ENPM 692
MANUFACTURING AND AUTOMATION

ADDITIVE MANUFACTURING

APPLICATIONS & CHALLENGES

Wednesdays 7:00pm - 9:40pm
Location: JMP 2222

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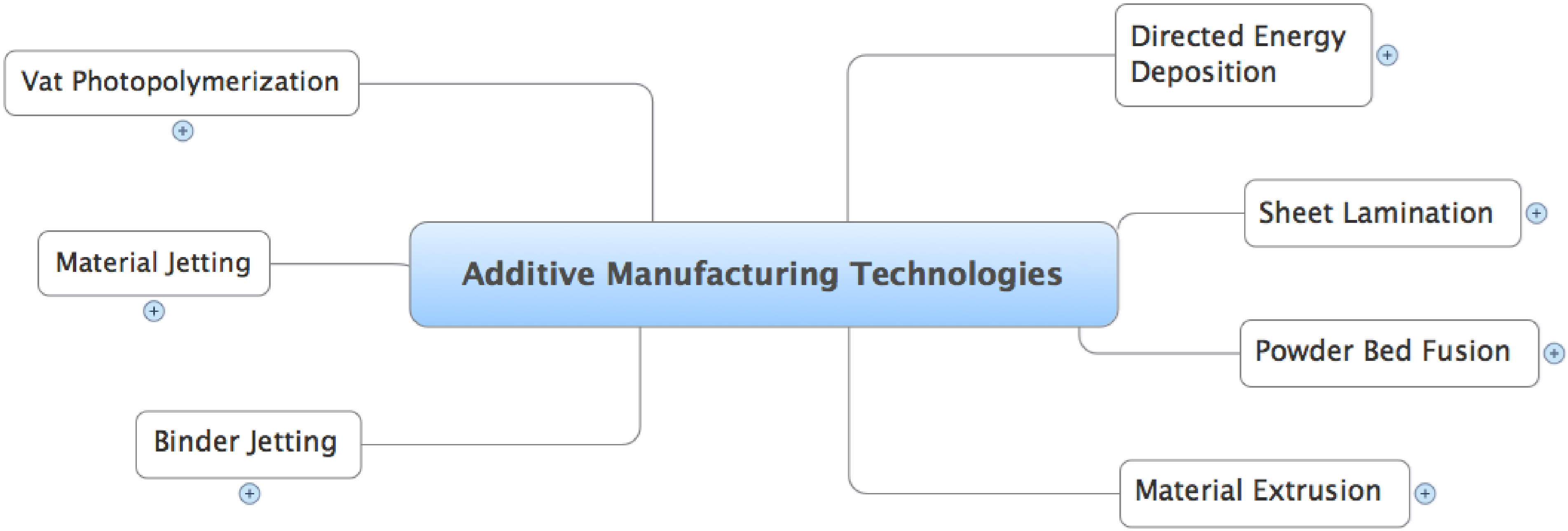
Email: mmani@umd.edu

