A systematic approach to improve performances of the AM-based value chain

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Outline of the presentation

- Circular Economy and Sustainable Manufacturing
- Additive Manufacturing as a key player
- Conclusions
Outline of the presentation

- Circular Economy and Sustainable Manufacturing
- Additive Manufacturing as a key player
- Conclusions
Circular economy

What is Circular Economy?

Circular economy systems keep the added value in products for as long as possible and eliminate waste.

They keep resources within the economy when a product has reached the end of its life, so that they can be productively used again and again and hence create further value.

Source: COM (2014) 398 "Towards a circular economy"
De- and Re-manufacturing and Circular economy

Design, management and control of demanufacturing and remanufacturing, Tullio Tolio, Alain Bernard, Olga Battaia, Marcello Colledani, Joost Duflou, Sami Kara, Guenther Seliger, Shozo Takata, Vol.66/2/2017, P.585-610

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Sustainable Manufacturing as a forecasted effect of Industry 4.0

AM: one component of the smart factory of the future

15 components of the smart factory of the future

Source: IoT Analytics, Quantifying the connected world

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Global schema of a systemic vision of AM

Source: Master thesis, Laura Martinez, IS3P team, LS2N, Centrale Nantes
**AM - based value chain**

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**Design (for AM)** → **Work preparation** → **AM process** → **Post-processing** → **Off-Line metrology and Quality Control** → **Use phase AM parts** → **Disposal Recycling**

- **Machines**
- **In-situ process monitoring & control**
- **Materials**

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**Transversal issues**
(interoperability, cybersecurity, digital logistics, certification and qualification, sustainability, KPIs, training and education)

Source: CIRP Collaborative Working Group on Additive Manufacturing, Birmingham, August 2019

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Interoperability between processes and actors of the value chain

1. Generate CAD model
   1.1 Scan Part
     1.1.1 Digitalize Physical Part
     1.1.2 Process Points Cloud
     1.1.3 Develop Geometric Model
   1.2 Obtain CAD File
   1.3 Optimize Topology
     1.3.1 Generate Optimal Topology
     1.3.2 Optimize 3D Model
   1.4 Analyze Model

2. Generate Tessellated Model
   2.1 Tessellate Model
   2.2 Repair/Modify Tessellated Model

3. Generate Build Model
   3.1 Plan process - Geometry information
     3.1.2 Choose orientation
     3.1.3 Generate supports
   3.2 Plan process - Process information
     3.2.1 Set Build Orientation
       3.2.1.1 Place Part
       3.2.1.2 Generate Slices
       3.2.1.3 Path Planning
       3.2.1.3.1 Determine Paths
       3.2.1.3.2 Compute Paths
       3.2.1.3.3 Determine Path Parameters
     3.2.2 Set Process Parameters
       3.2.2.1 Set Quality Parameters
       3.2.2.2 Set Control Parameters
       3.2.2.3 Set Powder Parameters
   3.3 Process simulation

4. Preparation of the Machine
   4.1 Review Job File
   4.2 Start Machine
     4.2.1 Configure AM Machine
     4.2.2 Set AM Machine Parameters
   4.3 Submit Job

5. Manufacture Part
   5.1 Preheat Build Plate
   5.2 Build Part
     5.2.1 Create Powder Layer
       5.2.2 Fuse Powders
       5.2.2.1 Melt Powders
       5.2.2.2 Solidify
       5.2.3 Lower Build Plate

6. Obtain Manufactured Part
   6.1 Extract Surplus Powder
   6.2 Treat Surplus Powder
     6.2.1 Recycle Powder
     6.2.2 Remove Non Profit Powder
   6.3 Remove Part from the Build Plate

7. Post-process Part
   7.1 Remove Supports
   7.2 Enhance Properties
     7.2.1 HIP Treatment
     7.2.3 Annealing
   7.3 Enhance Accuracy
     7.3.1 Machining
     7.3.2 Chemical Polishing
   7.4 Improve Surface Texture
     7.4.1 Shot Peening
     7.4.2 Milling
     7.4.3 Grinding
     7.4.4 Sanding,
     7.4.5 Polishing
     7.4.6 Abrasive blasting

8. Ensure Quality
   8.1 Test Mechanical Properties
   8.2 Perform a Non-destructive Evaluation

9. Create Digital Twin

10. Machine Maintenance
    10.1 Corrective Maintenance
        10.1.1 Powder Supply
        10.1.2 Reparation
    10.2 Preventive Maintenance
        10.2.1 Check recoating Blade
        10.3 Predictive Maintenance

