name	Description	Deliverable Type
1	Desktop Website code	Code for hosting the website	Software
2	Mobile Website code	Code for hosting the website	Software
3	Research Report	Documentation on the research activities	pdf
4	Final Report	Documentation on the project	.doc
5	Gap Analysis	Analysis of issues and gaps	.doc
6	Training Materials	Documentation of training	.doc

III. PROJECT REVIEW

In the original proposal there was not a deliverable item called “Research Report.” The desire to provide this deliverable developed out of the findings in the research portion of the project. In the following sections the team provides insights that indicated the need to modify the final product slightly to achieve the maximum desired outcome from the project.

INITIAL DATA COLLECTION APPROACH

The research team approached the research review from several directions. The major components of the research effort were:

- Input from industry on supplier-customer data interactions
- Interviews of suppliers with contacts made by industry partners
- Interviews made by the industry partners themselves
- Academic literature review
- Investigation of applicable and developing standards

The rest of this report will provide details and insight into the content and revelations made in each of these areas of research.

Industry Input

Industry partners were asked to provide input detailing the transactional data exchanges currently used in their supply chains. A format for this data was not provided as it was agreed upon by the group that this would imply an oversimplification of the process that would hinder data collection. Each of the partner's responses were aggregated and analyzed by the research team and processes were extracted into the Process Categorization Document.

Interviews

The interview portion of this project was focused on: 1) Interactions; 2) Inefficiencies; and 3) Motivators and barriers. These helped the research team develop an approach and message designed to accelerate adoption. Interviews were conducted using an interview guide developed by Chris Peters of The Lucrum Group so that the execution of all interviews was consistent, and the data could be easily aggregated and analyzed. The Interview Guide is in Appendix A and the Interview Question Script is in Appendix B of this report.

Methodology

The industry members on the project team provided a list of potential suppliers for the team to interview in the hope that this would provide insight into current state digital capability of the traditional supply chains functioning in industry today. It took significantly more time to make contact and then arrange time for a meeting with the suppliers than anticipated. This created delays in the project schedule that resulted in the need to request no-cost extensions to the project until November 22, 2019. Initially the interviews were to be made in person, but due to the extended time it took to get the suppliers scheduled, the team made the determination to use some telephone interviews instead. Even with this change it still took longer to get the interviews executed than the project team thought it should.

Identify objectives

This primary research provided qualitative evidence to inform development of the playbook (guide) content and structure. Recognizing that the ability to communicate and collaborate are fundamental to digital manufacturing, there were three primary objectives.

- Interactions - Determine what information is exchanged between customers and suppliers and how it is exchanged.
- Inefficiencies - Understand any impact from communications inefficiencies.
- Motivators and barriers - Identify potential motivations and barriers to the adoption of digital manufacturing for both customers and suppliers and the individual roles within.

Identify target audience

The target audience was Small and Medium-sized Manufacturers (SMMs) that manufacture both electronic and mechanical goods for large companies, original equipment manufacturers (OEMs), prime contractors and the DoD. These SMMs are the companies that typically lag in adoption of digital manufacturing but make up approximately 85% of today's supply chains.

Targeted individuals for these interviews were in positions where they personally exchange data with trading partners and/or must use data that is exchanged. For this exercise, we were most interested in subjects who exchange and use data related to the

design and manufacture of goods. The individuals were either an engineer, an operator, or even a small-business owner. In some cases, individuals in accounting or sales may also be responsible for exchanging engineering or manufacturing-related data. This is often true in small and medium businesses.

Approach

Three different groups of interviews were conducted in different settings with different subjects. A discussion guide (See Appendix A) was developed to be used with each to provide consistency, enabling the findings from all three interview groups to be aggregated. Thirteen total interviews were conducted as of the date of this report.

- **MxD Workshop Interviews**
Two interviews were conducted with MxD supply chain workshop participants on June 19th, 2018. Although the subjects did not meet the target criteria, they were able to provide some insights.
- **OEM Interviews**
The project team OEMs conducted four face-to-face interviews of suppliers that were representative of their supply chains.
- **Dedicated Team Interviews**
Project team OEMs suggested 26 suppliers to be interviewed by The Lucrum Group and Auburn University. That list was pared down to nine suppliers based on selection criteria that included company size, type of goods manufactured and location. Of those nine suppliers, four were cooperative in being interviewed – two in person and two by phone. Most of the remaining OEM-suggested targets were unresponsive to interview requests. One declined to participate. Several small manufacturers known to the interview team were included to supplement the data. Additionally, several interviews were conducted with large companies to get supplier insights from the customer perspective.

Due to delays caused by obtaining permissions, vacations, communications challenges and more, arranging the interviews proved difficult and scheduling took longer than anticipated. The final interview took place on June 6, 2019.

An important note is that all companies interviewed primarily have a low-volume, high mix of products produced. These companies are typical of aerospace and defense supply chains. No interviews were conducted with companies that are primarily focused on high-volume, steady-state production.

KEY FINDINGS

The subjects represent a good cross-section of size and type of goods manufactured, both mechanical and electronics. Only one company is highly reliant on DoD business, while the majority sell more commercial than defense products. Several interviewees did not know their mix of DoD vs. commercial revenue since they supply to OEMs that do not reveal where the product will be used.

Companies spanned the country and ranged in size from 28 employees to 400, with half of those interviewed having fewer than 50 employees and the other half had between 50 and 400 employees. Industries served include aerospace, defense, medical, automotive, semi-conductor and robotics.

The role of those interviewed was most often the owner or a senior executive, with program managers and engineers being the second largest group. These subjects had typically been in the industry for decades and in their role for more than five years. Findings from these interviews were relatively consistent. Following are four of the most important findings.

Little understanding of what is “Digital Manufacturing”

When asked for their definition of digital manufacturing, most respondents said that it means going paperless. They view it primarily as a means to move data between operators and equipment without manual entry or intervention. None of those interviewed mentioned integration, modeling, collaboration, analytics or similar terms associated with digital manufacturing.

One subject explained that most of their operators do not have computers. The organization still generates a significant amount of paper, such as quality inspection reports, corrective actions and first article reviews. They do not see an easy path to moving toward a paperless environment.

A few subjects did say that it was something that could positively impact the entire manufacturing process. One interviewee recalled an instance where they had to ramp up from 30 items per month to 30 per day in response to a surge in demand from DoD. They said that they learned then that you must go from “heroics” to “systems” to be able to scale quickly and that digital manufacturing provides that kind of system.

While interviewing a large manufacturer about their SMM suppliers, the large company expressed concerns about the ability of SMEs to adopt digital manufacturing. “Smaller suppliers are *focused on the work at hand rather than thinking strategically about the future*” (emphasis added). The subject said that even when they do look to the future, the SMM must set aside time and money to make those advances, which can often be challenging.

Despite those concerns, this large manufacturer had several good anecdotes of when they had brought in suppliers to educate them about the advantages of digital manufacturing. In one example, a subject matter expert from the large company was able to help the small supplier learn how to use Product and Manufacturing Information (PMI). The result was that the supplier then began producing more valuable 3D models than the 2D drawings they used to provide. The same large company also employed a third party to help their suppliers develop digital capabilities.

The findings in these interviews are echoed in a recent report on the adoption of digital manufacturing by the Information Technology & Innovation Foundation (ITIF) (Ezell, et al., 2018). In addition to pointing out the lack of quantitative data on the status of digital manufacturing adoption, they found that most U.S. companies are still in the initial phases.

Significant challenges in technical data exchange

There continue to be significant issues in the use and exchange of technical data and specifications. STEP files were the most common format for exchanging data, although there were instances of suppliers receiving files in PDF or native CAD. There were even a few reports of receiving paper drawings. Most interviewees are doing some translation from one format to another, largely through software although a few are done manually. Some suppliers validate these translations on their own, one requires that the OEM validate the translation and others do not validate at all. Several interviewees reported having to create an entirely new model from scratch, one of them as much as 50% of the time.

Many companies still receive a mix of both drawings and models from customers. When a customer sends both, suppliers often find inconsistencies in data between the two. (This seems to be particularly true when the DoD is the customer.) In some cases, the customer has said that the drawing is the official version and the model only for visualization. That situation often results in the supplier creating an entirely new 3D model for quoting and to generate machine code.

Suppliers also find wide variations in the completeness and accuracy of data provided. Not only is there disparity between customers, but between different engineers at the same customer as well. One subject commented that they used to see multiple signatures of reviewers on a drawing and now they typically see one signature. They view this as an indication that there are fewer checks, which could cause some of the issues they are encountering.

Most interviewees reported that they often must go back to the customer for additional data or clarification. Usually the need for additional information is discovered in the quoting process, although it also happens after the work has begun. One example provided was a part that shows engraving on the model and the print calls out engraving, but neither has data about line width, depth and so on.

This need for clarification exposed another impediment, and that is the lack of a direct connection between customer and supplier engineers. Most of the interviewees said that they must forward questions to the customer's buyer or purchasing agent, who then forwards it to the engineer. The customer's engineer reviews the question and sends their answer back through the buyer to be forwarded to the supplier. This process can often take weeks, which places an additional burden on the supplier to meet their deadline.

In addition to issues about the actual data, there are significant inefficiencies in transmitting that data. Many of the subjects, particularly those associated with an OEM, use their customer's portals to exchange data and manage version control. The primary challenge with this approach is the cost and effort SMMs must bear to learn and work with a different portal for each of their customers. One benefit of portals is that a few OEMs include both buyers and engineers in all supplier communications, removing the buyer bottleneck.

The greater challenge in exchanging technical data is that nearly all suppliers use email extensively as their primary means of communications. This leads to various issues ranging from delays to incorrect versions and loss of data continuity. That problem is exacerbated when those emails are sent to a large group of individuals or multiple companies in a supply chain.

Two of the most often cited results from all technical data issues are additional costs and customer rejects. In both cases, subjects said that they typically had to bear those costs regardless of where the problem originated.

Very little design collaboration

Subjects reported limited up-front design collaboration. Suppliers that interact through a customer portal seem to be the most likely to collaborate on design, although the focus is typically manufacturability issues.

Manufacturers that do not interact through a portal report less design collaboration. When these suppliers do collaborate, it is typically by email, although fax was cited as a communications method for collaborating by nearly half of the subjects. One supplier said that they must communicate with their customer several times weekly to address manufacturability issues that could be resolved by up-front coordination.

Two of the interviewees reported that the ability to collaborate on design is a selling point. One subject does extensive collaboration with customers on design, especially manufacturability, before the customer asks for a quote. The supplier considers this level of collaboration to be a sign of trust and a considerable competitive advantage. In cases where there is not up-front collaboration, this supplier will often return a quote with a price for the work as specified and then optional pricing if certain manufacturability challenges are removed.

Limited exchange of production data

Only a few interviewees reported providing any production data to the customer. The primary means was by email and tended to be in response to questions about order status or inventory. Several suppliers interacting through a customer portal said that they also provide data for items like material certification and inspections.

Most of the companies interviewed are not leveraging the Internet of Things (IoT) in their production facilities. The two suppliers that said they are somewhat advanced in their use of IoT are sharing production data with customers primarily through email.

ANALYSIS

The following is an analysis and presentation of the findings from the interview process.

The state of digital manufacturing adoption

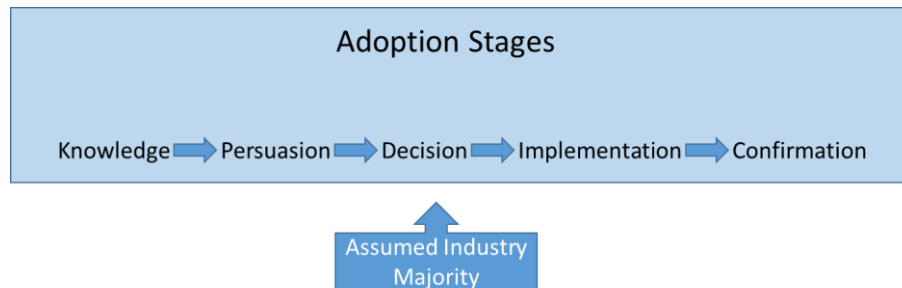


Figure 1. Technology Adoption Stages- Assumed Industry Maturity.

According to Dr. Everett Rogers, author of “Diffusion of Innovations,” the five stages of adoption are knowledge, persuasion, decision, implementation and confirmation shown in Figure 1 (Rogers, 2003). The findings from both primary and secondary research indicate that most SMMs are still at the beginning of the knowledge stage in the adoption of digital manufacturing. This is an important consideration as many existing initiatives seem to be focused on the decision and implementation stages.

The fact that many of the interviewees defined digital manufacturing using the word paperless but not with other relevant terms like integration, modeling or analytics, is a key factor in concluding that SMMs are at the early stage of knowledge. The team identified several potential causes of a limited understanding of the term.

- **Few resources that define digital manufacturing** - This is likely not the cause as conducting a Google search for “digital manufacturing definition” yields 226,000 responses and Google Scholar shows 16,900 scholarly works. Definitions are provided by Wikipedia, trade associations, trade journals, solution vendors, academia and others. (No definition was found on the MxD website.)
- **Limited exposure to materials that define digital manufacturing** - While no statistics were found to indicate exposure to or comprehension and retention of relevant information, it is reasonable to assume this is not likely a cause as the topic is so prevalent across all industries. However, many SMM management/owners tend to focus intently on the operation of their existing systems, which may not allow time for evaluation and understanding of potentially better, or superior, systems.