Recap

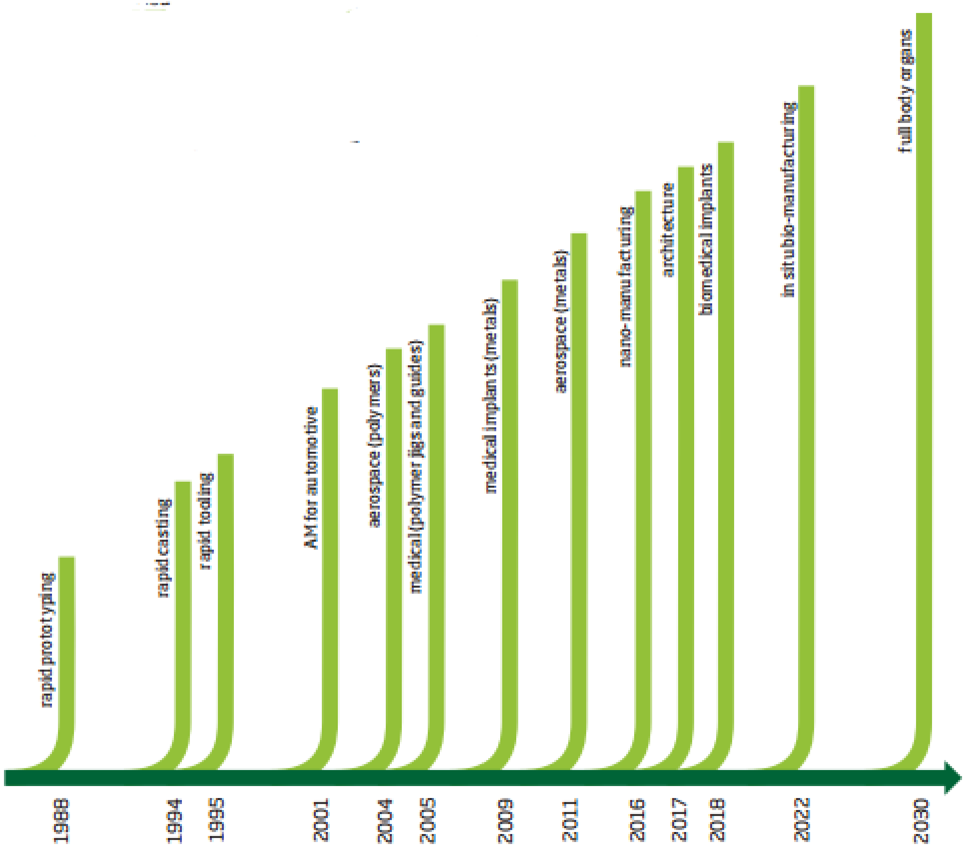


http://www.astm.org/COMMITTEE/F42.htm

AM Applications

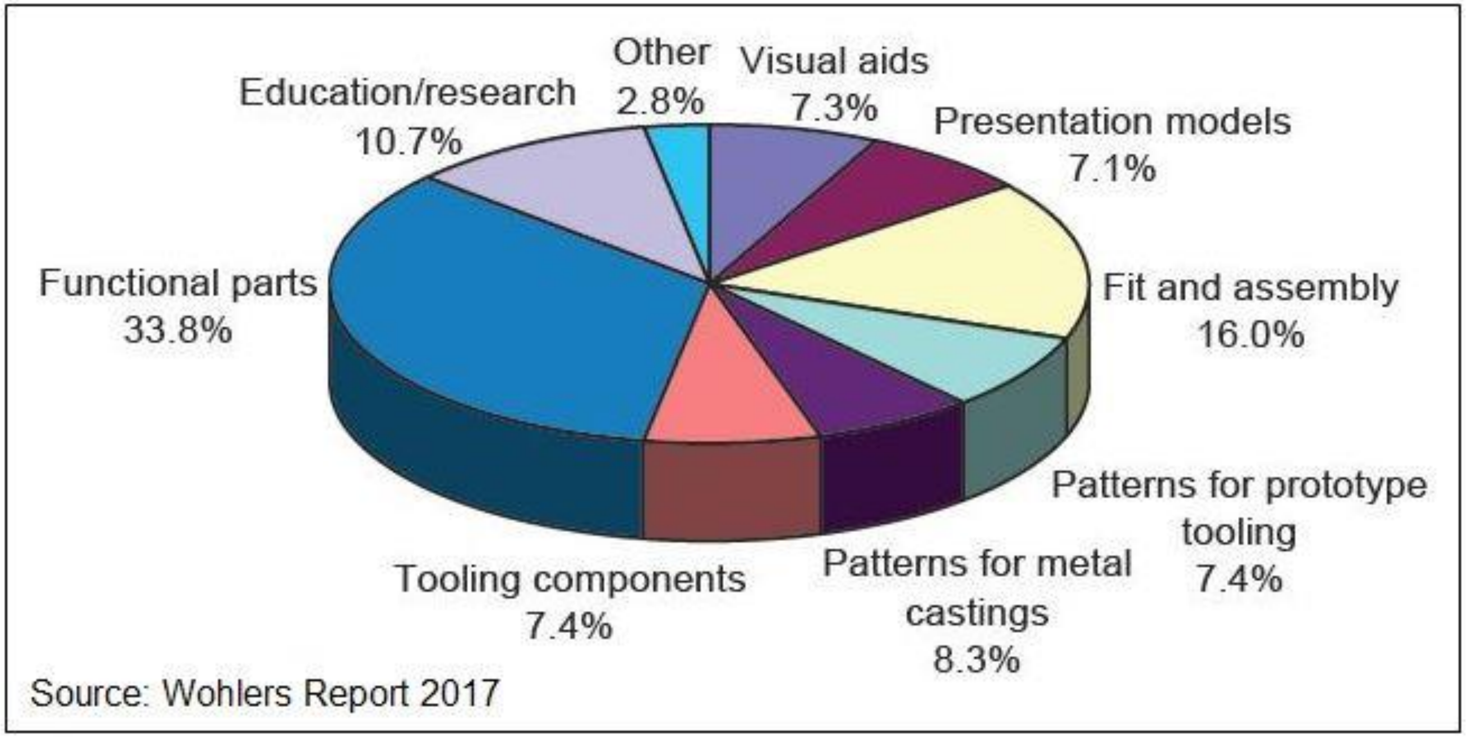
This timeline lays out past, present and potential future AM developments and applications.
(courtesy of Graham Tromans)

1988-1994	rapid prototyping
1994	rapid casting
1995	rapid tooling
2001	AM for automotive
2004	aerospace (polymers)
2005	medical (polymer jigs and guides)
2009	medical implants (metals)
2011	aerospace (metals)
2013-2016	nano-manufacturing
2013-2017	architecture
2013-2018	biomedical implants
2013-2022	in situ bio-manufacturing
2013-2032	full body organs



Reference: Additive manufacturing: opportunities and constraints. Royal Academy of Engineering

Industries Using AM



https://wohlersassociates.com/wp-content/uploads/2022/05/2022_ExSum.pdf

The Advantages of AM

- Efficiency, creativity, accessibility
- Low-volume production
    - replaces machine tooling- allows for cheap, low-volume production and facilitates personalized and customized products
- Lower-cost production
- Responsive production
- Shorter supply chains
- Democratization of production
- Optimized design

Comparison to Traditional Manufacturing

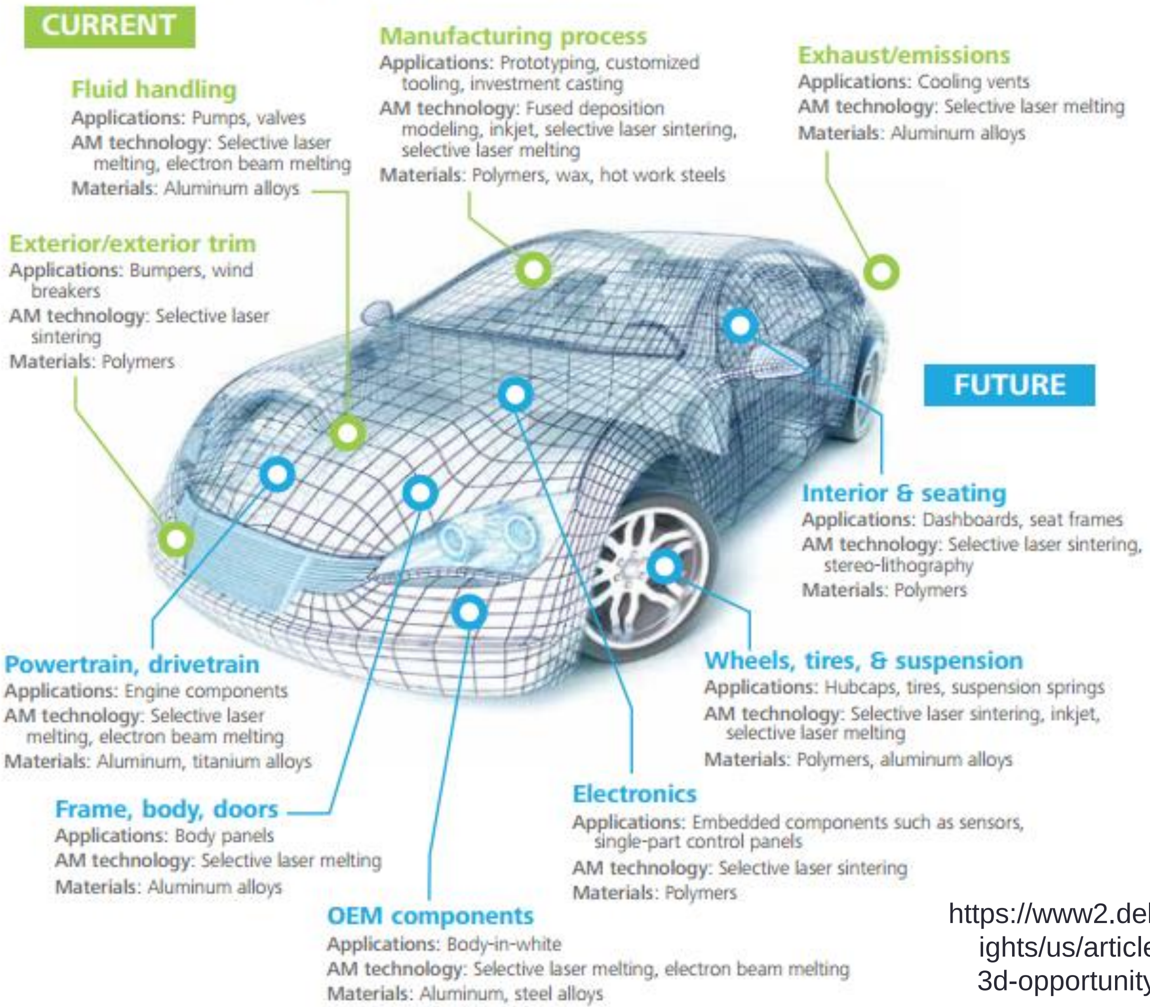
AM attributes compared to traditional manufacturing	**Impact on product offerings**	**Impact on supply chains**
Manufacturing of complex-design products	●	◕
New products that break existing design and manufacturing limitations	●	◕
Customization to customer requirements	●	◕
Ease and flexibility of design iteration	◕	◑
Parts simplification/sub-parts reduction	◑	◑
Reduced time to market	◑	◑
Waste minimization	◑	◑
Weight reduction	◑	◔
Production near/at point of use	◑	●
On-demand manufacturing	◔	●

