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Competence Unit Training CU 34 – Process Selection

**Course: AM Cost Evaluation and management based on
process oriented approach (Part 2)**

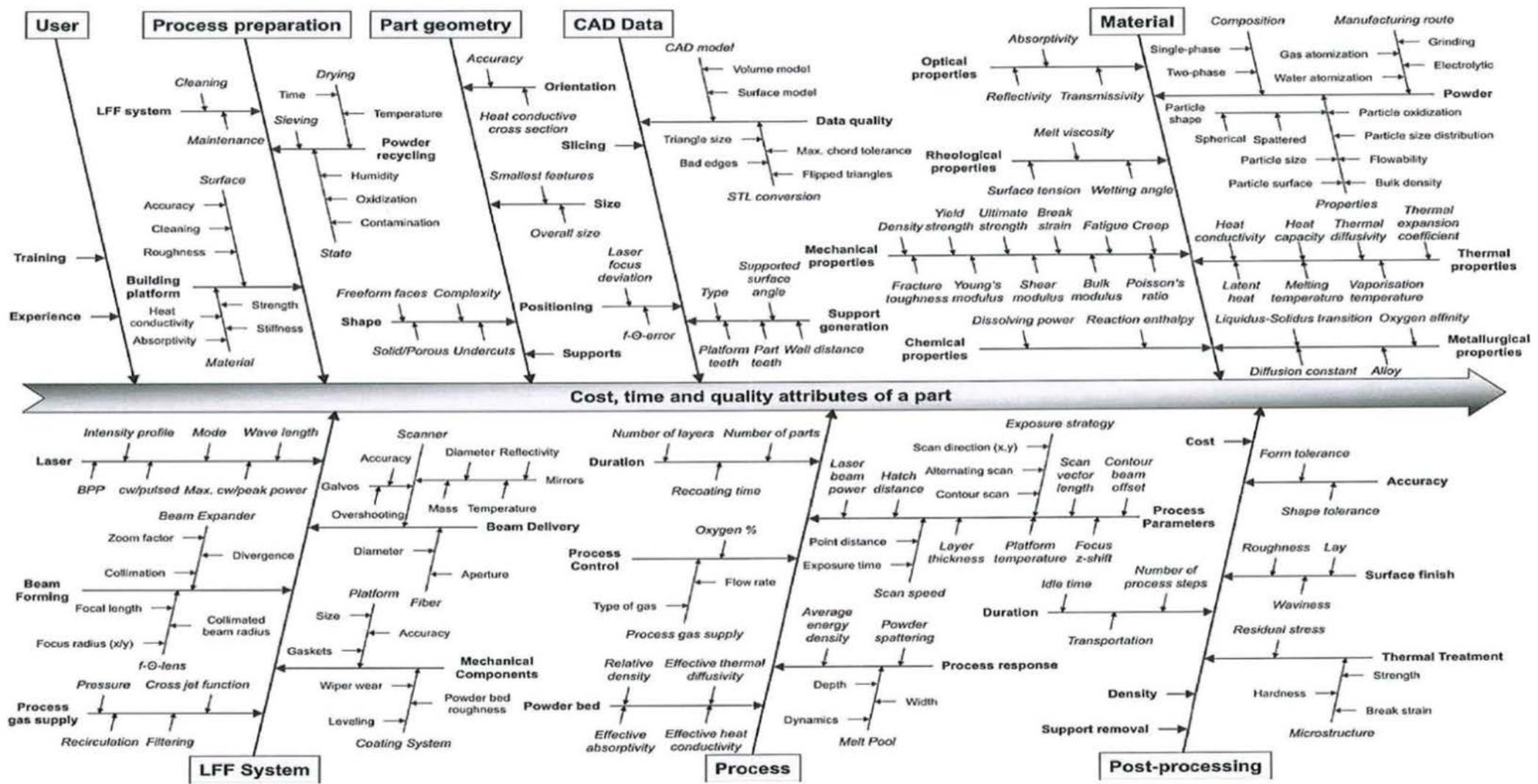
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AM Technology selection based on comparison of performance indicators

Main factors affecting the performance of AM processes



Over 200 different parameters that could potentially affect the main performance criteria of AM part, see following figure: by ("Cellular Design for Laser Freeform Fabrication", Dr. Olaf Rehme)

Additive Manufacturing Technology Selection

Critical process Selection Problems

- **Given Design !!** Which are the best technology/ Machine to use or buy?
- **Given Part !!** Which machine and material should I use to build?
- **Given Machine, Part, and Material !!** How to set the machine up to meet different requirement, in the most efficient manner?



Solution to Selection Problems

- **Capabilities and limitation** of 3D printing Technologies/Machines
 - For a given designs: achievable accuracy, tolerance, layer thickness, ...etc.
 - For a given materials: the compatible (Machine/ Material), the achievable mechanical properties
- **Costs** (Raw material cost, Machine/ technology installation price, Operation costs)
- **Time to market** (Velocity)



Additive Manufacturing Technology Selection

Major factors to consider

- **Part**
 - Size, weight
 - Geometrical complexity, accuracy, surface finish, color, ...
 - Costs (Part fabrication cost)
 - Quantity requirement (certification needed??)
 - Activity sector (purpose of use; mechanical properties, demo, replacement, repair, ...)
- **Machine**
 - Compatible material, allowable part size, ...
 - Build speed (real productivity, cm³/hour)
 - Achievable geometry (complex geometry, with/ without support structure)
 - Costs (Machine cost)
- **Material**
 - Compatible machines
 - Cost (Raw material cost)
 - Properties (mechanical, thermal, thermal, ...)

Additive Manufacturing Technology Selection

Further comparison (Major criteria)

- *Cost, Quality, and time are the most useful performance criteria that must be evaluated to give a measure of the product value and also the value provided by the value chain.*



Additive Manufacturing Technology Selection

Compatible materials with AM process category

	Material extrusion	Material jetting	Binder jetting	Vat photopolymerization	Sheet lamination	Powder bed fusion	Directed energy deposition
Polymers and polymer blends	x	x	x	x	x	x	
Composites		x	x	x		x	
Metals		x	x		x	x	x
Graded/hybrid metals					x		x
Ceramics			x	x		x	
Investment casting patterns		x	x	x		x	
Sand molds and cores	x		x			x	
Paper					x		

Source: Wohlers, Terry. "Wohlers Report 2012: Additive Manufacturing and 3D Printing State of the Industry." Wohlers Associates, Inc. 2012.

Additive Manufacturing Technology Selection

Material, and machine for different AM process category

Senvol Database is the first and most comprehensive database for industrial additive manufacturing **machines, and materials**.



<http://senvol.com/machine-search/>

Additive Manufacturing Technology Selection

Further comparison (Major criteria)

Competitive Criteria	Definition	Characteristic of Additive Technology	Relationship
Cost	Cost for acquisition.	Acquisition value	The smaller the better
Flexibility	The company's ability to adapt its products to customer needs or to an individual customer.	Maximum size of prototypes Layer thickness	The bigger the better The smaller the better
Quality	Offer products that are produced according to pre-established standards and low defect rate.	Precision Surface Quality	The bigger the better The bigger the better
Velocity	The company's ability to deliver products in the shortest possible time.	Velocity	The bigger the better

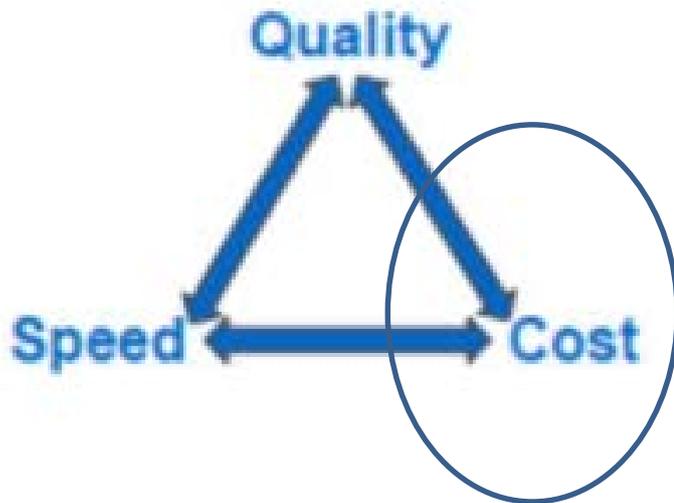
Additive Manufacturing Technology Selection

	Material Jetting (MJ)	Fused Deposition Modeling (FDM)	Binder Jetting (BJ)	Selective Laser Sintering (SLS)	Laminated Object Manufacturing (LOM)	Stereolithography (SLA)	Electron Beam Melting (EBM)	Selective Laser Melting (SLM)	Laser Engineering Net Shape (LENS)
Velocity	34800000000 mm/h	0,00059 mm/h	16,65 mm/h	32 mm/h	1828800 mm/h	14 mm/h	28800000000 mm/h	0,0024 mm/h	76,2 mm/h
Maximum size of prototypes	490 x 390 x 200 mm	406 x 355 x 406 mm	300 x 200 x 150 mm	340 x 340 x 600 mm	305 x 406 x 102 mm	380 x 380 x 250 mm	350 x 350 x 380 mm	420 x 420 x 400 mm	900 x 1500 x 900mm
Precision	140,0 µm	50,0 µm	100,0 µm	175,0 µm	100,0 µm	100,0 µm	140,0 µm	150,0 µm	186,0 µm
Layers Thickness	17,0 µm	400,0 µm	250,0 µm	400,0 µm	200,0 µm	100,0 µm	50,0 µm	100,0 µm	125,0 µm
Price	\$ 220,000.00	\$ 200,000.00	\$ 250,000.00	\$ 250,000.00	\$ 100,000.00	\$ 250,000.00	\$ 250,000.00	\$ 250,000.00	\$ 250,000.00
Surface Quality	+	-	-	-	-	+	+	-	-

Additive Manufacturing Technology Selection

Cost criteria

- **Cost** is one of the major performance criteria taking into account by benefiting entities. That takes huge interest because it concerns all product life stages.
 - Operation cost
 - Material cost (Raw material cost)
 - Machine cost (Machine price, running cost €/h, .. etc.)



Additive Manufacturing Technology Selection

Cost criteria (Cost characteristics of different AM processes)

AM Process Categories (ASTM)

Binder Jetting

Direct Energy Deposition

Material Extrusion

Material Jetting

Sheet lamination

Vat Photopolymerization

Powder Bed Fusion

Machines are less expensive than PBF, DED.

Produce metal part at lower cost than PBF.

But still high operation cost, and time.

High machine cost.

For metal parts it is cheaper than PBF. Cost effective (for repaired industrial).

For Material cost it is lower than powders material

Low cost of material.

Cheap and straightforward process.

Low machine cost

High machine cost.

High material cost

Cost effective for full color prototype.

Low material cost.

Low operation, and machine cost.

Low material cost.

Operation cost (relatively high, due to post process).

High material cost.

High Operation cost (due to post process).

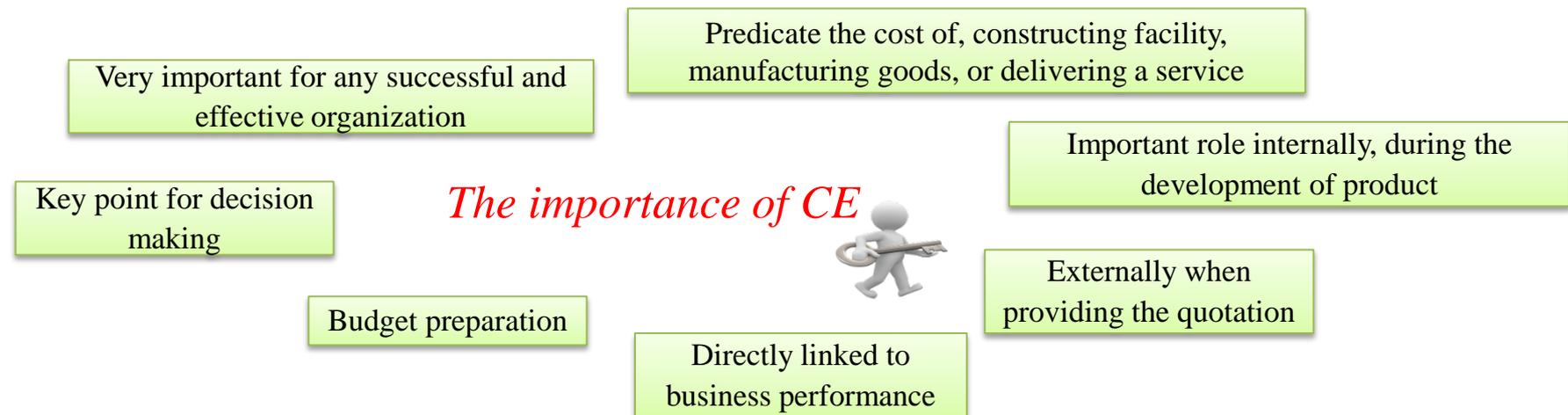
Relatively low machine cost.

Cost performance of an AM system depends on many different variables and parameters.