- **No perceived need** - According to Dr. Rogers, research does not provide a clear answer as to whether a need or knowledge of innovations to address that need comes first (Rogers, 2003). However, it can be a factor in comprehension and retention when exposed to relevant information. Most of the interview subjects believe that digital manufacturing can help solve some of their current problems and some see it as a competitive advantage. That finding would seem to rule out the lack of a perceived need as a cause.
- **Inconsistent definitions of digital manufacturing** - This issue would seem to be a major contributor to the current level of digital manufacturing knowledge. The most commonly found definition is the first sentence offered by Wikipedia, “Digital manufacturing is an integrated approach to manufacturing that is centered around a computer system.” However, most of the U.S. definitions vary widely after that, taking many tangents that range from “...solutions cover all business functions in Manufacturing, all links in Supply Chain, all layers in Manufacturing Technologies, and various levels of evolution (Anon., 2018).” to “...an emerging technology and a key element of Product Lifecycle Management (PLM) (Christman, 2002).” The problem is exacerbated as the similar term “Direct Digital Manufacturing” is often used to refer to additive manufacturing. By contrast, the definition of Industrie 4.0, which was promulgated by the German government, is more complex and consistent.

Another indicator of the lack of digital manufacturing adoption is that so few of the subjects are using technical data to facilitate collaboration with their customers. When there is any type of collaboration, it typically involves bypassing the original data files and resorting to communicating with screen shots and even fax.

Finally, there is the fact that only a few of those questioned exchange any kind of production data. Those that do most often send a static data file by email. If the thirteen interviewees are representative of most SMMS, then there is still much work to be done on educating U.S. manufacturers on just what digital manufacturing is and how it might help their businesses.

Exchange of technical data

Despite major initiatives like Standard for the Exchange of Product model data (STEP) and Model Based Enterprise (MBE), there continue to be significant challenges to effectively exchanging technical data and specifications. While this issue is more pronounced with the SMMS, many of the problems are originated by larger companies that are part of those efforts.

One of the most important enablers of digital manufacturing is the ability to generate complete and accurate technical data and then to seamlessly exchange that data between supply chain partners. The interview subjects provided many examples of missing and inaccurate information as well as inefficient means of exchanging that data. Those examples are no different than anecdotes heard by members of the research team for more than a decade.

These issues around technical data and specifications are a source of frustration for the subjects interviewed. They lead to additional costs and effort that must be borne by the SMMs. Failure to address these issues could impede the adoption of digital manufacturing.

MOTIVATORS AND BARRIERS

Understanding what will motivate a company or individual to use an innovation and the barriers to that use are crucial for driving adoption. Increasing the motivators and reducing barriers will significantly impact the depth, breadth and pace of adoption. A good plan will address each, with metrics for measuring effectiveness and progress.

Barrier: Lack of understanding

This barrier is likely one of the easiest to overcome. A succinct explanation of what digital manufacturing is and how it can help using would go a long way. One of the keys is that it must be in the vernacular of each target audience. Additionally, there does not exist a single source for this type of information to SMMs. It is important to create an awareness campaign that incorporates numerous information providers to bring a broad understanding and awareness to industry. However, the challenge is made harder as this material must help overcome an existing perception, as defined in the next barrier.

Barrier: Misperception

One of the biggest barriers to driving adoption of digital manufacturing is the misperception about what it is. If the majority of the country's SMMs hold the same view as the interview subjects – that digital manufacturing simply means going paperless – then extra effort is needed to help them realize the greater vision.

Compounding that challenge is that many of the subjects believe they are fully embracing digital manufacturing, which means they may not pay much attention to informative articles or materials on digital manufacturing. That will require that any playbooks or other materials designed to help educate the audience somehow make them aware that the scope and benefits of digital manufacturing may be greater than they understand.

Barrier: Interoperability issues

The research has shown that there are still significant interoperability issues for technical data and specifications. While an individual SMM may have some control over their internal use of such data, interoperability issues remain with their trading partners. The playbooks will need to offer approaches on how to identify, discuss and resolve these challenges with customers and suppliers.

Barrier: Cost/Effort

SMMs are particularly sensitive to the cost and effort to implement new solutions. Overcoming this barrier will require that the playbooks articulate the benefits of digital manufacturing and provide realistic estimates of cost and effort. Where possible, digital

manufacturing solutions should be broken down into smaller and more manageable segments. SMEs are more likely to accept this segmented approach to limit cost and effort while allowing them to learn more about the technologies as they progress.

Barrier: Lack of time

Most senior leaders or owners of SMMs are focused on daily production and often do not have a lot of time for learning and/or strategy development and execution. One element to overcoming this barrier is making the information succinct and pertinent. Another element to consider is the means of delivery, which could range from short case studies to micro learning modules.

Barrier: Lack of Resources

Most SMMs have the misconception that significant funding is necessary to adopt digital manufacturing technologies, and digital transformations are only for large OEMs that have the necessary funding. Many companies also believe they do not have the human resources or knowledge to be capable of adding digital capabilities.

Motivator: Increased sales

Increasing sales is the top objective for nearly every SMM and is therefore a powerful motivator. The playbooks should heavily reinforce how adopting digital manufacturing can help generate more revenue. Some examples include the following.

Competitive advantage

Large buyers are increasingly looking at desirability as a supply chain partner in addition to the typical selection criteria of price, quality and delivery. At the basic level, that desirability means being able to connect systems and exchange data digitally. More advanced levels of desirability involve providing real-time production data and the ability to analyze and quickly act on that data.

Faster and more thorough quoting

Developing quotes consumes valuable time and presents a risk in missing something that will add cost later. The playbook should highlight how digital manufacturing can help reduce the effort to quote and reduce the risk of missing something. One SMM interviewed cited how rapid turn-around of thorough quotes was valued by customers and gave them a competitive advantage.

Motivator: Reduced costs

Nearly all the subjects interviewed said that they often had to absorb the costs of inefficiencies and mistakes that resulted from communications inefficiencies. Providing relevant examples and case studies of how other companies have reduced their costs through digital manufacturing could be a strong motivator. Some examples include the following.

Greater efficiency

Digital manufacturing can generate efficiencies in several ways, ranging from the very basic to more advanced. The lower end could simply be faster and more accurate communications, while the higher end could include improved operations planning due to greater visibility throughout the supply chain.

Reduced rejects

This was an issue that all interviewees cited as a source of frustration. Adopting digital manufacturing can help reduce or eliminate the communications inefficiencies that often lead to customer rejects and rework. This not only reduces costs, it also helps improve customer satisfaction.

Motivator: Improved customer satisfaction

Faster response, greater efficiency and fewer mistakes are all benefits of digital manufacturing. These benefits lead to improved customer satisfaction, which helps companies better retain existing customers. In the case of some interview subjects, these benefits have translated into greater profit margins.

SUPPLY CHAIN WORKSHOP

The team attended the Supply Chain Technology Showcase and Workshop- Exploring Emerging Technologies at MxD in Chicago, Illinois on June 19 and 20, 2018. The reason behind attending this event was to gain a better understanding of current and emerging digital technologies that are applicable to the playbook being created. The time at MxD allowed team members to network with other MxD members, manufacturers, and universities. The time was also utilized to interview OEMs and SMMs. These interviews are summarized in the interviews section of this report. A focus of this event was blockchain: how manufacturers plan to use it in the near future and how it can transform supply chains. An interactive demonstration was shown, and a panel discussion was conducted.

OTHER INDUSTRY INPUTS (INTERVIEWS OF NORTH CAROLINA AND ILLINOIS DEFENSE INDUSTRY SUPPLIERS)

Illinois Defense Industry Adjustment Program Supply Chain Analysis by the University of Illinois System and North Carolina Defense Industry Diversification Initiative Supply Chain Analysis by North Carolina State University Industry Expansion Solutions (IES) were conducted in 2018. Three of the survey questions asked in the data collection process are pertinent to this guide to digital manufacturing project. These supply chain analyses contain insight on business systems and data/information flows currently being used in Illinois and North Carolina manufacturing industries. The companies were significantly different geographically and demographically, spanning multiple manufacturing types. The results of the analyses were very similar to the findings in the interviews by the 17-01-01 project team. This finding led the team to believe that results across the United States are similar and lead to a bigger issue than the team first thought. Note: IL, NC, and Aggregate Data are highlighted in yellow, blue, and green respectively.

Business Systems:

Respondents were asked to indicate the type of business system(s) they use in their organization: Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), Manufacturing Operations Management (MOM), Supplier Relationship Management (SRM), Supply Chain Management (SCM), or Warehouse Management System (WMS). It is important to note that these business systems were not defined for the survey users. According to the survey results, the most commonly used business system is ERP. However, only approximately half of the respondents in both states indicated they use ERP. Of the 57 respondents from Illinois, 56.1% said they use ERP. And of the 21 respondents from North Carolina, 52.4% of respondents said they use ERP. SCM was the second most common business system, and MES was the least common of the six business systems. One of the researchers went back to gather additional insight on the business systems. The researcher found that a number of respondents reporting use of ERP are actually using home-made systems, which include Excel and do not qualify as true ERP systems. Therefore, the percentage of ERP is likely lower than the percentages shown in the chart below.

Type of Business System	ERP	MES	MOM	SRM	SCM	WMS	Number of Respondents
IL	56.1%	8.8%	22.8%	17.5%	38.6%	22.8%	57
NC	52.4%	14.3%	28.6%	23.8%	28.6%	38.1%	21
Aggregate	55.1%	10.3%	24.4%	19.2%	35.9%	26.9%	78

Data Exchange Methods with **SUPPLIERS**:

Respondents were then asked to indicate their methods used to communicate design & specifications, accounting & order entry, and logistics data with **SUPPLIERS**: Fax, Email, Electronic Data Interchange (EDI), Portal, and Other. The percentages of organizations using fax were surprisingly high numbers. The team was also surprised to see the large percentage of organizations that use email. Since email is unstructured data that is typically siloed among users, it often leads to issues ranging from out of sync versions to missed changes. The team's interviews revealed that some companies may use EDI or a portal for some exchanges, but they also use email in addition. For example, a CAD model may originally be shared through a portal, but questions regarding the model may be communicated by email or telephone. Telephone was a form of communication that was mentioned by several companies in the "Other" category.

Illinois:

Data Exchange Method	Fax	Email	EDI	Portal	Number of Respondents
Design/specs	23.5%	91.4%	21.0%	28.4%	81
Order entry/accounting	34.1%	92.9%	32.9%	35.3%	85
Order status logistics	24.1%	93.7%	24.1%	35.4%	79

North Carolina:

Data Exchange Method	Fax	Email	EDI	Portal	Number of Respondents
Design/specs	22.7%	90.9%	18.2%	31.8%	22
Order entry/accounting	36.4%	86.4%	31.8%	13.6%	22
Order status logistics	17.4%	82.6%	21.7%	13.0%	23

Aggregate:

Data Exchange Method	Fax	Email	EDI	Portal	Number of Respondents
Design/specs	23.3%	91.3%	20.4%	29.1%	103
Order entry/accounting	34.6%	91.6%	32.7%	30.8%	107
Order status logistics	22.5%	91.2%	23.5%	30.4%	102

Data Exchange Methods with BUYERS:

The same question about data exchange methods was asked again but for communications with **BUYERS**: Fax, Email, EDI, Portal, and Other. Due to buyers typically being larger companies than suppliers, the level of EDI use was expected to increase in all three categories of data exchange methods, but when viewing the aggregate data, this is not the case. Order entry/accounting was the only category that EDI was higher for buyers than suppliers. It was also eye opening that use of fax with buyers was high and in some cases, higher percentages than with suppliers. With buyers usually being more sophisticated, the team expected to see a greater level of fax with suppliers but not the buyers.

Illinois:

Data Exchange Method	Fax	Email	EDI	Portal	Number of Respondents
Design/specs	29.3%	97.3%	14.7%	29.3%	75
Order entry/accounting	27.7%	94.0%	32.5%	33.7%	83
Order status logistics	23.1%	96.2%	19.2%	32.1%	78

North Carolina:

Data Exchange Method	Fax	Email	EDI	Portal	Number of Respondents
Design/specs	21.7%	95.7%	21.7%	26.1%	23

Order entry/accounting	36.4%	95.5%	40.9%	18.2%	22
Order status logistics	18.2%	95.5%	13.6%	22.7%	22

Aggregate:

Data Exchange Method	Fax	Email	EDI	Portal	Number of Respondents
Design/specs	27.6%	96.9%	16.3%	28.6%	98
Order entry/accounting	29.5%	94.3%	34.3%	30.5%	105
Order status logistics	22.0%	96.0%	18.0%	30.0%	100

Analysis of IL and NC Survey Results: The NC and IL Survey Analysis further demonstrates the lack of readiness of the manufacturing industry to adopt Digital Manufacturing. ERP and MES or MOM are important to the adoption of Digital Manufacturing. However, the percentages of IL and NC manufacturing industries using MES or MOM are rather low, MES: 10.3% MOM: 22.4%. The percentage of manufacturing industries using ERP was slightly over half at 55.1%. However, these percentages are questionable because the IL and NC research team uncovered that some companies' ERP systems do not actually qualify as ERP systems, even though they are called such. Therefore, an accurate percentage of manufacturing industries using ERP systems is more than likely lower than 55.1%.

Email is the predominate form of communication for data exchanges. NC and IL data in aggregate shows that over 90% of manufacturing industries are currently still using email as a form of data exchange for all three methods of data exchange (1. Design/specs, 2. Order entry/accounting, 3. Order status logistics). Email and fax are unstructured forms of communication compared to more structured forms of communication, such as EDI and portals. The team's interviews also revealed that some companies may use EDI or portal for means of communication, but they might use email or telephone in addition to ask questions about the information being exchanged. This shows reluctance to move toward a structured digital manufacturing form of communication. While EDI and portals exist, they are not being used to their full benefit. These percentages, along with other findings, brought the team to a realization that a majority of manufacturers are not as ready to adopt Digital Manufacturing as the team had originally anticipated.