Potential impact	**Very high**	**High**	**Medium**	**Low**
	●	◕	◑	◔

http://energy.gov/sites/prod/files/2015/02/f19/QTR%20Ch8%20-%20Additive%20Manufacturing%20TA%20Feb-13-2015_0.pdf

Applications of AM in an automobile

Figure 2. Illustrative applications of AM in an automobile[35]



Source: Deloitte analysis.

Graphic: Deloitte University Press | DUPress.com

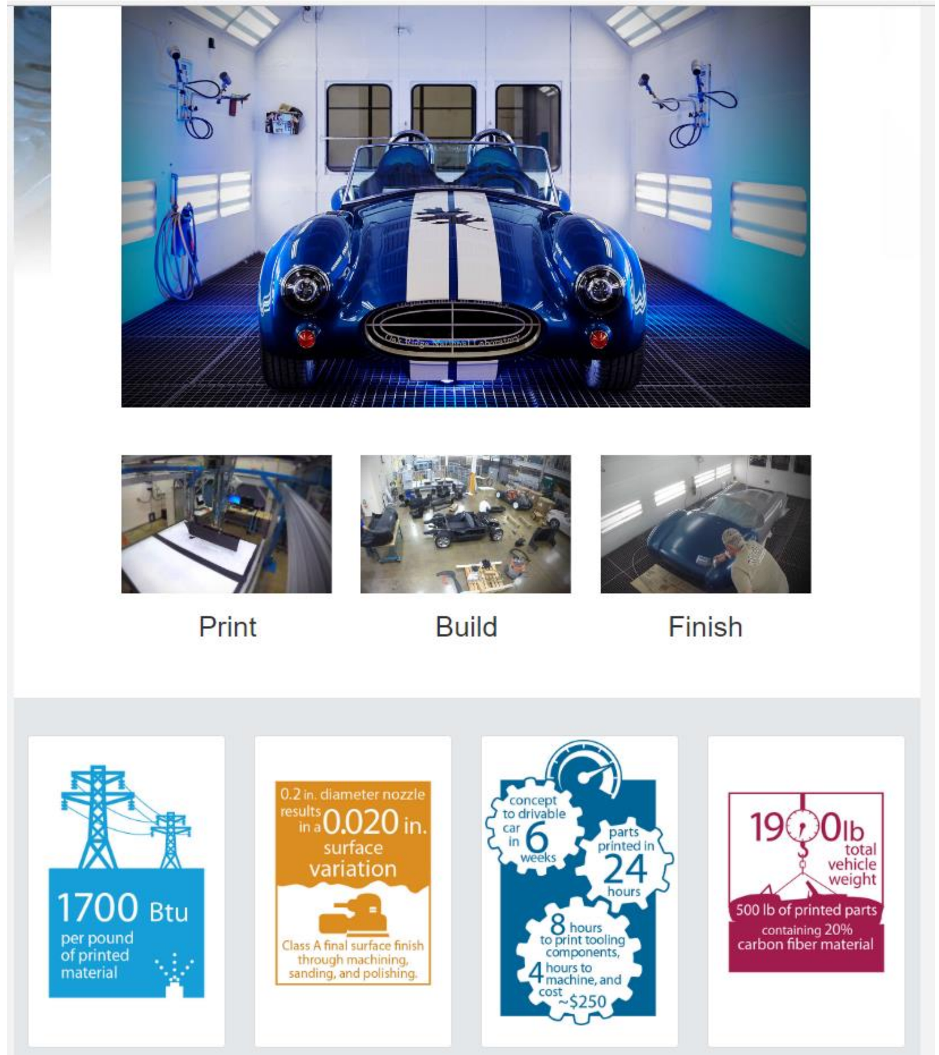
https://www2.deloitte.com/content/dam/insights/us/articles/additive-manufacturing-3d-opportunity-in-automotive/DUP_707-3D-Opportunity-Auto-Industry_MASTER.pdf

Drivers and Challenges in The Automotive Industry

- Drivers
  - More materials applicable to AM.
  - Improved AM manufactured product quality
    - With reduced post-processing.
- Challenges
  - Economics of AM limited to low volume production.
  - Manufacturing large parts.
  - Talent shortage.
  - Intellectual property concerns.