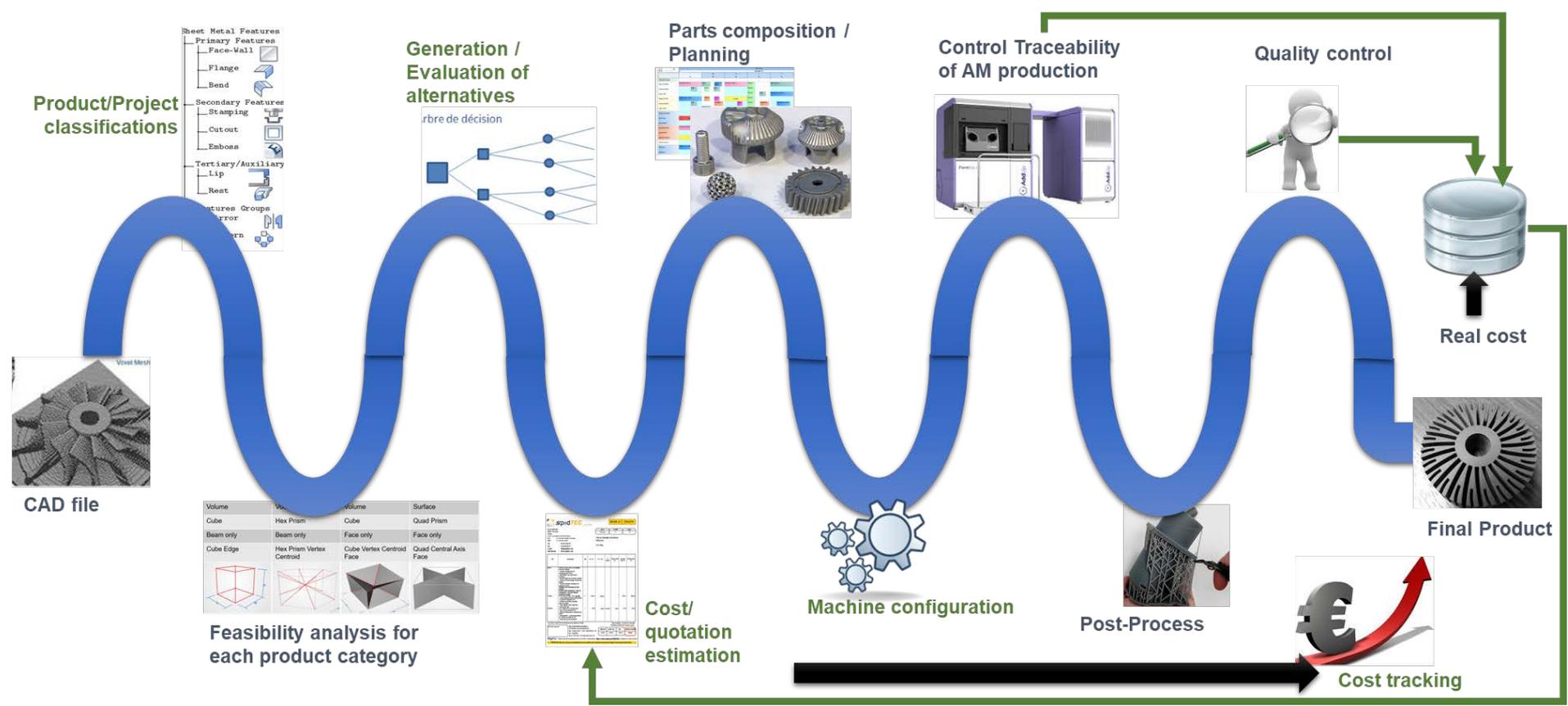
Cost Estimation Technics

Introduction in Cost Estimation

- ✓ Product cost estimation is often involved in estimating the cost of producing and selling a physical good, such as a car, which includes the costs of research and development, designing, manufacturing.
- ✓ Cost Estimation (CE) is the process of predicting the cost of a product before it is manufactured. The national estimating society has defined the cost estimation as: the art of approximating the probable cost of something based on the available information at the time.



Another objective Cost Monitoring in additive manufacturing

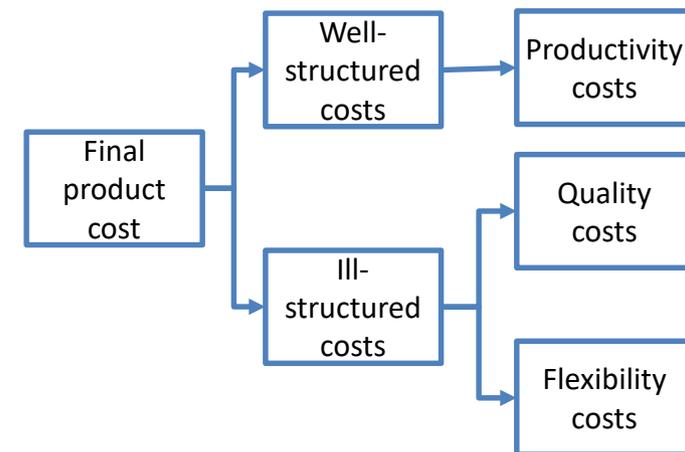


Cost Estimation Techniques

Type of costs found in product cost estimation

Additionally, it is also important, when investigating the costs of complex system, to distinguish between well-structured costs, and ill-structured costs.

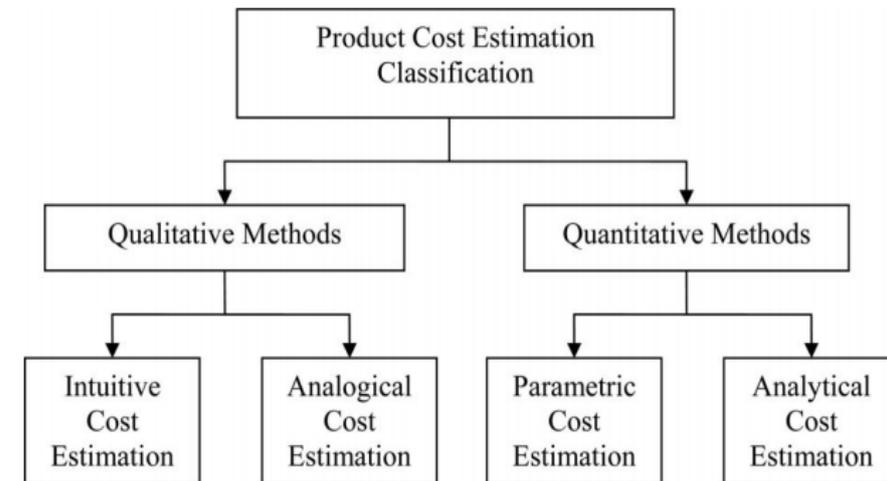
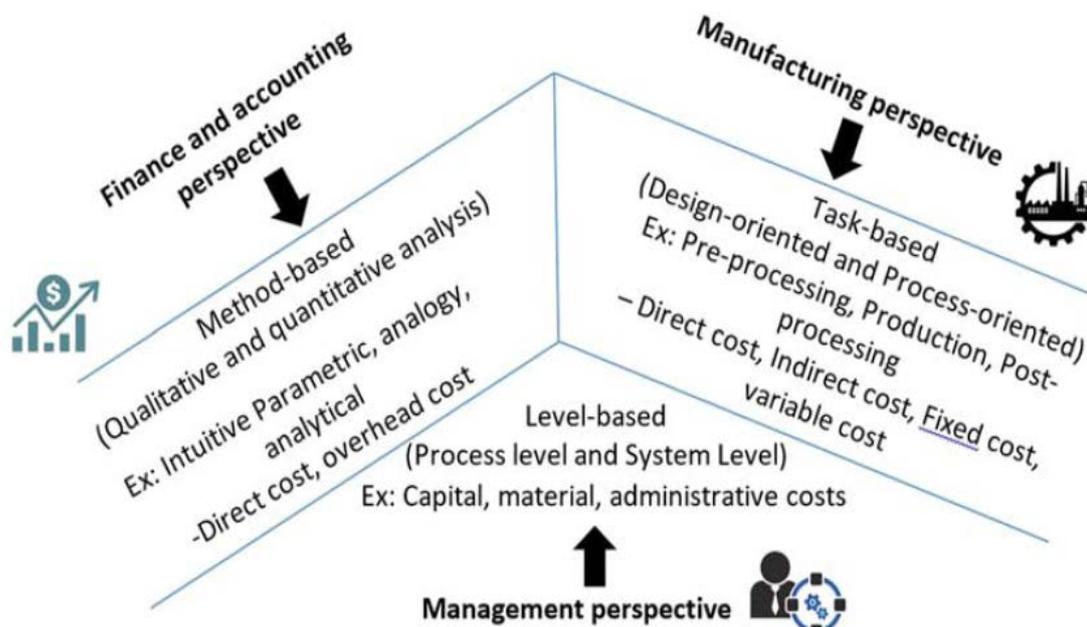
- ❑ Well-structured costs which includes production costs such as labor, material, depreciation, machine, tool, overheads (administrative/production), and computer software.
- ❑ Ill-structured costs which includes the quality and the flexibility cost.
 - ❑ The quality cost included expenses incurred for inspection and prevention of defects, as well as process failure.
 - ❑ The flexibility cost was addition of the cost incurred for setup, waiting, idle time of the machine, and inventory carrying cost



Cost Estimation Techniques

Different perspective of Cost classification

There are a wide range of classification regarding cost estimation, based on several aspects like; approach type, granularity level, tools used, and even the application phase.



Cost Estimation Techniques

Classification of the Product cost estimation techniques

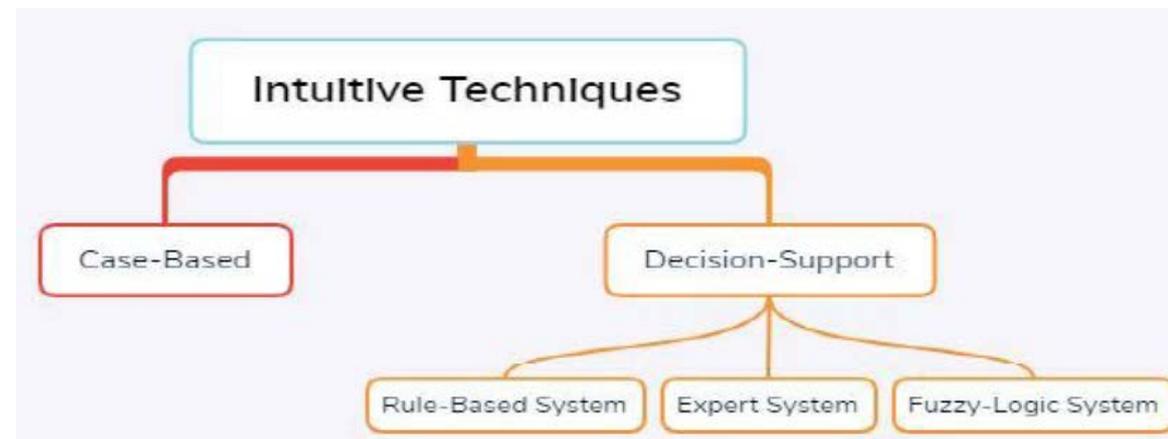
The **intuitive techniques** are primarily dependent on past experience, the expert knowledge is the key success of this method, where this experience can be applied either directly, or using different decision support systems:

- **Case-based reasoning**
- **Decision support technique**

Ex: “Expert opinion” “for software development”

Three software engineers are renown in the ERP software development.

- You hold interviews which each explaining the requirements, sizing level, and development process for your new system.
- Each member of the group submits their opinion of the final cost and the estimate converges to \$50M.



Cost Estimation Techniques

Classification of the Product cost estimation techniques

Analogical techniques use the similarity of products by assuming similar products have similar costs, the analogical techniques have two main types:

- **Regression analysis**
- **Neural network models**

Ex: “for software development”:

Your company is developing a new IT payroll system serving 5,000 people and containing 100,000 lines of C++ code. Another company developed a similar 100,000 lines of code system for \$20M for only 2,000 people. Your software engineers tell you that the new system is 25% more complicated than the other system. Other system development cost was \$20M.

Estimated cost for new system = $1.25 * \$20M = \$25M$ Plus $5,000/2,000$, or $2.5 * \$25M = \$62.5M$ total cost



Cost Estimation Techniques

Classification of the Product cost estimation techniques

The Parametric technique focuses on the characteristics of the product without describing it completely based on the relationship between a product's functional or technical characteristics and the cost.

Ex: "for software development":

You have a previously developed CER (cost estimation ratio) to estimate a new IT system based on SLOC "as number of function points", for ex "number of code lines".

$$\text{Cost} = \text{SLOC} * 25 \text{ \$/SLOC}$$

The CER is based on systems ranging from 1,000,000 to 3,000,000 SLOC.

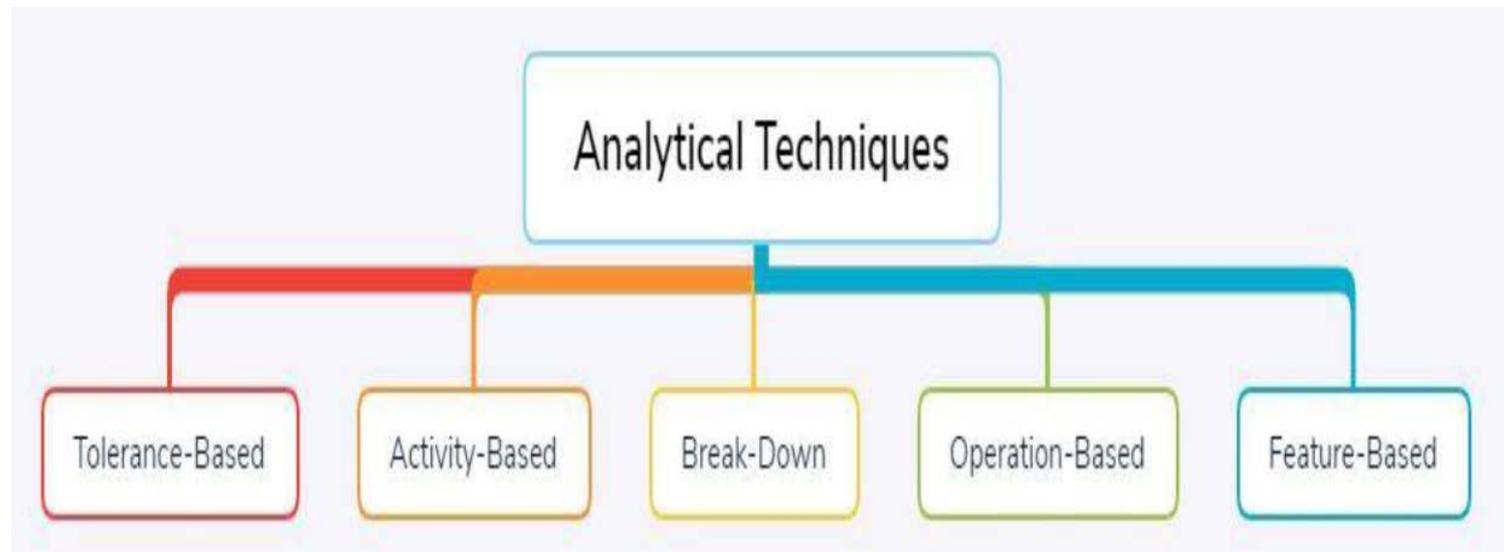
You have estimated 2,600,000 SLOC for new system

$$\text{Cost} = 2,600,000 * \$25 = \$65\text{M}$$

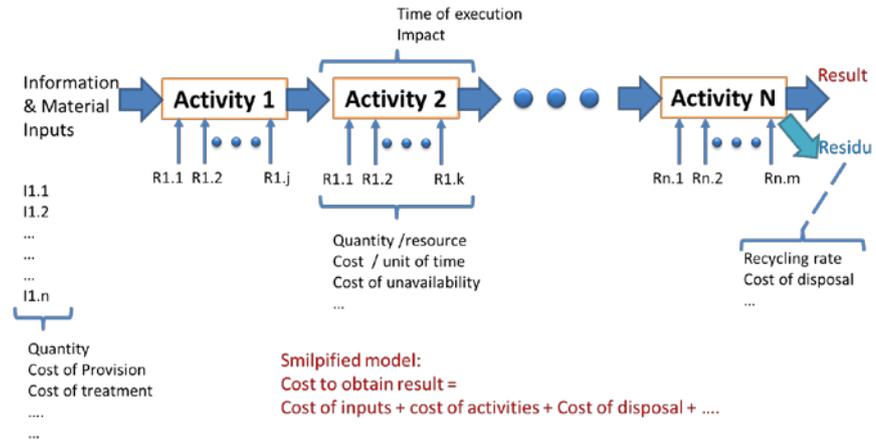
Cost Estimation Techniques

Classification of the Product cost estimation techniques

The **Analytical techniques**, which separate a product into several units, operations, and activities, that represent different resources consumed during the product life cycle, its further classified into:



