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DMDII
DIGITAL MANUFACTURING AND
DESIGN INNOVATION INSTITUTE



RECON Services

Phase 4 Report: Standards Development and Promulgation

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1 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 document.

API	Application Program Interface. APIs are software routines used by programmers to create custom programs/scripts that interface with other software or data files. APIs can be used to extend software applications beyond their “out of the box” functionality. APIs can also be used to extract data from the files that software applications create. One context in this case is that native CAD files can be opened to extract or input information developed in the AVM program.
AVM	Adaptive Vehicle Make. Initially a DARPA research program, now transitioned to become a DMDII research program whose intent is to automate certain product design and manufacturing planning and execution functions.
CAD	Computer Assisted Design. CAD software is used to design products as solid models and create drawings based on those models. (Drawings are current state of technology; in the past drawings were the only requirement.) (See MBD for more)
DARPA	Defense Advanced Research Projects Agency.
DAT	Design Assistant Tool. An application created for DMDII AVM program which will operate as a designer works on CAD product design to automate some or all the designer’s duties. The DAT will enforce pre-determined standards as the design progresses.
DFM/DFA	Design for Manufacturability/Design for Assembly. Using consideration for design practices that support the improved (less cost) manufacturability of products.
DMDII	Digital Manufacturing and Design Innovation Institute. DMDII is a national research foundation targeting improvement in the national manufacturing base through the improvement of digital design data and the use of that data.
GD&T	Geometric Dimensioning and Tolerancing is a method of communicating requirements for the manufacture of products made in manufacturing environments.

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IGES	Initial Graphics Exchange Standard. IGES is a precursor to STEP where geometry is defined as 3-D wireframe and surfaces. IGES is limited in its ability to carry more intelligent product data.
Kernels	CAD modeling Kernels are the base programming applications that CAD software systems are built upon. The Kernel software is the geometric engine that defines shape, surfaces and topology. The CAD software provides the graphic user interface (GUI) that allows designers to define the geometric shape and add other attributes to the design. ACIS: Cad modeling Kernel that is the basis for several Cad modeling systems including CATIA. ACIS and CATIA are both products of Dassault Systems. Granite: CAD Modeling Kernel that is the basis for PTC Creo CAD modeling system. It is unclear if any other CAD systems use this kernel. Parasolid: CAD Modeling Kernel used and owned by Siemens NX. Solidworks and others use Parasolid. Open Cascade: Open Source CAD modeling kernel. It is unclear if any commercial CAD systems utilize this kernel.
MBD	Model Based Definition. (3D Product Definition) A 3D annotated CAD model and its associated data elements that fully define the product definition in a manner that can be used effectively by all downstream customers in place of a traditional drawing. (A component of MBE.)
MBE	Model Based Enterprise. A fully integrated and collaborative environment founded on 3D product definition detail and shared across the enterprise; to enable rapid, seamless, and affordable deployment of products from concept to disposal.
PMI	Product Manufacturing Information. PMI is used on 2D and 3D product documentation. Several types of data entities comprise PMI including Annotations (both 2D and 3D), Attributes/Parameters/Properties stored within the model or in external data files.

STEP the Standard for the Exchange of Product Model Data, is a comprehensive ISO standard (ISO 10303) that describes how to represent and exchange digital product information.

AP203 (Configuration controlled 3D designs of mechanical parts and assemblies)

AP214 (Core data for automotive mechanical design processes)

AP238 (STEP-NC)

AP242 (ISO 10303-242) “Managed model based 3D engineering” is the merging of two ISO standards including AP203 and AP214, along with other enhancements.

Related (AP239, Product Lifecycle Support) (Exchange of PLM Data) (PLCS)

STL (STereo Lithography). STL is a geometric file type that is used in 3-D Printing.

QAP Quality Assurance Provision. QAPs are provided as supplemental documentation on some products to define Key and critical inspection/test requirements and the frequency of those tests. Other special quality testing requirements and methods might be documented here as well.

QIF 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 PLM/PDM domain.

XML Extensible Markup Language is a markup language that defines a set of rules for encoding documents in a format that is both human-readable and machine-readable.

2 Introduction

AVM Task three, Standards Development and Promulgation, was charged with creating a set of branded DMDII standards for the DMDII community centered around the AVM projects as defined in various contracts awarded in 2014. The projects were primarily focused on model based design and engineering workflow and tools to provide services that would improve aspects of these activities. They are as follows:

- 14-01-06: Structural Composites - Blade Multidisciplinary Design and Analysis
 - Summary: Composite analytics tools for design and engineering with integrated planning and costing.
- 14-01-07: Automated Manufacturability Analysis Software - “ANA”: Early intervention to aid the conceptual design process
 - Summary: Provide tools interactive tools that integrate in the design process to determine the manufacturability of a part and give feedback to the designer at the conceptual design phase.
- 14-01-09: Integration of AVM iFAB Tools for Industrial Use
 -
 - Summary: Maturing various AVM iFAB technologies including the component library for PTC Windchill PLM system and iFAB Manufacturability Analysis System (MAS)
- 14-01-10: Elastic Cloud-Based Make
 - Summary: Transition multiple of the manufacturing analysis tools developed under the AVM program to the DMDII DMC platform.
- 14-02-02: Mind the Gap- Filling the Gap between CAD and CNC with Engineering Services
 - Summary: Develop cloud based services for optimizing and monitoring CNC machining using browser based visualization compatible with mobile platforms.
- 14-02-04: Automated Assembly Planning: From CAD model to Virtual Assembly Process
 - Summary: Develop an analytical tool to automatically transform a CAD assembly from geometries to a set of assembly instructions with minimal user interaction.
- 14-02-05: Automatic tolerancing of mechanical assemblies from STEP AP203: Completion of AVM tasks
 - Summary: Develop analytical tools to automatically prescribe a first order Geometric Dimension and Tolerancing (GD&T) schemes of mechanical assemblies.

The DMDII projects span a broad spectrum of design and engineering concerns. The projects were originally conceived without any requirement to use standards for interoperability, with the notable exception of *Mind The Gap*, since it was led by

some of the principle contributors to the STEP-NC standard. The lack of upfront requirements meant that the projects were using a wide range of proprietary information models with no uniformity.

The second area of concern was how these projects would be able to interoperate with each other given a large variation in design choice and software architecture. The development of a standards based solution in isolation of a software architecture was viewed as providing a partial solution that would impede adoption since it is still lacking the mechanism to compose the various services, resulting in a set of disparate technologies that could use similar information models, but impossible for the customer to use.

The first phase of the project identified the drivers for standards adoption and how various industries and companies have been impacted by the choice to utilize standards or pursue proprietary solutions. The analysis looks at various types of standards and the definition of *Openness* and the differences between formal versus consortia and forum based standardization processes.

We also researched the prevalent direction and best practices of the leading Industrial Internet Architecture groups to determine how to position the recommendations to achieve the greatest value within the AVM projects as well as with the emergent technologies in the Industrial Internet of Things and Digital Thread activities. Meetings were held with numerous companies and individuals to determine how technology has been consumed in both manufacturing and other related domains and the best strategy for the manufacturing community.

We reviewed the common threads in the Industrie 4.0 and China 2025 initiatives going on in Europe and China respectively. There are many similarities and differences. There are many unique capabilities that can be leveraged from the United States as the leader in software technology and architecture as well as architectural patterns used in data center orchestration that are applicable, but have not presently been considered for use in the industrial domain.

The findings are compiled into a recommendation for standards adoption and system architecture that are included as the last three sections of this document with the conclusion of the branded set of standards and the architecture that will best serve the industry. This is our synthesis and opinion of how we believe the industry will find greatest utility and value from the AVM technologies.

2.1 Executive Summary

The manufacturing industry is going through an industrial revolution. Cyber-physical and Autonomous systems, Industrial Internet of Things, and Digitization are the primary topics being discussed. A revolution requires more than technology, it requires new business models and new ways of interacting with customers and new

customer expectations that will create the necessity for the revolution. Without the pull, there will be efficiency gains, but these will be incremental improvement, not revolution.

Much of the industrial internet focus has been focused on cost savings enabled by smart manufacturing. The latest NIST report has estimated the savings at \$57.4 billion annually. [1] Although this is impressive, cost savings alone will not produce a sustainable economic engine that will fulfill the promises of a true revolution. The next revolution will be based on new engines of innovation and agility that will necessitate efficiency - but will also require on-demand production, human machine collaboration, and outcome based economies culminating in autonomous pull based manufacturing that is continuously self-optimizing. [2]

To have an engine of innovation, agility is prerequisite. Innovation will be embodied by a product designer's ability to express the intent of the product and have technology determine the optimal way to produce it utilizing the manufacturing processes and materials available. Some of the optimization will be curated by humans, who will provide expert opinion and strategies. Feedback loops will allow the technology to learn from the experts and provide input to continuous improvement systems as the system moves towards increased autonomy.

The AVM 14-XX project calls are centered on the design and engineering phases of manufacturing. These calls provide some foundational work to demonstrate the capabilities necessary to enable innovation and agility discussed above. We have analyzed each project to determine what is required to enable the designer and engineer to ensure manufacturability, assembly, quality, functionality, serviceability and reuse of components at end of life.

To accomplish these goals, the industry must embrace rapid software innovation for these technologies to flourish. The current manufacturing market is siloed and most of the technology is proprietary. This is a similar situation to the software industry around 20 years ago, when proprietary technology gave way to open source and the dot-com and internet technology began to innovate exponentially.

To get the greatest economies of scale, open standards will be a prerequisite; allowing multiple unrelated parties to collaborate and experiment to create a rich ecosystem of solutions. Along with the standards will come experimental data and open platforms so small companies will be able to provide solutions without having to cross an impossibly high threshold.

2.1.1 Findings

In all but one of the AVM 14-XX projects, standards were not considered as a requirement since it was not written in the project calls. Most projects have taken

the path of greatest efficiency and used technologies that they were the most familiar with and were best fit for purpose.

The current Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), and Computer Aided Engineering (CAE) applications, referred to generally as CAX, have been built around assumptions of a proprietary ecosystem of applications that interact with each other inside a close-knit group of partners.

The current vendor space is small and therefore has been little impetus to adopt standards, but this is rapidly changing with new companies entering the design and engineering space, like OnShape and Cad.ai,. The largest benefit occurs when there are many vendors so the N-squared connections between companies and their products becomes sufficiently costly and burdensome that standards based approach becomes a requirement for market efficiencies.

Open standards that provide semantic meaning allow for a larger number of companies to participate since a common dictionary has been created for all participants, creating a broader field of innovation. Semantic standards provide information models that specify the context and meaning of the data, not just the structure and are required for analysis and reasoning on the data. To analyze data one must know what it means and what it is related to. Without semantic standards, an unstructured approach is usually taken and the discovery of meaning after the fact take significantly longer.

Standards research shows that standards have created many multi-billion dollar industries in information technology sector where the adopters significantly outpaced the proprietary solutions.

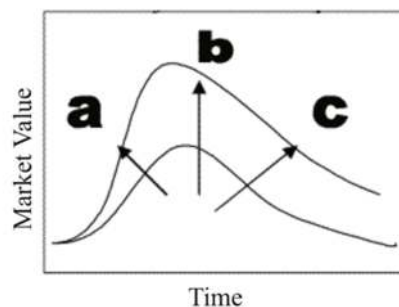


Figure 1: Potential for Standards Impact on Market Curve

The illustration shows the following three areas of market impact: [3]

- A: The initial market size increases faster with standards
- B: The size of the entire market is greater
- C: The market lasts longer and is more durable

Standards development and adoption must be driven from market needs. The first step is to demonstrate the business value of the technology the standard enables and begin to get an initial ecosystem constructed with early adopters. There are some promising service based offerings for digital manufacturing and all the smaller companies are requesting a need for open systems and standards.

In numerous interviews and discussion with leading systems architects at conferences like the Industrial Internet Consortium, IoT World Conference, and NSF Cybermanufacturing, the consensus was that we must move to a federated set of services in the same way other industries, such as finance and media, have already realized to achieve the goals of smart manufacturing. A siloed approach will only provide incremental change and the restrictive relationships will be an impediment to enabling new innovations.

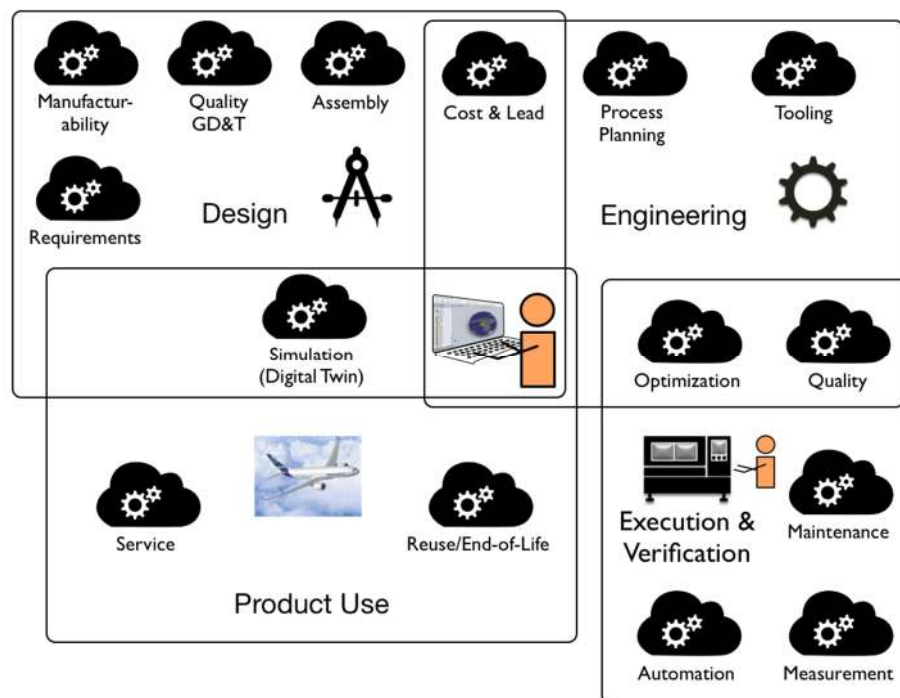


Figure 2: Manufacturing services architecture

The proposed architecture provides a set of composable services that can be integrated to provide a desired outcome where the inputs and outputs of each service will be open standards. The solution utilizes open standards for the communication of information and a common identifier scheme to connect various aspects of the models where multiple standards and specifications are required.

The security aspects of these services cannot be minimized; there are many organizations working on this problem and these concerns are being addressed in international open standards groups. Secure services require the following concerns to

be addressed: secure communications, secure storage, secure analytics, federated identity, federated chain-of-trust, and protection of IP using distributed data ownership and provenance for a federated service architecture to be successful.

Composable internet or cloud based services are required because the nature of the problems being addressed are internet scale. The complexity of the data and the models have exceeded the capabilities of an average on site information technology department. To manage and the cost of the solution, it will require economies of scale to provide a reasonable price to value offering. Providing the technology as a service means that the small to medium enterprise can now avail themselves of the same technology as the large enterprises and can be effective and participate in the new economies.

A natural byproduct of a completely standards based composable infrastructure is it fulfills the needs for Long Term Archival and Retrieval (LOTAR) since all the documents are stored in open formats and the data storage, chain of trust, and provenance requirements needed to implement federated services will serve both purposes. Data Archival becomes another service, and when combined with lifecycle data capture, allows for greater traceability beyond the original requirements. The standards that are recommended in this report have followed the recommendations of LOTAR, ASD, AIA, as well as other groups for the foundation since there has been significant work already done in this area and the concepts are well aligned.

The STEP community has covered a lot of ground with their current set of standards with AP242 Ed2 addressing a great deal of the product design and assembly requirements. AP233 and SysML can capture a portion the design intent when combined with the AP242 Ed2 kinematics and semantic PMI that has already harmonized with ASME product specifications.

From a software vendor and manufacturing enterprise perspective, the new ecosystem requires large scale, global services that can address the needs of many customers while maintaining fast response times and keeping cost at a reasonable level. These technologies are in use in many other industries and can be applied to manufacturing systems. We have seen the first shift in this direction with Autodesk and Dassault now offering service products. But the full complexity of the manufacturing data and systems will require a more advanced architecture than other domains to take manufacturing to the next level.

2.1.2 Opportunities

The most prevalent business models that have been evaluated to date are the cost and savings models. GE's power of one percent [4] and the NIST [1] report are examples. There are similar reports by Cisco [5] and McKinsey [6]. The operational and maintenance savings speak to how much inefficiency there is in the current

manufacturing processes, but not how the industry will address the next generation of design and on-demand production needs.

There is some initial evidence regarding the opportunity from some early movers in this space, GE and Rolls-Royce sell aircraft engines as a service and Caterpillar is doing the same with respect to earth moving equipment. We are seeing the movement to outcome based industries across multiple industries, for example in agriculture and transportation, where customer pays for an outcome vs a product.

The IT services companies are moving towards outcome based as well, where parallels can be drawn to contract and on-demand manufacturing. The progression is from a project based contract, to providing resources on a project as FTE for a period, to a transaction based project where the revenue from the job is linked to the customer's usage of the product. Outcome is where the customer only pays for results and usually has some revenue or upside sharing agreement where the service provider so the customer have effectively a partnership.

With outcome based models there are much greater upside opportunity for both parties as well as a shared concern in the success of the project. The risk to the service provider is much greater since a failure in a successful outcome will be borne by the provider. The risk in the diagram below is inverted from the customer perspective.

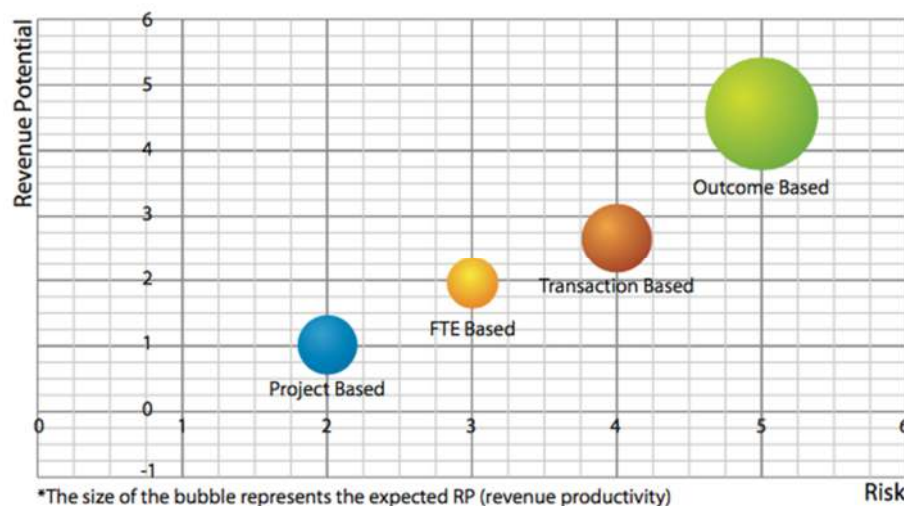


Figure 3: Risk vs Revenue Potential [7]

The benefit of outcome based is stronger relationships and better services. If one assumes the risk and ultimate benefit to all parties will be greater, then the sharing of the revenue and rewards becomes worth the change in compensation.

Outcome based economies will require the ability for many companies to provide quantifiable metrics that will allow for the accountability of multiple technical and physical services that all have a vested interest in the product being produced. As this moves to the next level of maturity, the systems will increase in autonomy with higher degrees of prescriptive analytics that will provide continuous optimization and demand based production reducing risk and increasing revenue.

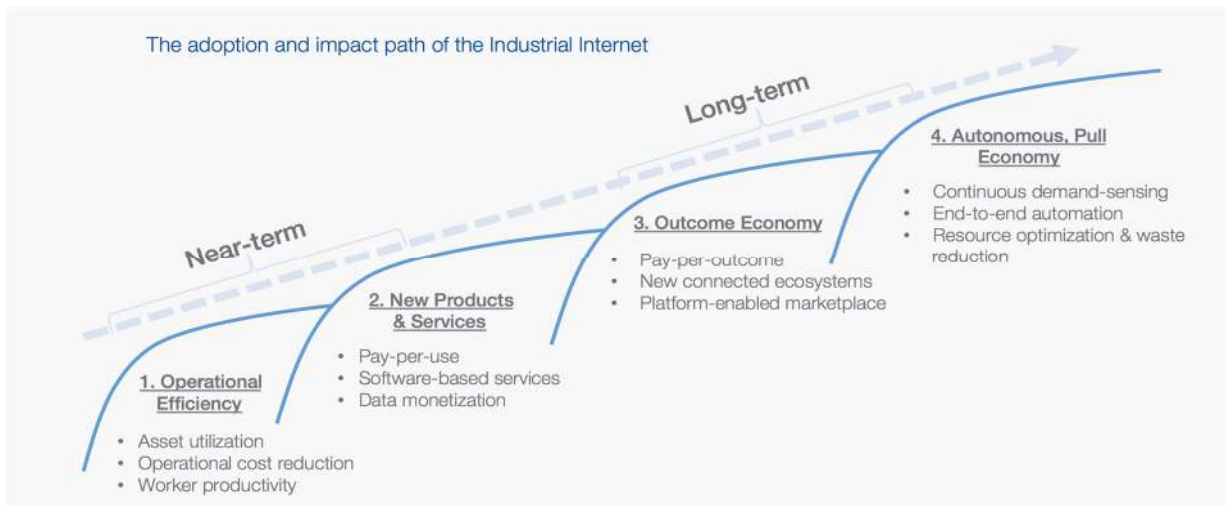


Figure 4: Adoption and impact of the industrial internet [2]

We are still far from realizing these systems, but the groundwork is being laid for the enabling technologies. Digitization is mandatory; all documents must be digital and all data must be in a standardized semantic model so we have an effective ecosystem. Full lifecycle analytics must also be enabled to allow for feedback from production, use of the product, maintenance of the product, and even reuse or end of life. The result will be new efficient economies and complete end-to-end accountability.

2.1.3 Risks

One of the greatest risks identified by the World Economic Forum was the lack of interoperability standards, 65% aggregate across Europe and the US, the largest concern, closely followed by security. [2] The resistance to adoption can result in a stagnation of the industry and the lack of response to changes in global economies. Security is the second largest concern and must be addressed along with data management and chain-of-trust to have a viable ecosystem that anyone would adopt.

Outcome economies are predicated on trust and transparency. When the risk has been shifted to the organization providing the service, there needs to be full accountability

about the use of the service to verify the products are being used and maintained properly. For example, if a company is purchasing tooling at a price per hole, the tool manufacturer will supply as many tools as required to make the number of holes agreed upon. It is in the tool suppliers best interest to have the most efficient and longest lasting tool possible, but this requires the user of the tool to operate at the optimal spindle speed and feed rate to maximize life. The supplier will need to be able to verify that the tooling is being used properly to ensure they are getting fair compensation for the capabilities of the tool. This is true when supplying any device, it must be maintained and used properly for the model to function.

Transparency and accountability also require security. If one company can verify processes in another company; it will require trust that trade secrets and intellectual property will not be compromised. A major risk when digitizing the entire workflow is security of the information being communicated and stored. Data rights management for everything from the design models to the analytically derived insights will need to be agreed upon by the industry. These issues have not been fully addressed to date, but the technologies and standards are being developed for transaction management in finance using technology relying trust based relationships verified by continuous auditing and verification services using distributed ledger technologies like blockchain. These technologies can be advantageous to industrial systems as well.

2.1.4 Recommendations

The following areas were identified as key concerns:

- Open standards based semantic information models
- Open communication standards to allow services to collect data and interoperate
- UUID version 5 specifications and domain specific formulas
- Methodology for identifying manufacturing entities including the following:
 - Design features
 - Engineering Features
 - Inspection processes
 - Manufacturing processes
 - Assembly processes
 - Materials
 - Measurements and the results
 - Design and engineering Intent
 - Manufacturing equipment and its components
 - Sensors and sensor Data
- Data rights management and distributed ledger based transactions
- Security and safety
- Relocatable services and analytics
- Analytics feedback from expectation and lifecycle

We are recommending that the Standard for the Exchange of Product model data (STEP - ISO 10303) standards be adopted for 3D geometry and Product Manufacturing Information (PMI), STEP AP242 Ed2 and harmonized with QIF to provide a quality feedback and execution model. AP209 be adopted for use with simulation and Finite Element Analysis (FEA), taking it beyond its current use in composites. AP233 and (Requirements Information Format (ReqIF) are to be used for requirements management along with AP239 for lifecycle. AP239 and AP233 should align and harmonize the models and have distinct responsibilities. AP238 should be adopted for manufacturing process and the stage models should harmonize with AP242 PMI and Quality Information Framework (QIF) (already underway). MTConnect should be used for shop floor execution feedback and harmonized with QIF and AP238 to correlate engineering intent with execution.

ISA-95 should be adopted for Enterprise Resource Planning (ERP) to Manufacturing Execution System (MES) and execution with focus on making it a full semantic model for discrete manufacturing - still work to be done. Systems Modeling Language (SysML) should be adopted to enable communication of system engineering models along with AP209 as the mechanism to express design intent. There are semantic models that will need to be layered on top of SysML to represent the domain specific engineering systems for manufacturing. Continued work on AP233 harmonization may get there; neither model may provide a high enough level of abstraction to provide a full intent based communication model. S5000 should be harmonized with AP239 for feedback of from maintenance events throughout the product lifecycle.

There has been a resistance to implementation of AP238 and this should be analyzed and addressed as the current G-Code (DIN) model is very out of date and will not support the higher-level goals discussed above. ISO 13399 should be used for cutting tool modeling and is already getting traction in the market.

MTConnect process flow, ISA-95 as represented in Business to Manufacturing Modeling Language (B2MML), and AP238 need to be harmonized to provide a consistent view of manufacturing processes. MTConnect process model will provide a capability based flow that can integrate with AP238 stage model paradigm.

Many of these standards are already recommended by LOTAR, Aerospace Industry Association (AIA) and AeroSpace and Defense Strategic Standardization Group (ASD-SSG), so there is general alignment, but the information models in many cases have not been widely adopted. There are service companies entering into the design and engineering space, such as OnShape and CAD.ai. As these services become established, the requirements for add-ons and new capabilities will begin to necessitate ecosystem, which will in turn necessitate standards to avoid N-squared integration overhead.

The security concerns are discussed in the IIC security architecture covers many of the details of communication and infrastructure security. They must be adopted as part of

a service based architecture. The work being done by Transglobal Secure Collaboration Partnership (TSCP) on federated identity needs to be incorporated as well. The current standards work being done to provide Mutual Distributed Ledger (MDL) needs to have manufacturing and industrial participation to make sure the concerns of digital thread and chain of trust are considered when the standards are developed. Currently MDL is being driven solely by the finance industry.

The remaining standards for communication are widely available and are beyond the scope of this work. Once security and service based concerns are addressed, a new area of inquiry into data rights management and analytics will be required to provide a model where outcome based services can deliver on the opportunities mentioned above.

When we consider an implementation, from the conceptual design of a product to end of life; the following diagram depicts the groupings and interaction between loosely coupled federated services using standardized information models with real-time feedback. The information flow will require many feedback loops that will involve multiple concerns. Using a micro service architecture approach, each service will have a focused set of responsibilities and the information models will be required to carry the complete context and meaning of all the design and intent. The following is a limited conceptual model:

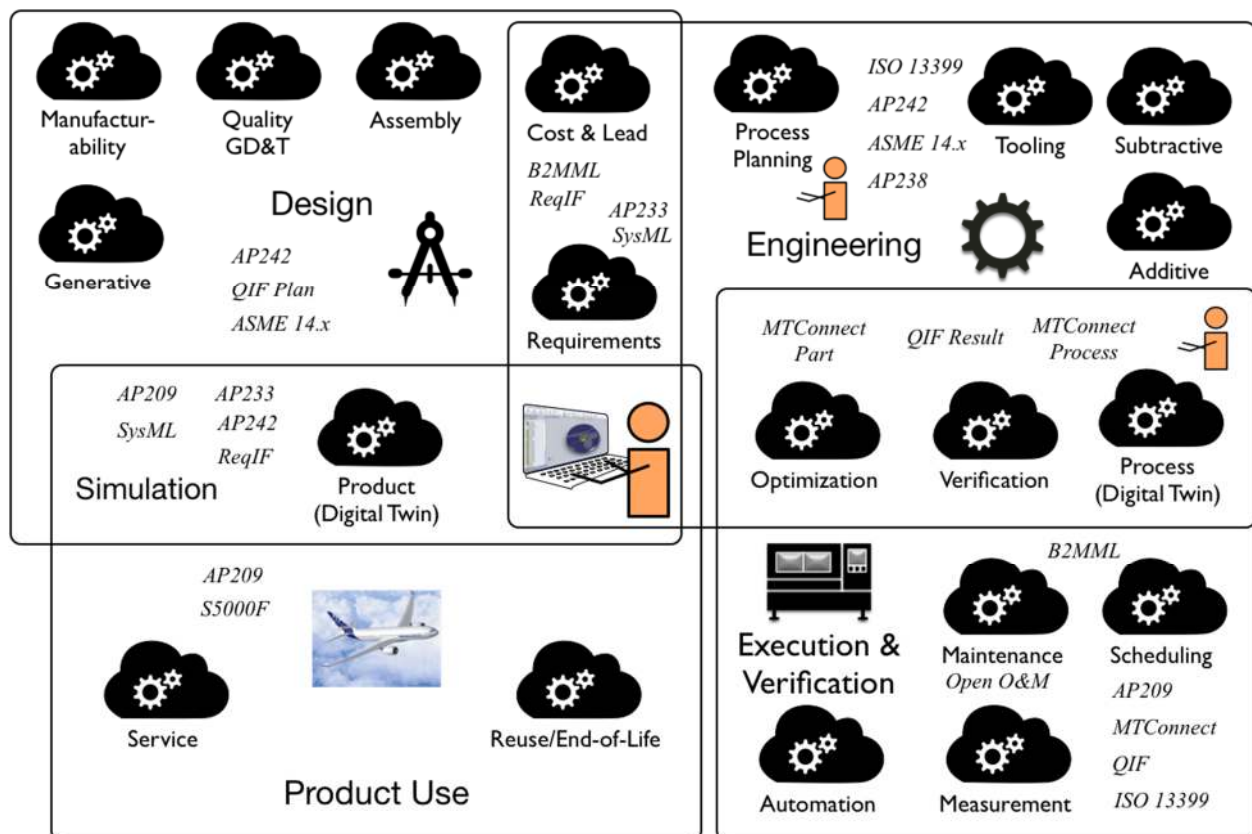


Figure 5: Services and Standards

The primary standards are grouped into domains, but the entire collection of information models are available at any location to any service. The interaction model can utilize services in any domain with parallel digital twins serving the purpose of verification of design intent and manufacturing process intent by providing a full simulation capability across the product use lifecycle and the manufacturing lifecycle. The digital twin will provide the ability to detect deviation from plan or intent and feedback to the services for continuous improvement and learning. The services will also be curated with expert design, quality, and engineering personnel advising and evaluating the services. The hybrid model will allow for human judgement to integrate with learning and automation.

This architecture will allow for services to be chosen and composed as necessary to achieve a desired outcome. Also, service specialization can occur where, for example, a 3D printing scheduling service interacts with a milling and turning service to provide information about a part as it flows from one manufacturing technology to another. The ecosystem will allow for specialization and integration. The key to making this work will be harmonized and completion of the information models.

The final recommendation is that there is support for CAD graphics kernel that are available in the three following ways: (1) as an open source project similar to FreeCAD, (2) a service based offering with a high-performance query API that can handle complex models, CAE, and kinematics, and/or (3) a low-cost SDK that can be imbedded in services with a redistribution fee that would allow for small companies to participate.

In the 3D gaming industry, there are over 15 such offerings. Unity, Turbulenz, or MonoGame for the 3D gaming industry that offer either full open source or low cost licensing of kernels that allow companies to develop applications that are cross platform and high performance using higher level primitives and physics models. If we consider manufacturing as a similar marketplace with open source or API support, the emergence of new technologies can be greatly accelerated by the availability of open and low cost technologies that will be able to build revenue share by increasing the size of the developer and consumer marketplace.

An active and healthy technology ecosystem will be key to the success of standards and advanced manufacturing. The current foundation is emerging, but the pace must be accelerated to meet the needs of the business drivers. It is our opinion that this can have a dramatic effect on the development and promulgation of standards for manufacturing.

3 Definition of DMDII internal standards development, documenting and advocacy mechanisms

3.1 Overview

System Insights and RECON have catalogued each project's set of standards and sought to understand why certain standards were chosen and why others decided to opt for proprietary interchange formats like ACIS and Creo. We needed to better understand the requirements that influenced the decisions from the project perspective; often there was no upfront guidance to utilize standards and therefore the choice was based on what was easiest and most effective way to meet the requirements of the project as understood at the time.

When conducting the interviews of the AVM program leadership, we found very little consistency. Of all the standards being referenced, AP203 and STL were the most common. ACIS was used in a few and the remainder were proprietary. One project is developing an open source project, but the interchange format is not standardized. To this end, the existing projects cannot interoperate to provide a platform based on common information models and protocols.

This paper frames the issues facing standards adoption across industries and how market drivers are the foundation for adoption. We've applied these findings to manufacturing and taken into consideration the unique aspects of design and engineering activities and how services that provide these capabilities may provide sufficient market pull to overcome the impediments to adoption.

We spoke with DMDII members and industry professional to determine the relevant standards, existing and emergent, and the technological approach for the future of the manufacturing industry given the market forces to reduce cost and increase agility. We also explored the implications of democratizing design and engineering and the perception on business impact across the SME base.

3.2 Some Comparisons and Context

Intuition states that in a Darwinist environment where standards compete for survival, the best standard would win and the others would slowly go extinct and pass from memory. This is rarely the case since standards bodies and organizations often fail to take into consideration the business needs and drivers and therefore adoption is severely impeded. Therefore, we collected the business requirements and impediments from the industry; the following are examples from other industries:

Betamax vs. VHS is an old example that is often cited regarding standard competition. Betamax video tape format had better picture quality but shorter playing time as opposed to VHS had relatively poor quality and a two-hour playing time. It also utilized cheaper equipment, since JVC licensed the technology to other manufacturers whereas Sony held rights to Betamax and would not license. Two takeaways, cost and open often will help to win over closed and expensive regardless of quality - within limits. VHS is still in existence and one could argue has outlasted it obsolesce, whereas Betamax has completely ceased to exist.

Another standard war was over peripheral connectivity that played out in the 2000s between FireWire and USB. The FireWire standard was developed by Apple to replace SCSI (a standard that was used to connect disks and peripherals), USB was developed by a consortium. Both were open standards—USB is an ISO standard and FireWire is an IEEE standard—but FireWire was primarily supported by Apple. From a technical perspective, FireWire was a superior standard, it was much faster and had a peer-to-peer communications protocol that would allow all connected devices to communicate with any other connected device while USB was slower and had a master-client relationship with a single master device could communicate with each of the clients and the clients could only communicate with the single master.

FireWire held on for a long time in the Audio Visual (A/V) space because of faster speeds required for video. When USB 3.0 came out, the lack of speed and capabilities were resolved and in the next version, USB-C solved the remaining limitations and is now the standard that will dominate. FireWire has faded and is for the most part dead, not even supported by Apple devices.

The main differentiator between these standards was that USB worked with a broad consortium whereas FireWire was promoted primarily by a single company, Apple. The takeaway is that a broad consortium usually wins over a better standard being promoted by a single vendor. There is no faster way to kill a standard than make it appear that a single entity controls the standard, regardless of how open. The competition will not adopt since they do not want to be locked into a something they cannot control.

There are many examples in many industries where standards have competed and companies have had to adapt or fail. The industry will often force companies to comply because supporting competing platforms is too costly. Browsers are a good example. In the early days of the internet browser wars, Netscape was the leader. Microsoft introduced Internet Explorer and installed it for free on Microsoft Windows and used its operating system as a distribution medium to get market domination.

Microsoft implemented many non-standard extensions and interpretations of the W3C display standards for HTML and CSS that made content designed for Internet Explorer display incorrectly on any other browser technology. This worked for a while, Netscape was almost destroyed and sold to AOL where the core was open sourced and

became the heart of many of the current browsers, but Netscape browser itself does not exist.

At the same time Firefox, Opera, and Safari were beginning to trend and they all had a stricter interpretation of the standards. Google introduced Chrome shortly after which also adhered to the standards and had a very advanced JavaScript engine that web developers found to be the best and enabled the richest interactive user experiences.

Internet Explorer started losing market share and fewer companies supported their misinterpretations of the standards, advising users to switch to a more compliant browser. Eventually Microsoft made Internet Explorer compliant, but in the meantime they have lost significant market share to the other browsers. One may ask why it matters to have control of a *free* piece of software. The reason is because the browser is configured with the place where users begin their search, in the case of Chrome it is Google, with Microsoft it is Bing. Search equates with advertising revenue, so it directly hits the bottom line.

The more standards compliant browsers also pushed for HTML 5 and CSS to provide more capabilities without having to use external proprietary plug-ins. Which had a side effect of enabling mobile devices. Analysis of standards and the impact of CSS (Cascading Style Sheets) has shown a positive impact on network efficiencies and enabled the mobile internet. CSS and HTML 5 have made it possible to provide a single version of the content and separate out the visualization concern so the rendering of the content can be optimized to the user's device. This removed the burden from the web designer and developer to have to in effect create multiple applications for the same core set of features and improved the user experience at the same time, provide a net win for all parties. [8]

Programming languages make for an interesting comparison to open standards and semantic models. There have been many programming languages developed over the years, hundreds in fact. Many of the languages have been used in specialty domains and are not what we would consider general purpose languages applicable to solving a wide range of problems. Languages are semantic interfaces that instruct a computer to execute a series of instructions, and since they must be interpreted by a machine, there are similar requirements to semantic standards that are considered for the AVM projects, since the information must also be interpretable by a computer.

In the software industry, we have seen languages like Haskell, one of the first pure functional programming languages, languish for years while its users extolled the benefits and would outcompete others in performance of both the final product as well as the ability to create a correct application. However, the adoption is still slow because the constructs are difficult for the public to grasp, and it has never had wide adoption because the level of skill required to use Haskell is beyond the average

programmer. It has been shown that learning Haskell has benefits regardless of what language you end up using since the skills one acquires can be generally applicable.

This is a case where a highly-standardized solution that meets all the open standard requirements has not been adopted because it is too hard for general use. There are some new languages, like Scala, that provide a gentler approach to the concepts of functional programming. Scala has now outpaced Haskell in adoption, but many of the users are not using it to the full potential.

The takeaway is that a standard must also make itself accessible to the common practitioner in the domain it is being developed for. If it takes a purist approach, the adoption of the standard will be hindered and the benefit, though it may be greater, will never be realized. Adoption of standards will require compromise and will require documentation that is accessible by the individuals and companies that will be implementing the standard as well as using it.

3.3 Standards and Standard Development Organizations

The following is a categorization of standards development organizations: [9]

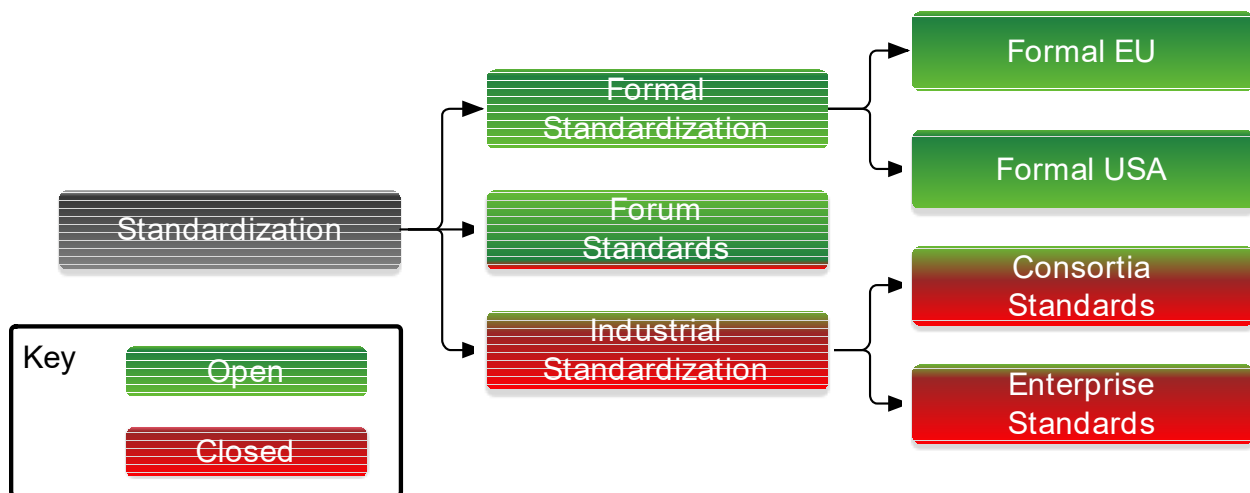


Figure 6: Types of Standards Organizations

There are principally three categories of standardization processes as follows: (1) Formal, (2) Industrial, and (3) Forum. Formal standards are developed by organizations like ISO, ANSI, DIN, or JIS. They are often slow moving and meticulous.

The second category, Industrial standards, are created by a subset of industrial organizations that form a consortium and develop either open or closed standards. There are two subcategories of Industrial standards as follows: (1) Consortia standards are often developed within a closed group of limited participants and (2) Enterprise standards - like Microsoft® Word - can be adopted by a large company and becomes a

corporate standard. CATIA is an example in manufacturing when Boeing decided to standardize on it for the 787 development.

The third category, Forum standards, are organizations that operate outside of the formal process and develop open or closed standards using an independent organization that has broad membership. Forum standards can have processes as rigorous as Formal organizations, but choose to remain independent. MTConnect is as an example of a forum standards organization as is MQTT from the Eclipse organization.

All standards that are part of a formal process are always open and they have the advantage of being organized and structured by a known entity. They also have the disadvantage of being very slow to adapt and this has led to a lack of market adoption because the market will often outpace the standard and it will become irrelevant. This has impeded adoption of many of the standards as the cost of implementing is not justifiable given the gaps in the standard and the requirements of the industry. In this case, the software developers will often forgo the standard in favor of proprietary solutions. This has been the prevalent situation in manufacturing.

Analysis of what constitutes an open standard have been outlined in *Open Standards Requirements (2008)* and are as follows: [10]

- The standard is adopted and will be maintained by a not-for-profit organization, and its ongoing development occurs based on an open decision-making procedure available to all interested parties (consensus or majority decision, etc.).
- The standard has been published and the standard specification document is available either freely or at a nominal charge. It must be permissible to all to copy, distribute and use it for no fee or at a nominal fee.
- The intellectual property – i.e. patents or copyright – of the standard, or part of the standard, is made irrevocably available on a royalty-free basis.
- There are no constraints on the re-use of the standard.

These constraints are widely understood and, with the exception of enterprise standards, are required for large scale adoption and promulgation. In general, one cannot expect to have wide market impact unless an open standard is used since the benefits will be too constrained to a fraction of the possible users and therefore will not encourage innovation beyond the limit of the enterprise using the standard.

The ten requirements of an open standard are as follows: [10]

1. Open Meeting - meetings must be available to anyone who wants to contribute for a minimal fee or free
2. Consensus - decisions must be made by consensus in the group and cannot have a single party driving decisions

3. Due Process - there must be a well-documented process regarding how all decisions are made and how the standard is developed
4. Open World - the standard must be globally available
5. Open Intellectual Property Rights - nothing in the standard must impede a user from implementing the standard and put any of their use in jeopardy of conflicting with patents or copyright
6. Open Change - there must be an open process for changing and maintaining the standard
7. Open Documents - all the documents must be made available to the community for free or a nominal fee
8. Open Interface - implementation of the standard must support open access and is not hidden or controlled
9. Open Use - there must be no impediments to using the standard
10. On-Going Support - the standard must be supported and evolving

The ability of a standard to meet all these requirements will greatly impact its ability to gain adoption and succeed. Failures in one or more of these dimensions will often cause standards to eventually be dropped or for the industry to move to another standard that meets more of the requirements.

3.3.1 Market Impact

The primary driver to adoption is business need and necessity. If there is insufficient market pull or the market is immature, standards adoption can deteriorate and fail. A failure often will have a negative effect because the same companies who invested in the previous effort will be less likely to make immediate subsequent attempts to correct issues with respect to implementation. It can be years before there is another attempt.

This situation has been documented in various supply chain standards where the standards were not fit for purpose or the systems and technology suppliers did not have adequate capabilities to implement. The failures often increase the amount of time to develop a workable standard since the new groups often believe they need to make a clean start.

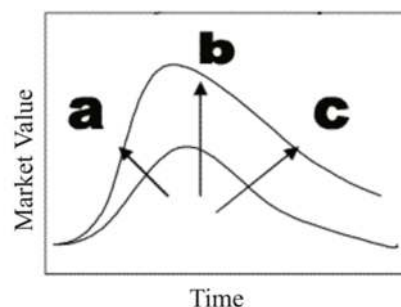


Figure 7: Potential for Standards Impact on Market Curve

In technology, standard have been shown to have a positive impact on the market. The illustration shows the following: [3]

- A: The initial market size increases faster with standards
- B: The size of the entire market is greater
- C: The market lasts longer and is more durable

Standards have been the driving force behind many billion dollar industries. For instance, in 2008 the POSIX market, based on open standards, and open source implementations like LINUX and BSD UNIX were responsible for a net market size of \$18 Billion dollars. Standards like HTTP, XML, and most of what we now consider the Internet technologies are all standards based and the market they created is vast. It is arguable that there would have been a proprietary emergent technology, but the business models that have arisen would not have been supported where interoperability was limited to a single vendor or the cost was prohibitive.

We are seeing this play out with the slow erosion of Flash as the dominate interactive media and video platform for the web. With HTML5 and new standards based media solutions that have zero licensing cost for developers or media providers as well as Apple refusing to put Flash in their mobile devices, the market has been moving towards abandoning Flash in favor of standards based solutions. As the standards reach parity with proprietary solutions, the standards usually win because of licensing, cost, and democratized control.

If one considers the incredible exponential rise in internet companies and services, it is due to the availability of low cost or free technology that can quickly move from ideation to product without the overhead of costly equipment, software, or development environments. This is a very different marketplace and environment compared with manufacturing that has not kept pace with technology innovation even though the market value has been estimated to be over one trillion dollars, far outpacing the *advertising* and *media* industries impacted by the current internet technology.

3.3.2 Network Effects

To understand the positive and negative effects of standards in various industries, a study was done to create an analytical model to characterize complex supply chains in a few illustrative industries where standards were and were not used. The objective was to determine if there was a net benefit or detriment to the individual businesses considered in the study. The model considers factors like supply chain flexibility, connectedness, concentration of control, and market power. [11]

The study also looked at the industries themselves and analyzed the stability of supplier and customer relationships and how standards propagate along value chains and the consequences of the diffusion within the whole network. These were considered in how an individual would have positive or negative network effect. They define a network effect as “the utility that a given user derives from the good depends on the number of users who are in the same ‘network’ as he or she” [11].

