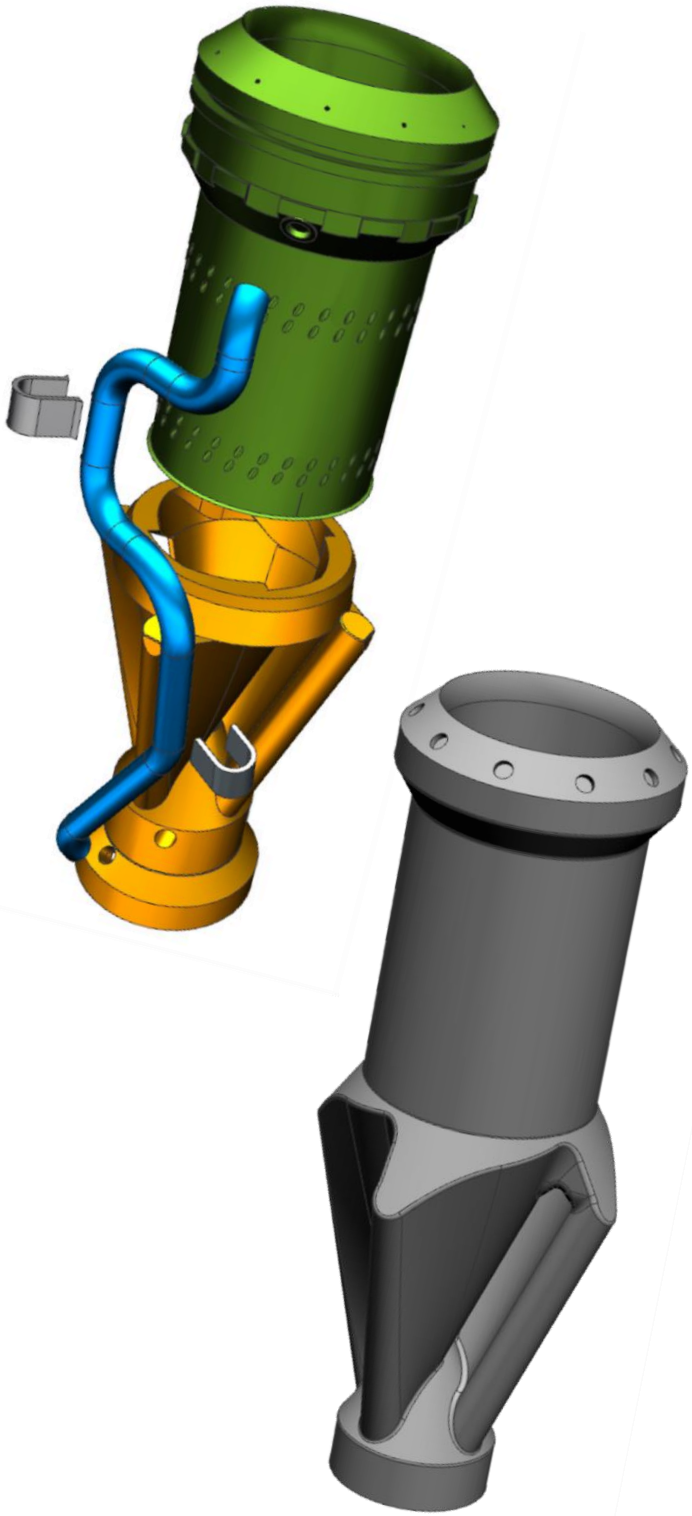

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CIMdata eBook

Sponsored by Siemens PLM Software

Industrializing Additive Manufacturing

How to fully leverage Additive Manufacturing from one-off prototypes to production end use parts

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AM Hype Cycle; Nature Meets Science

Additive Manufacturing (AM) was limited to making prototypes, one offs, and your favorite Disney character; now it is time to put AM into production

Media hype

Media attention on 3D Printing fueled peoples' imaginations, investors speculated that AM would be the next big thing, and technology companies tried to deliver. Stock prices surged then sunk as the reality of AM adoption failed to meet expectations.