3D Printed Shelby Cobra

Printing Revolution
Researchers printed the Shelby Cobra at DOE's Manufacturing Demonstration Facility at ORNL using the Big Area Additive Manufacturing (BAAM) machine, which can manufacture strong, lightweight composite parts without the need for tooling. The new BAAM system, which was jointly developed by ORNL and Cincinnati Incorporated, is 500 to 1000 times faster and capable of printing polymer components 10 times larger than today's industrial additive machines— in sizes greater than one cubic meter.



https://www.energy.gov/eere/amo/3d-printed-shelby-cobra

Aerospace Applications

	Current applications	Potential applications
Commercial aerospace and defense	• Concept modeling and prototyping • Printing low-volume complex aerospace parts • Printing replacements parts	• Embedding additively manufactured electronics directly on parts • Printing aircraft wings • Printing complex engine parts • Printing repair parts on the battlefield
Space	• Printing specialized parts for space exploration • Printing structures using lightweight, high-strength materials • Printing parts with minimal waste	• Printing on-demand parts/spares in space • Printing large structures directly in space, thus circumventing launch vehicles' size limitations

http://energy.gov/sites/prod/files/2015/02/f19/QTR%20Ch8%20-%20Additive%20Manufacturing%20TA%20Feb-13-2015_0.pdf

3D Printed Aircraft

https://www.youtube.com/watch?v=DNdt9nfU050

Opportunities Vs Challenges

OPPORTUNITIES

- Unprecedented design flexibility, allowing customization and new product development
- Consumerization/personalization of manufacturing
- Novel end-market applications in areas such as regenerative medicine
- Relocalization of US manufacturing
- Rapid product development and deployment
- Improving process sustainability (fewer yet greener materials; less energy and waste associated with production)

CHALLENGES

- Exuberance vs. natural evolution and true potential of the technology
- Ethical considerations (e.g., guns, bioprinting of human cells)
- Intellectual property/privacy issues
- Regulatory uncertainty in different countries
- Limited choice of materials
- Materials and process manufacturing qualification and certification standards
- Small production runs and scalability limitations

http://energy.gov/sites/prod/files/2015/02/f19/QTR%20Ch8%20-%20Additive%20Manufacturing%20TA%20Feb-13-2015_0.pdf

AM Paths And Value

Source: Mark Cotteleer and Jim Joyce, "3D opportunity: Additive manufacturing paths to performance, innovation, and growth," *Deloitte Review* 14, January 2014.

Graphic: Deloitte University Press | DUPress.com

The Road Ahead-opportunities For AM

- Materials
- Software
- Data management
- Sustainability
- Affordability
- Speed
- Reliability
- Intellectual property
- Standards
- Business funding
- Education

Reference: Additive manufacturing: opportunities and constraints. Royal Academy of Engineering

Standards for AM

ASTM/ISO active for AM standards development:

- Qualification and certification methods,
- Design guidelines,
- Test methods for characteristics of raw materials,
- Test methods for mechanical properties of finished additive manufacturing parts,
- Material recycling (reuse) guidelines,
- Standard protocols for round-robin testing,
- Standard test artifacts, and
- Requirements for purchased additive manufacturing parts.

Source: 3D Printing in Space, National Academies Press

Structure of AM Standards

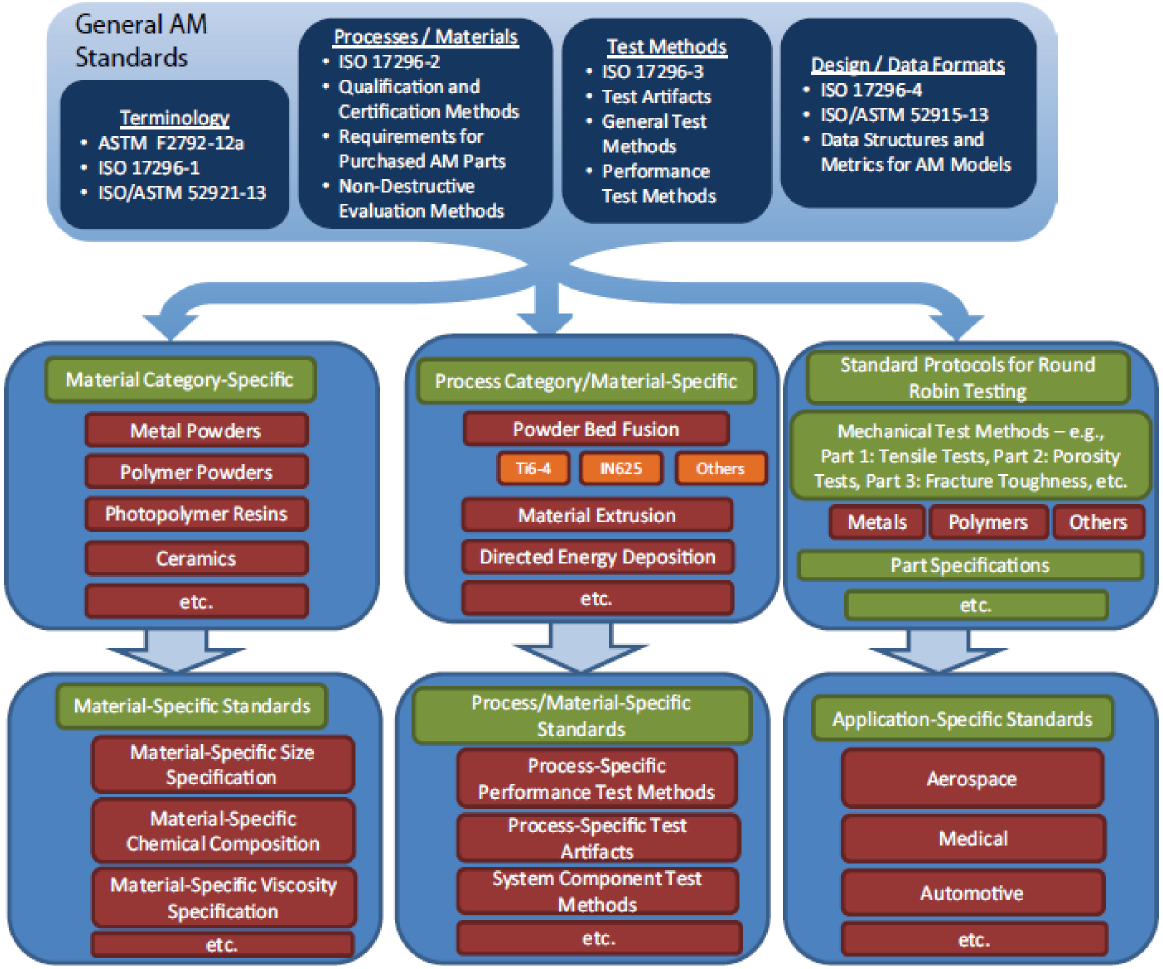


FIGURE 1.3 Structure of additive manufacturing (AM) standards for ASTM and ISO. SOURCE: Courtesy of ASTM Committee F42 on Additive Manufacturing Technologies, copyright ASTM International.