Examples of positive network effects in manufacturing would be reduction of product development costs due to design miscommunication. Vendor lock in is viewed as a negative network effect due to the cost of switching when one is required to change vendor or use a standard to take advantage of capabilities and ensure competitiveness. Since decisions are made at a point in time where the capabilities of a proprietary vs. standards based solution are competing, the models are non-deterministic since each sequence of decisions is made within the context of the current economic and business environment. All factors that influence a decision cannot be taken into consideration and therefore stochastic methods must be used.

There is another factor which is referred to as the standardization problem. Standardization assumes that all players in the network will choose the same standard and the uncertainty that the other participants will act accordingly. The utility of a standard only works if the decisions of all the players align. Competing standards decrease the probability that all parties will achieve greatest utility.

The following table summarizes the determinants used developing the diffusion dynamics in the supply networks:

Table 1. Determinants and parameters simulating diffusion dynamics in supply networks

ID	Determinants	Parameters	Description
1	Communication intensity	Size of enterprise q_i	Size of an organization (define size distribution for each type)
2		Number of sourcing relationships g_i	Sourced parts of agent i from different tier
3	Costs	Implementation costs $K(q_i)$	Costs to implement a standard
4		Maximum communication costs $C(q_i)$	Maximum savings per relationship
5	Communication partner influence	Communication cost savings $C(q_i, q_j)$	Reduction of communication costs for partners implementing the same standards
6	Personal network exposure	Relationship stability between tiers p_c^{main}	Probability of transaction with main supplier
7		Number of suppliers n_c	Number of potential suppliers per sourced part
8	Opinion leadership (power)	Economic base power b_i^{eco}	Power sources other than size-based technological and economic power
9		Technological knowledge b_i^{tech}	Network participant's technological knowledge
10	Opinion leadership (location)	Set of agents in tier $O_c \subset Agents$	Position (tier c) within the supply network
11	Intragroup pressure toward conformity	Market pressure functions	Pressure that partner agents can exert on the deciding agent to implement their standard

Figure 8: Determinates and parameters simulating diffusion dynamics in supply networks

In the paper by Schwind, Stockheim, and Weiss, this model was applied to two industries, Automotive Supply Chain in Germany and the Paper and Publishing Industry to illustrate two divergent structures. [11]

The automobile manufacturing industry from a specialty job-shop driven industry to mass customization with an n-tier supply network. There has been considerable consolidation in the automotive industry across the entire supply chain with projections that this trend will continue to be led by Europe and North America [12]. Consolidation has been driven by the industry requiring increasingly specialized parts that led to partnerships between direct suppliers. The additional factor that needs to be considered in the dealerships are often selling a single brand of car from one carmaker which creates static relationships as well. [11]

The supply chain for the European automobile industry look like the following:

- **Retailer:** Sells cars directly to the customer. Relatively small companies with high transaction and switching costs.

- **Carmakers:** Large companies that possess most of the economic power. They have a lot of the technical knowledge, though Tier 1 suppliers are now gaining traction in supplying complex components.
- **Tier 1 Suppliers:** Medium sized companies that focus on specialized components with high complexity. Their economic power is still small compared to the carmakers. They have stable business relationships with the carmakers for the most part.
- **Tier 2 Suppliers:** Small economic power and technology producing parts of little complexity.

The paper industry is very different with a highly dynamic supply chain with rapid changes occurring in relationships between printers and paper producers. The supply chain is relatively simple compared to automotive. The following is the organizational structure:

- **Publishing House:** Creates products that are distributed to resellers using various paper from various printers.
- **Printer:** Generic printing services and strong relationships with its clients.
- **Producer:** Produces paper products characterized by medium to large companies with some small specialty shops.

The results of the analysis were a general characterization of the use of standards given the business and economic structure of a supply chain. Their hypothesis was that the network topology and participants market power will directly influence the adoption of standards and how rapidly they will promulgate throughout the network.

The following is a quote from their conclusions on the concentration of open standards within a network or supply chain: [11]

1. *High relationship stability (inflexible supply chain) leads to a decrease in concentration.*
2. *Supply chain connectivity strongly influences the outcome in two ways. First, an increase in leads to higher tendency toward the standard' concentration since an increased connectivity reduces the probability of subnetworks. Second, an increase in connectivity often leads to a shift of market pressure along the supply chains, leading to changed relevance of the tier organizations.*
3. *Market power and network topology strongly influence the propagation of standards along the supply chains. These results are confirmed by recent study of Gerst and Bunduchi (2005) who recognized a strong impact of powerful firms in the automotive supply chain, particularly practiced by using the influence of few manufacturers on the ISO (International Standards Organization) standardizing committee. In certain constellations, however, the market pressure on organizations does not suffice to enforce a further*

propagation of the communication standard to the next tier. This leads to a low change of a single standard's domination.

The results of that analysis led them to the conclusion that the following four factors lead to the tendency to adopt open standards:

- Low relationship stability
- Highly connected supply chains
- Low centrality of supply structures
- Homogeneous market power

These studies show how market factors in manufacturing with few suppliers of software and technology in the design and engineering space as well as builders of manufacturing equipment with stable relationship networks has led to relatively little adoption of standards. Having more diverse supply chains and decentralized power structure requires more connections.

The more static your supply chain, the more an industry can rely on bespoke connections between companies in the network. As the number of companies at each tier level increase and the relationships become more dynamic, open standards become beneficial since each node in the network will be also be connected to multiple other nodes.

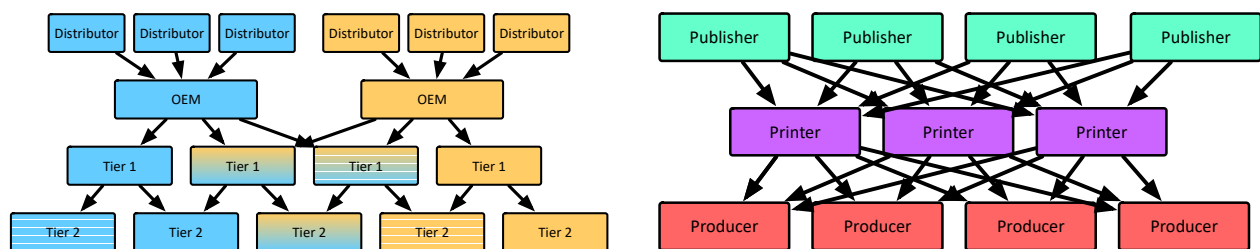


Figure 9: Supply chain network effect of dynamic vs. static relationships

When a company has complete control over their suppliers, they can dictate the information models. This was apparent when Boeing required that all suppliers for the 787 used CATIA. The tier 1 suppliers could all manage, but many of the smaller shops at the tier 2+ level could not and it became the responsibility of the tier 1 suppliers to convert the CATIA designs into something consumable by their suppliers. If an open standard was used, the cost of a CATIA license would not have been a blocking issue for the tier 2 suppliers who would be able to consume the models directly, possibly avoiding drawings.

3.4 Resistance and Obsolescence

Standardization often elicits a Pavlovian response in many venues because they are viewed as burdensome, having a net negative affect on innovation, and a waste of

time. The perspective is that the slow pace of standardization creates specifications that are often obsolete before they are released and the industry has moved on. The time spent standardizing has been a futile effort. There are many standards where this has occurred and they will often perish due to lack of adoption.

The issue is with the standardization process, and equally, a misunderstanding of standards. People often make broad generalizations where one must understand that standardization can be achieved using multiple different processes, but the process must meet the criteria for openness and must have the correct level of rigor for the type of standard being developed if it can create new markets. Manufacturing often suffers from this issue where standards take decades to complete and once they are complete the industry has new technologies and the standards lose relevance.

There are different levels of rigor depending on the type of standard and the target technology. For semantic information models, the objective is to move to more agile processes and shorter release cycles. Similar processes have been used to develop programming languages and that pattern can be applied to semantic models. Semantic information models must be allowed to evolve rapidly. If the goals of the standard are too broad and perfection is the target; it will most likely fail.

Once a standard is implemented and put into use, a similar reality occurs to any tactical engagement, as Field Marshall H.K.B Graf von Moltke said: “No Battle Plan Survives First Contact with the Enemy”. A standards committee’s attempt to foresee every possible use and predict how the industry will evolve will be bound to fail. One should avoid boiling the ocean and keep focused when developing standards. Also, a focused scope allows for better harmonization with other standards.

In general, for semantic information models, a lighter weight process where each iteration and release ensures some value and a network efficiency have been created will serve the industry the best. This has been effective for MTConnect and in many programming languages like Ruby and Python that at first use rapid evolution of the language built on a small set of base principles. The language then evolves using input from the community while always keeping utility and usability as a principle concern. This topic will be discussed in more detail in section 6.

3.5 How This Relates to Manufacturing

Manufacturing systems have some interesting characteristics that differentiates it from the consumer and media industries. Manufacturing has a relatively small number of end users when compared with retail, media, or consumer IoT devices like thermostats and health monitors. Unlike consumer industries, manufacturing creates value, meaning it converts lower valued material to higher valued products. Because of the limited number of companies that are currently supplying design, engineering, and execution software, manufacturing is often characterized by closed systems that

are operating within the confines of a specialized process. Openness has been either actively resisted or undervalued.

Historically, manufacturing equipment has had limited contact with other systems. Even with respect to Design and Engineering systems, the number of vendors and formats were few and therefore they became industry standards like some word processing document formats have become standards for interchange in corporate IT. We see this with ACIS and CATIA (Dassault), NX from Siemens, and DWG from Autodesk. Each vendor of any downstream system, like CAM, is responsible for supporting all proprietary formats and making sure they are correctly represented.

The issue with proprietary formats is they are at the mercy of a single organization and can change at any time. They are also subject to certain parties being locked out since they are perceived as competitors. When we consider other models such as STL (STereo Lithography) file formats; it has broad use since it is simple and open and has a strong adoption in the 3D printer space, but for interchange it has very limited capabilities and does not have adequate complexity to be considered a full CAD model for complex products. STEP AP203 has been to most widely adopted standard for CAD interchange, but until AP242 Ed, it is also not adequate to carry all the information require for CAD product information. AP242 is just starting to be widely adopted and is available in many CAD applications for import and export to various levels of completeness.

Internal to manufacturing equipment there are also many standards at play, mainly around the connectivity of various components such as drives and motion controllers. Field busses like Ethernet/IP, DeviceNet, EtherCat, and Profibus/Profinet as well as standards like SERCOS and such are common, but are not as relevant to these projects as they rarely expose their data outside of the machine's control systems. They can be used with data collection services and transformed into externally facing standards like MTConnect, but their requirements are not suited for communication outside of networks that do not support time-sensitive messaging.

3.5.1 Regulations

Many standards have been adopted because of government or regulatory organizations like OSHA or NFPA for electronics. These standards are related to worker safety, business processes, or hardware specifications like electrical wiring or mechanical properties. These standards can prevent the sales or use of equipment and therefore have a clear path to adoption.

In the areas of highly regulated industries like aerospace and medical, there is a need to capture all the factors from design, macro-planning, engineering, and tool selection, followed by execution, measurement, and inspection. These needs are not being met right now and could provide significant drivers for standards adoption in

the future. The correct platform must exist to overcome the cost and complexity of implementation.

Forced adoption can also result in an impediment to developing a standard that is truly fit for purpose since the standards groups will be heavily lobbied by the implementers to ensure the requirements are compatible with that they can readily supply without having to incur additional cost.

Business process standards do not have technical concerns, since they are primarily focused on standardization of a method of achieving a set of goals; for example, the ISO 9000 series for quality management. These standards do not provide interoperability; they ensure a process is being implemented and adhered to, to meet contractual requirements and vendor selection.

LOTAR (LOng Term Archiving and Retrieval) has also been very effective at increasing awareness around manufacturing data and digital thread for the aviation and defense industries. The requirements to archive CAD and 3D models as well as system engineering and simulation has forced companies to be able to provide data in standardized information models. LOTAR compliance is one of the best drivers for industrial adoption of common CAD models and their association with PDES and the ISO 10303 (STEP) application protocols (APs) will provide the necessary impetus for many CAD application companies. [13]

3.5.2 The Small Shop and Standards

The small shop's intellectual property resides in its abilities to differentiate itself from other shops with specialized engineering, quality, planning, and execution. When contracted to produce a part, the shop demonstrates its capabilities by meeting the quality and delivery requirements given the material and design constraints provided to them, and then competing on cost and scheduled with similar shops with similar capabilities. The dilemma is when the shop is not given the creative control over the process, they lose their unique ability and become a commodity.

Standards and commoditization are what drove a lot of outsourcing of services in the last decade - if anyone can make a part, why do we bother making it here where labor is more expensive? If all manufacturing became standardized, will this increase or reduce our manufacturing potential in developed countries like the US? Will we have to resort to trade protections to reduce foreign competition and their ability to provide specialized capabilities? And, how will we enforce or manage these services since many are already developed by global organization around the world?

From an industry perspective, democratization of capabilities is positive since it lowers cost and provides redundancy in the supply chain. This drives the tension between the small shop trying to retain their advantage and the industry trying to gain agility and save money. The solution most likely lies in the space in between

where we can provide enhanced services to SMEs to increase their capabilities without removing their unique talent and investment.

Some manufacturers we spoke to were resistant to standards like AP238 (STEP-NC) since they see it as obviating the need for the shop to perform specialized engineering and process planning since all the required engineering information is specified in the model and therefore can be produced anywhere. There have been many attempts to replace G-Code (the original DIN spec to control machine tool motion and still the most prevalent in the industry) and 2D drawings over the last 30 years, and none have succeeded.

From some initial interviews, the consensus indicates that the CAM, Machine Builders, and shop owners have not pushed to adopt AP238 because the existing mechanisms are working and there is no strategic reason to change. Some perceive it as reducing their differentiation and their ability to manufacture product. This is a limited position and will eventually have to change, the question is how long it will take to transition the industry.

One solution is to allow services that can provide financial compensation for expertise where the engineering capabilities of individual shops can be monetized and provided on a global basis without losing intellectual property or chain of custody. This will require services that act as a black box with respect to the information models and will produce process plans, material selection, tolerancing, and inspection processes that will meet the requirements of the design intent.

The engineering services will allow for experts in various areas to expand their influence beyond their own location. One model would compensate the loss of production revenue by revenue obtained through services that enable local advanced manufacturing closer to the point of consumption. If the manufacturing processes can be regionally located, then there should be a net increase on the impact on jobs at all levels and transportation costs should be reduced.

One of the principle issues will be the task of enforcing chain of custody and chain of trust across the supply chain. The participants and service providers must be able to ensure that the IP of all the parties is protected and that the resulting product of the services cannot be replicated without compensation. It becomes a similar problem to DRM (Digital Rights Management) in publishing and movie distribution.

In the ideal, the volume of manufacturing will increase and since location is less of an issue and cost is reduced. Since the manufacturing can be performed locally to the site of consumption, it will provide for higher job growth since automation will level the cost and delivery, quality, and agility will be the differentiators. The result will be more manufacturing in more locations.

3.6 The AVM Projects

This document prescribes the most effective way to promulgate a set of branded standards that can be utilized to create an architecture for interoperability between different applications. The goal was to provide a digital thread linking the many phases of the design and engineering processes. To achieve this goal, there needs to be an assessment of the current standards currently in use, their present adoption over time, and if there is a lack of adoption, the impediments, and how these impediments can be addressed from a business and market perspective.

There are many forces at play when evaluating the viability of a standard. This is similar to evaluating a startup when considering investment or putting together an initial business plan. There are some fundamental differences; a standard is, by definition, public and is almost always created by a group of volunteers with a small team of authors who do the majority of the work. The authors are supported by industry and/or a standards body, depending on the standards funding model.

The seven AVM projects that were part of the first to DMDII project call concerned themselves primarily with the design and engineering phases of the manufacturing processes. If we consider the steps in the manufacturing process at a very high level, we have the following flow:

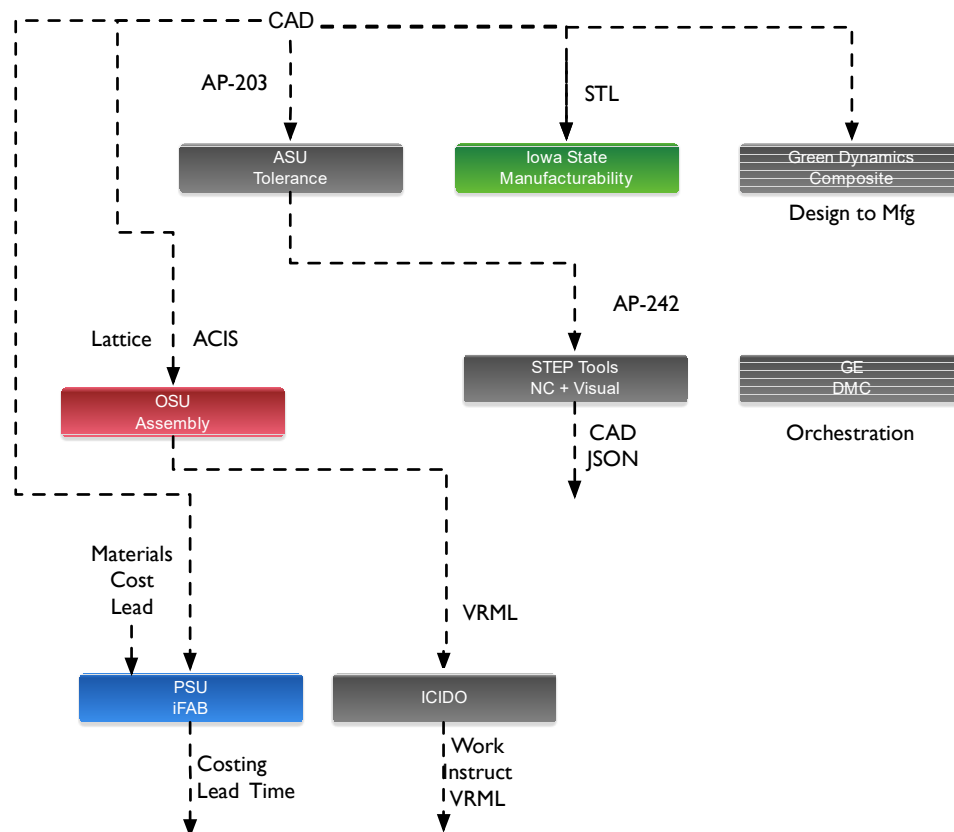


Figure 10: Information flow in the AVM programs

With respect to the design to manufacturing flow, we can map some standards to the various projects and determine where additional work is required to define a platform given the existing information models that are available. One example that has been mentioned multiple times by various projects is design intent. This is a requirement by both auto-tolerancing and assembly as well as tool path generation and optimization.

Design intent speaks to the use phase of the product being made including the materials, loads, assembly assumptions and processes, mating surface constraints, temperatures, etc. At present, these are being inferred from the geometries and tolerancing (if present) in the CAD models.

There are existing standards that address, to some extent, the area of design intent and provide requirements throughout the product lifecycle. AP233 combined with SysML have been suggested as the best fit in 2009, but there has been little work done on AP233 in the intervening years. Manufacturing requirements have been addressed by ReqIF combined with SysML to describe the engineering and simulation concerns for the automotive supply chain. This topic will be covered in detail in section 6 of this document.

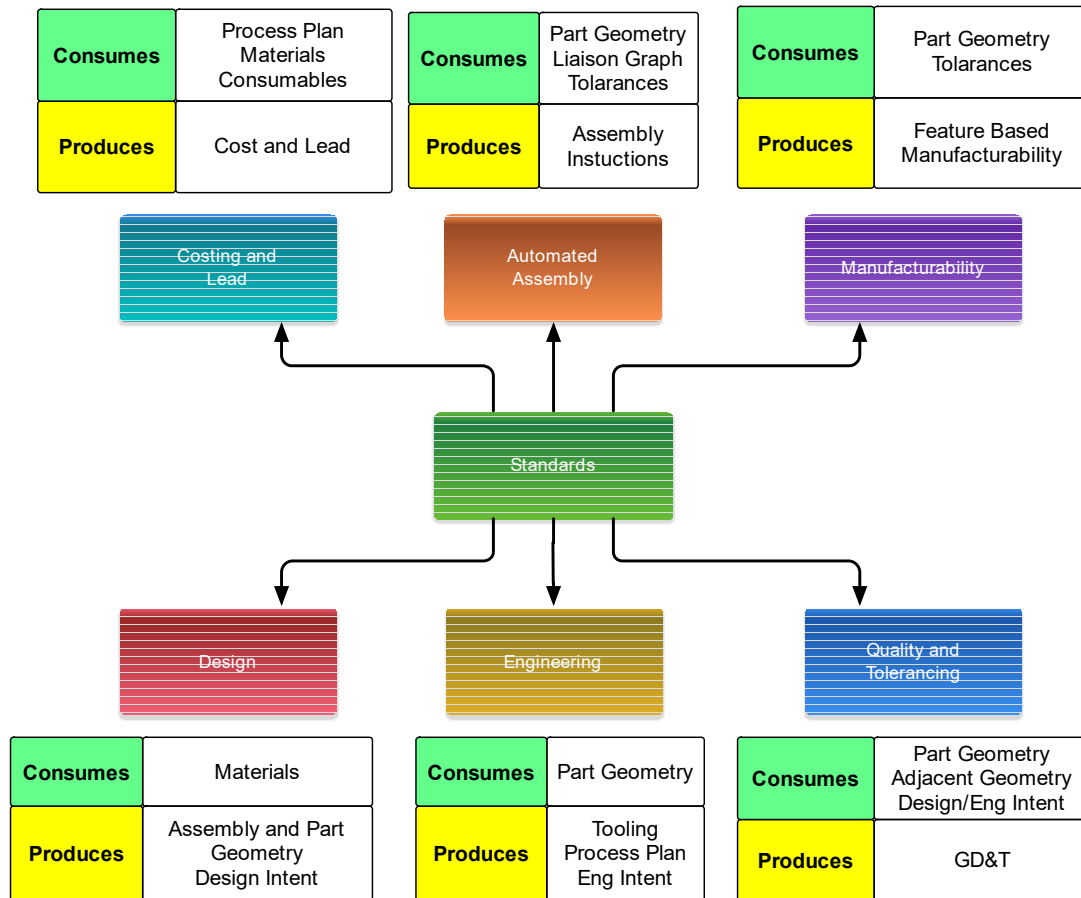


Figure 11: Example interconnected service input and output

The design and tolerance (D&T) information models need to be augmented with design requirements that have sufficient levels of meaning to determine manufacturability with complete product definition that provides sufficient information to meet the requirements of design intent. The assemblies will also need to be annotated to insure operation and maintenance of the parts being D&T to satisfy the requirements of the product. This will require extending the existing product definition and engineering information models.

Whenever engineering documentation on parts and assemblies are communicated using paper based drawings and notations, there is an interpretation that takes place. The education and knowledge base of the person receiving the drawing will often decide the success or failure of the project and their assumptions regarding how to implement the process to meet the requirements using their experience.

It is impossible to remove the experience and expertise of individuals from the design and engineering process. It will be a very long time before there is a suitable replacement that can interpret the intentions and optimal strategy for manufacturing a product. Many of the simpler decisions and judgements can be cast as rules and

machine learning models to remove the repetitive decisions and focus on the complex areas of the design.

Eventually software will be able to do a lot of what humans do, including reasoning, assuming a good set of rules and analytical models are provided and the information models are rich enough they can be reasoned upon. To develop these systems, the first step is to standardize the information models so the rules can be created in a simple and clear manner that provides the capability to support decisions.

Geometric models have also become a point of contention where some groups have decided to use AP203 for solid geometries and others have moved to STL. The issue with this approach is the transformations are irreversible and the PMI (Product and Manufacturing Information) and GD&T data (Geometric Dimensioning and Tolerancing) must travel with the solid models, and more importantly, the feature identity and feature relationships must also remain intact. STL and AP203 are not adequate and do not support PMI or GD&T. AP203 is a little better with features, but neither will suffice as an interchange format for a complete digital thread. As well, AP214 was not used in the projects alongside AP203 for geometric PMI.

In CAM and execution, information is lost when CAD models are turned into machine instructions, and thus, we lose the ability to have production traceability and the feedback to inform design and engineering for manufacturing. There is a need for references from all stages to the feature level information and there is the necessity to create a conceptual model for *engineering features* that can be tied back to the original design.

Engineering features are being developed in the AP238 stage models and should be sufficient to drive the current interoperation semantics. The current limitation is the number of CAM systems that can currently work with the AP238 standard as well as other services and manufacturing equipment.

Even at the design stage traceability is a major concern because we don't have persistent identifiers that stay with features throughout the design lifecycle. This is especially important when the data will be augmented by external standards that need a stable reference model. The current applications cannot represent a persistent identifier when they export to standards based information models making it nearly impossible to incorporate the analytical results in a clean and unambiguous manner. The Mind-The-Gap project is working on addressing many of these issues.

3.6.1 Current Manufacturing Systems Architecture

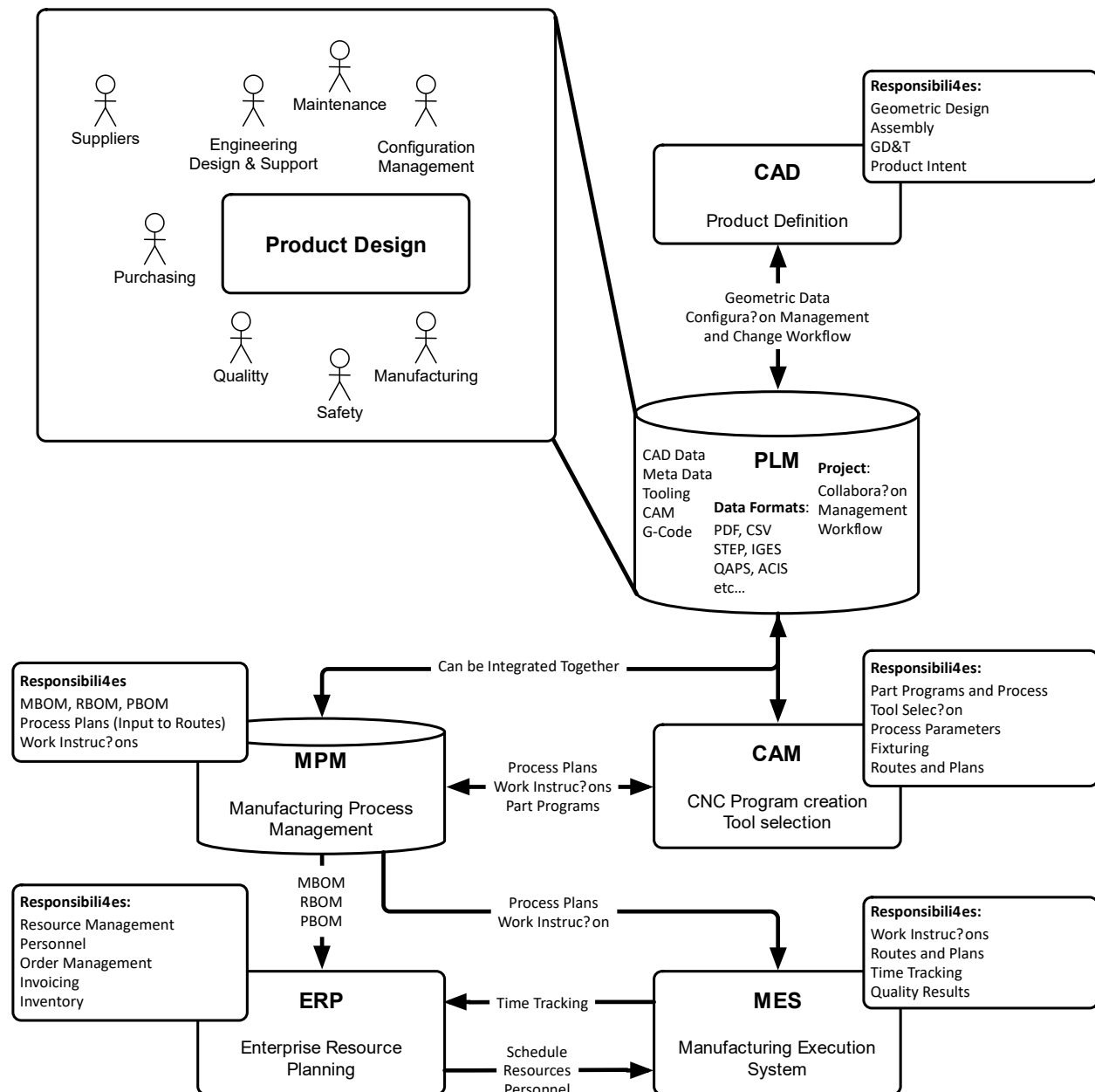


Figure 12: Existing manufacturing system architecture

The diagram portrays the current segmentation of functionality that is present in manufacturing systems today. The responsibilities of various components, such as MES and ERP, overlap and the definitions are sometimes not clear. The PLM system often resides at the center of these system architectures and acts as the clearing house for all documents and data about a process where the other systems pull from the PLM system as needed.

The existing model of system integration in manufacturing is rife with duplication of data, unclear responsibilities, and multiple representations of models based on the application of the data. If interoperability and traceability are requirements, then at the very least, the systems will be required to have common identity, vocabulary, and semantic definitions of each of the critical components of the information model. Currently system integration is done in a bespoke manner and is tightly coupled to the existing software vendors. This implies lock-in and brittleness where even upgrading software versions can become prohibitively difficult and expensive.

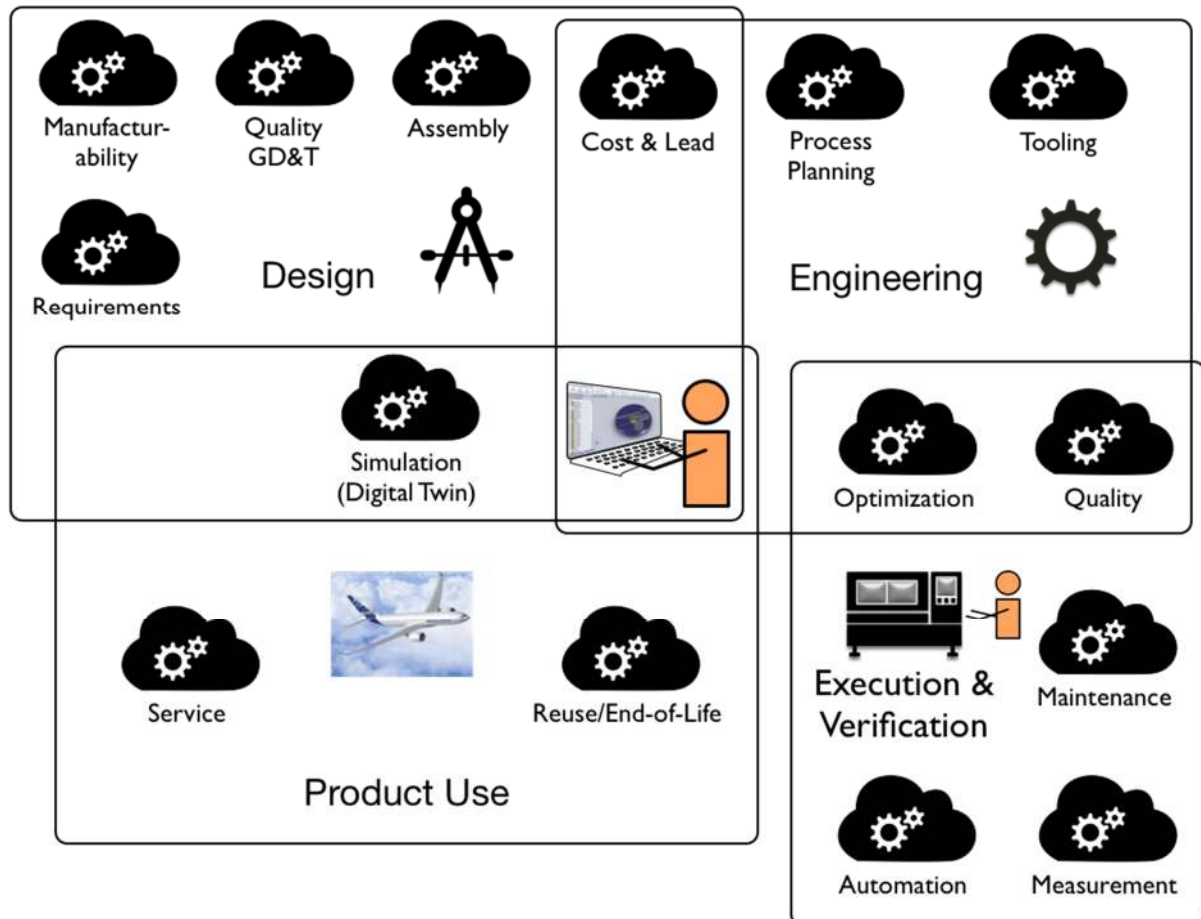


Figure 13: Manufacturing services architecture

If we move to a more service oriented model, many of these data silos will be removed and a more distributed system will emerge. The digital thread and software architecture groups will need to restructure the responsibilities of all the components and incorporate feedback as a key concern.

This model will also provide for better separation of responsibilities to segment the requirements of the industry into a set of technologies that can be composed to

achieve the complete information workflow and management, but with greater interoperability and choice. Services can be used as needed depending on the requirements of the project. This will be covered in detail later in this document.

The federated service based architecture has been referenced many times as the future of emergent business models in many industries. Adobe is now only sold as a service and Autodesk is moving in that direction. Dassault has been creating service based offering of its desktop products and now SolidWorks can be purchased as a subscription. The economies of scale and increased support and capabilities as well as reduction in cost of maintaining legacy software versions has caused the software industry to begin developing new service oriented software models.

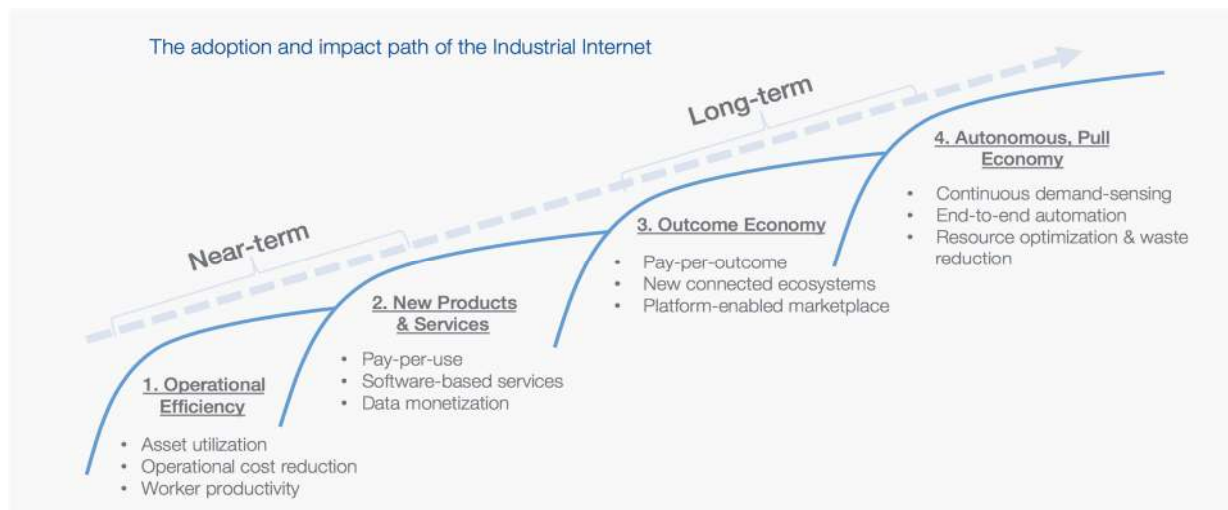


Figure 14: Adoption and impact of the industrial internet [2]

The report from “World Economic Forum and Accenture Industrial Internet of Things: Unleashing the Potential of Connected Products and Services” [2] predicts that manufacturing will be moving from new pay-per-use to an outcome based economy that will be pay-per-result. This model fits into a strategy of design and engineering democratization, but needs to be introduced as a set of value added services that can increase design and engineering skills without removing the revenue stream of specialized engineering companies. Instead, this is a road to increasing their reach and possibly productizing their services; it is yet to be seen how the new economies will play out, but we are beginning to see business transformation in multiple areas.

An interesting comparison was given in research done by Forrester on enterprise marketing software ecosystems. Forrester stated that there is no off the shelf one size fits all platform that will work for all organizations. The Enterprise Marketing Software Suite (EMSS) was going to combine multiple systems of insight and engagement in a single vendor offering: Warner defines EMSS as follows:

An integrated portfolio of marketing technology products that provide analytics, automation, and orchestration of insight-driven customer interactions to support inbound and outbound marketing.
[14]

The interesting takeaway, from another industry that is more mature in the cloud technologies and integrated services, is that customers want an integrated solution that seamlessly worked together, but did not believe a single vendor could supply all the capabilities. It is important to realize that this will be the case in most domains and integration of services will provide the greatest opportunity for success.

Even within a portfolio of services, many companies are still using an approach that limits the available participants in the eco-system. Integration requires aligning with the core services, but still allows support for external services. The ability for services to work and appear native to multiple product portfolios is one of the areas that should be explored as we create the ecosystem.

3.7 Conclusions

When we collected information from practitioners of manufacturing design and software architects who have been actively been working in the field for many years and have seen standards and efforts like this start and stop, the effort to promulgate a set of standards is often affected more by the business environment and the needs of the industry than it is with the innate quality of the standard.

The lesson is that the best standards do not always get adopted - the standard that gets adopted meets the business and market needs and often unintended side effects also come into play, such as the *killer application*, for example, in the case of DOS it was Lotus123 and in the case of the Ruby language it was Rails web development framework.

Standards can languish for many years without adoption because they do not have the drivers to succeed. To promulgate a set of standards, there will need to be an identified need, a business case, and a lack of impediments.

Impediments are defined as aspects of the standard that would discourage someone from adoption. Common examples are decreasing a company's ability to make money or the perception that it compromises a key facet of a business, such as intellectual property. An example of this is the automation of the engineering function by using services. This capability appears to be something desirable from an industry perspective, but not for the small shop whose contracts and capabilities are defined by their ability to engineer.

The fear associated with losing customer lock-in is one of the largest impediments to standard adoption in the manufacturing industry. Adopting a standard that allows the

competition to gain access to a customer and displace the use of a product or service is the reason many standards are actively blocked. On the other side, companies that implement standards can often ride the adoption curve of successful standards and enhance their business - given they have a product that meets a business need - but the reality is the competition is always there with the ability to come in and displace with lower switching costs than proprietary systems.

To overcome these fears, the standard must show adequate business value and solve a problem that was either overly complex or costly without the standard. The benefit must be compelling enough to exceed all perceived impediments listed above. Another driver will be a corporate or government requirements and regulations where the requirements provides significant benefit to those who adopt versus those who do not.

Adoption can only happen when there is a confluence of economic and industry drivers that make adaptation and support beneficial. To find the requirements and constraints that will push adoption, we interviewed various individuals in the two areas of system architecture and industrial design and engineering and the results are discussed in section 4 of this document.

It has been shown in multiple studies that standards increase market size and stability while both increasing the initial rate of technology adoption to increasing the peak market size and allowing technology to have a longer lifecycle and relevance. These positive factors are weighed against market perception and cost for companies to adopt.

There are additional factors like the supply chain network effects that can create demand for standards pressure first and second tier companies exert on their suppliers and the competition in the market. This is balanced against supplier contracts and specialization that can resist change to control the relationship.

Taking all these factors into consideration, we can chart a course that enables the creation and adoption of standards while not decreasing the competitiveness and talent in our manufacturing base. The manufacturing base needs to be enabled to find new markets for their knowledge and new models to increase their revenue. We can also use automation where it can add most value and focus on increased production and re-sourcing manufacturing at competitive costs.

4 Engagement with relevant standards bodies in industry (i.e., PDES Inc., ISO), academia and professional organizations

4.1 Overview

The second phase of the project focused on the collection of information from inside and outside the manufacturing community. By utilizing the network of contacts from MBD, MTConnect, PDES, IIC, Industry 4.0, NIST, and numerous other organizations, System Insights and RECON amassed considerable information to gain a better understanding of the needs of the industry and an effective architecture that will allow for rapid adoption and advancement of the design and manufacturing community. This turned out to be a cross disciplinary approach and the timing is fortuitous since there is a general desire to converge.

There has been a false impression from both communities that there is something special about manufacturing and the industrial technology space that is uniquely different and therefore requires a novel approach. This disconnect has provided the impetus for the IT and OT disciplines to go down separate paths; the manufacturing technology path has focused on safety and reliability while information technology has focused on agility and scalability. A major effort of the IIC and Industry 4.0 communities have been to find architectural solutions and common ground so that manufacturing can take advantage of the advances in information technology and conversely information technology can provide valuable services to manufacturing.

The manufacturing community has grown accustomed to a reduced level of service and IT innovation that does not take advantage of the advances made in information technology, namely cloud computing and big data analytics that have become necessary to compete in media, retail, and advertising. The issue with approaching a topic as broad as manufacturing is finding a key objective to frame conversation and provide a foundation that will necessitate change.

Manufacturing, by its nature, is averse to change. Processes used to make products are created to reduce variation and embrace consistency. Information technology has embraced change, since change is the core of innovation, and software can afford greater agility since it can be updated and changed without safety concerns or disruption. This has also led to the breakneck pace at which information technology advances, often with considerable business risk. All information technology companies understand that the only way to survive is to innovate. This makes the two industries at odds with each other: Technology pushing for rapid change and manufacturing for consistency and safety.

The process of understanding the requirements for the industry to achieve its goals requires participants to get out of their comfort zone and realize an outcome that they may not consider possible or desirable at first. This was the strategy System Insights took to extract requirements from industry insiders and from outsiders to provide a motivation that would be sufficient to peak their interest.

4.2 Industrial Alignment

During the project, we evaluated the major trends in the industry. There has been significant attention paid to the industrial and manufacturing sectors in the last couple of years due primarily to Cisco, McKinsey, and GE analyzing the opportunity to reduce the inefficiencies in the industrial sector. Organization like DMDII, Industry 4.0 in Germany and 2025 in China are all grasping for the same outcome, dominance in the manufacturing space since a large portion of the GDP of industrialized countries derives directly from production of goods. Industrial Internet Consortium and Open Fog were created as international efforts to unify architectural aspects of the industrial platform and provide interoperability between services globally.

In manufacturing, the initial focus of all these efforts centered on increasing the efficiency and productivity of our existing processes. This approach lead to the forecasted potential savings of \$1.2T - \$3.7T by 2025. There was nothing new in this revelation, the underutilization of manufacturing assets has been known for years, but it took companies like Cisco and GE to popularize the topic and pique the interest of the information technology industry.

The consumer Internet of Things hype, often conflated with the industrial internet, is primarily a Business to Customer (B2C) strategy and is already seeing difficulty in providing direct value drivers that supported the revenue models where the margins on consumer electronics could sustain the projected growth. Much of the value is derived from the data collected from the *Things* and making use of that data to create additional secondary revenue streams from monetizing the analytical insights. The true value of that opportunity is unknown at this point and only a few examples exist, like Nest and Fitbit. The complexity of data rights and privacy issues have become blockers in many areas that will need to be overcome so the data can be used while protecting individuals right to protect their privacy, health, and safety.

The Industrial Internet of Things (IIoT) provides a Business to Business (B2B) approach that will directly impact the cost of manufacturing and therefore cost of goods; the value is a direct function of savings. The initial estimates of potential savings were enormous with respect to industrial efficiency, unexpected downtime, and worker efficiency and productivity.

The unfortunate side effect of this approach is it only focuses on improving our existing systems and does not consider any systemic changes that will necessitate a rethinking of our design, engineering, and manufacturing platforms, that most people

who were interviewed agreed had significant legacy and needed to be rethought. When computer aided design tools first appeared, they were revolutionary; they provided designers and engineers with new levels of freedom and capability. At that time, we could design geometries we could not manufacture.

In this regard, we have come full circle, we can now manufacture more complex geometries than we can design. The current suite of tools with boundary representations cannot efficiently represent the complexity of internal geometries that can be manufactured with 3D printing and hybrid additive systems. If we take a cynical view, when the designs and engineering capabilities are bounded by our design and engineering tools, then innovation will also be limited.

This led to the following thought process when considering the current innovation and savings models:

- If the industry does not have the necessity for change, why change?
- Is efficiency and savings sustainable as a business model?
- What will motivate the industry to adapt to new models and standards and what are the principle drivers?
- What are sustainable models of growth?

4.2.1 Sustainable Models

Sustainable growth requires a business model that is unbounded and provides the foundation for new companies and sectors to form. The problem with savings and efficiency is they will only reduce costs, but there is a limit to how much cost can be eliminated without cutting into safety, personnel, or quality. A company will quickly achieve most of their savings addressing the obvious inefficiencies and then spend ninety percent of their time scraping out the last ten to twenty percent. The savings will eventually reach a point of diminishing returns where the cost of the program will be greater than the savings; future improvement programs will be canceled and the current efficiency will be locked in with the program going into maintenance.

What is needed is a growth driver that will provide an unbounded opportunity for businesses to advance. The best choice is an innovation driver. Since there is an unlimited opportunity to create new products and services, this will be the core driver of the revolution and lead to rapid innovation and evolution of the industry.

When we look at internet service companies in the media, retail, and advertising industries; the enormous valuations did not come from taking existing advertising and entertainment models and making them better. Imagine if the Google® was only focused on making ad placement in print media more efficient? If Amazon® only provided feedback to brick and mortar stores for better product location and pricing? The internet would not have advanced beyond the technology of the 90's, since that was adequate to meet the existing needs.

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Cost savings can drive some initial technology development; the effort will not be wasted, since everything we do to improve efficiency is necessary to spur innovation, but inadequate. The current manufacturing technology and processes need to be rethought if we are going to evolve existing methodologies and move into a fully digital enterprise that enables innovation and agility.

4.2.2 Revolution in the Internet Technology

The innovations that marked the Internet revolution were led by new business models and revenue streams at a speed that caused traditional markets to be disrupted. Manufacturing could be in a similar place right now; there is a need, but the technology has not been emergent since the current processes and equipment do not provide adequate support and the impediments are often seen as insurmountable.

One of the key drivers of the Internet technology was standards. The base protocols, IP, TCP, HTTP, DNS, NAT, etc... and document representation standards using XHTML, ECMAScript (better known as JavaScript), Media Codecs like H.264 and MPEG-DASH, and CSS enabled what we now take for granted as the *web*.

As the internet matured, content and presentation were separated using CSS, this allowed for representation on differentiated platforms necessitated by the emergence of ubiquitous mobile devices with substantial bandwidth [8]. The simplicity of HTTP and the layered approach to the Internet technologies and the separation of responsibilities allowed for rapid adoption and eventual enhancement into real-time communications and content rich applications that rivaled native desktop applications.

When these capabilities became ubiquitous, applications that were once considered as only possible with the full power of the desktop, such as word processing, spreadsheets, and image editing, were transitioned to services and the result was much greater functionality and choice at greatly reduced costs. New business models also became prominent, such as subscription models, advertising, and *freemium*. These new models brought services to customers at a lower cost and resulted in increased revenue to the companies providing the services because of the larger market size and economies of scale.