Novelty to industrialization

Hobbyists and early adopters used AM machines to make freeform organic shapes they couldn't make before. Now, driven by investments by industrial companies seeking to improve engineering processes and make better products, attempts are being made to use AM for industrial end-use products. Big challenges remain such as materials, regulatory compliance, speed, and reliability.

What can we learn from nature?

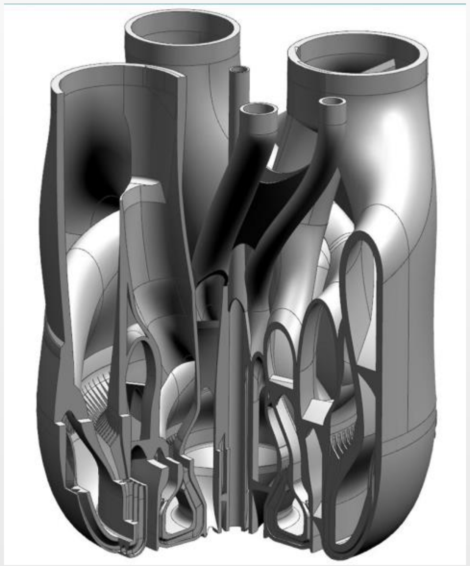
There's also hype about copying nature; humans created biomimicry to emulate nature's time proven design methods. But mostly man copies *outcomes* of nature's design rather than emulating nature's design *process*. In engineering terms its about functional design not shape.

- **Nature:** Integrated System and Structure; multiple materials yet all a single structure.
- **Science:** Separate Systems and Structure; individual components assembled to be, or attach to, the structure.

The AM industrialization journey

A plan is essential. Don't just buy a machine then start making AM parts. A carefully thought out plan is essential. Some plan elements are:

- **SMART Goals:** Specific, Measurable, Achievable, Relevant and Timebound.
- **ROI:** Find ROI in new and existing designs, complexity reduction, product optimization, maintenance, and more.
- **Education:** Talent, skills of CAD engineers, machine operators, financial, operations.
- **Organizational:** Roles, policies, processes, span of control.
- **Machine:** Decide whether to Try, using an expert service provider, or Buy for trials or prototypes.



Images courtesy of Siemens PLM Software

Design for Additive Manufacturing (DfAM)

AM helps us make complex organic shapes we couldn't make any other way—the shape, is an *outcome* of the AM design process, not the objective

DfAM, a new way to think

Design for Additive Manufacture (DfAM) is a new approach to how we imagine designs from the very beginning. Traditional designs are constrained by what we can manufacture, the material used, and things like cost and time. Creativity of the designer is often compromised due to these constraints. AM releases designers from many of these traditional constraints, but the approach to design must change.

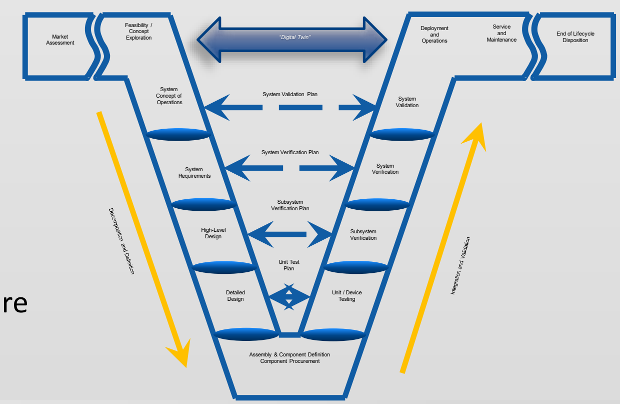
DfAM methodology

1. Vee-Model
2. Functional Design
3. Generative Design
4. Topology Optimization
5. Lightweighting
6. Simulation
7. Validation: Print, Inspect
8. Iterate
9. Final industrial quality part

Model-Based Systems Engineering

There is low or no cost penalty for geometric complexity when using AM. What this means is AM manufactured components can have very complex organic-like forms yet cost the same as a much simpler shape. This means engineers need to change from defining the shape features and focus upon the desired ***function*** instead.

