# Process costs

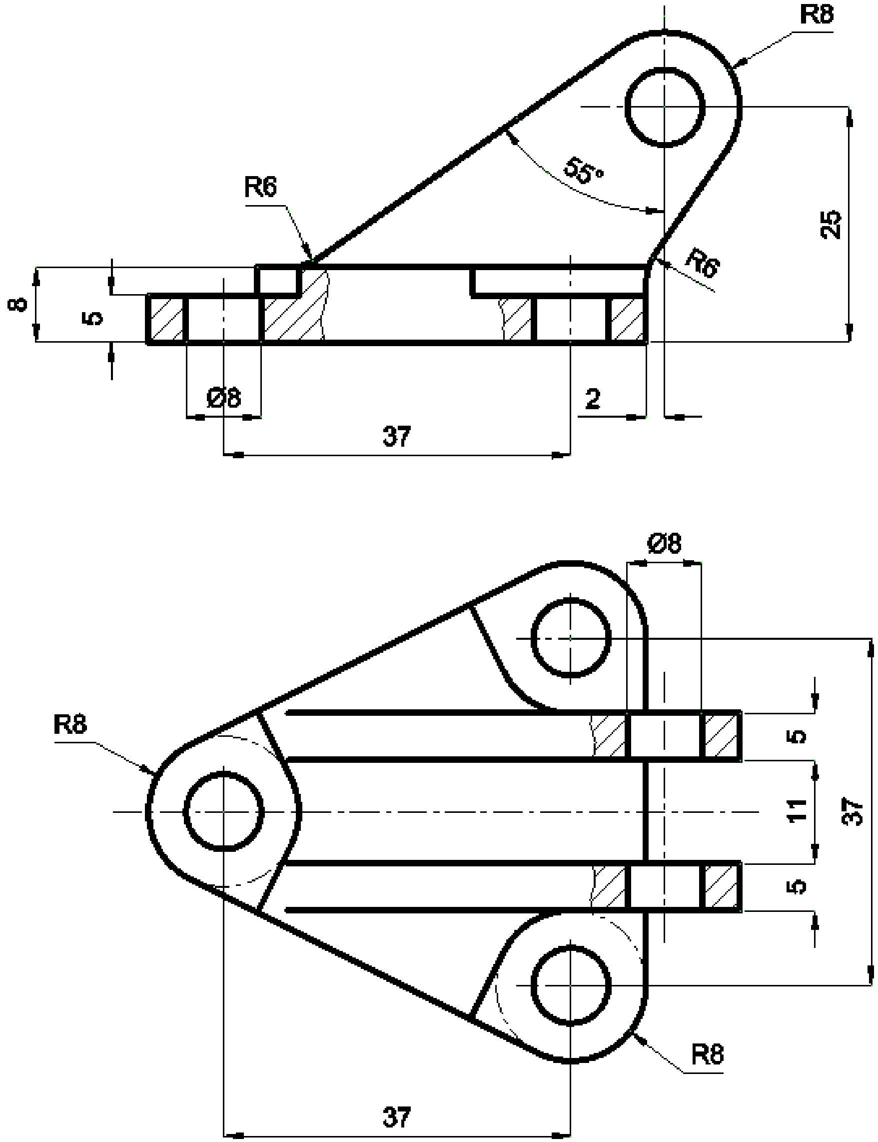
How much does it cost to produce a 3D printed part?

