MULTICRITERION EVALUATION OF ADDITIVE MANUFACTURING PROCESSES

Mazyar YOSOFI, Olivier KERBRAT, Pascal MOGNOL
**Introduction**

<table>
<thead>
<tr>
<th>Invention of Additive manufacturing</th>
<th>Fused deposition modeling</th>
<th>Open source machines</th>
<th>First robotic heart is printed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>1986</td>
<td>1996</td>
<td></td>
</tr>
<tr>
<td>First photopolymerization machine. STL file</td>
<td>Introduction of 3D printing</td>
<td>2007</td>
<td>Personal 3D printing</td>
</tr>
<tr>
<td>Aerospace</td>
<td></td>
<td>2012</td>
<td>3D printed clothes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2013</td>
<td>Surgeons implanted 3D printed pelvis</td>
</tr>
</tbody>
</table>

**What about the environmental impact?**

- **Technical ✓**
  - Exact amount of material
  - Economic ✓
  - Incomplete inventory data

**Reducing the environmental impact**

- Lack of information
- Imprecise life cycle assessment
- Why...
Bibliographic review

Environmental phenomena participating in the realisation of a part for AM processes:

- Luo et al. 1999
- Morrow et al. 2006
- Gutowski et al. 2006
- Telenko et al. 2012
- Wittbrodt et al. 2013
- Faludi et al. 2014
- Mani et al. 2014
- Huang et al. 2015...
- Yoon et al. 2014
- Mognol et al. 2006
  - Reeves 2009
  - Le Bourhis et al. 2014
  - Meteyer et al. 2014
  - Kerbrat et al. 2015
  - Kellens et al. 2014
  - Ford et al. 2015
  - Burkhart et al. 2015...
- Kara et al. 2011

- Electrical energy
- Material, fluids
# Bibliographic review

## Electric consumption of different additive manufacturing process:

<table>
<thead>
<tr>
<th>Processes</th>
<th>Material</th>
<th>VAT photopolymerization</th>
<th>Powder bed fusion</th>
<th>Directed energy deposition (metal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEC (kWh/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>23 - 697</td>
<td>21 - 41</td>
<td>15 - 1346</td>
<td>31 - 710</td>
</tr>
<tr>
<td></td>
<td>24.2 - 385</td>
<td>15 - 41</td>
<td>15 - 41</td>
<td>24.2 - 385</td>
</tr>
</tbody>
</table>

## Disparities in the electrical consumption of machines

- **Choice of processes?**
- **Factor 22 !**
- **Factor 35 !!**
- **Factor 90 !!!**
- **What data to take for a LCA?**
- **Accurate evaluation of AM processes**
Methodology
Definition of a multicriterion evaluation method:

Step 1: Acquisition method
- Decomposition in manufacturing stages
  - E_CAD file + E_Idle + E_Preparation + E_Forming + E_Post-process
  - V_process + V_Auto + V_Manual

Step 2: Model’s writing
- Method for obtaining the electrical model
- Method for obtaining the fluids model
- Method for obtaining the material consumption model
- Method for obtaining the economic model
- Method for obtaining the technical model

Step 3: Results
- Technical-economic and environmental evaluation model
- Multicriteria optimization
- Inventory data
- Cost
- Mechanical characteristic
- Technical evaluation
- Ra, Re...
Results – Decomposition in manufacturing stages

**Stages:**
- CAD file preparation
- Idle
- Warm-up/preparation mode
- Forming
- Post-process

**Processes:**
1. CAD file preparation
   - Maintain the enclosure $T^\circ$
   - Idle
   - Nozzle warm-up
   - Forming
   - Post-process

2. CAD file preparation
   - Plate Warm-up
   - Maintain the plate $T^\circ$
   - Nozzle warm-up
   - Maintain the nozzle $T^\circ$
   - Forming
   - Post-process

**Duration:**
- Part
- Machine and part
- Part

**Notes:**
- HP designjet 3D
- Makerbot replicator 2X
Results – Acquisition, repetition and evaluation of inventory data

30 x 30 x 10 mm, ABS plus

- 5 repetitions
- Same initial conditions
- Fabrication time: 22 min
Results – Data processing

<table>
<thead>
<tr>
<th>Phases</th>
<th>Power (W)</th>
<th>Duration(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD file preparation</td>
<td>31,6</td>
<td>300</td>
</tr>
<tr>
<td>Idle</td>
<td>130</td>
<td>1320</td>
</tr>
<tr>
<td>Maintain the enclosure $T^*$</td>
<td>276</td>
<td>1320</td>
</tr>
<tr>
<td>Nozzle warm-up</td>
<td>294,9</td>
<td>84</td>
</tr>
<tr>
<td>Forming</td>
<td>81,2</td>
<td>1236</td>
</tr>
</tbody>
</table>

Mass part: 8,4 g
Mass support: 1,2 g
Results – Cost and technical characteristics

**Total cost:**
- Equipment cost
  - Machine purchase cost, depreciation/year, Number of hour the machine is used/year -> Hourly cost
- Material Cost
  - Material quantity used, cost of material per kg -> Material cost
- Staff cost
  - Time spend for CAD file preparation and post process stages

**Technical characteristics:**
- Data extracted from the litterature
  - Prediction of the arithmetic roughness of a part produced by fused deposition modeling as a function of the layer height and the deposition angle (Boschetto et Al. 2014)
## Results