Source: 3D Printing in Space, National Academies Press

ASTM AM Standards

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- Technical Committees
- Membership
- Meetings & Symposia
- Students & Professors

Committee F42 on Additive Manufacturing Technologies

Staff Manager: Pat Picariello 610-832-9720

Subcommittees and Standards

Standards under the Jurisdiction of F42

Each main committee in ASTM International is composed of subcommittees that address specific segments within the general subject area covered by the technical committee. Click on the subcommittee links below to see the title of existing standards for each subcommittee. Then, click on the resulting titles to see the standard's scope, referenced documents, and more.

- F42.01 Test Methods
- F42.04 Design
- F42.05 Materials and Processes
- F42.05.01 Metals
- F42.05.02 Polymers
- F42.05.05 Ceramics
- F42.06 Environment, Health, and Safety
- F42.07 Applications
- F42.07.01 Aviation
- F42.07.02 Spaceflight
- F42.07.03 Medical/Biological
- F42.07.04 Transportation/Heavy Machinery
- F42.07.05 Maritime
- F42.07.06 Electronics
- F42.07.07 Construction
- F42.07.08 Oil/Gas
- F42.07.09 Consumer
- F42.07.10 Energy
- F42.08 Data
- F42.90 Executive
- F42.91 Terminology
- F42.95 US TAG to ISO TC 261

Recommended

ASTM Training: Apply standards more effectively

Train at our location or yours, and get instruction on the most important standards you use

https://www.astm.org/get-involved/technical-committees/committee-f42/subcommittee-f42

ISO AM Standards

Standards catalogue

Browse by ICS | Browse by TC

Subscribe to updates

ISO/TC 261 - Additive manufacturing

Items to be displayed:

- [x] Published standards
- [x] Standards under development
- [ ] Withdrawn standards
- [ ] Projects deleted (last 12 months)

Standards and projects under the direct responsibility of ISO/TC 261 Secretariat

Standard and/or project	Stage	ICS
ISO 17296-2:2015 Additive manufacturing – General principles – Part 2: Overview of process categories and feedstock	60.60	25.040.20
ISO 17296-3:2014 Additive manufacturing – General principles – Part 3: Main characteristics and corresponding test methods	60.60	25.040.20
ISO 17296-4:2014 Additive manufacturing – General principles – Part 4: Overview of data processing	60.60	25.040.20
ISO/ASTM 52900:2015 Additive manufacturing – General principles – Terminology	60.60	01.040.25 25.040.20
ISO/ASTM DIS 52901 Additive manufacturing – General principles – Requirements for purchased AM parts	40.60	25.040.20
ISO/ASTM NP 52902 Additive manufacturing – General principles – Standard test artifacts	10.99	
ISO/ASTM DIS 52903-1 Additive Manufacturing – Standard Specification for Material Extrusion Based Additive Manufacturing of Plastic Materials – Part 1: Feedstock materials	40.20	25.040.20
ISO/ASTM CD 52903-2 Additive manufacturing – Standard specification for material extrusion based additive manufacturing of plastic materials – Part 2: Process – Equipment	30.99	25.040.20
ISO/ASTM DIS 52910 Standard Practice – Guide for Design for Additive Manufacturing	40.99	25.040.20
ISO/ASTM 52915:2016 Specification for Additive Manufacturing File Format (AMF) Version 1.2	60.60	35.240.50 25.040.20
ISO/ASTM 52921:2013 Standard terminology for additive manufacturing – Coordinate systems and test methodologies	60.60	25.040.20

The Next Industrial Revolution

Additive Manufacturing The Next Industrial Revolution

https://www.youtube.com/watch?v=cAbnhY27m6M

Design for Additive Manufacturing (DFAM)

Motivation for DFAM

- Design for Manufacturing (DFM) vs Design for Additive Manufacturing (DFAM).
- What are the unique capabilities of AM technologies.
- Design synthesis approach to optimize designs.

Design for Manufacturing and Assembly

Definition:

Practice of designing products to reduce, and hopefully minimize, manufacturing and assembly difficulties and costs.

DFM efforts:

- Industry practices including concurrent engineering and others.
- Collections of DFM rules and practices.
- Research in DFM methods, tools, and environments.

Core DFAM Concepts and Objectives

- Objective of DFAM :
  - Maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to capabilities of AM technologies.

- Guidelines for designing products:
  - Complex Geometry: AM processes are capable of fabricating parts with complex geometry.
  - Customized Geometry: Mass customization instead of mass production can be realized in this guideline.
  - Integrated Assemblies: Integration of features from multiple parts, possibly yielding better performance.
  - Elimination of Conventional DFM Constraints: Challenge here is to explore new design spaces, innovate new product structures and developing products in unconventional ways.

AM Unique Capabilities

<u>Shape Complexity</u>

- In AM the capability to fabricate a layer is unrelated to the layer’s shape.
- Part complexity is virtually unlimited.
- A related capability is to enable **custom-designed geometries.**

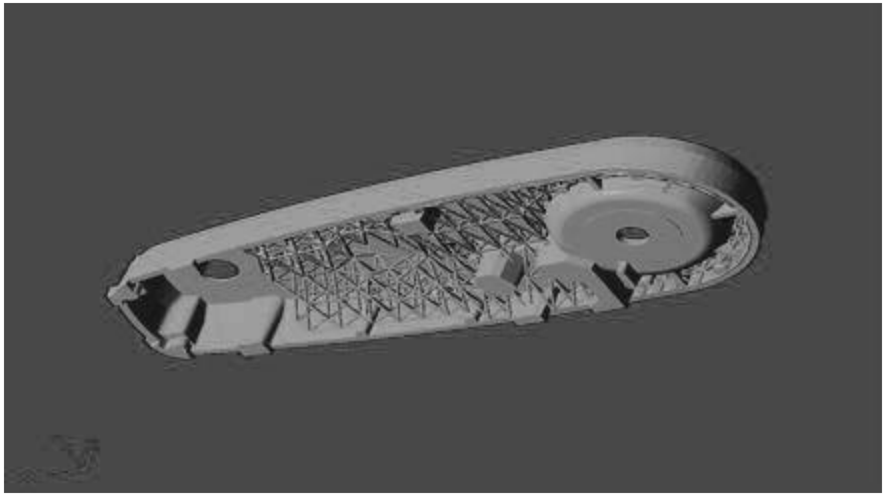


Figure 11.3 Robot link stiffened with lattice structure

AM Unique Capabilities

Hierarchical Complexity

- AM enables the design of hierarchical complexity across several orders of magnitudes in length scale.
- Extensively studied set of processes in this concept are the Directed Energy Deposition by varying either materials present or the processing of the materials, **nano/microstructure control** is possible.
  - material extrusion, ink jet printing, photopolymer, and sheet lamination AM technologies as well.