- **Vee-model.** An AM specific Vee-Model is a good tool for overall AM product development. It helps graphically depict all stages from requirements gathering to final product manufacture. It also shows milestones, and verification loops back to design.
- **Functional design.** Definition of a design by its function, rather than shape or number of components, method of assembly, or shape.
- **Generative design.** An algorithmic definition of the design. This requires criteria to be defined then used as input into a generative design software tool to create topology output. Results become the starting point from which final geometry is derived. Unnecessary design features such as draft angles, blend filets, excessive material, and prismatic bodies are eliminated; replaced by organic forms.
- **Topology optimization.** A Topology optimization (TopOpt) tool is used to *refine* the geometry further, to optimize the form to be the most efficient in according to some set of criteria compared to one that meets only functional parameters. This often results in very organic shapes that an engineer wouldn't conceive.



Design for Additive Manufacturing (DfAM)

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DfAM, a new way to think *Continued…*

Design for Additive Manufacture (DfAM) is a new approach to how we imagine and make designs.

- **Lightweighting.** Latticing or light weighting uses a TopOpt tool. The process reduces weight while maintaining set weight, strength, spatial parameters, etc. A honeycomb-like structure is created inside the item. Biasing of the lattice is possible, e.g., a high density structure in high load areas, low density, or hollow, in low load areas.
- **Refine.** Single AM components usually mate with adjacent components. Designers use advanced 3D CAD functionality to add fixturing devices, machined surfaces, and other adjacent geometry.
- **Simulate.** Simulation helps check the design for its functional performance under load, material choices, thermal conditions, as well as things particular to the AM process including slicing, hatching pattern, stripe overlap, and build-tray conditions to verify thermal effects, part touch, warpage, etc.
- **Validate.** Unlike traditional manufacturing, 3D printing or manufacturing is relatively easy, therefore validation of designs may be done quickly and inexpensively to validate results against digital simulations. Validation is conducted throughout the DfAM process to ensure results meet quality metrics, cost, and time estimates. Collecting all results and feeding them back into design using a closed loop process is key.
- **Prepare for printing.** Before final production printing, parameters such as orientation, support structures, machine slicing, hatching pattern and distance, stripe distance and overlap, all must be planned. Experience with AM machine settings and behavior is essential.
- **Postprocess and inspection.** Following production, the component may need to be postprocessed. This involves controlled cooling, support removal, surface finishing, etc.
- **Iterate.** The Vee-Model helps manage the end-to-end process including milestone reviews, final quality readiness, and to connect the physical to the digital components; connecting the Digital Thread.

DfAM methodology

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AM Use Cases

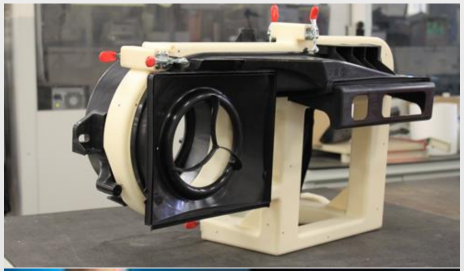
Viable use cases for Additive Manufacturing are numerous; vanity apparel, lifesaving devices, lowering factory worker fatigue; industrial costs are a few

Individualization
Often consumers are individuals yet must buy mass produced products that only approximately fit. People might want a unique wearable to amplify their persona, or a better fitting shoe or racing helmet. In Industrial cases a unique product can improve quality of life, or save one, enhance human performance, and reduce fatigue. Advances in AM now makes it practical to achieve production runs of 1, and to meet unique needs of individuals whether for consumer or industrial cases.

Manufacturing evolution
Industrial jigs and fixtures, locating templates, and product packaging, are examples where manufacturing equipment must fit exactly to a component. AM makes this easier by being able to manufacture geometry directly from the source design without expensive human tasks or tooling, and achieve a better fitting outcome.
For example, production dies or molds may be made directly from their defining digital geometry. Changes to source geometry may be rapidly propagated to produce another die or mold.
AM can improve hand held tools. In factories, humans often spend all day carrying tools to do their work. To the extent tools are lighter, fit better, and are better adapted to their bodies, life quality of workers will be improved.