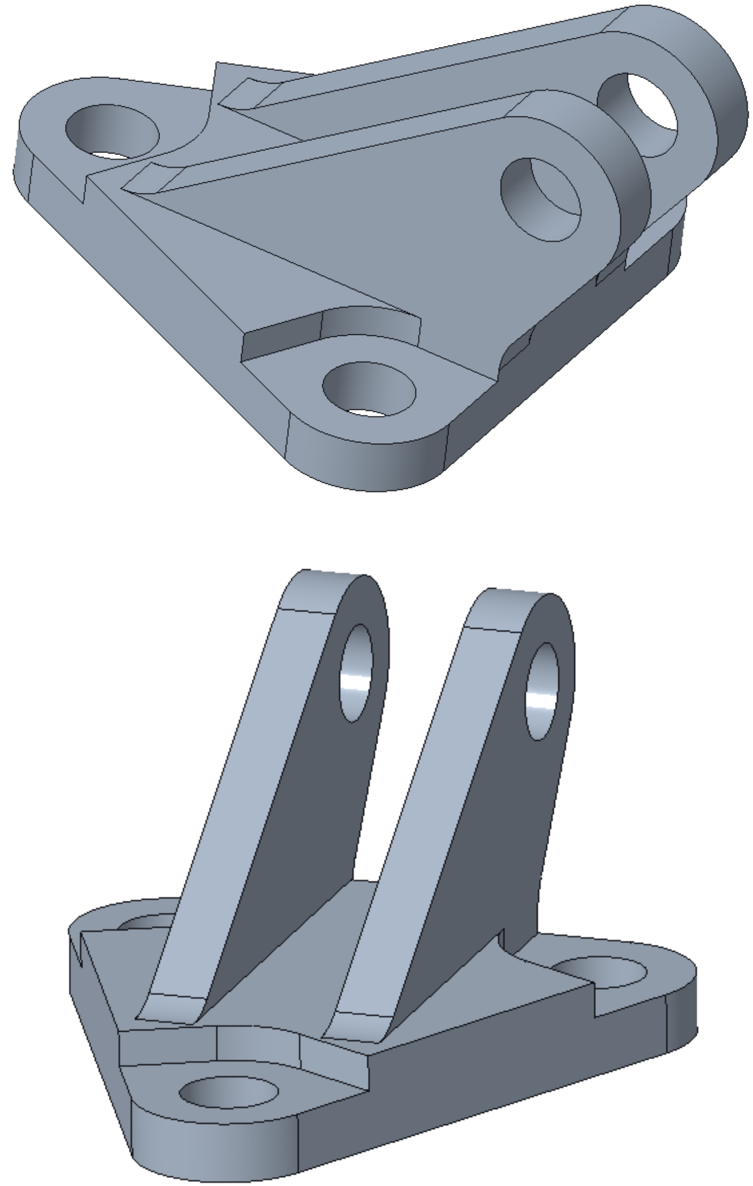
# Process description

- The process chain of Metal-ME and MIM can be divided in three main stages:
  - the first one involves all the necessary activities for designing parts and then for designing and processing any tool useful for starting the production
    - CAD modelling, topological optimization, STL exporting, 3D printer part program realization …
  - the second stage involves the actual production of designed parts, including all the activities necessary for setting up the equipment
    - part program loading, wire or powder preparation, machine preparation, part production …
  - the last stage is related to the post-processing activities
    - part support removal, sandblasting for metal parts, debinding and sintering for metal extrusion, surface finishing, painting, thermal treatment …

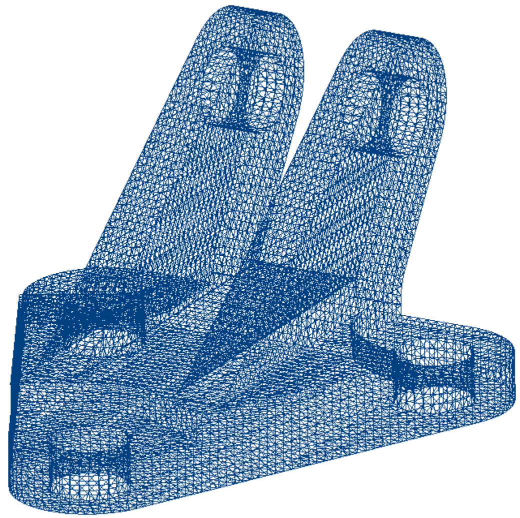
- The time required and the costs are greatly influenced by the complexity of the part, by the chosen process and by the used material