Cost Estimation Techniques



Example of ABC

The implementation of this ABC approach follows these 7 steps, example from “Ben-Arieh et al. (2003)”:

- **Identify cost centres:** which are the resources that are used directly to produce the final product, include, human resources (designer, labour, ... etc.), and equipment/machines.
- **Analyse the indirect cost and calculate their cost drivers rate:** which are the overhead costs, the are needed to allocated to the final product, like (room rent, maintenance, ... etc.). Each resource cost driver rate is determined by dividing the total annual cost of the resources by the total number of cost drivers used in one year.
- **Assign resources to each cost centre:** where the indirect cost allocated to cost centre. In this step the total cost for each cost centre is calculated, then for each cost centre one cost driver is identified.
- **Identify the activities:** The activities that take place in the product development process.
- **Analyse each activity and find the total cost of each activity:** Based on cost-centre resources for each activity. Using cost-centre drivers rate multiplied by the amount of the drivers consumed by each activity.

$$RR(\text{resource rate}) = \frac{\text{Total cost for 1 year}}{\text{Resource drivers spent in 1 year (RD)}} \quad (1)$$

$$\text{Total annual cost for cost center} = \sum_{i=1}^{\text{number of resources}} RR \times RD \quad (2)$$

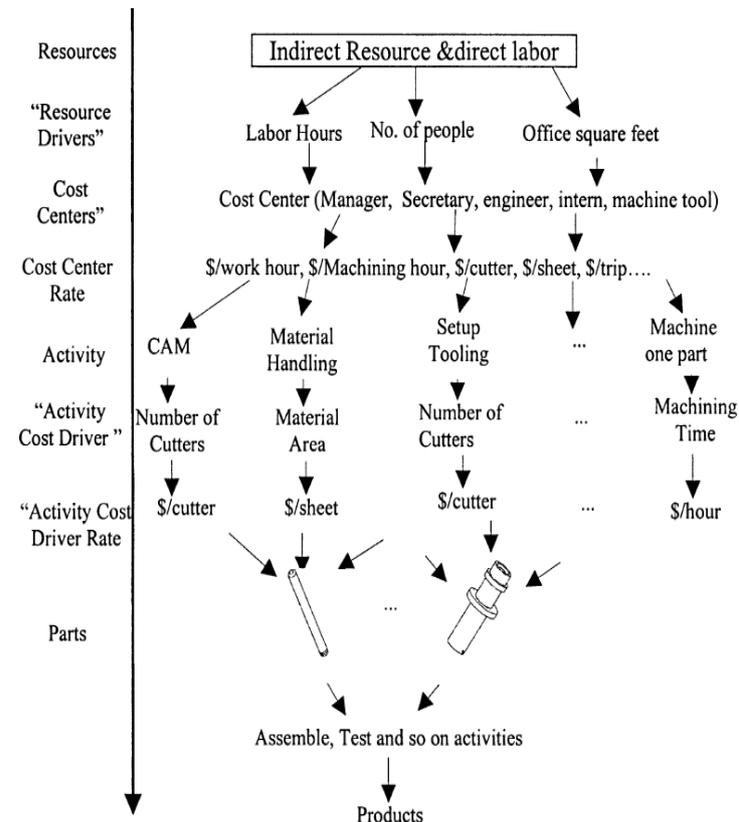
and RD is the amount if each resource driver spent by the cost center in 1 year.

$$CCR(\text{Cost centre rate}) = \frac{\text{Annual cost of center}}{\text{Cost center drivers spent in 1 year (CCD)}} \quad (3)$$

$$ACDR = \frac{\text{Cost of one activity}}{\text{Activity cost driver spent}} = \frac{\sum_{i=1}^{\text{number of cost centers used}} (CCR_i \times CCD_i)}{ACD} \quad (4)$$

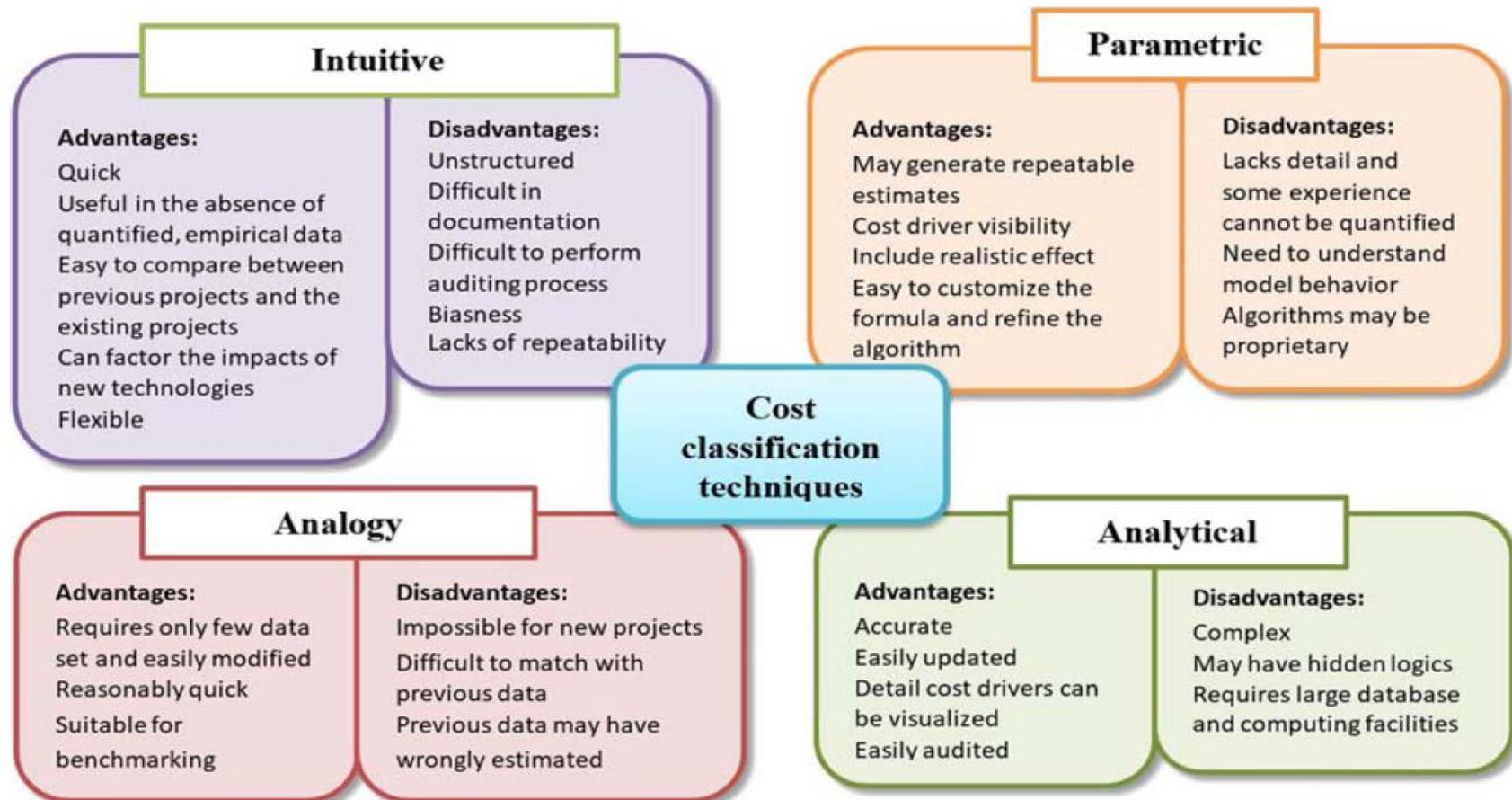
where CCD_i is the amount of the driver of center *i* used for the activity, and ACD is the amount of the activity's cost driver used. ACDR is the activity cost-driver rate cost.

$$\text{Total cost of one part} = \sum_{i=1}^{\text{number of activities}} (ACD_i \times ACDR_i) \quad (5)$$



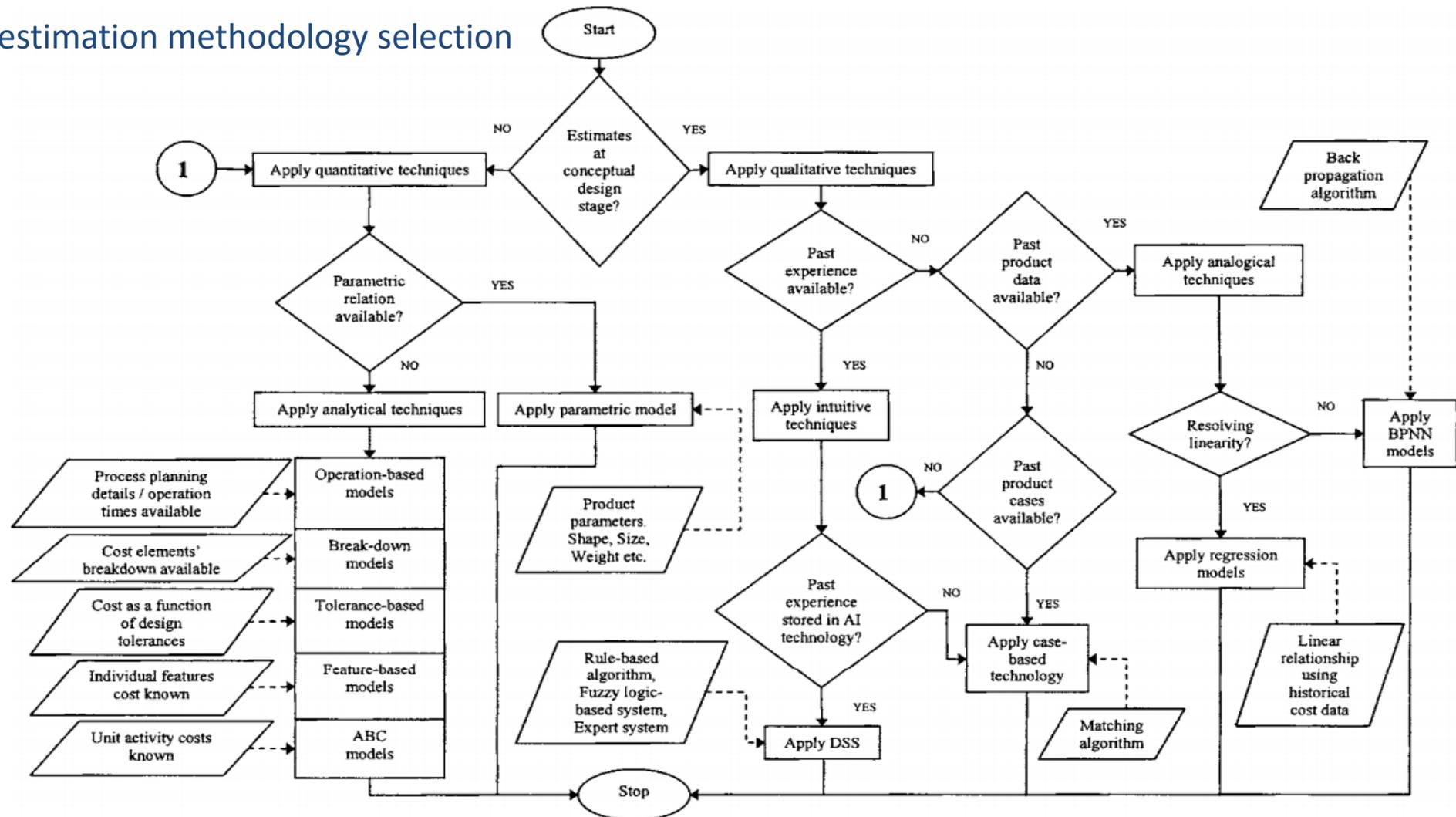
Cost Estimation Techniques

Advantages, and disadvantages of various Cost estimation techniques



Cost Estimation Techniques

Cost estimation methodology selection



Learning AM Process Cost by examples

Understanding of cost in Additive Manufacturing

Introduction

- The investigation of costs incurred by AM has a large interest by several parties; technology users, AM providers, software developers, technology vendor and investment community.
- Product Cost estimation play a significant role in the evaluation of AM. It represents the basis to develop the key decision variable on AM, which is the cost of product.
- Helpful to understand the cost drivers associated with the manufacturing process, which help to find innovative ways to enhance the operation efficiency from the AM facility manager perspective.
- There are two major motivational categories for examining additive manufacturing costs:
 - ❑ The first is to compare additive manufacturing processes to other traditional processes such as injection molding and machining. to determine under what circumstances additive manufacturing is cost effective.
 - ❑ The second category involves identifying resource used at various steps in the additive manufacturing process. The purpose of this type of analysis is to identify when and where resources are being consumed and whether if there can be a reduction in resource use.