PROCESS AND ACTIVITY CLASSIFICATION

Interviews with industry indicated that there is uncertainty regarding what data transactions take place within a supply chain. To provide data regarding the implementation of digital capabilities within supply chain processes, the team needed a way to organize the data into common supply chain processes. Initially the team believed that attempting to utilize an existing framework would minimize work while increasing adoption. Because of this, the Supply Chain Operations Reference (SCOR) model was selected as the starting point for process categorization. Other information methods were later chosen, and the SCOR model was not utilized in the final project deliverable.

However, it is mentioned here because the team began the collection of research in the SCOR model form.

SCOR MODEL

The SCOR model is a well-accepted industry model for analyzing and improving supply chain processes. The SCOR model provides a framework through which a supply chain can be decomposed into general processes with performance metrics that determine their effectiveness. The model is curated through APICS and has become a well-known tool in structuring supply chain improvement efforts. It is this status that led the MxD 17-01-01 Project team to choose the SCOR Model framework as the foundation upon which the playbook's processes and activities are classified. Industry input would be gathered and sorted amongst the main SCOR categories of: Plan, Make, Source, Deliver, and Return. However, Initial discussions by the Project team resulted in an agreement that the Return aspects of the Supply Chain was out of scope and should be removed as a classification for future processes. The underlying processes of the SCOR model were researched to determine if a suitable framework already existed that could describe the data transactions that are the focus of the project. It soon became clear through the analysis that the SCOR model was not designed to describe the technical data transactions needed for the project, but instead was made to classify entire supply chain processes, internal and external, for further analysis. As a result, the processes and activities in this level of the SCOR model would be useful as Industry input for the creation of the model but would have to be heavily reworked to serve as the framework. The result is that the SCOR Model categories are adequate for a top level structure but would not be the entire framework for the structure of the playbook, and a hierarchy would have to be made to reflect the specific scope of the project. The top categories were then defined by the team, shown in Table 2, and the hierarchy would have to be developed in other ways.

Table 2. SCOR Model definitions

Category	Definition
Plan	A set of processes and activities that work within current business rules to balance Demand and Supply.
Source	A set of processes and activities that procure goods and services used to meet demand.
Make	A set of processes and activities that work together to realize products that meet demand.
Deliver	A set of processes and activities that provide products to meet demand.

Classification Process

The research team grouped the industry data to form common processes across the various industries. The list of processes was non-specific and captured all supply chain technical data transactions described by industry regardless of form or format. Filtering was performed to determine if processes were in or out of scope and which would be included in the final list. Once this list was assembled several gaps were identified in the sequence that needed to be addressed to create a complete list of supply chain technical data transaction activity. Discussions with Industry and consulting partners resulted in processes identified that did not have specific Industry input to support it but were considered necessary by the team for the scope of the project. The result of this work was a General Process List that can contain the total scope of Supply chain activities within its structure.

Playbook Hierarchy Creation

Once the team defined the top level of the process hierarchy, a lower level hierarchy was created to connect the general processes to the information a User would use to navigate the playbook to find the appropriate information. The result was the Final Playbook Hierarchy that would be constructed through an IDEF0 structure that would produce a logical model (Figure 2). As stated earlier, the SCOR Model approach was eventually abandoned.

Creation of Process Map

To facilitate the project team’s understanding of the Playbook structure an analysis of the flows was undertaken to identify the logical sequence associated with the processes within each phase of the SCOR model. Review of the map with industry resulted in modifications to both the General Process List and the General Process Map.

Table 3. Classification of General Supply Chain Technical Data Exchange Processes

SCOR Category	Defined Processes
Plan	Product Design and Release
Plan	Sales & Operations Planning
Plan	Risk Assessment
Plan	Review (Supplier Scorecard)
Plan	Forecast
Source	Buy/Make Decisions
Source	Sourcing
Source	Quote
Source	Supplier Selection/Contract
Source	Supplier Qualification
Source	Onboarding
Source	Order
Source	Inventory Management
Make	Production
Make	Inspection
Make	First Article Inspection
Make	Machine Maintenance
Make	Machine Setup
Make	Engineering Change Order
Make	Corrective Actions
Deliver	Schedule Shipment
Deliver	Route, Prepare, and Load Shipment
Deliver	Ship Product
Deliver	Order Reception and Approval

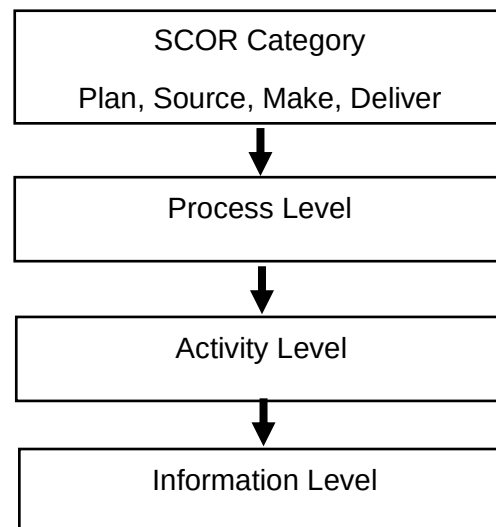


Figure 2. Hierarchy

Table 4. SCOR Category definitions

Level	Contents
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SCOR Category	Plan, Source, Make, Deliver
Process Level	A general action that must be performed within the supply chain by either the supplier or its customer
Activity Level	General Enabling Tasks and Data Exchanges that must be performed by the supplier and the customer for the process to be completed.
Information Level	The playbook information regarding the enabling task or data exchange activity.

ACTIVITY DEFINITION

During the definition of the activities, it became apparent that a decision on scope for the playbook (guide) was necessary to refine the hierarchy from a general list to something that was more capable of reflecting the intended purpose of the project. Through interviews and discussion, it became clear that the OEMs were already knowledgeable on the existence of Digital Supply Chain technologies and were making some progress towards implementing digital practices. SMMs, with limited resources to facilitate change, were stakeholders that would benefit the most from the utilization of the playbook (guide). OEMs could utilize the playbook in tandem with an SMM to resolve technological gaps between the two entities.

The research team began to populate processes with the activities that are undertaken to achieve a successful process outcome. A rough draft was produced that was then peer reviewed by the partners on the project. The research team then made the decision that this would be the appropriate time to tailor the entirety of the hierarchy to the intended scope. The process list was tailored to represent the enabling internal actions and technical data transactions of the SMMs. The activities that aggregate into processes were defined, and an IDEF0 chart was created that include the inputs, outputs, constraints and enablers related to the activity (See Figure 3).

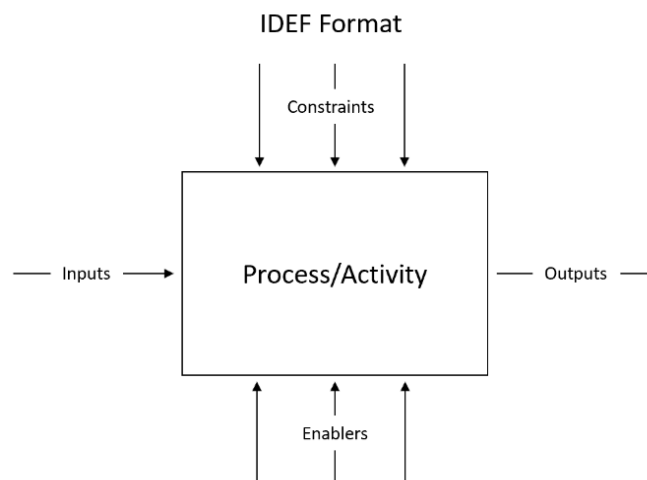


Figure 3. Process Box

COMMERCIAL SYSTEMS INVESTIGATED

After some in depth discussion, the idea of including a listing of commercial systems was removed from the playbook requirements. The team believes that this is an area that moves too quickly for a playbook or guide to stay relevant. The intent was to mention the functions available in the current software where it is applicable to help explain activity and process actions.

PREVIOUS RESEARCH PROJECTS

The project aimed to leverage as much previous work as possible. The team reviewed recent and ongoing research at MxD and other relevant projects from DoD, NIST and industry/standards organizations, to identify opportunities to leverage, maturation opportunities of previous project results, and integrate the solutions into an implementation plan and strategy. The following is a partial list of projects that were reviewed. The goal of this effort was to provide users with publicly available summaries of previously completed projects in the digital manufacturing realm. This will create a common source of information about previously completed projects.

MxD

- MxD 14-06-01: Supply Chain Model Based Enterprise and Technical Data Package Improvement
- MxD 14-08-01: Integrated Design and Manufacturing Models with Metrology
- MxD 14-10-01: AVM Standards Development and Promulgation
- MxD 14-02-02: Mind the Gap – Filling the Gap between CAD and CNC with Engineering Services
- MxD 15-11-08: Capturing Product Behavioral and Contextual Characteristics through a Model-Based Feature Information Network
- MxD 14-06-05: Operate, Orchestrate and Originate (O3)
- MxD 14-01-10: Elastic Cloud-based Make
- MxD 15-16-02: Democratizing the Model based Domain from Design to Verification: Automatic Generation of Optimized CMM Programs on the DMC
- MxD 15-05: Smart PCB Digital Factory

NIST

- Identified Research Directions for Using Manufacturing Knowledge Earlier in the Product Life Cycle
- Towards Identifying the Elements of a Minimum Information Model for use in a Model-Based Definition
- Design and Configuration of the Smart Manufacturing Systems Test Bed
- Software Requirements Specification to Distribute Manufacturing Data
- Measuring the PMI Modeling Capability in CAD Systems: Reports 1, 2 & 3
- Gap Analysis of Integrating Product Design, Manufacturing, and Quality Data in the Supply Chain Using Model-Based Definition

- A Summary Report on the Model-Based Enterprise Capability Index and Guidebook Workshop
- Toward a Lifecycle Information Framework and Technology in manufacturing
- Investigating the Impact of Standards-Based Interoperability for Design to Manufacturing and Quality in the Supply Chain
- Testing the Digital thread in Support of Model-Based Manufacturing and Inspection

DoD ManTech

- Supply Chain Social Media Study (AFRL ManTech)
- Connecting American Manufacturing (AFRL ManTech)
- Network Centric Model Based Enterprise (Army ManTech)
- Network Centric Model Based Enterprise II (Army ManTech)
- Customer/Supplier Interoperability during Collaborative Design (CSI) (AFRL ManTech)
- Accelerated Adaptive Army Innovation Fabrication Enterprise (A3FABE) (Army ManTech)
- AgilePod Digital Thread (AFRL ManTech)

Others

- Reference Architecture Model Industrie 4.0 (RAMI4.0)
- Information sharing and exchange in the context of product lifecycle management: Role of standards
- Analysis of Standards for Lifecycle Management of Systems for US Army --- a preliminary investigation

STANDARDS

The team had several connections to the standards communities and reached out to those bodies to achieve a greater level of validation. The team reviewed the current state of model-based technology solutions and standards such as STEP AP242, STEP AP203, STEP AP214, JT, and QIF that may affect how data is created, transferred and consumed by entities within the supply chain.

A new process, technique, tool, etc. cannot be successfully implemented across an extended enterprise without standard methods of use. To try and do so would result in chaos and ultimately failure. Model Based Enterprise (MBE) is no exception to this rule. The problem is that many of the needed standards either do not exist or are still being developed. This section presents some of the key standards that are either in existence or in development. It will also discuss several key gaps in the area.

Table 5. Standards Efforts in the Model Based Enterprise Domain

	Standard	Area of Effect	Note
1	ASME Y14 Series	Engineering Product Definition and Related Documentation Practices	This is a set of standards originally created with traditional drawings in mind. However, with the addition of Y14.41 Digital Product Definition Data Packages and soon Y14.47 3D Model Data Organization Schema they are starting to address MBE directly. The other standards are still relevant when model data is presented for human readable consumption.
2	GEIA 836	Configuration Management Data Exchange and Interoperability	The primary focus of this standard is information of interest to Configuration Management (CM) practitioners related to the performance of CM functions as products are conceived, proposed, defined, developed, produced, operated, maintained, modified, and disposed. This information is stored when generated and, from time to time, must be moved or shared with others.
3	GEIA 859	Implementation Guide for Data Management	Provides implementation guidance for ANSI/EIA 859, with discussions of applications of the standard's principles, tools, examples, and case studies. Handbook 859 is organized according to the lifecycle of data management and covers activities from the pre-RFP stage through records disposition. It also provides annexes on topics which apply at multiple stages in the lifecycle, such as protection of data, continuous improvement and knowledge management.
4	GEIA-STD-927-A	Common Data Schema for Complex Systems	Specifies the data concepts to be exchanged to share product information pertaining to a complex system from the viewpoints of multiple disciplines. It supports the exchange of data across the entire lifecycle for the product from the concept stage through disposal.
5	MIL-HBK-288	Review and Acceptance of Engineering Drawing Packages	Originally focused on the review and acceptance of traditional drawings, this handbook is under revision to expand its scope to include Model Based Definition and Digital Data Sets.
6	MIL-STD-31000A	Technical Data Packages	Originally created to define a traditional 2D based TDP, it has undergone extensive re-write to include 3D TDPs or mixed data TDPs. It should also be noted that Appendix B of this document (3D Model Organization Schema) is being transferred to ASME Y14.47.
7	MT Connect	Manufacturing Machine Data Exchange	This standard or protocol allows the exchange of manufacturing data between various Computer Numeric Controlled (CNC) machines regardless of type or controller used. Vital for the creation of a smart machine shop floor.
8	QIF	Quality Information Framework	The Quality Information Framework (QIF) is a unified XML framework standard for computer-aided quality measurement systems. It enables the capture, use, and re-use of metrology-related information throughout the Product Lifecycle Management (PLM)/Product Data Management (PDM) domain.
9	S Series	Integrated Logistics Support Specifications	Is a suite of specifications for product support that will provide the seamless passage of technical data (logistics, provisioning, technical publications/IETMs, scheduled maintenance and maintenance data feedback). The S Series suite is a joint project between the Aerospace Industries Association, Aerospace and Defense Industries Association of Europe and the ATA eBusiness Program (on S1000D).
10	STEP ISO 1030	Standard for the Exchange of Product Model Data (STEP)	Is an international product data standard to provide a complete, unambiguous, computer-interpretable definition of the physical and functional characteristics of a product throughout its lifecycle. It is a much broader standard than data interchange standards such as IGES since it is intended to support product data throughout the lifecycle of a product including engineering, manufacturing and support data. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving.