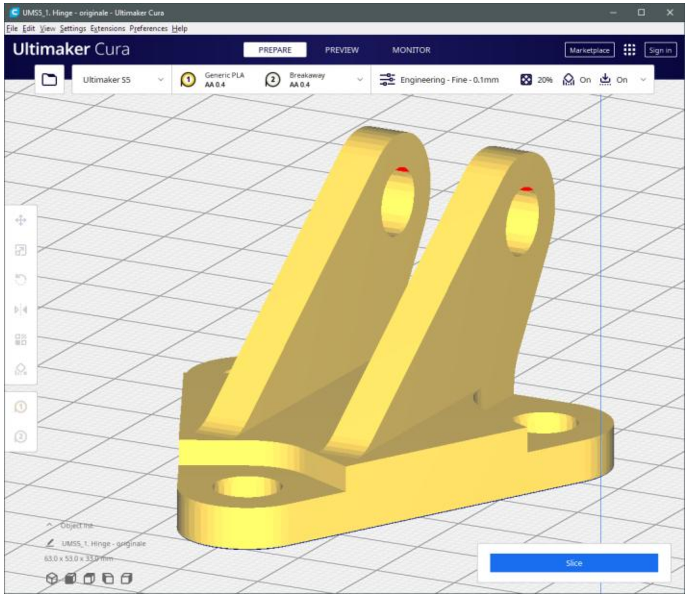
# Part to be produced

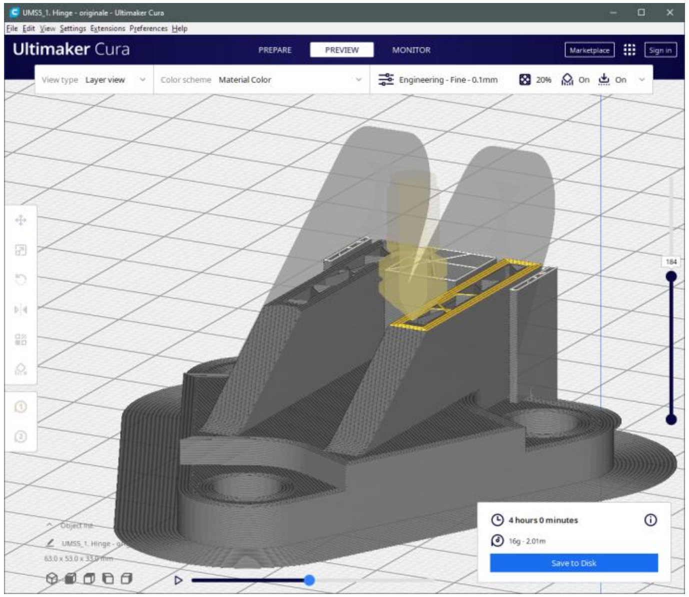


# STL from CAD to SLICER for FDM program preparation



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M82
G92 E0
M109 S200
G280 S1
G0 Z20.001
G1 F1500 E-6.5
M204 S625
M205 X8.33 Y8.33
G1 F600 Z2.2
G0 F6000 X199.364 Y136.245 Z2.2
M204 S500
M205 X5 Y5
G1 F600 Z0.2
G1 F1500 E0
G1 F1200 X198.928 Y136.85 E0.0112
G1 X198.429 Y137.405 E0.02245
...
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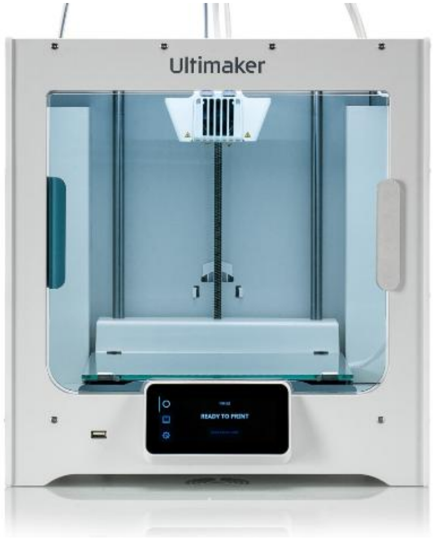


# Cost estimation – FDM process

- **The first stage**, mainly involves costs related to the time spent for the design and the optimization of the product and for defining the tool/nozzle path and can be considered **as fixed costs**, i.e. they are independent of the number of the part to be produced
- For **the second stage** the main cost terms are related to:
  - Fixed cost ($C_0|_{1h}$) involves all the costs that do not change with a variation in the production volume. It considers the fixed costs, such as the depreciation, the ordinary and extraordinary maintenance, and the operator cost, and they are related to the operating time of the machine during a year. In this way it is possible to define the **hourly cost**
  - Variable costs ($VC$) group all the cost drivers that change with a variation of the production volume involving the materials, consumables, and energy consumption
  - Defective parts fraction ($\varepsilon$) is a percentage indicating that for satisfying a certain production volume, it is necessary to increase the total number of produced parts to balance the scrapped parts

**FIXED COSTS**

- Machine cost
- Ordinary/Extraordinary maintenance
- Operator

**VARIABLE COSTS - PRODUCTION PROCESS**

**CONSUMABLES**

- Machine nozzle
- ...