11. Clean AM Machine

12. Supply Powders to the Machine

13. Ensure Safety

Source: Master thesis, Laura Martinez, IS3P team, LS2N, Centrale Nantes

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Outline of the presentation

Circular Economy and Sustainable Manufacturing

Additive Manufacturing as a key player

Conclusions
Additive Manufacturing

- Less material need
- Zero additional cost for complexity and diversity
- Less environmental impacts
- Integration of functions
- Production on demand - Zero stock
- No tooling use
- Spare parts
- Digital logistics

Photo credit: www.canadianmetalworking.com
Additive Manufacturing

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Photo credit: www.canadianmetalworking.com
Integration of functions

Multi-material part

General Electric

Farinia Group

16 parts + assembly

1 part

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Integration of functions

Conformal cooling
(Source: Fusia)

Vibration dampening
(Source: Multistation)

One part medical device
(Source: PhD A. BRUYAS, University of Strasbourg)
Additive Manufacturing

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Photo credit: www.canadianmetalworking.com

17/09/2019

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Less material need

Topological optimization

Source: Grégoire Allaire, Laboratoire CMAP, Ecole Polytechnique, AEPR 2015
Less material need

Sketch or Import a Part/Assembly
Defeature the Part
Assign Materials and Loads
Generate Ideal Shape
Confirm Performance (optional)
Refine Concept in CAD

918g
- 64%
326g

Source: Multistation, Assises Européennes de la Fabrication Additive, juin 2014

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Less material need

Lattice structures

Source: Olivier Jay, Industry Days, Bologne
Additive Manufacturing

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Photo credit: www.canadianmetalworking.com
Zero additional cost for complexity and diversity
Zero additional cost for complexity and diversity

Part manufactured with EBM (TA6)
Source: Philippe Bauer THALES

Part manufactured by Volum-e company

Additive Manufacturing

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Photo credit: www.canadianmetalworking.com
Less environmental impact

Manufacturing preparation → Material qualification → Manufacturing

Geometry and material design → Post-treatments
Less environmental impact

AddUp Flexcare System
Additive Manufacturing

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Photo credit: www.canadianmetalworking.com
Spare parts

Source: http://3dprint.com/tag/ebm/

Source: BeAM, Courtesy: Chromalloy France

Source: BeAM, Courtesy: Chromalloy France

Source: Leolane, Courtesy: PWC(PriceWaterhouseCoopers)

Source: Leolane, Courtesy: Mercedes Benz truck
Additive Manufacturing

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Photo credit: www.canadianmetalworking.com

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Digital logistics

Source: http://software.materialise.com/integrate-our-software-solutions
Digital logistics

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
<th>Phase 5</th>
<th>Phase 6</th>
<th>Phase 7</th>
<th>Phase 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Part geometry /design)</td>
<td>(Raw/tessellated data)</td>
<td>(Tessellated 3D model)</td>
<td>(Build file)</td>
<td>(Machine data)</td>
<td>(Fabricated part)</td>
<td>(Finished part)</td>
<td>(Validated part)</td>
</tr>
<tr>
<td>Geometry information</td>
<td>Tessellated data</td>
<td>Sliced 2.5 D for general AM</td>
<td>Processing data for specific machine/material</td>
<td>Information for AM process</td>
<td>Information for post process</td>
<td>Information for part qualification (quality assurance)</td>
<td></td>
</tr>
<tr>
<td>- Vertex inform.</td>
<td>- Vertex inform.</td>
<td>- Geometric information</td>
<td>- Information for start</td>
<td>- Process information</td>
<td>- Process information</td>
<td>- Required resources for testing</td>
<td></td>
</tr>
<tr>
<td>- Color inform.</td>
<td>- Normal information</td>
<td>- Process information</td>
<td>&gt; Setup for AM</td>
<td>- Path</td>
<td>- Type, processing time</td>
<td>- Testing information (e.g., method)</td>
<td></td>
</tr>
<tr>
<td>- Mesh inform.</td>
<td>- Triangle information</td>
<td>- Material information</td>
<td>&gt; Post</td>
<td>- Extrusion length</td>
<td>- Machine environment (e.g., manufacturer, place)</td>
<td>- Results from the testing (e.g., material testing)</td>
<td></td>
</tr>
<tr>
<td>- Other attributes</td>
<td>Tessellated model</td>
<td>- Support structure</td>
<td>&gt; Information for end</td>
<td>- Feed rate</td>
<td>&gt; Fabrication environment</td>
<td>&gt;</td>
<td></td>
</tr>
<tr>
<td>- Topological optimization</td>
<td>Optimally sliced data for specific machine</td>
<td>- Scaling factor</td>
<td>&gt; Teardown for AM</td>
<td>- Lattice structure</td>
<td>&gt;</td>
<td>&gt;</td>
<td></td>
</tr>
<tr>
<td>- Lattice structure</td>
<td></td>
<td>- Orientation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design requirement</td>
<td>Digital thread (data information representation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Data generation**
- 3D scanning sensor
  - ... 