AM Unique Capabilities

Functional Complexity

- By controlling the fabrication of each layer, **fabricating operational mechanisms** in some AM processes is possible.
- Components have been inserted into parts being built in SL,FDM,SLS,UC and other AM machines, enabling situ assembly.
- Functional complexity can also be achieved

by unique combination of AM technologies like 3D integrated electronics.

Fig. 11.5 Pulley-driven snake-like robot

AM Unique Capabilities

Material Complexity

- It is possible to **process the material differently** at different points, causing different material properties in different regions of the part.
- A significant issue hindering the adoption of AM’s material complexity is the lack of design and CAD tools that enable representation and reasoning with multiple materials.

Exploring Design Freedoms

Following are the approaches of design, representing unique capabilities of AM:

- **significant part consolidation**- combining several parts into a single part.
- **hierarchical structures** can result from structuring the material in parts using meso-scale or micro-scale features to produce so-called cellular materials.
- Industrial designers have explored **new design concepts** for some everyday products.
  - E.g. plates, chairs and clothing

Part Consolidation and Redesign

- Geometric complexity and suitability for low volume production combine to yield substantial benefits.
  - consolidating parts into a smaller number of more complex parts fabricated using AM process.
- Several significant advantages over designs with multiple parts.
  - 1. Dedicated tooling for multiple parts is not required.
  - 2. Possibility to design the consolidated parts to perform better than the assemblies.

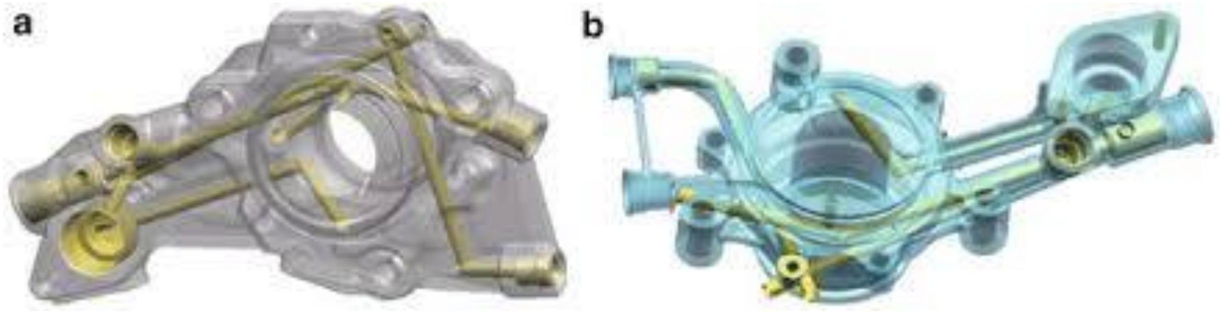


Figure 11.8 Diesel front plate example

Hierarchical Structures

- The basic idea of hierarchical structures is that features at one size scale can have smaller features added to them, and each of those smaller features can have smaller features added, etc.
- Lattice materials have received considerable attention, and lattice structures tend to have geometry variations in three dimensions.

(a) (b) (c)

Figure 5. CAD images of unit cells comprised of octet-truss structure, (a) single octet, (b) 2x2x2 array of octets, and (c) 3x3x3 array of octets.

Source: Johnston, Scott R., et al. "Analysis of mesostructure unit cells comprised of octet-truss structures." *Proceedings of the The Seventeenth Solid Freeform Fabrication Symposium Austin, TX*. 2006.

Industrial Design Applications

- Some approaches to product design have been demonstrated that take advantage of the shape complexity capabilities of AM, as well a some material characteristics.

- Different classes of products have been developed.

Refer book for further information.

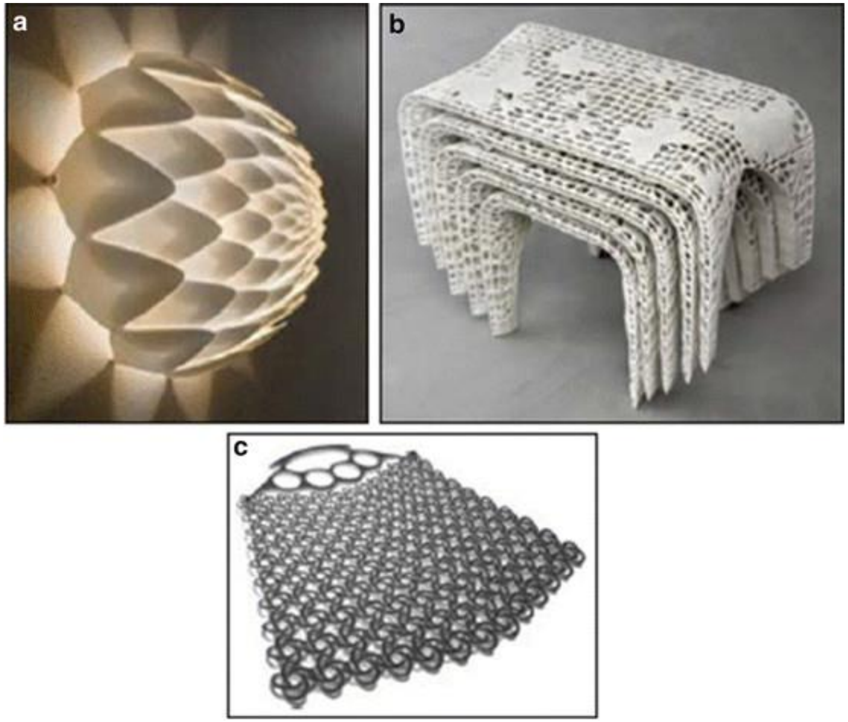


Fig.11.11 Example products from Freedom of Creation

Lattice structures

https://www.youtube.com/watch?v=WMCR6VBSV-E

Design Tools for AM

- Current solid-modeling-based CAD systems have several limitations that make them less than ideal for taking advantage of the unique capabilities of AM machines.

Challenges for CAD

- <u>Geometric Complexity:</u> Need to support models with various features.
- <u>Physically based material representations:</u> Material compositions and distributions must be represented and physically meaningful.
- <u>Physically based property representations</u>: desired distributions of physical and mechanical properties must be represented and tested for their physical basis.