**ENERGY**

- Machining time
  - Set-up time
  - Warm-up time
  - Working  time
  - Auxiliary time
- Machine power consumption
  - In idle state
  - In warm-up state
  - In working state

**RAW MATERIAL**

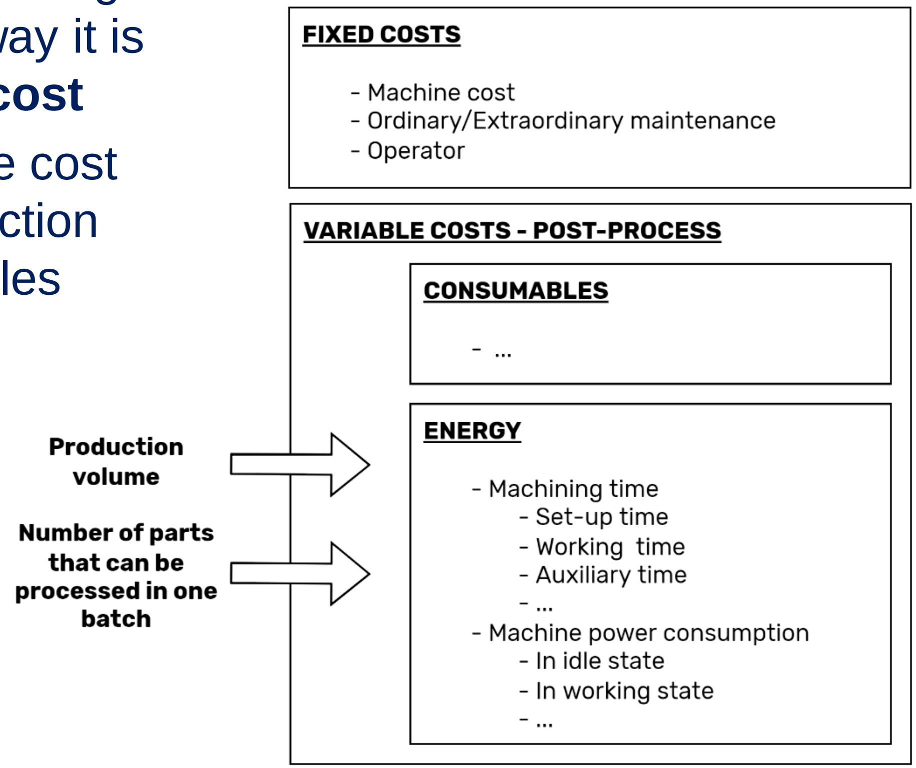
- Part volume
- Infill
- Material density
- Number of parts to be produced

**ORDER**

**Production volume**

**Defective parts fraction**

- For the **third stage** the costs are related to the post-process required and can be related to:
  - <u>Fixed cost</u> ($C_0|_{1h}$) considering the depreciation, the ordinary and extraordinary maintenance, and the operator cost, and they are related to the operating time of the post-processing machine during a year. In this way it is possible to define their **hourly cost**
  - <u>Variable costs</u> ($VC$) group all the cost drivers changing with the production volume; they involve consumables and energy consumption



# Fixed costs

- The fixed cost ($C_0|_{1h}$) is estimated as an hourly cost including the depreciation of machine, relative infrastructure, and their ordinary and extraordinary maintenance compared to their annual usage and the hourly cost of the operator ($C_{op}$)

# Fixed costs

- The costs of machine $(C_{mac})$ and infrastructures $(C_{infr})$ can be split on their lifetime $(\tau)$, defined by the number of years it is supposed to use this machine. Then, the hourly cost has been defined considering the machine uptime in one year $(t_{op})$ as the sum of the idle time, stand-by time and the time for breakdowns and maintenances:

$$C_0\Big|_{1h} = \frac{\frac{C_{mac} + C_{infr}}{\tau} + C_{om}|_{1y} + C_{em}|_{1y}}{t_{op}} + C_{op}$$

where $C_{om}|_{1y}$ and $C_{em}|_{1y}$ are the annual cost of the ordinary and extraordinary maintenance activities, including the machine and the infrastructure repairs, replacements, and upkeep work required for the general use and operation to maintain and preserve the equipment in good order and to restore the working conditions after any breakdown

# Actual number of parts to produce

- For considering a certain amount of non-compliant products, it is necessary to calculate the actual number of parts to be produced to satisfy the entire order with compliant pieces. Consequently, defining as $N_{ord}$ the dimension of customer order, the actual production volume ($N_p$) can be estimated as:

$$N_p = \frac{N_{ord}}{1 - \varepsilon}$$

where $\varepsilon$ is the probability of having defective parts that must be discarded