**3D model editing**
- Registration
- Mesh generation
  - ... 

**Activities for AM process**
- Slicing with considerations of
  1) geometry information, 2) process information, 3) material information, 4) machine information,
  \[ \Rightarrow \text{Find optimal values for AM process} \]

**AM machine/material**
- EOSint M270/Ti64
- Optomec MR-7/IN625
- Sclay NG1/Stainless steel
  - ... 

**Test method**
- Round robin test
- Property test
- NDE
  - ... 

**Post process**
- Support removal
- Heat treatment
- NC machining
  - ... 

**Machine code generator**
- Software (e.g., materialize)
  - ... 

**Supporting infrastructure (Standards/Methods/Techniques/Hardware/Software for AM process and analysis)**

Source: Streamlining the additive manufacturing digital spectrum: A systems approach
http://www.sciencedirect.com/science/journal/aip/22148604
Digital logistics

<table>
<thead>
<tr>
<th>Purpose</th>
<th>STL</th>
<th>AMF</th>
<th>3MF</th>
<th>STEP</th>
<th>STEP-NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Format, Schema</td>
<td>Printing</td>
<td>Printing, information model</td>
<td>XML, XSD</td>
<td>XML, XSD</td>
<td>STEP Part 21, EXPRESS</td>
</tr>
<tr>
<td>Tessellated Geometry</td>
<td>Unstructured</td>
<td>Mesh defined by list of vertices and triangles</td>
<td>Mesh defined by list of vertices, edges, and faces</td>
<td>Mesh defined by list of vertices, triangles, edges, and vertices</td>
<td>STEP Part 21, EXPRESS</td>
</tr>
<tr>
<td>Material</td>
<td>Composite, multi-materials, for representing heterogeneous materials</td>
<td>Functional representation of material properties</td>
<td>Functional representation of material properties</td>
<td>Functional representation of material properties</td>
<td>Functional representation of material properties</td>
</tr>
<tr>
<td>Lattice Structures</td>
<td>Functional representation of lattice geometry</td>
<td>Functional representation of lattice geometry</td>
<td>Functional representation of lattice geometry</td>
<td>Functional representation of lattice geometry</td>
<td>Functional representation of lattice geometry</td>
</tr>
<tr>
<td>Build Orientation, Placement</td>
<td>Orientation and orientation of parts in build volume</td>
<td>Placement of parts in build volume</td>
<td>Placement of parts in build volume</td>
<td>Placement of parts in build volume</td>
<td>Placement of parts in build volume</td>
</tr>
<tr>
<td>Color and Texture</td>
<td>2D and 3D color maps, color at the material and object, volume, triangle, or vertex level, functional representation</td>
<td>Texture map, color at the material and object, volume, triangle, or vertex level, functional representation</td>
<td>Texture map, color at the material and object, volume, triangle, or vertex level, functional representation</td>
<td>Texture map, color at the material and object, volume, triangle, or vertex level, functional representation</td>
<td>Texture map, color at the material and object, volume, triangle, or vertex level, functional representation</td>
</tr>
<tr>
<td>Support Structures</td>
<td>Any geometry can be modeled</td>
<td>Explicitly not to be used for support structures</td>
<td>Mesh defined as support object</td>
<td>Any geometry can be modeled</td>
<td>Any geometry can be modeled</td>
</tr>
<tr>
<td>Validation Properties</td>
<td>Tessellation volume</td>
<td>Number of triangles, surface area, centroid</td>
<td>Number of triangles, surface area, centroid</td>
<td>Number of triangles, surface area, centroid</td>
<td>Number of triangles, surface area, centroid</td>
</tr>
<tr>
<td>Metadata</td>
<td>Object name, revision number, URL, producer, material strength, etc.</td>
<td>Designer, copyright, license terms, creation date, modification date, build instructions, etc.</td>
<td>Designer, copyright, license terms, creation date, modification date, build instructions, etc.</td>
<td>Designer, copyright, license terms, creation date, modification date, build instructions, etc.</td>
<td>Designer, copyright, license terms, creation date, modification date, build instructions, etc.</td>
</tr>
<tr>
<td>Tolerances</td>
<td>Single tolerance value entire part</td>
<td>Based on ASME Y14 standards</td>
<td>Based on ASME Y14 standards</td>
<td>Based on ASME Y14 standards</td>
<td>Based on ASME Y14 standards</td>
</tr>
<tr>
<td>Other</td>
<td>Many potential future features</td>
<td>Thumbnail usage, digital signature, extension mechanism</td>
<td>Long-term archiving and retrieval, research related to heterogeneous materials and shapes, future version considering curved triangles, build placement, texture maps</td>
<td>Machining operations, future version considering AM, proof-of-concept representing CLI in STEP-NC</td>
<td>Machining operations, future version considering AM, proof-of-concept representing CLI in STEP-NC</td>
</tr>
</tbody>
</table>