Design Tools for AM

- Solid modeling CAD Systems
  - used for mechanical product development and are used in university education and research.
  - Two main geometry-related capabilities are needed to support many emerging design applications, particularly when AM manufacturing processes will be utilized.
    - 1. Representation of tens or hundreds of thousands of features, surfaces, and parts.
    - 2. Managing features, materials, surfaces, and parts across size ranges of 4-6 orders of magnitude.

Design Tools for AM

- Proposed DFAM System

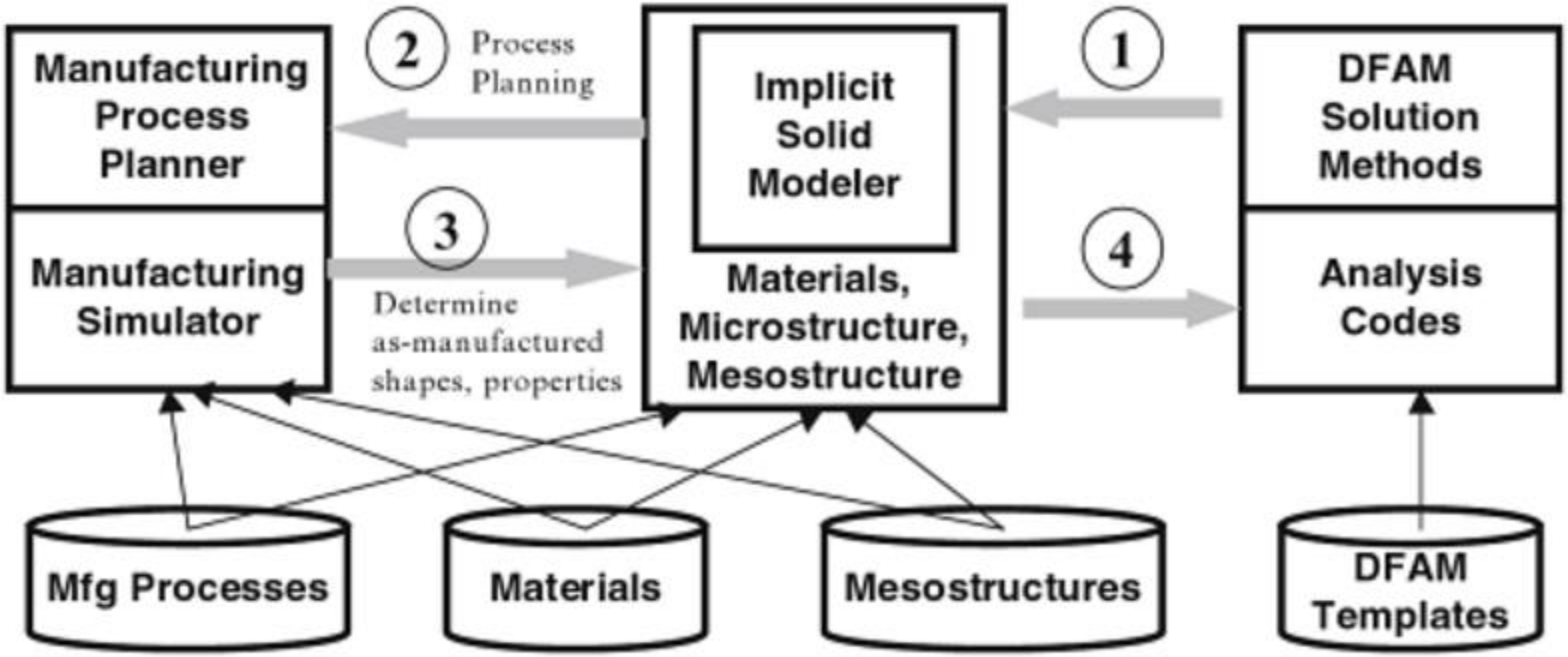


Fig. 17.13 DFAM system and overall structure

Design Tools for AM

Implicit Modeling

- Implicit modeling has lot of advantages like its conciseness, ability to model with any analytic surface models, and its avoidance of complex geometric and topological representation.
  - Suggestion: Consider the example of implicit modeling in the book.

Search and Synthesis Methods.

- Design synthesis approaches for complex structures have tended to utilize some kind of stochastic optimization method such as Genetic Algorithms.

Summary DFAM

- Unique capabilities of AM technologies enable new opportunities for designers.
- Comparison and contrasts of traditional DFM approaches to DFAM.
- AM enables improvements that are important to DFAM in many ways.
- Challenges and potential methods for CAD tools to overcome the limitations.

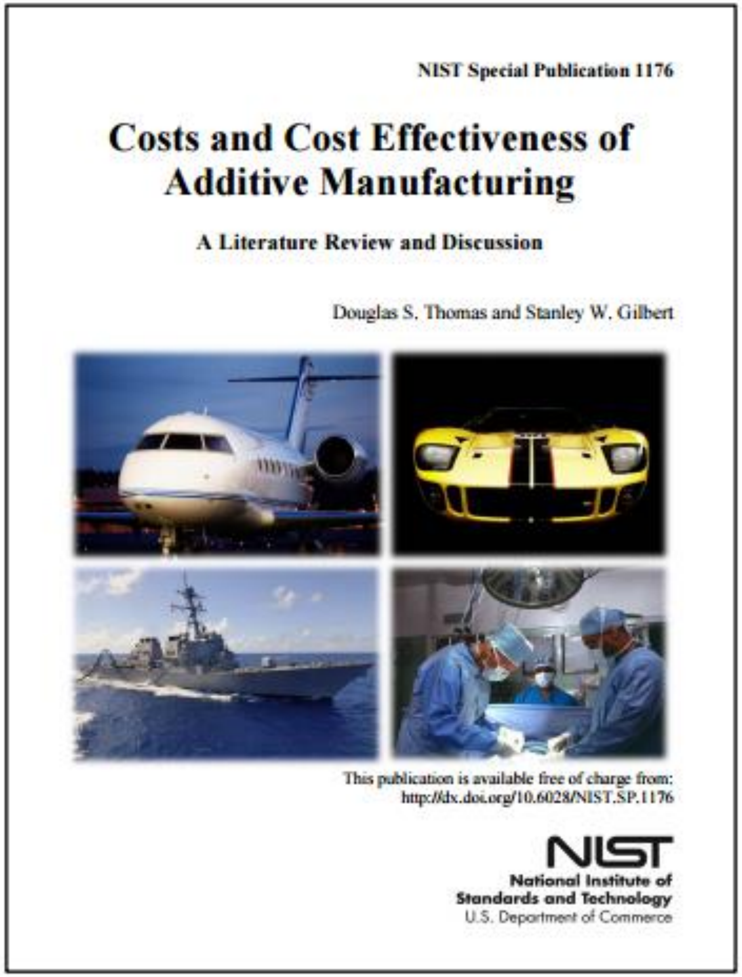
- Additional Information, take a look at this presentation http://www.naefrontiers.org/File.aspx?id=39135