# Variable costs

- The variable costs consider the cost drivers related to the production volume and can be classified into three categories:
  - Material cost ($C_m$) considers the material necessary for producing all the required parts as a function of the material density ($\rho$), the unit cost of material ($c_{mat}$ in [€/Kg]), and the volume of a single part ($V$):

$$C_m = c_{mat} \cdot V \cdot \rho \cdot N_p$$

  - Consumables cost ($C_c$) considers all the consumable elements ($i$) that can be deteriorated during the production that must be replaced (e.g., the nozzle). Knowing how many units of single consumable ($N_i$) are needed for producing the defined production volume and the unit cost of the $i-th$ element ($c_i$), the consumables cost can be estimated as:

$$C_c = \sum_i c_i \cdot N_i$$

# Variable costs

- <u>Energy cost</u> ($C_e$) considers the energy consumption of machine in its different state (idle, working and warm-up). Each state has a different power absorption, and the cost of energy depends on how long the machine remains in a certain state. In general, the idle condition is maintained during the setup ($t_{su}$), the consumable replacement activities ($t_{cc_i}$) and the auxiliary activities (e.g., loading material in MIM). The auxiliary activities (movements and activities focused to the preparation of the process) time ($t_{aux}$) can be evaluated as a fraction ($\gamma$) of the entire production time ($t_w$). The warm-up condition is maintained during the heating phases of either the build plate or the moulds ($t_{wu}$), if it is required. The working state corresponds to the actual production process ($t_w$). $c_{en}$ is the unit cost of the energy (€/kWh), while $P_i$, $P_{wu}$ and $P_w$ represent the power consumption of the machine in idle, warm-up and production state, respectively:

$$C_e = \left(t_{su} + \sum_i t_{cc_i} N_i + t_w \gamma\right)\left(C_0\Big|_{1h} + c_{en} P_i\right) + t_{wu}\left(C_0\Big|_{1h} + c_{en} P_{wu}\right) + t_w\left(C_0\Big|_{1h} + c_{en} P_w\right)$$

# Working time calculation

- It is possible to obtain the working time (i.e. the time needed to print the part) in two ways:
  - Starting from the printing parameters, introducing the concept of Material Deposition Rate (MDR [$mm^3/s$]) representing the volume of the material printed in the unit of time. Since the extruded material is characterized by an elliptical section at the outlet from the nozzle, MDR can be calculated as function of the printing parameters, i.e. the print speed $(s)$, the layer thickness $(h)$, and the diameter of the nozzle ($\phi$). The printing time can be expressed as the ratio between the material volume and the MDR:

$$t_w = \frac{V \cdot \delta}{MDR} = \frac{V \cdot \delta}{\pi \cdot \frac{h}{2} \cdot \frac{\phi}{2} \cdot s}$$

    where $V$ indicates the volume of the part and $\delta$ is the infill percentage affecting the quantity of material involved in the deposition process
  - Alternatively, the printing time can be calculated by the slicer software

# Total material cost

- The  total material cost can be written as:

$$C_m = c_{mat} \cdot V_1 \cdot \rho \cdot N_p \cdot \delta$$

- A further analysis of the costs regards the effect of the number of parts obtained in a single working cycle. In particular, for FDM this is represented by the possibility of printing more than one part on the same plate ($N_b$)

  This reduces the total time due to the set-up, while the other costs remain almost constant

# Unit cost

- The cost to produce a single part ($UC$) can consequently be expressed as:

$$UC = \frac{C_0|_{1h} \cdot t + C_e + C_m + C_c}{N_{ord}}$$

where $t$ is the sum of the duration of all activities listed in the energy driver