Often overlooked in the standards space is the role of languages and frameworks that emerged around the same time that led to the rich dynamic environment we have today. Going back a little over fifteen years to 2000, the content of most Internet sites was primarily static, hand edited or generated, and then served up as linked pages-often coming from print media and catalogs as the medium. At that time, a simple shopping cart web application took nearly a year to complete. Dynamic applications were a rarity and the overhead to support the various browsers and incompatibilities often made it cost prohibitive for small companies to get traction.

At that time, the tools were inadequate for the task since the software frameworks were complex and cumbersome to work with and one had to think about how the machine would execute the code since efficiency bottlenecks were often a principle concern. There were attempts in the past to solve these issues, but the attempts often went too far by providing tools for business analysts with the stated goal of eliminating the software engineer and they had inadequate sophistication to be usable beyond a very small set of applications.

The success of Internet applications and services was predicated on new languages that allowed engineers to write at high levels of abstraction with efficient constructs that eliminated the need to focus on the machine performance, the compiler, and infrastructure, and instead focus on the customer needs and the business value. These languages were not standards in the classical sense; they were managed by consortiums that provided the resources to advance the capabilities and semantics of the languages and frameworks. The consortia created a specification that was adopted and maintained with many of the same constraints applied to standards bodies. They were all open and free to use and the source code was available to the community.

The key characteristic was elevating the engineering task from writing low level code for a particular computer architecture to writing abstractions that can be composed to solve business problems. With open source sharing of frameworks and core technology, the industry could remove the mundane burden of recreating infrastructure and core services. The frameworks were built upon new dynamic programming languages that, as Yukihiro Matsumoto “Matz”, the creator of the Ruby language, was quoted as saying: “computer languages should follow the principles of good user interfaces design and therefore they should be optimized around the user (programmer), not the machine.” [15] This was his philosophy and is now a common philosophy that is guiding many new languages.

Modern languages and frameworks can express the business intent using constructs that allow one to use abstractions that express the original problem statement in a natural form. These mechanisms translate the business requirements into functionality that fulfills the product requirements and the ability to verify the solution with tests that provide the basis for the documentation. This reduced the obsolescence of documentation and maintenance issues with complex systems.

These languages have been around for a long time, but the computer performance was always a blocker to adoption. Fortunately, as predicted by Gordon Moore in 1965, Hardware has been following Moore’s law [15], he stated “that the transistor count and complexity of components would double every year”, later revised to two years, and now normalized to 18 months. “At the same time the per unit component cost would also decrease.” This has held true for the last 50 years, but is expected to decrease in the near future since we are reaching the boundaries of physics. We must wait for the next revolution in computer hardware to get the next bounce.

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This progression has had a profound effect on software. As the performance of the underlying hardware was no longer a primary concern, languages and frameworks became more dynamic and the focus switched from writing software that optimized for performance to software that could solve business problems, and the realization that developer efficiency was more important than machine efficiency. By focusing on developer efficiency, the companies make more profits.

With cloud technology, the industry achieved on-demand horizontal scalability, “Infinite” storage, and infrastructure as a service, so the issues of storage and performance were lessened even more. The additional benefit to startups was that the upkeep of the physical hardware in the data center and scaling of the infrastructure became a concern for service companies like Amazon and Rackspace, thus freeing startups from upfront IT costs and complexity. This freed the software companies to be more creative, utilizing tools that were over ten times more efficient and more reliable since their time could be devoted to solving business problems.

One of the latest trends in technology is the concept of function composition and category theory from abstract mathematics. The concepts are applicable to systems design and fit very well in supporting distributed and federated services. A service’s input and output need to be well understood where they take a known set of inputs with complete information models that can be reasoned upon and similarly, the output information models must also be complete and have well defined semantics and relations to the input. Most advanced applications are moving in this direction, referred to as composable micro-services.

Most of the cloud technologies we now take for granted have only evolved over the last ten years. The trends in functional composition have only become prevalent in the last five years. The technology advancement in software moves at a breakneck speed, which has its pluses and minuses for industries like manufacturing which is looking for consistency. There is a need to bridge these philosophical differences to find a way to get the benefits of rapid innovation with quality, safety, and functionality.

4.2.3 Manufacturing Systems Through Composition

When compared to manufacturing technology and the advances over the same period, the changes in manufacturing have lagged the advancements in software and technology. What is needed is a strategy to close the gap and lay the groundwork for the rapid advancement of manufacturing technology. There are many differences between manufacturing and IT, so the technology cannot transition without re-evaluating the requirements, but at the same time, manufacturing should not disregard advancements made in other domains.

There are many parallels with respect to the role of the software engineer, the designer and manufacturing engineer when one considers the current technology and

processes used in the design, engineering, measurement, and the execution of manufactured processes. In manufacturing, the role of the engineer is still fairly manual as is the execution of a process.

The current situation will need to go through the same type of transition that software industry took where software engineers work at higher levels of abstraction; in manufacturing this means a designer and engineer can specify the functional requirements and constraints without having to worry about how a specific machine will interpret the low-level movement commands and operations.

The current manufacturing technology fails to achieve this. The first principle models of the equipment are not sufficiently well developed and do not have empirical feedback to be prescriptive where a desired outcome can be obtained on the first attempt. This is often not a result of the inability to physically model the materials and process, but because the equipment does not operate exactly as expected and the small changes are made in situ by experienced personnel. The changes are never fed back to the simulation, so the errors are never corrected and therefore the intelligence is lost.

This necessitates the following two areas of concern: the first is to provide higher level of abstraction in the engineering tools and allow for software to handle the individual machines and the manufacturing processes. The second is to provide feedback from the manufacturing equipment so that the engineering software can "learn" from the execution of the processes. With a completed feedback loop, the manufacturing systems can increase their ability to optimize processes and remove the burden from the engineer.

To provide the feedback loop, we need to have a complete the digital thread throughout the entire manufacturing process, from design through the lifecycle of the product. This has been discussed in length and there have been many attempts to provide solutions. Many of these approaches have solved isolated problems, but the software was often specialized for a single scenario and did not work with any other technology since the dependencies on proprietary data and information models differed from other projects, even when part of the same program.

There is a need for standardized information models that provide enough specificity that we can reason using analytics and build the next layer of intelligent applications. Analytical models require the ability to understand the data and turn the data into information that is actionable. Semantic standards provide the data in a form where the data has been imbued with meaning and context so the analytics can understand what the data refers to and how it relates to other data and information throughout the product lifecycle. A pragmatic approach is required to find the holes in the existing information models and then utilize standards fora and consortia to fill the missing pieces. Standards are the only way to build a platform that will support the integration of services where the services can interoperate.

The second key facet we need to take into consideration is identity. For every piece of data and every information model we create, everything needs to have a unique identity that can be composed in such a way that any other information modes can construct that identifier and refer to the product or part throughout its lifecycle. This requirement spans from design to execution to measurement and even into the use of the product during its life. One can even envision the continued association when a part is recycled or repurposed.

Identity is a primary concern when considering manufacturing service interoperability. We define an identity as providing a stable identifier; one that never changes for the lifecycle of the product. These identifiers also correspond to the manufacturing devices and their components as well as the inspection equipment and any sensors. Having stable identifiers allows services to associate data in information models across services. Extensibility in this manner will allow for augmentation of existing information models with light-weight consortia based standardization processes.

From the perspective of standardization, one key concern in solving this problem is harmonization. Standards provide similar schemes for referring to specific components of the product, equipment, and the material as it is transformed. Harmonization requires the models use similar semantics and identity. The models can be synthesized into companion specification through joint relationships between groups and the resulting capabilities will provide a much richer model than each individual group trying to extend beyond their capabilities.

This is now underway between STEP, MTConnect, DMSC (QIF), UPnP, ISA-95 (B2MML), MIMOSA, MQTT, SysML, ReqIF and OPC. Each group provides expertise in certain areas and regardless of overlap, the compatibility of these models allows for the software and services to understand the models and transform where necessary. The complexity of the manufacturing information models requires this to an even a greater degree than most of the business and media services.

4.2.4 Manufacturing System Architecture

Discussions with systems architects from major technology companies, such as Microsoft, IBM, ABB, Siemens, SAP, and Cisco indicated that the adoption of micro service based architecture is the prevalent direction of their organizations because of its ability to provide flexible deployment and scalability of individual components that afforded many more options and form the foundation for an effective separation of responsibilities between architectural concerns. Micro services are becoming the architectural best practice when constructing complex systems that have distributed components with different latency, storage, and compute requirements.

The various AVM project areas cannot be provided using a singular platform or architecture. The needs are too diverse. When creating abstractions, we will need to consider each component and how it interacts with each other component as well as

the temporal domain it resides in with respect to sensitivity to the timeliness of responses.

This is where micro services provide the ability to create separate independent components that provide functionality that can be composed. If we use standards based communications and information models, we can arbitrarily compose these services and each company can manage the services to the needs and business model that is best suited for its market and value proposition.

Federated micro-services allows for all business models from a traditional software licensing model to a shared savings model to be used, with the flexibility to support subscription, services, implementation, and maintenance as well. When models are dictated by a singular platform provider, the business model is constrained and often deployment and product offerings must comply. This can lead to lockout in certain industries like defense manufacturing where the platform constrains the product in such a way they become in conflict with the customer requirements.

4.2.5 Deployment Models

The leading industrial internet companies believe that new services will not only be cloud deployed, but will need to exist at the control domain, meaning in the motion control loop of the equipment, in the *fog*, which is the boundary between the shop floor and the information technology, and in the cloud domain. The location of these services will be defined based on the requirements of the service and the customer. There are emergent technologies that support relocation of services using the intent of the service and its constraints on determinism.

The new services will also take advantage of feedback loops using machine learning in the cloud to update models at the control, enabling self-optimizing systems that rely on the immense compute and storage capabilities of the cloud infrastructure. The industry currently considers the industrial internet to be a cloud scale problem where the actuation will be at the edge and in the controls. The cloud also provides economies of scale where these services can be made available to shops of all sizes, from tier one multinationals to small mom and pop shops since the overhead is balanced by the size of the market.

The architecture will be expanded in section 5 as will the objectives of time sensitive networking (TSN) using intent based communication and deployment.

4.2.6 Security and Provenance

Security is a primary concern of the industrial internet consortium and one of the areas of greatest contribution. Security in the manufacturing space takes on several dimensions, the first dimension is the physical security, addressing data in memory, on the wire, at rest, and during analysis. The second dimension is the verification of

the origin, or provenance, of the data to ensure that the instructions from design to execution to inspection have not been tampered with and signatures of personnel or systems can be verified. The third dimension is the safety aspects of the equipment and verification of correct operation.

The first-dimension deals with the aspects of communication and secure hardware. These areas have largely been address with existing and some emergent technologies. These technologies are primarily in the IT space, but OT systems have been slow to adopt and they have very poor support in this area. The equipment is often unprotected and cannot be easily secured. This has led to the need for edge devices to provide a secure perimeter around the devices. The equipment needs to be protected against any modifications and attacks that could reduce the safety or operation of the machine.

The second dimension provides assurances that the data throughout the manufacturing process, from design to engineering to execution and inspection has been properly communicated and that it has been signed by the authoring system and personnel giving an auditable chain of trust. There are numerous types of cyberattack that involve altering of critical documents and programs to introduce failures in the manufacturing processes. These issues are now being addressed with joint groups working with NIST.

The next dimension of safety is related to attacks from external sources. Building on the first two concerns, safety requires physical security and trusted information as well devices with adequate safety mechanisms built into the machines. Safety is a primary concern and separates the industrial technology domains from all other areas. Since industrial systems have physical components and are inherently dangerous, they need special consideration regarding safety.

4.2.7 Disconnect

The latest in industrial architecture has been primarily concerned with data collection and analysis. Industrial internet initiatives came out of Industrial Internet of Things where the motivation was applying learning models to machines and sensors. The AVM projects are primarily the first principles and geometry based analytics and do not take into consideration the feedback from the processes. It is necessary to combine both disciplines to complete the goals of connecting the digital thread, but these communities are divergent on their approach and technologies.

There has been recent movement of the computer aided tools (CAX) to cloud services, but these are only addressing cloud storage and licensing; they are not addressing the integration of services. As well, none of these initiatives have addressed data feedback to the CAX tools to provide closed loop feedback mechanisms. They have also been unable to integrate with services outside of the narrow-scoped set of features and partners with which they interoperate.

The lack of integration and feedback has created a gap that has slowed down innovation and prevented smaller companies from entering the market. When smaller, innovative companies cannot compete in a market, the progress slows and technology stagnates.

A standards-based approach to information exchange will open the market to companies that would like access to the industrial data, but cannot pay the costly licensing or are not powerful enough to enter into agreements with the dominant players in the industry. Previously, we made the case for standards and market growth. Progress has been impaired, but with open source initiatives and pragmatic standards, the industry can quickly advance.

4.2.8 Standards Processes and Lessons from Other Domains

A common reaction to standards at technology meetings, for example NSF Cybermanufacturing Workshop on Enabling Composable and Modular Manufacturing [16] meeting and Industrial Internet Consortium (IIC) [17], was immediate resistance. Standards are often seen as moving too slow to address the needs of technology since it is often thought that once the standard is published, it is already obsolete. Information technology has moved in the direction of using consortia and fora to create standards for various technology domains often manifesting themselves as frameworks or languages. Frameworks are often created using very lightweight process whereas languages often have a more formal change process.

Programming languages are an interesting parallel to semantic information models discussed in this document. Programming languages have many of the same characteristics regarding expression and interpretation that are required for information models. One could even say that a programming language is a semantic information model describing the process instructions to achieve a task.

The methodologies that have been successful for creating and maturing programming languages have been primarily run by public consortia like the Java Community Process. The Java Community uses Java Specification Request (JSR) to suggest new enhancement that are then reviewed and revised by the community. The Scala, Ruby, and Python languages all utilize a community approach to defining new capabilities of the languages and their standard libraries.

Using this approach, semantic models can be quickly revised while keeping backward compatibility and change management under the control of the community. The formal processes are too heavy weight for the semantic model definitions and therefore act as a deterrent to participation and adoption. There will be much greater acceptance and adoption in the IT community if the standards can be developed using a process that will be agile and maintain relevance.

The MTConnect Institute has been utilizing a similar methodology to develop and evolve its standard, striking the balance between stability of the information models and the need to evolve and change to meet the demands of the industry. MTConnect has also achieved rapid success and adoption because of this and its flexibility and rate of change has provided necessary value to the industry with many new entrants in the market of manufacturing data analytics.

The same formula can be applied to rapidly fill the holes and provide the necessary models to make the digital thread continuous. The existing standards can be leveraged using common identity schemes to allow the new standards to sit alongside and augment the existing models using references to components of the principle models. This information model composition technique can allow for rapid evolution around the core of stability.

4.3 Conclusion

The interviews with leading experts at multiple leading technology companies have consistently indicated that the architecture of the industrial internet will be a set of composable services deployed based on the intent and requirements of the service. This means that all areas of manufacturing must be addressed, from the motion controller to cloud based technology and every step in between, from design through end of life. The industry has identified a common set of architectural and technology concerns that will comprise the foundation of the industrial internet. These initiatives have primarily focused on data collection and analysis, but not on planning, design, and engineering.

There are many common concerns that are being addressed in the areas of service interoperation based on common semantic information models, safety, and security. These areas are being addressed using common components, services and infrastructure. If the manufacturing industry once again decides to ignore the mainstream of technology innovation, the gap will widen even further.

The following areas were identified as key concerns:

- Semantic information models
- Communication standards to allow services to collect data and interoperate
- UUID specifications and implementations
- Methodology for identifying manufacturing entities including the following:
 - Design features
 - Engineering Features
 - Inspection processes
 - Manufacturing processes
 - Assembly processes
 - Materials

- Measurements and the results
- Design and engineering Intent
- Manufacturing equipment and its components
- Sensors and sensor Data
- Data rights management
- Security and safety
- Relocatable services and analytics

The industry consensus is that there is no one vendor who can serve all needs and the current dominant players will be forced to change. This disruption happened in the information technology industry where market leaders were displaced by smaller companies with better technology and more agile platforms. This is a threat to the existing dominant players in this industry who are resisting change.

There are compelling reasons why the manufacturing industry must change, but many organizations are very resistant because they fear they will be accelerating the pace beyond where they can adapt. There has been active resistance to change, but the danger is that the industry will evolve despite the resistance and like many areas, if the leaders do not get ahead of the curve, then the new markets may not be advantageous to the economies that currently dominate.

A pure savings model will not suffice to spur change in the industry. Savings are the easiest issues to address, but they will not provide a sustainable model of growth once the initial benefits are realized. Innovation is the best driver for sustained growth and will necessitate new manufacturing technology and business models to make rapid innovation a reality.

There are some finite steps that can be undertaken to fill in the missing pieces in the existing set of standards. There are also new areas we need to explore in the standards like communications and service frameworks to provide the requirements that will aide in enumerating the requirements for manufacturing.

The recommendations are to pursue an agile and light weight process when creating semantic standards and model it on the process that have been successful in developing programming languages. Since there are many similarities in the domains of developing a programming language and a semantic information model, we feel this will strike the balance between rigorous progress and agility.

Adopting these approaches along with standardized communication, security, and identity should provide a platform for future innovation. Composing these federated services will allow them to interoperate in a dynamic fashion and provide the greatest flexibility from a business and licensing standpoint without allowing any single entity to gain sufficient control to slow down the rate of progress.

The result will have the greatest community and market effect with economies of scale for the application vendors to provide cost effective and value driven solutions to the industry. There are still huge holes to fill and the following sections will document those holes and provide details on the next generation architecture of federated platform made up of open standard based information models and communication protocols. The target of this approach is a cross functional platform that will allow for rapid innovation while keeping the manufacturing environment safe and secure.

5 Architecture for Standards Based Service Layer

5.1 Overview

Software systems architecture brings together the areas of domain modeling for each of the DMDII AVM program areas combined with the latest best practices in software and technology. The cross-domain requirements and principle concerns are discussed in this section to provide a foundation for interoperability and maximum synergy between the various AVM Programs. The specific standards used for the interfaces between these programs will be discussed in the next section of the document.

5.1.1 System Architecture

The following are the two key factors that play into the slow adoption of advanced manufacturing: (1) the desire to reduce variance and change which is key to stable production and (2) the safety and physical nature of manufacturing equipment where problems can result in injury or death.

The resistance to change permeates the industry and inhibits its ability to evolve. Manufacturing equipment has a functional life of between fifteen to thirty years and often the computer technology on the control systems will be at least two to four generations behind even when the machine is brand new since the machine was designed and the specifications were locked down over a decade ago, and the machine is still being produced with the same exact systems.

What would be considered legacy in the IT world has become the accepted norm for the industry. Many of the latest innovations around cloud technologies, data analytics, machine learning, and micro-services have been largely overlooked by the manufacturing industry. In the design and engineering areas as well, the software is often struggling with significant legacy architecture and it has been slow to adopt new architectures to address the needs of the industry. Since the customers are not demanding new software architectures, it has not been a key driver and the cost and availability of solutions have resulted in these issues not ranking in the top priorities of the manufacturing industry.

Safety is an area that is unique to the industrial domain. In other areas, like finance, media, and retail, safety is not considered since the worst case is usually a loss of revenue. Therefore, there is additional rigor required to develop industrial systems, but this does not preclude the use of techniques for system analysis and implementation and does not prevent the industry from utilizing the latest technologies that have benefitted many other industries.

When speaking with experts in the field, one finds a scarcity of literature on industrial systems architecture, let alone manufacturing, that have addressed modern technical concerns in the design and operations domain to derive the requirements of the next generation services. It is the goal of this document to address the areas of software architecture from the perspective of a common standards based infrastructure and supporting the internet scale problems the industry must solve to enable rapid innovation and economic growth.

The largest companies may be able to manage the technology and scale, but this does not solve the problem for the SME (Small to Medium Enterprise) manufacturer who cannot support the IT infrastructure and accommodate the complexity of these systems. The only way to efficiently provide solutions that utilize advanced technologies and achieve significant value for the customers with limited resources is to utilize cloud based services. Cloud services spread the costs of the IT infrastructure and software maintenance across many customers by using shared infrastructure and resources that allows customers to pay for only what they need.

The next generation of design, engineering, execution, and verification services will incorporate both first principles models as they have historically, with empirical feedback from the execution and life cycle of the products. Feedback systems will allow them to better understand the behavior of both the experienced operators and the equipment to construct predictive analytics and digital twins; feedback from the execution will drive the new models when combined with manufacturing fundamentals and deep domain knowledge.

Large software companies and startups will need to work together to solve these problems, since innovation has often come from smaller companies. This will maximize the velocity of innovation and development of new technologies that will can move past current impediments. These problems are too complex to rely on a few vendors to provide all the solutions and will therefore an ecosystem of solutions from multiple loosely coupled vendors is required.

From a software systems architecture perspective, the question is how to best service the needs of the manufacturing community and provide the most flexible platform for companies to adopt and extend without intellectual property and licensing impediments. Standards are the answer when systems are required to communicate complex information models in a secure and open manner with adequate protection of data rights to effectively address the needs of the industry.

5.1.2 AVM Projects

The AVM projects can be viewed as a set of siloed technology solutions that address various design, engineering, manufacturing, and business concerns relative to advanced manufacturing. Each has taken a unique and distinct architectural approach

and, except for Mind the Gap, the projects have not been developed in a way that considered interoperability as an initial concern.

Most of these projects reveal some common aspects that can be utilized to determine the most efficient way to provide maximum business value to the stakeholders and how these technologies can be leveraged to advance the state of the art in manufacturing. If the output of these projects were to be utilizable as a cohesive service platform, the synergy would provide a large impact on manufacturing effectiveness.

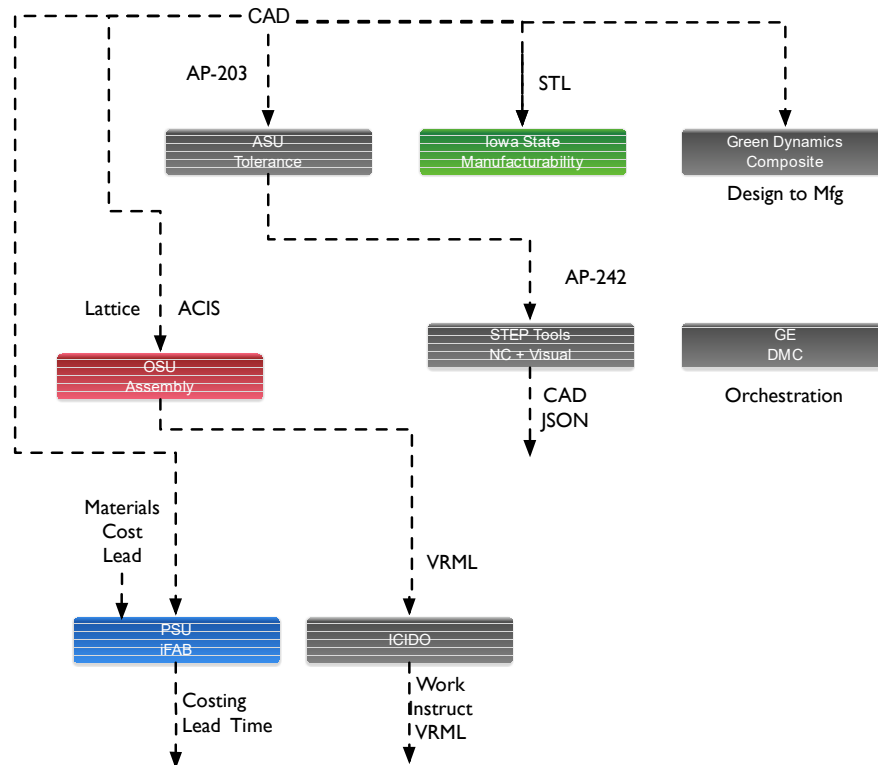


Figure 15: AVM Projects in Relation to Each Other

Of the current projects, we will consider the following areas: automated measurement and tolerances, automated assembly, costing and lead time, manufacturability and visualization, as these can be best integrated and analyzed as a cohesive set of services since they touch on some common domain areas.

We must first take a step back and reevaluate the business concerns that are being addressed by each project and how they can be augmented by the other projects. The synergies will only be possible when the projects utilize common input and output semantic models that will allow for free flow of data that can be reasoned upon by all the projects. This means that visualization will be considered an anti-pattern and should be discouraged as the primary objective. Visualization will be one of the

multiple projections of the underlying information model and can be layered on afterwards.

When one prioritizes visualization as the principle representation of the service, the value of the project greatly decreases. All services need to interoperate to allow for the system to leverage both present as well as future value from the ecosystem. We cannot foretell how the technology will evolve in the future, so the architecture needs to future-proof itself as we build the systems today so they are still relevant in twenty years. This means prescribing information models that can be automatically reasoned upon.

5.1.3 Standards

As discussed earlier, standards help to make markets, increase velocity of technology, create a larger market, and allow those markets and technology to have a longer duration. We are experiencing this right now with the MTConnect standard, which has enabled the development of new markets for manufacturing execution software that provides visibility and analytics applications and services. There has been an increase in the number and variety of solutions, and since it has been adopted by most major machine tool builders, the velocity is increasing.

Standards provide the ideal method to integrate disparate technology platforms using common communications, security, and information models, so the applications can achieve quicker results and reduce costs since multiple proprietary connections and transformation will not be required

5.1.4 Distributed Technology and the Need for Services

The technologies being developed are going to necessitate the use of cloud based services since the scale of the problems has now exceeded the desktop computer and the private data center in all but the largest companies. If these technologies are going to be available to the mainstream manufacturers, they will require a significant amount of storage and compute power that can only be achieved using share services that will provide the economies of scale and platform as a service.

5.1.5 Services as a Business Model

There are many advantages to a service based business model, both from the consumer as well as the provider's perspective. From the consumer perspective, services provide the value you need, at the time you need it, at the scale you require, without the overhead of maintaining complex software systems. A customer can scale up or down their use without having to pay a penalty and it provide less upfront investment and lock-in. Upgrades are usually included with the subscription and since all customers are upgraded together, resulting in no legacy software version issues.

From the supplier perspective, a service based business has the advantage of recurring revenue that is preferred by investors and market analysts. The scalable platform based approach allows for economies of scale and the ability to quickly accommodate new customers and even provide free pilots since the overhead is much less than an on-premises deployment. Immediate improvement, while beneficial to the customer, also are beneficial to the application provider since they remove the overhead of supporting and maintaining legacy software.

From a support perspective, the model allows companies to provide better support and customization without having to be on site, allowing for greater geographic freedom and international coverage for small and large multinational companies. For this reason, many companies like Adobe, Autodesk, and Microsoft have all been moving to a services based model. Cloud services also provide the greatest economies of scale for both compute and storage. The next generation of manufacturing technologies will be solving problems at internet scale, not desktop; it is no longer possible to be confined to the limited resources of a desktop PC.

5.1.6 Security

With cloud based services comes the concerns around security and privacy. Companies will not move their data to the cloud until they are certain that it is being protected and conversely, that it does not compromise their OT environment. There are fears of safety and loss of IP since the current manufacturing technology is not secure and the current solution is to air-gap the operational technology which greatly limits the availability of advanced technology on the shop floor.

There are many aspects of security; there is the data in the control systems, data on the wire and in storage when it is at rest and then the active data in motion in queues and in analytics that produces derived data. Each of these areas are concerns for both data to and from all systems in the manufacturing eco-system. In the manufacturing domain, there are also concerns over geometric representations and regulatory restrictions as well as security around processes and materials that are used.

As systems become model based and digital, the possibility of unauthorized access to intellectual property is an increasing concern. There exists a large body of standards in the Industrial Internet Security Architecture from the IIC and this can be leveraged for use within the emergent services and systems.

There are guidelines outlined in the Common Criteria (CC) ISO/IEC 15408 that correspond to computer security criteria to assert and validate that the technology being (Target of Evaluation (TOE)) offered meets the criteria of the Protection Profile (PP) and the Security Target (ST) given Security Functional Requirements (SFR) as laid down by the user community.

5.1.7 Provenance

Provenance is often considered an aspect of security, but for this discussion, it will be treated as a separate concern since it can provide the assurance and trust that a document has not been modified and guarantees the authorship of the document. In a model based digital system all document and artifacts will need to be signed in a secure manner using a method where the signature cannot be forged and the certificate is also validated by a root level certificate authority. This is the same mechanism used by browsers when validating web site certificates.

The same system for analyzing the security requirements using the Common Criteria are used for ensuring digital signatures are secure and cannot be forged. It is also possible to use a certificate based smart card to store the private key and sign the documents, making forgery nearly impossible. There are many solutions for secure signatures that can be verified with public keys that have been authenticated by a centralized root signing authority.

5.1.8 Data Rights Management

Data rights is also a separate architectural concern. It specifies the ownership and intellectual property of data. One of the biggest changes when moving to a service based economy is the monetization of data; something that was not an issue as long when data would reside on the local hard drive. This has all changed and the value of the data as an asset has become both a concern and a source of great opportunity.

There is insufficient precedent to understand all the ramification of manufacturing data monetization and the effect it will have on the economy and business. There are efforts underway in the IIC Data Management Group to characterize how ownership of data will be treated from the raw data being collected from equipment and products to the derived data that has gone through multiple complex proprietary transformations. Mutual Distributed Ledger mechanisms will be discussed as a possible solution. The architecture of the services will be required to manage digital rights and properly reflect the contractual constraints.

5.2 Software Architectural Patterns

Software architecture utilizes the idea of *patterns* to provide common solutions when creating software. Architecture patterns are higher level abstractions than design and implementation, rather, they look at the abstract concerns of the software systems and their interoperation between components and other systems. The architectural patterns also provide the functional and non-functional requirements of the system such as performance, scalability, quality, interoperability, and availability.

These patterns can be applied to the design and implementation, insuring it must meet all the architectural requirements and address all the concerns. The design will

specify the implementation concerns like operating systems, communications protocols, package dependencies, frameworks and languages used when constructing the software system. Using *Architecture Patterns* allows systems to be created with the confidence that the higher-level needs have been documented and taken into consideration.

The current work being done in the industrial Internet of things (IIOT) has not envisioned the information flows of the manufacturing designer and the engineer, they are concerned principally with the data produced by manufacturing execution and the analysis and feedback of actionable events and activities. The current set of AVM projects are primarily first principles and feed forward technologies, meaning they are not receiving any empirical feedback, except for Mind the Gap. The OSU automated assembly project is currently not utilizing the execution of the process as feedback, but envisions it will in future iterations.

There is a large technology gap between manufacturing as it exists in many small shops and what is being developed by these projects. The current manufacturing community has significant attachment to paper for designs and execution in most manufacturing enterprises. As stated before, this is at odds with where the industry needs to go and how these future services will interoperate.

As we discuss these architectures, we will be referring to various terms that define deployment decisions that are made regarding various services. The current terminology we will be adhering to defined the following areas or domains of the system architecture:

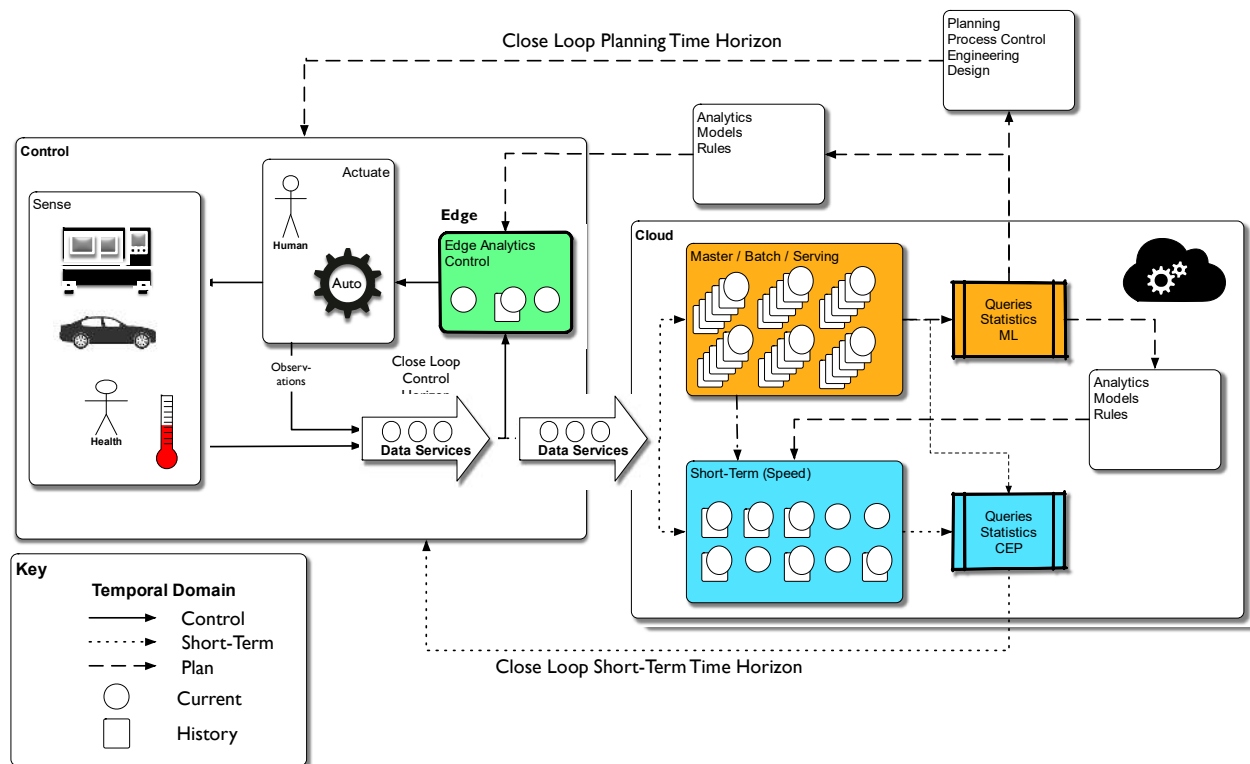


Figure 16: Industrial Internet Analytics Architecture

Control: The control domain is defined as directly connected to the device and is communicating to the control system within the time constraints that can manage motion and safety. The control loop is often referred to a sense, compute, and actuate system and it is usually in close proximity to the components of the machine.

Information Technology (IT): When referred to in this context it refers to the collection of business services and applications that are located within the company and constitute the core technology of the enterprise. IT resides at various locations within the enterprise. Depending on these size of the enterprise, this can be local to a single site or centralized or some combination.

Operation Technology (OT): The technology that connects the equipment used in the production or operation. These networks are designed to interact with systems that are insecure and have limited ability to update any of the software. OT Is always limited to a single site.

Cloud: An internet-based infrastructure as a service that provides highly scalable on-demand shared compute and data management resources. The economies of scale make cloud a very cost effective solution to

providing services to multiple customers without costly infrastructure spend.

Edge: The edge domain is defined as the next step away from the control where the device is communicating with the outside world and the latency may be greater than what is required to control motion. The edge also provides a security boundary between the network and the device.

Fog: The fog domain is defined as the boundary between the Information Technology (IT) and Operation Technology (OT). It is co-located with both the OT network and provides a bridge between the IT and OT environments. Often referred to where the carpet meets the cement.

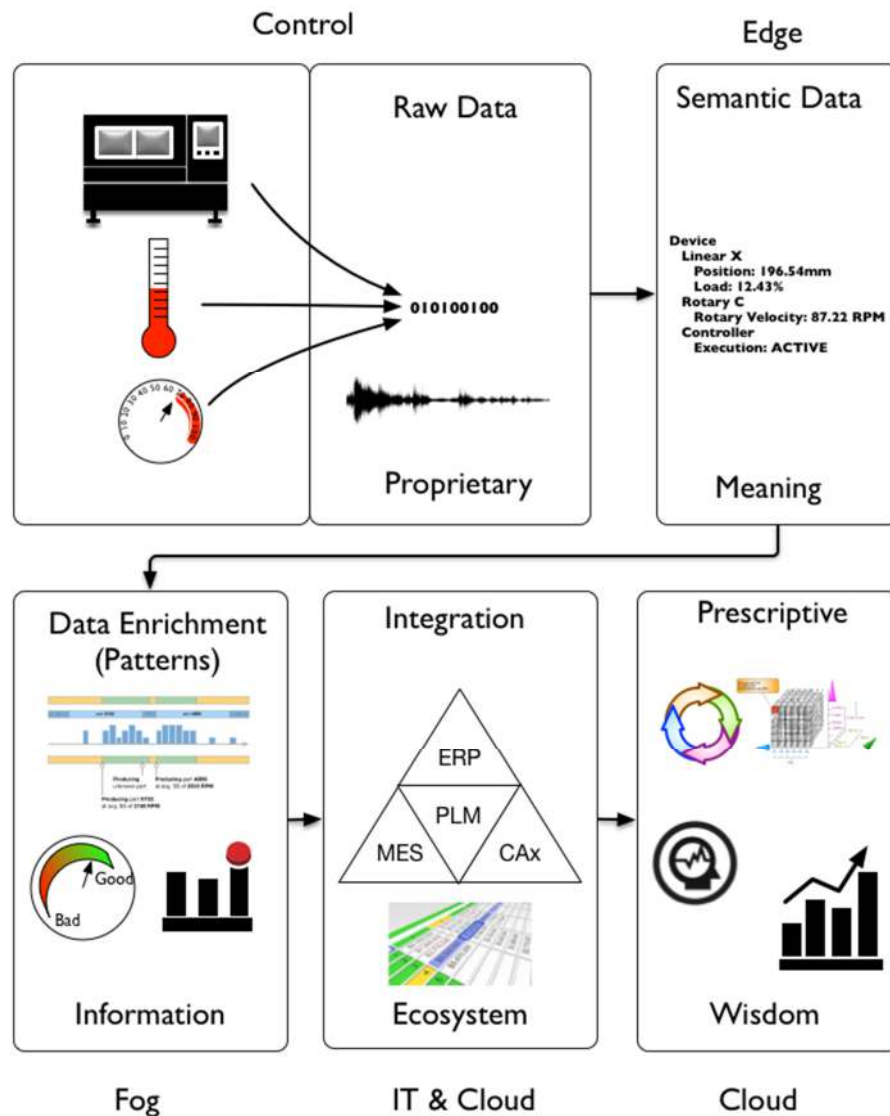


Figure 17: Segmentation of Responsibilities in IT/OT Architecture

Design and engineering applications are typically on the IT network where the Product Lifecycle Management (PLM) systems cross the boundary between engineering and operations. The AVM technologies have typically been within the IT domain and the major change that will be occurring is the move of the applications from the IT domain to the cloud. There are already some instances where this is happening with Autodesk and Dassault, but the use of the cloud for highly scalable compute in manufacturing is still very limited.

5.2.1 Federated Services

The architectural patterns proposed in this document are an embodiment of a federated architecture pattern where we have loosely coupled, semi-autonomous systems that interoperate with each other. The idea of federation is in relation to the de-centralized orchestration of these services where they can be combined based on the needs of the business or the system. In this instance, the systems are communicating using standards based protocols and information models.

Many of the most complex and scalable services, like Google and Netflix, utilize federated micro-services as the core of their offerings. There are many benefits from scalability and operations perspective to providing a platform for rapid innovation and limiting disruption by isolating the responsibilities of any individual service so that it is resilient and issues can be quickly addressed.

There are many ways to create complex computational systems. Historically the software industry has moved from monolithic systems, to multi-tier-separating of data storage and access-and then to federated services where each service has specific responsibilities that can be recursively composed all the way down to micro-services that can be connected like Legos to provide new capabilities without effecting the functionality of the higher-level services.

Composable services have become the recommended architecture for many computationally complex systems because they allow for each service to benefit from capabilities that may be outside an enterprises core competencies. There are key characteristics that allow this to function, namely the services are stateless, they have common information models and protocols for communication, referred to as the service contract, and they are loosely coupled, meaning they are capable of running independently of each other and utilize other services that adhere to the same contract.

Large platform services like Amazon Web Services (AWS) and OpenStack are architected as federated services that work with external and internal resources to enable complex capabilities like monitoring, load balancing, dynamic scaling, routing, etc. to provide the user with the maximum capability with the least effort. Many of

these systems are highly complex, but the complexity is hidden behind a service layer that communicates using standardized information models and APIs.

5.2.2 Common Semantic Information Models

One of the requirements is that the services agree on how they will exchange data and information. There are two aspects of information exchange, (1) the first is the protocol that is to be used to communicate the information, this includes messaging, discovery, on-the-wire security, connectivity and communication. Communication concerns have been largely addressed as well as the security concerns around communications. (2) The second, Information modeling is the definition of the structure, meaning, and context of the data being communicated. The information models are domain specific and are often developed by consortia that are responsible for the advancement of the models as the industry moves into new areas and adopts greater technical capabilities.

When we are referring to information models, we are specifically referring to semantic information models that provide both the meaning and the context of any piece of information. This is an important concept since there are many information models that provide an abstract data structure and typing system like OPC/UA and EXPRESS (ISO 10303) used in the STEP data models.

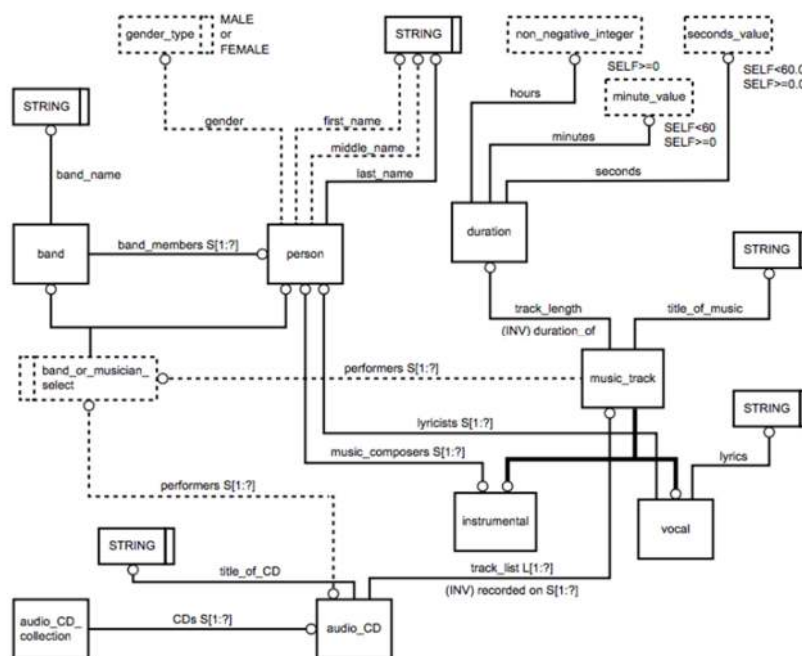


Figure 18: A Conceptual Data Model of Datum Systems [18]

A syntactic information models requires a layer on top to allow analytical systems to understand the meaning of the data. In the example from NIST, the ISO 10303 standard is utilized to describe the information model for a compact disk database. This has no bearing on manufacturing systems and is very general purpose. For that reason, using a purely syntactic model, one cannot analyze or reason about the data since this requires a complete understanding of the meaning and context.

For that reason, the focus for a comprehensive manufacturing system's architecture will require semantic information models for all inputs and outputs to allow for the greatest degree of utility. We must also have all models provide harmonized mechanisms for identifying each component of the information model so it can be tracked throughout its lifecycle as well as the associations with secondary models that will be created to extend the capabilities of the existing standards.

5.2.3 Standards

The standards we are considering are all semantic in nature and some will utilize underlying syntactic models, but these will not be the primary focus or concern since it is an assumption that any semantic standard is based on a standardized syntax and grammar. The other assumption we have made is that these standards all follow the requirements outlined in the first section regarding open standards.

Analysis of what constitutes an open standard have been outlined in *Open Standards Requirements (2008)* and are as follows:

- The standard is adopted and will be maintained by a not-for-profit organization, and its ongoing development occurs based on an open decision-making procedure available to all interested parties (consensus or majority decision, etc.).
- The standard has been published and the standard specification document is available either freely or at a nominal charge. It must be permissible to all to copy, distribute and use it for no fee or at a nominal fee.
- The intellectual property – i.e. patents possibly present – of (parts of) the standard is made irrevocably available on a royalty-free basis.
- There are no constraints on the re-use of the standard. [10]

These are key constraints that allow for open use and open development of the critical information models that will be considered and interconnect the service architecture. Some of the standards were conceived with a physical document as the medium for communication-ASME standards are specified for drawings-so the concerns of the model may not be directly relevant or are counterproductive to a purely digital workflow in their current form.

For this reason, many of the existing standards will need to be reimagined to provide additional representations that are better suited for a purely digital workflow and

information that was once annotated directly on the drawing will need to be captured in a semantic model that can represent the data in a way that can be utilized by other services.

5.3 Analytics and Feedback

The current standards never envisioned that there would be feedback from the execution of the manufacturing processes. The standards were concerned with a unidirectional process of communicating design to engineering and then to execution and verification. Feedback was a manual process comprised of anecdotes from people performing each step in the process. Each group was a separate silo with different concerns that led to the gaps we have today in the information models and the representations.

Standards like MTConnect and QIF (Results) are examples of standards that provide semantic information feedback from the manufacturing execution processes. As the industry moves into the next generation of capabilities, the ability to understand the results from the as-built system versus the hypothetical assumptions made using first principles will become an imperative for digital twins and predictive analytics.

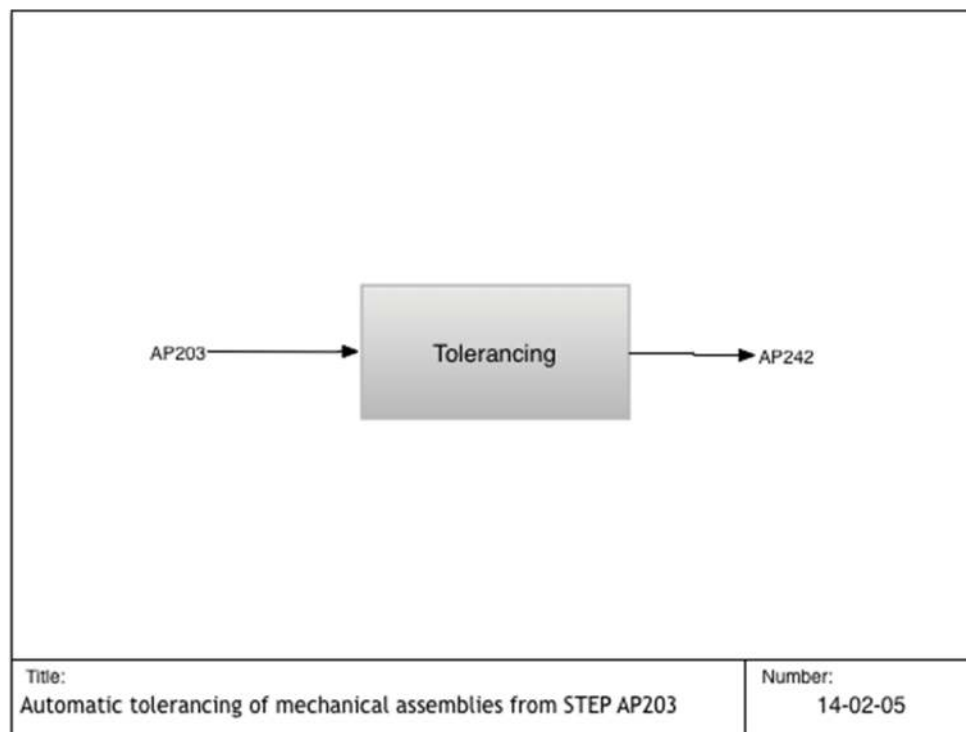


Figure 19: Example IDEF0 Diagram for Automated Tolerancing

Feedback is not only limited to the existing systems, but incorporates the lifecycle analysis of the manufactured part as well as costing and scheduling to allow the

services the full range of information that is required for decision making. The example in the diagram above is currently limited to the AP203 solid model input and the AP242 Ed2 model with semantic PMI as output. There are many other inputs that are required to make an automated tolerancing service provide full value, many of these models are not available or in use at present, as represented below.