Cost Effectiveness in AM

NIST Special Publication 1176

Costs and Cost Effectiveness of Additive Manufacturing A Literature Review and Discussion

http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1176.pdf



Business Opportunities

Product Realization

- No reason to bring the products into the market through centralized development, production and distribution.
- AM provides for product conceptualization, product creation, and product propagation.
- Progress in AM provides potential markets for the outputs of digiproneurship.

Important Definitions

- Conceptualization
  - Forming and relating ideas including the formation of the digital version of the ideas.
- Creation
  - Bringing an idea into physical existence.
- Propagation
  - Multiplying by reproduction through digital means.
- Digipreneurship
  - Digital to physical product entrepreneurship.

Reference: See Textbook and http://www.vtt.fi/inf/pdf/workingpapers/2009/W113.pdf

New Types of Products and Employment

- AM developments along with advanced Information and Communication Technologies (aICT) etc are making it possible for specific products to be created much more quickly and much lower costs.
- These products characteristics are superior to that of the old conventional ones.
- Using additive approach to production, the consumption of value adding sources can be reduced.
- Digitally-driven technology which directly transforms digital information into physical good can fall within the scope of Digiproneurship.

New Types of Products and Employment

- From an engineering and design standpoint, AM technologies are becoming more accurate and can build small products (micron sized) to large scale products (building sized).
- Innovative combinations of AM and aICT creates diverse product types by people without prior knowledge of design &/or production.
- This could lead to distribution of work amongst various kind of people from different backgrounds.

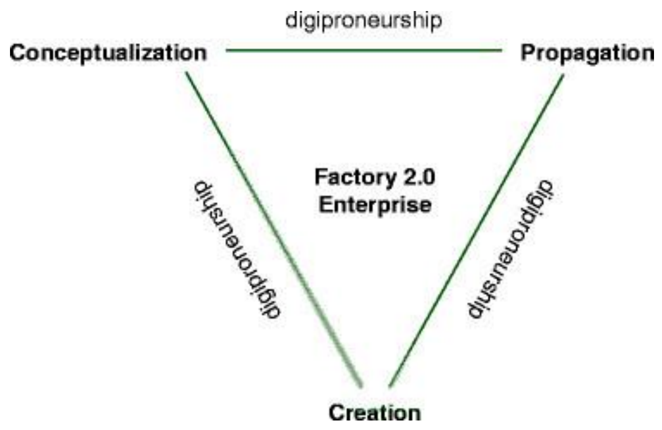
Digipreneurship

- By taking digital entrepreneurship one step further, into creation of physical goods, Digiproneurship represents the next logical step.
- Digiproneurship opportunities are now being considered early in the conceptualization stage for new products.
- In future, inexpensive, intuitive solid modeling tools such as Google SketchUp, maybe used widely by the consumers to design their own products.
- There are various Digiproneurship -related research and development priorities for aICT and AM.

Reference: Additive Manufacturing Technologies, pp.475-486

Business opportunities: summary

- Breakthrough through product conceptualization and creation.
- Digiproneurship offers many opportunities and eliminate the need for costly market, research, warehouses, capital investments etc.
- Digiproneurship is just taking off and will expand further when Factory 2.0 becomes a reality.



Reference: Additive Manufacturing Technologies, pp.475-486

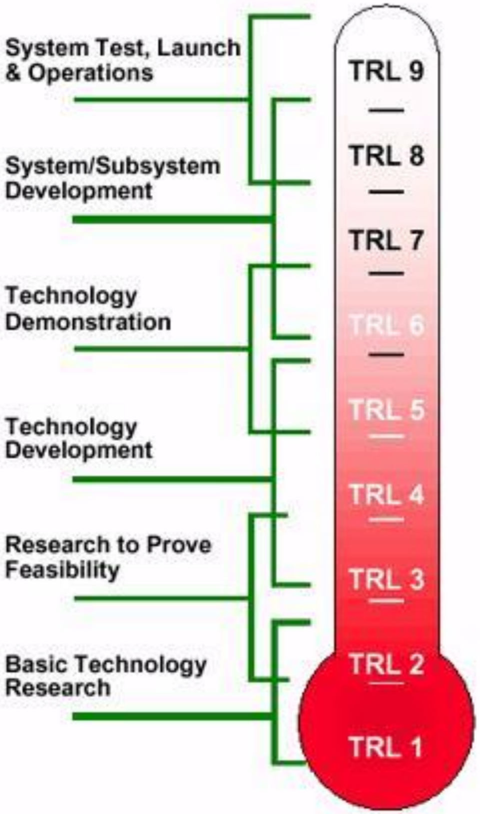
America Makes

America Makes IMPACT - 5 Years Later

[America Makes IMPACT - 5 Years Later - YouTube](#)
[Technology Roadmap - America Makes](#)

A Note of Technology Readiness Level

Technology Readiness Level	Description
TRL 1.	basic principles observed
TRL 2.	technology concept formulated
TRL 3.	experimental proof of concept
TRL 4.	technology validated in lab
TRL 5.	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6.	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7.	system prototype demonstration in operational environment
TRL 8.	system complete and qualified
TRL 9.	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)



ASSIGNMENT & DISCUSSION

Assignment 1

Consider additive manufacturing performance against a traditional manufacturing scenario- and then explore what hinders the widespread implementation of additive manufacturing.

What should you do?

- Choose any industrial sector or application (example: automotive, aerospace, tooling, bio-medical, toys or even consider less popular applications or new ideas).
- Perform a literature review to assess the current state of additive manufacturing in the chosen area.
- Examine the impacts of additive manufacturing vs traditional manufacturing.
- Your analysis should help decision making.

Assignment Documentation

- Research- state of art based on the application.
- Analysis- analyze manufacturing process capabilities.
- Synthesis- potentially as a decision matrix or a table.
- Decision support- Is AM a better alternative, or not, or complimentary.
- References
- Page limit: Maximum 6 pages.