Understanding of cost in Additive Manufacturing

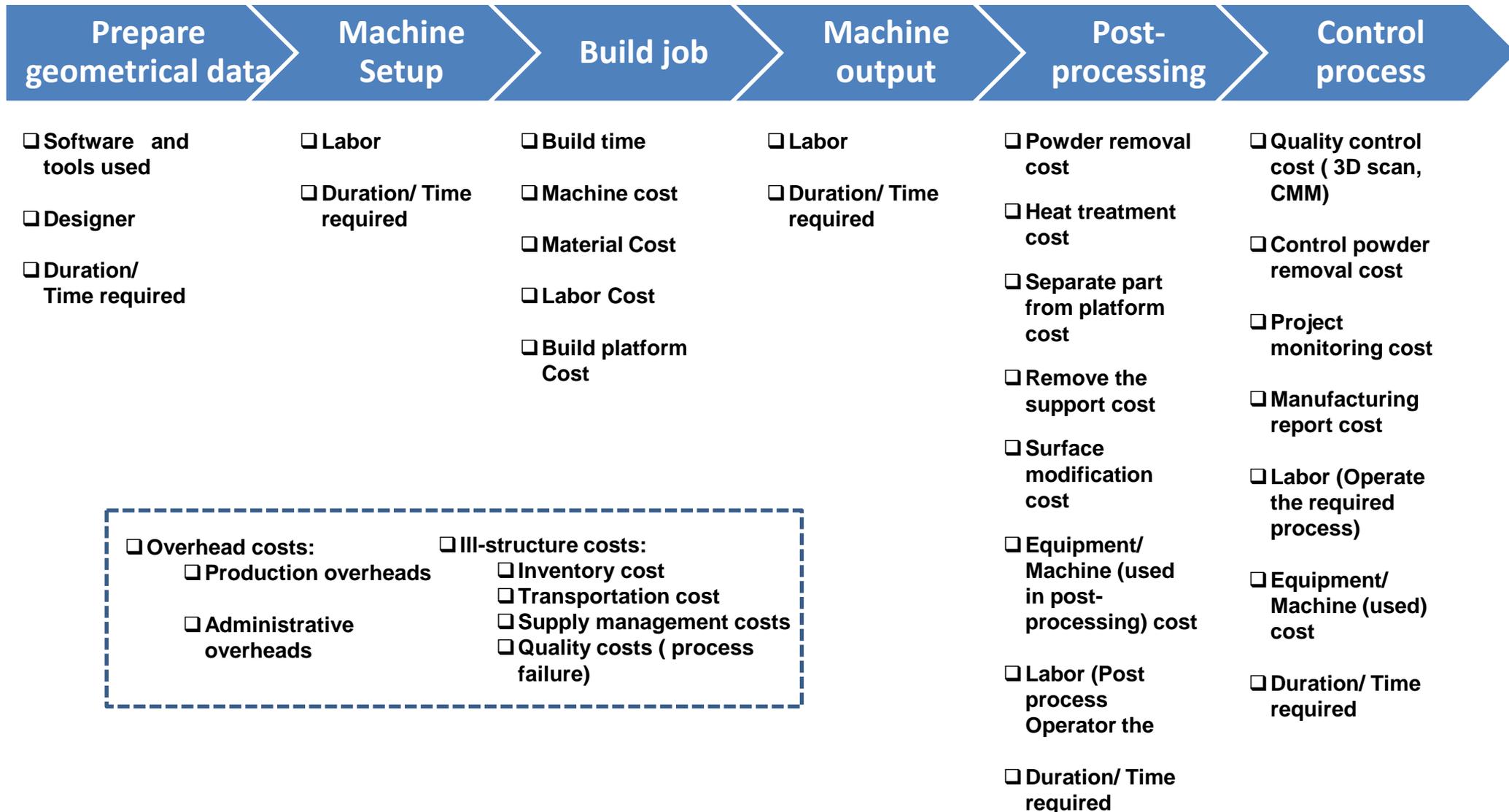
Introduction

The analysis of AM production costs:

- **Cost estimators:** Are specified to yield insight into the absolute cost performance within a manufacturing approach. Judged on the base on their accuracy and consistency.
- **Cost Model:** Are designed to represent cost relationships. Not only to produce valid cost estimates, but to reflect the relationships between various relevant aspects. Judged based on their ability to capture important aspects in an appropriate ways, also the accuracy and consistency of their results.

Cost models proposed for AM mainly fall into the categories of **Parametric Costing**, and **Analytical, “Activity Based Costing”** . Fewer models may fall **into Analogy, statistical models, or Intuitive, using different machine learning techniques.**

Understanding of cost in Additive Manufacturing

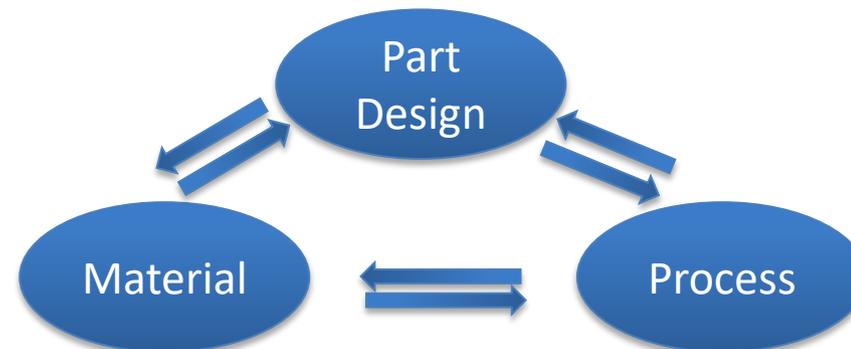


Understanding of cost in Additive Manufacturing

Additive Manufacturing Cost Structure/Factors

*In engineering domain, it is generally assumed that the choices of **material, design and manufacturing process** are interdependent, which means one aspect cannot be normally changes without effecting on the other two aspects.*

Thus, it is important to investigate these aspect and their correlation with the main cost factors/Drivers, therefore the final cost of product and AM processes. Which definitely increase the robustness of cost investigation.



Understanding of cost in Additive Manufacturing

How to build an AM Cost Model

The influential AM cost model was published in 1998 by (Alexander et al.1998)

The activity-based costing is flexible, where it is possible to adapt individual steps depending on the scope of the cost investigation and AM technology type. To construct AM activity based-costing type, a number of steps are required:

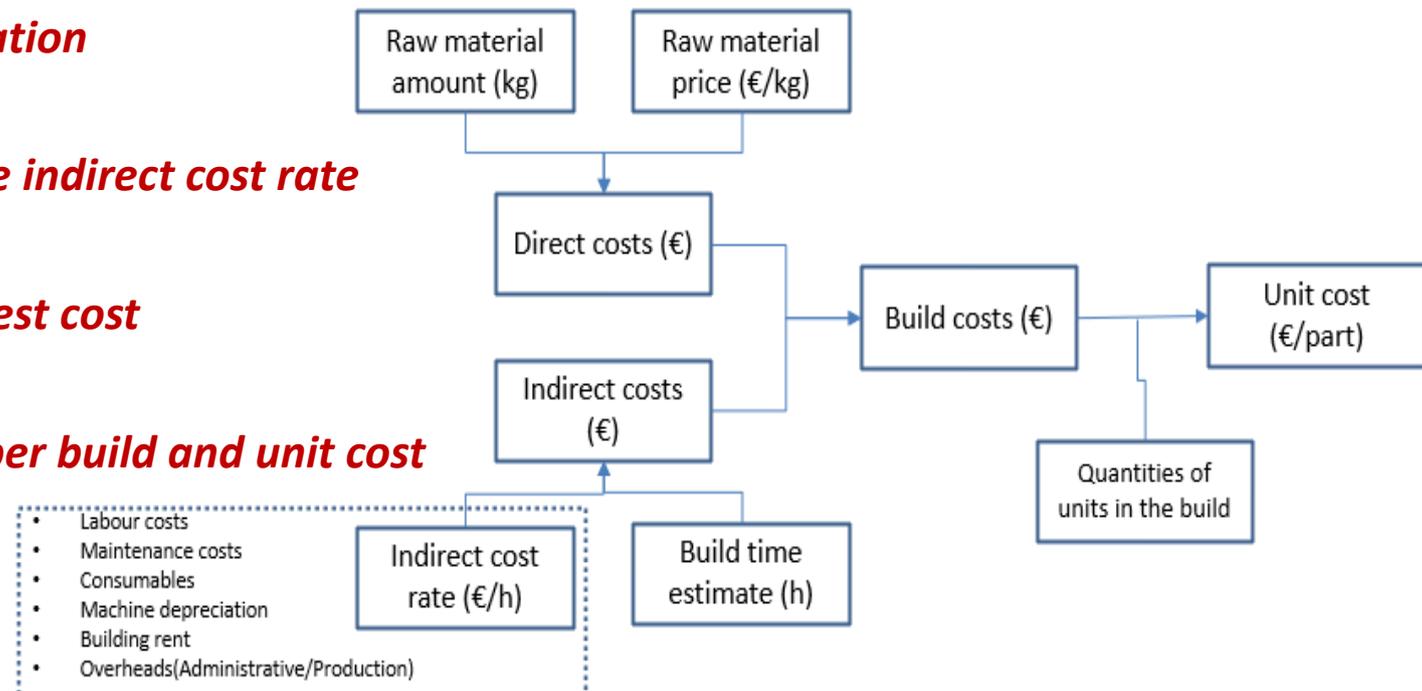
✓ **Step1: Definition of the scop of the costing model**

✓ **Step2: Build time estimation**

✓ **Step3: Calculation of the indirect cost rate**

✓ **Step4: Estimation of direct cost**

✓ **Step5: Specify the cost per build and unit cost**



Understanding of cost in Additive Manufacturing

✓ Step1: Definition of the scop of the costing model

AM processes are not stand alone systems, specially when it is adopted for Manufacturing purpose. So it is necessary to define the scop of the cost model as first step. By asking *the question of **what are the process of Product life cycle that will be included in the cost model.***

For example: here in this figure we can see the typical scop of AM cost model. (*scop of the cost investigation in generic AM process*)



✓ Step2: Build time estimation

Next step is to estimate the build time required by the AM system to execute the build operation. However the accurate estimation of build time can be complex and highly specific to **product geometries** and **build composition** in the operation. Also as many systems require **significant time to warm up, and cool down**, during which no other activities take place within the machine, such durations should be included in the build time.

This factor is significant components in regard to estimate the cost of AM, build time can vary from few hours to 150 hours. . Many developed models and approaches put effort to estimate this value, also different software packages are available for estimating build time.

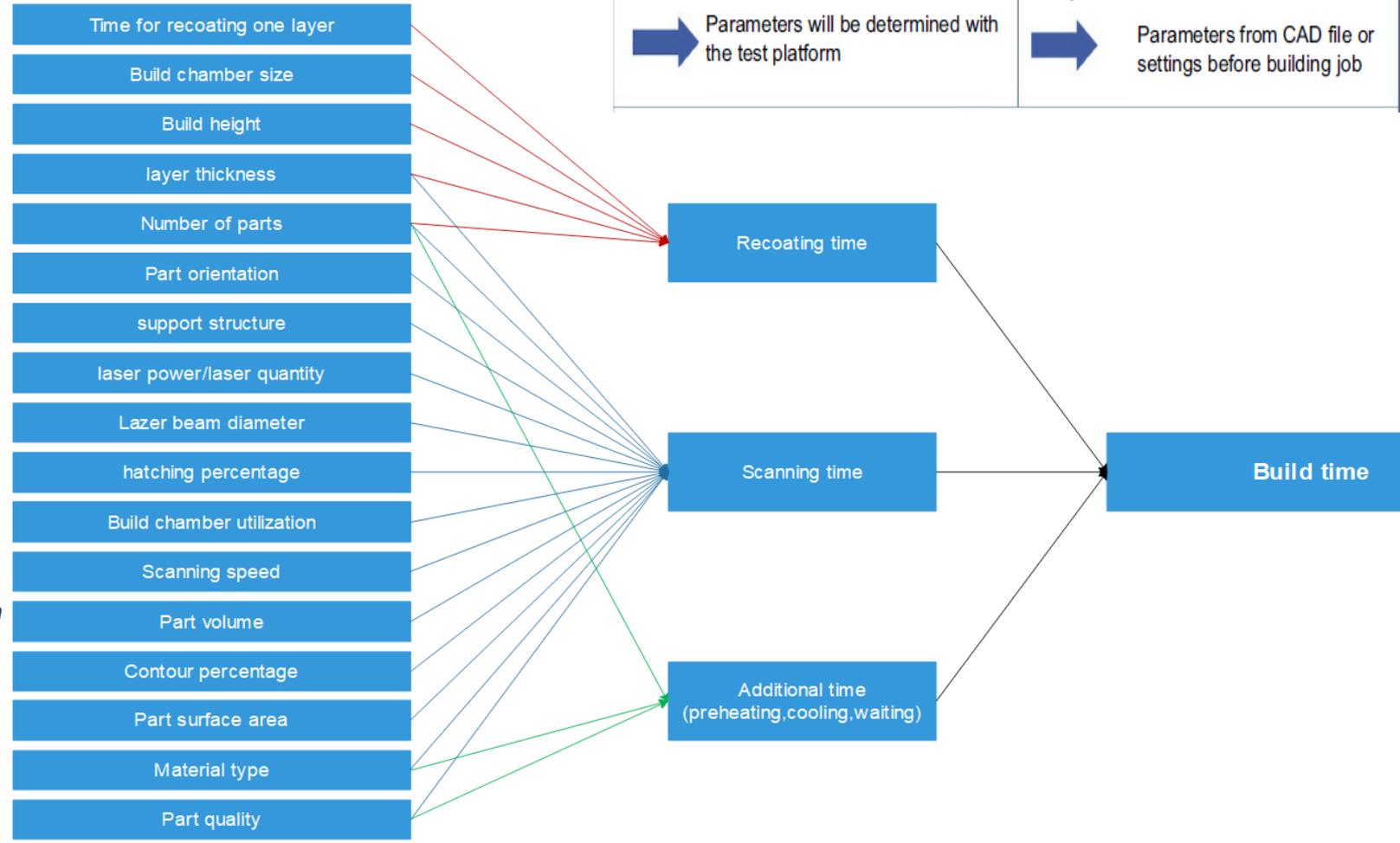
Understanding of cost in Additive Manufacturing

✓ Step2: Build time estimation

Machine specific parameters:	Part specific parameters:
<ul style="list-style-type: none"> • Time for flooding of build chamber = t_{F1} • Volume related build speed = $b_M (V_B)$ • Build rate of basic support = $b_{MGS} (V_S)$ • Recoating time for one layer = t_{r1} 	<ul style="list-style-type: none"> • Part volume = V_B • Volume of internal support = V_S • Height of basic support = h_{GS} • Surface of basic support = A_{GS} • Part height = h_{GS} • Layer thickness = d
<p>➔ Parameters will be determined with the test platform</p>	<p>➔ Parameters from CAD file or settings before building job</p>

For simple build time estimation, which rest on the assumption that **processing speed is constant per layer**, (where in complex way it might be also based on **other factors like: hatch, contour, laser power, scanning speed, material thermal properties, ...etc.**). Making this simplification, the overall build time could approximated as follow:

Build time= Time for setup “Initialization and warm up” + (Total build volume/Building speed rate) + (Time to recoat on layer* Total number of layers) + Time for cool down