Performance optimization
Ergonomics: AM design tools can model shapes exactly contoured to worker's hands, arms, and body, and uniquely personalized to a single person.
Weight reduction: Topology optimization is used to reduce weight, improve strength, and reduce material. AM can print lightweight polymer and other materials and print shapes that minimize material use.
Efficiency: High temperature burners need to be cooled. AM helps make them compact with cooling ducts that can't be otherwise manufactured, providing better performance, and fewer parts.

Complexity reduction
Multi-part assemblies can be consolidated into single structures with no need for assembling parts like bolts, nuts, washers or gaskets. This relegates a multi-part assembly to become essentially a single component, making it much cheaper to manufacture and maintain throughout its lifecycle.



Images courtesy of Siemens PLM

AM Data is at Risk

The highest incidents of cyberattacks is not in the finance or defense industries, it's in manufacturing*—protect your digital engineering data or risk losing it

Digital thread

AM digital files describe topology, material, texture, color, and a "print ticket" for a target AM production machine. The final AM part may have embedded IIoT devices and collect real-time performance data such as device traverse cycles, wear, temperature, etc. The digital thread allows these data to be connected directly to the master digital design and manufacturing records, allowing replacement parts to be made and ready prior to a component failure. This shows the power of the digital thread.

Cyber attacks

People worry about identity theft and with so many incidents each year of large businesses suffering cyber attacks, it's no wonder. But people don't worry about counterfeit parts finding their way into flying commercial aircraft or automobiles because they assume strict regulatory supervision governs quality standards. An AM file, if stolen, could be proliferated to multiple recipients in different locations and countries, and used over and over. There is high risk, that if stolen, these could be used to make counterfeit parts that could enter the supply chain undetected, resulting in high risk of whole product failure.

Security

Despite the high risk to AM assets being stolen, few companies are taking adequate precautions; often using regular MS Windows security to manage their data. To protect AM digital assets, to enforce standards such as quality and manufacturing intent, and ensure traceability, systems and standards are emerging to support the digital manufacturing trend.

- **Blockchain.** Blockchain uses cryptographic hash functions to verify authenticity of data between the sender and receiver, and is an emerging standard.
- **Commercial solutions.** The company Identify 3D offers a 3-stage workflow: Protect, Manage, and Enforce to manage the end-to-end AM lifecycle including user authenticity, target AM machine, and material selected.

*Reference Dept of Homeland Security, 2015

Unrealized Potential

Additive Manufacturing will not reach its full potential without the industrialization of the entire end-to-end process

The challenges of industrializing AM

Missed opportunity

Missed opportunities for AM exist throughout most companies. Too often AM is restricted to very complex and expensive to manufacture components and is treated only as a new type of machining. Comparing an AM machine to an injection molding machine yields a comparatively weak ROI compared to defining a new end-to-end ROI spanning Design through Manufacturing and maintenance, and comparing this to a traditional end-to-end process. Strong ROI metrics may surface from an holistic review of design, manufacturing, maintenance, and logistics processes.

Imagination

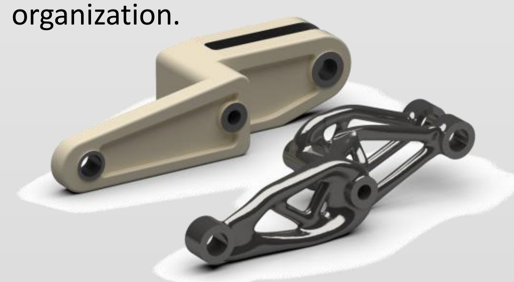
Engineers are trained to approach design in traditional ways; components get assembled then housed in a container which is held together by fixturing devices such as screws. Ultimately designs reflect traditional manufacturing constraints. DfAM presents new opportunities beyond making the same thing a different way. Younger engineers, or even non-engineers, often grasp DfAM concepts more easily than more experienced engineers due to being familiar with video games such as Minecraft, which offer a non-analytical approach to creation of structures in 3D space.

Bin of broken dreams

Often the first few items made are perfect, but the next one fails, and it's not clear why. This creates scrap, lost time, and extra cost. End-to-end process planning is essential to improve quality metrics and to accumulate corporate IP. Process plans must encompass component design, simulation, 3D build tray nesting, material performance, postprocessing, machine settings, and environmental management, e.g., temperature, humidity, and air quality control. Only by employing this level of planning can a repeatable process be created.