- Estimated value
- Real value
- Gap in %

<table>
<thead>
<tr>
<th></th>
<th>Small gaps</th>
<th>Reproducible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (Wh)</td>
<td>183,3</td>
<td>193</td>
</tr>
<tr>
<td>Material (g)</td>
<td>8,2</td>
<td>8,4</td>
</tr>
<tr>
<td>Cost</td>
<td>21,4</td>
<td>21,3</td>
</tr>
<tr>
<td>Ra (µm)</td>
<td>17,2</td>
<td>17,2</td>
</tr>
</tbody>
</table>
Methodology

Input
- Numerical model of the part
- Process data

Step 1
- Decomposition in manufacturing stages
- E_CAD file + EIdle + E_Preparation + E_Forming + E_Post-process
- V_process + V_Auto + V_Manual
- Method for obtaining the electrical model
- Method for obtaining the fluids model
- Method for obtaining the material consumption model
- Method for obtaining the economic model
- Method for obtaining the technical model

Step 2
- Electrical energy evaluation
- Fluids consumption evaluation
- Material evaluation
- M_part (g)
- M_support (g)
- Cost evaluation
- Technical evaluation

Step 3
- Technical-economic and environmental evaluation model
- multicriteria optimization

Output
- Inventory data
- Cost
- mechanical characteristic

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Results – Step 2 of the methodology: Models writing

Information to enter in the numerical tool:
• Total manufacturing time = $T_{\text{Manufacturing}}$
• CAD file preparation and post-process times
• Volume of the part and the material
• Layer height and the deposition angle

Electrical evaluation

$$E_{\text{Total}} = (P_{\text{CAD file preparation}} 	imes T_{\text{CAD file preparation}}) + (P_{\text{Idle}} 	imes T_{\text{Manufacturing}}) + (P_{\text{Warm-up}} 	imes T_{\text{Warm-up}}) + (P_{\text{Enclosure}} 	imes T_{\text{Manufacturing}}) + (P_{\text{Forming}} 	imes T_{\text{Forming}}) + (P_{\text{Post-process}} 	imes T_{\text{Post-process}})$$

Fluids evaluation

$$V_{\text{Total}} = V_{\text{Process}} + V_{\text{Auto}} + V_{\text{Manual}}$$
$$V_{\text{Process}} = d_{\text{Gas}} 	imes t_{\text{Gas}} + d_{\text{Water}} 	imes t_{\text{Water}}$$
$$V_{\text{Auto}} = V_{\text{(Water automatic post-process)}} (V_{\text{Part}})$$
$$V_{\text{Manual}} = V_{\text{(Water manual post-process)}} (d_{\text{pump}}, t_{\text{handling}})$$

Material evaluation

$$M_{\text{Total}} = \rho_{\text{Part}} 	imes V_{\text{Part}} + \rho_{\text{Support}} 	imes V_{\text{Support}}$$

Cost evaluation

$$Cost_{\text{Total}} = Cost_{\text{Equipment}} + Cost_{\text{Material}} + Cost_{\text{Staff}}$$

Technical evaluation

$$Ra = \frac{L \cdot \csc (\alpha)}{9 \sqrt{3}}$$
Résultats – Step 3 of the methodology: Results displaying

<table>
<thead>
<tr>
<th></th>
<th>Model</th>
<th>Real</th>
<th>Gap (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (kWh)</td>
<td>6,44</td>
<td>6,34</td>
<td>1,63</td>
</tr>
<tr>
<td>Fluids (liters)</td>
<td>0,5</td>
<td>0,5</td>
<td>0</td>
</tr>
<tr>
<td>Mass part (g)</td>
<td>65,5</td>
<td>63,3</td>
<td>3,36</td>
</tr>
<tr>
<td>Mass support (g)</td>
<td>14,8</td>
<td>13,7</td>
<td>7,4</td>
</tr>
<tr>
<td>Cost (Euros)</td>
<td>41,7</td>
<td>42,5</td>
<td>1,92</td>
</tr>
<tr>
<td>Ra area A (µm)</td>
<td>16,6</td>
<td>18,8</td>
<td>13</td>
</tr>
<tr>
<td>Ra area B (µm)</td>
<td>19,5</td>
<td>22,6</td>
<td>15,8</td>
</tr>
</tbody>
</table>
Results – Application and validation on other machines

<table>
<thead>
<tr>
<th>Code</th>
<th>Machine</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDM1</td>
<td>Makerbot replicator 2X</td>
<td>Fused deposition modeling</td>
</tr>
<tr>
<td>FDM2</td>
<td>Rapman 3.2</td>
<td>Fused deposition modeling</td>
</tr>
<tr>
<td>FDM3</td>
<td>Stratasys Mojo</td>
<td>Fused deposition modeling</td>
</tr>
<tr>
<td>FDM4</td>
<td>HP designjet 3D</td>
<td>Fused deposition modeling</td>
</tr>
<tr>
<td>FDM5</td>
<td>Dimension Elite</td>
<td>Fused deposition modeling</td>
</tr>
<tr>
<td>JET1</td>
<td>Stratasys Objet 30 pro</td>
<td>Material jetting</td>
</tr>
<tr>
<td>JET2</td>
<td>Stratasys Objet260 Connex</td>
<td>Material jetting</td>
</tr>
</tbody>
</table>
Synthesis

Balance of contribution:

- Predictive model
- Inventory data
- Goal and scope definition
- Interpretation
- Inventory analysis
- Impact assessment

- CAD file
- kWh
- kg
- Litres
- Cost
- Mechanical properties
Thank you for your attention

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