Understanding of cost in Additive Manufacturing

✓ *Step3: Calculation of the indirect cost*

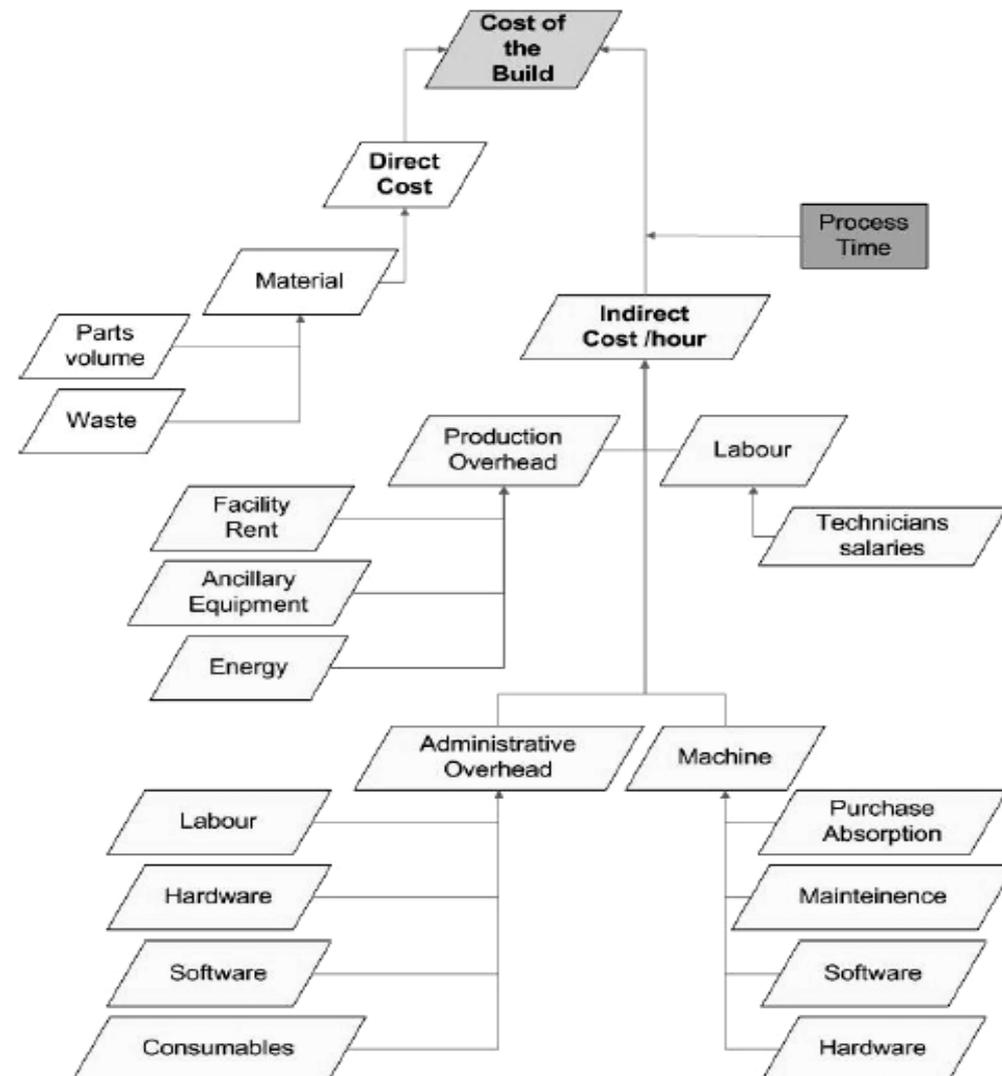
Several cost elements and activities are attributed to overall costs through build time. So this requires the calculation of an indirect costs, measured as costs incurred per unit of operating time (€/h). The elements of indirect costs are normally obtained on an annualised bases, then these costs are broken down into hourly rate, by dividing the annual cost through the number of operating hours per year ("***the capacity utilisation over time WH***", which relies on the share of operating hours of overall times, where in most models the operating time is assumed to lie between **50% and 90%** of total time.

Understanding of cost in Additive Manufacturing

✓ Step3: Calculation of the indirect cost

The most important elements that are included in indirect costs:

- **Machine cost:**
 - **The purchase cost of AM system and ancillary systems**
 - **Maintenance expenses and costs of consumables**
- **Labour cost:**
- **Overheads:** which are allocated to the operation of the AM system
 - **Overheads from production**
 - Additional overheads **are administrative**



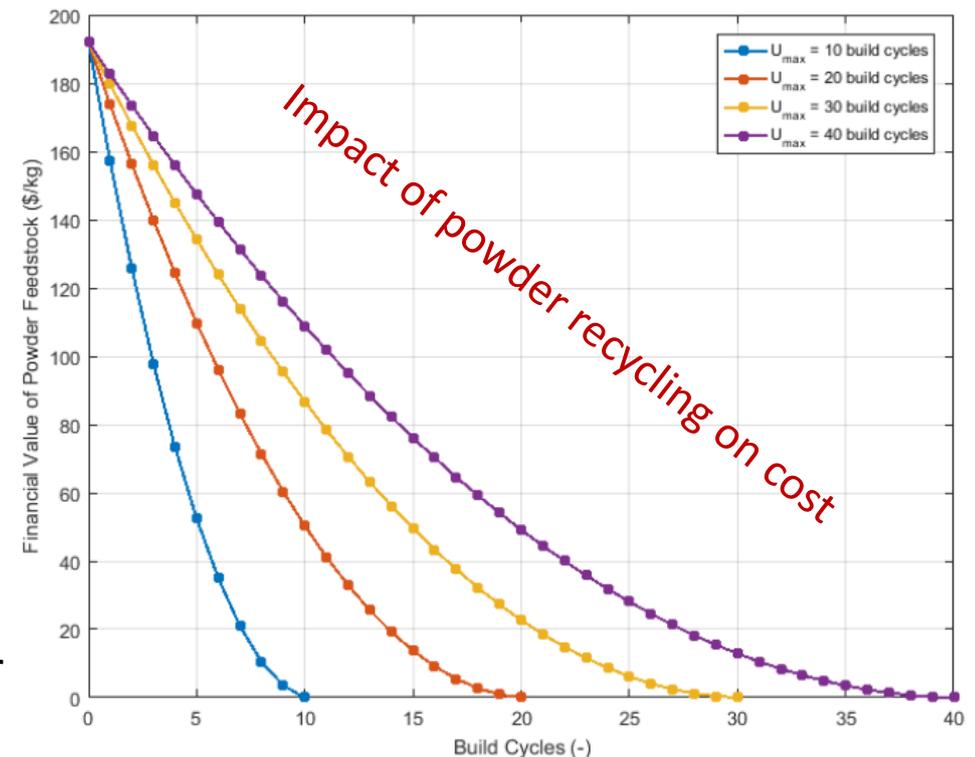
Understanding of cost in Additive Manufacturing

✓ Step4: Estimation of direct cost

Direct costs are the costs associated with physical inputs required for the operation of an AM system. The most important direct cost arises through the **raw materials used** in the process, including one or more build material. **Material cost:** is one of the major cost factor for AM technology. It is quite high, when compared to traditional manufacturing.

It Based on:

- **Build volume** (including part, support, and other test parts if required)
- **Material type** (the density of the material, and the material price/kg)
- **Material waste** (loss) “based on the manufacturer, and machine type” or waste powder inside the build part
- **Capacity utilization (packing ratio)**, number of parts inside the build)
- In some project some quality test for the powder has to be done, where, it important to include the **quantity of powder for the test**
- **Raw material refreshing or state**



Understanding of cost in Additive Manufacturing

✓ *Step5: Specify the cost per build and unit cost*

After obtaining the required data and computing the elements described above, it is possible to specify the cost model for the build (C_{build}), including ***pre-processing, and post-processing costs***.

$$C_{build} = C_{pre} + (C_{indirect} * T_{build} + C_{direct}) + C_{post}$$

However, If ***multiple parts*** are contained in the build volume, it will be important to break down the build cost for the level of individual part contained. The volume of part i divided by the volume of all j parts in the build:

$$C_{unit} \text{ (for } i \text{ geometry)} = C_{build} * (V_i / \sum_j V_j)$$

If all part have the same geometry then:

$$C_{unit} = C_{build} / \text{number of parts}$$

Understanding of cost in Additive Manufacturing

Why such models are important:

- Reliable and used for different purposes (inter process comparison to evaluate cost performance of different AM systems against each other, or cost performance of conventional manufacturing technologies*

- Explore the cost effects of changes to product design*

- How unit costs relate to the quantity of products manufactured*

Understanding of cost in Additive Manufacturing

Example 1.1: "see the excel file"

The scope: Activity involved in the Cost Estimation	
Material	Cost of material purchase
Machine cost	(Machine purchase, support equipment and (hardware, Software), Maintenance, Machine utilization rate, Depreciation)
Labour	Labour cost for machine set-up and machine output
Production overhead	Costs incurred due to production, energy, and floor rent
Administration overhead	Costs incurred due to running the enterprise, administrative staff, office space, and consumables

Assumption: It supposed that the Operator is only working on AM system.
The total Indirect cost rate of Operating AM machine

The Ruffo et al., 2006 Model

Data:	
Production overhead	
Yearly rent /m2	130,5
Building area (m2)	168,5
Energy consumption/h	1,5
(Rent/ y)/WH	4,4
Administration overhead	
Hardware purchase €	2175
Software purchase €	2175
Consumables (€/year)	1450
Software cost/year	435
Hardware cost/year	435
Production labour	
Operator annual salary + employer contribution €/y	39894
Machine costs	
Machine purchase	362500
Support machine	24360
Maintenance /year	21750
Hardware and software	11600
Software upgrades/ year	1450
Purchase cost/year	48357,5
Hardware and software cost/y	2320

EOSINT M280	
Utilization rate	57,08%
Depreciation time (y)	8
Machine WH/year	5000
(365*24*Utilization%)	
Hardware&Software	5
Depreciation (y)	

$$\text{Indirect cost rate} = \frac{\sum \text{Indirect costs}}{\text{Working time (WH)}}$$

$$\text{Machine working time (WH)} = 365 \times 24 \times \text{Utilization rate \%}$$

$$\text{Prod. overhead rate} = (\text{Rent} \times \text{building area} / \text{WH}) + \text{Energy consu.}$$

$$\text{Admin. overhead rate} = \left(\frac{\text{Hard \& Soft}}{\text{Depretation for Hard \& Soft}} + \text{Consu per year} \right) / \text{WH}$$

$$\text{Machine costs rate} = \left(\left(\frac{\text{Hard \& Soft}}{\text{Depretation for Hard \& Soft}} + \text{Soft. Upgrad per year} \right) + \text{Maintenance per year} + \left(\frac{\text{Machine+support machine purchase}}{\text{Depretation for Machine}} \right) \right) / \text{WH}$$

$$\text{Labour cost rate} = \text{Annual salary and employer contribution} / \text{WH}$$

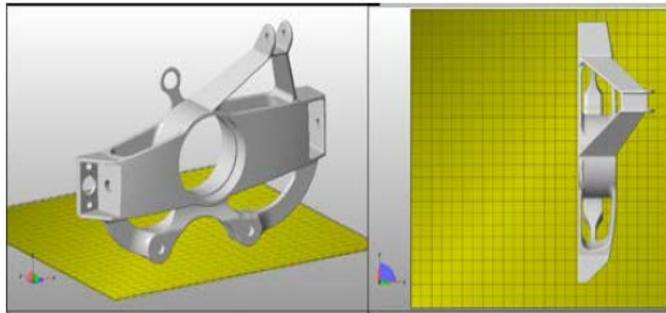
Result:	
Indirect hourly rate €/h	
Production overhead	5,90
Admin. overhead	0,46
Labour/ machine hour	7,98
Machine costs	14,78
Total rate (indirect)	29,12

The total cost
= Indirect cost rate × Build time
+ Material used × Material price

Understanding of cost in Additive Manufacturing

Example 1.1: "see the excel file"

Estimate the cost of the following part:



Cost structure(€)	
Material	2644,3
Machine	813,9
Prod.over	324,9
Admin.over	25,6
Labour	439,5
Total(€)	4248,06

Part Geometry	
V part (cm3)	175
V support (cm3)	412
V total (cm3)	587
Bounding Box (mm)	74 x 218 x 172
Number of layers	3360
time for racoting one layer (sec)	9
time for cooling and pre heating (h)	3,2
Material waste (kg)	1,3
Material	
Type	Ti64 (Titanium)
Density(g/cm3)	4,41
Material price (€/kg)	680
Build speed (cm3/h)	13,5

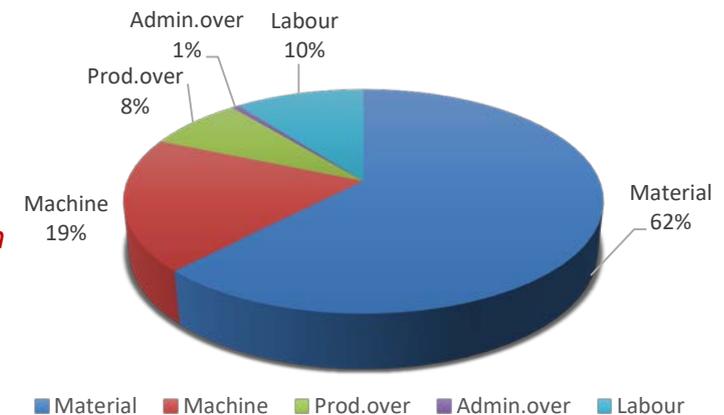
Build time
 = Time for cooling and preheating
 + $\left(\frac{V_{total}}{build\ speed}\right)$
 + (time for coating one layer
 × Number of layers

Build time(h) 55

Material used = $V_{total} \times Density + Material\ waste$

Matrial used(kg) 3,9

Simplified from Lindeman et al.,2017



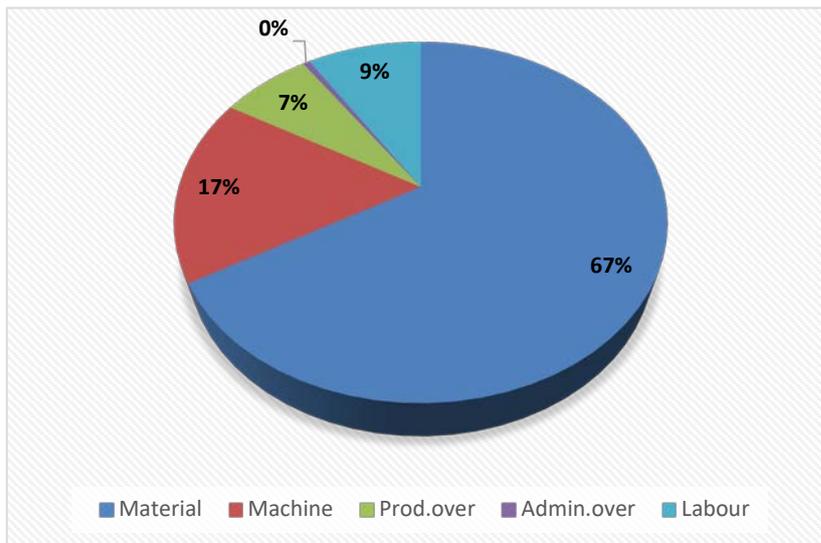
What if we change the machine utilization rate % to (70%) ??

Understanding of cost in Additive Manufacturing

Example 1.2: "see the excel file"

What if we change the machine utilization rate % to (70%) ??