Existing Standards

There are many standards that have been created to governing items such as traditional drawings, neutral Computer Aided Design (CAD) files, interactive technical manuals,

Technical Data Packages (TDP), etc. Some would say that these are quickly becoming obsolete and are not relevant to MBE, but some would argue that many still have a role to play. For instance, the ASME Y14 series of standards were created to address traditional drawings and in some cases 3D drawings. While in a true MBE where representation of machine readable data is the core of the definition data set, Y14's relevance is minimal. But, the presentation of that data in a format that can be read by humans is still paramount for both actual acquisition actions and for quality control. In other words, Y14 now covers the presentation of data for human consumption and future standards can focus on the representation of that data for electronic consumption. While the Y14 example is only one of many, it outlines the evolution of the standards and their relevance in a digital era. Table 5 displays a short list of other existing standards and their relevance.

It must be noted that this is just a partial list that reflects a mechanical focus. There are many other relevant standards for electrical, ship building, logistics, construction, etc. The architecture and construction industries have started using Building Information Modeling (BIM) techniques that share many similarities with MBE and could warrant further research.

Ongoing and Future Standards Efforts

There are several ongoing efforts to create new or modify existing standards to aid in MBE adoption. One of the more exciting initiatives is the creation of a new suite of standards by ASME that will focus solely on MBE. This effort is in its infancy but has already gained a lot of interest from industry. It will also cover all aspects of MBE from a digital representation perspective. Over time this effort shows promise as the foundational set of standards that are needed for MBE to finally take hold across both industry and government.

As noted earlier, many of the existing standard groups are starting to add new standards to focus on MBE. ASME has also added Y14.47 to define how models should be organized for ease of reuse and interpretation. QIF has added many features to facilitate the representation of MBE data.

Another significant area of growth is the release and evolution of STEP AP242. This is an enhanced application protocol that facilitates the neutral exchange of mechanical MBE data. It also aids in the exchange of related Meta Data and PLM data such as Bills of Material (BOMs). Many items in this exchange are also representation based verses the traditional presentation based approach. This will allow for more reuse of data by many downstream applications.

The disruptive technology of additive manufacturing is one that is enabled by MBE and shares in the lack of standards. Organizations such as America Makes and ASME are creating new standards focused not only on the material side of additive technology but the digital side as well. For example, ASME has added Y14.48 which adds new geometric tolerancing techniques just for additive.

With all the new standards noted above and others coming, there are still gaps in the standards, such as:

- Formally defining MBE and all its related disciplines
- A common PLM framework based upon the Digital Product Definition Package (DP2) that many use as the core of MBE
- Formal processes and schemas for the various model based disciplines like manufacturing and sustainment
- Guidance for the use of MBE in contracting (especially in government contracting)
- Proper guidance on modeling for intellectual property protection
- Multi-domain PLM and Enterprise Resource Planning (ERP) exchange and integration

These are but a few of the gaps that need to be addressed before MBE can be adopted in a common and effective manner. The current standards are only a fraction of what is needed before MBE can be implemented in such a manner that data can truly be shared across multiple enterprises without massive rework of the data.

TOOLS USED TO EXECUTE PROCESSES

The team took an approach to this project intending to maximize the leverage achieved from previous research successes by DoD, ManTech, NIST, MxD and industry. By starting from the foundation of the previous projects, the team was able to focus on the integration of the individual components and the maturation of the tools and capabilities necessary to weave together the pieces into the digital supply chain.

To provide system validation and demonstration the team will conduct validation efforts with participating manufacturers and their supply chain partners to confirm processes and tools that will showcase the principles identified for digitally enabled supply chain participation. These demonstrations will show the current state of the practice, implement the suggested digitally enabled practice, and capture the benefits that can be attributed to the implementation. The team will connect with standards communities to identify opportunities to enhance and improve current or future standards.

Demonstrations were originally planned take place in multiple process areas and will utilize existing tools along with newly developed capabilities from DoD, ManTech, NIST, MxD and industry. Some of the functions and processes to be demonstrated would include:

- Manufacturing - Design, Prototype, LRIP and Production, tooling, manufacturing programs (CAM and CAI, etc.), planning, work instructions, inspection, data collection and transmission capability
- Engineering - analysis, design, test
- Procurement - bids, purchases, inspection
- Support operations – maintenance, training, spares provisioning

But, after the refocusing of the project the demonstrations were removed from the scope of work.

MODELS

Classification Model

Utilizing the classification of industry data to form the list of common processes shown in Table 3, the research team used the General Process List to create models, visual representations, to better describe each process. The collection of these visual representations produces a classification model to be used in the development of the framework and platform of the playbooks.

FFBD/IDEFO

The creation of the process and activity classification requires the analysis of inputs and outputs to link the entities into a completed supply chain model. The research team concluded that the IDEFO (Integration Definition for Process Modeling) format should be used in conjunction with the process and activity classification to construct the final framework for the playbook (see Figure 3). This format allows users to have a visual representation of how processes and activities link together. Initially each of the processes were analyzed to determine inputs, outputs, enablers, and constraints.

The hierarchy of the playbook (guide) implies that the inputs and outputs of the processes would have to be linked to the inputs and outputs of the activities in some form. It was decided that the inputs and outputs of the processes would also serve as the inputs and outputs to the activity system within that process. In other words, the external inputs and outputs to the system of activities within the processes would be equivalent to the inputs and outputs of the process that the activities represent. The result of this work is a complete logical model that can describe the information. A portion of the model was created and is shown below (Figure 4).

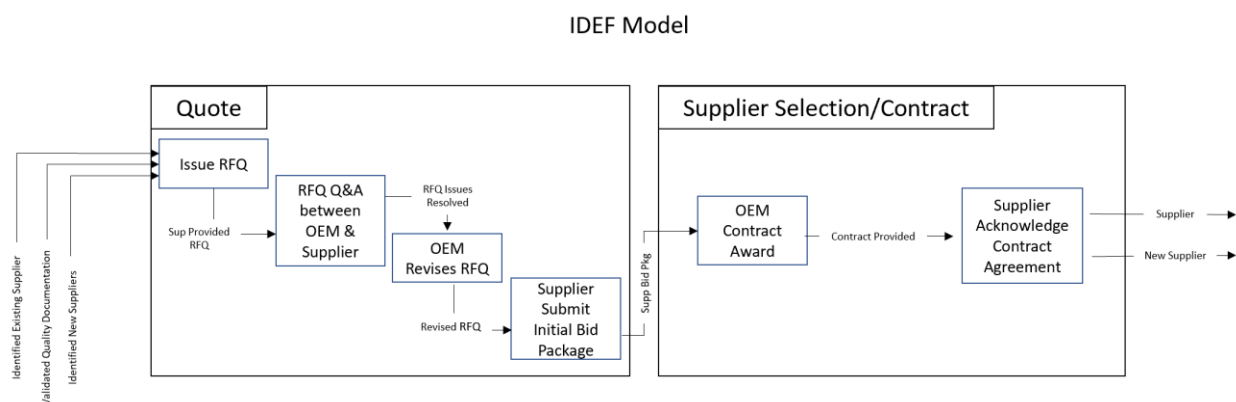


Figure 4. Representative IDEFO model

LITERATURE REVIEW

The literature review finalized the plan to abandon the playbook in favor of an awareness website called an online Digital Manufacturing Guide. The following is a list of references to articles that indicated SMMs are lagging in the adoption of digital manufacturing capabilities:

Ezell S, Atkinson RD, Kim I, Cho J. Manufacturing Digitalization: Extent of Adoption and Recommendations for Increasing Penetration in Korea and the U.S. Information Technology and Innovation Foundation; 2018.

Schroeter, M. "Industry 4.0 possible for all with collaborative approach," *Manufacturers' Monthly*, 04-Mar-2019.

Mittal S, Khan MA, Romero D, Wuest T. A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for small and medium-sized enterprises (SMEs). *Journal of Manufacturing Systems*, 2018; 49:194–214. doi:10.1016/j.jmsy.2018.10.005.

Büyüközkan G, Göçer F. "Digital Supply Chain: Literature review and a proposed framework for future research." *Computers in Industry* 2018; 97:157–77. doi:10.1016/j.compind.2018.02.010.

Nguyen TH, Newby M, Macaulay MJ. Information Technology Adoption in Small Business: Confirmation of a Proposed Framework. *Journal of Small Business Management* 2015; 53:207–27. doi:10.1111/jsbm.12058.

Ghobakhloo M, Hong TS, Sabouri MS, Zulkifli N. Strategies for Successful Information Technology Adoption in Small and Medium-sized Enterprises. *Information* 2012; 3:36–67. doi:10.3390/info3010036.

Korchak R, Rodman R. eBusiness adoption among U.S. small manufacturers and the role of manufacturing extension. *Economic Development Review*; Park Ridge 2001; 17:20–5.

Kamble SS, Gunasekaran A, Sharma R. Analysis of the driving and dependence power of barriers to adopt industry 4.0 in Indian manufacturing industry. *Computers in Industry* 2018; 101:107–19. doi:10.1016/j.compind.2018.06.004.

Wuest T, Schmid P, Lego B, Bowen E. Overview of Smart Manufacturing in West Virginia. Morgantown, WV: Bureau of Business & Economic Research, West Virginia University College of Business and Economics; 2018.

"Digital transformation simmers in supply chain planning circles – CSCMP's Supply Chain Quarterly." [Online]. Available: <https://www.supplychainquarterly.com/news/20191002->

[digital-transformation-simmers-in-supply-chain-planning-circles/](#). [Accessed: 07-Oct-2019].

The following is a list of articles the team wrote about SMMs lagging in the adoption of Digital Manufacturing capabilities. Publications and presentations can be found in Appendix C:

Harris, G., C. Peters, R. Whittenburg, R. Hughes, K. Fischer, D. Hartman, K. Ma, J. Shubrooks, and T. Hedberg, “Digitally Enabling the Supply Chain,” Proceedings of the 9th Model-Based Enterprise Summit, April 2-5, 2018, Gaithersburg, MD. <https://doi.org/10.6028/NIST.AMS.100-22#page=30>

G. Harris, C. Peters, A. Yarbrough, C. Estes, and D. Abernathy, “Industry Readiness for Digital Manufacturing May Not Be As We Thought - Preliminary Findings of MxD* Project 17-01-01,” in *Proceedings of the 10th model-based enterprise summit (MBE 2019)*, Gaithersburg, MD, 2019, pp. 110–116. <https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.100-24.pdf>

G. Harris, A. Yarbrough, D. Abernathy, and C. Peters, “Manufacturing Readiness for Digital Manufacturing,” *Manufacturing Letters*, vol. 22, pp. 16–18, October 2019. <https://doi.org/10.1016/j.mfglet.2019.10.002>

SCOPE & OBJECTIVES

Several things took place that changed the direction and focus of the project. The original assumptions were that defined supply chain processes in the exchange of data, technical and business, were being used and documented, and the team could evaluate and consider options for inclusion as a best practice. This was not the case for technical data exchanges. An assumption made by the team when putting the proposal together was that the team would find approximately half of the supply base, at least in the DoD industrial base, ready to engage in the digital supply chain. After performing the interviews, this was found not to be the case. The team found that less than 20% of the supply base are trying to do anything toward developing digital capabilities. The assumed industry majority vs. the assessed industry majority stages of adoption are shown in Figure 5. This early finding required the team to re-evaluate where the value will be in the playbook. OEMs and the large first tier manufacturers have the resources and funding to engage in digital manufacturing, but the 2 – n tier suppliers do not.

PROJECT RESTRUCTURING MEETING

After recognizing the need to restructure the project deliverables, the team met in Arlington, VA on January 17, 2019 to discuss the development of the new deliverables. The research team identified that there was a problem. The assumption that a majority of industry would be in the implementation stage of adoption was incorrect. The assessed industry majority was actually in the knowledge and persuasion stage of digital manufacturing adoption as shown in Figure 5. This meeting was to discuss the problem at hand and determine how to change the deliverable to properly assist manufacturers in their current state. The team decided to switch from creating a playbook to creating a guide. The team then discussed the content that we thought should be

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shown in the digital manufacturing guide. Manufacturing processes were discussed in-depth and then broken into four major processes to encompass a manufacturing system. The four major processes and the activities within those processes are discussed in the following sections.

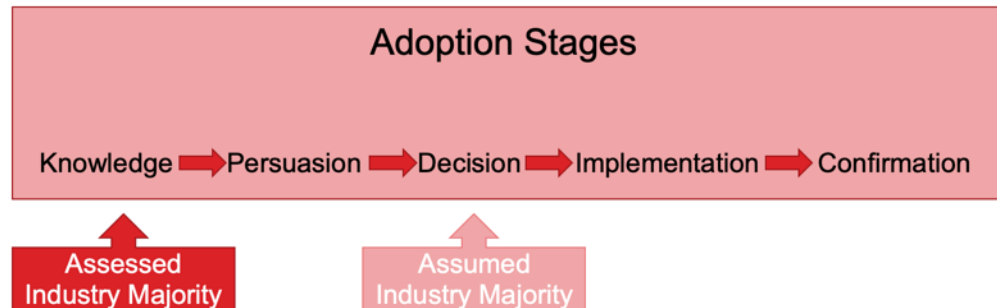


Figure 5. Technology Adoption Stages- Assumed vs. Assessed Industry Majority.