Organization

Organizations are made up of departments which grew up to reflect traditional manufacturing processes. These departments, while structured to efficiently support traditional manufacturing, may be impediments in the AM era. AM enables the digital thread because the geometry, material recipe and process are all digital, unlike traditional manufacturing with "hand offs", a seamless closed-loop, all digital thread is possible with AM. Organizations must enable people to take advantage of the digital thread; to function with seamless interaction between all departments. Span of control, milestones, and change control must be examined in context of a new borderless virtual organization.



Images courtesy of Siemens PLM

Take Control of AM Data

Unsecured engineering data risks being lost, duplicated, changed, or accessed and shared by unauthorized people; its essential to control all engineering data

What is AM data?

AM digital files are different from traditional manufacturing files. A modern AM format such as 3MF (3D Manufacturing Format) possesses topology, material, texture, color, and a "print ticket" specific for the target AM production machine. This comprehensive file enables any recipient to make AM finished parts, needing only an AM machine, material, and an operator. Its essential not to enable an unauthorized recipient for example a factory knowledge worker, a commercial competitor, or an enemy country to have access to the AM manufacturing definition. AM data must be carefully controlled.

Product Data Management

Product Data Management (PDM) is a solution that manages engineering data, usually in conjunction with authoring tools such as CAD and CAE. Security in PDM solutions prevent engineering collaborators from working on out-of-date information, overwriting another engineer's work, and proliferating copies of data files. Despite this, a CIMdata poll revealed rudimentary management practices are common in industry; 75% of respondents use either Windows folders or nothing, to manage their AM data.

- **Vaulting**. Securely storing AM data is important to ensure all design records are kept. Security permissions to access the vault may be assigned at the file or vault level. Vault level means with proper permission, all files in the vault are available to the user. File level means individual permissions are assigned to the files as well as the vault, making it more secure. File level security would be desirable when vaulting combined AM and traditional engineering data for the same product.
- **Search.** Engineers spend a lot of their time finding information. Advanced search capabilities are essential to find AM data. Capabilities and attributes such as where-used, material, simulation results, supplier, cost, print ticket, etc., are important to supporting AM.
- **Versioning.** Versioning is used to manage saved changes to product information. Versioning prevents collaborators working on out of date files which would cause rework and lost time, or worse, the wrong version getting released to manufacturing.
- **Previsioning.** Previsioning is similar to versioning but involves the released product information. Previsioning prevents collaborators working on out of date files which would cause rework and lost time, or worse, the wrong revision getting made and shipped.
- **Bills of Materials.** A Bill of Materials (BOM) is the hierarchical product structure denoting component parent/child relationships, and material, surface finish, tolerance, color, topology, and print ticket.

AM Governance: Controlled End-to-End

All data in all stages of the lifecycle must be governed by enterprise PDM solutions, including AM information

Governance, what is it?

Governance is the corporate framework defining people, policies, practices, rules, and processes concerning how a company gets work done. In engineering companies, PLM systems provide that governance for product development. Too often, mature companies with advanced AM and PLM systems, don't incorporate AM under PLM, exposing significant risk. Governance should be defined by people, but managed by systems such as PLM, to ensure repeatability, adherence to quality standards, and corporate IP retention.

AM Governance

1. People
2. Policies
3. Practices
4. Processes
5. Rules
6. File naming
7. DfAM framework

AM Governance

AM governance is important to define, document, and publish to all stakeholders, data consumers, knowledge workers, and executives, so everyone understands how and why the AM workflows should function. The following are essential elements of AM Governance.

- **People.** All stakeholders involved in the AM lifecycle; their roles, span of control, skill set, responsibility, and authority.
- **Policies.** Policies defining planning, data management, security, design methodology, production, inspection, material management, waste disposal, and personnel education must be defined, documented, and published as corporate policy.
- **Practices.** Best practices, or tips and tricks, define how all AM stakeholders do their work and interact with each other. These may include design engineering BOM structure definition, AM build tray nesting layout, material recipe management, SLS laser beam replacement frequency, and other factors.
- **Processes.** Define how the work gets done throughout the organization.
- **Rules.** Business rules govern the AM workflow. Rules cover quality standards, milestones, escalation triggers, etc.