# An example – A turbine blade

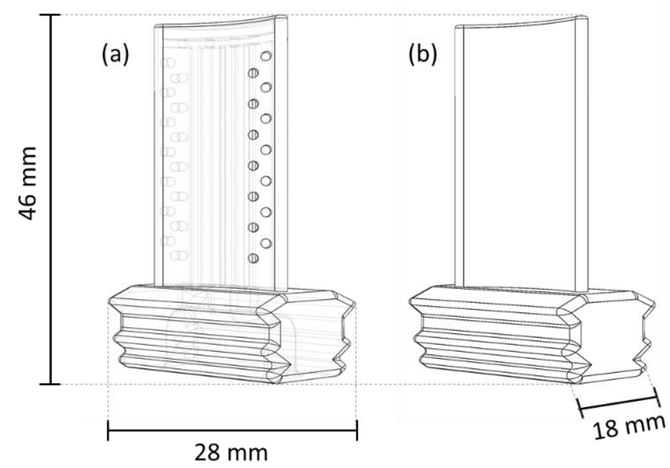
| Printing parameters | | |
|---|---|---|
| h [mm] | 0.1 | *Layer thicknes* |
| s [mm/s] | 20.00 | *Print speed* |
| Infill | 100.00% | |
| Travel | 3.00% | |
| ϕnozzle [mm | 0.6 | |
| **Machine Data** | | |
| Cmac [€] | 7,000.00 | *Machine cost* |
| Cinf | - | |
| λmac [years] | 3.00 | *Machine lifetime* |
| Deprec [€/y] | 2,333.33 | *Depreciation* |
| OM [€/y] | 350.00 | *Maintenance cost* |
| h/d | 8.00 | |
| d/w | 5.00 | |
| w/y | 40.00 | |
| %mac | 80% | |
| top_1y [h/y] | 1,280.00 | *Operating time in a year* |
| Cop [€/h] | 12.00 | *Operator cost* |
| Defects | 5.00% | |
| **Materials & Consumables** | | |
| ρ [g/cm3] | 4.95 | *Material density* |
| Mspool1 [kg] | 3.00 | *Filament spool mass* |
| τnozzle [Kg] | 20.00 | *Nozzle lifetime* |

| Fixed Time | | |
|---|---|---|
| tcn [min] | 15 | *time for nozzle change* |
| tcspool [min] | 5 | *time for filament change* |
| tcbuild [min] | 2 | *time for plate change* |
| twarm up [min | 5 | *Warm-up time* |
| tsu [min] | 15 | *Set-up time* |
| **Fixed Cost** | | |
| Co [€/h] | 14.10 | *Hourly cost* |
| Cen [€/kWh] | 0.23 | *Cost of energy* |
| Cn [€] | 290.00 | *Nozzle cost* |
| Cmat1 [€/kg] | 129.00 | *Cost of spool* |
| **Fixed Power** | | |
| Pidle [kWh] | 0.22 | *Power idle* |
| Pwork [kWh] | 0.16 | *Power print* |
| Pwarm-up [kW | 0.45 | *Power warm-up* |

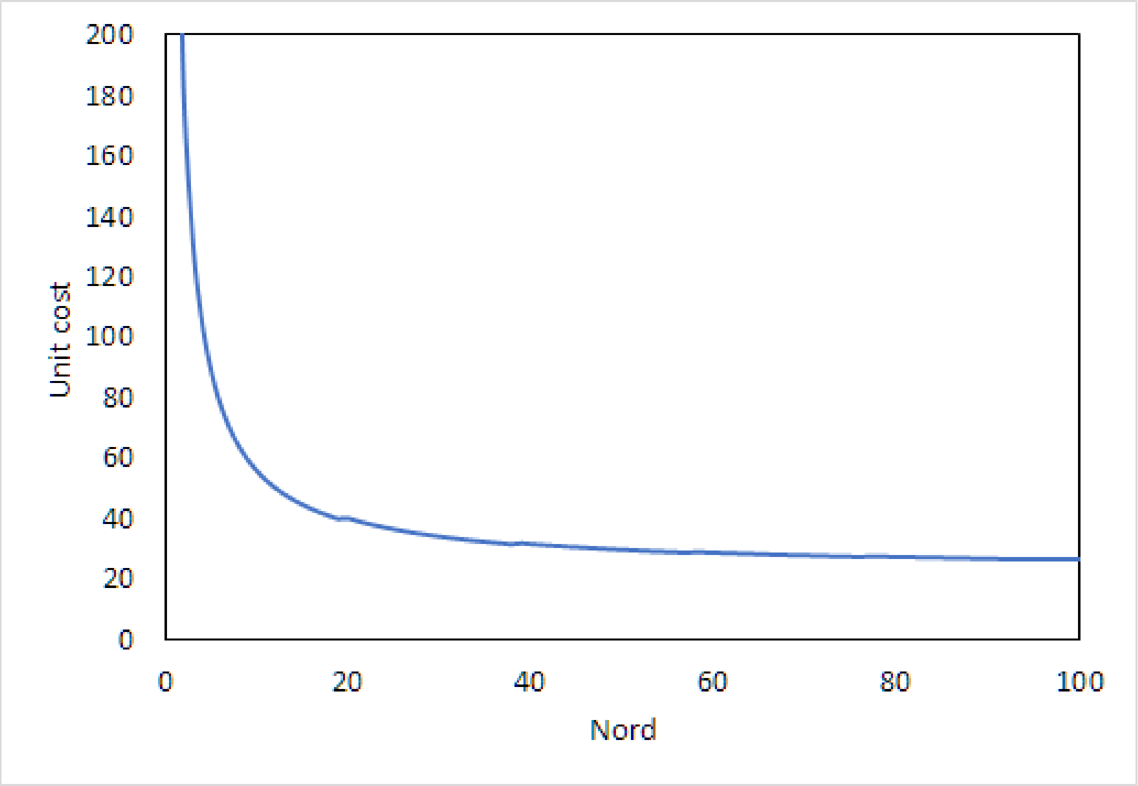
| Part characteristics | | |
|---|---|---|
| V1 [mm3] | 4600 | *Single part volume* |
| m1 [g] | 22.77 | *Single part mass* |
| **Process characteristics** | | |
| Nord | 100 | *Customer order* |
| Np | 106 | *Production volume* |
| Np/bulid | 2 | *Part per build* |
| MDR [mm3/min] | 56.55 | *Material Deposition Rate* |
| Mtot [Kg] | 2.41 | |
| tprint1 | 81.35 | *Print time for single part* |
| tprint | 8622.66 | *Print time for Np* |
| taux | 83.79 | |
| Nbuild | 53.00 | *Number of build for covering the Np* |
| Nnozzle | 1 | *Number of nozzle for covering Np* |
| Nspool | 1 | *Number of spool for covering Np* |