REVISED PROBLEM STATEMENT

The team re-evaluated the value proposition for this project and realize that static content would simply not be used by the target audience of SMMs. The target became a less static and more engaging web presence for the deliverable with less focus on the OEMs and the large first tier manufacturers. The focus changes from assisting adoption to creating awareness. The objective then became to create content for the four processes thought to cover most of manufacturing, which are discussed in 'Process Descriptions' section. The deliverable became an online digital manufacturing guide that was to be developed for the intended audience and then verified and validated by industry.

TECHNICAL APPROACH

PROCESS DESCRIPTIONS

Quoting Process

Activities within Quoting Process: Prepare RFQ, Communicate RFQ, Evaluate RFQ, Develop & Submit Quote

The quoting process involves a buyer's creation and dissemination of a request for quote (RFQ) and the receipt and analysis of supplier responses. When done well, the buyer should receive enough qualified quotes that meet the time, quality and cost requirements. Performing these steps digitally can provide several benefits

- Decreased buyer effort and time to generate RFQs.
- Reach more potential suppliers with less effort.
- Reduced seller effort and time to respond.
- Increased number of responses, which has shown to decrease product cost and time.

Purchase Order to First Article

Activities within Purchase Order to First Article: Purchase Order Receipt, Production Plan, Work Scheduled, Execute Buy Plan & Order Materials, Receive and Inspect Material, Fabricate-Purchase-Inspect Tools, Fabricate-Assemble-Inspect Components, Conduct component functional test/certification test, First Article Inspection (FAI)

A supplier can have many tasks to complete from the time it receives a purchase order to when it produces an item ready for first article inspection. These tasks may require the use of many different computer programs and manual steps. The more convoluted and less automated this process is, the more likely the supply chain will experience unexpected costs and delays. Performing these steps digitally can provide several benefits.

- Reduced costs and effort to document and communicate intra-company and inter-company activities.
- Lowered risk of errors from mistakes and delays in data entry or exchange.
- Increased customer satisfaction through greater quality and responsiveness.

Recurring Manufacturing

Activities within Recurring Manufacturing: Data Management, Gage R&R, Inspection & Quality, Inventory Management, Issues and Corrective Actions, Manufacturing Processes, Materials Acquisition, Inspection, & Management

There are numerous processes that occur during recurring manufacturing, most of which require effective communications between trading partners. Examples of such processes could include packaging, shipping, receiving and inspecting an order. Results from these processes must flow up or down the supply chain quickly to initiate corrective actions when necessary. Performing these steps digitally can provide several benefits.

- Reduced cost and effort to document and communicate inter-company activities.
- Faster identification of production problems throughout the supply chain.
- Lower risk of excessive claims from quality issues.

Engineering Change

Activities within Engineering Change: Source of Change Request, Engineering Change Analysis and Approval, Change Communication, Supplier Processes Change

Engineering change orders are a common vehicle to communicate design changes between one or more trading partners. In complex supply chains, engineering change orders must be communicated quickly and effectively to minimize disruptions and cost. Performing these steps digitally can provide several benefits.

- Reduced costs and delays by communicating to the right people quickly.
- Reduced rework and scrap by ensuring that manufacturers are working to the most current design version.
- Lower supply chain risk by keeping all trading partners in sync.

WEBSITE DEVELOPMENT

The online digital manufacturing guide was designed by Wei Wang, Professor and Program Chair of Auburn University's Graphic Design Program. The code for the website was written by Auburn University PhD student in Computer Science & Software Engineering, John Osho, with the help of Dr. David Umphress, Professor in the Computer Science and Software Engineering Department.

WEBSITE SECTIONS AND DESCRIPTIONS

When the user first enters the website, they will be presented with a home page which provides them with a description on what the website's purpose is. The user is presented with three options on how to get started: 1. What is it? 2. Why do it? and 3. How to do it?

1. What is it?

'What is it?' is the entry point of the website. This is for the individual that is interested in learning about digital manufacturing and all the different terms that are associated with it. The 'About Digital Manufacturing' page will give the user a description of digital manufacturing. The user is introduced to the four industrial revolutions. It explains the different components of digital manufacturing. There is a diagram that shows the different components of digital manufacturing. One important feature is that when you scroll over a specific component in the diagram, the definition of a component will appear. The 'Definition of Common Terms' page is for someone interested in learning about the different terms that are associated with digital manufacturing, or if there is a term that the user does not understand or is not familiar with, they can look up the definition. Users can scroll to find a word, search for a word, or click on a letter that will take them to that point in the list. Many definitions were compiled for each term and then the team chose the definition that best fit the context of a digital manufacturing guide specifically for manufacturing.

2. The Why do it?

The 'Why do it?' portion of the website is for companies that are interested in understanding why digital manufacturing is something that should be pursued. The value drivers are described on the 'Why Pursue Digital Manufacturing' page, which are: increase profits, greater competitive advantage, and remain viable. The 'Future of Digital Manufacturing' page gives an explanation of where manufacturing is headed and growth of the market for digital manufacturing capabilities. The 'Adoption Issues' page explains the issues and barriers that are associated with adopting digital manufacturing, and it also explains some of the motivations.

3. The How to do it?

The 'How to do it?' section takes the user through step-by-step on how to implement digital manufacturing throughout the four major manufacturing processes: Quoting Process, PO to 1st Article, Recurring Manufacturing, and Engineering Change. There are drop down lists that take the user to activities within the four major processes or walk through the processes one at a time by clicking on the 'Next' button at the bottom of the page. When clicking on the name of one of

the four major processes, the user is given a description of that process and some of the benefits for implementing digital manufacturing throughout that process. There are content pages for each activity within the four major processes.

For example, the first activity is 'Prepare RFQ' under the Quoting Process. The 'Prepare RFQ' content page contains an explanation of prepare RFQ, and there is an option to 'Read More' for the user that wants to learn more. When clicking the 'Read More' button, there is a diagram that highlights the current stage in the Quoting Process. The data exchanged is presented as either an input or an output. The tools that are used for data exchange are listed. Digital solutions and potential issues with the activity are provided and explained. The '+' button functions as a way to read more about the topic. Users can move on to the next content page by clicking on the 'Next' button or the name of the next content page at the bottom of the page. When the user gets to the last page within a major process, the 'Next' button will take them to the process description of the next major process. For example, if the user is on the 'Develop & Submit Quote' content page, which is the last content page within Quoting, clicking the 'Next' button will take them into the description of Purchase Order to 1st Article, which is the next major process description.

Benefits

The benefits show snippets of success stories of companies that have implemented digital manufacturing. There is a description of what they did and the benefits that were realized. There are several benefits listed. Users can access the benefits section by clicking on the gold 'Benefits' button that is on each of the content pages. When on a Quoting content page, the 'Benefits' button will only pull up the benefits that are associated with the Quoting Process. All of the benefits can be viewed by clicking on the 'Benefits' button in the header or footer of the site.

Business Cases

The business cases are for people that want to dive a little bit deeper than the short snippets that are in the Benefits section. The business cases will take users into a full story that has a description, the challenges that were faced, the motivations for digital transformation, and the solutions that were implemented. Users can continue on to the next business case by clicking the 'Next' button at the bottom of the page.

Projects

The projects page has a list of all MxD projects that are associated with this digital manufacturing topic and can be accessed on one of the project hyperlinks to open a description.

Contact Us

The Contact Us page allows the user to communicate with the web site host. There is a place for name, email, their company or organization, and a message box. Once all information is entered click the 'Submit' button.

About

The about page explains why this website was created, lists the members of the MxD 17-01-01 project team, gives a short explanation of how to use the site, and provides an explanation of the three main sections of the site.

PLANNED BENEFITS

As an OEM or large manufacturer, I want to help my suppliers understand and adopt digital manufacturing practices so that I can achieve the increased levels of efficiency and profitability waiting to be seized.

As a Small or Medium-sized Manufacturer, I want a resource to help me understand and implement digital manufacturing practices so that I can achieve the promise of increased levels of efficiency and profitability.

As a manufacturer, I need a trusted resource to guide me through the morass of disinformation currently clouding the marketplace. My resources are few and I cannot afford to waste time looking for answers throughout the internet or sales pitches. I want to have access to a resource that I can understand and become knowledgeable in what digital manufacturing really is and how I might engage. Is there an organization out there (MxD) that I can trust to help me without selling me on a canned solution?

IV. KPI'S & METRICS

The table below outlines the key performance indicators and metrics used to evaluate the success of the project outcomes in comparison to the current state and proposed goals.

- The eventual metrics for this project will be the number of hits on the website. NIST will be monitoring this on an ongoing basis.

Metric	Baseline	Goal	Results	Validation Method
Enter Metric	Enter Baseline	Enter Goal	Enter Results	Enter Validation Method



V. TECHNOLOGY OUTCOMES

TECHNOLOGY DELIVERABLES

#	Deliverable Name	Description	Format of Delivery
1	Website	Digital Manufacturing Guide	Code for website was delivered to NIST for vetting.
2	Website content	All content for website pages	.doc, .pdf

SYSTEM OVERVIEW

See above documentation.

SYSTEM REQUIREMENTS

A computer, or phone, with internet access is all that will be needed to access the website.

SYSTEM ARCHITECTURE

See Appendix E.

FEATURES & ATTRIBUTES

See above.

TARGET USERS & MODES OF OPERATION

Small and Medium-sized Manufacturers, Operating Managers and Owners. Educators, students, solution providers for digital capabilities.

SOFTWARE DEVELOPMENT/DESIGN DOCUMENTATION

All code and documentation have been delivered to NIST and MxD.

VI. INDUSTRY IMPACT

Reduce costs, gain efficiencies, and grow business with the online digital manufacturing guide. The Digital Manufacturing website was developed to provide something for everyone to learn through the Guide. The website will provide materials to help make the business case for the adoption of Digital Manufacturing which is crucial to maintaining competitive advantage and profitability in the ever changing and improving world of manufacturing. The Guide can help your company successfully implement Digital Manufacturing solutions and overcome potential barriers by going step-by-step through the major process of manufacturing such as the Quoting Process, Purchase Order to First Article, Recurring Manufacturing, and Engineering Changes.

VII. TRANSITION PLAN

TRANSITION CHART

The transition chart provides a catalog of all of the project deliverables and their respective transition route. Deliverables can transition through deployment at an industry member's site, as an educational reference or through a commercialization effort. Each of these transition routes are detailed in the Transition Summary section below.



#	Deliverable File Name	Technology Integration	Education	Commercialize
1	Website has been delivered to NIST to be launched on the NIST web site in Jan – Feb, 2020	X	X	
2	A workshop will be held at the MBE Summit 2020		X	
3				
4				
5				

TRANSITION SUMMARY

The website content and code has been delivered to NIST. NIST is betting the code for hosting.

Journal articles have been published and some are currently still under review (see Appendix C). Presentations have been made at three conferences with one more submitted. Two conference papers have been published in the conference proceedings. Two invited talks were presented to communities outside of MxD. The research team will be attending the MBE Summit 2020 and will conduct a workshop on how to utilize the digital manufacturing guide. NIST will be hosting the website in its current form. The website will be available in January or February 2020. When the website is live, the team will work to get the website link to company and professional society websites. The team believe that this site should be a living and growing resource that is community supported. To make the system where it can be added to by the digital manufacturing community, there will be a few modifications required. A follow on project would be to make the website community based and establish the management plan for curating the site.

RECOMMENDED SEQUENCE OF USE

~~This section does not really apply to this project.~~

~~X~~.VIII. WORKFORCE DEVELOPMENT

TRAINING & EDUCATIONAL MATERIALS

The Digital Manufacturing site was created to help companies and individuals learn about the Digital Manufacturing technologies that can help decrease costs, increase profits and win more business. The information provides an overview of these technologies and examples of their use without promoting one vendor over another. To get started, the user simply chooses whether they would like to learn about what Digital Manufacturing is all about, a specific technology or how these technologies can help solve common problems. The user is presented with three options regarding Digital Manufacturing:

1) What is it?

Learning Objectives: Definition of Digital Manufacturing, Components of Digital Manufacturing, Definitions of Common Terms

This portion of the site is for an individual who is new to Digital Manufacturing and is interested in learning about the capabilities of Digital Manufacturing or for those that could use a simple refresher. A description of Digital Manufacturing and its related terms (Industry 4.0, Smart Manufacturing, and Smart Factory) are presented. The eight different components of Digital Manufacturing are presented. And common terms used in the Digital Manufacturing realm are defined. The Definitions of Common Terms is a beneficial tool when the user runs across a term or acronym in which they are unfamiliar.

2) Why do it?

Learning Objectives: Value Drivers of Digital Manufacturing, Future of Digital Manufacturing



This portion of the site provides an explanation of why adopting Digital Manufacturing is crucial to maintaining a competitive advantage in the ever-changing and improving world of manufacturing. Not only does Digital Manufacturing help companies become more profitable, it is vital to the survival of manufacturers in the future. There are also tabs within 'Why do it?' that take the user to description of the future of Digital Manufacturing and motivators and barriers to the adoption of Digital Manufacturing.

3) How to do it?

Learning Objectives: An understanding of Quoting, Purchase Order to First Article, Recurring Manufacturing, and Engineering Change Processes, What Digital Solutions Exist, and Issues that can occur with the 4 major processes

Now that the user has knowledge of Digital Manufacturing and why it should be pursued, the big question is 'How to do it?' This part of the website takes the user step-by-step through the lifecycle of a product from the Quoting Process, Purchase Order to First Article, Recurring Manufacturing, to Engineering Change. When clicking on each of these four major processes, a general description of that specific process is given. Each of the four major processes are broken into manageable learning chunks, called 'content pages.' For example, the Quoting Process has four activities described within the content pages: Prepare RFQ, Communicate RFQ, Evaluate RFQ, and Develop & Submit Quote. These content pages can be simply navigated in order by going through the content and then clicking 'Next' at the bottom of the page. For the novice user, the content pages are a great source to learn about the various components of a manufacturing lifecycle.