Solution



Machine utilization rate 70% (6132 h/year)

Cost structure(€)	
Material	2644,3
Machine	663,6
Prod.over	280,1
Admin.over	20,8
Labour	358,4
Total(€)	3967,246

Machine utilization rate 57% (5000 h/year)

Cost structure(€)	
Material	2644,3
Machine	813,9
Prod.over	324,9
Admin.over	25,6
Labour	439,5
Total(€)	4248,06

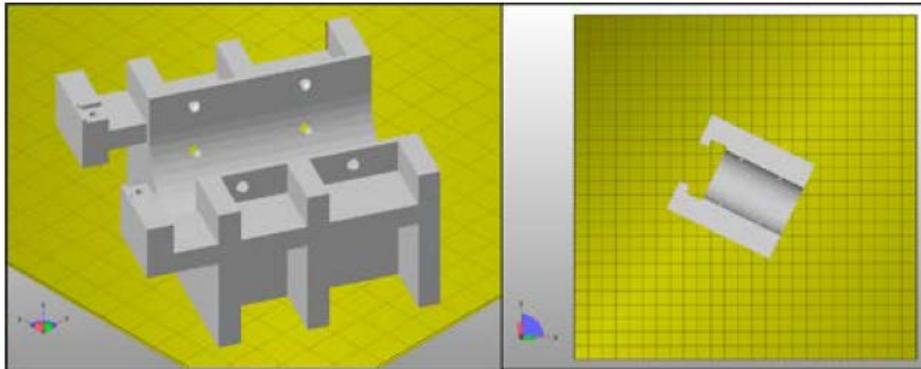
Compare



Understanding of cost in Additive Manufacturing

Example 1.3: "see the excel file"

Estimate Using the data from Ex.1,1 estimate the cost for different part ??



Part Geometry	
V part (cm3)	95
V support (cm3)	97
V total (cm3)	192
Bounding Box (mm)	76 x 84 x 47
Number of layers	1058
time for racoting one layer (sec)	9
time for cooling and pre heating (h)	1,8
Material waste (kg)	0,7
Material	
Type	GP1 (StainlessSteel)
Density(g/cm3)	7,8
Material price (€/kg)	100
Build speed (cm3/h)	7,2

Use the data from the previous ex??

The total cost
 = **Indirct cost rate**
 × **Build time** + **Material used**
 × **Material price**

Build time
 = **Time for cooling and preheating**
 + $\left(\frac{V_{total}}{build\ speed} \right)$
 + **(time for coating one layer**
 × **Number of layers**

Material used = $V_{total} \times Density + Material\ waste$

Result:	
Indirect hourly rate €/h	
Production overhead	5,90
Admin. overhead	0,46
Labour/ machine hour	7,98
Machine costs	14,78
Total rate (indirect)	29,12

Understanding of cost in Additive Manufacturing

Example 2 : “see the excel file”

For this example different way to estimate the cost, include the cost of electrical consumption and protective gas consumption **as a direct costs** related to the build job activity, because PBF "SLM", is involved in high power and protective gas consumption

- ❑ **Machine set-up/Machine output:** labor work for AM operator. For **machine set-up**, several tasks like uploading the digital file, selecting process parameters, and changing material if required. For **machine output**, in order to remove the entire build and manually removing the powder from the build. The cost of these activity based on the cost of **AM operator, and the duration required for these activity** which highly based on the Machine type, material type, also If other tasks are required (e.g. Material change).

$$\text{Total cost} = \text{Setup cost} + \text{Build cost} + \text{Machine output cost}$$

$$\begin{aligned} \text{Machine output cost} \\ = \text{Labour hourly rate} \times \text{time for remove part, remove powder} \end{aligned}$$

$$\text{Setup cost} = \text{Labour hourly rate} \times \text{time for setup}$$

$$\begin{aligned} \text{Build job cost} \\ = (C \text{ machine hourly rate} \\ + C \text{ protective gas hourly rate}) \end{aligned}$$

$$\text{Build time} = \frac{\text{Total Volume}}{\text{Build Rate}}$$

Yi al.,2019



$$\begin{aligned} C \text{ machine} \\ = (\text{Machine purchase per year} \\ + \text{Maintenance per year} \\ + \text{Room rent per year} \\ + \text{Interst per year}) / \text{WH} \end{aligned}$$

Understanding of cost in Additive Manufacturing

Example 2.1 : “see the excel file”

Utilization rate= (90%) for both machine, WH= 7884h

Machine, Gas, Electricity Data		
Machine	M290	M400-4
Manufacturer	EOS	EOS
Size of build (mm)	250 x 250 x 250	400 x 400 x 400
Space Required (m2)	17	39
Purchase price (€)	480000	1420000
Depreciation (year)	6	6
Maintenance (per year)	48000	142000
Room Rent (€/m2)	130	130
Interest (€/year)	24000	71000
Working time (WH) (h)	7884	7884
Avg. Power (KW)	2,4	22
Electricity cost (€/h)	0,2	1,76
Gas cost (€/h) (Argon)	60	60
Gas cost (€/h) (Nitrogen)	0,228	0,228
Labour cost (€/h)	39	39

Case no.1	
Machine	M290
Material Type	316L (stainless steel)
Material price (€/kg)	40
Density (g/cm3)	7,9
Build rate (cm3/h)	13,3
Number of part per build	15
Material waste (kg)	Assump. = 0 kg
Total volume(include support) cm3	346,5
Protective gas	Argon
Time for set-up (h)	0,3
Time for machine out-put (h)	0,75

Results	
Setup cost (€)	11,7
Machine output cost (€)	29,25
Build time (h)	26,1
Material cost (€)	109,49
Build job cost (kg)	2077,95
Total cost (€)	2228,40
One Part cost (€)	148,6

Understanding of cost in Additive Manufacturing

Example 2.2 : “see the excel file”

Estimate the final cost of the following different cases:

In this case we will use the same machine, and part, but we change the used material type(from case1)

Case no.2	
Machine	M290
Material Type	ALSi10Mg (Alu)
Material price (€/kg)	75
Density (g/cm ³)	2,7
Build rate (cm ³ /h)	26,6
Number of part per build	15
Material waste (kg)	Assump. = 0 kg
Total volume(include support) cm ³	346,5
Protective gas	Argon
Time for set-up (h)	0,1
Time for machine out-put (h)	0,75

In this case we will use different machine, and different part, but we will keep the material type and protective gas (from case1)



Case no.4	
Machine	M400-4
Material Type	316L (stainless steel)
Material price (€/kg)	40
Density (g/cm ³)	7,9
Build rate (cm ³ /h)	42,6
Number of part per build	40
Material waste (kg)	Assump. = 0 kg
Total volume(include support) cm ³	924
Protective gas	Nitrogen
Time for set-up (h)	0,8
Time for machine out-put (h)	2

Case no.3	
Machine	M400-4
Material Type	316L (stainless steel)
Material price (€/kg)	40
Density (g/cm ³)	7,9
Build rate (cm ³ /h)	42,6
Number of part per build	40
Material waste (kg)	Assump. = 0 kg
Total volume(include support) cm ³	924
Protective gas	Argon
Time for set-up (h)	0,8
Time for machine out-put (h)	2

In this case we change the protective gas (from case no.3)

Understanding of cost in Additive Manufacturing

- ❑ **Capacity utilization of the build chamber:** "packing build volume", number of part in the build job, (in order to minimise the unused space in the building chamber). (used volume/ possible build volume)

- Some cost models, allow for significant unused build volume capacity in the estimation of unit cost, where this in manufacturing configuration considered as inefficient.
- Here it comes the ability to minimise the cost by efficient configuring or packing build volume.
- As we saw before this factor has an effect on both the build time, and the material cost thus, the cost of additive manufacturing product.
- This factor is linked to the Build envelop or the bounding box (The build envelope is the maximum area for part production in an additive manufacturing system).
- The higher the packing ratio, the lower the waste in material and the production time per component, with a consequent cost saving.

Understanding of cost in Additive Manufacturing

AM as a Multi-step process: as we describe before, AM can't be a stand alone process, it is integrated into a chain of surrounding process steps. Thus, the challenge is to define the boundaries of cost investigation, which is also challenging without sufficient knowledge of product characteristics, and the AM technology. (for example some AM technologies variants will require entirely different pre- or post-processing, which is also the case for different product characteristics).

□ Prepare the geometrical data:

The CAD/CAM preparation related to the initial CAD data, placement in the building chamber, orientation, and creating the support. Carried by the Design engineer, using workstation (Pc, software) using **software** packages like (CATIA, Solid Work, NetFabb, Materialize Magic, ..etc., which can support and automate these processes. The cost of this activity based on the cost rate of the design engineer, and the used workstation (pc, software). Multiplied by the duration of this task.

The time/duration of this activity based on the tasks required, (for example if topology optimization is required), also the **geometrical complexity of the product** to be produced (if it has difficult support to create, difficult orientation and build composition (number of part to be produced) build chamber utilization.

Understanding of cost in Additive Manufacturing

- ❑ **Post-processing:** This step is the sum up of all necessary post-processing, after machine output, (Powder removal, separate the part from the platform, support removal, mechanical process for surface modification, and heat treatment).

This cost can be a main part of the total part costs. Also, it is important to consider these activity at early stages of the design.

The post-process highly depend on **the costumer requirement, and customer activity sector “end user”**.

The **labour cost, and machine/Equipment Type** used cost, and duration/ time for the required process.

- ❑ **Quality Assurance/Control:** The different steps needed to evaluate and ensure accuracy, surface finish, and other feature detail to achieve part quality. Like (3D scan, CMM, Powder removal control check “tomography, Endo scoping”, ..etc.).

The cost of Quality controls/assurance, can play an important role on the total part cost.

The part requirement, and customer activity sector “end user” are the main factor for this cost. Among labour, and machine running costs.

For example: for complex commercial Aerospace component like *LEAP fuel injection nozzle*, which will require extensive test process like; full traceability of each component, source material, and computer tomography(CT) scan,.

Also, If the build include test parts, several controls/test will be associated to this cost.

One needs to consider that post-processing and quality costs may take up to 50% of the final product costs.



Understanding of cost in Additive Manufacturing

Example 3: “see the excel file”

From the previous example (case no.1), the cost estimation need to be extended to include the following activity (CAD/CAM preparation, EDM, and manual post-process).



Estimate the cost of one part??

From case no.1 result	
Setup cost (€)	11,7
Machine output cost (€)	29,3
Material cost (€)	109,5
Build job cost (kg)	2077,95
Number of part (-)	15
Note:	All parts have the same geometry
For one part (€)	
Setup cost (€)	0,78
Machine output cost (€)	1,95
Material cost (€)	7,30
Build job cost (kg)	138,53
Operator cost(€/h)	39



Data	
T prep (h)	0,5
C Designer (€/h)	90
C Pc (€/h)	90
C EDM (€)	150
C tool (€/h)	40
T post (one part) (h)	0,1

$$C_{Prep}(P_i) = (C_{Oper} + C_{PC}) * \frac{T_{Prep}(G_i)}{N_i}$$

$$C_{Substrate}(P_i) = \frac{C_{EDM}}{\sum_i A_{Con}(G_i)} * A_{Con}(G_i)$$

Simplified from
Rickenbacher
et al.,2013

$$C_{Substrate} = \frac{C_{EDM}}{\text{Numbe of part}}$$

$$C_{Postp}(P_i) = T_{Postp}(G_i) * (C_{Oper} + C_{Tools})$$

Understanding of cost in Additive Manufacturing

Inventory cost

This inventory is for products that are unused or undelivered yet. They occupy physical space, buildings, and land while requiring rent, utility costs, insurance, and taxes. Thus, the products are becoming obsolete. Additive manufacturing provides the ability to manufacture parts on demand, which reduces the need for maintaining large inventory and eliminates the associated costs.

Transportation cost

Additive manufacturing allows for the production of multiple parts simultaneously in the same build, making it possible to produce an entire product. which reduces the transportation of parts produced at varying locations

Understanding of cost in Additive Manufacturing

The supply management cost

includes purchasing, operations, distribution, and integration. Purchasing involves sourcing product suppliers. Operations involve demand planning, forecasting, and inventory. Distribution involves the movement of products and integration involves creating an efficient supply chain. Additive manufacturing may have significant impacts on the manufacturing supply chain, reducing the need for supply chain management.

Quality cost (process failure)

During machine operation This type of process failure is associated with significant costs for repeating the build and also disruption to the production schedule.

Rejection of individual parts after completion of the build The nature of the cost models changes in a subtle way if the risk of failure is included, so the model become “probabilistic”

Review of main cost models in the litterature

Cost Models in AM

Cost Estimation models in Additive Manufacturing

In this section we will present some of the existing costing model in additive manufacturing:

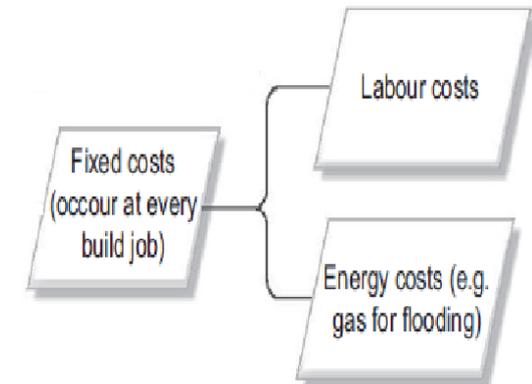
Note: The main factors affecting the cost during various processes of AM are called “Cost Drivers”.