Some of these values are assigned, others are calculated according to the previous formulas

| COST | | |
|---|---|---|
| Cidle | 53.00 | *Cost of idle state* |
| Cwarm-up | 6.06 | *Cost of warm-up stage - it is repeted for each build* |
| Cprint | 2,031.09 | *Cost of print stage* |
| Ccons | 290.00 | *Cost of consumables* |
| Cmat | 311.36 | *Cost of material* |
| TC | 2691.51 | *Total Cost - Considering the p%of defects* |
| UC | 26.92 | *CT/Np* |
| **RATE** | | |
| PR [pz/h] | 0.6584400 | *Productivity rate* |
| DT [h/pz] | 1.68 | *Dummy time* |

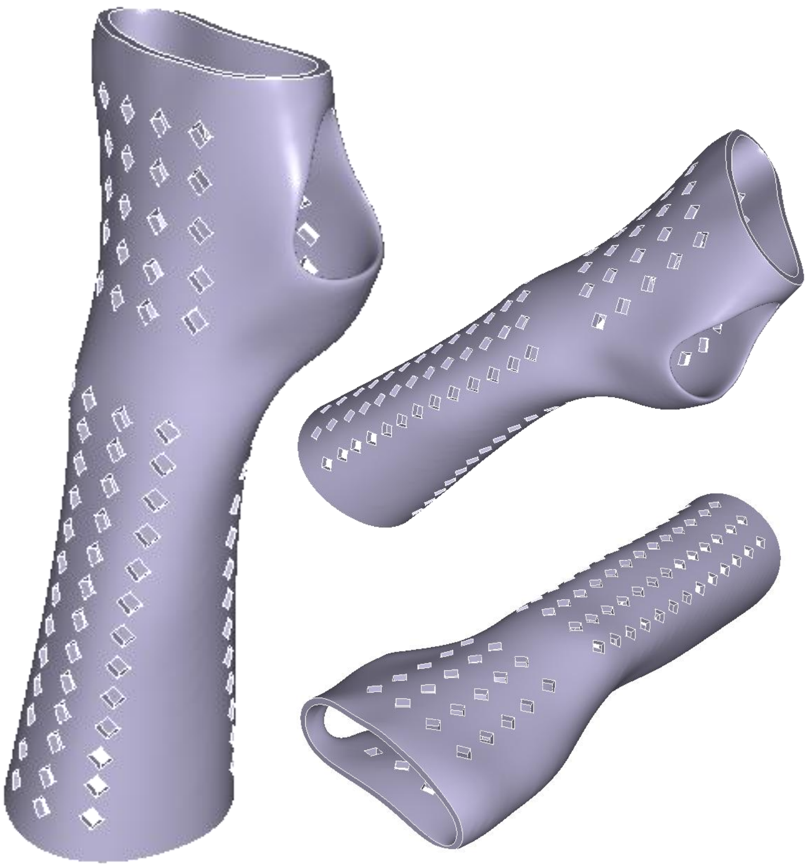


# An example – A turbine blade



# An example
# Wrist prosthesis

In this case a similar approach is used.
It is possible to see the comparison between the costs when using different materials