For the more experienced user, there are drop-down box options to learn more. Following a brief description of each activity within a content page, there is an option to 'Read More' and get a more in-depth explanation of that specific activity. Within 'Read More' for each activity, there is a diagram that shows the user where they are at within a process. The specific activity they are learning about on that content page is highlighted in yellow in the diagram. This allows the user to have a higher-level systems view while still gaining an understanding of the current location of the process of which they are learning. The inputs, constraints, and outputs of each activity are listed. The tools that are often used for the activity are listed. Digital solutions for each activity are listed and then further described when clicking the '+' option. Potential issues with each activity are also listed and then further described when clicking the '+' option. Many of the activities have related projects and standards listed as 'Additional Resources.' The projects serve as a lens into what other research has been performed to solve similar problems and issues in the implementation of Digital Manufacturing in their processes. The standards are provided to help inform the user of best practices that have been developed, tested and proven to be successful when performing the selected activity.

'BENEFITS' and 'BUSINESS CASES'

Learning Objectives: How companies are already leveraging Digital Manufacturing capabilities and realizing a return on investment

On each content page, there is a golden button labeled 'BENEFITS.' When clicking this button, the user will be presented with business case snippets from companies that have shown a return on investment from implementing Digital Manufacturing in their facility or deploying digital capabilities throughout their supply chain. To view a full list of these business case snippets, the user can click on 'BENEFITS' in the header or footer of the page. Notice there is also a 'BUSINESS CASES' link in the header and footer of the site. When choosing this option, the user will be taken to in-depth business cases that tell the stories of different companies and their journey of adopting Digital Manufacturing.

'ABOUT' this site



In the top left-hand corner of the site, there are two logos: NIST and MxD. The host of this site is the National Institute of Standards and Technology (NIST). The sponsor of this site is Manufacturing times Digital (MxD), formerly the Digital Manufacturing and Design Innovation Institute (DMDII). The 'About' page can be reached from the header or footer of the site. It gives a concise explanation of the site, a list of team members who contributed to the site's development, a brief description of how to use the site, and a short explanation of each of the three website categories: What is Digital Manufacturing, Why is Digital Manufacturing Valuable, and How to Implement Digital Manufacturing Capabilities.

'CONTACT US'

In the header and footer of the site, there is a 'Contact Us' option that allows users to provide comments, feedback, or ask questions. The user is asked to provide their name, company/organization, and contact information so that they can receive feedback on their submission.

XLIX. CONCLUSIONS & RECOMMENDATIONS

This project has been quite a journey. Initially intended to be some "how to" manuals on becoming digitally enabled, early on discoveries of the previously unknown, and un-considered, state of the supply chain in terms of readiness to engage in the digital supply chain threw the project team a curve. It took three months to understand what the team had uncovered and then develop a solution for this effort to provide value for industry and MxD. Issues were discovered that indicated the solution for this project was to develop a tool that could be used to increase awareness and understanding of what digital manufacturing is and how it can benefit a SMM. Some of these issues include:

- Multiple studies indicate a serious gap between the OEMs (early adopters) and their SMM supply chain partners (laggards).
- The technical issues of connecting the digital thread have overshadowed the business and cultural issues.
- The MBE community has mainly consisted of researchers, solution providers and OEMs thus far, but very few lower-tier suppliers.
- Lower-tiered suppliers in the supply chains that do not have the resources and funds to participate in the development of the technology.
- SMMs need greater awareness of what digital manufacturing is and the business cases to help them justify the cost and effort.
- Lack of adoption by SMMs impacts the entire U.S. industrial base.
- A lack of understanding of what digital manufacturing by SMMs or what Industry 4.0/Smart Manufacturing means to the future of their organization.
- A lack of awareness by OEMs and large manufacturing operations as to the state of their supply chain in terms of digital capabilities.
- There is a significant issue with infrastructure for digital manufacturing, system capability to handle digitalization, and work force availability and skills to engage in digital capabilities.
- There is much confusion in the marketplace about Industry 4.0/Smart Manufacturing, which causes the SMMs with few resources to apply to the problem to essentially ignore the trends and technologies that are changing their ability to survive in the business of manufacturing.

These findings led the project team to the solution of developing a website to increase the understanding and awareness of digital manufacturing capabilities that would improve the adoption of these digital capabilities within the supply chain. The website solution must be considered a "Trusted Source" to be effective, therefore NIST has agreed to host the website as a neutral party thus providing assurance that the



website is not trying to “sell” a solution to the SMM but rather is there to provide a one stop location to generate awareness and understanding.

The project team firmly believes that the website is vital to increasing adoption of digital capabilities in the industrial supply chain and that the material should be continuously added to and kept up to date. To make the website truly vital it is desirable to create a process for community input and provision. This will require additional effort to make the website functional for community input and management.

XII.X. LESSONS LEARNED

- **What went well?**
 - Team worked well together
 - When the initial assumptions were found to be false the team worked to develop a good solution that basically brought value to the effort.
- **What went poorly? And associated learnings?**
 - Obviously, the original assumptions were flawed.
- **What would you want to do differently?**
 - It would have been good to validate the team’s initial assumptions earlier.
 - It would have been good to have a larger sample size, perhaps using the entirety of MxD membership.

XIII.XI. ACCESSING THE TECHNOLOGY

- The website will be accessible to all with an internet connection.
- The website will be hosted on the NIST website under the Model Based Enterprise program in the Engineering Lab and is public facing.
- The website will be accessible from all web browsers.
- NIST has agreed to maintain the website for the foreseeable future.

DEFINITIONS

What follows are a set of definitions, terms, and acronyms used in this document. These definitions were gathered from various source including the internet, reference papers, standards organizations, and the authors of these documents.

Word	Definition	Website Name/Source	URL
Agile Sprint	Sprint is one timeboxed iteration of a continuous development cycle. Within a Sprint, planned amount of work has to be completed by the team and made ready for review.	Yodiz	https://yodiz.com/help/what-is-sprint/
Augmented Reality (AR)	Augmented Reality (AR) is an interactive experience of a real-world environment where the objects that reside in the real-world are enhanced by computer-generated perceptual information, sometimes across multiple sensory modalities, including visual, auditory, haptic, somatosensory and olfactory.	Wikipedia	https://en.wikipedia.org/wiki/Augmented_reality
Autonomous Robot	An autonomous robot is a robot that is designed and engineered to deal with its environment on its own, and work for extended periods of time without human	Techopedia	https://www.techopedia.com/definition/32



	intervention. Autonomous robots often have sophisticated features that can help them to understand their physical environment and automate parts of their maintenance and direction that used to be done by humans.		694/autonomous-robot
Bid Package	The full set of bidding documents a supplier is required to submit for a bid to be considered. This package may include drawings, models, timelines, charts, exceptions and pricing.	The Law Dictionary	https://thelawdictionary.org/bid-package/
Big Data Analytics	Big data analytics is the use of advanced analytic techniques against very large, diverse data sets that include structured, semi-structured and unstructured data, from different sources, and in different sizes from terabytes to zettabytes.	IBM	https://www.ibm.com/analytics/hadoop/big-data-analytics
Bill of Materials (BOM)	A bill of materials (BOM) is an extensive list of raw materials, components, and assemblies required to construct, manufacture or repair a product or service. A bill of materials usually appears in a hierarchical format, with the highest level displaying the finished product and the bottom level showing individual components and materials.	Investopedia	https://www.investopedia.com/terms/b/bill-of-materials.asp
Buyer	The buyer is responsible for overseeing and managing the purchasing process of goods and services for industrial or manufacturing operations. An “engineering buyer,” often has detailed knowledge of industry tools, equipment, and supplies.	Randstad (with modification)	https://www.randstad.ca/buyer-jobs/
CAD Data Exchange	CAD data exchange is a modality of technical data exchange used to translate data between different Computer-aided design (CAD) authoring systems or between CAD and other downstream CAx systems. Many companies use different CAD systems internally and exchange CAD data with suppliers, customers and subcontractors. Transfer of data is necessary so that, for example, one organization can be developing a CAD model, while another performs analysis work on the same model; at the same time a third organization is responsible for manufacturing the product	Wikipedia	https://en.wikipedia.org/wiki/CAD_data_exchange
CAD Data Exchange Validation	Software that identifies model-based design (MBD) data quality issues that impact downstream reuse for manufacturing, simulation, data exchange and collaboration. CADIQ enables you to validate critical engineering processes including engineering change, revision control and manufacturability.	ITI	https://www.iti-global.com/validation/
Central Data Management System	A centralized database is a database that is located, stored, and maintained in a single location. This location is most often a central computer or database system, for example a desktop or server CPU, or a mainframe computer.	Wikipedia	https://en.wikipedia.org/wiki/Centralized_database
Computer Numerical Control (CNC)	CNC is the automated control of machining tools and 3D printers by means of a computer. A CNC machine processes a piece of material to meet specifications by following a coded programmed instruction and without a manual operator.	Wikipedia	https://en.wikipedia.org/wiki/Numerical_control
Computer-Aided Design (CAD)	Computer-aided design (CAD) is the use of computers (or workstations) to aid in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the	Wikipedia	https://marketbusinessnews.com/financial-glossary/computer-aided-design-cad/



	quality of design, improve communications through documentation, and to create a database for manufacturing. It can be used to produce either two-dimensional or three-dimensional diagrams, which can then when rotated to be viewed.		
Computer-Aided Design (CAD)	Computer-aided design (CAD) is the use of computers (or workstations) to aid in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing.	Wikipedia	https://marketbusinessnews.com/financial-glossary/computer-aided-design-cad/
Computer-Aided Engineering (CAE)	Computer-aided engineering (CAE) is the use of computer software to simulate performance in order to improve product designs or assist in the resolution of engineering problems for a wide range of industries. This includes simulation, validation and optimization of products, processes, and manufacturing tools.	Siemens	https://www.plm.automation.siemens.com/global/en/our-story/glossary/computer-aided-engineering-cae/13112
Computer-Aided Manufacturing (CAM)	The use of software to control machine tools and related ones in the manufacturing of workpieces. CAM may also refer to the use of a computer to assist in all operations of a manufacturing plant, including planning, management, transportation and storage. CAM often refers to software that takes the geometric design authored with CAD software as input and outputs manufacturing instructions that are downloaded to automated equipment such as a computer numerically controlled (CNC) machine tool.	Wikipedia	https://en.wikipedia.org/wiki/Computer-aided_manufacturing
Concept Extraction	Concept extraction is the technique of mining the most important topic of a document. In the e-commerce context, concept extraction can be used to identify what a shopping related Web page is talking about. This is practically useful in applications like search relevance and product matching.	Science Direct	https://www.sciencedirect.com/science/article/pii/S1567422313000227
Connectivity Platforms	An Internet of Things connectivity management platform that enables enterprises to effectively manage connectivity on a global scale throughout the full device lifecycle.	Sdx Central	https://www.sdxcentral.com/products/ericsson-device-connection-platform/
Coordinate Measuring Machine (CMM)	A coordinate measuring machine is a device that measures the geometry of physical objects by sensing discrete points on the surface of the object with a probe. Various types of probes are used in CMMs, including mechanical, optical, laser, and white light	Wikipedia	https://en.wikipedia.org/wiki/Coordinate_measuring_machine
Corrective Action Report (CAR)	Procedure used in response to a detected non-conformance and have determined root cause to correct this from reoccurring.	Isixsigma	https://www.isixsigma.com/dictionary/corrective-action-report-car/
Customer-Relationship Management (CRM)	Customer relationship management (CRM) is an approach to manage a company's interaction with current and potential customers. It uses data analysis about customers' history with a company to improve business relationships with customers, specifically focusing on customer retention and ultimately driving sales growth.	Wikipedia	https://en.wikipedia.org/wiki/Customer_relationship_management
Cyber Security	Cyber security refers to the body of technologies, processes, and practices designed to protect networks, devices, programs, and data from attack, damage, or unauthorized access. Cyber security may also be referred to as information technology security.	Digital Guardian	https://digitalguardian.com/blog/what-cyber-security



Data Analytics (DA)	Data Analytics (DA) is the process of examining data sets in order to draw conclusions about the information they contain utilizing qualitative and quantitative techniques and processes. Data is extracted and categorized to identify and analyze behavioral data and patterns.	Search Data Management	https://searchdatamanagement.techtarget.com/
Design and Engineering Transfer	Establishes a framework for transfer and any changes to the design that manufacturer must use when developing and then implementing this relationship between, for example, design engineers and manufacturing engineers.	Orthopaedic Specialty Metal Solutions	https://www.bonezonpub.com/233-design-controls-design-transfer-changes-and-the-design-history-file
Device-to-Cloud Connectivity	In a device to cloud communication model, the IoT device connects directly to an Internet cloud service like an application service provider to exchange data and control message traffic. This approach frequently takes advantage of existing communications mechanisms like traditional wired Ethernet or Wi-Fi connections to establish a connection between the device and the IP network, which ultimately connects to the cloud service.	Isecurion	http://blog.isecurion.com/2017/05/11/iot-communication-protocols/
Digital Manufacturing	Digital Manufacturing is the application of digital technologies as the means to plan, assess and operate a manufacturing system. Digital Manufacturing requires that the right information, is in the right place, at the right time, in the right format for the optimization of decisions and the efficient manufacture of a product.	Auburn University	
Disruptive Technologies	Disruptive technology refers to any enhanced or completely new technology that replaces and disrupts an existing technology, rendering it obsolete. It is designed to succeed a similar technology that is already in use. Disruptive technology applies to hardware, software, networks and combined technologies.	Techopedia	https://www.techopedia.com/definition/14341/disruptive-technology
Dynamic Visualization	Dynamic visualization simply refers to those representations that go beyond traditional static forms, such as printed media. The defining characteristics of dynamic visualization are animation, interaction and real-time. Dynamic visualization is a mundane tool in several fields, such as geology, medical science, statistics and economics (especially in the form of visual data mining).	Markku Reunanen	http://www.kameli.net/marg/wp-content/uploads/2013/02/dynamic-english.pdf
E-procurement	E-procurement (electronic procurement, sometimes also known as supplier exchange) is the business-to-business or business-to-consumer or business-to-government purchase and sale of supplies, work, and services through the Internet as well as other information and networking systems, such as electronic data interchange and enterprise resource planning.	Wikipedia	https://en.wikipedia.org/wiki/E-procurement
Electronic Product Data Management (ePDM)	Product data management (PDM) is the use of software to manage product data and process-related information in a single, central system. This information includes computer-aided design (CAD) data, models, parts information, manufacturing instructions, requirements, notes and documents. The ideal PDM system is accessible by multiple applications and multiple teams across an organization and supports business-specific needs.	Siemens	https://www.plm.automation.siemens.com/global/en/our-story/glossary/product-data-management/13214
Engineering Change	Engineering changes refer to the documentation of changes from the identification of the required change, through the planning and implementation of the change, and culminating with the closure of the issue.	Aligni (with modification)	https://www.aligni.com/doc/engineering-change-management/