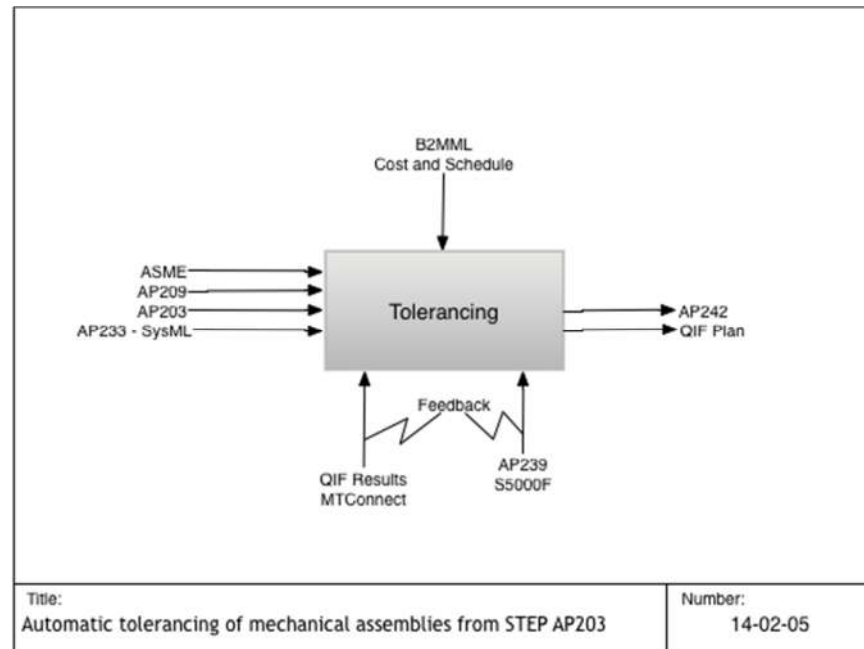


Figure 20: Example IDEF0 Diagram for Automated Tolerancing (2)

5.3.1 Analytics

Modern cloud based services that have a significant analytical component are composed of tens of thousands of machine clusters. Services like Facebook, Netflix and Google have conquered the scalability and reliability problem by developing micro-services that can be horizontally scaled along with storage and data replication techniques that eliminate single points of failure and allow for global access and high performance computing that is incomparable to even the fastest super computers.

Manufacturing software has been primarily desktop based and limited to the resources of a single machine. This limits the capabilities and ultimately the functionality of the products and by extension—since there are so few vendors in the market—the capabilities of the industry. The result is a slow-moving industry that cannot accommodate rapid change. The problems that are being addressed in the AVM projects are internet scale problems and will not succeed unless there are sufficient economies of scale and resources available to perform their function.

This same transformation occurred in many other industries as we have moved from analytics on a spreadsheet to cloud based big-data services that incorporate data

from thousands of sources. An example is the CRM market where the products capabilities exceeded the ability of stand-alone products to cloud based offerings from Salesforce and Microsoft that are investing heavily in advanced analytics, machine learning, and AI.

As Louis Columbus said in an industry report in 2016:

Cloud-based analytics platforms offer the scale, speed of deployment, agility, and ability to rapidly prototype analytics workflows that support the next generation of CRM workflows [19]

If we contrast with IT cloud infrastructure and DevOps technologies that have moved from statically deployed applications to dynamic self-organized orchestrated systems, manufacturing will need to follow the same maturation process to achieve the same level of capability that is available from products like Mesosphere [20] and Google Kubernetes [21].

As we move from backward looking reactive systems to cognitive systems that can self-organize and prescribe, manufacturing systems will need to follow the same maturity model as cloud analytics systems that are moving to cognitive orchestrated models with learning. The following diagram illustrates the maturity model:

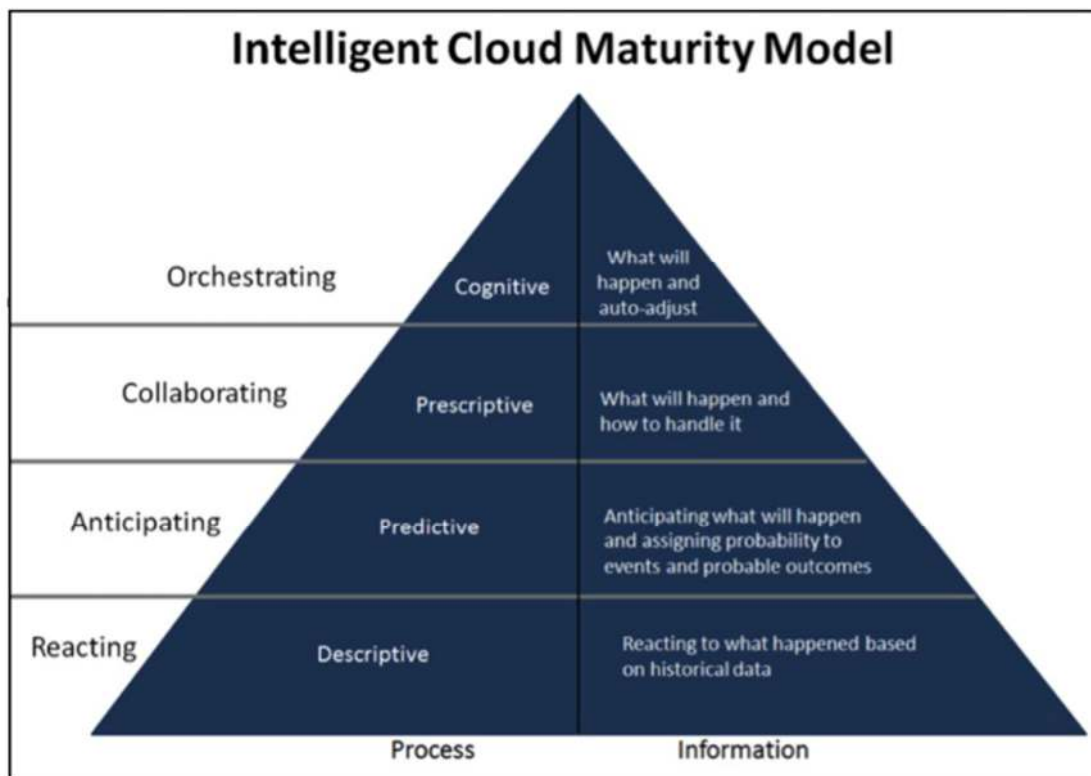


Figure 21: Intelligent Cloud Maturity Model [19]

5.3.2 Composable Design and Engineering Services

Modern software design has moved from monolithic systems that comprise entire software systems, to three tier where the data management and persistence were factored out as stand-alone processes for resilience and performance to micro-services, where each concern is separated out into an independent service. The benefits of a micro-service architecture are the ability to distribute load and scale complexity as the system grows. It also allows the system architect to create components that can be verified independently and with minimal dependencies to other systems.

Composability comes from mathematics where a series of functions can be combined where one function consumes the results of the other. If the functions operate on suitably chosen domains and codomains, then the functions can be composed together. This concept, which came out of set theory and made its way into computer science through the functional computing community, has now been incorporated into the preferred architectural patterns for highly scalable web architectures.

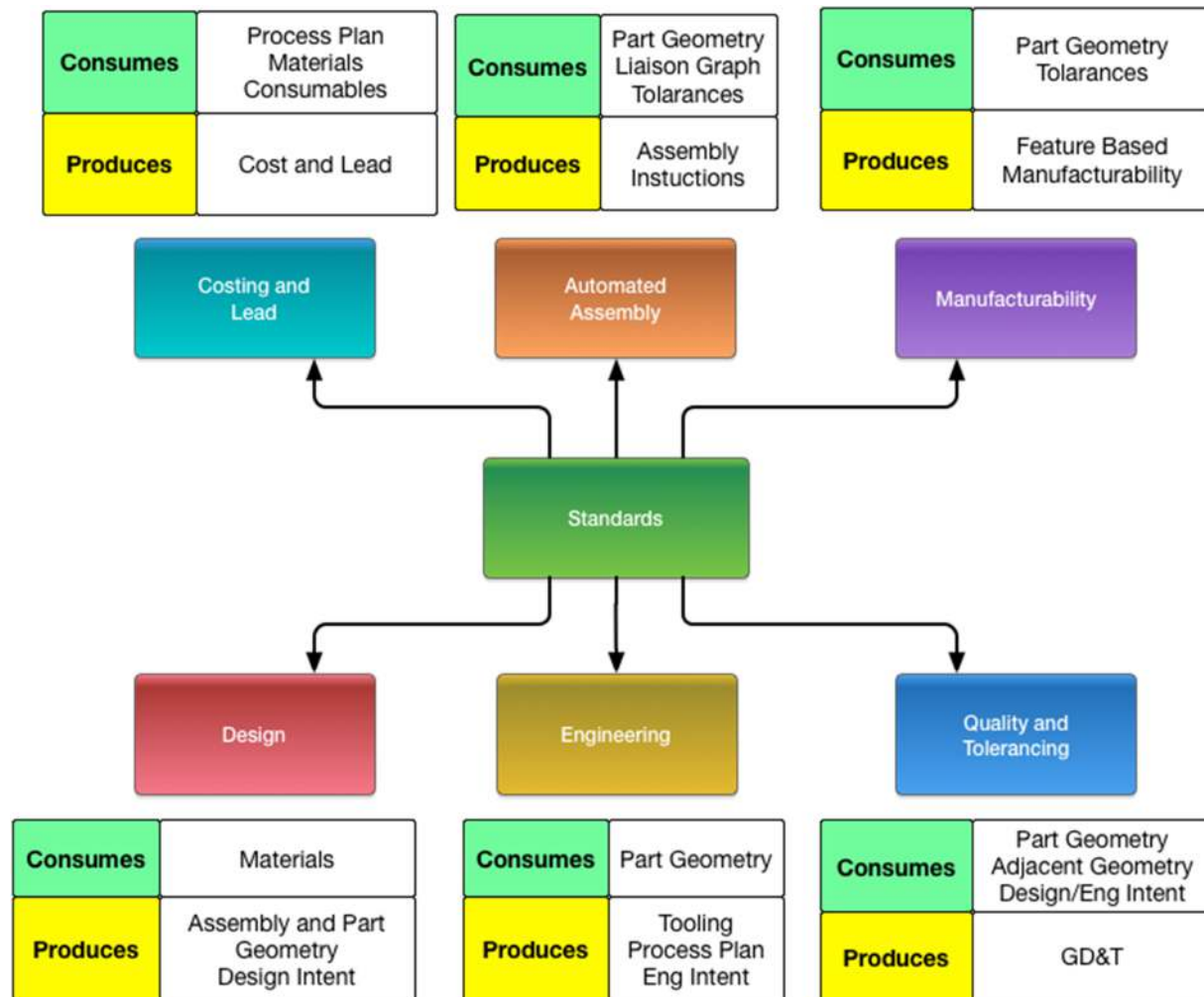


Figure 22: Service Inputs and Outputs

The core principles behind this methodology are as follows: (1) The services or components, of the system, are all operating on a set of standardized inputs and producing standardized outputs, (2) the state the service is operating on is defined by the inputs, (3) and the service will perform a set of transformations that are limited to scope and responsibilities to produce a set of outputs that can be consumed by other services. The benefit of this architecture is a very modular design where every component can be replaced without effecting the entire system and since they are independent, they can be easily replicated.

The services can also be developed using different hardware, operating systems, programming languages, and databases; where they are optimized around the best solution for the job. The concepts behind this architecture can also be considered at all levels, from the application that incorporates multiple services down to each component of the system that can be developed as a separate micro-service and

composed together to provide higher level functionality, or split apart and redeployed to at different levels of the system.

Composable architectures also provide the capability to relocate components to differing deployment domains. An analytical system developed in the cloud can be deployed at the edge if the necessary inputs are available. By minimizing the set of inputs to any service, the greatest value and utility is achieved.

5.3.3 Ubiquitous Analytics

Manufacturing systems require rapid response to changes in the manufacturing environment for safety and security. As products become more data driven, for example, the new Tesla automobile is referred to as a computer with wheels, the line between the digital and the physical world is getting blurred. The result of this is twofold, (1) first there will be much more data about the use of our products that can be used to feedback to design and engineering, and second, (2) the technology utilized on the device will become much more sophisticated and connected.

The design and production of continuously connected devices provides a great opportunity to interact with a system long after it is manufactured. It also means the conceptual models of how physical systems will interact with analytics and how changes will be made to existing systems will be drastically different. Design for manufacturing assumes static products, but when one considers dynamic products, in the way one considers software systems, the concerns of design and engineering change.

The analytics that are used to control these devices, whether they are airplanes, cars, boats, shoes, or refrigerators, will be continuously analyzed and create new models that will be deployed to optimize upstream processes. The new models for optimal performance will be communicated to the devices in a continuous improvement cycle. The new design and engineering tools will need to consider how to best instrument and manipulate products without sacrificing their safety and reliability.

The models that are communicated will need to be simulated and tested before deployment. They will therefore need to be transportable where an analytical model and system can be tested in a controlled environment and then delivered to the site where the behavior of the model can be ensured. The systems architecture will need to abstract the physical platform and the latency related issues with absolute assurance that the simulation will function the same given the same set of inputs.

This is also relevant for manufacturing equipment where adaptive optimizations will be delivered to the manufacturing devices and will need to incorporate these optimizations. A first example of this is being done in the Mind the Gap and O3 projects right now. The technology is still in its infancy, but if one extrapolates using other industries as models, the use of transportable models and a new generation of

adaptive manufacturing platforms that are informed by manufacturing and lifecycle are made possible, but it will require services that can be updated and verify analytical models in a controlled manner.

5.3.4 Feedback and Closing Loops

To take advantage of a cloud scale analytical platform, the core technologies that are currently being used by manufacturing software vendors will need to be redesigned. This becomes especially important when execution and use feedback will be used to enhance the analytical models and build digital twins. The Industrial Internet of Things will be required to handle huge amounts of data at enormous rates. The models must be able to handle the influx of data as well as analyze the data with a latency that still allows the results to be utilized in the process.

Predictive models that operate with a longer time horizon will also utilize this data to make better decision and improve the first principles models to more accurately represent the physical world. The new design tools will balance manufacturing and engineering knowledge with machine learning systems that compare the predictions with reality and improve the models dynamically. The resulting systems will be able to deliver a much greater degree of accuracy.

Closed loop has been defined by the Industrial Analytical community as any information has been communicated that changes or effects the operation of a device. The time horizon can be a nano-second or years, the time domain is not important from a conceptual perspective, from an implementation perspective, the differing time horizons will require different technological approaches.

Leaders in networking infrastructure are now working on protocols that incorporate TSN (Time Sensitive Networking) as a key concern. TSN abstracts the concepts of latency, synchronization, response times, and resilience to provide intent based solutions. There are assumptions about the technical requirements that have driven decisions based on existing network infrastructure and design. The next generation control systems that will incorporate cloud based analytics and feedback loops will react to changes and the systems will self-optimize depending on the latency and response time requirements of the adaptive algorithms. The software systems will express their requirements for communications and the networking system will adapt based on its capabilities.

Dynamic deployment and system configuration based on capabilities and requirements will be negotiated to create an optimal solution from both a cost and complexity viewpoint. Early pull based orchestration tools like Capistrano led to more complex services that could dynamically scale and manage clusters of computers like Chef and Puppet. Feedback systems were provided by companies like Splunk and Elastic Search (Kibana) that would monitor the real-time efficiency and load on the system and provide reports and proactive changes. With Docker containers that could encapsulate

the configuration and requirements of a service; the services could be rapidly deployed and distributed as needed across multiple hosting environments.

Technologies like Apache Mesos are now capable of abstracting the data center into a set of distributed, fault-tolerant resources that can be dynamically orchestrated to perform tasks. The Mesos system would be a good proxy if one was to view manufacturing resources as a pool of capabilities and then distribute the resource and scheduling services across the entire set of machines.

In autonomous driving vehicles, there are some emergent closed loop analytics systems that can be deployed in a flexible manner for navigation, safety, and performance. The same types of services have not made it into manufacturing systems. These systems are being developed to be adaptive to road and environmental conditions with the ability to make decisions in near real-time. It would be interesting to compare the adaptive control systems for autonomous vehicles with adaptive control in manufacturing systems.

5.4 Industrial Internet Security

The following is a summary of work done in the IIC G4 on security for IIoT- systems and the work being done at NIST on the digital thread and now being incorporated into MTConnect and QIF standards for identity and provenance. The seminal work on industrial security was done by the IIC Security Working group who addressed the concerns around trustworthiness of various industrial and business systems and the architectural patterns that would be required to ensure that new technologies and services could be utilized.

The OT (Operation Technology) systems have historically been protected by physical barriers, air-gap (completely disconnected from outside world), and obscurity. There was little known in the IT world about the technology used for industrial systems that even if one could gain access, to alter the state of the device where the chance was undetectable by the operator was very challenging without intimate knowledge of the workings of the equipment. For this reason, the industrial equipment has been relatively safe and not the target of attacks.

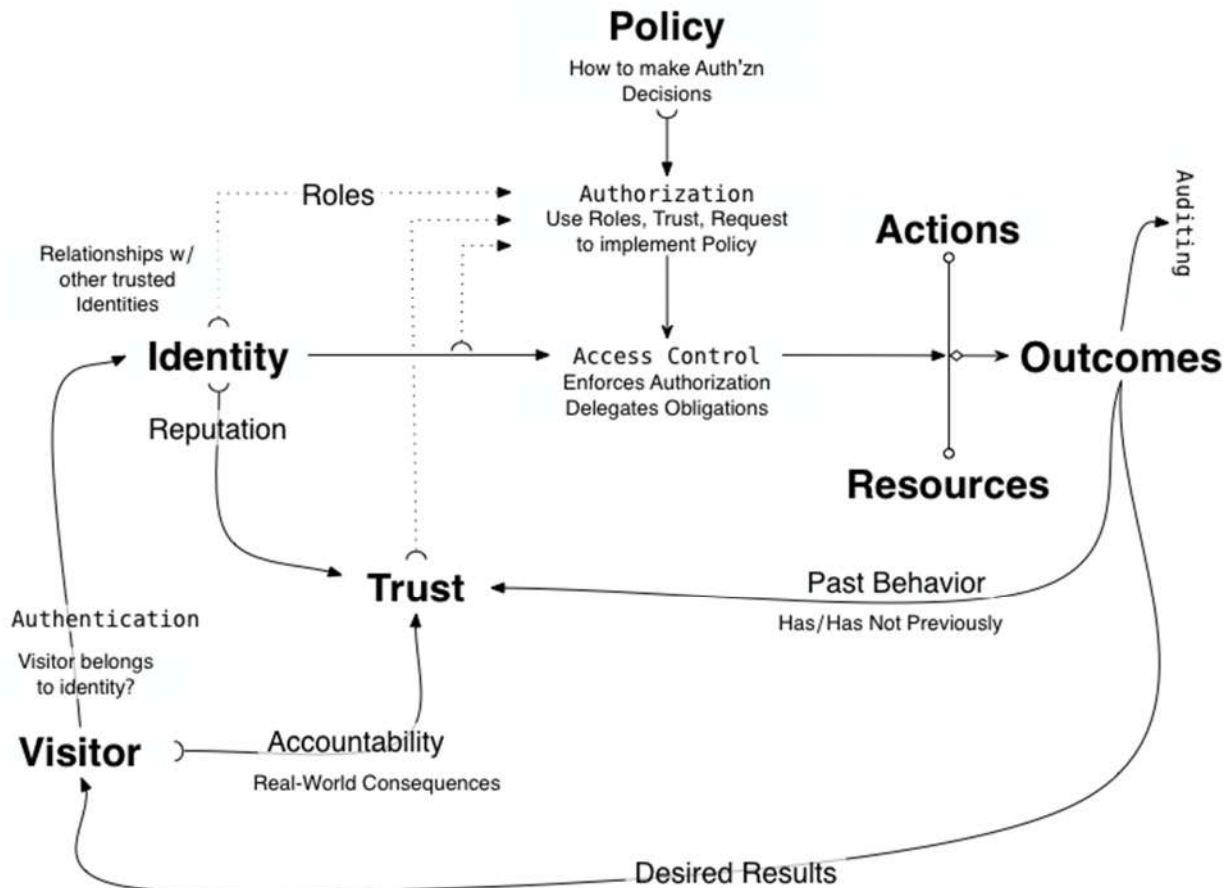


Figure 23: Security Domains and Trust

The diagram illustrates an information model that describes the policy management architecture for a secure system with the high-level concerns highlighted. All of these areas need to be addressed in the system architecture to provide trust that the system can manage, secure, and audit itself reliably.

5.4.1 Vulnerabilities

There are three general areas of attack that can be perpetrated on a manufacturing industrial system. They are as follows: introduction of defects or changes to the manufacturing process, compromising the function or safety of the manufacturing equipment, and unauthorized access to intellectual property or trade secret.

Studies have been done regarding the vulnerability of these systems and how through corporate and government sponsored attacks serious damage could be done to critical products without detection even in final inspection. This is becoming even more critical as new technologies like 3D printing are used and small defects can be introduced by changing the operational state of a machine or the program being executed. One such study was done by Virginia Tech [22] where the students could

introduce a small defect into a part by a minor alteration of the part program, unbeknownst to the operator or inspector.

Such defects may not have immediate impact, but because the parts are assumed to have an expected lifecycle, critical systems in power generation or transportation can fail unexpectedly and cause serious damage. The current technology used for the management of critical manufacturing artifacts did not envision these threats when it was created nor did it envision a connected environment where external systems would be required to optimize and control manufacturing systems.

The second vulnerability is with respect to the operation of the equipment. The equipment is inherently dangerous and an attack that disables critical safety systems can cause serious injury and possible loss of life. Once the system has been compromised, the entire enterprise will need to be shut down until all systems can be verified for safety. This will have a huge impact on a company's ability to operate, damaging their reputation, and resulting in loss of revenue. When governments and multinational companies are targeted, the consequences can cascade to a global scale.

The third vulnerability is related to theft of intellectual property or trade secrets that are one of the first targets of the industrial attacks to date. Coordinated attacks against major defense manufacturers have been underway for many years and many safeguards have been put in place. Most of these safeguards are implemented with the IT systems and the OT technology is isolated to protect the manufacturing assets. Most of the current manufacturing processes are still based on drawings and notes. This renders a level of security due to the physical nature of the media, but also severely limits the enterprise's capability to innovate or optimize. As these systems move towards model based, this will become a more pressing issue and steps will need to be taken to ensure the artifacts are protected and the information can be trusted.

5.4.2 Information Technology vs. Operational Technology

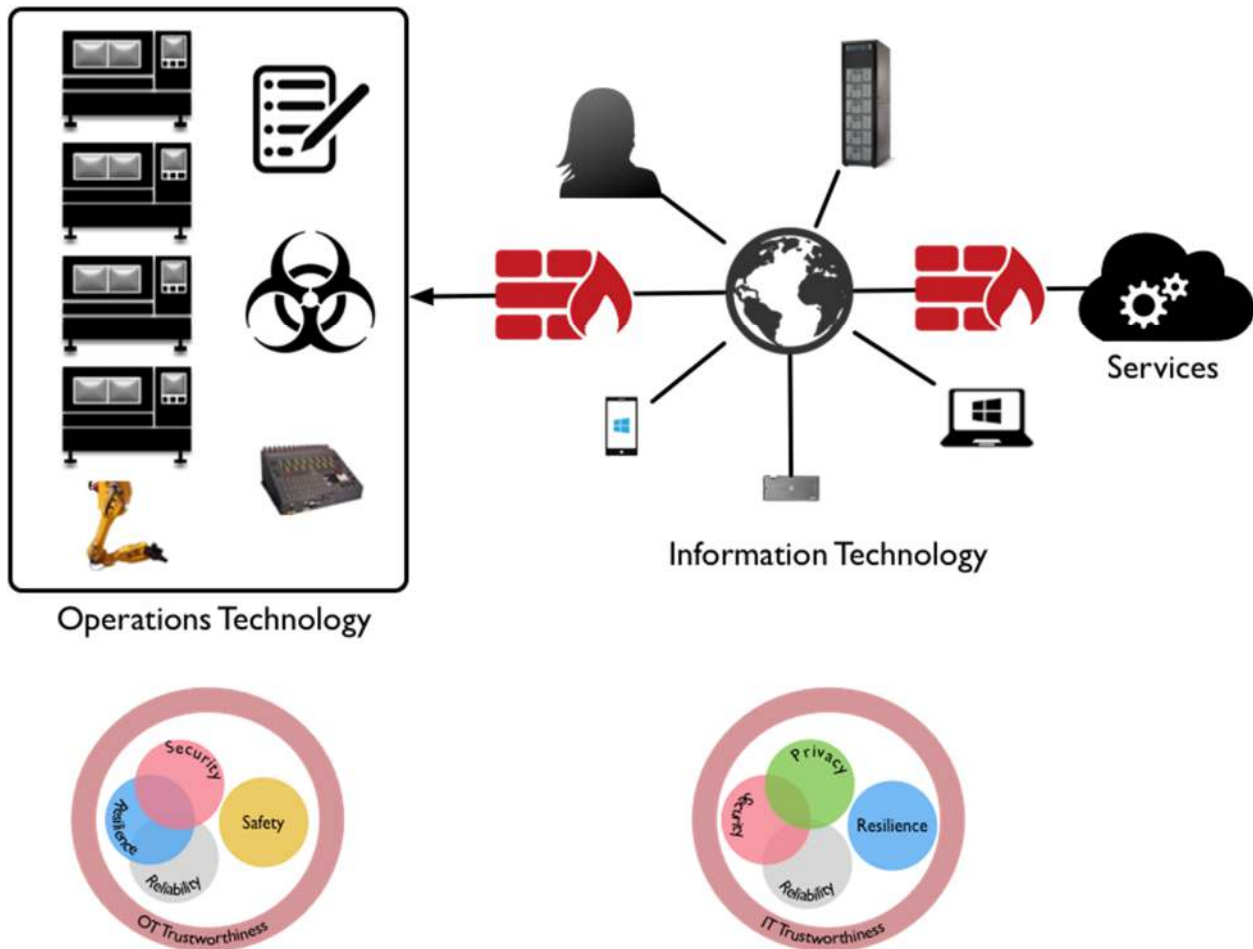


Figure 24: Information Technology vs. Operational Technology Concerns

When comparing Information Technology (IT) systems and Operational Technology Systems (OT) priorities, the principle concerns have historically been different. IT has been primarily concerned with privacy, security, and reliability of systems whereas OT have been primarily concerned with safety, resilience, and reliability. This mismatch has led to systems that have very different software architecture and design. The new systems will need to combine all the concerns from both the IT and OT environments. This will require a synthesis of the two sets of concerns and a reprioritization. The major differentiator in physical versus information technology systems is the physical security concerns. When these systems are combined, the safety concern must be considered first before all others.

Another large differentiator when considering OT systems is the existence of legacy technology. For IT systems, replacing the hardware and operating systems on a regular basis is standard practice. A computer typically has a three-year depreciation

and is assumed to be obsolete after four years and is replaced. Software is updated on a daily or weekly basis with patches and updates to functionality and security. As business systems move into the cloud, the burden of distributed security and attacks becomes more complex, but the centralized nature of software services also provides greater control on the critical systems and their data.

OT systems on the other hand are often static after they have been installed and configured. A typical machine tool will not update the control software or even patch the operating system for fear it may interfere with the operation of the machine. Therefore, manufacturing equipment is often disconnected from the network for fear it may try to patch itself without the operations personnel being aware.

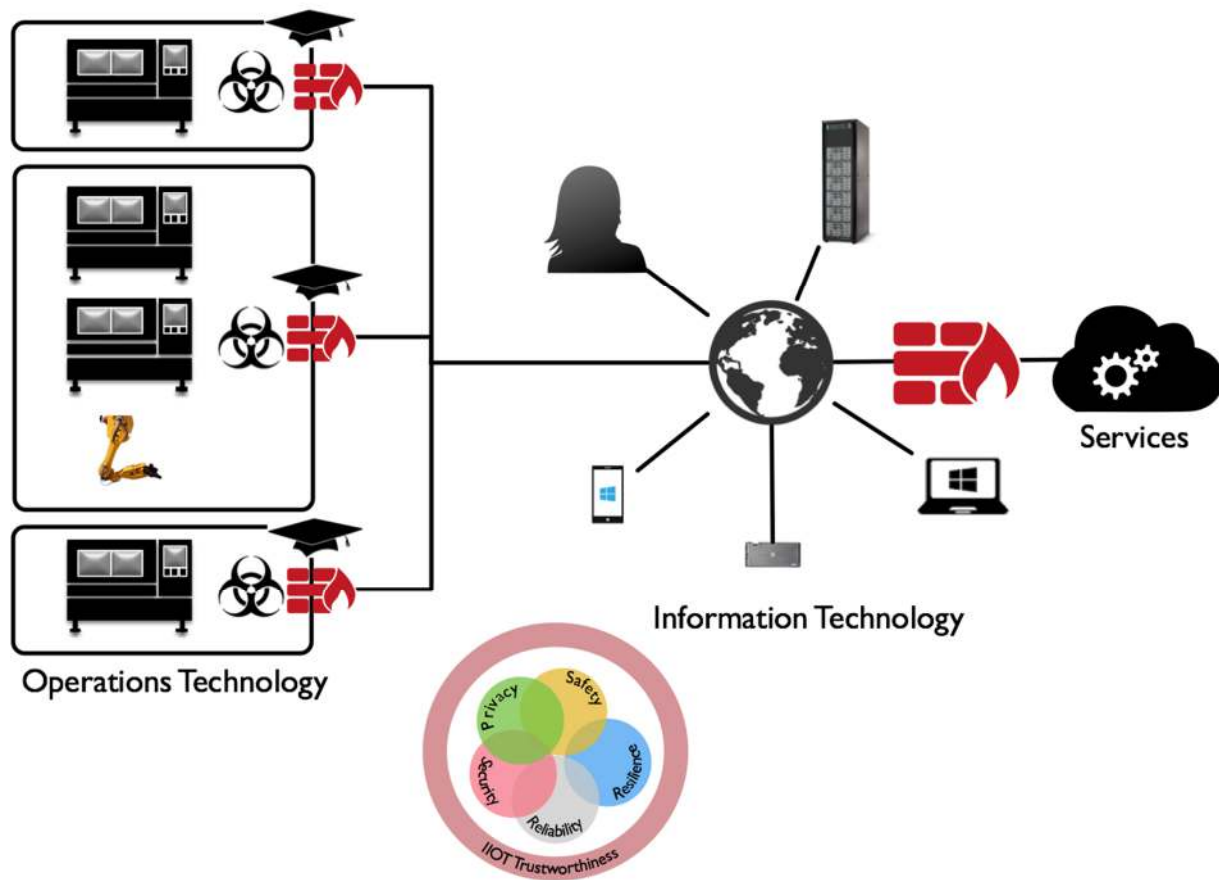


Figure 25: IIOT Security Concerns

When we begin to merge the IT and OT domains together, the result combination of all the concerns becomes more complex and therefore has been resistant to consolidation do to the inherent differences in the architectural concerns. These issues are being considered as part of a unified approach to industrial systems and IIOT, but the technology is in the early days of formation and the systems have not

been fully analyzed. In the next few years these concerns will be better understood and the impediments will begin to be removed.

5.4.3 Security Program Activities

NIST Framework for Improving Critical Infrastructure Cybersecurity has identified 5 essential program activities. The following is a summary of the specifications:-

The core elements of the framework are broken down across the following areas: Functions organize the high-level cybersecurity activities. These functions are Identify, Protect, Detect, Respond, and Recover. NIST organizes the management of the cybersecurity risk information in the following areas: decision making, addressing threats, and improvement based on prior experience. The Categories subdivide the functions into groups of cybersecurity outcomes tied to the programmatic needs for an activity. Subcategories further divide the categories into specific outcomes from a technical or managerial activity. Information resources provides references to the standards, guidelines, and best practices.

Function	Category	Subcategories	Information References
Identify			
Protect			
Detect			
Respond			
Recover			

Figure 26: NIST Five Core Security Functions [23]

The five framework core functions are as follows [23]:

- Identify** Develop the organizational understanding to manage cybersecurity risk to systems, assets, data, and capabilities
- Protect** Develop and implement the appropriate safeguards to ensure delivery of critical infrastructure services.
- Detect** Develop and implement the appropriate activities to identify the occurrence of a cybersecurity event.
- Respond** Develop and implement the appropriate activities to take action regarding a detected cybersecurity event.

Recover Develop and implement the appropriate activities to maintain plans for resilience and to restore any capabilities or services that were impaired due to a cybersecurity event.

The objective is not to develop a set of static practices, but to have a process for addressing security concerns that is continually evolving as new threats are discovered or new best practices are implemented.

The framework also species the use of a tiered approach depending on how the organization views the cybersecurity risk and how they plan to manage the risks. The specification currently has four tiers from Partial (Tier 1) to Adaptive (Tier 4) with increasing degrees of rigor.

5.4.4 Framework Profiles

The framework specifies profiles that are a combination of the functions, categories, and subcategories as aligned with the business requirements and risk tolerance for the assets of an organization. A profile provides the guidelines for an enterprise to have a set of targeted goals to meet their business, legal, and regulatory requirements and a roadmap of how to get there. An enterprise may choose to have multiple profiles for different divisions or organizational units depending on their needs.

The process suggested in the framework document is to first assess the current profile of the company and perform a risk assessment of the enterprise in its current state. The next step is to create a target profile and analyze the gaps between the current profile and the target and then implement an action plan to implement the target. This will be a continuous process of assessment and improvement as the industry and the enterprise evolve.

There is a cyber-security framework profile for manufacturing that is in draft from NIST. This document goes into a detailed analysis of manufacturing systems from the physical assets to the business systems across discrete batch to continuous processes and provides risk assessments and document references. The business and mission objectives outlined in this document are as follows:

These Business/Mission Objectives Are Not Listed in Prioritized Order. [23]

Maintain Personnel Safety *Reduce cybersecurity risks that could potentially impact personnel safety. Cybersecurity implementations on the manufacturing system could potentially adversely affect personnel safety. Understand and train personnel on cybersecurity and personnel safety interdependencies.*

Maintain Environmental Safety *Reduce cybersecurity risks that could adversely affect the environment, including both accidental and deliberate damage. Cybersecurity implementations on the manufacturing system could potentially*

adversely affect environmental safety. Understand and train personnel on cybersecurity and environmental safety interdependencies.

Maintain Quality of Product *Reduce cybersecurity risks that could adversely affect the quality of product. Protect against compromise of integrity and confidentiality of product data.*

Maintain Production Goals *Reduce cybersecurity risks that could adversely affect production goals. Cybersecurity implementations on the manufacturing system could potentially adversely affect production goals. Understand and train personnel on cybersecurity and production goal interdependencies.*

Please refer to the documents for more detailed information on the latest information the security framework profiles.

5.4.5 Security in System Domains

A separate risk assessment will need to be done for each of the domains identified earlier, namely control, edge, fog, and cloud. Depending on the business and the legal/regulatory requirements, there will be differing levels of threats and risk. A separate profile will need to be created for each domain, but some standard profiles can be developed for these purposes. The risk profiles being developed by NIST are a good start, but are still incomplete.

The cybersecurity concerns are in the initial state of development and there is still a lot to learn about the full extent of industrial systems and the management of data and assurances across all the different dimensions. The security threats have caused the industry to retreat to the simplest solution, air-gap, which mean that all services have been disconnected from the internet. This approach creates a bubble where no value-added capabilities can be used and will impede evolution of the industry.

At the same time, keeping all data local and never allowing any designs or manufacturing data to leave the physical location also has the same limiting effect. Isolation is not the solution in a rapidly evolving technological environment. There are many efforts underway to find secure solutions that are applicable to the manufacturing domain and these will be emergent in the next few years. A technology strategy should assume that services will be available to all the domains and that these transformative services will be secure.

5.4.6 Provenance, Trustworthiness, and Identity

Another dimension that is often associated with security, since it uses many of the same technologies, is provenance and identity. Provenance is the ability to determine the original creator of all data and information used in the manufacturing systems. The solution is to use secure digital signatures, but often as documents are

transformed and additional information is added, so it is also necessary to track all changes and history from both human and automated interactions. This will require all people and systems to have secure private/public key certificates as part of a Public Key Infrastructure (PKI) that can be verified to a root certificate issued by a trusted signing authority.

The certificate will also verify the document has not been modified since the signature verifies the content as well as the signer. The key concept here is the trustworthiness of the document and its chain of trust as it has been communicated between systems. There are techniques that have been discussed, such as block-chain, used in digital transactions like Bitcoin, to provide a history of the owners associated with the document. More research needs to be done on the applicability of these techniques.

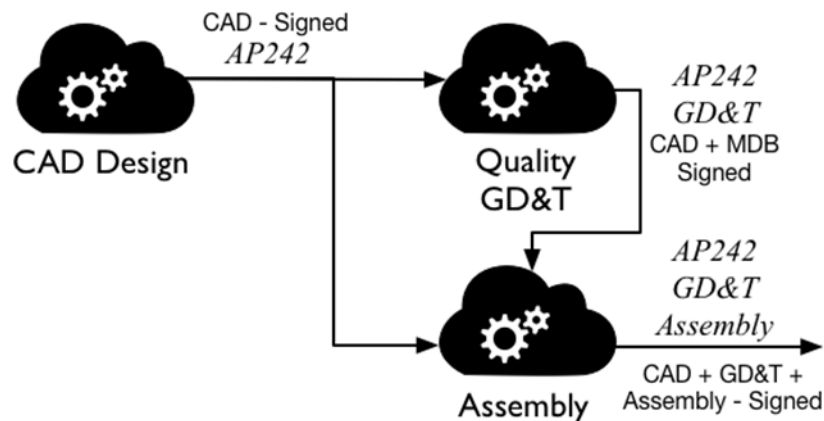


Figure 27: Design Workflow

Services will also be required to sign the results and additions to any digital model. If we imagine the following workflow where a design is created using a CAD application, the application and the designer will both sign the document as the original geometry of the assembly. The document is then communicated to an assembly and metrology service that add tolerancing and assembly instructions. The associated information will need to be signed by the associated services. If the original model is appended, the signatures of the original design and the new signatures with the additional information will need to be included with a complete chain of trust back to origination.

The same holds for document versioning and engineering plans. This becomes a necessity for proper data management and data monetization since it will require that the identity and ownership as well as the provenance of the data is correctly tracked throughout its lifecycle so that legal and regulatory requirements can be handled. Encryption of the data can be done using the same mechanism, but we will consider it as a projection of the combination of security and identity.

5.4.7 Identity Federation (Transglobal Secure Collaboration Participation)

TSCP is a partnership between industry and government to reduce the cost and complexity of compliance for collaborative aerospace and defense programs that span national boundaries. TSCP is providing standards based framework and guidance to enable federated trust between systems for sharing sensitive information. [24]

TSCP has been suggested as a set of common rules for providing federated identity management and will be a core concept to composability of services. The standard goes into detail regarding the requirements and the underlying technologies and services required to implement a distributed security and identity service. It has been included as part of the AeroSpace and Defense (ASD) Strategic Standardization Group (SSG) as an adopted standard for system interoperability.

The following is quoted from the TSCP 1.4 specification: [19]

This TSCP describes the Common Operating Rules (COR) that pertain to organizations that desire to use Identity Federation technologies to collaborate across participating organizations in a secure and interoperable manner. The Common Operating Rules establish mandatory operational policy for Credential Providers and IdPs that, when implemented, enable RPs to have increased confidence in the assertion data passed by the IdP. The COR can serve as a basis for:

- *Establishment of a compliance infrastructure for identity federation.*
- *Inclusion by reference in business agreements and contracts between federation participants.*

The roles are provided in the following diagram:

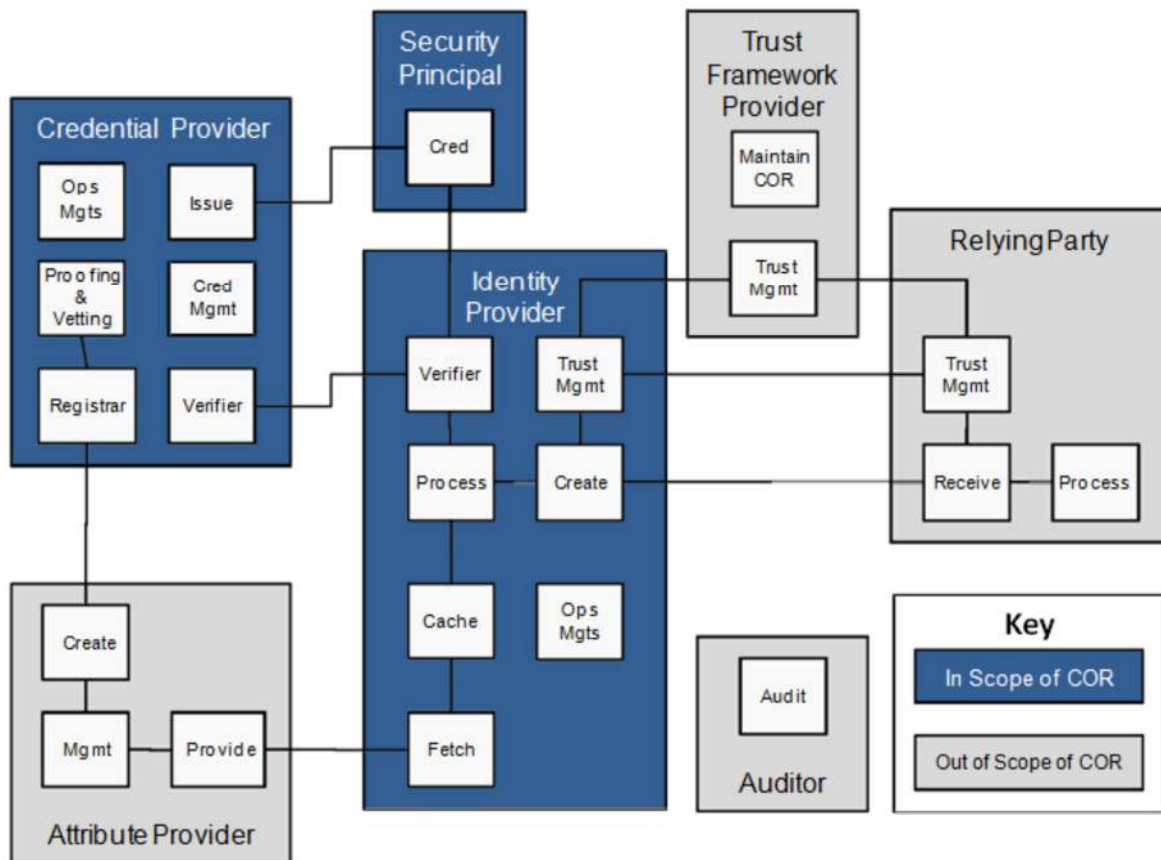


Figure 28: Federation entities interaction and function roles [25]

An identity federation infrastructure involves the following entities:

- **Attribute Provider** - An entity that stores authoritative data related to the Security Principal. The attribute provider may provide attributes to the IdP that are included in the assertion issued by the IdP.
- **Auditor** - An entity that audits the implementation of the COR by the IdP and Credential Provider(s). Audits 1) compare the mapping of the COR to the IdP's practice statement and 2) examine the IdP's systems and operations for compliance with the practice statement.
- **Credential Provider** - An entity that issues digital identities to Security Principals and performs any identity proving or vetting that may be required to ensure a valid binding of a Credential to the Security Principal.
- **Relying Party (RP)** - An entity that accepts an assertion as a method of authentication of a Security Principal. Examples of relying parties include systems that will use the attributes associated with the identity to make access control decisions.

- **Security Principal** - An entity, usually a person, who requests access to resources maintained by the Relying Party. The Security Principal can be positively identified and verified via an authentication process by the IdP, using the Credential provided by the Credential Provider.
- **Identity Provider (IdP)** - An entity that validates that the Security Principal has possession and control of a Credential that is issued by the Credential Provider. The IdP may or may not be the same entity as the Credential Provider. The IdP consumes one or more Credentials presented by the Security Principal, supplements that Credential with attributes obtained from one or more Attribute Authorities, and creates a new assertion incorporating the obtained attributes for transmission to Relying Parties.
- **Trust Framework Provider (TFP)** - An entity that defines or adopts an on-line identity trust model, and then certifies identity providers that are in compliance with that mode. The TFP is responsible for establishing and maintaining the COR. [25]

5.4.8 Mutual Distributed Ledger and Federated Chain of Trust

Like federated identity, there is a need for a federated chain of trust that will allow any service or system to immediately confirm the provenance and the series of transactions that have been applied to the data as it proceeds through its lifecycle. The advances in Mutual Distributed Ledger (MDL) or by its common name, blockchain, to provide verifiable records of changes to a document or an asset without a central authority is applicable to managing design and execution documents as well.

The following is from the Wall Street Journal with a brief description of Blockchain:

A blockchain (MDL) is a data structure that makes it possible to create a digital ledger of transactions and share it among a distributed network of computers. It uses cryptography to allow each participant on the network to manipulate the ledger in a secure way without the need for a central authority.

Once a block of data is recorded on the blockchain ledger, it's extremely difficult to change or remove. When someone wants to add to it, participants in the network – all of which have copies of the existing blockchain – run algorithms to evaluate and verify the proposed transaction. If a majority of nodes agree that the transaction looks valid – that is, identifying information matches the blockchain's history – then the new transaction will be approved and a new block added to the chain. [26]

This concept has been used in the digital currencies like Bitcoin, but it has a much broader applicability when coupled with federated design and engineering services that also support strong identity platforms as well. The impact on the existing standard

will be small, they will need to include a transaction log in a similar way to a signature block associated with each digital document. There are some emergent standards that are being developed as part of an ISO group that started in April of 2016 to begin working on international standards for MDL. [27]

The outcome of the standards organizations needs to provide a foundation that will exceed the requirements of financial industry and be applicable to other industries as well. The standardization process and advances should be tracked and the manufacturing concerns must be represented to make sure the standards will not preclude the manufacturing use cases and manufacturing can adopt and make use of the open source technology that will be created to support MDL.