Other forms of governance include:

- Search templates to bring repeatability and automation. Templates encapsulate active project IDs, autocomplete fields, auto populate fields, and load matching files with thumbnails.
- DfAM framework to force the innovative application of AM during design processes. Commencing at requirements management then high level and detailed design stages.
- Auto file naming.
- Finishing and inspection criteria.
- PLM workflows with intelligent decision nodes, branching, business rules, states, roles and permissions.

Simulation

Use simulation to drive efficiency gains from AM manufactured components, to discover issues and make decisions before products are real

Simulation, why use it?

The more repeatable a process is the easier it is to simulate digitally; AM, being all digital is ideal to allow simulation in almost every aspect of a product's lifecycle. Simulation allows us to experience final components and whole products before they exist. We can simulate how they will perform under load, heat, vibration, and other factors in the real world. We can simulate how parts fit with other parts, their motion, how products are assembled and dissembled, a surgeon's hand using surgical tools in theater, and how components flow though factories. Collectively, we can now experience designs before they exist using simulation.

Design

Traditionally, engineers use CAE tools to simulate their design after it's created. They then iterate to converge on the best solution. Now, with advances in generative design, designs commence with algorithmic input, and algorithms powered by high-performance computer systems (cloud or on-premise, compute ideal ranked options for the engineer to choose from. This saves iterations by converging directly on the best choice of options.
Tools such as HEEDs leverage cloud computing to algorithmically simulate many alternatives of single components or entire systems, to determine the best option which meets design criteria.
Emerging tools leverage biological-like algorithms which, starting from set constraints, "grow" cell like forms into final parts, just as nature does.

Performance

Performance tradeoffs can be easily simulated to iterate to the best design solution. A requirement such as "*reduce weight by 30%*" could be achieved in many ways. Simulations of thinner wall section, lighter material, latticing, product complexity reduction, and lighter and fewer fasteners, are all options that could be simulated before making the physical part.

Manufacturing

Simulated printing that anticipates heat build up in single components and interaction between others, warpage, and collisions are available.

End-to-end process flow

Simulates the end-to-end process, identifying bottlenecks, delays, dependencies, need for storage, costs of material, equipment, time, manual touch, etc.

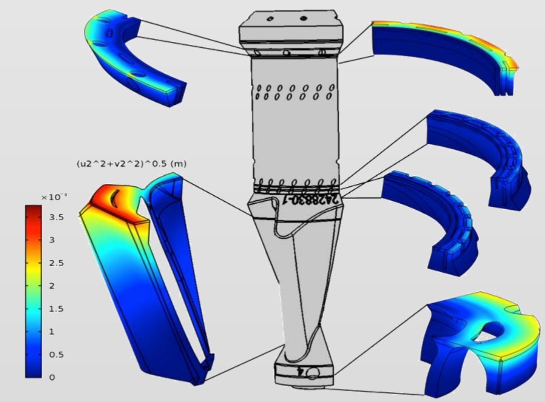


Image courtesy of Siemens PLM Software

AM Action Plan

To industrialize AM into your company, follow an action plan, AM is more than a new production technique to make the same parts a different way

Make a plan

Plan for the following:

- Business objectives based on SMART goals (Specific Measurable Attainable Realistic Timebound)
- Resources including money, premises, people, education and training, equipment, time, etc.
- Project management, e.g., using a Vee model to graphically plan out and manage AM projects.
- Use a Vee model applied to AM to chart requirements gathering, milestones, event riggers, validation loops, span of control, and other activities.

DfAM

Implement DfAM to help reimagine product design, be creative, unconstrained by traditional manufacturing conventions such as enclosures, fixturing devices (screws, washers, bolts), draft tapers, blend radii, etc.

- Look for DfAM opportunities in existing as well as new products.
- Identify how and where to apply generative design.
- Introduce tools into the design process: topology optimization, latticing, and simulation of both component performance and printing processes.