Author	Main Cost Drivers	System-level	Process /task-level	Used method/technique
Schroder et al. (2015)	CAD preparation cost, Operating cost (preparation process), material cost, machine cost, Labour cost (production), post-processing cost, quality control process, administrative cost		✓	ABC
Rudolph et al. (2017)	CAD preparation cost, set-up cost, operating cost, labour cost (production), production overhead, pricing mode cost, material cost, part removal cost, treatment cost, post-processing overhead		✓	Analytical
Chan et al. (2018)	Material cost, machine cost, labour cost (production), production cost, production overhead		✓	(Analogical) ML algorithms, Net regression
Barclift et al. (2017)	Material cost, machine cost, depreciation cost (powder feedstock)		✓	CAD-based software
Lindemann et al. (2017)	Inventory cost, setup cost, material cost, machine cost, labour cost (production), depreciation cost, post-processing cost, part removal cost, Production overhead, logistic cost	✓	✓	ABC (time-driven)
Facchini et al. (2018)	CAD preparation cost, Operating cost (preparation process), setup cost, labour cost (preparation process), material cost, labour cost (production), part removal cost		✓	Parametric
Kamps et al. (2018)	CAD preparation cost, setup cost, material cost, machine cost, labour cost (production), depreciation cost, maintenance cost, electrical cost, gas cost, energy cost, production overhead, post-processing cost, part removal cost	✓	✓	Intuitive, Analogical LCA life cycle assessment
Tosello et al. (2019)	Operating cost (preparation process), setup cost, labour cost (preparation process), material cost, machine cost, labour cost (production), depreciation cost, maintenance cost electrical cost, production overhead, labour cost (post processing), part removal cost, finishing cost, curing cost		✓	ABC
Cunningham et al. (2017)	Operating cost (preparation process), setup cost, material cost, machine cost, labour cost (production), part removal cost, post-processing cost, quality control cost, tooling cost, treatment cost		✓	ABC
Ruffo et al. (2006)	Material cost (direct costs), Machine cost (indirect costs) “only build job cost”		✓	parametric model, and the engineering approach

Cost Models in AM

Lindemann et al. (2017)

Represent the costs generated by product during the whole lifecycle. Which exceed the price the customer will pay for the final product. That cover all expenditures during the different phases of the lifecycle, from the perspective of the manufacturer and user. **Production costs, Self costs, and Life-Cycle Costs.**



Production costs: using **Time driven activity-based costing**, where process factors are replaced by time consumption. Considering the main processes:

- Preparation of the part: Designer cost, duration of this task (which affected by part complexity, build composition)
- Production of the part:

$$\text{Costs}_{\text{Build}} = \text{Costs}_{\text{Fixed}} + \text{Machine hourly rate} \times \text{Build time} + \text{Material costs}$$

Method for build time estimation: $T = t_{Fl} + t_B + t_{GS} + t_r$

Expected build time = T ; additional processing times (e.g. pre-heating) = t_{Fl} ; scanning time part = t_B ; Scanning time basic support = t_{GS} ; recoating time = t_r

Scanning time of the part: $t_B = \frac{V_B}{b_M(V_B) * K_S(V_S)}$

Volume of the part = V_B ;

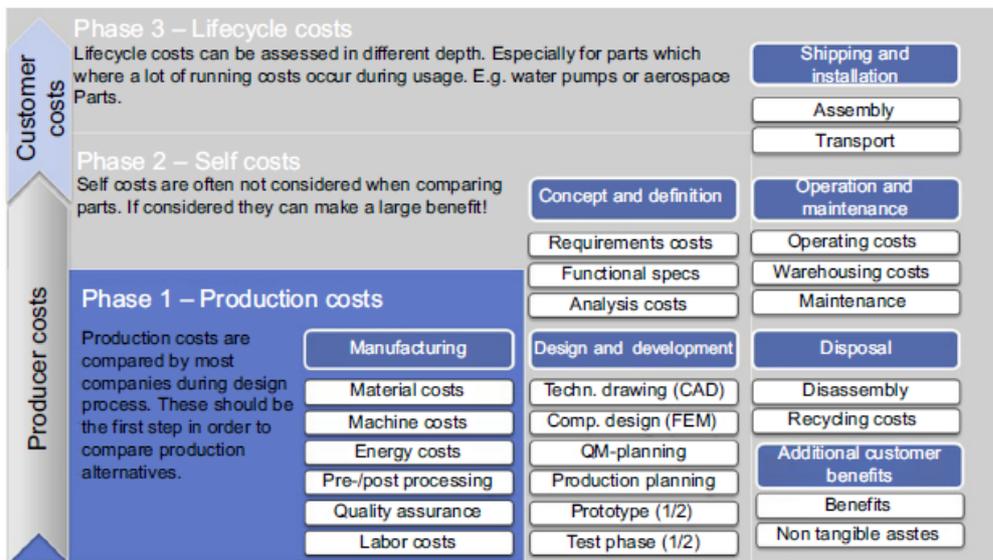
Volume related production speed = $b_M(V_B)$ (compare Fig 11.7);

support based correctional factor = $K_S(V_S)$

Recoating time: $t_r = t_{r1} * \left(\frac{h_B + h_{GS}}{d}\right) * K_r(A_{GS})$

Recoating time for one layer = t_{r1} ; max part height = h_B ; height of basic support = h_{GS} ; layer thickness = d

Correctional factor for basic support = $K_r(A_{GS})$



Cost Models in AM

Lindemann et al. (2017)

- **Post-processing:** (sum up all the necessary; mechanical post-processing steps :support removal, sand blasting or milling , drilling, ..etc.). Which has to be considered during the design phase.
- **Adjustment of mechanical properties:** as an optional process that aims to change the microstructure of the material to obtain different characteristics. (for example: hot isostatic, heat treatment.
- **Quality control costs:** Manly based on the part requirements. Test like; (initial set-up costs, cost for ensuring process stability, and tests for ensuring the part quality (ex: tomography), the test methods has also to be considered during the design phase.

Self costs: costs accrued directly at the begging of product development (product development process, product optimization), practically, they include all costs to produce and distribute a product. These phases have a high fluence on the later parts costs.

Lifecycle costs: are the costs associated with the product users as the sum of all costs due to purchase and during the period of use of a product

$$LCC = C_{CD} + C_{DD} + C_{Pro} + C_I + C_U + C_D$$

The variables have the following meanings:

C_{CD} = costs in the concept and definition phase (conception & definition)

C_{DD} = costs in the design and development phase (design & development)

C_{Prod} = costs at the manufacturing phase (production)

C_{INST} = costs in the installation phase (installation)

C_U = costs in the operation and maintenance phase (usage & maintenance)

C_{DIS} = costs in the disposal phase (disposal)

Cost Models in AM

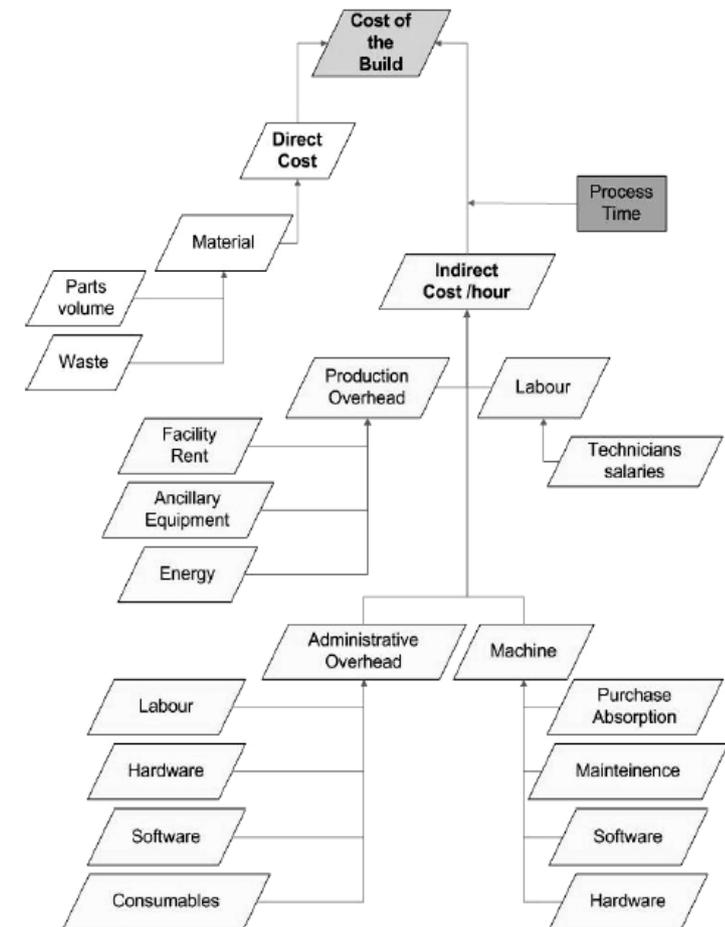
Ruffo et al. (2006)

This model is placed between **parametric model, and the engineering approach “analogy”**, as the relationships found are approximation based on statistics.

The model assumed, that the material used and time required are the main variables of the cost model.

The indirect costs as cost rate €/h, the Sum of (indirect costs annualized) over the total working time per year

The equation for times are estimated using empirical time estimator based on simulation results obtained with build **Setup ver3,4**. Based upon object geometry (height, volume, bounding box volume) and, therefore, to estimate the (scan time, cooling/preheating time, and doating times)



$$\text{Build Cost} = \text{Indirect Costs} * (t_{XY} + t_z + t_{HC}) + \text{Material Cost in Euros per unit mass} * (p * ((V_p * \eta_p) + (V_{beds} - V_b) * \alpha))$$

Variable	Description
t_{XY}	Laser on and actively sintering time
t_z	Recoating time
t_{HC}	Temperature stabilization time.
<i>direct costs</i>	Material cost and waste material.
<i>indirect costs</i>	Costs associated with labor/hour, machine costs/hour, as well as production and administrative overhead/hour

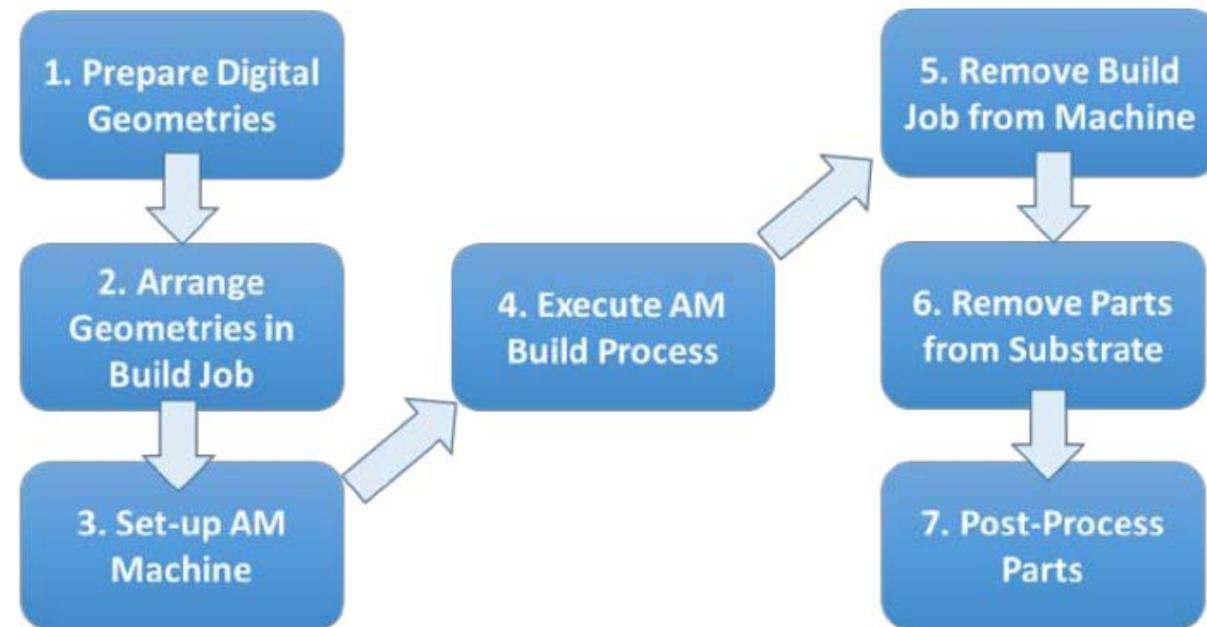
Variable	Description	Unit
m_B	Material mass	g
p	Material density	g/cm ³
V_b	Volume of build	cm ³
η_p	Total number of parts	N
V_{beds}	Total Beds Volume	cm ³
W_b	Volume material wasted	cm ³
V_p	Volume of the part	cm ³
α	Waste Factor	

Cost Models in AM

Barclift et al.,2016

A cost model was created for reused metal powder feedstocks using SOYD depreciation to account for costs pertaining to the diminishing and depletion of a metal powder feedstock's properties in PBF.

This depreciation model was implemented in a generic **activity-based costing** model for PBF.



$$C_{Total}(P_i) = C_{prep}(P_i) + C_{buildjob}(P_i) + C_{Setup}(P_i) + C_{Build}(P_i) + C_{Removal}(P_i) + C_{Substrate}(P_i) + C_{Postp}(P_i) \quad (12)$$

Cost Models in AM

Barclift et al.,2016

$$C_{setup}(P_i) = (C_{op} + C_{Mach}) \cdot \frac{(T_{setup} + T_{mat.change})}{\sum_i N_i}$$

where:

C_{setup} is the cost per part for setting up the AM machine (\$),

P_i is the built-up AM part corresponding to i th geometry (-),

C_{Mach} is the AM machine's hourly rate (\$/h),

C_{oper} is the operator's hourly rate (\$/hour),

T_{setup} is the time for setting up the machine (h),

$T_{mat.change}$ is the total time for changing the material, including corresponding activities (h),

N_i is the quantity of parts with i th geometry (-).

$$C_{build}(P_i) = C_{build-Machine}(P_i) + C_{build-Material}(P_i) + C_{build-Depreciation}(P_i) \quad (4)$$

where:

C_{build} is the cost per part for building up a part using the AM machine (\$),

P_i is the built-up AM part corresponding to i th geometry (-),

$C_{build-machine}$ is the cost per part for operating the AM machine during a build job (\$),

$C_{build-material}$ is the cost per part for the melted powder feedstock in the AM process (\$),

$C_{build-Depreciation}$ is the cost per part for the un-melted feedstock used in the AM process (\$).

$$C_{build-machine}(P_i) = T_{build} \cdot (C_{mach} + C_{gas}) \quad (5)$$

where:

$C_{machine}$ is the cost per part for producing a build job in the AM process (\$),

P_i is the built-up AM part corresponding to i th geometry (-),

T_{build} is the time for building up the entire job in the AM process (h),

C_{mach} is the AM machine's hourly operating cost (\$/h),

C_{gas} is the cost for inert gas consumption during the build (\$/h),

N_i is the quantity of parts with i th geometry (-).

$$T_{build}(P_i) = \frac{T_{idle}}{\sum_i N_i} + T_{build\ speed} \cdot \sum_i (N_i \cdot V_{total_i}) + T_{recoat}(P_i) \quad (3)$$

where:

T_{build} is the total time required for building up a single part in a given build job (h),

P_i is the built-up AM part corresponding to i th geometry (-),

T_{idle} is the time when the AM machine is inactive (e.g., heating, cooling) (h),

$T_{build\ speed}$ is the average time for the AM machine to consolidate a voxel of powder (h/cm^3),

N_i is the quantity of parts with i th geometry (-),

V_{total_i} is the total volume of the part and support structures for i th geometry (cm^3),

T_{recoat} is the total recoating time allocated to a single part (h).

$$C_{build-material}(P_i) = M_i \cdot C_{m_u} \quad (6)$$

where:

$C_{build-material}$ is the cost per part for the powder feedstock melted in the AM process (\$),

P_i is the built-up AM part corresponding to i th geometry (-),

M_i is the mass of a part with i th geometry (kg),

C_{m_u} is the cost of the powder feedstock that has been used in u build cycles (\$/kg).

$$M_i = (1 + \alpha) \cdot \rho_w \cdot (V_{part_i} + V_{support_i}) + \gamma \cdot \rho_t \cdot V_{support_i} \quad (7)$$

where:

M_i is the mass of a part with i th geometry (kg),

α is the percentage of powder loss due to process inefficiency (%),

γ is the percentage of powder loss due to being trapped within support structures (%),

V_{part_i} is the volume of the part body for the i th geometry (cm^3),

$V_{support_i}$ is the volume of the support structures for the i th geometry (cm^3),

ρ_w is the powder wrought density (kg/cm^3),

ρ_t is the powder tap density (kg/cm^3).