Engineering Change Order (ECO)	An Engineering Change Order (ECO) is a documentation packet that outlines the proposed change, lists the product or part(s) that would be affected and requests review and approval from the individuals who would be impacted or charged with implementing the change. ECOs are used to make modifications to components, assemblies, associated documentation and other types of product information.	Arena	https://www.arenasolutions.com/resources/articles/engineering-change-order/
Engineering Change Request (ECR)	An engineering change request (ECR) describes an identified problem or suggested enhancement with a product. The ECR is used to record the discussion surrounding the issue, determine the affected parts, and evaluate the impact of the required changes. Once closed, the ECR persists as a permanent record to help tell the story of the development and evolution of a product.	Aligni	https://www.aligni.com/doc/engineering-change-management/
Enterprise Asset Management (EAM)	Enterprise asset management (EAM) involves the management of the maintenance of physical assets of an organization throughout each asset's lifecycle. EAM is used to plan, optimize, execute, and track the needed maintenance activities with the associated priorities, skills, materials, tools, and information.[1] This covers the design, construction, commissioning, operations, maintenance and decommissioning or replacement of plant, equipment and facilities.	Wikipedia	https://en.wikipedia.org/wiki/Enterprise_asset_management
Enterprise Portal	The enterprise information portal (EIP), also known as a business portal, is a concept for a Web site that serves as a single gateway to a company's information and knowledge base for employees and possibly for customers, business partners, and the general public as well. Access to enterprise portals is controlled through passwords and the data is protected behind a firewall.	SearchSAP	https://searchsap.ectarget.com/definition/enterprise-information-portal
Enterprise Resource Planning (ERP)	Enterprise resource planning (ERP) is the integrated management of main business processes, often in real-time and mediated by software and technology. ERP is usually referred to as a category of business management software — typically a suite of integrated applications—that an organization can use to collect, store, manage, and interpret data from these many business activities.	Wikipedia	https://en.wikipedia.org/wiki/Enterprise_resource_planning
First Article	When a product of any kind is in the development stages – regardless of whether it is being designed for civilian or government (military or aerospace) use – it goes through several design iterations. When the design has been finalized and specifications for its manufacture finalized, the product must be manufactured for the first time using component parts designed for the purpose. The very first part (or assemblage of parts) to be manufactured is a “first article.”	Nel PreTech	https://nelpretech.com/first-article-inspection/overview/
First Article Inspection (FAI)	A first article inspection (FAI) is a formal method of providing a reported measurement for a given manufacturing process. Both the supplier and purchaser perform the First Article on the ordered product. The evaluation method consists of comparing supplier and purchasers results from measuring the properties and geometry of an initial sample item against given specifications.	Wikipedia	https://en.wikipedia.org/wiki/First_article_inspection
Gage Repeatability and	Gage Repeatability and Reproducibility (Gage R&R) is a methodology used to define the amount of variation in the measurement data due to the measurement system. It then compares measurement variation to the total variability	Quality One	https://quality-one.com/grr/



Reproducibility (Gage R&R)	observed, consequently defining the capability of the measurement system. Measurement variation consists of two important factors, repeatability and reproducibility. Repeatability is due to equipment variation and reproducibility is due to inspector or operator variation.		
Government Contractor	A government contractor is a company (privately owned or publicly traded but not a state-owned enterprise) – either for profit or non-profit – that produces goods or services under contract for the government.	Wikipedia	https://en.wikipedia.org/wiki/Government_contractor
Horizontal and Vertical System Integration	Horizontal integration means networking between individual machines, items of equipment or production units. Vertical integration networks beyond traditional production hierarchy levels – from the sensor to the business level of the company.	Copadata	https://www.copadata.com/en/hmi-scada-solutions/horizontal-vertical-integration/smart-factory-23/
Industrial Internet of Things (IIoT)	The industrial internet of things (IIoT) refers to the extension and use of the internet of things (IoT) in industrial sectors and applications. The industrial internet of things (IIoT) refers to interconnected sensors, instruments, and other devices networked together with computers' industrial applications, including manufacturing and energy management. This connectivity allows for data collection, exchange, and analysis, potentially facilitating improvements in productivity and efficiency as well as other economic benefits. The IIoT is an evolution of a distributed control system (DCS) that allows for a higher degree of automation by using cloud computing to refine and optimize the process controls.	Wikipedia	https://en.wikipedia.org/wiki/Industrial_internet_of_things
Information Technology (IT)	The use of any computers, storage, networking and other physical devices, infrastructure and processes to create, process, store, secure and exchange all forms of electronic data. Typically, IT is used in the context of enterprise operations as opposed to personal or entertainment technologies.	Search Data Center	https://searchdatacenter.techtarget.com/definition/IT
Initial Graphics Exchange Specification (IGES)	The Initial Graphics Exchange Specification (IGES) is a vendor-neutral file format that allows the digital exchange of information among computer-aided design (CAD) systems.	Wikipedia	https://en.wikipedia.org/wiki/IGES
Inspection	An organized examination or formal evaluation exercise. In engineering activities inspection involves the measurements, tests, and gauges applied to certain characteristics in regard to an object or activity. The results are usually compared to specified requirements and standards for determining whether the item or activity is in line with these targets, often with a Standard Inspection Procedure in place to ensure consistent checking. Inspections are usually non-destructive.	Wikipedia	https://en.wikipedia.org/wiki/Inspection
Inspection Plan	Provides instructions on how an inspection of a product is to take place. Inspection plans provide details about what characteristics must be tested to ensure the product meets specifications. An inspection plan contains inspection elements that represent the specific data that you want to collect and report on. It also contains information about when and how often you collect that data.	Business Dictionary & Oracle	http://www.businessdictionary.com/definition/inspection-plan.html
Inspection Planning	A document that provides instructions on how an inspection of a product is to take place. Inspection plans provide details about what characteristics must be tested in order to	Business Dictionary	http://www.businessdictionary.com/definition/



	ensure the quality of the product, as well as specific metrics and measurements that must be achieved in order for the product to be judged in compliance with standards.		tion/inspection-plan.html
Intellectual Property (IP)	Intellectual property (IP) is a category of property that includes intangible creations of the human intellect. Intellectual property encompasses two types of rights: industrial property rights (trademarks, patents, designations of origin, industrial designs and models) and copyright.	Wikipedia	https://en.wikipedia.org/wiki/Intellectual_property
Intelligent Manufacturing System	Intelligent manufacturing (IM) means using the combined intelligence of people, processes and machines, to impact the overall economics of manufacturing. Its purpose is to optimize manufacturing resources, improve business value and safety, and reduce waste – both on the floor and in back office operations, all while meeting customer demands for delivery and quality.	Pyramid Solutions	https://pyramidsolutions.com/2016/05/what-is-intelligent-manufacturing/
Internet of Things (IoT)	The Internet of things (IoT) is the extension of Internet connectivity into physical devices and everyday objects. Embedded with electronics, Internet connectivity, and other forms of hardware (such as sensors), these devices can communicate and interact with others over the Internet, and they can be remotely monitored and controlled.	Wikipedia	https://en.wikipedia.org/wiki/Internet_of_things
Inventory Management System (IMS)	A component of supply chain management, inventory management supervises the flow of goods from manufacturers to warehouses and from these facilities to point of sale. A key function of inventory management is to keep a detailed record of each new or returned product as it enters or leaves a warehouse or point of sale.	SearchERP	https://searcherp.technet.com/definition/inventory-management
IoT Gateway	An internet of things gateway (IoT gateway) is a device that lets legacy industrial devices report data using the internet, participating in the internet of things concept, as well as enabling technologies or systems with disparate protocols interact with one another. An internet of things gateway allows a device to report data using its sensors to a remote location.	Techopedia	https://www.techopedia.com/definition/32198/internet-of-things-gateway-iiot-gateway
Just-In-Time (JIT)	Just in time (JIT) inventory is a strategy to increase efficiency and decrease waste by receiving goods only as they are needed in the production process, thereby reducing inventory costs. In other words, JIT inventory refers to an inventory management system with objectives of having inventory readily available to meet demand, but not to a point of excess where you must stockpile extra products.	Study.com	https://study.com/academy/lesson/just-in-time-inventory-definition-advantages-examples.html
Manufacturing Bill of Materials (MBOM)	A manufacturing bill of materials (MBOM), also referred to as the manufacturing BOM, contains all the parts and assemblies required to build a complete and shippable product. MBOM is focused on the parts that are needed to manufacture a product. In addition to the parts list in an EBOM (engineering Bill of materials), the MBOM also includes information about how the parts relate to each other.	Wikipedia	https://en.wikipedia.org/wiki/Manufacturing_bill_of_materials
Manufacturing Engineer (ME)	Manufacturing Engineering is a branch of professional engineering that shares many common concepts and ideas with other fields of engineering such as mechanical, electrical and industrial engineering. Manufacturing engineering requires the ability to plan the practices of manufacturing; to research and to develop tools, processes, machines and equipment; and to integrate the	Wikipedia	https://en.wikipedia.org/wiki/Manufacturing_engineering



	facilities and systems for producing quality products with the optimum expenditure of capital.		
Manufacturing Execution System (MES)	Manufacturing execution systems (MES) are computerized systems used in manufacturing, to track and document the transformation of raw materials to finished goods. MES provides information that helps manufacturing decision makers understand how current conditions on the plant floor can be optimized to improve production output. MES works in real time to enable the control of multiple elements of the production process (e.g. inputs, personnel, machines and support services).	Wikipedia	https://en.wikipedia.org/wiki/Manufacturing_execution_system
Manufacturing Process Planning (MPP)	The systematic determination of the detailed methods by which work pieces or parts can be manufactured economically and competitively from initial stages (raw material form) to finished stages (desired form)	Hong-Chao Zhang Texas Tech University	https://www.researchgate.net/publication/284188843_Manufacturing_Process_Planning
Military Specification (MIL-SPEC)	The United States Defense Standards, often called Military Standard, (MIL-STD), or Military Specification (MIL-SPEC), are used to help achieve standardization objectives by the U.S. Department of Defense. Defense Standards are also used by other non-Defense government organizations, technical organizations, and industry.	Wing Government Contracts	http://www.wingovermentcontracts.com/military-specifications.htm
Military Standard (MIL-STD)	The United States Defense Standards, often called Military Standard, (MIL-STD), or Military Specification (MIL-SPEC), are used to help achieve standardization objectives by the U.S. Department of Defense. Defense Standards are also used by other non-Defense government organizations, technical organizations, and industry.	Wing Government Contracts	http://www.wingovermentcontracts.com/military-specifications.htm
Model-Based	An approach which is based upon the usage of software models in order to develop or specify an application or platform.	IGI Global	https://www.igi-global.com/dictionary/model-based-approach/35014
Model-Based Definition (MBD)	The production of a complete digital definition of a product within a 3D model. A product's MBD includes a dataset comprising the model's 3D geometry and annotations.	Quintana, Rivest, Pellerin, Venne, & Kheddouci, 2010 (with modification)	
Model-Based Enterprise (MBE)	Model-based enterprise (MBE) is a term used in manufacturing, to describe a strategy where an annotated digital three-dimensional (3D) model of a product serves as the authoritative information source for all activities in that product's lifecycle.	Wikipedia	https://en.wikipedia.org/wiki/Model-based_enterprise
Model-Based Manufacturing	Model-Based Manufacturing (MBM): a production environment that uses the model created in the design process, eliminating the need to recreate the model and data to plan, produce, fabricate, assemble, inspect and certify products.	NIST MBx Workshop	
Model-Based Quality	Model-Based Quality (MBQ): the conformance of the physical product and process to the requirements of digital product definitions and process specifications using measurement planning, execution, and evaluation in combination with three-dimensional (3D) annotated models and associated data.	NIST MBx Workshop	
Model-Based x (MBx)	Model Based "x" or "MBx" is a designation used to represent the constituent components and disciplines of the model-based enterprise (MBE).	NIST MBx Workshop	