5.5 Distributed Data Management

Large scale distributed data management concerns have been largely overlooked in existing manufacturing systems since the data was closely held on site by the manufacturing enterprise or communicated from site to site. The current manufacturing software has not had the capability of utilizing data that was beyond the control of the enterprise with the unfortunate side effect of limiting the functionality and business models that have been beneficial to other industries.

Manufacturing enterprises are concerned about the loss of intellectual property and adherence to contractual obligations for trade or government secrets. The issues can be resolved using contracts between the service provider and the customer, but this becomes burdensome if many service providers are used since it will require separate contracts between all parties.

In addition, there are still issues with respect to derived data rights and the service provider rights as opposed to the customer. The derived data may even embody the intellectual property of the manufacturing enterprise, especially if they have special techniques or knowledge that can be utilized by the service provider to enhance their product offering or resell that knowledge to other parties which can reduce the principle's competitive advantage.

Design and engineering services will need to address these issues since they need to have access to the geometric and process information models. The current information models did not envision the need to secure the model or utilize partial information where the subsets can be distributed as fit for purpose. The previous section discussed the application of secure signatures and identity to provide traceability for each document through the product lifecycle. The distributed data management systems will need to handle strict adherence to the requirements for data security, ownership, and access.

For feedback systems to be incorporated in sensitive manufacturing environments, the same approach that has worked in the health care and genetic research industries

may be applicable where anonymized data can be used to provide sufficient content for analysis, but not enough to understand the geometric form or the intent of the part. If features are divorced from the physical location and the key characteristics are communicated with opaque identity that can be analyzed without access to the original design, the results of the analysis can be re-associated by re-associating the identity with the original design.

The management of anonymous data and the process of transforming it for value added analysis will be a key component of future IIOT systems to protect intellectual property and allow manufacturing enterprises to take advantages of key services without having to sacrifice security and intellectual property. This way, best practices for tooling and manufacturing strategies can be evaluated and communicated to the design and engineering applications to improve using knowledge capture.

These services will reside at the edge or the fog domains and will provide secure transport of data designated for utilization in analytics where the service provider does not have access due to regulation or need. The services will provide data streams using various standards, like MTConnect, to communicate the data by acting as a secure gateway and limiting access to the actual data items and in their place providing obfuscated information. As MTConnect moves into security, this will be one area it will be addressing to enable closed loop manufacturing services.

5.5.1 Composition and Data Management

There are some new approaches that will can be considered to handle the use of services where the intellectual property is restricted because of government or trade secret. Utilizing the concepts of Composition and stateless services that operate on the data but do not store any of the data, but only keep it for the duration of the analysis, the services can be utilized to provide additional associative information. The second component of this approach is a limited view of just the necessary information for each contextual analysis.

For example, the design of the product will need access to the full model for the assembly and will need to associate the designer's intent and product information so the engineering and downstream services can provide solutions that will meet the needs of the final form and function. The design and engineering services for individual parts will only need to access the portion of the model that is relevant to the manufacturing of each component of the product. The information contained in the model and the associate descriptive information about adjoining surfaces and attachments will be included, but the complete geometry can be suppressed.

In this way, the service will not have access to the entire geometry, and if strict security and data management policies are enforced by the service, the service can provide the capabilities without compromising the security of the model as well as managing the ownership of the services intellectual property without risk to the

service provider that their capabilities will be reverse engineered or distributed without their knowledge.

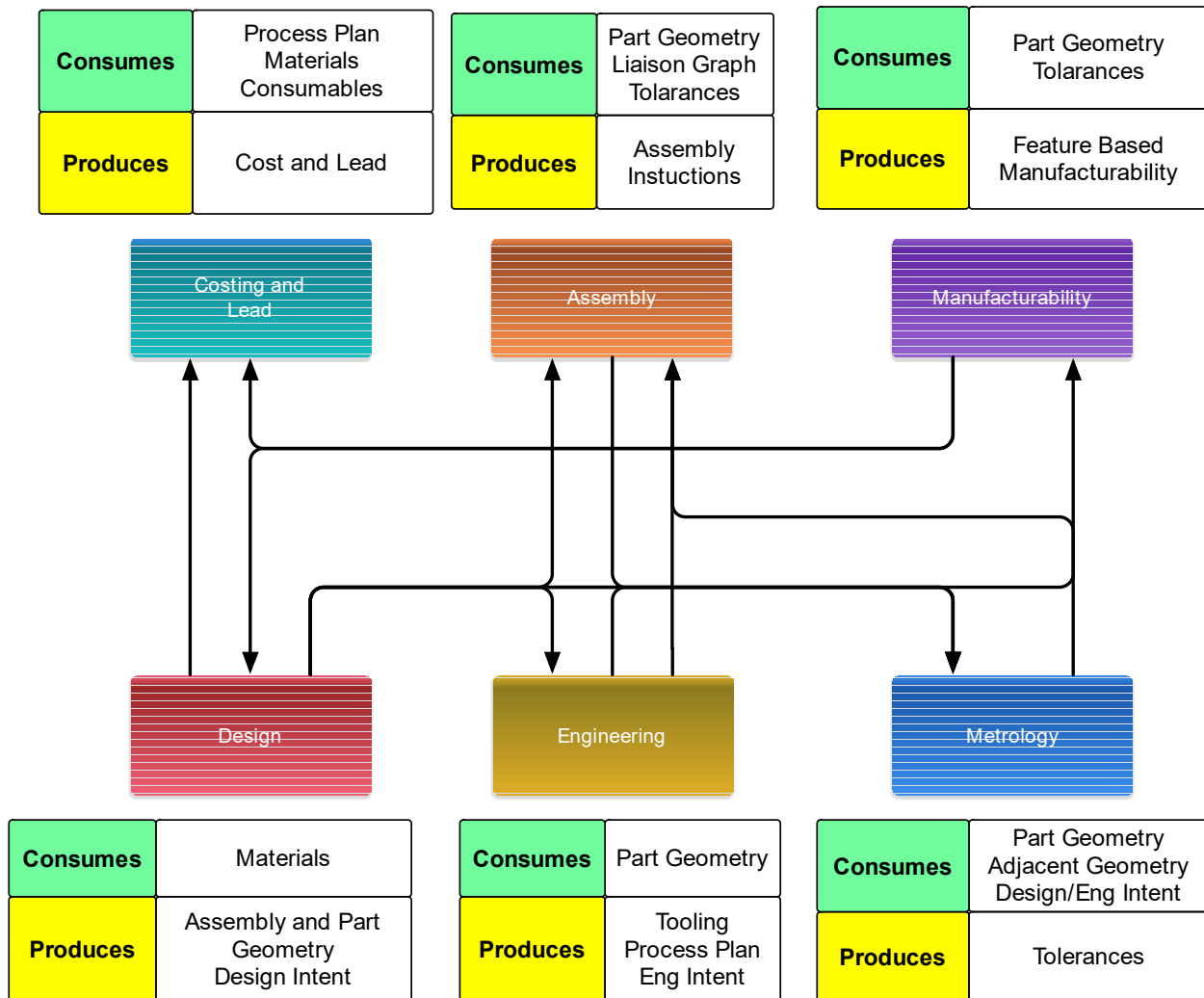


Figure 29: Integration of services

The above diagram provides a representation of some possible information flows and inputs and outputs of each of these services. This is similar to the completely federated services discussed before, but in this scenario a centralized service acts as a data mediator and enforces the data rights and data access policies. Since this architecture requires a single point of access, the service will be required to be replicated for resilience and depending on the five Vs of big data, volume, variety, velocity, value, and veracity of the data. The data will need to be distributed, signed, and possibly encrypted.

Solving this problem will require new kernel technologies and the ability to work with partial representation of the complete design that can be queried from multiple

services where the complete information model can be protected. The approach will allow for stateless analysis of constrained views of the model depending on the needs of the service using a stateless access protocol where the necessary information for any analysis will be utilized and then discarded once the results have been provided. This follows the core principles of Composable services.

The kernel will provide a set of interfaces that allow the services to query for certain information by interrogating the model. The data management kernel will provide the system of record and can be maintained by a cloud service or an enterprise service that exposes a standardized API to the cloud based services. All communications will be secure and the data will be signed by the authorized authorities. This pattern will allow for custom data management while allowing the services to operate independently and still provide value, while not having to reside on site.

There are some new data management services that can provide access to encrypted data for analysis that can provide analytical services with data that is opaque to the service, but can still be utilized. These are new services that are in the process of being developed and their fit for purpose with manufacturing systems is still yet to be proven. Companies like Thales has a product, Vormetric, that provides database level encryption across multiple platforms, such as Microsoft SQL Server, SAP HANA, and other platforms. Hitachi is currently working on technology that can analyze data without having to decrypt. This will provide the capability to not expose sensitive information but still to derive value. There are a few other companies working on similar technology as well. [28]

5.5.2 Identity as a Primary Concern

A key concern of data management is the identification of individual designs, parts, features, characteristics, and components as well as the devices and the eventual products. Each part must have a solution to uniquely identify it and this identity must be composable using the context of the part with its greater whole and it must be stable for its lifetime. The identity must also be derivable from the underlying information models, so completely opaque ids will not suffice.

RFC 4122 from the IETF- specifies a mechanism for creating a standard UUID using a namespace and contextual data, as described in Versions 3 or 5 of the standard. The difference between 3 and 5 is the secure hash scheme used for creating the unique identifier. Using this methodology, the UUID can always be recreated and will not result in an unusable model if the UUID is corrupted or is recreated. This was one of the issues with versions 1 and 2 for this purpose. [29]

The UUID is composed of specific components of an information model that provide a composite uniqueness, such as a manufacturer, a model, and a serial number, and part which are combined with a namespace specifying the context the UUID was created. The identity concern is one of the principle objectives of a complete

architecture for manufacturing and feedback since the only to understand the functionality of the system is to collect empirical data and associate it back to the original model.

Since there will never be a singular model that will encompass all needs in the manufacturing domain, all information models must be able to interoperate and associate, not necessarily in the same artifact, but in the references imbedded in the documents and information models. UUIDs provide the referential mechanism to achieve this. This is true for both the manufacturing execution and the use phase (of which there are no standards) to provide the validation of the decisions made in earlier stages of the lifecycle.

This is already being done between the STEP AP238 R2 and the QIF Quality Measurement Plan and Results information models. MTConnect will be adopting the same scheme where applicable so that the engineering to execution and inspection models can be associated.

5.5.3 Feedback Systems

The feedback mechanisms will provide value back to the services by contracting with data providers, OEM or customers, who can supply data from the execution or use phase of the product lifecycle. Feedback requires identity as defined above and as the industry has the projected exponential increase in sensors associated with all the products we purchase, the use data can be utilized to inform the designers and in turn, to the services that automate the decision making. Data ownership and rights associated with the data collected from the end users will be a concern.

This is a very complex area of investigation that has not been specified and the legal and contractual ramifications of how this will manifest itself have not been fully understood, but the next generation of architecture for manufacturing services will need to have this awareness architected in so that as the contractual concerns are defined, the services will be capable of adapting.

The architectural requirements must associate ownership and data access rights to all data and derived data and to be able to express rules that will allow services to extrapolate the ownership from the source data and the contractual agreements with the various parties. Ownership and feedback related to parts of the model that were created by a service, such as the assembly instructions, and then execution of those instructions, will need to have an agreement between the company that is assembling and following the instructions and the assembly service.

There may be additional parties, such as the CAD design tool manufacturer that provided the geometric models and the companies that provide the associated assembly instructions. The feedback from the assembly process and the assembly service will be valuable to the design services to become instructive to the designer

by finding issue that may affect the assembly of the product before the design is complete. These prescriptive services can be defined based on crowd sourcing of data, but the relationships between all parties and the use of the information must be defined.

This will prove to be one of the more contentious areas as the new services emerge. Understanding the architectural concerns upfront will allow the service providers to quickly adapt to the changes in the legal and regulatory landscape and not become obsolete before they can add significant value. Using composable micro-services will provide the most flexible architectural pattern to isolate these concerns and possible become a separate service unto themselves.

5.5.4 In Process Measurement, Feedback, and Verification

Manufacturing experts have known that capturing defects early in the manufacturing process would have huge benefits, but the loss in value added time combined with the lack of technology to analyze and utilize the data effectively, where it would more than cover the loss in productivity, have not been possible until now. The non-functional security requirements have been documented by the industrial internet community and are reaching a level of understanding that they are no longer considered a critical blocker.

The capabilities to analyze results within the amount of time where the machine or the operator can make changes to the manufacturing systems are possible by utilizing service based technology where the amount of compute power will be amortized across many enterprises and machines. The compute requirements for these systems are by nature bursty, meaning that a brief high intensity of compute will be followed by idle time when a single piece of manufacturing equipment is being considered.

Standards like MTConnect and QIF are currently working on addressing these gaps with association with STEP, B2MML, and other standards in the manufacturing domain to provide interoperable information models that can combine representations from multiple different domains. The feedback still needs to be associated with the design and engineering systems as discussed in the data management section.

The O3 project led by STEP Tools is working on this problem right now and is using the following architecture:

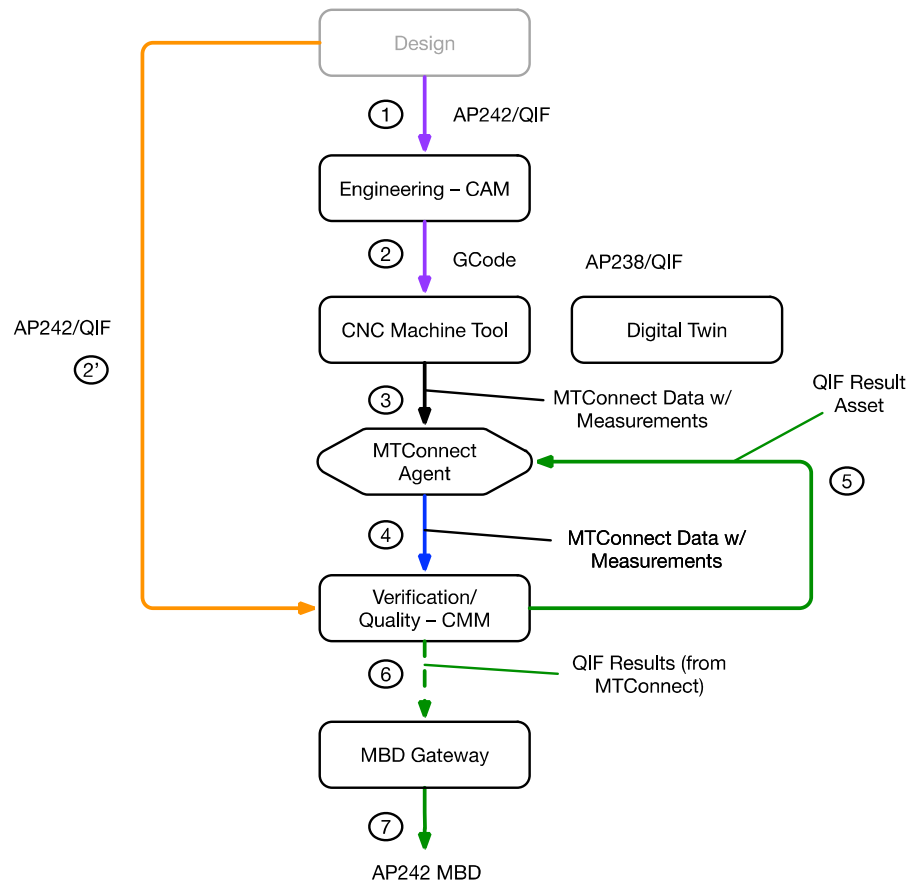


Figure 30: O3 Workflow for In-process feedback and Verification

The feedback loops from the manufacturing processes will be compared with the results from the inspection process on machine and the system will adaptively correct the process as a future capability. The transformations are based on the current limitations of the equipment and the systems doing the analysis. In the future, these will be services that will be able to process the information without the additional components.

5.5.5 Engineering Features and Process Constraints

The models to represent all the engineer constraints and assumptions have not been completed. These include the following: the engineering systems that determine how a part is to be made, the series of subtractive and additive processes, the tooling, fixturing and all associated assets as well as resources, both human and mechanical, will need to be specified. STEP AP238 Ed 2 is addressing some of these concerns, but it is not currently available in CAM systems or on machine tools. B2MML and MTConnect are also working on providing the process flow and machine constraints necessary for execution, but these models are not available and are not complete.

These representations need to be harmonized and supported across all phases of the manufacturing process and associated with the feedback mechanisms for both asset data as well as quality. There is initial progress in the Mind the Gap and O3 projects mentioned above. The advances made in this project can be effectively applied once the standards are fully harmonized, they are now being integrated in ad-hoc with special annotations to support traceability.

There is a lot more work to harmonize between the various MES and ERP standard that are concerned with manufacturing assets and resources and the design and engineering applications that are concerned with a series of geometric transformations and verifications, and the capabilities of individual assets and resources. Neither is complete by itself, they are looking at the same problem from different directions. The role of standards organizations will be to find ways to harmonize and not compete so as an industry we can create complete representation of the manufacturing and product lifecycle.

There are standards that are addressing these issues, but they are incompatible. B2MML for example, which represents the business processes has not been harmonized with AP233, ReqIF, or AP239 (from my research). For the business systems to interoperate, they will need to have common schemes for referring to requirements and manufacturing constraints.

5.5.6 Part Assembly Association - Liaison Graph

Once the parts are manufactured, they must be assembled. The existing information models do not contain the necessary information to adequately supply an automated assembly service. There are two major pieces that are missing from our existing information models, they are the design intent as mentioned before and the liaison graph that specifies the association of all the parts of an assembly and how they go together. The annotation of that model will also help to make better decisions for tolerancing and by association engineering and costing.

As with the other models, this is one piece that when not standardized, limits the value of the service to what it can infer from the geometries. Inference is inferior to explicit expression of intent and therefore the issue is not that the intent is unknown, but only that there is no current model to carry the information and no standard vocabulary to express it.

5.6 Conclusion

The architectural concerns outlined in this document are a high-level exploration of the requirements for a federated service architecture that will provide capabilities to take the industry forward and ensure our ability to effectively compete in a global economy by enabling rapid innovation. The fundamental goal is to provide an architectural platform, not as a singular entity, but as a set of services that can

rapidly evolve and compete to get exponential improvement in the software technology base for manufacturing.

Rapid innovation is the key to the next revolution in manufacturing. The current methodologies, rooted in legacy technology and practices, are restricting our ability to adapt to a rapidly changing technical environment with new capabilities for connected devices and analytics that will change the way products are manufactured and consumed. To be a leader in these new markets, the current methodologies that have served the industry for the last 50+ years will need to evolve as well and the new platforms will need new information models and services to realize this vision.

Industry analysts are projecting these new economies and we are seeing the first emergent forms in products that are being sold by outcome, such as earth moving equipment and airplane engines. When products are sold, or leased by their outcome, the onus is on the manufacturer to guarantee the performance of the product, so they will naturally instrument the product to achieve greatest value and make the largest margin. Because the manufacturer's profit is tied to performance, they will also want to improve the manufacturing processes so they can increase profits.

The other driver will be the expectation that products will be adapting to the consumer and that changes can occur per use dynamically or can be provided by the manufacturer as they observe use patterns to better tailor to the consumers' needs. These concepts are being discussed in advance manufacturing conferences, but the current design and engineering systems are not currently capable of directly supporting dynamic on-demand workflows. As the industry move from the current product develop process to a more dynamic federated process that is driven by data and feedback, the need to accept and embrace change will become more prevalent.

Manufacturing will also need to evolve, and even though it is by nature averse to change, it will need to figure out how to overcome these limitations. The initial companies and societies that figure this out will be the ultimate beneficiaries of the new economies. As evidence, GE is now branding itself as a software company that manufactures. This development presages the emergence of the changes to come and lays out the most prescient architectural concerns that will guide the development of these new services.

There is a lot of work being done in industrial groups like the Industrial Internet Consortium (IIC), OpenFog, and many consortia and formal standard bodies like MTConnect, DMSC, and PDES to solve the architectural needs as well as the information modeling requirements. Even with all this effort, there are still significant areas of the industrial space that have not been addressed. These topics will be discussed in more detail in the next section.

6 AVM Standards and Model Based Definition

6.1 Overview

The AVM projects touch on many of the manufacturing domains, from product design to manufacturing execution and quality control. Interoperability between each phase of the manufacturing process is key to the success of the AVM programs. This leads to the need for standardization and extension of the information models to provide interoperability between manufacturing services, as discussed in the previous section. The standards Discussed in this section of the document cover the current and emergent standards in the manufacturing ecosystem.

When reviewing the AVM projects, manufacturability stands out as a key component in several projects. The design services are meant to include manufacturing analysis or utilize the analysis tools in the manufacturing services space. In fact, the individual services should be able to be utilized at various points of the product lifecycle.

6.2 Manufacturability

Q: What makes a product manufacturable?

A: Almost anything is manufacturable with enough effort. The real question is, how much it will cost and how long will it take until we get it, and is it worth it?

The concerns of manufacturability and maintainability of products are very similar and both need to be considered early in the design cycle. The projects that are considering manufacturability are not considering maintenance as a driver for their product and from the information modeling standpoint, maintenance has not been a key concern. In future considerations of these standards, maintenance concerns will need to be included as part of the manufacturing intent.

Processes like Additive Manufacturing will allow almost any geometry to be manufactured, but cost of such processes can still be prohibitive. Also, the raw material micro-structure might be different than anticipated, so the solution may still not be viable or may require extensive finishing processes. The concerns must be factored into design and manufacturing planning. If cost is really what determines manufacturability, we need to look at what factors are present that will affect cost as well as the capabilities of each location to manufacture.

We live in an era where some people use some of the following statements, sometimes within the same breath depending upon special interests involved.

- *Design Anywhere, Manufacture Anywhere*
- *Design Here, Manufacture Anywhere*
- *Design Anywhere, Manufacture Here*
- *Design Here, Manufacture Here*

Assuming ubiquitous manufacturing and distributed capabilities, allows the industry to consider manufacturing requirements up front at the design stage and be passed to other users of the data in downstream processes. *Design Here, Manufacture Here* has a great potential to provide value to the United States manufacturing base and allow us to excel in product and capabilities targeted to specific markets.

If one considers where a product will be manufactured when a product is designed, one can target specifications for the products that are as manufacturable as possible within that targeted environment. This will effectively lower the cost of manufacturing as much as possible. Of course, the opposite may occur if it is later determined that there is no in-house process that can make that part to the specified tolerance and at reasonable cost. Very often designers design without thought of where the product will be manufactured. Thinking about where things are made at design time will allow manufacturing cost and lead time to be more predictable.

The following priorities need to be considered for all design processes:

1. Functionality
2. Manufacturability
3. Maintainability

Functionality is the capability of the product to meet the design, quality, and operational requirements as defined by the designers and the engineers. There may be numerous ways to design the form of the product to satisfy the requirements, so it is up to the designer to specify what the product must do and the expectations for its entire life cycle.

Manufacturability is a measure of cost, time, and complexity to manufacture a product. This includes the materials, process steps, and the assembly of the components. There are some changes in this domain due to introduction of new technologies like 3D printing which allows us to make any geometry, but the cost and time required may be prohibitive.

Maintainability is the products ability to be services throughout its life cycle. If a product is not maintainable because the components cannot be replaced or repaired, then the value of the product will be limited to the first point of failure. There are trade-offs when designing for maintainability, consumer electronics are often designed to not be maintained whereas devices in the transportation and industrial domains have this as a priority.

6.3 Model Based Definition (MBD)

Model Based Definition (MBD) is the practice of imbedding all information required to define the product within the CAD Model (both parts and assemblies) so that the CAD model contains “Complete Product Definition” that is consumable by downstream processes. “Product Definition” can be looked at from two different points of view. The “Systems Engineer” might consider “Product Definition” to describe and capture the functional requirements of a component. The “Manufacturing Engineer” considers “Product Definition” to be the specifications to which a component should be produced. In the context of this document “Complete Product Definition” means the specifications for producing that component in a proper manufacturing environment is present within the model itself. If a model is a complete MBD, then any 2D drawings should not be required.

Product Manufacturing Information (PMI) is the method of imbedding this complete product definition, MBD, information in CAD models. It consists of the following individual entities as part of the complete MBD:

- **GD&T: Geometric Dimensioning and Tolerancing**
 - **Dimensioning:** The dimensions and measurements of all components of the solid geometric model.
 - **Tolerancing:** Describes the allowable variation with respect to the normal geometry defined in the solid model.
- **Material Specifications:** Describes the chemical and physical properties of the components
 - **Composition:** The chemical composition of the material
 - **Treatments:** Techniques used to alter the physical, and sometimes chemical properties of a material
 - **Finishes:** Processes that alter the physical or chemical properties of the surface of the part
 - **Coatings:** Chemical or substrates that are applied to the surface of a part
- Torque Specifications
- Test (Inspection) Requirements (QAPs {Quality Assurance Provisions})
- Packaging Requirements

PMI within a CAD model can take the form of 3D annotations consisting of dimensions and tolerances. Special symbol can be provided as described in the ASME Y14.X series of standards, such as surface finish and many other characteristics. PMI can also consist of attributes, parameters, and properties stored within the product CAD model or an associated data set (as described in ASME Y14.41). The preference is to store this within the product CAD model (not linked to any external files).

Using MBD, the complete product definition should be available for extraction and reuse. Dimensions and tolerances should be semantically related to the associated geometry (Faces, Features, Surfaces and Topology). This association should be available for query by both human and machine (computer) interaction.

The current model of human interaction, using 2D drawings, can be replaced by digital 3D models and queries that can extract the views of the data to provide the necessary geometric and product information to the end user. Various services can also provide more sophisticated reasoning about the geometries and product information to provide a better level of content for the user's requirements.

Machine (computer) interaction would be able to access the CAD model using software APIs (Application Program Interface) to extract the semantic geometry definition and dimensional and tolerance information such as properties describing surface treatments, heat treatments and others to systematically create process definitions. In the future, these models will be used for automated execution and optimization of processes to create the product defined in the model data.

Additive Manufacturing (3D Printing) already uses geometric CAD models to directly produce parts or component of the product. The part often requires other processes not directly defined in the 3D geometric model to finalize the part since surface finish and very tight tolerances are not achievable by the current technology, so even using additive technology, full automation is not fully achievable now. Eventually the entire process from 3D to final form for every part and assembly will be possible without the need for paper or physical drawings.

The AVM projects each target some aspect of the description "Machine interaction". This is a case where the use of semantic data standards and information models will improve the outcome of the AVM research. Each of the AVM projects started under DARPA leadership at a time prior to the existence of the standardization of critical pieces of information. Well designed, semantic standards could help facilitate the use and expedite the evolution of the design and engineering space by allow more companies to collaborate in this ecosystem.

The four standards that are now available, but were not around when the DARPA AVM project started, are STEP AP242e2, STEP AP238e2, QIF, and MTConnect. These are being used in some of the projects and are described as follows:

STEP AP242e2 combines AP203 and AP214 (geometry and some other attributes) and allows the storage of PMI (dimensions, tolerances, notes and other attributes) that is semantically related to the geometry. Already, AP 203 and 214 are being phased out and STEP AP242 is becoming more comprehensive in the ability to contain MBD data as described in Native CAD software tools as an interchange format.

STEP AP242 file types can be stored as ASCII or Binary for consumption by translation software for interoperability between various CAD software formats.

STEP AP238e2 is often referred to as STEP-NC since it contains the intermediary stage models for each of the geometries and processes to make a part. STEP-NC has been in development for many years and has not had wide adoption, most machines still operate from the legacy DIN standard from the 1970's called G-Code. AP238 specifies complete information about each step in the process, the tool paths as well as references to the tooling used. Recently in the latest revision, additional geometric PMI information models (taken from AP242) have been incorporated to support in process measurement and verification.

QIF (Quality Information Framework) combines geometry with semantically related definition of features or inspection characteristic. This "semantically related definition" includes all the information required to determine and execute Quality Control processes. Semantic PMI is the base of this Quality process definition. QIF utilizes XML as the file type for distribution and interoperability.

Both STEP AP242 and QIF should have sufficient capabilities to store the data required to meet the requirements for AVM interchange formats. Complete domain coverage will need to be verified and specific modeling differences may make either standard become the dominant in each area depending on the needs. At present, they are being harmonized so translations can be made between the standards.

MTConnect is standard for communicating semantic data from manufacturing equipment. It allows equipment on the shop floor to publish their current state, telemetry, and sensor data in near real time as well as providing information on the use of various assets in the manufacturing process, like cutting tools, files, and parts. The standard is currently used to understand operation efficiencies and utilization, in more recent products, it is being used for process optimization and as the foundation for execution feedback and process digital twins.

6.4 Information Models and Standards

For the purposes of this analysis, the discussion is limited to the standards used in the DMDII AVM set of programs and the individual choices made by each program to use various standards or industry information models to achieve their goals. Although the final goal of these programs was interoperability, it was not stated as an upfront requirement and therefore the projects became disparate in their selection of standards, using what best fit their requirements and knowledge at the time.

6.4.1 Communication and Document Formats

The discussion of standards often conflates all standard development processes into a monolithic conceptual framework where the standardization methodology and design

goals are always the same. This is not the case and for this discussion it is necessary to detangle the purpose of the standard and the methodology from how it is developed and maintained. We differentiate between the requirements for communication, representations, syntactic, and the semantic models to achieve interoperability and the layer of software they will be interacting with.

Depending on how the standard will be used and the assumptions around the stability of certain aspects of the design, there are many areas where standards can advance quickly whereas some that must remain static. This will largely affect the development cycle and implementation. For example, a standard that will affect the implementation of communication hardware must be significantly more static than a standard that defines the logical model of a machine tool.

The discussion will start at the bottom of the protocol stack, and using the OSI model as a guide, help to understand the core concerns of each area. The second part will discuss the semantic models that are domain specific and must receive special treatment. Once the stack is laid out, it will be compared to the standards in Industrie 4.0 and how they have branded the standards for their analysis.

6.4.1.1 Communications Standards

The purpose of a communication standard is to ensure that the data or information sent arrives at the destination according the reliability and timeliness constraints of the application. Communications standards do not help the application understand the data, it is just an envelope where the application knows who sent the message, sometime when the message was sent, and the size of the contents. They still need to unpack the envelope and interpret the contents.

Any discussion of communications standards should begin with the OSI Model. In the early 1980s, ISO merged their communications model with CCITT (the international telephone and telegraph consortium) to create a reference model for communications called the Open Systems Interconnection Reference Model or OSI Model for short. The model provides a seven-layer abstraction that separates out the concerns for communicating data reliably over a network. [30]

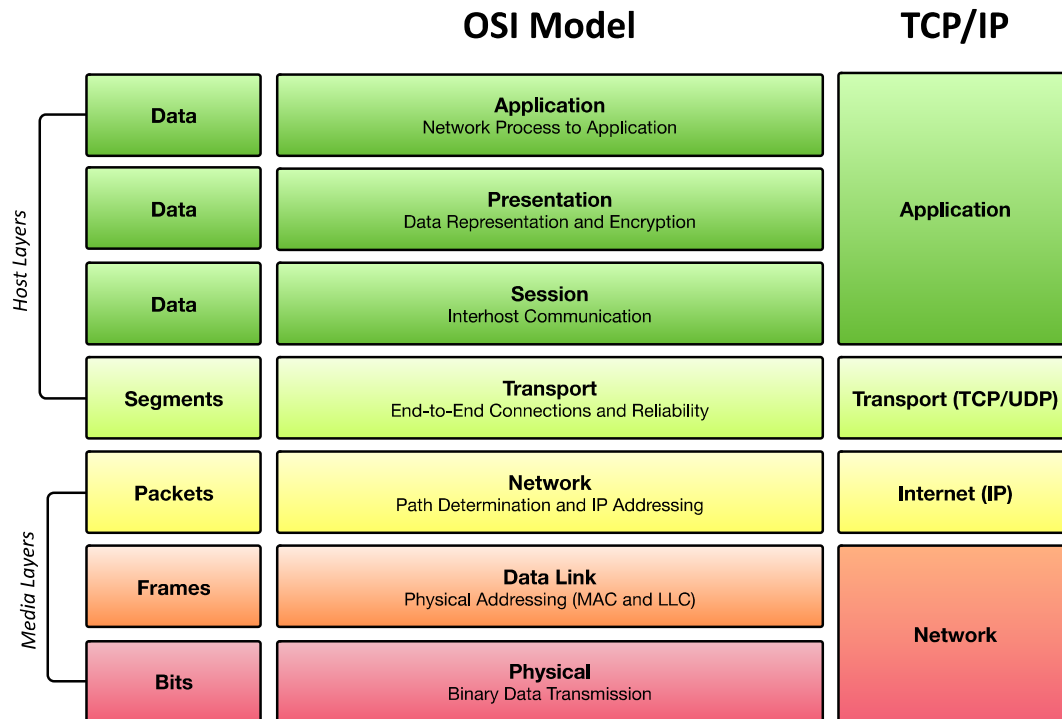


Figure 31: Open Systems Interconnection Reference Model (OSI Model)

The OSI model has been a useful abstraction for discussing the concerns of each part of a comprehensive communications model. The lowest two levels, the physical and data link layers, are implemented in the hardware of the network interface card (NIC) and in nearly all implementations will use the 802.X protocols which are often referred to as Ethernet protocols. Since this level is hardware dependent and can have an operational lifecycle of tens of years, the standards have a high degree of stability.

The responsibilities of the physical and data link layers are to transmit data bits and frames over a local set of connections using wired or wireless technology. The protocols at this level are best effort communications and the data at this level cannot be routed beyond the set of physically connected devices. The hardware components that handle the local routing of packets are referred to as layer 2 switches and repeaters and utilize the MAC address to route 802.X packets from the source to one or more destinations.

As we move up the stack, the network layer, or in TCP/IP, the Internet Protocol (IP), is used for route packets from one device to another device or set of devices on networks that can extend to physically disparate devices. The network routing is handled by software imbedded in the operating systems and hardware appliances, like layer 3 and layer 4 switches and routers, that can determine the next destination to send a packet. The network layer is also a best effort communication layer and reliability and the ordering of packets cannot be expected.

The transport layer provides end to end communication with the reliability guarantees that are provided by underlying protocol being used. TCP (Transport Control Protocol) provides a reliable byte stream of data where the ordering and retransmission of data is handled. UDP (User Datagram Protocol) provides a minimal level of protocol that provides a best effort delivery of a network packet. UDP takes care of packet fragmentation and delivery to applications.

Since TCP/IP is used for almost all communications, but can map roughly to the OSI model. In most networking we interact with today, TCP/IP stack is the foundation set of communication protocols and has been for over thirty years. IPv6 is a recent update (within the last ten years) to TCP/IP that provides significantly more address space and some features like stateless address auto-configuration, network-layer security, expanded multicasting, enhanced routing, privacy extensions, and more.

The API to establish the connections like, Sockets, provides a common framework for interfacing with the low layer communications protocols managed by the operating system. This layer provides the specification of how connects are created, managed, and terminated. This manifest itself in the TCP/IP protocol with the various ways to establish and gracefully shutdown a connection.

The presentation layer provides capabilities for encoding, encryption and translation between machine dependent formats. This is sometimes referred to as the syntax layer. The application layer is the point where the protocols directly with the software application and where the application implements the communication abstractions. In an example, this would be an application using HTTP or HTTPS to communicate with a server and the structuring of the request, handling communication issues, encryption, and unpacking of the results will be handled by an underlying software layer that provides the Layer 7 capability. Protocols like HTTP, OPC-UA, MQTT, AMQP, and FTP all reside in this layer.

Looking at the available services, there is little that is needed in addition to what is currently available to interconnect devices and send and receive data securely. The concerns of on the wire security, network efficiency, publish/subscribe semantics, authentication, and reliability have been solved by the various efforts in these areas over the last forty years.

One area that is now becoming relevant is at the Network layer of the protocol stack and the ability to greatly increase the number of addressable devices. For a long time, it has been known that IPv4 addressing will not accommodate the vast number of connected devices with each device being uniquely addressable. For the most part, this has not been an issue because of Network Address Translation (NAT) that allows for numerous internal addresses to share a single external address by translating the internal address and port to an external address and port associated with a conversation to an external host. The process does not allow for external hosts to connect to internal hosts directly, unless the ports are mapped. NAT provides a

modicum of security, but also restricts some types of communication that may be desirable.

IPv6 only has any relevance at the Network or Internet (IP) layer of the stack. It is nothing new, it was first proposed in 1998 by the IETF in RFC 2460. The final set of standards were released in 2006 and are present on most computers, although most still use IPv4, even though there are numerous advantages to IPv6. Standards like IP protocols are very slow to change since they will require changes to all the communications infrastructure throughout the entire path from the user's desktop to the host computer in the cloud. Therefore, we are only beginning to see IPv6 getting some traction nearly twenty years after it was first standardized.

The further we go down the OSI stack, the slower standards tend to change. The obvious reason is because the hardware must be replaced increases as we change key components. Higher level protocols, like HTTP and MQTT can evolve faster, utilizing the stable substrate to build upon.

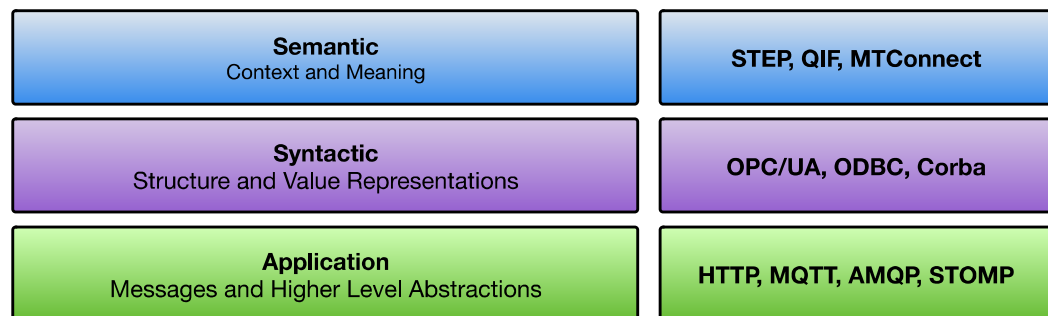


Figure 32: Higher level application protocols

Above the application layer, there is a distinction between protocols that provide a pure, uninterpreted payload of data, and standards that provide the syntactic rules to interpret the structure of the data like OPC/UA and Corba. The rules provide an abstract information model that can be used to represent the underlying structure of the data and the types, strings, integers, floats, and such.

STEP, QIF and MTConnect are considered Semantic information models. Protocols like OPC/UA and DDS provide a syntactic model to the data by providing the data types and a nested structure that does not give the meaning of the data, but organizes it so it can be easily parsed using a common grammar. There are also representations, like XML, EXPRESS, and JSON, that provide the grammar of the document so it can be verified when it is ingested into the application using a common set of tools. Often Syntactic standards, like OPC/UA utilizes XML and add some additional structure and protocol, where XML is used as a base to create the abstract information model. Standards like MQTT and AMQP communicate data associated with meta data that ensures quality of service and reliability of message delivery.

6.4.1.2 Syntactic Standards

Syntactic standards provide the structure and the types of the data, but not the meaning. The information models are very generic and provide a structure that allows one to understand the relationships of between pieces of data and how they should be interpreted. An example is OPC/UA that is very popular in the automation world and has been adopted by Industrie 4.0. The model provides a hierarchical type and information structure that allows one to model different pieces of equipment or applications.

For example, the OPC/UA model has an abstract information model that has a base set of types that represent objects, variables, references, methods, and views. By extending those types, the implementer can create any structure that represents the device or service. The model is very generalized and does not provide domain specific definitions, but allows for multiple domains to be use the model to satisfy their needs.

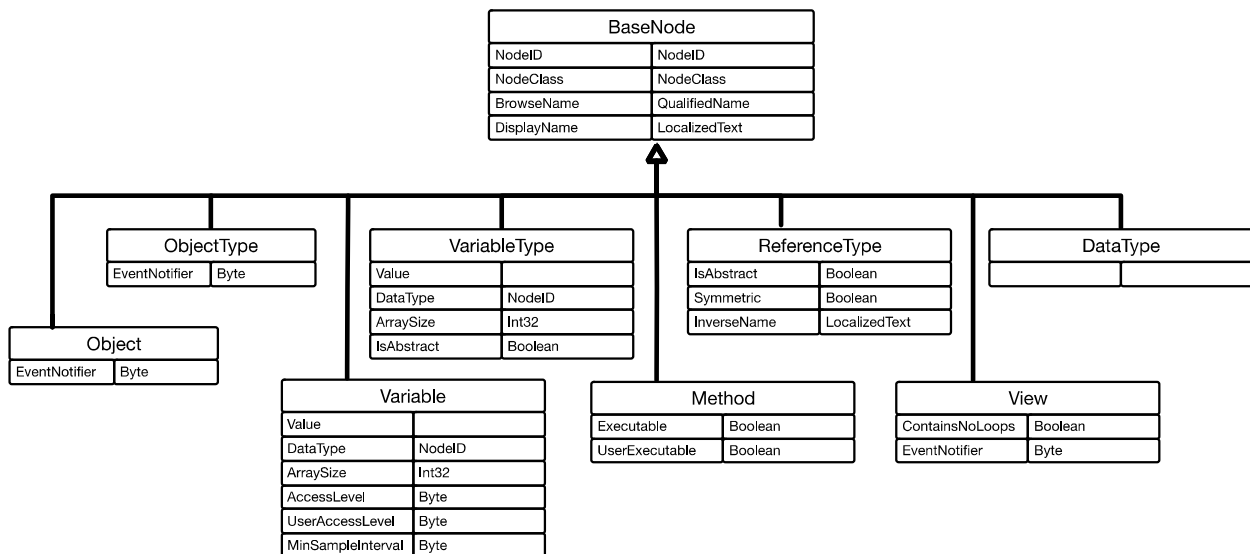


Figure 33: OPC/UA Information Model

The model begins with a BaseNode that represents any abstract type in the system and from which everything is inherited. When implementing a model, you can model your device as given in this example on the open62541 site [31]:

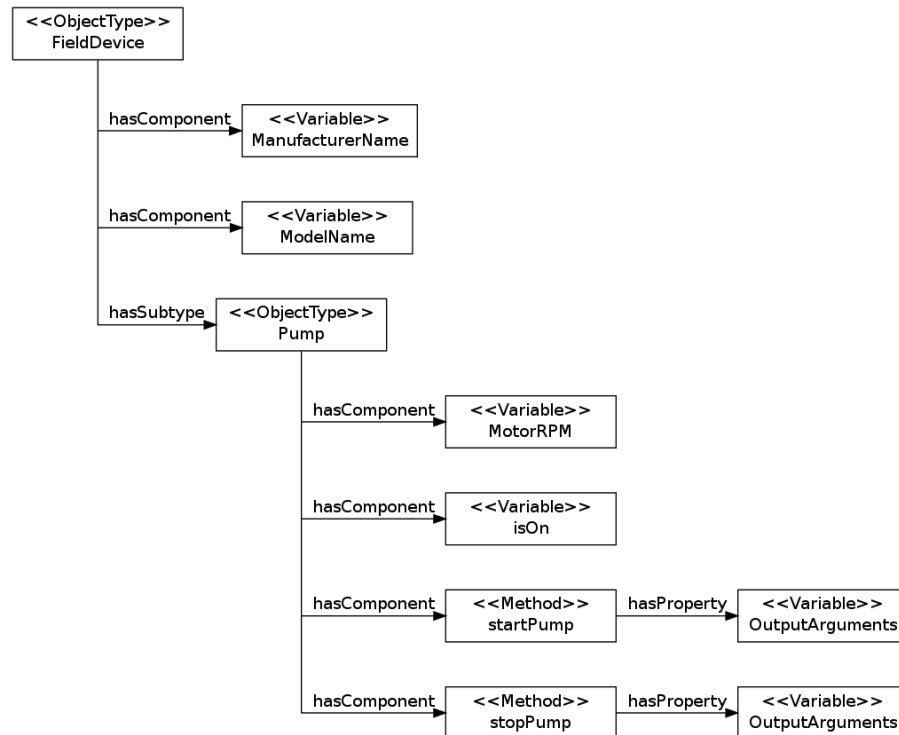


Figure 34: OPC/UA Example Model

The above diagram has a few variables giving some base state of a pump and a few methods that provide actions the pump can provide. There is no requirement in OPC/UA that the data for a Pump must be model this way, any structure will suffice. The Variable, MotorRPM could be a MotorSpeed or RotaryVelocity, depending on the implementation. The definition of these terms will define the semantic space that is used to provide the meaning of the data.

Getting the data syntactically structured provides a valuable step to the next phase, semantic definitions, where meaning and context within a domain are applied. Semantic standards can also be represented using Syntactic Standards, like MTConnect and PLCOpen can layer on top of the OPC/UA model. The abstractions provided by syntactic standards are insufficient to allow for generic analytics to understand the data without bespoke implementations for each specific instance of the information model.

6.4.1.3 Semantic Standards

Semantic standards are sometimes referred to as domain models or domain vocabularies by groups like the Industrie 4.0 initiative. These information models need to be differentiated from other standards that provide abstract structural models like OPC/UA. Semantic standards provide the meaning and context of the data so it can be immediately analyzed, reasoned upon, and understood. To analyze data,

it is imperative to have a semantic understanding of the data, otherwise simple meaning such as if this is a temperature or a position and the units such as centigrade or millimeters needs to be inferred from the data or the tag name. Even simple visualization and correlation cannot be done efficiently.

When semantic standards are not used, a proprietary solution is often prescribed that requires a set of transformations to understand the meaning of the data, units, and context. The result is the data will be effectively locked into that proprietary system. A proprietary domain model will immediately remove any benefit discussed in this document because the services will need to be aware of each proprietary model's structure and conventions and the cost of integration will quickly subsume any value that service can provide. This is the reason the industry has proceeded at its current pace.

The benefit of standards is the ability to communicate information where at each layer of the protocol stack, the level of understanding, utility and value of the data increases. A semantic standard provides meaning where every term is defined unambiguously with a label that is understood within the larger context of the product. This is effective from the design through the data collected from the machines performing the steps.