Source: Exploring model-based engineering concepts for additive manufacturing, Robert R. Lipman, Jeremy S. McFarlane
Proceedings of the 26th Solid Freeform Fabrication Symposium; Austin, Texas; August 2015
Additive Manufacturing

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- Digital logistics

Photo credit: www.canadianmetalworking.com

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No tooling use

HP Jet Fusion 3D Processing Station with Fast Cooling

HP Jet Fusion 3D 4200/3200 Printer

1. HP Jet Fusion 3D 4200 printing solution
   - Ideal for your prototyping and short-run manufacturing needs, with high productivity to meet same-business-day demands, at lowest cost per part.

2. HP Jet Fusion 3D 3200 printing solution
   - Ideal for prototyping, giving you improved productivity and the capacity to grow your usage at a low cost per part.
No tooling use

Source: Georges Fadel, AEFA 2015

Source: Georges Fadel, AEFA 2015

Source: Phenix Systems

Source: Volum-e, Courtesy: Airbus defense and space
Additive Manufacturing

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Photo credit: www.canadianmetalworking.com

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Production on demand
Zero stock

Source: http://www.camboxisis.fr/shop/fr/content/16-3dprinting
Production on demand
Zero stock

Scanner
Conception numérique de l’implant

Chirurgie
Stérilisation
Contrôle
Fabrication

Source : www.osseomatrix.com
Outline of the presentation

Circular Economy and Sustainable Manufacturing

Additive Manufacturing as a key player

Conclusions
We can do that today!
And also that…
Not only parts: Toolings!

Inserts in molds
Source: PEP

Inserts in molds
Source: Realizer

Blowing tools
Source: CIRTES

Injection molding toolings - PS Application PMP
R&D contract PSA / CIRTES
(Aluminium)
Next stage of AM

Main expected evolutions

- **Material**
  - Enhancement of material portfolio
    - High performance materials
    - Multi-material and in-situ alloying

- **Data preparation and process simulation and modeling**
  - Pre-defined processing strategies
    - Combining data preparation and process simulation
    - Multiscale simulations & iteratively running optimization strategies

- **System technology**
  - Automation of AM systems with increased build-up rates
    - Multi-beam systems
    - Enlarging build envelopes
    - Beam shaping
    - Integration in process chain

Source: Laser based Additive Manufacturing in industry and academia, M. Schmidt at al., Cross-STC Kn, CIRP Annals, 66/2/561-583

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Next stage of AM

Main expected evolutions

- Process monitoring
  - Development of closed loop feedback control systems
    - Prediction of process irregularities
    - Adjusting the processing strategy in-situ

- Quality assurance
  - Development of in-process quality assurance
  - From data preparation & simulation to post-processing
  - Documentation and non-destructive testing

- Post-processing
  - Individualized post-processing
  - Adjusting final part properties
  - Safe and automated routines for part finishing

Source: Laser based Additive Manufacturing in industry and academia, M. Schmidt at al., Cross-STC Kn, CIRP Annals, 66/2/561-583
Integrated production units

AddUp FormUp 750

AddUp FlexCare System

Source: AddUp
AM factory of the future
Conclusions

- Additive manufacturing is one of key players for manufacturing sustainability.

- Additive manufacturing is an additionnal set of technologies that has to be integrated in different productive sectors.

- Additive manufacturing allows complexity and diversity of products and processes without additionnal cost.

- Additive manufacturing needs the creation of 3D digital model, new formats are being created, and virtual engineering is supporting process development and simulation.

- Additive manufacturing allows rethinking part design and material characteristics after fabrication with respect to product variety and customization.

- Additive manufacturing allows putting the « just necessary material at the right place, less energy consumption, less fabrication time, lees environmental impact »

- Additive manufacturing is a very strong growth market because of a real maturity and of standardisation efforts
Thank you for your kind attention!

Questions / Discussion

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