Gather lifecycle data

Gather current product cost data to use for ROI:

- Tooling, e.g., dedicated molds, dies, jigs, fixtures.
- Capital equipment usage; heavy foundations.
- Human labor during machine set up and assembly.
- Hazardous materials disposal, e.g., coolant, oil, chips.
- Process loops, gaps, manual touch.
- Maintenance operations.
- Design points of failure.
- Logistics: design/make centrally, ship everywhere.

Analyze lifecycle data

Capture and evaluate data such as:

- Accumulated costs from conventional manufacturing compared to AM scenario cost models.
- Consider things you can *stop* doing after implementing AM.
- Add AM specific capital costs, e.g., machine, environment management for air quality, material storage, part cooling, postprocessing, and inspection.
- Human training; both for design and manufacturing.

Security and data management

Secure and manage the digital thread to ensure data is protected and the design through manufacturing process is documented, repeatable, auditable, and traceable.

- Implement management tools such as PDM.
- Vault AM data assets in PDM.
- Implement security standards such as Blockchain or commercial solutions such as “Identify 3D” to manage stages of the AM workflow: Protect, Manage and Enforce.

Siemens AG; Industrializing AM

How a German engineering company continuously reinvents itself over 170 years to become a global innovator, technology leader

Industrialization over 170 years

Siemens' long history of innovation manifests in product groups such as:

- Power generation technology
- Industrial, buildings automation
- Medical technology
- Railway vehicles
- Water treatment, fire alarms
- PLM software

Eating their own dog food

Siemens makes many industrial products using Siemens PLM Software tools from the Industrial Automation Group.

Industry 4.0, the digital thread

- Additive Manufacturing
- Digital Twin
- Industrial Internet of Things (IIoT)
- Cloud computing
- Augmented Reality, Simulation
- Big Data
- Machine learning

Industry 4.0

Starting as a German government initiative, Industrie 4.0, is now a commonly adopted term globally. Siemens has solutions and services in all areas of Industrie 4.0

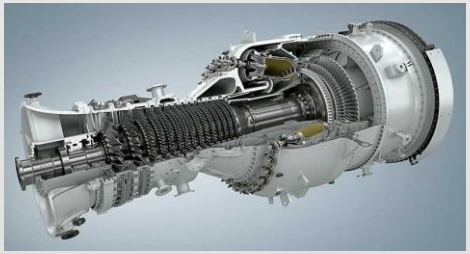
The Digital Thread

Additive Manufacturing is all digital; the geometry, the material recipe, and communication between engineering and production. AM technologies support an end-to-end digital thread, making change requests from production, customers or real-time data from IIoT devices immediately accessible

Ongoing Research

Siemens Corporate Technology serves corporate research needs in many areas:

- Digitalization competence center
- Innovation management
- Digitalization & automation
- Energy systems & electrification
- Research cooperation



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Ingenuity for life

Siemens PLM Software

Hannover Messegelände Germany was the ideal showcase for Siemens PLM Software to showcase their AM solutions in context of parent Siemens AG

Proof of Siemens PLM Software's AM solutions

Siemens PLM Software, a business unit of the Siemens Digital Factory Division, chose the perfect venue to showcase their suite of Additive Manufacturing solutions. Hannover Messegelände in April 2018 attracted more than 200,000 visitors and more than 5,000 exhibitors, who got to see Siemens PLM Software in both Hall 6 for Digital Factory solutions like CAD, CAE, and PLM, and in Hall 9 for Industrial IT and Integrated Automation. Siemens AG group was the largest exhibitor which allowed Siemens PLM Software to show real examples of their Additive Manufacturing solutions in action. Examples of AM from customers included Bugatti and Siemens AG, while partners such as Stratasys, EOS, HP, and DMG Mori highlighted the broad ecosystem.

End to end AM solutions

Siemens PLM Software showed significant capability by highlighting end-to-end AM software solutions, actual end-customer products, a partner eco-system, and extended capability from sister companies within Siemens AG group who bring complementary software and physical industrial machines and equipment, proving that Industrial AM products are now possible.

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