Most of the information models used in the AVM projects are geometric in nature that provide a set of 3D abstractions for the communication and manipulation of solid models. AP242 takes the existing geometric models in AP203 and extends them in many areas that are directly related to the work being done in the AVM programs. The following is the scope for AP242:

Scope of STEP AP 242 edition 2

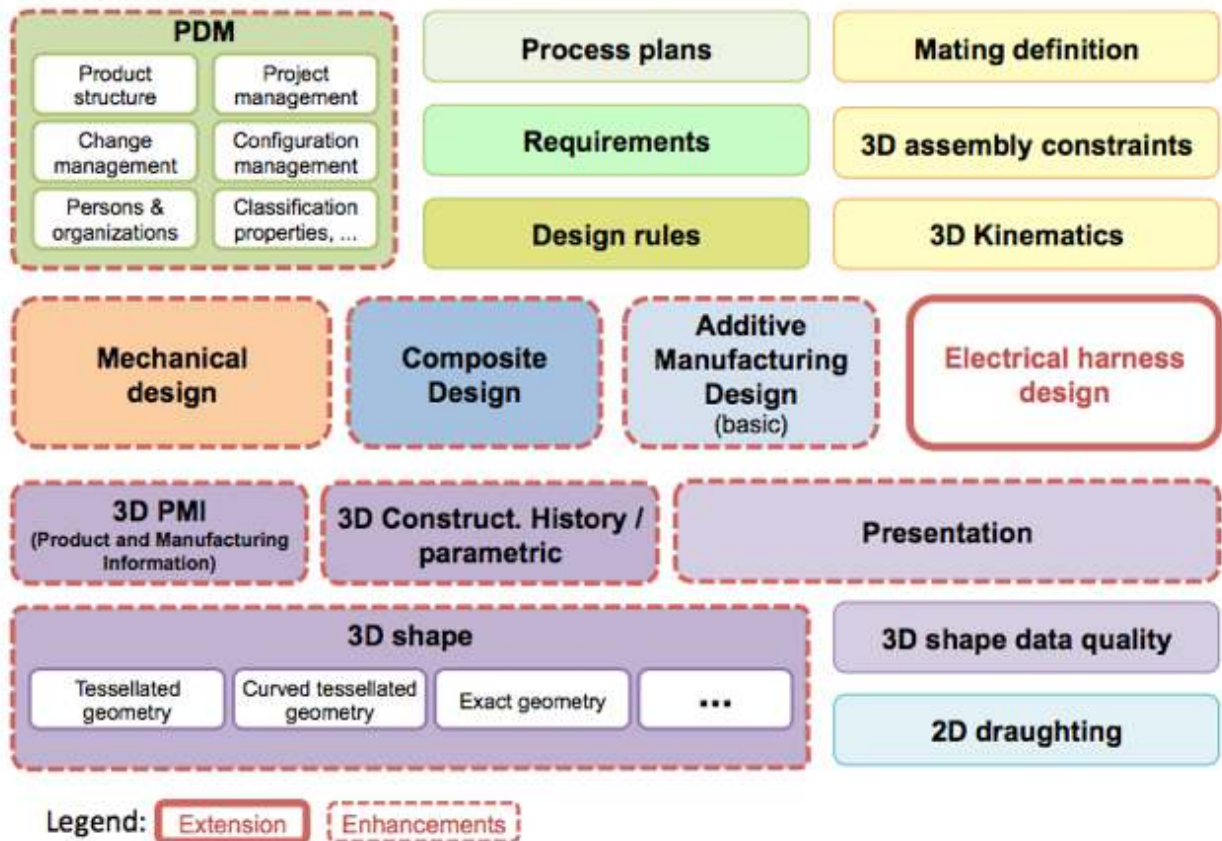


Figure 35: STEP AP242 Ed2 Scope [32]

The AP242 Ed2 scope will cover many of the areas of interest from composite to assembly. Though the new enhancements to the STEP models, the standard will be able to provide semantic definitions for product and manufacturing information (PMI) and communication of this information. [32] In this context the semantic definitions will be providing the meaning of the types of the PMI, for example, there are definitions for Screw Thread, Weld, and Surface texture that can be specified using a common vocabulary with references to the ASME and ISO GPS standards for the specific constraints.

The combination of the geometric tagging with references to the ASME standards provides semantic content that can be reasoned on by analytics. The semantic nature of the models allows for them to be used in higher level processes as opposed to a model like STL that provides a set of vertices, but no higher-level constructs that allow for attachment of semantic meaning to various geometric artifacts. The major complaint with respect to STEP is the speed at which they innovate. Common identity

schemes and harmonization of modeling constructs will allow for other open standards to extend and accelerate the STEP models without having to be directly incorporated.

Another example is the comparison of MTConnect to OPC/UA where MTConnect provides a specific model that addresses the specific requirements of getting data from CNC manufacturing equipment in a consistent way where every Position is called a Position and is in millimeters and we know which Axis it is associated with and how the axis relates to the Path of the Controller. We can also know the Motor temperature of the Axis and differentiate it from the Amplifier.

The detailed set of definitions allows the applications to compare Motor temperatures across multiple machines while also being able to evaluate the CNC controller states and operational modes. The combination of this consistent data is most beneficial when using a disparate set of data sources across multiple vendors.

Semantic models provide the foundation for interoperability between services and are the only way to create a dynamic marketplace for the next generation applications. The current semantic information model development needs to be accelerated so the goals of AVM can be fully realized.

6.4.1.4 Document Formats

A *Document Format* refers to the structure and rules for encoding information that communicates in primarily machine readable formats, but will be better served if it also permits human interpretation. The rules provide a set of prescribed semantic and structural constructs that allows applications to easily parse the contents of the document using open libraries and documentation that allows for one to use the information models with no IP restrictions. Examples of these representations are XML, JSON, or ISO 10303 (commonly referred to as EXPRESS).

The requirements are the following: there is an open structure and syntax to the data, the model supports a mechanism for expressing rules to validate the syntax and grammar in the file, and the tool to consume the data are readily available to an average practitioner in the industry. Of the three document formats mentioned above, XML and JSON are the prevalent document formats in the industry. JSON and its variants like BSON (a binary representation), Smile, and UBJSON are used in frequently used with Internet services since they are easily consumed by web browser technology using JavaScript (ECMAScript) and are more efficient than XML.

XML is the most common format when standardization and validation is required because of the rigorous document format and the widely available schema validation tools like DTD, XMLSchema and RELAX NG. The two-level verification of XML documents where first level verification checks if the document is well-formed, indicating it adheres to the common syntactic structure of an XML document, and the

second level of validation that checks the document against a schema to verify the structure is correct given the rules provided in the schema file.

The schema rules allow schemas for documents to be combined using multiple namespaces that provide for extending and embedding new content. Each of these schema verification mechanisms allow for extensibility while providing a level of assurance that the document is correct. The document verification allows the application to reliably ingest the data without having to be concerned about the format and syntax of the data since it can validate it against a known set of rules.

JSON now has a similar capability called JSON Schema to XML Schema. The community using JSON is not as concerned about correctness so the JSON Schema has not been widely adopted in the industry. This is one of the main reasons that XML is still dominant in the standards communities because of the wide availability and use of validation.

The following are some examples of equivalent documents in JSON and XML [33]:

JSON

```

1. {
2.   "glossary": {
3.     "title": "example glossary",
4.     "GlossDiv": {
5.       "title": "S",
6.       "GlossList": {
7.         "GlossEntry": {
8.           "ID": "SGML",
9.           "SortAs": "SGML",
10.          "GlossTerm": "Standard Generalized Markup
    Language",
11.          "Acronym": "SGML",
12.          "Abbrev": "ISO 8879:1986",
13.          "GlossDef": {
14.            "para": "A meta-markup language, used to
    create markup languages such as DocBook.",
15.            "GlossSeeAlso": ["GML", "XML"]
16.          },
17.          "GlossSee": "markup"
18.        }
19.      }
20.    }
21.  }
22. }
```

And the in XML:

```

1. <!DOCTYPE glossary PUBLIC "-//OASIS//DTD DocBook V3.1//EN">
2. <glossary><title>example glossary</title>
```

DISTRIBUTION STATEMENT A. Approved for public release; distribution unlimited.

```

3.    <GlossDiv><title>S</title>
4.    <GlossList>
5.        <GlossEntry ID="SGML" SortAs="SGML">
6.            <GlossTerm>Standard Generalized Markup Language</GlossTerm>
7.            <Acronym>SGML</Acronym>
8.            <Abbrev>ISO 8879:1986</Abbrev>
9.            <GlossDef>
10.                <para>A meta-markup language, used to create markup
11. languages such as DocBook.</para>
12.                <GlossSeeAlso OtherTerm="GML"/>
13.                <GlossSeeAlso OtherTerm="XML"/>
14.            </GlossDef>
15.            <GlossSee OtherTerm="markup"/>
16.        </GlossEntry>
17.    </GlossList>
18. </GlossDiv>
19. </glossary>

```

EXPRESS Part 21 Format [34]:

```

1. ISO-10303-21;
2. HEADER;
3. FILE_DESCRIPTION($, '1');
4.
5. FILE_NAME($, '2000-01-31T17:24:16+00:00', $, $, $, $, $);
6.
7. FILE_SCHEMA(('VPM12_fidji'));
8.
9. !FILE_SCHEMA_VERSION(1,1);
10.
11. ENDSEC;
12. DATA;
13. #2=cdma_id('3D3D91B1369B4E4F', '3030303030303030', 'VPM1', 'PART_LIST',
    #1);
14. #15=cdma_id('3D3D91B1369B4E4F', '3D3D91B136C00A13', 'VPM1', '$EXTcar', #
    14);
15. ...
16. #49=event_sequence(':Promote', 'DSGproposed', '01062000175858', 'PMA', '
    No Comment');
17. #50=event_sequence(':Promote', 'DSGin
    work', '01062000175900', 'PMA', 'No Comment');
18. ...
19. ENDSEC;
20. END-ISO-10303-21;

```

It is possible for an application to convert between equivalent *Document Formats* without losing any data or structure. For example, the ISO 10303 standard also has a representation in XML that is specified in Part 28 allowing for the data to be taken from the EXPRESS text format and communicated in XML. The advantage is that there are far fewer EXPRESS parsers and EXPRESS aware applications than XML.

There are more resources on the web and research that will guide someone in the transformation and representation process. On such example is a paper by NIST, IBM, NASA, and Georgia Institute of Technology:

<http://eislabs.gatech.edu/pubs/conferences/2004-asme-detc-lubell/2004-asme-detc-lubell.pdf>

The EXPRESS schema given in part 11 provides a much more robust grammar for expressing the relationships between parts of the data model. XML Schema can provide constraints on the structure, patterns, and the allowable values of any element or attribute in the document. EXPRESS also provides the capability to constrain mathematical relationships between pieces of data. EXPRESS Part 11 can also be provided in XML and can augment the XML Schema validation with a capable parser.

The *Document Format* is not key to the discussion for interoperability if there exist open tools that can easily convert between the formats and if there are equivalencies in the capability of the format to represent the information contained without losing meaning. The information models will be the primary focus of this document and will assume that a suitable format is being used.

6.4.1.5 Industrie 4.0

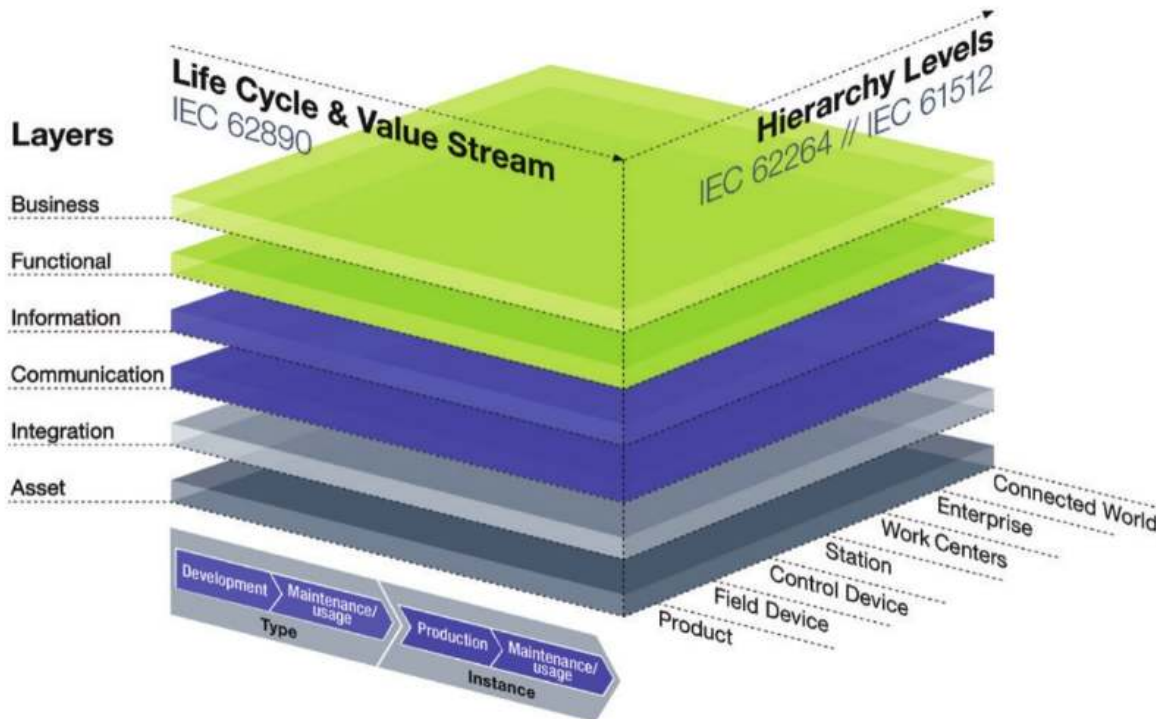


Figure 36: RAMI Architecture [35]

The German initiative has chosen OPC/UA for application communication to manufacturing equipment and EtherCat for the time sensitive communication in the control domain. They have chosen some representational models like AutomationML as well for representation of automation equipment, commonly found in continuous process manufacturing and electronics assembly. OPC/UA is now working with both MTConnect and AMQP for semantic manufacturing execution data and message publish-subscribe support.

Industrie 4.0 has not specified, to our knowledge, a definitive design and engineer standard for the representation of 3D geometries, measurement, verification, and assembly, though this may have changed. Since those are the primary concern of the AVM projects, we will not focus on the standards around communication and device automation, but will utilize the Industrie 4.0 capabilities when they are available. From our research, the product and geometric models mentioned in the documents all reference ISO-10303 and related standards.

QIF is a metrology standard that is developed by DMSC under ANSI. They are being harmonized with AP242 semantic PMI and are gaining traction in the CMM and quality measurement space. There are differences in the representation of the geometric models between QIF and AP242, but the two standards can be associated at the feature and characteristic level given a common unique identifier scheme. QIF utilizes QPID (QIF unique identifiers) that can be referenced in the AP242 model so they can be used together. The relationship between all these standards will provide multiple paths to gaining access to the information models.

6.5 Standards and Information Model Focus Areas

The areas we will be focusing on are as follows: CAD and Geometry, Product Life-Cycle, System Engineering and Simulation, Product Manufacturing Information, Raw Materials, Fasteners, Paint and Coatings, Design Standards, Manufacturing Standards, Quality Standards, and Manufacturing Execution Standards. These standards taken together describe the bulk of the design, manufacturing, and quality models. There are areas that are still not covered by any standards bodies or consortia that will be discussed in the gap analysis.

6.5.1 CAD and Geometric Standards

CAD information models have been around for a long time, the most widely adopted standards are the STEP ISO 10303 standards and the STL standard. STEP AP203 is a geometric standard that is often used as an interchange format between applications and provides NURB based boundary representations. STL is a standard that is used principally in 3D printing and is based on facets that are made up triangles in three space and is also a boundary representation.

Boundary representations (BREF) give the external surfaces of the 3D object where the internal volumes are inferred from the closed surfaces. The two other STEP standards that have been defined, but are in limited use are as follows: The first is AP242 that provides Geometric Product Manufacturing Information associated with the various features and is a combination of AP203 and AP214, and the second is STEP AP238 or STEP-NC that provide a digital model of each stage of the manufacturing process and all the instructions to perform each step.

The following are a list of Semantic Information Models used in the industry:

- **IGES (Initial Graphics Exchange Standard)** is an old wireframe and surface data information model that was developed in 1978 with the first release in 1980. It was developed in the early days of CAD to allow interoperability between native CAD and other software. IGES is no longer maintained and has not been updated since 1996. It has been largely replaced by STEP which was released in 1994.
- **STEP (Standard for the Exchange of Product model data)** is an ISO Standard (10303) using the EXPRESS representation
 - STEP is broken down into multiple parts called Application Protocols (AP) that address various components of the digital design information modeling
 - CAD files can be translated into STEP to allow open access to the data stored within. AP242 is the most comprehensive version of STEP to date. STEP AP242 combines AP203 and AP214 including some of the attributes that are also specified within those Aps.
- **STL (Stereo lithography used in 3D Printing systems)** has triangulated surface data. This type of file while passable for 3D printer applications and rough lightweight viewable is not precise enough to satisfy extraction of Product Definition.
- **QIF** is an ANSI standard that is principally concerned with metrology and quality but also contains a complete CAD model for representing geometry, features, and tolerances with some overlap with AP242.

Geometry standards are getting better adoption-STEP AP203 has been well adopted and STEP AP242 has been moving up the adoption curve from many of the major CAD vendors. The STEP standards are not one hundred percent compatible between systems as the interpretations differ and volumetric inconsistencies can cause issues when moving between solutions. [36]

The following were the results from the volumetric analysis of importing and exporting of models between applications. The metric is given in absolute change and mean absolute deviation (m.a.d):

		STEP	JT	3D PDF
CATIA V5	%	5.76%	-	-
	m.a.d.	10.27%	-	-
Inventor	%	13.22%	7.16%	-
	m.a.d.	24.36%	13.32%	-
NX 7.5	%	0.0004%	12.56%	-
	m.a.d.	0.0006%	24.24%	-
Pro/E	%	0.19%	-	n/a
	m.a.d.	0.25%	-	n/a
SolidWorks	%	4.16%	-	-
	m.a.d.	7.98%	-	-

Figure 37: CAD Export, Absolute Change in Volume [36, p. 44]

The following table details the volumetric changes with respect to importing the models in various applications:

		STEP	JT	3D PDF
CATIA V5	%	4.61%	n/a	-
	m.a.d.	8.68%	n/a	-
Inventor	%	4.49%	1.42%	-
	m.a.d.	8.35%	2.24%	-
NX 7.5	%	2.36%	0.00%	-
	m.a.d.	4.24%	0.00%	-
Pro/E	%	2.10%	n/a	-
	m.a.d.	3.73%	n/a	-
SolidWorks	%	0.18%	n/a	-
	m.a.d.	0.24%	n/a	-

Figure 38: CAD Import, Absolute Change in Volume [36, p. 45]

CAX Implementor[sic] Forum has been working with NIST to verify the capabilities of application to import and export STEP models. The capabilities of these application may have improved significantly since the research was performed. Refer to the following link for more information on the latest results of their findings: <https://cax-if.org>

6.5.2 Design Standards

The ASME Y14.XX series of standards are still designed to support annotations of 2D drawings. Like the ASTM standards, there are standards for Engineering Drawing Practices (14.100), Dimensioning and Tolerancing (14.5), and Digital Product Definition Data Practices (14.41). ASME also defines many other standards that can be used in this space.

There are no specific Design for Manufacturing or Design for Assembly standards presently. This is one of the areas that will need to be addressed to complete the Digital Thread and provide a complete product definition. These standards will need to cover the design constraints and design intent as well as the assembly intent and feature associations as mentioned in section 6.8 Gaps.

6.5.3 Product Requirement, Engineering, and Life-Cycle Standards

The following standards can be used to address the product lifecycle information models from the point of conception to the end of life or reuse of the product. There is a lot of overlap and duplication in these standards and it would be advisable for the standards groups to narrow the focus of the standards to increase adoption.

- **STEP (Standard for the Exchange of Product model data)** is an ISO Standard (10303) using the EXPRESS representation
 - **STEP AP209** supports distributed simulation processes during the design and engineering phases. The standard has been primarily focused on composites, but can be applied to other materials as well.
 - **STEP AP233** is a standard to exchange systems engineering data between applications. There is significant overlap between AP233 and SysML and the two standards have been harmonized to better support interoperability.
 - **STEP AP239** supports lifecycle management from design through end of product life. It can be combined with other standards, like S5000F to provide maintenance and service data for feedback during the use phase of the project. There are overlaps between AP233 and AP239 and it would be advisable to separate out the responsibilities as best as possible from the lifecycle management perspective. It would be advisable to supersede AP233.
- **SysML (System Engineering Modeling Language)** is a general purpose visual modeling language for systems engineering applications. It has been widely adopted and is currently maintained by OMG. SysML has been combined with STEP AP233 to provide complete engineering requirements.
- **ReqIF (Requirements Interchange Format)** is a standard provided by OMG (same group as SysML) and supports the communication of requirements

throughout the supply chain. ReqIF has been adopted by the Automotive industry and, like AP233, is interoperable with SysML.

The AeroSpace and Defense Strategic Standardization Group (ASD-SSG) has released a white paper that reviews the concerns of product life cycle from the perspective of the aerospace industry using ISO 10303 (STEP) AP239 edition 3 [37].

Within the STEP standards, there is a lot of overlap and one must understand the intricacies of each of the models to fully understand the selection and the use of the various components. This could be one of the reasons for the perceived complexity of the STEP standards and must be considered as the industry promotes adoption since there are parallel efforts in other organization, government agencies, and industries.

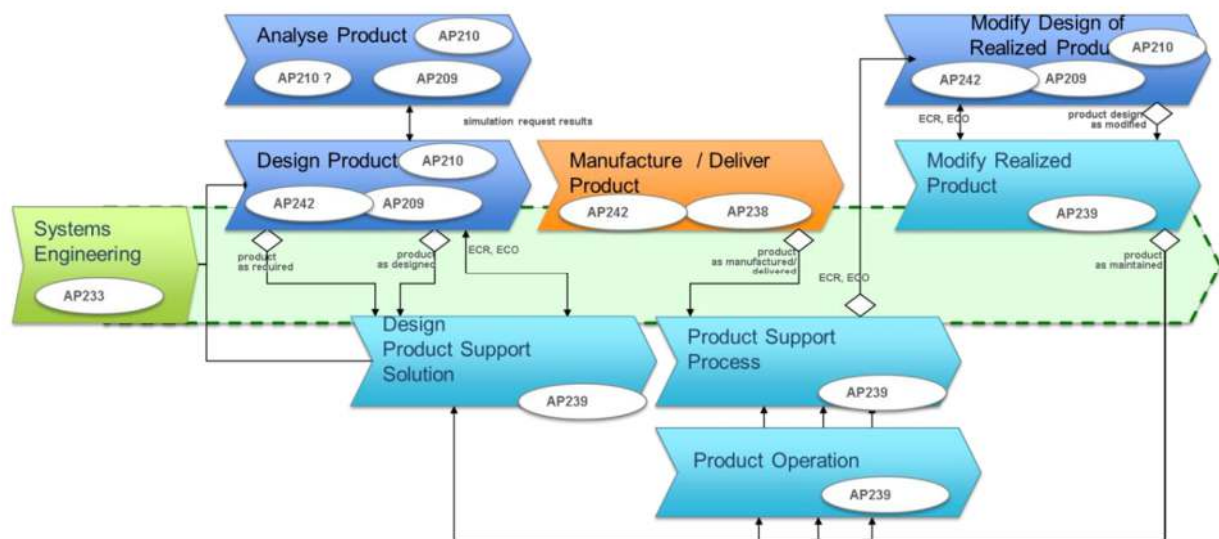


Figure 39: Overall information flow covered by the STEP Application Protocols [37]

For example, there is a parallel effort being done as part of Government Electronics and Information Technology Association (GEIA) standards project as the GEIA-STD-0007 [38]. The desire is to harmonize AP239 with GEIA-STD-0007 and move to AP239 as the definitive standard in the AirForce. It is not clear the level of support and adoption for GEIA outside of the military. This study will focus on AP239 and suggest harmonization between the GEIA effort and STEP.

Most of the AVM projects that are fundamentally concerned with the first phases of the product lifecycle - concept, design, and simulation. O3 is the only program that touches on manufacturing. It would be arguable that the entire life cycle must be considered since any engineering activity requires the analysis of maintenance, reuse, and disposal as part of the design. The standards that are considered must first support the direct needs of the programs and not preclude future development of the technologies.

In the non-defense related industries, there are four standards that are being used for product requirements, they are Requirements Interchange Format (ReqIF) [39], System Modeling Language (SysML), STEP AP233, and AP239. There was significant work done in 2009 to harmonize STEP AP233 and SysML, but there appears to be little follow-up on these efforts and AP233 has not been advanced in the last seven years.

In the German automotive industry, requirements have been communicated using the ReqIF standards developed by OMG. The standard provides a means to communicate the product design and manufacturing requirements in a consistent information model across the supply chain. This allows partner companies to collaborate on the same set of requirements without having to share the same requirements authoring tools. [40]

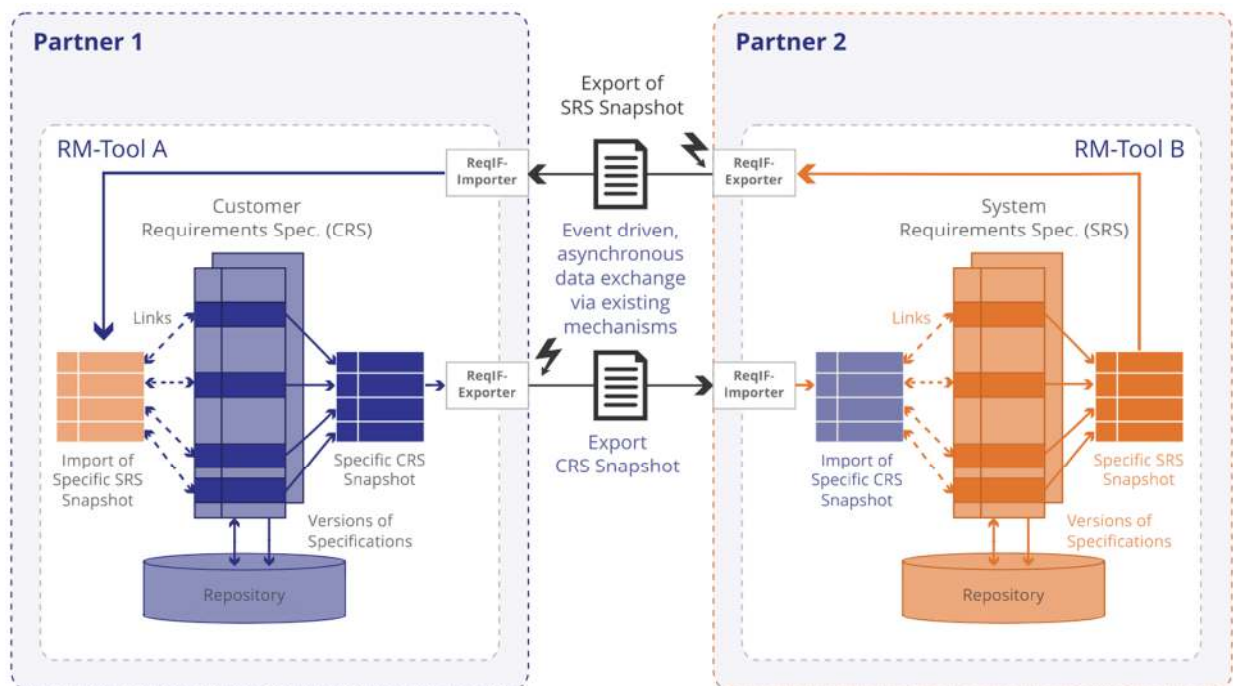


Figure 40: Requirements Exchange Using ReqIF [40]

SysML has been actively developed and is being integrated into many tools to provide support for engineering models and simulation. The adoption of SysML and harmonization with the other standards will allow for a common language to communicate these complex engineering requirements. AP233 has a lot of overlap with SysML and the relationship between the two standards was addressed in an attempt to harmonize. The following diagram shows the relationship between AP233 and SysML:

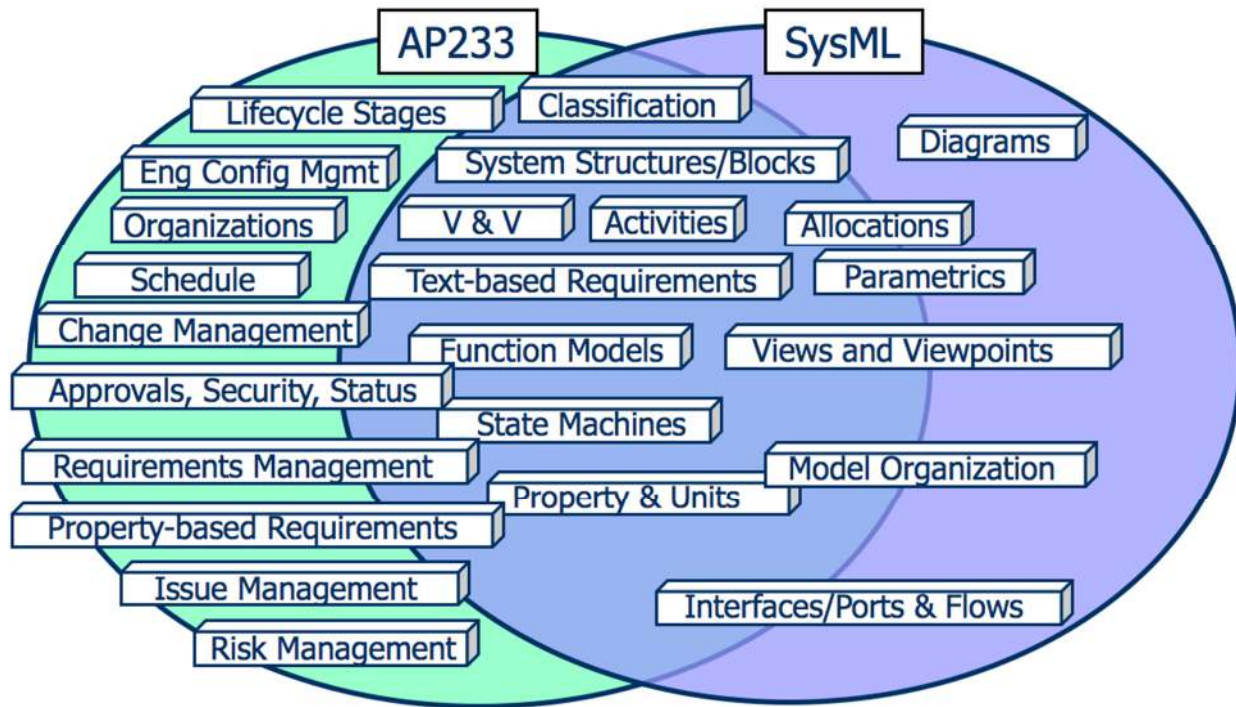


Figure 41: SysML/AP233 Data Overlaps [41]

SysML is in active development with the latest version being released in September 2015 [42]. The STEP AP233 support seems to have waned and there are proceedings from conferences with active development of alternatives instead of working on developing the STEP AP233 model further. One such project is being carried on by intercax and was presented at the International Council on System Engineering (INCOSE) conference with the proceedings written up in Model-Based Systems Engineering Across System Lifecycle (MBSE++) [43].

Since there appears to be significant overlap between AP233 and AP239, SysML, and ReqlF; the interaction of these various standards needs to be fully analyzed and there will need to be a final harmonization and scoping of the various standards to create clearer delineation. AP239 and SysML combined with ReqlF will most likely subsume AP233. If the industry focuses on harmonization and reducing duplication; there may be increased adoption due to cleaner use cases and instructions to implementers. For example, STEP AP239 [44] covers the later phases of product requirements, namely maintenance and repair and is less focused on the initial phases of design and engineering.

There are many other standards that we can consider, such as ISO-15531 (MANDATE) for manufacturing overview model, ISO 13584 (PLIB) for part families, and ISO 18629 for a semantic discrete manufacturing process activity definition. The discussion will

be limited within the scope of the AVM projects and other standards will be referenced as they are required. The core requirement is that the standards are open and they have sufficient semantic content to support communication of the application requirements to achieve the goal of digitization of the complete product lifecycle.

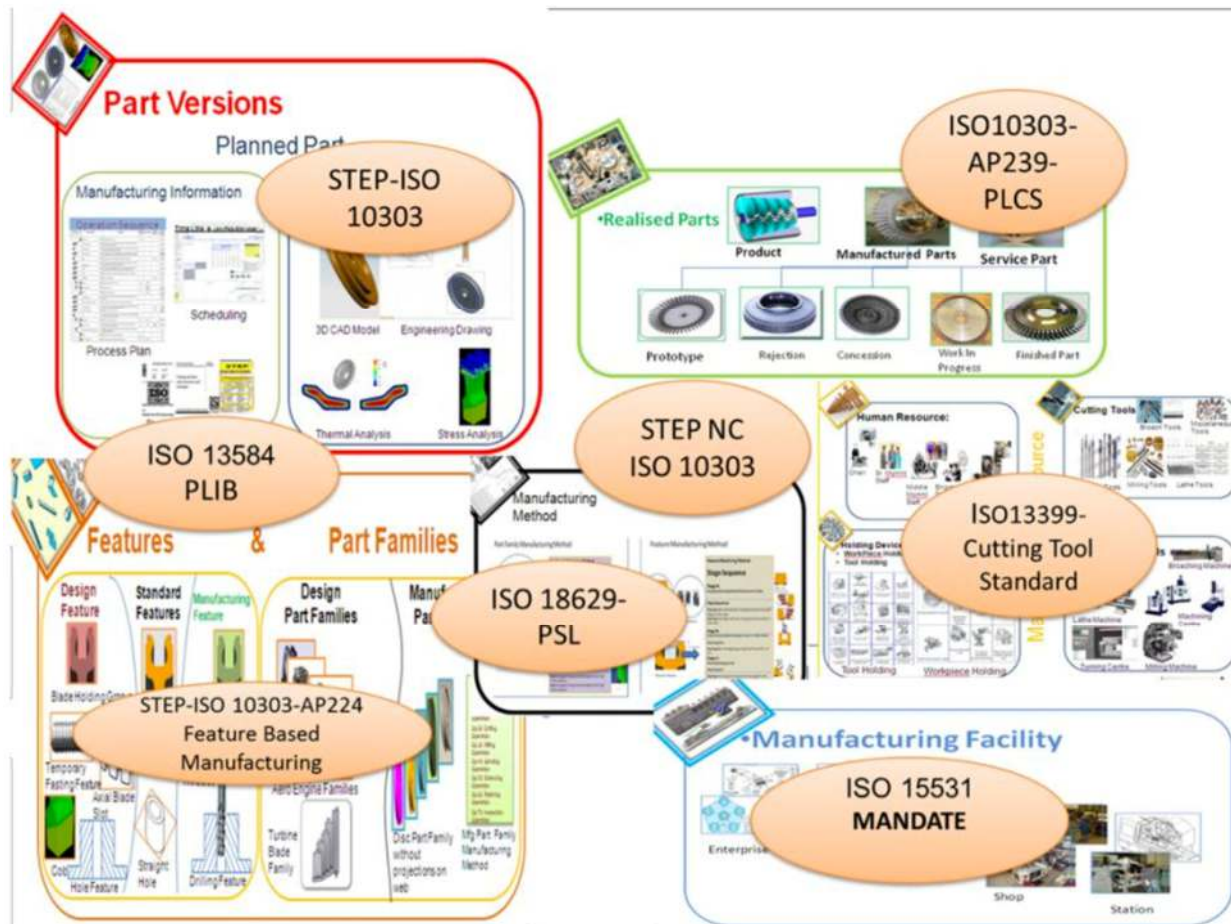


Figure 42: Manufacturing Standards Landscape [37]

6.5.4 Raw Materials, Fasteners, Painting, and Coating

There are few standards that can qualify as information models that cover these areas. The current standards were defined for 2D paper documents and designs as the target media and therefore they are not structured in such a way as they can be used in a digital information model. The primary standards in this space are developed by ASME and ASTM; other proprietary standards are used as well in addition to bespoke

design annotations for things like fastener torque and other special engineering instructions.

As the industry moves from 2D drawings to digital models, the standards that were focused on 2D visual annotations will need to be transformed into structured information models that can be attached to geometric and logical entities that exist as part of the CAD design.

ASME material standards began in 1914 because of numerous deaths due to boiler explosions in steam engines. The specifications provided instructions on materials, design, fabrication, and inspection of boilers. They have grown significantly from the first boiler book in 1915 weighing in at 114 pages to the latest at 16,000 pages in 2010. These are still print documents that must be referenced by qualified engineers. There are now information models that encapsulate the rules and requirements for a design given the intent of the designer.

For example, if the designer wanted to build a boiler and knew the expected temperatures and pressures, there is no automated system that could provide the necessary constraints to engineer and test the product without consulting the documents. There are currently no information models that would directly associate the ASME specifications to the parts of the product design and incorporate in the CAD file in standardized way that can be reasoned upon by another system.

6.5.5 Manufacturing Process Standards

STEP AP238 often referred to as STEP-NC provides the manufacturing digital model in a series of stage geometries using the STEP AP203 semantic geometric model. In the latest version, the semantic geometric PMI information model that is described in AP242 has been merged into the AP238 stage models to provide dimensioning and tolerancing at each step in the manufacturing process.

Process parameters are specified by many of the cutting tool manufacturers and the machine tool builders. These are not standards, but are best practices that are known in the industry. They are often specific to a company and used for competitive advantage to have specialized knowledge of how to work with specific materials.

Cutting tool standards like ISO 13399 and MTConnect provide information models about the geometry and the usage of the tools respectively. Currently only one project, Mind the Gap, is using execution standards in addition to design standard for tooling and feedback from the manufacturing process for primarily visualization. In the associated project, *Operate, Orchestrate, and Originate (O3)*; measurement, GD&T, and feedback from the manufacturing process are also being incorporated.

6.5.6 Manufacturing Feedback

When we consider discrete and batch manufacturing, the execution of the manufacturing process has been a black box with the techniques used and alterations made on the shop floor rarely making it back to engineering and design. The people who execute the process will modify the steps and change where needed to get the desired result.

This had led to a disconnect between the various stages of the manufacturing process and has impeded our ability to rapidly adapt to change and create new products. The manufacturing equipment has been a large factor in our lack of ability to collect critical data and provide dynamic refinement and adaptive controls to our processes. The access to the numerical controls of machines that were designed before data access was considered as a requirement.

With the emergence of MTConnect and the focus on the Industrial Internet of Things (IIOT), the technology to analyze data in real-time and perform analytics that close the loop to engineering and design are being developed. MTConnect will play a big role in the next generation of tools that will allow for adaptive and predictive analysis of design and engineering decisions by using data collected during execution compared to first principles models and rapidly refine the models with the actual processes.

MTConnect comprises the core of the shop floor feedback semantic standards and, as part of the standards efforts, will be harmonizing with STEP-NC and QIF to enable the standards to associate the design, engineering, and measurements from the in-process equipment and correctly contextualize them. The measurements and process parameters can then be fed back to the engineering and design applications to refine the engineering and planning models.

6.5.7 Quality and Measurement

The most widely adopted standards are developed by Dimensional Metrology Standards Consortium (DMSC) that developed the Dimensional Measurement Interface Standard (DMIS) and following that the Quality Information Framework (QIF) set of standard information models that has now become an ANSI standard.

Another effort is the Inspection Plus-Plus Dimensional Measurement Equipment (I++ DME) specification, not a standard, that was developed by the European Automobile manufactures as a loose consortium of CMM users and manufacturers and is being used and contributed to by NIST. I++ DME supports both the measurement commands and the results from the measurement equipment.

AP242 and AP238 (STEP-NC) have now added geometric Product Manufacturing Information into the models that allows them to attach tolerances and dimensional

constraints on the features of a model. These can be used to create measurement plans for parts and assemblies and translated into the other models mentioned above.

The AP242 and QIF models have been associated by using a common unique identifier scheme and formula to reference features in each of the models. Even though the geometric models differ, software has been developed that can translate between the models and not lose content or context.

6.6 Proprietary Information Models

Design tools and applications have been controlled by a limited number of vendors. Currently there are only around five solutions in common use. This concentration of solutions and market has caused most companies to “standardize” on a proprietary information model such as CATIA, ACIS, or NX. Standards have not made significant progress since the prevalent communication medium is still 2D drawings and when required and a tier 1 or OEM can require the supplier to adopt their proprietary technology.

This has led to the highly static supply chains as discussed in section 1 regarding the treatment of the automotive supply chains in Germany. Many of the AVM projects chose proprietary models since the current standards based systems do not provide a graphics kernel or the capabilities they need beyond the raw geometries.

The resulting output of the projects is often a visualization format that is unusable by any recipient other than a human and has been stripped of all the semantics and reference to the original design. This practice is common and in manufacturing the assumption that a human will always be in the loop has allowed the industry to fall back on human intuition and skills rather than systematize the creation of comprehensive information models to communicate between all phases in the product lifecycle.

6.6.1 Proprietary CAD Data Formats

The following are a list of Proprietary CAD data formats (Kernels are the base for the CAD systems). Many of these have become industry standards, but they are not interoperable and there are fees associated with using them:

- ACIS (.sat) (Dassault Systems (DS) modeling Kernel)
- Granite (.gl) (PTC modeling Kernel)
- Parasolid (.x_t) (Siemens modeling Kernel)
- CATIA (DS) CAD Files
- Creo (PTC) CAD files
- NX (Siemens) CAD Files
- SolidWorks (DS) CAD Files (use Parasolid Kernel)

- Autodesk (.dwg) CAD Files

The following are also enterprise standards that are adopted by companies and are not communicated outside the enterprise or division:

- Corporate Design Best Practices
- Corporate Manufacturing Best Practices
- Corporate Quality Control Best Practices

6.7 Internal Standards Used in Programs

Each of the service providers must utilize standards within their applications to provide good interaction with traditional design and manufacturing processes. An example of this could be where a design specifies a fastener of a certain size and grade, that fastener should be able to be acquired based on a published standard. Some examples of standards organizations who publish material standards are ASTM, ASME, AIA...

Since a major thrust of the AVM projects is design and manufacturing process automation, design and manufacturing standards should be followed. Of course, where product documentation is being produced, regardless of whether it is digital or traditional 2D Drawings, the ASME Y14 series of standards should be used where they are applicable. The ASU Tolerancing project should utilize ASME Y14.5 and 14.41 to be certain.

DFM (Design For Manufacturing)/DFA (Design for Assembly), while the information for working to these constraints is not well standardized, there are documents available that define best practices during design and manufacturing planning. RECON services published a document titled “iFABFoundry Design Guidelines” that should be useful for a designer who is manually designing new products and wants to incorporate DFM/DFA considerations into that design. The guide is also useful for programmers who are developing DATs (Design Assist Tools) for the AVM program or any other automation effort.

Other standards or best practices that need to be considered are manufacturing cutting speeds and feeds. While not public standards, there are various texts that can be used to compare cutting material with material being cut then determining a usable speed and feed for this cut. “Machinery’s Handbook” is one example and others exist as well, plus cutting tool distributors typically have guides for their tools available.

For metal removal processes, the process parameters are supplied by the cutting tool manufacturers and there is a parallel effort to provide these via web based services, namely the Machining Cloud and Sandvik each have solutions to provide ISO 13399 data with suitable constraints. These constraints are determined in lab settings and

there is a need to utilize empirical data to determine the best conditions in all cases given the manufacturing equipment, material, hardness, etc.

Most companies have corporate “Design Guidelines”, “Manufacturing Guidelines” and Quality Control Guidelines” that are to be followed by their organizations when performing these duties. These are often internal guidelines and they are sometimes limited to single divisions or shops within an organization. Since these best practices have not had a common information model and the software services to promulgate them, the groups and systems have been siloed.

MTConnect, QIF, OMG, and PDES (STEP) have been working to provide this information in standard information models. The migration from proprietary systems to standards has been slow in these areas, but with emergent services that utilize these information models, the utility value in the form of decreased cost of engineering and scrap will provide the impetus to adopt.

6.7.1 Suggestions for AVM Service Required Output Data Standards

Output from any of the AVM projects should be formatted in the following manner:

- **Geometric based Models** (With embedded PMI where applicable)
 - STEP AP242, include Native CAD where available.
 - If the app operates on native CAD then both native CAD and AP242 should be output.
 - QIF, Same rules for QIF as listed under STEP output (If QIF is determined viable)
 - STEP AP203
- **Manufacturing Execution Models**
 - MTConnect
 - STEP-NC AP238 with geometric PMI for the stage models
 - ISO 13399 for tooling
- **Manufacturing Engineering Models**
 - AP233 or AP239 with SysML
 - ReqIF with SysML
 - AP209
- **Representation**
 - Where possible, XML or other widely adopted standard should be used. Currently the STEP (AP) standards use the EXPRESS format (ISO 10303). Semantic models should utilize the most widely adopted technology available.
 - JSON representations of semantic models can also be used for representation of data between services and for visualization applications.

6.7.2 Current Standards Used by AVM Projects

The following is the set of projects that are being developed under the DMDII 14-XX project calls and are currently part of this project scope. The projects were not developed with standards as a requirement, so most are using proprietary models for both input and output.

This section will present the current set of inputs and outputs as were described during the initial interviews and the recommended set of standards that are the recommended direction if interoperability is desired. The proposed architecture requires common open standards models; if the projects considered helping to further the standards communities and provide the necessary support to accelerate the required enhancements, there would be a significant benefit to the manufacturing industry.

We will be using an IDEF0 diagram to illustrate the inputs, outputs, and the various standards used by the different services that will make up the manufacturing ecosystem. The following template will provide the structure used in this discussion:

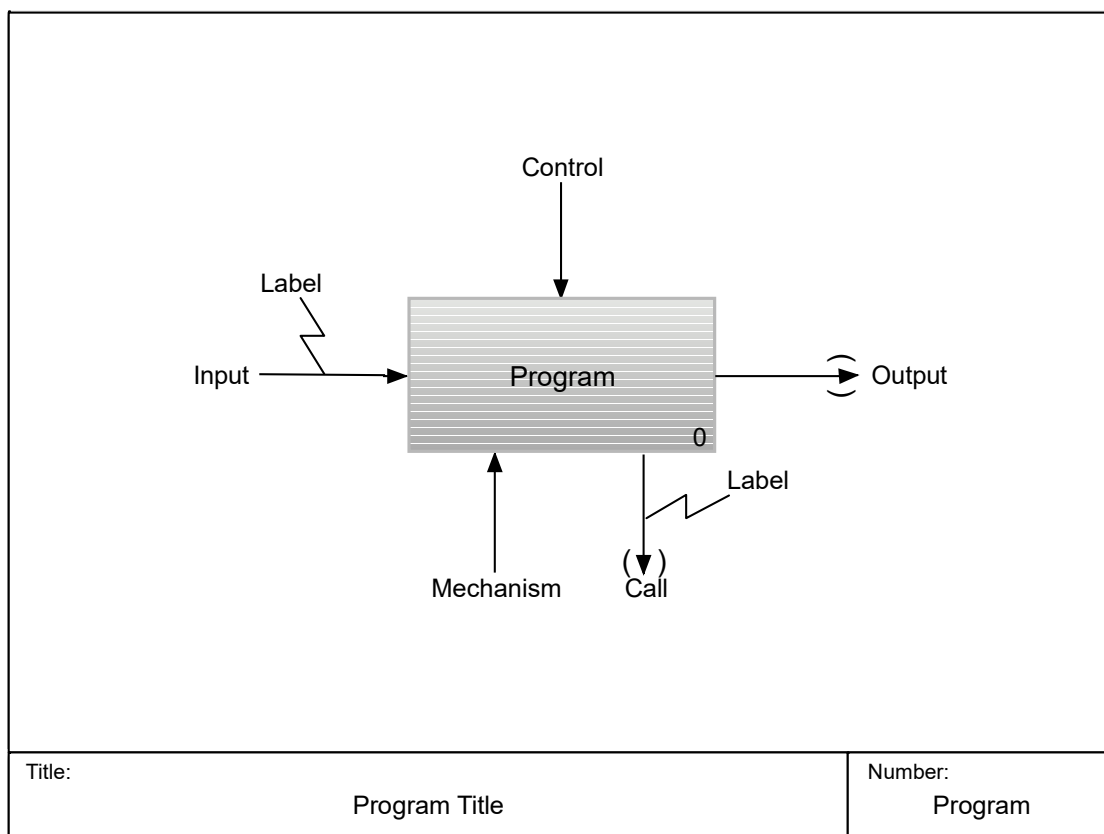


Figure 43: IDEF0 Diagram

6.7.2.1 14-02-05 ASU, Automatic Tolerancing of Mechanical Assemblies

Arizona State University led by Jami Shah has been working on a methodology for automatically determining the measurement constraints by recognizing features and geometries and determining which are critical and to what accuracy they need to be measured.