| | | ABS | PLA | PC |
|---|---|---|---|---|
| **COST OF THE AM TECHNOLOGY** | **T [€]** | **0.60** | **0.59** | **0.59** |
| Production time | tp [h] | 2.20 | 3.00 | 3.00 |
| (1) warm-up time | twu [h] | 0.12 | | |
| (2) set-up time | tsu [h] | 0.03 | | |
| (3) cooling time | tc [h] | 0.13 | | |
| (4) deposition time | td [h] | 1.92 | 3.00 | 3.00 |
| technology price | pt [€] | 6000.00 | 6000.00 | 6000.00 |
| employment rate | er1 [1] | 0.50 | 0.70 | 0.70 |
| technology life | y1 [y] | 5.00 | 5.00 | 5.00 |
| **COST OF THE 3D SCANNER** | **S [€]** | **0.24** | **0.04** | **0.04** |
| scanning time | ts [h] | 0.03 | 0.03 | 0.03 |
| scanner price | ps [€] | 70000.00 | 70000.00 | 70000.00 |
| employment rate | er2 [1] | 0.10 | 0.60 | 0.60 |
| scanner life | y2 [y] | 10.00 | 10.00 | 10.00 |
| **COST OF THE TECHNOLOGY EMPLOYMENT** | **ET [€]** | **0.14** | **0.12** | **0.24** |
| deposition time | tp [h] | 1.92 | 3.00 | 3.00 |
| deposition power consumption | wp [kW] | 0.23 | 0.15 | 0.30 |
| other times (warm-up, set-up, cooling) | t [h] | 0.28 | 0.00 | 0.00 |
| other power consumption | wo [kW] | 0.3135 | 0.23 | 0.35 |
| electricity price | pe [€/kWh] | 0.26 | 0.26 | 0.26 |
| **COST OF THE SCANNER USE** | **ES [€]** | **0.00** | **0.00** | **0.00** |
| scanning time | ts [h] | 0.03 | 0.03 | 0.03 |
| scanner power consumption | ws [kW] | 0.19 | 0.19 | 0.19 |
| electricity price | pe [€/kWh] | 0.26 | 0.26 | 0.26 |
| **COST OF THE MATERIAL** | **M [€]** | **4.714** | **8.65** | **9.06** |
| % infill materiale | im [1] | 1.000 | 1.00 | 1.00 |
| material price | pm [€/kg] | 50.000 | 44.00 | 72.67 |
| material weight | mw [kg] | 0.094 | 0.20 | 0.12 |
| *material volume* | mv [mm^3] | 85538.511 | 158603.97 | 104469.68 |
| *extruded wire length* | ewl1 [mm] | 13510.000 | 25050.00 | 16500.00 |
| *layer area* | hl [mm] | 6.331 | 6.33 | 6.33 |
| *layer radius* | hw [mm] | 1.420 | 1.42 | 1.42 |
| *material density* | mp [g/cm^3] | 1.100 | 1.24 | 1.19 |
| % infill materiale di supporto | ims [1] | 0.100 | 0.10 | 0.10 |
| support material price | psm [€/kg] | 72.670 | 72.67 | 72.67 |
| support material weight | smw [kg] | 0.001 | 0.00 | 0.00 |
| *support material volume* | smv [mm^3] | 1013.039 | 0.00 | 2405.97 |
| *extruded wire length* | ewl2 [mm] | 160.000 | 0.00 | 380.00 |
| *layer area* | hl [mm] | 6.331 | 6.33 | 6.33 |
| *layer radius* | hw [mm] | 1.420 | 1.42 | 1.42 |
| *support material density* | smp [g/cm^3] | 1.220 | 1.22 | 1.22 |
| **LABOUR COST** | **L [€]** | **20.15** | **15.00** | **15.00** |
| Labour time | tl [h] | 0.50 | 0.50 | 0.50 |
| Labour price | pl [€/h] | 40.00 | 30.00 | 30.00 |
| **TOTAL** | | **25.85** | **24.40** | **24.93** |