Modelling	The representation, often mathematical, of a process, concept, or operation of a system, often implemented by a computer program.	Dictionary.com	https://www.dictionary.com/browse/modeling
Numerical Control (NC)	Numerical control, popularly known as the NC is very commonly used in the machine tools. Numerical control is defined as the form of programmable automation, in which the process is controlled by the number, letters, and symbols. In case of the machine tools this programmable automation is used for the operation of the machines.	Bright Hub Engineering	https://www.brighthubengineering.com/manufacturing-technology/55670-what-is-numerical-control-machine/
Operations Technology (OT)	the hardware and software dedicated to detecting or causing changes in physical processes through direct monitoring and/or control of physical devices such as valves, pumps, etc.	Wikipedia	https://en.wikipedia.org/wiki/Operational_Technology
Original Equipment Manufacturer (OEM)	An original equipment manufacturer (OEM) makes equipment or components that are then marketed by its client, another manufacturer or a reseller, usually under that reseller's own name. An OEM may make complete devices or just certain components, either of which can then be configured by the reseller.	Inc.	https://www.inc.com/encyclopedia/original-equipment-manufacturer-oem.html
Performance Data	Data on the manner in which a given substance or piece of equipment performs during actual use.	The Free Dictionary	https://encyclopedia2.thefreedictionary.com/performance+data
Predictive Analytics	Predictive analytics encompasses a variety of statistical techniques from data mining, predictive modelling, and machine learning that analyze current and historical facts to make predictions about future or otherwise unknown events.	Wikipedia	https://en.wikipedia.org/wiki/Predictive_analytics
Probability Analytics	a collection of methods of uncertainty propagation for making qualitative and quantitative calculations in the face of uncertainties of various kinds. It is used to project partial information about random variables and other quantities through mathematical expressions.	Wikipedia	https://en.wikipedia.org/wiki/Probability_bounds_analysis
Process Plan	the systematic determination of methods and means to manufacture a part. It is a description of the production process and how the product will be produced. Process planning converts design information into the process steps and instructions to powerfully and effectively manufacture products.	Civil Service India & Science Direct	https://www.civilserviceindia.com/subject/Management/notes/process-planning.html
Product and Manufacturing Information (PMI)	Product and manufacturing information, also abbreviated PMI, conveys non-geometric attributes in 3D computer-aided design (CAD) and Collaborative Product Development systems necessary for manufacturing product components and assemblies. PMI may include geometric dimensions and tolerances, 3D annotation (text) and dimensions, surface finish, and material specifications. PMI is used in conjunction with the 3D model within model-based definition to allow for the elimination of 2D drawings for data set utilization.	Wikipedia	https://en.wikipedia.org/wiki/Product_and_manufacturing_information
Product Drawings	Drawings that detail the manufacturing and assembly of products.	Wikipedia	https://en.wikipedia.org/wiki/Production_drawing
Product Lifecycle Management (PLM)	represents an all-encompassing vision for managing all data relating to the design, production, support and ultimate disposal of manufactured goods. PLM can be thought of as both (a) a repository for all information that affects a product, and (b) a communication	Product Lifecycle Management	https://www.product-lifecycle-management.com/



	process between product stakeholders: principally marketing, engineering, manufacturing and field service. The PLM system is the first place where all product information from marketing and design comes together, and where it leaves in a form suitable for production and support.		
Product Lifecycle Management (PLM)	Product lifecycle management (PLM) is the process of managing the entire lifecycle of a product from inception, through engineering design and manufacture, to service and disposal of manufactured products. PLM integrates people, data, processes and business systems and provides a product information backbone for companies and their extended enterprise.	Wikipedia	https://en.wikipedia.org/wiki/Product_life_cycle
Product Models	Product models are containers of the nominal geometry and any additional information needed for production and support. The additional data is defined as Product Manufacturing Information (PMI) and can include geometric dimensions and tolerances (GD&T), material specifications, component lists, process specifications, and inspection requirements.	Lubell, J., Chen, K., Frechette, S., Horst, J, & Huang, P., 2012	
Product Requirements	Product requirements are established in a product requirements document (PRD) and defines the value and purpose of a product or feature. It is written by the product manager to communicate what is being made, who it is for, and how it benefits the end user. It is often confused with a market requirements document (MRD), but they are different. An MRD should be created before a PRD so you can document what the customer needs and wants from your product or service before you define the requirements.	Aha!	https://www.aha.io/roadmapping/guide/requirements-management/what-is-a-good-product-requirements-document-template
Purchase Order (PO)	A buyer-generated document that authorizes a purchase transaction. When accepted by the seller, it becomes a contract binding on both parties. A purchase order sets forth the descriptions, quantities, prices, discounts, payment terms, date of performance or shipment, other associated terms and conditions, and identifies a specific seller.	Business Dictionary	http://www.businessdictionary.com/definition/purchase-order.html
Quality Assurance (QA)	Quality assurance (QA) is any systematic process of determining whether a product or service meets specified requirements. QA establishes and maintains set requirements for developing or manufacturing reliable products. A quality assurance system is meant to increase customer confidence and a company's credibility, while also improving work processes and efficiency, and it enables a company to better compete with others.	Search Software Quality	https://searchsoftwarequality.techtarget.com/definition/quality-assurance
Quoting	A formal statement of promise (submitted usually in response to a request for quotation) by potential supplier to supply the goods or services required by a buyer, at specified prices, and within a specified period. A quotation may also contain terms of sale and payment, and warranties. Acceptance of quotation by the buyer constitutes an agreement binding on both parties.	Business Dictionary	http://www.businessdictionary.com/definition/quotation.html
Radio Frequency Identification (RFID)	Radio Frequency Identification (RFID) technology uses radio waves to identify people or objects. There is a device that reads information contained in a wireless device or "tag" from a distance without making any physical contact or requiring a line of sight.	Homeland Security	https://www.dhs.gov/radio-frequency-identification-rfid-what-it



Real-time Data	Real-time data refers to data that is presented as it is acquired.	Techopedia	https://www.techopedia.com/definition/31256/real-time-data
Recurring Manufacturing	An ongoing, systematic series of mechanical or chemical operations that produce or manufacture something. This is describing a current and active customer-supplier relationship.		
Relational Database	A relational database is a type of database that stores and provides access to data points that are related to one another. Relational databases are based on the relational model, an intuitive, straightforward way of representing data in tables. In a relational database, each row in the table is a record with a unique ID called the key. The columns of the table hold attributes of the data, and each record usually has a value for each attribute, making it easy to establish the relationships among data points.	Oracle	https://www.oracle.com/database/what-is-a-relational-database/
Request for Quote (RFQ)	A request for quote is a standard business process whose purpose is to invite suppliers into a bidding process to bid on specific products or services. RfQ generally means the same thing as Call for bids (CfB) and Invitation for bid (IfB). An RfQ typically involves more than the price per item. Information like payment terms, quality level per item or contract length may be requested during the bidding process.	Wikipedia (with modification)	https://en.wikipedia.org/wiki/Request_for_quotation
RFQ Requirements	A Request for Quote (RFQ) typically involves more than the price per item. Information like payment terms, quality level per item or contract length may be requested during the bidding process. RFQs include the specifications of the items/services to make sure all the suppliers are bidding on the same item/service. Logically, the more detailed the specifications, the more accurate the quote will be and comparable to the other suppliers.	Wikipedia	https://en.m.wikipedia.org/wiki/Request_for_quotation
Secure File Exchange	Secure file transfer is data sharing via a secure, reliable delivery method. It is used to safeguard proprietary and personal data in transit and at rest.	Globalscape	https://www.globalscape.com/solutions/secure-file-transfer
Simulation	The computer-based modeling of a real production system. Simulation allows organizations in the manufacturing industry to analyze and experiment with their processes in a virtual setting, reducing the time and cost requirements associated with physical testing. Inventory, assembly, transportation and production can be assessed within a simulation model, resulting in information that can preserve or improve value at the lowest possible cost.	FlexSim	https://www.flexsim.com/manufacturing-simulation/
Small-to-Medium Enterprise (SME)	Small and medium-sized enterprises (SMEs) are non-subsidiary, independent firms which employ fewer than a given number of employees. This number varies across countries. The most frequent upper limit designating an SME is 250 employees, as in the European Union. However, some countries set the limit at 200 employees, while the United States considers SMEs to include firms with fewer than 500 employees.	Organization for Economic Co-operation and Development	https://stats.oecd.org/glossary/detail.asp?ID=3123
Small-to-Medium Manufacturer (SMM)	Small and medium-sized Manufacturers (SMMs) are non-subsidiary, independent firms which employ fewer than a given number of employees. This number varies across countries. The most frequent upper limit designating an SMM is 250 employees, as in the European Union. However, some countries set the limit at 200 employees,	Organization for Economic Co-operation and Development	https://stats.oecd.org/glossary/detail.asp?ID=3123



	while the United States considers SMMs to include firms with fewer than 500 employees.	(with modification)	
Standard for the Exchange of Product Model Data (STEP)	STEP-File is the most widely used data exchange form of STEP. ISO 10303 can represent 3D objects in Computer-aided design and related information. Due to its ASCII structure, a STEP-file is easy to read, with typically one instance per line.	NPD Solutions	https://en.wikipedia.org/wiki/ISO_10303-21
Subordinate Supplier	A supplier who provides goods, products or services to another supplier.	Definitions.net	https://www.definitions.net/definition/sub-supplier
Supplier	A party that supplies goods or services. A supplier may be distinguished from a contractor or subcontractor, who commonly adds specialized input to deliverables. Also called vendor.	Business Dictionary	http://www.businessdictionary.com/definition/supplier.html
Supplier Relationship Management (SRM)	The term "supplier relationship management (SRM)" refers to the practice and process for interacting with suppliers. Most supply professionals view SRM as an organized approach to defining what they need and want from a supplier and establishing and managing the company-to-company (or procurement-to-sales) link to obtain these needs. Even when there is no conscious procurement-to-supplier's sales link, there still are practices and processes in play — informal as they might be. Formal or not, academic and consulting company research shows that organized approaches to supply and suppliers produce positive sourcing results.	Institute for Supply Management	https://www.instituteforsupplymanagement.org/content.cfm?ItemNumber=20233&SSO=1
Supply Chain Management (SCM)	Supply chain management (SCM) is a total system approach to managing the entire flow of information, materials, and services from raw-material suppliers through factories and warehouses to the end customer.	Operations and Supply Chain Management Textbook	
Technical Data Package (TDP)	A technical description of an item adequate for supporting an acquisition strategy, production, engineering, and logistics support. The description defines the required design configuration and procedures to ensure adequacy of item performance. It consists of all applicable technical data such as drawings, associated lists, specifications, standards, performance requirements, quality assurance provisions, and packaging details.	as defined in Ballistic Missile Defense by U.S. Department of Defense	https://definedterm.com/technical_data_package
Three-Dimensional (3D)	A three-dimensional shape is a figure or an object or that has three dimensions – length, width and height. Unlike two-dimensional shapes, three-dimensional shapes have thickness or depth.	Splash Math	https://www.splashmath.com/math-vocabulary/geometry/3-dimensional
Three-Dimensional Portable Document Formats (3D PDFs)	Portable Document Format (PDF) is a file format used to present and exchange documents reliably, independent of software, hardware, or operating system. Invented by Adobe, PDF is now an open standard maintained by the International Organization for Standardization (ISO). PDFs can contain links and buttons, form fields, audio, video, and business logic. PDF allows for the embedding of three-dimensional (3D) objects. They can also be signed electronically and are easily viewed using free software.	Adobe (with modification)	https://acrobat.adobe.com/us/en/acrobat/about-adobe-pdf.html with modification
Tooling Plan	Tooling, also known as machine tooling, is the process of acquiring the manufacturing components and machines needed for production.	SearchERP	https://searcherp.target.com/definition/tooling



	The common categories of machine tooling include fixtures, jigs, gauges, molds, dies, cutting equipment and patterns.		
Transportation Management System (TMS)	A transportation management system (TMS) is a subset of supply chain management (SCM) that deals with the planning, execution and optimization of the physical movements of goods. In simpler terms, it's a logistics platform that enables users to manage and optimize the daily operations of their transportation fleets.	SearchERP	https://searcherp.target.com/definition/transportation-management-system-TMS
Two-Dimensional (2D)	A two-dimensional object or figure is flat rather than solid so that only its length and width can be measured.	Collins Dictionary	https://www.collinsdictionary.com/dictionary/english/two-dimensional
User Interface (UI)	A user interface (UI) is a conduit between human and computer interaction – the space where a user will interact with a computer or machine to complete tasks. The purpose of a UI is to enable a user to effectively control a computer or machine they are interacting with, and for feedback to be received in order to communicate effective completion of tasks.	Every Interaction	https://www.everyinteraction.com/definition/user-interface/
Virtual Product Development (VPD)	The practice of developing and prototyping products in a completely digital 2D/3D environment. VPD typically takes place in a collaborative, web-based environment that brings together designers, customers/consumers, and value chain partners around a single source of real-time product "truth". VPD enables practitioners to arrive at the right idea more quickly, and to accurately predict its performance in both manufacturing and retail settings, ultimately minimizing time to value, market failure potential, and product development costs.	Wikipedia	https://en.wikipedia.org/wiki/Virtual_product_development
Wearable Technology	Wearable technology is a category of electronic devices that can be worn as accessories, embedded in clothing, implanted in the user's body, or even tattooed on the skin. The devices are hands-free gadgets with practical uses, powered by microprocessors and enhanced with the ability to send and receive data via the Internet.	Investopedia	https://www.investopedia.com/terms/w/wearable-technology.asp
Work-In-Progress (WIP)	Work in progress (WIP) is a form of inventory, usually unfinished goods which still require further work, processing, assembly and or inspection. This type of inventory is usually found within steps or sub-processes of a production process. Only raw materials which have commenced to move through their value adding processes can be classified as WIP. Raw materials which have still not been worked with are still classified as raw materials.	Lean Manufacture	http://www.leanmanufacture.net/leanterm/wip.aspx

IV.XII. APPENDICES

Appendix A: OEM Interview Guide

Appendix B: Team Interview Guide

Appendix C: Papers Published and Presentations Made

Appendix D: Content on Website

Appendix E: Website Architecture