Current

- Inputs:
 - STEP AP203
 - ASME 14.x?
- Outputs:
 - STEP AP242

Proposed Standards

- Standardized Inputs:
 - STEP AP203 for raw geometry or AP242 with additional product information that can help refine quality based on a priori knowledge
 - ASME Y14.x/ASTM for engineering requirements
 - B2MML for cost and lead
- Standards for communicating engineering and simulation models
 - STEP AP209 will FEA simulation models to understand design and engineering intent
 - AP233 and SysML for communication of system engineering models and requirement
- Feedback Mechanisms Inputs:
 - MTConnect for process information to inform quality
 - QIF to verify the results and the process control for refinement
 - AP239 - S5000F for maintenance and service feedback
- Control standards:
 - B2MML will provide process cost and lead information to make determinations regard quality budget
- Outputs:
 - STEP AP242
 - QIF
 - ASME Y14.x (series of engineering standards, see Appendix “A”)

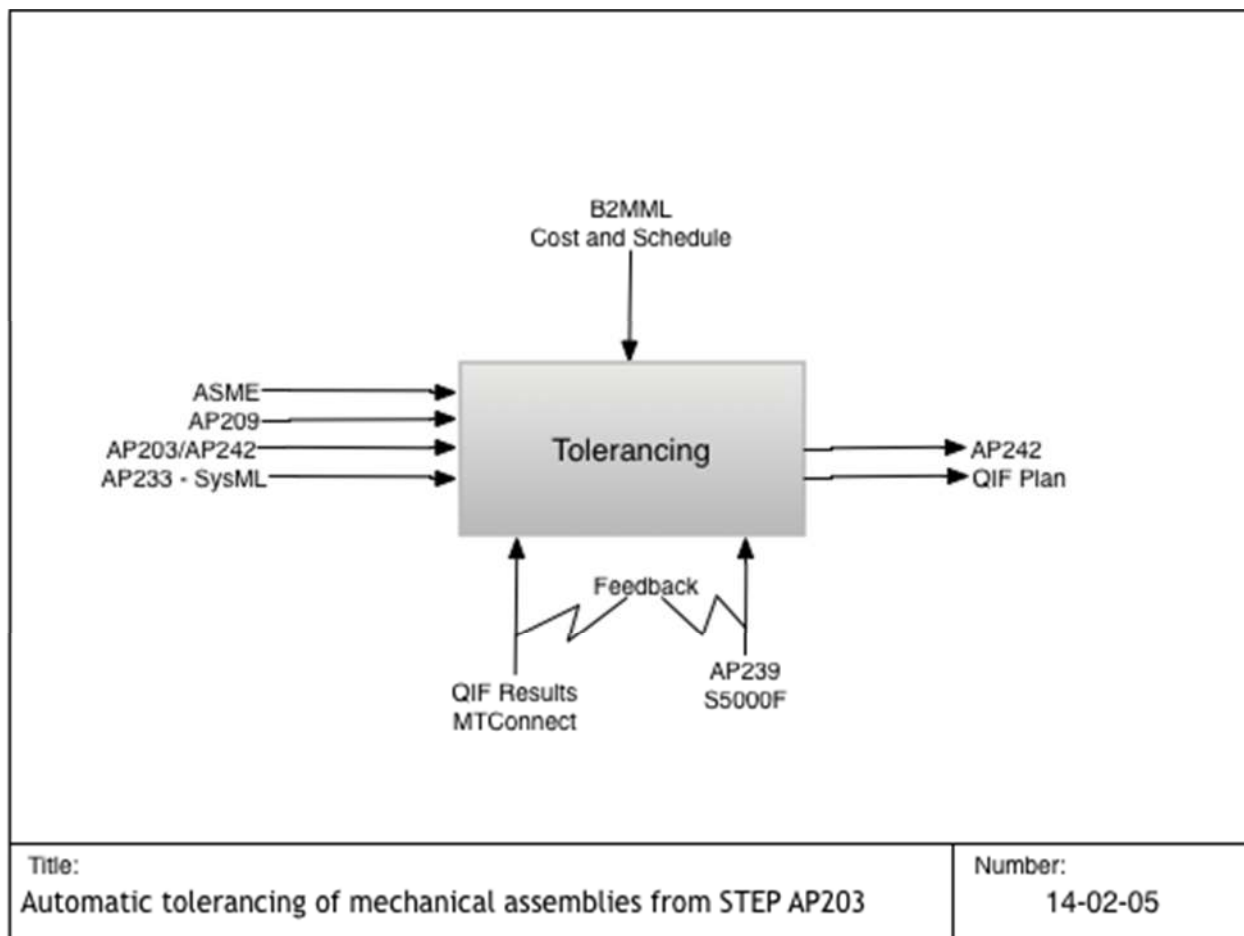


Figure 44: 14-02-05 ASU, Automatic Tolerancing of Mechanical Assemblies

Automatically determining dimensioning and tolerancing schemes for assemblies and the associated “down parts” is extremely important. Young Engineers (and many older ones) do not know how to properly define dimension and tolerance schemes for parts they are responsible for within the design process.

Dimension and tolerance schemes should:

- Consider the operational requirements of the assembly.
- Provide for the most manufacturable (cost effective) design and balance quality with cost.
- Do not apply tolerance tightness to appease the designer.
 - Available Tolerances can be exactly calculated. Every bit of the available tolerance should be made available to the manufacturing process through the dimensioning and Tolerancing schemes applied to the “Product Definition”.

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- Fudge factors do not apply in exact science.
- Be properly calculated and be distributed to correct sub component features of an assembly.

The folks on the ASU project understand this and if they can create an automated system or even a DAT (Design Assist Tool) their project results can be used to significantly improve the results of product design programs. Perhaps this service could be applied to existing or legacy assemblies that are reverse engineered due to lack of TDP information

As listed at the beginning of this section inputs to this service should be STEP since it is the most prevalent CAD model currently available. Mix that with good DFM and DFA practices; we see how a “Smart Software System” could determine/reason what a given assembly is, and reason as to what the operational requirements might be and then determine a dimension and tolerance scheme for that assembly.

This project should always output one of these file types as a minimum:

- STEP AP242 with geometric PMI
- QIF Plan

STEP AP242 should be used to communicate the geometry along with the semantic PMI (Dimensions and Tolerances). QIF should also be used to communicate the measurement plans and the instructions to guide the measurement process. The two models QIF, AP242, and AP238 models should be harmonized so they can interoperate since they serve different functions even though there overlap in their representation of the geometric models.

At a minimum, the STEP and QIF standard should have a common definition of a feature, a characteristic, and an identity scheme to allow for cross model references. With interoperability, the models should be usable without loss of meaning and the result value is increased by joining the needs of the designer with the needs of the quality engineer. QIF can also be utilized to represent the measurement results once the plan is executed.

Most of the ASME Y14.x standards deal with 2D Drawings and are only applicable in this project when 2D drawings are used as supplemental data. Two standards that are applicable to the ASU project are Y14.5 and Y14.41. Others that might be applicable are Y14.24, Y14.34 and Y14.38. The Dimensioning and Tolerance scheme should utilize GD&T as described in ASME Y14.5 and ASME Y14.41. Some specialty Y14.x standards might also be applicable. These basic and specialty standards are listed in a document called “The ASME Y14 Policies”.

AP242 is working on incorporating the ASME standards into the PMI references, but when that will be available to the public is unknown. The capability is a first step to

allowing for designers to express intent and these annotations are required to accurately drive tolerancing.

See Appendix “A” for an excerpt from “The ASME Y14 Policies”.

6.7.2.2 14-01-10 GE, Elastic Cloud (ECBM) (DMC, Service used to distribute AVM service tools)

Current

- Inputs:
 - Native CAD (CATIA, Creo, NX, Solidworks)
 - Proprietary analytics (Abaqus, Adams, Excel, Ideas, Ideas8, Mathematica, Matlab, Nastran)
 - Possibly others, dependent on the implementation
 - Name-Value inputs with units
 - Custom
- Outputs:
 - Output as related to the DMC data views

Proposed

- Standardized Inputs:
 - Various STEP: AP242
 - ASME 14.x/ASTM
- Standards for communicating engineering and simulation models
 - AP209 for simulation and FEA
 - AP233 and SysML for communication of system engineering models and requirements
 - ReqIF for requirements as an alternate to AP233
- Outputs:
 - STEP AP242
 - ASME 14.x constraints
 - AP233 and SysML for communication of system engineering models and requirements
- Desired Standards
 - Standardized mechanical calculated results standards beyond ASME/ASTM

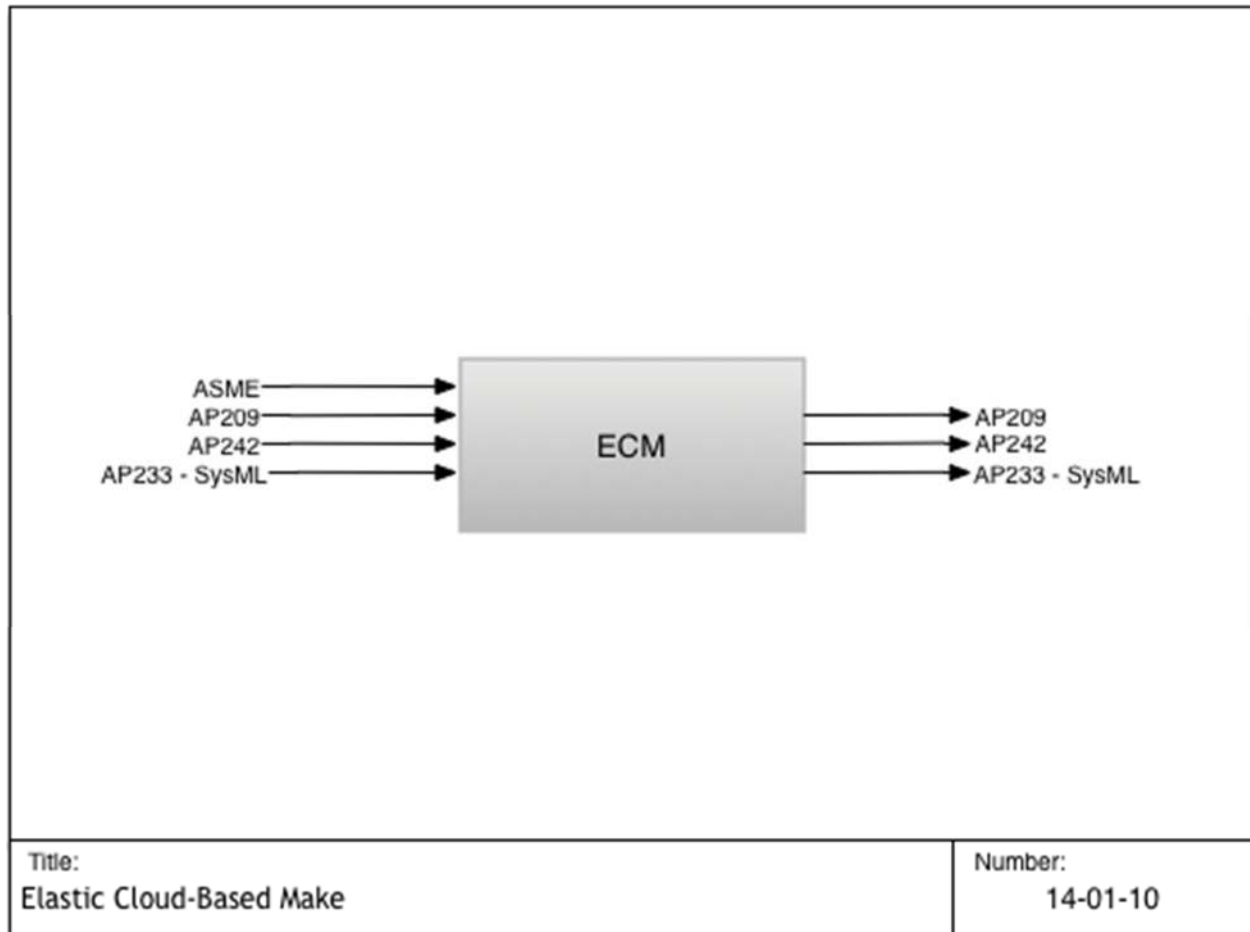


Figure 45: 14-01-10 GE, Elastic Cloud (ECBM) (DMC, Service used to distribute AVM service tools)

Elastic cloud provides the initial framework to begin transitioning projects from the AVM to the DMC platform being developed by GE for DMDII. The project will attempt to combine various tools that were developed around the original iFAB projects, the hope is it will prime the marketplace with some useful design and make capabilities. Since DMC was model agnostic and it initially was engineering focused based on geometries, the project did not focus on standards as a core tenant of the platform.

The key to making platforms like DMC viable is to have free and open information models that can be used to interoperate with the information flow and incorporate the feedback loops to learn from execution. There is a lack of certainty that a platform that is operated by a single vendor can dominate, as AWS has done in infrastructure as a service, or if an OpenStack approach will work better in an industry where the network of relationships is more complex and the management of the data and intellectual property adds additional complexity.

From a standards perspective, the Geometric models provided by AP203, AP242, and QIF will be useful to any design/make analysis. The results of such a platform is

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harder to define within the current set of industrial standards. Possibly an annotated AP242 model where the ASME annotations have been attached to the PMI would be a possibility, but it was difficult to determine from the initial discussions.

It would also be advantageous to utilize standards like SysML and AP209 to provide a standardized semantic model to represent the system engineering requirements as well as the simulation models in AP209. For the automotive industries, ReqIF should also be considered since it has wider adoption outside of aviation.

6.7.2.3 14-01-09 ARL at PSU, AVM, IFAB Tools for Industrial Use

Current

- Input:
 - STEP AP203
 - Native CAD (PTC CREO)
- Output:
 - Native CAD (PTC CREO)
 - Custom XML or JSON

Proposed

- Standardized Inputs:
 - Various STEP: AP242
 - ASME 14.x/ASTM
 - B2MML for cost and lead
- Standards for communicating engineering and simulation models
 - AP233 and SysML for communication of system engineering models and requirements
 - ReqIF for requirements as an alternate to AP233
- Outputs:
 - STEP AP242
 - ASME 14.x constraints
 - AP233 and SysML for communication of system engineering models and requirements
 - AP239 for lifecycle requirements
- Desired Standards
 - Standardized mechanical calculated results standards beyond ASME/ASTM

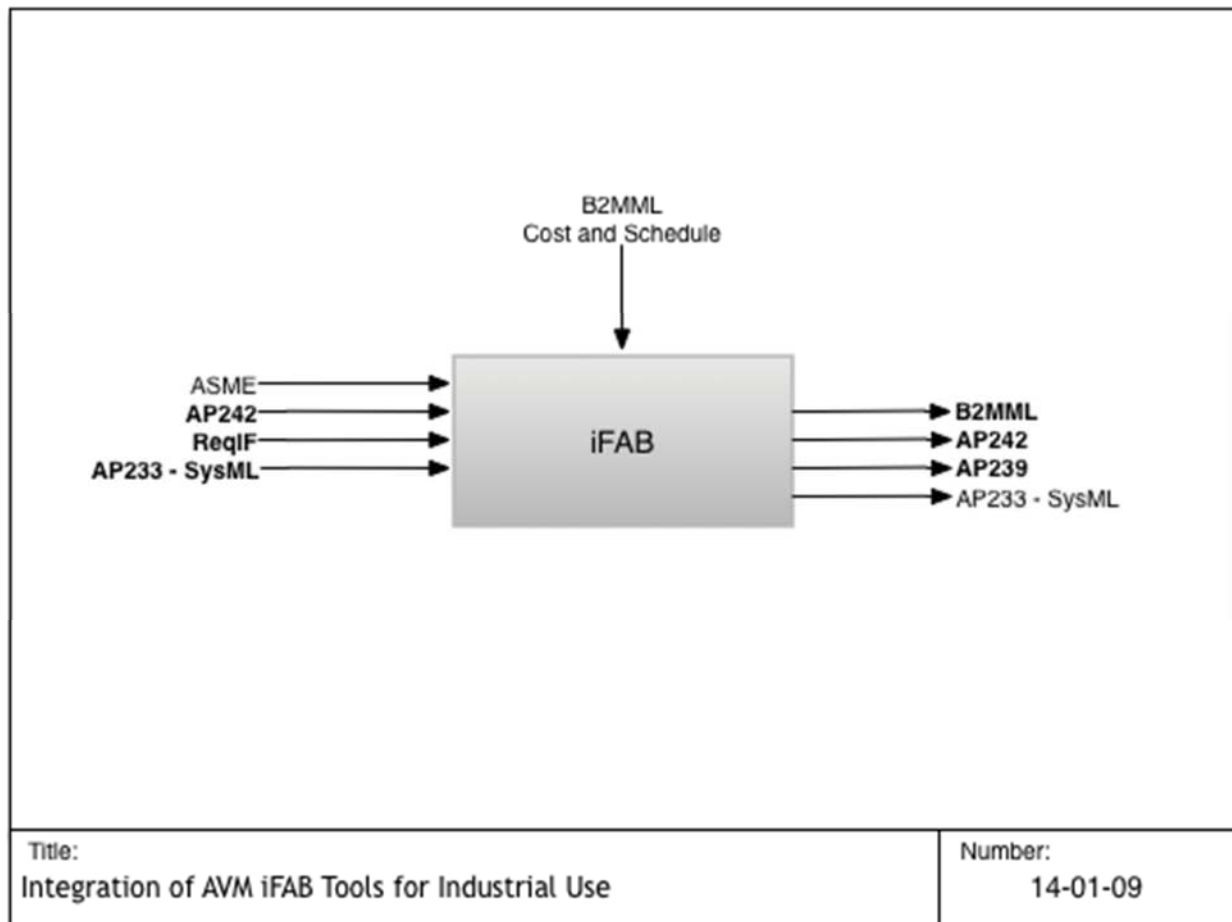


Figure 46:14-01-09 ARL at PSU, AVM, iFAB Tools for Industrial Use

At the time when DARPA AVM started, STEP AP242 was not released as an ISO standard and there were no commercial applications using it or with adequate support for AP214. If AP242 would have been available at that time, the data types used might have been different. At that time IGES and STEP AP203 files were reviewed to determine manufacturing cost. Results were stored within XML files and parsed elsewhere to score designs as to their “Manufacturability” (based on cost and lead time to acquire). Since both IGES and STEP AP203 consist of basic geometry, many assumptions needed to be made to create the XML file. The results were prone to error due to a lack of inbound data that could be evaluated.

If STEP AP242 files with Semantic PMI imbedded was available, a much smarter analysis could have been applied to the manufacturability assessment and a much better result would have been possible. QIF can augment the STEP AP242 semantic PMI with references to ASME to provide material and manufacturing constraints.

The DAT (Design Assistant Tool) service can be used inside a commercial CAD system by integrating the service and allowing analysis of the geometric and manufacturing information. This would allow the DAT to guide the Engineer/CAD user in the development of the models. Use of standardized information models will increase the applicability of the capability to a wider range of CAD applications.

6.7.2.4 14-01-07 Iowa State, Automated Manufacturability Analysis (ANA Software)

Current

- Inputs:
 - STL
- Output:
 - 3D PDF

Proposed

- Standardized Inputs:
 - Various STEP: AP242
 - ASME 14.x/ASTM
- Standards for communicating engineering and simulation models
 - AP209 for simulation and FEA
 - AP233 and SysML for communication of system engineering models and requirements
- Outputs:
 - STEP AP242
 - AP233 and SysML for communication of system engineering models and requirements
 - AP238 stage model exceptions for manufacturability

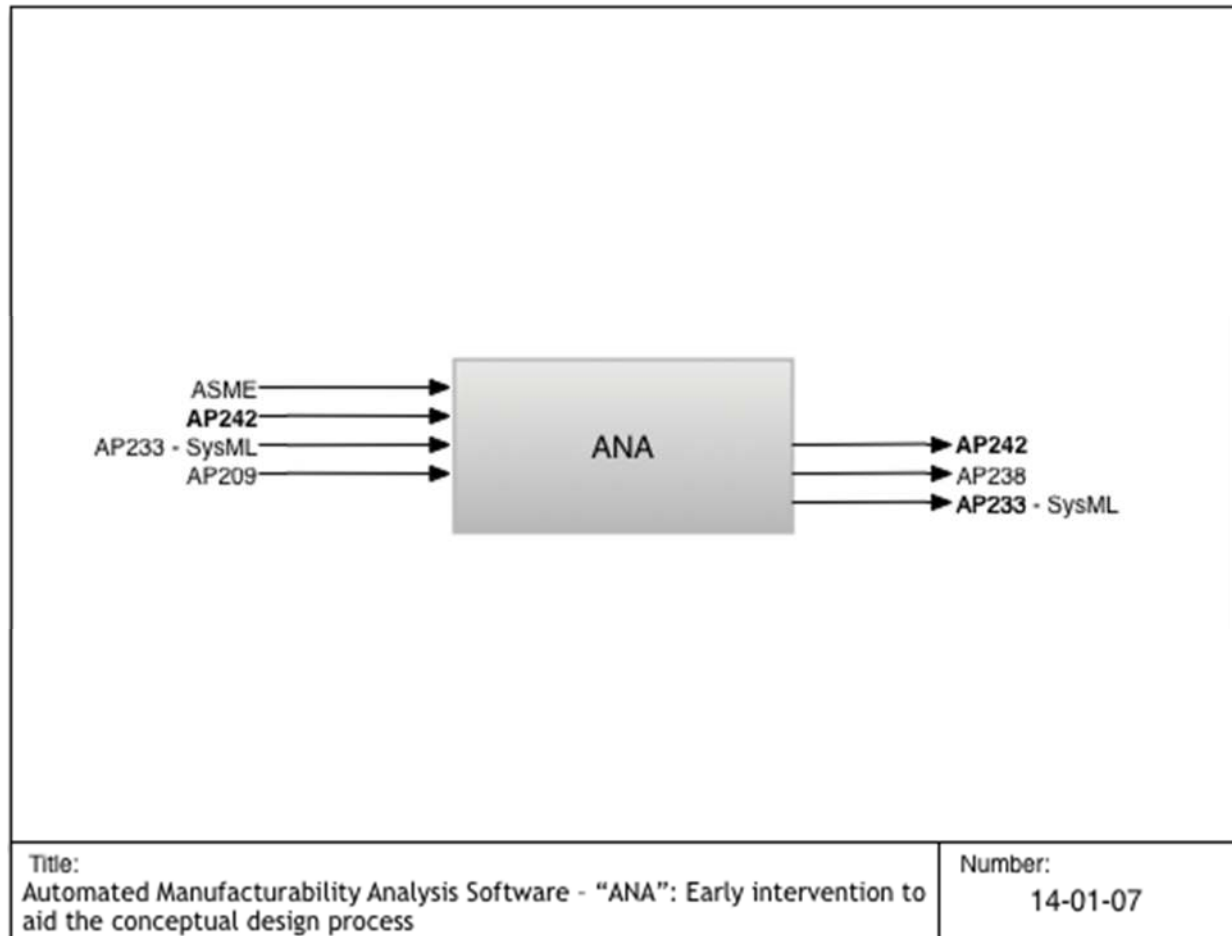


Figure 47: 14-01-07 Iowa State, Automated Manufacturability Analysis (ANA Software)

The manufacturability tool is designed as an entry level product that can analyze a solid model geometry and determine manufacturability by providing a color-coded 3D document as a report. The preferred way to do this would be to provide feedback associated with the features in the original AP203 or AP242 model and utilize the PMI and GD&T data to help guide the analytics.

Even though the initial project only had STL input, we have added the ASTM and ASME standards since they will be attached to the AP242 model. If AP242 is chosen, it can provide a lot of additional information to drive intelligent systems. This is predicated on CAD software, especially less expensive CAD software, to fully support the AP242 models and providing the necessary semantic PMI.

Without a semantic PMI model, an AP203 model would still be preferable since it will have a model that can be referenced and associated with the results. The results will be required to be used as input to another process as well as drive visualization. AP242 should be able to represent the information regarding reachability. AP238 can be used if explicate tool paths or execution constraints are given.

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With AP238 and the edition 2 extensions for engineering PMI and GD&T, more information can be provided that can be of use in other projects and services in the industry. B2MML is also included since any information regarding cost and lead would be useful when evaluating strategies, but it is not included in the initial scope of the project.

Product requirements provided by the designer regarding design intent of the product are also useful for determining the optimal strategy given the product requirements will need to be inferred or communicated in a proprietary format. Engineering requirements are provided using AP233 and SysML in this case. In moving to standards based information models, the original scope of integrated manufacturability assessment can be extended to other services as well.

6.7.2.5 14-02-04 Oregon State, Automated Assembly Planning

Current

- Inputs:
 - Native CAD (ACIS)
 - Proprietary feedback from ICIDO
- Outputs
 - Proprietary from ICIDO

Proposed

- Standardized Inputs:
 - STEP AP242
 - Optional QIF for tolerances
 - STEP AP209 will FEA simulation models to understand design and engineering intent
 - STEP AP233 - SysML provide system engineering models for engineering intent and for process verification
 - STEP AP242 provides additional product information that can help refine quality based on a priori knowledge
 - ASME Y14.x/ASTM for engineering requirements
 - B2MML for cost and lead
- Feedback Mechanisms Inputs:
 - MTConnect for assembly process feedback
 - QIF from final inspection and the process control for refinement
 - AP239 - S5000F for maintenance and service feedback
- Output:
 - STEP AP242

- Desired Outputs that are not in standards:
 - Extensions to AP242 that can reference the components of the assembly and provide the liaison information for each set of associated parts
 - Assembly Instructions

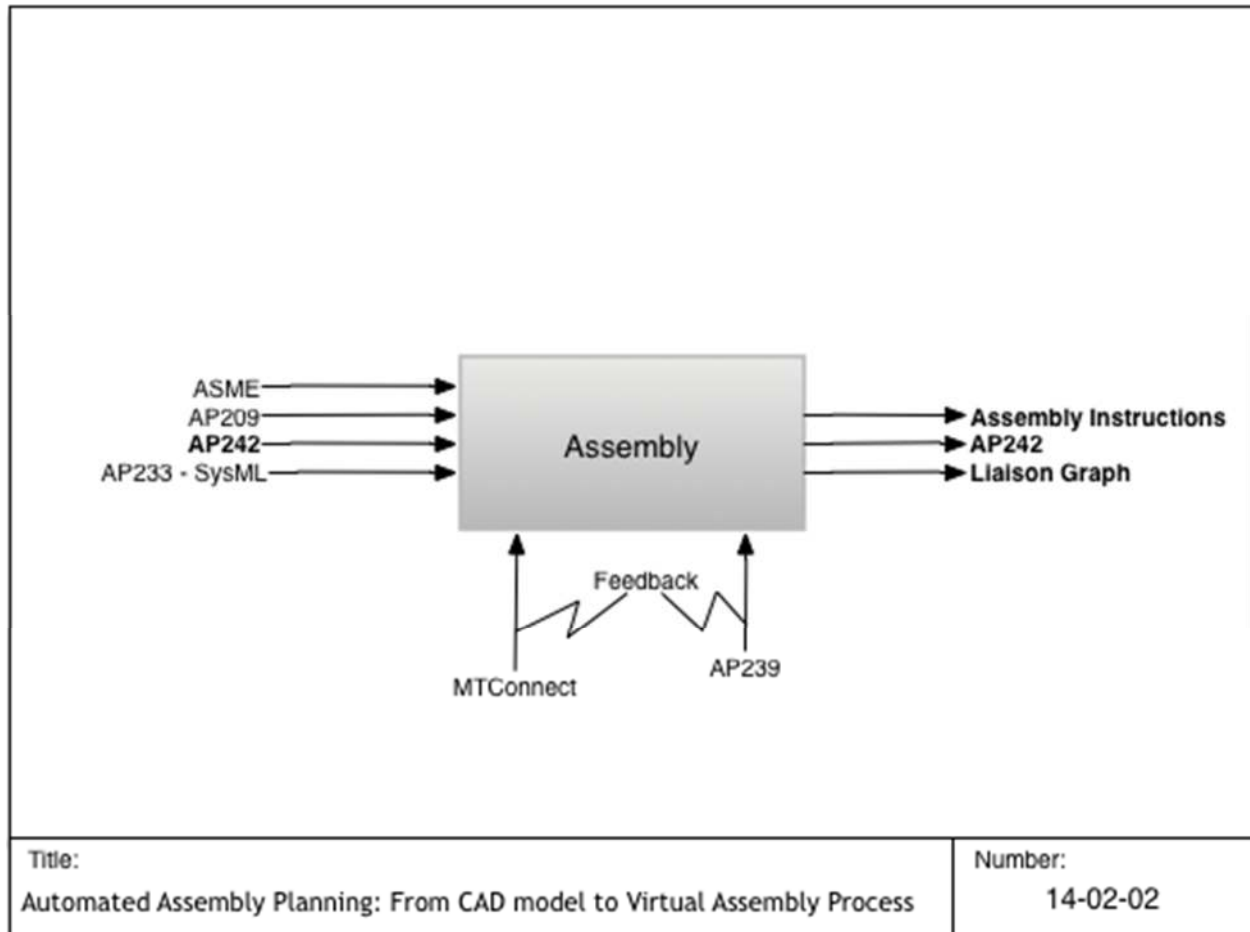


Figure 48: 14-02-04 Oregon State, Automated Assembly Planning

The Oregon State program offers automated Assembly plans based analytics that determines an optimal assembly approach by first exploding the assembly and then re-assembling all the parts. The analytics currently use the information in ACIS, including any geometries, PMI, and shape histories using the ACIS kernel. The solution is also able to take into consideration the feedback from the assembly process that is tracked by their partner ICIDO.

The AP242 GD&T as well as QIF measurement plans will provide valuable input that will help infer the type of attachments that are being used. What would be preferable

is a full liaison graph that would provide a detailed set of information about the designer's intended attachment requirements and the type of fittings that will be used. The lack of any existing standard means that proprietary models and inference were used to proxy for information that should be provided as explicit annotations.

The output is currently a set of instructions in the ICIDO format and cannot be used by any other service since they have no semantic content. The OSU team was going to consider changing this, but will most likely be out of scope. There is no current assembly standard that using a set of operations and properties that can be used to fulfil the requirements. Assembly is in the AP242 roadmap, but it does not currently exist.

6.7.2.6 14-02-02 STEP Tools, Mind the GAP

Current

- Inputs:
 - STEP AP203/AP242
 - ISO 13399
 - MTConnect
- Output
 - cad.js (an open source CAD representation in JSON: <https://github.com/ghemingway/cad.js>)
 - STEP AP238

Proposed

- Input
 - STEP AP203/AP242
 - ISO 13399
- Feedback Mechanisms Inputs:
 - MTConnect for process feedback
 - QIF from final inspection and the process control for refinement
- Output
 - cad.js (an open source CAD representation in JSON: <https://github.com/ghemingway/cad.js>)
 - STEP AP238

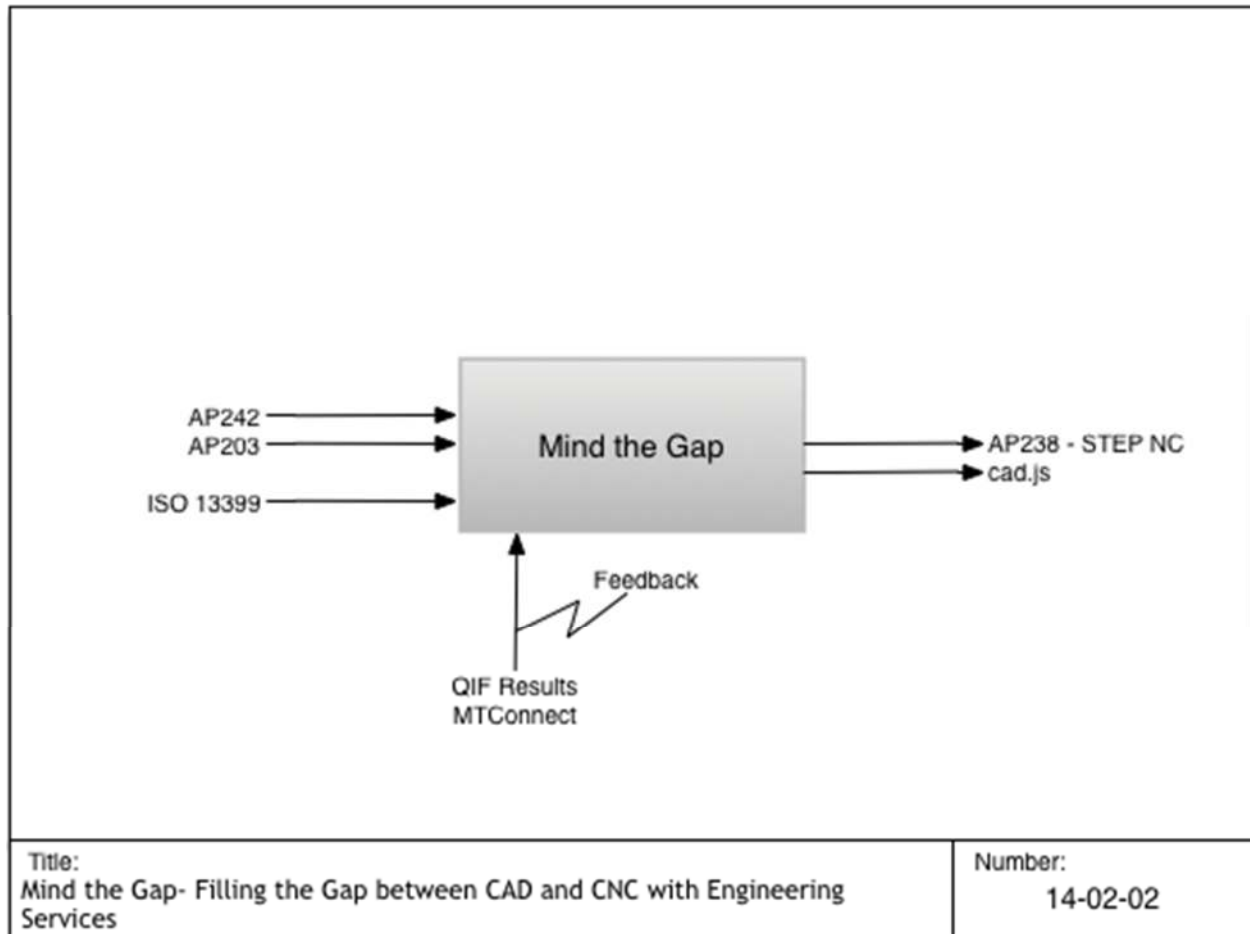


Figure 49: 14-02-02 STEP Tools, Mind the GAP

Mind the Gap is working on creating a harmonization between MTConnect and STEP-NC AP238 that allows direct feedback from the manufacturing equipment to be merged into the initial plan and then rendered with a relatively low latency. The models are merged in a cloud service and then the tool paths and volume removal are rendered in a browser using CAD.js.

Mind the Gap is the most standards compliant project currently in the suite of AVM projects. The Mind the Gap tools could be integrated into services without modification since the information models are open standards or open formats.

Combined with the subsequent project, O3 (Operate, Orchestrate, Originate), the value of measurement feedback and model associates become more apparent. Combining this project with ASU Auto Tolerancing and using the AP242 GD&T capabilities will allow for an integration between projects that could show benefit to the industry.

6.7.2.7 14-01-06 Green Dynamics, Composite Wind Turbine Blade Design

Current

- Inputs:
 - Native CAD
 - STL
 - IGES
- Outputs:
 - VRML

Proposed

- Standardized Inputs:
 - Various STEP: AP242
 - ASME 14.x/ASTM
- Standards for communicating engineering and simulation models
 - AP233 and SysML for communication of system engineering models and requirements
 - STEP AP209 will FEA simulation models to understand design and engineering intent
- Feedback Mechanisms Inputs:
 - MTConnect for process feedback
 - QIF from final inspection and the process control for refinement
- Outputs:
 - STEP AP242
 - ASME 14.x constraints
 - AP233 and SysML for communication of system engineering models and requirements
 - STEP AP209 will FEA simulation models

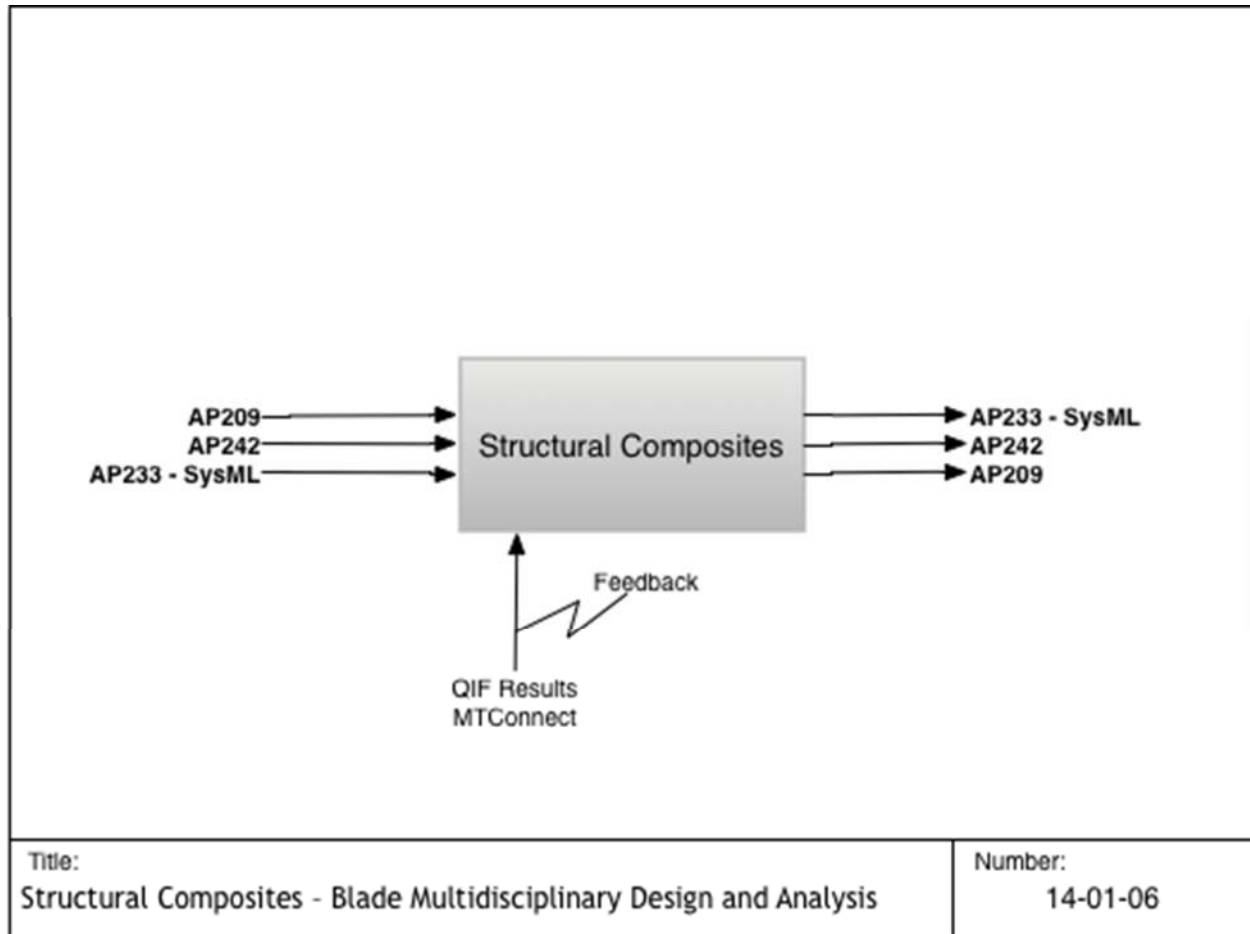


Figure 50: 14-01-06 Green Dynamics, Composite Wind Turbine Blade Design

MBD methods developed under the Army MANTECH programs is full of gaps, especially as the product mix becomes more diverse. The design of airfoil shapes is especially full of unique requirements. As we solve automation requirements for one airfoil type, some of the lessons learned can flow to other similar product classes.

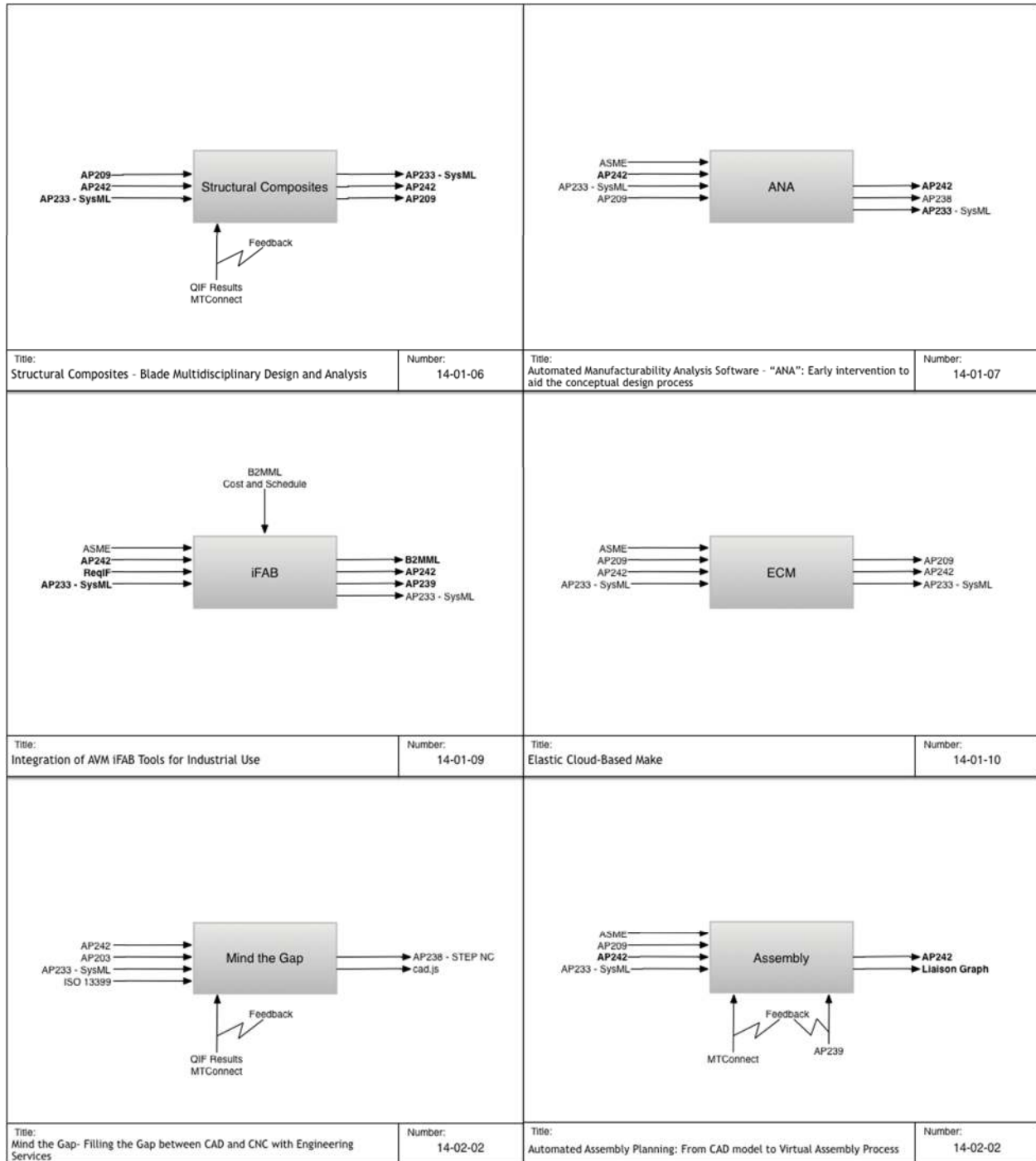
The current product direction will produce a VRML image and a set of process steps in a proprietary format. The MTConnect, B2MML, and AP238 all have the capability of representing a series of process steps and attach artifacts to these steps. The AP238 model may be the best choice since an arbitrary geometric model can be associated to each stage and the current VRML image would be a 2D projection from the 3D model.

The AP238 stage models would have the advantage of having associated PMI as well as having the full 3D geometry that could be utilized in additional services with references back to the original geometric models used in the analytics. One of the goals is to have the output models have adequate capabilities to have a fully referenced set of geometries that can be used to provide traceability and consistency.

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6.8 Summary

The following is a summary of the various projects and the proposed inputs and outputs:



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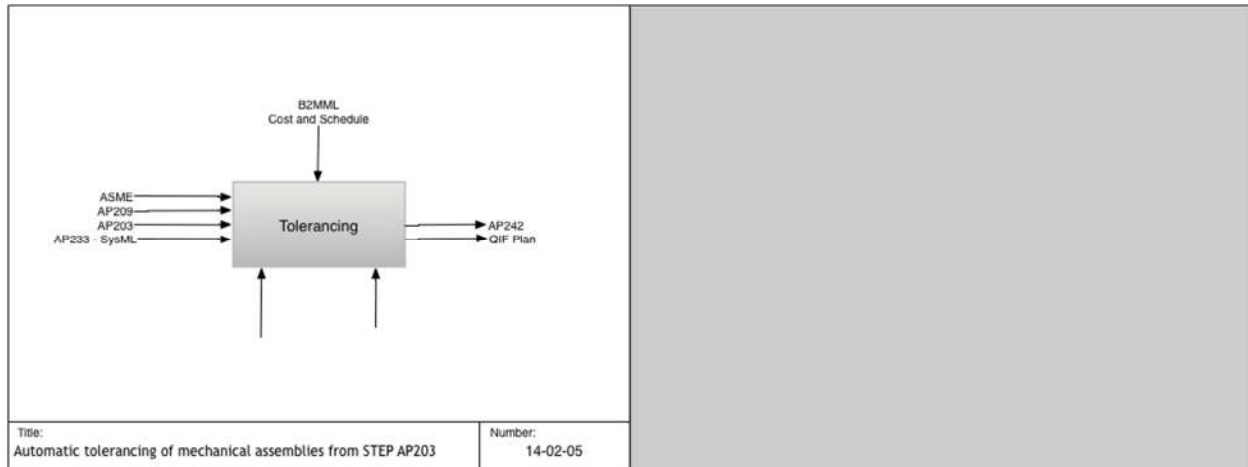


Figure 51: Combined programs and standards

In the diagram above, most of the services can be composed since the inputs and outputs are using the same set of base standards. There are still many gaps to fill, which will be discussed next, but if the programs were directed to provide standards based inputs and outputs, the resulting value would increase significantly because each of these services would be able to augment the other services.

For example, the output from the ASU Tolerancing could directly feed into the OSU Assembly service. And resulting assembly information models could augment the ASU tolerancing with the additional insights regarding how best to assemble the product. Both services can be combined with either of the two projects that are addressing manufacturability to allow for immediate feedback to the designer.

The process would be a continual loop of services that will guide the design and engineering capabilities of the customer to increase productivity, first time yield, and time to market. These services can also provide the foundation for manufactures to provide production capacity since the models will have a complete set of necessary information from which to work with.

The information models are not complete and there is still a lot of work to fill in the gaps. If the existing models are not used and the standards groups are not encouraged and assisted by real-world examples and advanced technology, they will not make any progress. The eventual result will be a collection of siloed products that alone do not have adequate scope to move beyond a small set of customers.

6.9 Missing Standards and Gaps in Standardization

AP203 has been out for a long time and is well adopted, although the implementations still have some issues with repeatable import and export. It is available on most platforms and is often considered the best interchange format to use between

applications. It is now being superseded by AP242 that has many new capabilities and will be a large improvement over the core geometry provided in AP203.

There is at least a two to five-year lead time for applications to adopt and commercialize most standards. AP242 has been out for one and a half years and it is only now beginning to be implemented and Ed2 is scheduled to be released mid-2018. The implementations may not support the full model as well; this is yet to be seen. The existing CAD systems are not capable of accommodating all the PMI included in the 3D annotations that are required to provide complete product definition to all industries that are moving to model based designs. There does appear to be more effort being put in place to address the gaps in implementation.

For example, Autodesk AutoCAD 2017 can only import AP242, but cannot export and does not support any of the PMI data whereas Autodesk Inventor 2017 can Export full PMI, but can only import the graphic representation. Siemens PLM 9.0.3 has minimal AP242 import models. The rest of the matrix can be found at on the CAX Implementor[Sic] Forum. [45]

The scope of AP242 is very large and will require work to harmonize with other standards that it will need to interact with, such as the harmonization with B2MML with respect to the business object and process. AP242 has plans to cover the set of requirements necessary to design, engineer, and manufacture a part. It does not contain the machine instructions, like AP238, but will be able to interoperate.

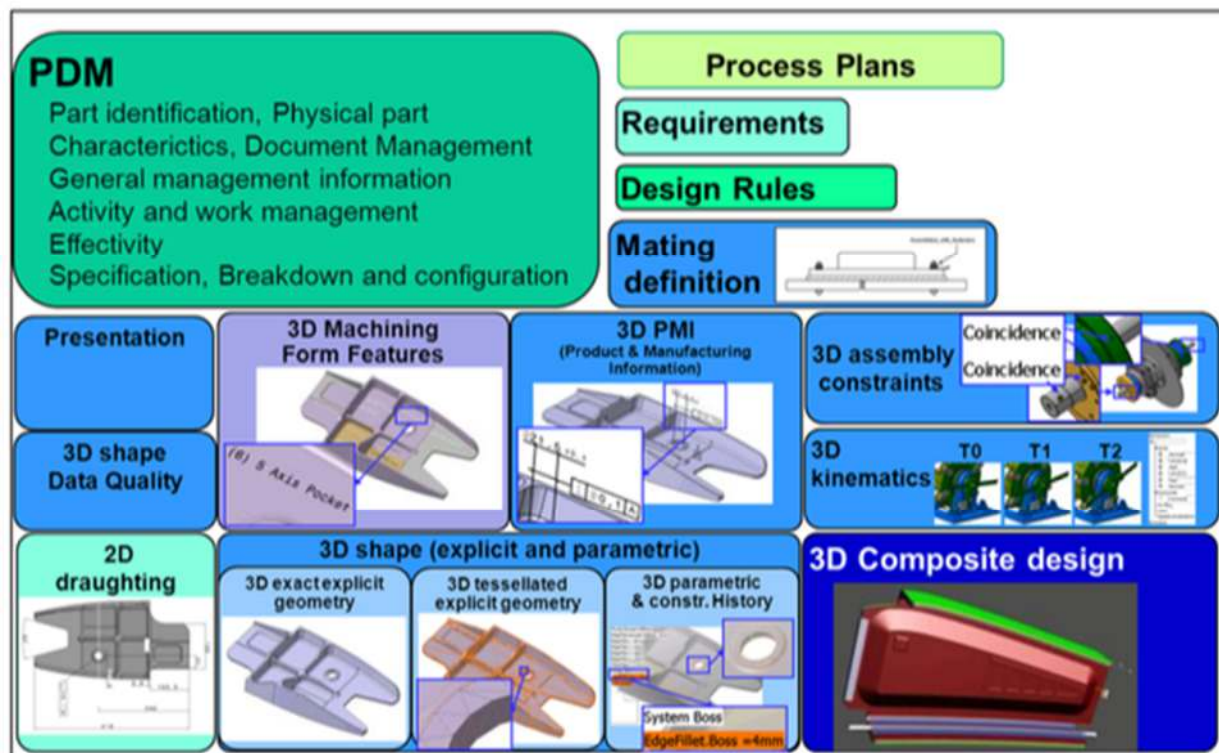


Figure 52: ISO 10303 standard STEP AP242 [46]

QIF has begun to get traction in the CMM world with two manufactures now supporting it in their products and AP238 has not been implemented beyond the lab. To fully transition to model based design and enterprise, the standards must be present.

The last area to consider is analytics from services like DMC. Analytical results are often the last to be standardized and when they are non-geometric results from engineering or execution processes, they often cannot be directly associated with the geometry of the design. This means another mechanism is required to associate the analytical results with a product model and allow the characteristics to associate with the processes and engineering choices, material properties, and other characteristics.

There is a general construct that is missing in most of the existing standards and is now being addressed in QIF and STEP-NC. That construct is UUID (universally unique identifiers). The UUID is of fundamental importance because it will allow for models to interoperate and connect by providing a singular reference that can then be referenced in an unambiguous manner. The other caveat to making this work is the models must have a similar concept of the object they are referencing.

The full complexity of the models has not been analyzed and it appears that the foundations for providing the complete product lifecycle have been identified and what remains is to implement and synthesize the models so they can interoperate. The good news is the standards are being developed and what is needed is a set of drivers and technology to move the industry away from paper and proprietary interchange formats.

In the next section, we will be recommending standards that are currently leading in the industry and suggest how proceed to help promulgate the standards in the most expedient manner. The outcome will be dependent on the ability of the industry to embrace a more innovative and agile manufacturing environment with distributed services acting as the platform to combine capabilities from experts in multiple fields, both in manufacturing and beyond.

7 Branded Standards and Service Architecture

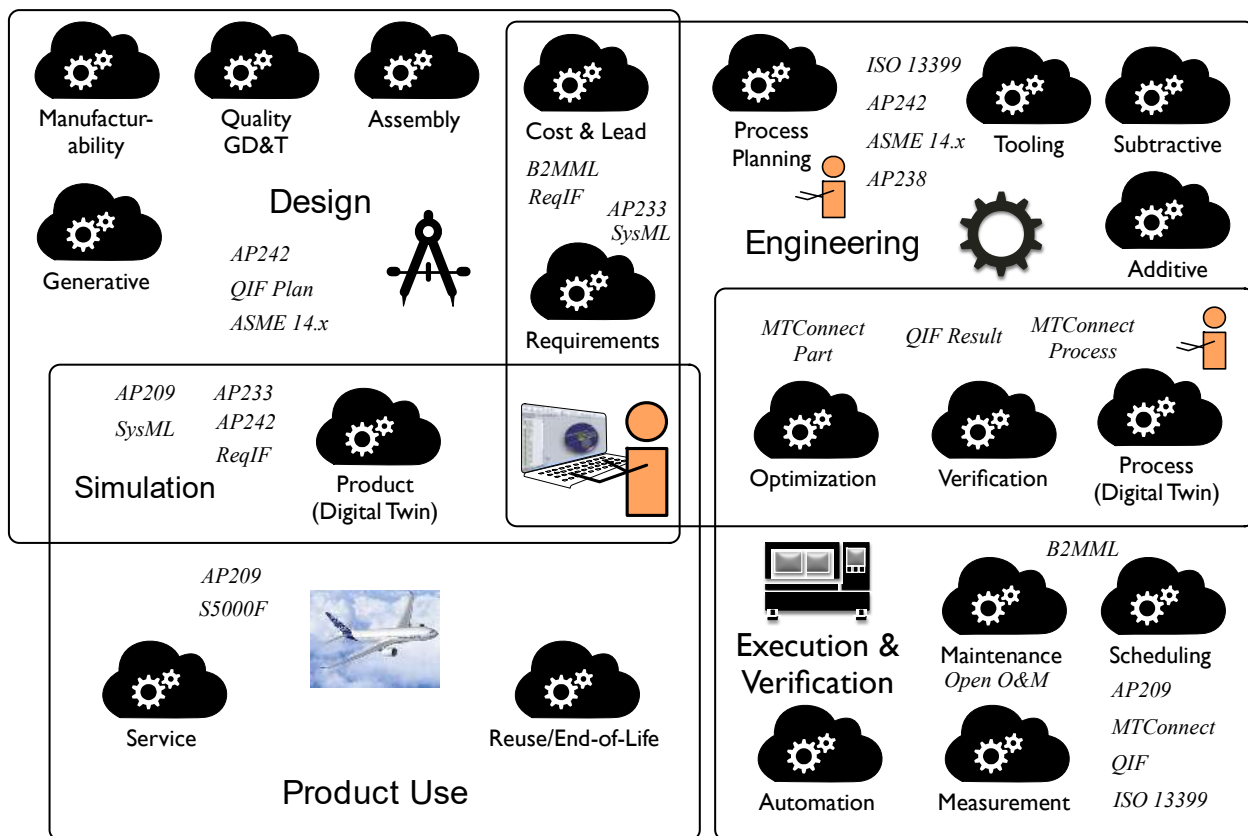


Figure 53: Standards by Domain

7.1 Branded Standards

The goal of developing a set of branded standards is not to create a new set of standards, but to specify a set of standards that have the best adoption, models, and support for the goals as outlined in this document. In the case of the DMDII AVM projects, it is the integration of the various programs that will enable a digital manufacturing eco-system for the manufacturing industry. The result is rapid growth and a sustainable outcome with respect to global competition.

When a suitable digital standard is not present, a new standard must be created. There are many areas that are not adequately addressed by exiting industrial standards. This is because they were not designed for a digital information model or they have never been developed. The first situation can be accommodated by providing a harmonization between the paper based standard using the existing vocabulary and symbology, such as the special marks used for measurements, that can

be translated into words. This is what QIF did when translating many of the features and characteristics in the ASME 14.X standards to XML.

The second situation will require new standards be created. This process will involve finding the current standards body that has the closest relevant domain and working with the organization to extend the standard to encompass the new capabilities. There is a variant to this approach where a new consortium is created that will address a specific area and then provide a compatible information model that can be used as an extension or as a separate associated document. The new standard must be open and must abide by the open characteristics referenced in section 1 of this document.

This document has addressed information models and semantic standards since there is adequate treatment of communications and security. We have reviewed the communications and inter-device communications briefly and will not expound on this area since it is not germane to the AVM projects. But, we have covered these topics briefly since they are still important to the creation of a composable integrated service architecture and for providing synergy between the various DMDII technologies.

One of the principle concerns that has not been addressed by the industry is identity and chain of trust. There has been work done in this area, but harmonization and integration into the existing suite of standards, such as STEP, QIF, and MTConnect, has only just begun and has not been addressed in a holistic manner. This area is being discussed within the scope of the joint working groups of PDES, QIF, and MTConnect, but will need to be coordinated across all concerns.

7.1.1 Design and Engineering Models

The most prevalent standards used in the AVM program are currently STEP and ASME 14.X standards. In the industry, STEP AP203 is most widely adopted of the various modules, where AP242 has moving forward in adoption by many CAD applications and will most likely replace AP203 in the near future. AP238 is still struggling for acceptance as is AP233. AP209 appears to have some level of adoption in the Composite Manufacturing space, but we could find little mention in other domains. ASME and ASTM are commonly used, but do not have representations that can be easily incorporated in digital models.

Within the AVM projects, STL was used in one project as was 3D PDF. STL is very popular in the 3D printing space, but is not capable of representing the feature based GD&T information that is required in precision and high value manufacturing. Other geometric representations like IGES should be viewed as legacy and would not be considered since they are not under active development. The issue with standards like STL is the lack of a feature abstraction in the model that can be referenced with an identifier to associate with other semantic models. This prevents the augmentation of

STL with other models to add additional capabilities that are required in the AVM projects.

Visualization standards like 3D PDF, VGML, and SVG would be discouraged since they are primarily display models and do not provide any capability to represent features and product information. Visualization is one representation of the information created by the service, but it cannot be used by any other services; it is a dead end. If the output of the service has any value beyond being viewed by a human, then a semantic information model is required.

MTConnect is used in Mind the GAP and would be suggested where feedback from execution is required along with QIF for quality and measurement. All the other projects are design, quality, engineering, and manufacturability related and do not require data from the process execution. OSU has plans to provide feedback from the assembly process. They should consider MTConnect as a possible way to collect the information and provide support to help extend MTConnect to include critical assembly performance metrics.

One standard that was not being used, but would be applicable to many of these projects is QIF since the tolerance information is required to improve inference. QIF is not currently being used in any of the projects, but the successor to Mind the GAP, the *DMDII 14-06: Digital Standards for the Advanced Manufacturing Enterprise "Operate, Orchestrate and Originate (O3)"* project is using QIF to feedback measurements from the manufacturing process before final inspection.

The recommendation is that the industry adopt the STEP standards, AP242, and AP238, and plan on migrating from AP203 to AP242 for interchange with semantic PMI. For measurement and quality, QIF should be adopted for representing measurement plans, results, and statistics. There are overlaps between the QIF geometric and feature models with STEP AP242 and those should be resolved and harmonized as soon as possible. For execution and shop floor data, MTConnect should be adopted and harmonized with AP242 and QIF to support process verification and feedback. The first step is a common identifier scheme that will span all the standards.

Standards that have been designed for paper documentation and annotation, like ASTM and ASME must be transformed into digital standards that can be harmonized with AP242 and QIF. The material and inspection requirements can either be added directly to the existing information models or can be added using an information model that can be delivered along with the geometric models using a harmonized identifier scheme to provide the feature level associations.

One area that has been common to these projects is the need for business level data driving cost and lead assessment to understand the manufacturability of a design. B2MML is the most complete standard in this space. It is an implementation of the ISA-95 standard, but has not been widely adopted by ERP systems. The standard has

the capability to represent most of the ERP information models necessary for resource management and accounting.

There has been criticism of ISA-95 regarding its ability to represent the models for the discrete and batch Manufacturing. Since its genesis was from the continuous process manufacturing, coming from ISA-88, it was extended to cover discrete, and some areas are not complete or sufficiently specific. B2MML should be considered and enhanced so that the barriers to utilization are removed and the business data can be represented and analyzed without having to use proprietary ERP software interfaces.

To address the areas of design and engineering requirements, the recommendation is to use AP209, SysML, AP233, and STEP AP239. It would also be advisable to harmonize ReqIF and STEP APs utilizing AP233 and SysML to describe the engineering requirements to drive simulation and design intent and AP239 for the remainder of the product lifecycle to disposal or reuse. AP242 is also planning on providing full product requirements, assembly, and kinematics. There was inadequate time to determine the roadmap for all the STEP standards and if AP242 will subsume, as it did with AP214, or integrate with the other parts of STEP, as is being done with AP238.

Regarding lifecycle, S5000F combined with AP239 completes the requirements for tracing maintenance and feedback of use to the end of life. AP239 does not seem to be adequate alone. It would be advisable to harmonize these efforts to provide maximum tracability within the ISO STEP standard framework to have a common foundation to reference components, features, and characteristics of the product.

7.1.2 Common Identifier Mechanism

One of the major challenges when connecting information models is the use of a common mechanism to identify a specific entity in the information model. There are two things that must occur for this to happen, the identifier composition and structure (formula) must be the same and the meaning of the thing they are referring to must be harmonized.

A common identifier scheme can be simplified if UUIDs (universal unique ids) are being applied to common components of the model. If a UUID is not used, then often an ID is created that is unique within a specific context. For example, a part with an ID XYZ123 with a feature that has an ID of 23 does not represent a universally unique way of referring to that feature of that part. If the feature had an ID 2b027bba-c0bc-11e6-975c-28cfe91a82ef, the feature could be referenced with respect to all other features in all other models.

The second aspect that must be harmonized is the meaning of the thing being referenced. This is complex if the levels of abstraction are not the same in the standards or one of the standards is designed for paper or 2D models. In this case, a

new information model will be required to bridge the standards and unify the meaning of the components.

Having unique identifiers is the principle mechanism to integrate information models. There are some examples that are currently being implemented. QIF and STEP AP238 Ed 2 are developing a common feature definition that can be referenced using the AP242 extensions in the STEP AP238 stage models. MTConnect, QIF, and AP238 will be working on a similar harmonization to allow for measurements to be communicated from machine tools to measurement and then to traceability software using a common UUID scheme.

The primary requirement of all standards used in this eco-system is that there is a common system that can be consistent across all the standards and all the services. This will allow for services to reference a feature in the design and have a consistent relationship to the quality constraints, the manufacturability of the feature, the materials, and the plan for making the feature.

The final aspect of common identifiers is the ability to compose the internal information model components into an identifier that can be reconstructed from the information in the model. Take the example of the part `XYZ123` and feature `23`. The UUID standard, RFC 4122 [29], specifies a methodology to compose a version 5 UUID that is made up of a namespace and unique then domain specific unique identifiers. The combination of the namespace and the IDs are then put into a secure hash scheme (SHA1) and the results turned into a hexadecimal string.

For example, if the feature ID has been created by a company “Example” using the namespace domain name `com.example` and name `part:XYZ123:feature:23`, the result would then be `1c0470ba-4307-5586-95d1-8fba6284e4e3`. The advantage to a version 5 UUID is the following: if we carry along the original context, the same exact UUID can be reconstructed from the given components of the model.

The resulting singular identifier can now be used as a shorthand for a complex set of context and internal identifiers, like a shortened URL that is supplied for a long web address. The result can be shared with all services, applications, and information models to reference a consistent identifier and allow the models to communicate additional information about an aspect of the digital design without having to carry the entire associated model. In some cases, the identifiers can be carried opaquely to provide context to an associated piece of data.

This is being done with MTConnect and QIF, where QIF has the knowledge of the meaning of the feature being measured and MTConnect only provides the identifier that allows QIF to correlate the results back to the original model. This can provide additional security and separation of responsibilities between semantic layers.

7.1.3 Chain of Trust

Chain of trust will be addressed using a Mutual Distributed Ledger (MDL) approach which is the generic name for blockchain, the same technique use in the crypto-currencies like Bitcoin. The advantage to this approach is the complete federation of the processes and the ability to have an agreement about the truth without a central system that coordinates and approves all transactions.

This will allow systems to operate independently on information models in collaboration where transformations will have a complete audit trail and provenance will be associated with the data using secure distributed identity management.

There are many areas in this domain that need to be extended and developed to make MDL fit for manufacturing and address the concerns for distributed manufacturing and services. Data rights also are a major concern of chain of trust and each system that is involved with any data concerning a user must be associated with the user and based on agreements. Derivations of the data must also have clear ownership and accountability associated with each of the transformations.

7.1.4 Gaps and New Standards Development

The engineer does not have a mechanism to communicate their execution intent to operators and personnel in charge with making the part. These gaps in the manufacturing process lead to many iterations between design, engineering, execution, and quality to create processes that produce parts that meet the original requirements. When these requirements are communicated, they are often annotations on drawings or work instructions that can be understood by a professional, but have no computational relevance.

Assembly instructions is another area that do not have information models that can be reasoned on by computation systems to determine if a product can be assembled and if the methods use in connecting the parts will be effective and the ramifications on the manufacturing process used to create and measure the parts. Often this is encoded in the GD&T as geometric constraints, but does not get provide the underlying rational and therefore cannot be optimized to remove unnecessary complexity.

ASME and ASTM standards have a very rich vocabulary for specifying constraints and requirements, but they were developed before digital standards existed. There are projects currently underway in the STEP community to add ASME, ISO, and SAE semantic representations to the AP242 Edition 2 standard to provide many of these characteristics. For this reason, the work on AP242 needs to be supported and will most likely be the best fit for the interchange formats required by these services.

To provide computational services, the information around the product requirements, the designer, manufacturing, and inspection engineer's intent need to be understood in a digital form that can be utilized by analytical systems to make decisions. The standardization is underway, but the formal processes often take longer than the technology innovation cycles will allow and proprietary solutions emerged that are not open because the market demand will not wait. Once this occurs, the opportunity to create non-proprietary solutions is lost.

To efficiently fill these gaps, the existing standards and technology surrounding the standards needs to be made available quickly. This may require developing adjacent open specifications and reference implementations that can be subsumed by the standards as they become tested in the industry. This approach needs to be explored to make sure the standards can be promulgated.

7.2 The Semantic Standard Dilemma

Kurt Cagle, one of the leaders of the semantic web movement, wrote in an article on LinkedIn, "*Why the Semantic Web Has Failed*" [47], that the semantic web has failed. The idea behind the semantic web was that web content would not be display oriented, but would be composed of semantic meaning that would be rendered for visualization but could also be reasoned on by machines. For example, an address would not be a `<div/>` with a few formatting rules that would make it look like an address with a street number, street, city, state, and zip code, that could only be interpreted as an address if the software could guess correctly.

In the semantic web, an address would be called out explicitly as an `<Address/>` with a `<Street/>`, `<City/>`, `<State/>`, and `<ZipCode/>`; where each element would unambiguously describe the meaning of the content, with open standardized microformats (μF). The search engines would no longer need to guess the meaning of the content and the information of the web could be aggregated to increase knowledge.

For the most part, this concept is dead. The Semantic web was a very popular topic in the early to mid 2000's, but never caught on. The reasons Kurt Cagle gives are as follows:

- Semantics is hard to understand.
- Semantics is invisible to most people.
- Semantics is difficult to open and read.
- Semantics does not fit into the dominant Algol/C++/Java OOP paradigm.
- Semantics is hard to add manually to content.

Even though the benefits are as follows:

- Semantics can connect things within an organization.
- Semantics can make it possible to query across multiple entities.
- Semantics can significantly enhance search and NLP.
- Semantics can contain subclassing to simplify notation.
- Semantics can be added to documents and data stores dynamically.
- Semantics provide powerful constraint queries.

This relates to the manufacturing semantic standards and the slow adoption of standards like ISO 10303 (STEP) that offer obvious benefit. The primary issue is that semantics are hard to understand and hard to implement.

Semantic standards, like STEP, MTConnect, and QIF have had thousands of person-years of work by large numbers of participants and are offer much more capabilities than are currently being used. The question remains, why are semantics difficult to adopt and how does manufacturing not fail like the semantic web? And secondly, are there some changes to the existing standards that may increase adoption?

The answer is a focus on the follow two areas: (1) make the standards accessible by having clear delineation of responsibilities between the standards, and (2) provide open source tools to interact with the models so they can be incorporated into new technology with a smaller learning curve and open APIs to interact with the models.

7.3 Low Cost/Open Source Tools for Manufacturing

There needs to be focused effort on extending and building software libraries that provide key geometric kernel capabilities and support the full manufacturing models that are required for supporting the capabilities of the AVM projects. Currently there is FreeCAD, which is an open source toolkit for parametric modeling and has basic support for AP203 but no PMI (AP214) and does not support colors or assemblies.

There are about another 21 open source projects, most of them only handle STL and tessellated models and none support any of the PMI or any of the concerns that are required for the AVM projects like assembly and GD&T. The lack of support for STEP in the open source community, which is servicing the 3D printing maker community and the hobbyist as well as game developers, is not motivated to support more industrial manufacturers.

There are services based alternatives that may provide the capabilities necessary for industrial manufacturing in the same way geographic mapping services have been provided as imbeddable service based offerings from Google and Microsoft. The service based graphics kernel would need to provide a robust and performant query model and support digital rights and IP protections necessary to meet the security needs of the industry. OnShape and CAD.ai are examples of these services that may suffice as well as some of the latest offerings from Autodesk.

The offerings can also be low cost redistributable libraries like Unity, Turbulenz, or MonoGame for the 3D gaming industry that offer either full open source or low cost licensing of kernels that allow companies to develop applications that are cross platform and high performance using higher level primitives and physics models. If we use consider manufacturing as a similar marketplace with open source or API support, the emergence of new technologies can be greatly accelerated by the availability of open and low cost technologies that will build revenue and market share by increasing the size of the developer and consumer marketplace.

7.4 Innovation and Business Drivers

EXHIBIT 5: Increased revenue and customer satisfaction as biggest benefits of Industrial Analytics

Question: *What are the biggest benefits of Industrial Data Analytics for your company?**



*The survey specifically asked for the top three benefits. The ranking was generated by giving points – three points for first biggest, two points for second biggest and one point for third biggest benefit – The percentage is based on the overall number of points.

In the Industrial Analytics report, the survey revealed that most businesses were looking for capabilities to increase their revenue and customer satisfaction more than cut costs [48].

The current technology stack for manufacturing execution has been static using the same five layers to represent the execution of manufacturing processes. The layers are as follows: ERP, MES, SCADA, PLC, and I/O, from top to bottom. There are many other services that will need to be used and the existing application areas will need to be exploded to their constituent concerns.

Each of the concerns can be architected as a microservice, such as scheduling and resource planning, and then provided as composable units depending on the needs of

the system. Manufacturing must transition from monolithic systems to smaller components if it wishes to take advantage of the best practices and most advanced aspects of software systems architecture and productivity.

7.4.1 Manufacturing as a Service

In the same reference, the discussion of the next generation of technology transformation will be on demand manufacturing as a service:

“Forward thinking manufacturers are considering new ways to use capacity that does not necessarily belong to them. Consider how Uber and Airbnb create value by using assets that they do not possess. The same movement may take over the manufacturing industry as it seeks to advance agility in product development and market testing.

As an example, FirstBuild, a partnership between GE and Localmotors, is a micro factory that crowd sources and manufactures automobiles. GE and Localmotors use this concept to design, build prototypes and test the market for new products. If the products prove to be attractive to the market, they will find their way to GE manufacturing sites for mass production.

Dassault MySolidWorks is another example. It is a virtual online community of companies that specialize in CNC Milling, injection molding, 3D Printing and sheet metal manufacturing. This platform gives clients the opportunity to use Dassault’s software not only to create designs but also to put users in contact with manufacturers who then reply to a bid in hours. Protolabs, Dassault’s partner for this project, is now able to generate thousands of quotes per day for its clients - thanks to the online community.

The manufacturing-as-a-service trend requires perfect visibility into the how of product and data in order to take momentum and is therefore highly reliant on IoT Data and the corresponding analytics.” [48]

There are many new entrants into this space as well, MakeTime, Xometry, Protolabs, and Plethora all have capacity on demand. Plethora and Xometry provide solid model analysis for cost and manufacturability with different value propositions on how the information is communicated. Xometry does this with a SolidWorks plugin to upload the geometric data. These new offerings are not using standards and this is a missed opportunity to use standardized information models, like AP242, for these new services to help drive standards adoption.

7.5 Federated Architecture

Manufacturing as a Service will be created by numerous related capabilities that will be provided by various companies, universities, and labs that will be able to provide

their unique talents to solving complex design and engineering problems. The industry cannot wait for a large company or government to solve all these problems. This has been the approach for the past decades and it has not yielded significant results.

The tech industry found that innovation comes on the edges by small companies and it is then incorporated into the offerings of larger companies. Some companies get absorbed, and some continue independently. The industry progresses because of high energy risk takers that thrive in small independent organizations. As the industry matures, we will see consolidation, but there will always be the next step and the next innovation that cause the industry to rethink their approach.

The ability to loosely couple services and use open standards will build the most fertile eco-system for innovation at every scale and will allow for small companies to interoperate with larger companies and will facilitate incorporating those innovations into larger offerings with less effort.

Well-structured systems architecture has a minimum amount of coupling between components with narrow interfaces that are well defined and that adhere to documented contracts. Standards provide the contracts that allow for unfettered information with a minimum of coupling since neither party can change the standard without a public process. This eliminates the need to chase proprietary formats and APIs, even when a company is starting out and does not have the relationships to get adequate support.

7.5.1 Services

In this document, we have referred to the technologies as services and not applications. This is intentionally to move the thinking away from a set of applications that are stand-alone functionality to a set of interconnected technologies that can provide a combined capability that is much more valuable than any service individually. This is what is being done with technologies that are providing advance computational capabilities in other analytically oriented domains.

Examples of these technologies are companies like alteryx that are working with incoming data from salesforce, Oracle, Hadoop, or excel and then uploaded the microservice to run the analytics on demand and then visualize and explore in tableau, excel, and pdf.

Services allow technology providers to provide advanced products where they can share and apportion resources in an on-demand basis allowing them to provide advanced solutions without having to increase pricing. The efficiencies of scale will provide the same capabilities to a two-person shop as a 10,000-person enterprise since the service provider can create a right-sized slice for each customer and share cloud based computational resources.

This has been happening in many other industries, examples of these technologies are Splunk, Bitstew, Google, Microsoft, Teradata, etc.... There are numerous service providers across the spectrum of services. IT and Platform as a Service provider like AWS and Microsoft Azure are dominating the hosting market and creating unmatched capabilities for data and analytics.

7.5.2 Composability

To enable interoperation of services, they will need to be composable; this requires that the outputs from one service can be utilized by another service to provide additional value. All the services can operate independently without more context than the information provided to them. They can operate on the information models, transforming the information and provide transactional audit trail regarding the contributions, and produce results that can be associated with the original models.

All services will not be required for all manufacturing processes. Composable micro-service architecture allows for the orchestration of only the required services necessary to reach a result. From a cost and value model, the necessary services and processes can be utilized and an optimal solution can be determined using historical information combined with design and engineering intent.

Moving to a federated composable architecture will not happen quickly, but the transition has been very effective in other industries and it is a natural evolution of information systems. Manufacturing is a complex industry with complex models, so the first step is to enable the existing systems with standards based information models that can be communicated without loss of information and misinterpretation. The next phase will be to continue the transition to service architecture as we already see in the industry with Autodesk and Dassault.

7.6 Building the Eco-System

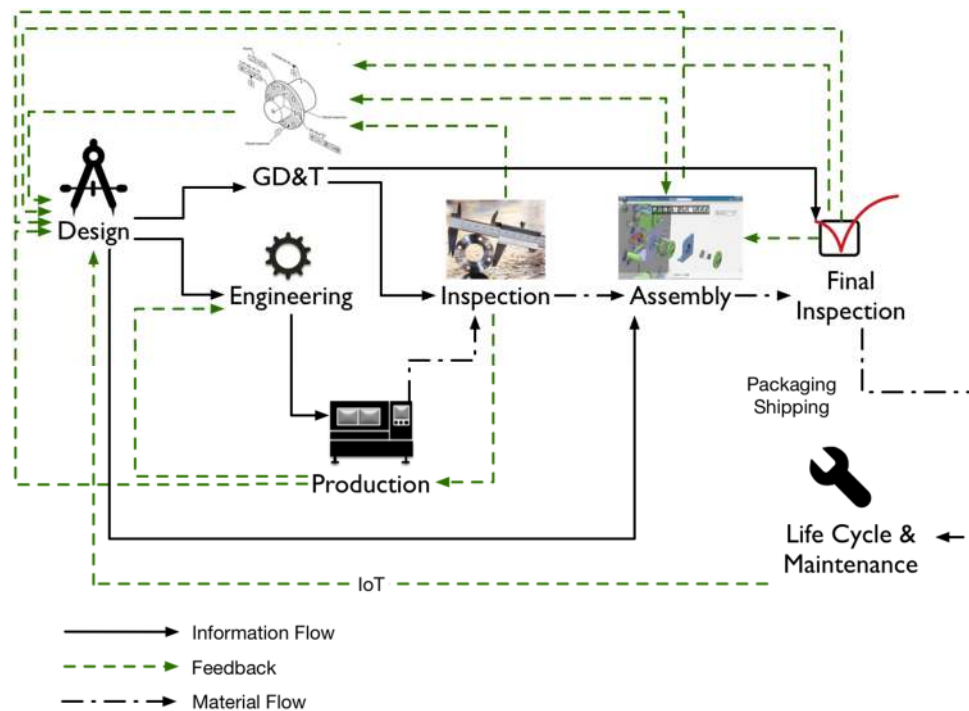


Figure 54: Design Information Workflow

The following discussion is a high-level view of the emerging ecosystem that can be created with a new generation of composable services that interoperate. The services will be a combination of curated and autonomous applications that will provide secure interfaces in a loosely coupled architecture. There may be a central orchestrator, but it is not a requirement. In this discussion, the example is without central orchestration.

Even though it is not centrally orchestrated, the services will be viewed as a cohesive collection of services. If one had to pick a central axis, it would be around the digital twin for the product lifecycle that will be integrating all models and design decisions and providing a simulation model with geometry, kinematics, and product maintenance and service characteristics.

There will be a similar capability in the engineering and manufacturing process phase with a process twin providing a complete simulation of the manufacturing flows given each process and the required capabilities of the manufacturing equipment. Applying standardization of machine tool precision and verification information models along with reduction in variance in geometric precision should enable developing predictive models around particular machines based on empirical and testing results. [49]

A conceptual model for a new product is created with information about the business requirements that will govern its functionality and form. The specifications will be created using a design tool that will interact with services that provide feedback for the conceptual model and concept design. Given the specifications, an initial model can be created by sending the specifications and form guidelines in AP233 and SysML for geometries to a service that can provide a generative structure in AP242 that can then be modified while constraining the physics and lifecycle requirements.

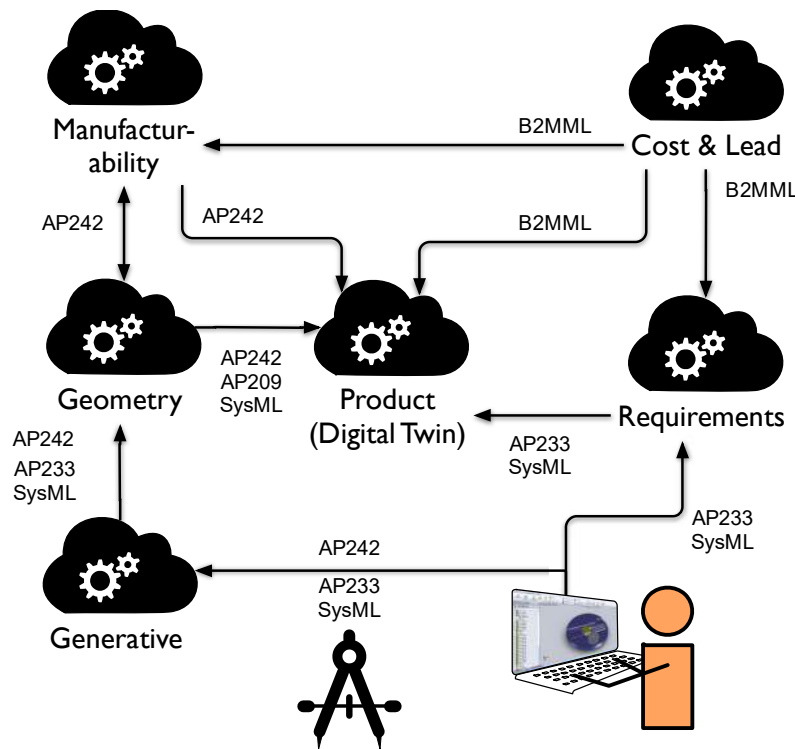


Figure 55: Interconnection of Design Services

Combining the manufacturing budget, cost, and lead information into B2MML or AP242 Business Objects as a set of constraints, the AP242 model combined with the AP233 and SysML models will be evaluated for manufacturability by services that will look at the design constraints to determine if the parts of the assembly can be manufactured given the business requirements using various manufacturing processes. The process is curated by experts in materials and manufacturing process to provide feedback as to how to optimize the design.

The designs will be secured with attributable digital rights as they are communicated to each service and each resulting modification or addition to the AP242 models will be annotated with a transaction record in the block chain that will provide traceability for each of the set of additions and modifications of the models and the requirements. Complete accountability and traceability of the models is key to having a functional service based architecture.

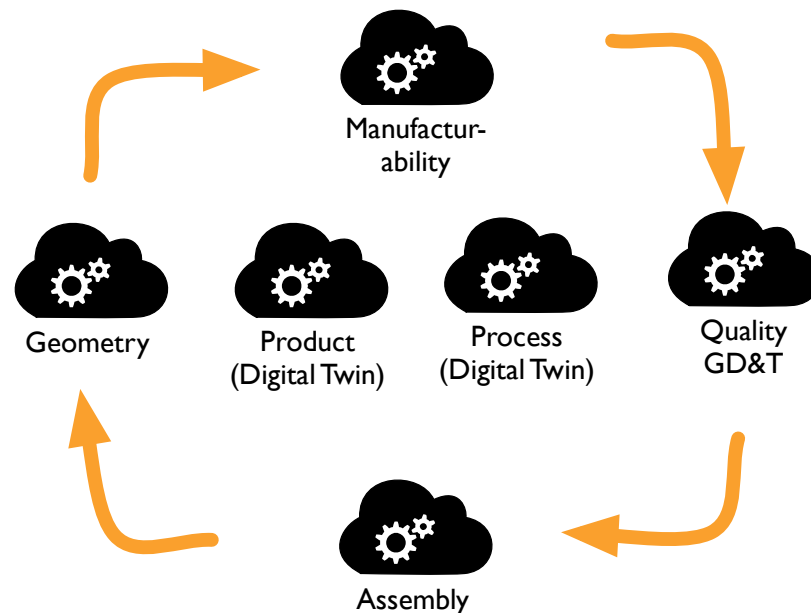


Figure 56: Continuous Optimization Loop

The AP242 models as well as the AP233 and SysML models will cycle between design, manufacturability, tolerancing, and assembly services to provide continuous feedback and optimization of the product and its parts while maintaining budget and delivery constraints. ASME 14.x standards will be utilized to provide the core set of common manufacturing requirements.

A process digital twin will evaluate the AP242 models using AP209 and the system engineering specifications to determine the necessary engineering requirements for manufacturing and verification. The process twin will provide multiple solutions and possible optimizations to achieve the end results.

As the product design becomes finalized, the engineering plans for each component of the product will be created. Since the manufacturing equipment is not known upfront, the manufacturing processes will be created on-demand in AP238 with key tolerances for each manufacturing stage model provided. AP238 will harmonize the tolerances and geometric PMI with QIF Results to provide feedback to the manufacturing process as it executes.

The execution and scheduling service will utilize MTConnect manufacturing and device information to allow the scheduling system to find an optimal set of resources to manufacture the parts. The scheduler will consider the requirements for each part as well as material availability, location and transportation, and capabilities of manufacturing equipment and personnel to determine the optimal solution with complete accountability since all processes will provide continuous feedback. The

scheduler can move processes in real-time if the chosen path has unexpected results or is failing to deliver.

All possibility manufacturing processes will be considered as well as raw material in near net or standard stock sizes using forging or additive processes. Simple versus complex machine tool production processes will evaluate lot size and engineering complexity to determine optimal strategies. On demand allows for a complex supply chain to be formed given that the capabilities and outcomes are consistent enough and cost effective.

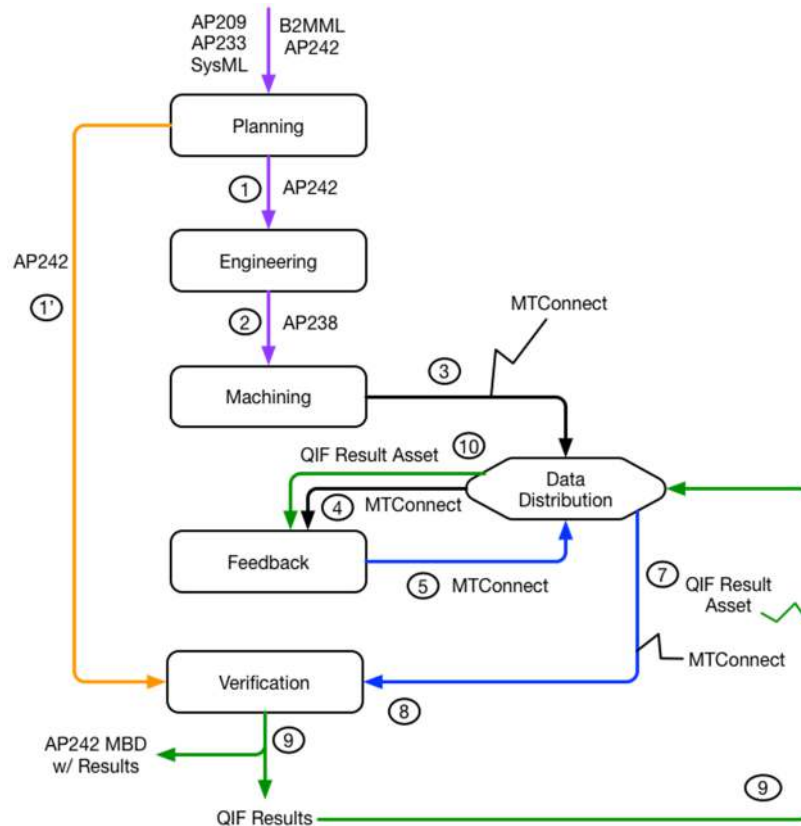


Figure 57: Execution Information Flow

Execution services will utilize standards like B2MML, MTConnect, OSA-CBM, and AP238 to determine the best way to manufacture a part. For a single product, a single execution service can be utilized or multiple depending on the specialization of the services. A single model can be broken down into constituents and sent to multiple services where the services can coordinate the processes and dependencies for final assembly.

The results as well as the execution progress will be collected and analyzed on a continuous process to project delivery times and to prescriptively identify any issues before they occur. The QIF Results as well as all the process parameters and actual

process data will be communicated using MTConnect for visibility and real time analysis to verify the process is being executed as prescribed. Any deviation will have required additional verification of the parts begin produced.

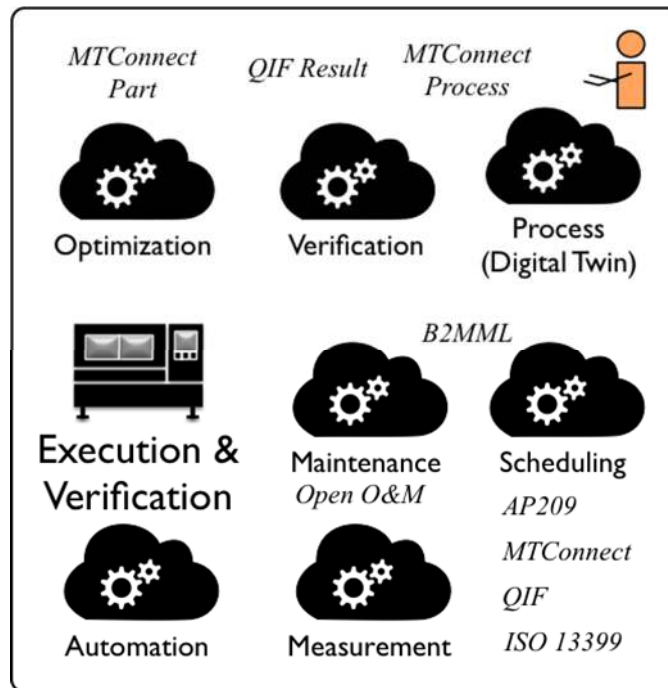


Figure 58: Process Services

When the parts reach assembly, the assembly instructions that were automatically created during the design process and communicated as part of AP242 (or another to-be-developed standard). Feedback from the assembly process will be collected in real time using MTConnect and the actions and non-optimal process will be corrected as the parts are connected. The assembly system will learn from the execution of the assembly steps to improve future processes.

What was provided was a limited example of a federated set of manufacturing services. This is not complete or final and the final implementation may look very different. The dynamic refinement of the models and continuous improvement will allow the services to build upon expertise of the service providers and the curators of these services as well as creating an increase in automation and productivity. The service and on-demand technologies are predicated on having fully defined semantic information models since each system will need to have a complete understanding of the product without having to ask the origination system for additional data.

This will require a complete set of information models that can interoperate, share identity schemes down to the individual features and characteristics of the parts. Many of these models are being developed. There are a lot of details that will need to be provided for this to work. The completion of the AP242 and harmonizing it with the

other STEP models as well as QIF, MTConnect, B2MML, and SysML will get us a long way towards the goal of on-demand autonomous manufacturing.

8 Appendix A: Excerpt from “The ASME Y14 Policies”

8.1 Data applicable to more than one drawing type shall be added to the applicable basic Y14 standard

The following are basic Y14 standards:

- ASME Y14.1- Drawing Sheet Size and Format
- ASME Y14.1M- Metric Sheet Size and Format
- ASME Y14.100- Engineering Drawing and Practices
- ASME Y14.2- Line Conventions and Lettering
- ASME Y14.3- Orthographic and Pictorial Views
- ASME Y14.4- Pictorial Drawings
- ASME Y14.5- Dimensioning and Tolerancing
- ASME Y14.24- Types and Applications of Engineering Drawings
- ASME Y14.34- Associated Lists
- ASME Y14.35- Drawing Revisions of Engineering Drawings and Associated Documents
- ASME Y14.38- Abbreviations and Acronyms on Drawings and Related Documents
- ASME Y14.41- Digital Product Definition Drawing Practices

8.2 Data applicable to a specialty standard or specialty type drawing shall be added to the applicable specialty Y14 standard

The following are Y14 specialty standards:

- ASME Y14.6- Screw Threads
- ASME Y14.7- Gears and Splines
- ASME Y14.8- Casting and Forgings
- ASME Y14.13- Springs
- ASME Y14.18- Drawings for Optical Parts
- ASME Y14.31- Undimensioned Drawings
- ASME Y14.32- Ground Vehicle Drawing Practices
- ASME Y14.36- Surface Texture Symbols
- ASME Y14.37- Composite Part Drawings
- ASME Y14.40- Graphic Symbols
- ASME Y14.43- Dimensioning and Tolerancing Principles for Gages and Fixtures
- ASME Y14.44- Reference Designations

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