Cost Models in AM

Barclift et al.,2016

Instead of using a fixed value for material price the model proposes a feedstock value for the used material based on cycle numbers.

$$C_{m_{u+1}} = C_{m_u} - (C_{m_0} - S) \cdot \left(\frac{U_{max} - u + 1}{\frac{U_{max}(U_{max} + 1)}{2}} \right)$$

where:

C_{m_u} is the cost of the powder feedstock that has been used u times (\$/kg),

C_{m_0} is the cost of a virgin powder feedstock (\$/kg),

S is the salvage value of the powder at the end of its depreciable life (\$/kg),

U_{max} is the maximum number of build cycles a powder can be used for a PBF technology (-),

u is the number of build cycles a powder has underwent in PBF (-).

$$C_{build-Depreciation}(P_i) = \frac{M_i}{\sum_i(N_i \cdot M_i)} \cdot \left(M_{FB} - \sum_i(N_i \cdot M_i) \right) \cdot (C_{m_u} - C_{m_{u+1}}) \quad (8)$$

where:

$C_{build-Depreciation}$ is the cost per part for the un-melted feedstock used in the AM process (\$),

P_i is the built-up AM part corresponding to i th geometry (-),

M_i is the mass of a part with i th geometry (kg),

N_i is the quantity of parts with i th geometry (-),

M_{FB} is the total mass of the powder loaded into the AM machine's feed bed (kg),

C_{m_u} is the cost of the powder feedstock that has been used in u build cycles (\$/kg).

Depreciation cost is calculated by taking the mass of the powder loaded in the feed bed and subtracting the total mass of all built-up parts, including their corresponding powder losses. This is multiplied by the difference in financial value of the feedstock at its present state to the diminished value after one additional build cycle.

Cost Models in AM

Barclift et al.,2016

$$M_{FB} = CA \cdot D_x \cdot D_y \cdot Bh(P_i) \cdot \rho_t \quad (13)$$

where:

M_{FB} is the total mass of the powder loaded into the AM machine's feed bed (kg),

CA is the vertical rise of the feed bed per layer thickness in the build (-),

D_x is the length of the dispenser platform in the feed bed (mm),

D_y is the width of the dispenser platform in the feed bed (mm),

Bh is the build height of the tallest part in the build job (mm),

ρ_t is the powder tap density (kg/cm^3).

Based on Machine type (the build chamber dimensions)

$$C_{Removal}(P_i) = (C_{op} + C_{mach}) \cdot \frac{T_{Rem}}{\sum_i N_i} \quad (9)$$

where:

$C_{Removal}$ is the cost per part for removing the substrate/parts from the AM machine (\$),

P_i is the built-up AM part corresponding to i th geometry (-),

T_{Rem} is the **time required to remove parts**, clean machine, and perform all ancillary tasks (h),

C_{oper} is the operator's hourly rate (\$/hour),

C_{Mach} is the AM machine's hourly operating cost (\$/h),

N_i is the quantity of parts with i th geometry (-).

$$C_{Substrate}(P_i) = \frac{C_{stress}}{\sum_i N_i} + C_{EDM} \cdot \frac{A_{con}(G_i)}{\sum_i N_i \cdot A_{con}(G_i)} \quad (10)$$

where:

$C_{Substrate}$ is the cost per part for separating a part from the substrate (\$),

P_i is the built-up AM part corresponding to i th geometry (-),

C_{stress} is the cost for stress-relieving a build plate(\$),

C_{EDM} is the total cost for separating a part via EDM (\$),

A_{con} is the connected area of a part to the substrate (cm^2),

N_i is the quantity of parts with i th geometry (-).

$$C_{postp}(P_i) = \sum_i (T_{postp}(G_i) \cdot (C_{op} + C_{tools}))$$

where:

C_{postp} is the total cost for post-processing (\$),

P_i is the built-up AM part corresponding to i th geometry (-),

T_{postp} is the **time required to post-process** a part geometry (\$),

G_i is the i th geometry (-),

C_{op} is the operator's hourly rate (\$/hour),

C_{tools} is the hourly rate of tools and machines for post-processing (\$).

Cost Models in AM

Schroder et al. (2015)

- Provide business model which evaluates process cost of additive manufacturing technologies, serve as a tool to support the industrial decision makers. Using **Time-driven activity-based costing**.
- The tool has two main areas: the **data input area and the data output area**.
- For a detailed cost calculation, an overall of **77 input** values is needed.
- Because of this high amount of values **the input area** is divided into
 - **process-specific information:** Includes quality-related investments, process relevant cost rates and machine and material settings

The screenshot shows a software interface for AM cost evaluation, divided into four numbered sections:

- Section 1:** Manufacturing process parameters.

manufacturing process	Selective laser melting	
machine	Standard SLM	
construction material	Normal	
support material	No material	
quantity	100	running time (h) 90
- Section 2:** Component and enveloping body parameters.

component volume (mm ³)	20429	enveloping body length (mm)	48
component volume (%)	80	width (mm)	38
volume filling degree (%)	10	height (mm)	14
support structure (%)	0		
- Section 3:** Process parameters.

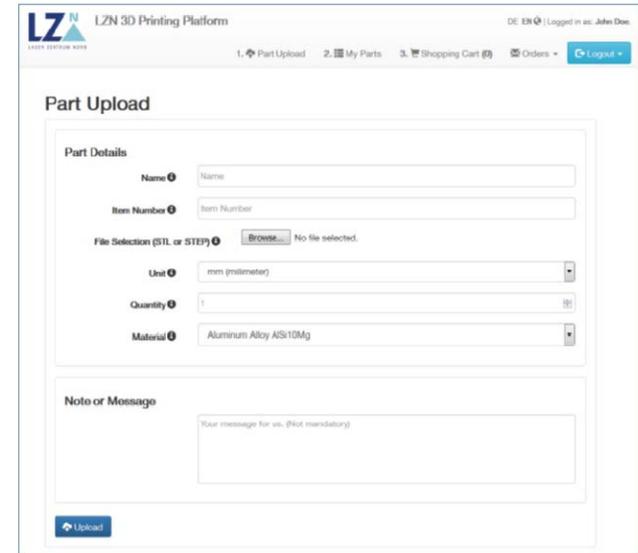
layer thickness (mm)	0,12	reject rate (%)	10
construction time (h)	5	Post-Processing (h)	0,05
- Section 4:** Control buttons.

choose quality characteristics	edit preferences	edit quality characteristics
edit machine	edit material	close

Cost Models in AM

Rudolph et al. (2017)

- Develops an automated, self-learning calculation –Cost model- for SLM, focusing on a cost of the generation process “build processes”.
- In which the customers are able to upload the part geometrical data, then converted into STL, to execute the algorithms, so the given geometry is automatically analyzed to identify the key characteristics: **volume, surface, and dimensions**.



- The cost model uses **analytical and “analogical” statistical based functions** to determine the $t_{Exp} = \frac{(V_{Part} + V_{Sup})}{v_{Melt}}$ part
- $C_{Part} = t_{Part} \cdot C_{mh}$ des that **the capa** $V_{Sup} = V_{Part} \cdot a_{Sup}$
- **Build height** $t_{Coat} = \frac{h_{Gen,Part}}{h_{Recoat}} \cdot t_{Recoat} \cdot \frac{(V_{Part} + V_{Sup})}{u_{BJ} \cdot h_{Gen,Part} \cdot l_{BC} \cdot W_{BC}}$
- $t_{Part} = t_{Exp} + t_{Coat}$ ation w $= \frac{t_{Recoat} \cdot (V_{Part} + V_{Sup})}{h_{Recoat} \cdot u_{BJ} \cdot l_{BC} \cdot W_{BC}}$
- **regression.**

$$u_{BJ} = \alpha_0 + \alpha_1 \cdot dim_{Part_1}$$

$$h_{Gen,Part} = \beta_1 \cdot dim_{Part_1} + \beta_2 \cdot dim_{Part_2}$$

Cost Models in AM

Some limitation Of The exist Cost Models

- ❑ Cost models are always discussed based on unique case study components that focus on targeted AM technologies in a specific application.***
- ❑ A versatile cost calculation model that can represent AM in general is still missing.***
- ❑ Neglecting other important characteristics, for instance, the part functional requirements, such as mechanical properties and surface roughness, may lead to a misleading decision being made. Which AM cost models should take into consideration.***
- ❑ There have been limited studies to utilize the AI technique.***
- ❑ Not many studies were found that contribute towards providing a variation of web-based cost models services.***
- ❑ A customer-oriented user perspective is still not widely explored, “where target***

The proposed cost model

The proposed cost model

The proposed cost model is part of our current work to develop decision support system, “using knowledge based approach”, for estimating the additive manufacturing product cost. In order to provide a support for the AM cost estimation of products at early stages, when receiving the customer order, therefore to achieve relevant cost estimation.

However, to perform a manufacturing cost estimation it is important;

- ✓ From one side, to define the cost model that could be used to estimate the product cost. In which it could be equations, or relationship between different cost factors/ parameters.
- ✓ Where the other part is resides in the knowledge that is essential to determine the activity and the factors that generate cost, as well as the knowledge required to link the product, and customer requirement to cost factors.

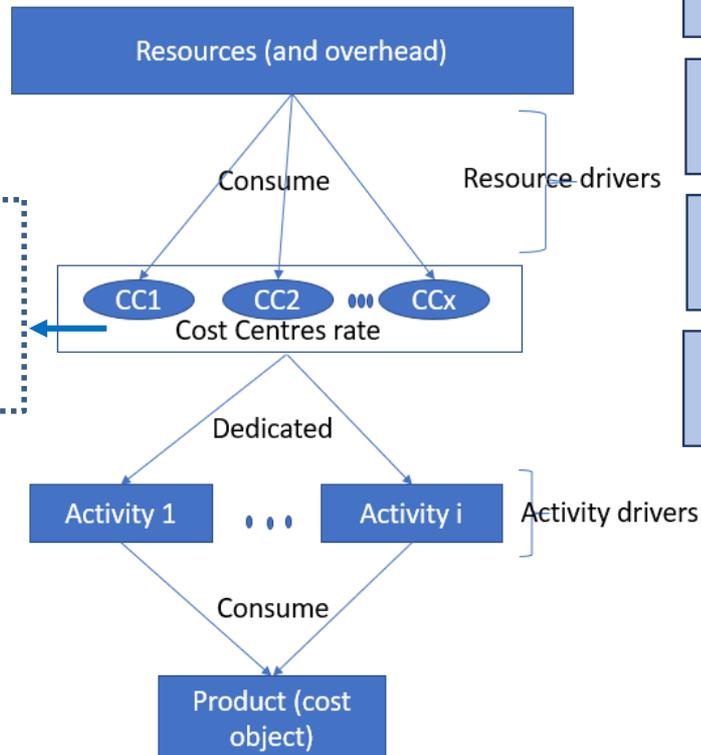


The proposed cost model

For the cost model we used **Activity based approach** (among other advantages we've described previously):

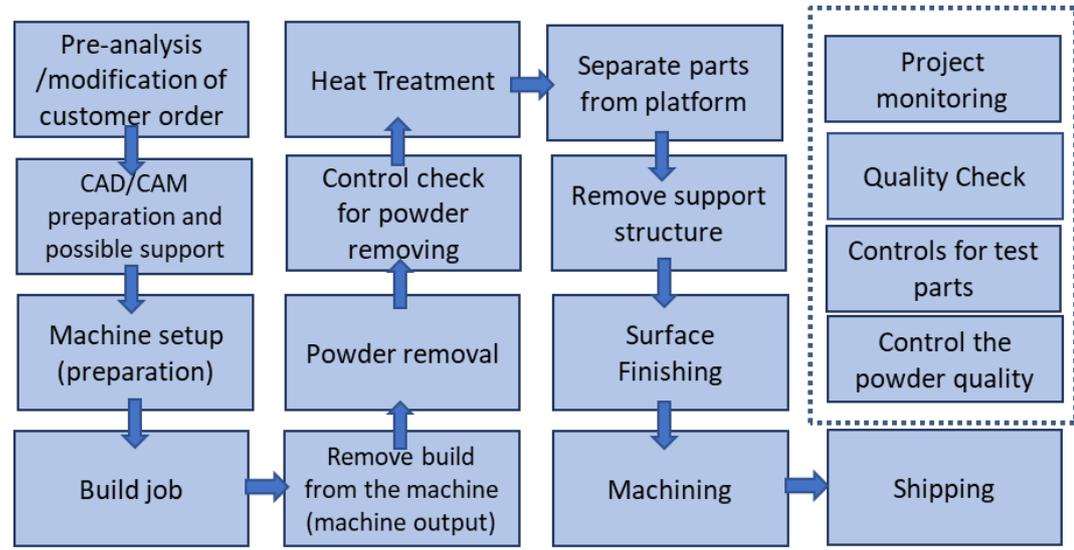
- ABC could provides the structuring support (the activity) to keep non financial information such as defect rates (quality), throughput rates (effectiveness of the industrial process) and delivery time.
- Better profitability measures, Better decision and control, better information for controlling capacity cost.
- Help the companies to improve product design and manufacturing process.
- In addition, it can lead to classifying activities as value-added and non-value added

The proposed cost model



- Machine rate
- Labor rate
- Overheads rate (Administrative/Pr action)

Consumed by activity (based on the activity)



$$\text{Final Product Cost} = \text{Material cost} + \text{Build}_{\text{platform}} \text{ cost} + \sum_{i=1}^n \text{Activity}(i) \text{ Cost}$$

n: Number of activities (-)

$\sum_{i=1}^n \text{Activity}(i) \text{ Cost}$: the sum of all activity cost (€)

Final product cost: the cost of the final product (€)

□ **Build platform:** The cost of the used platform in the build can vary based on the material type, and dimension of the platform.

The proposed cost model

For the sake of example, let's assume that the product will have one activity (build job), and the final cost will be as follows:

$$\text{Final product cost} = \boxed{\text{Material cost}} + \text{Build platform cost} + \text{Build job cost}$$

$$C_{\text{material}} = M_{\text{material}} * C_{\text{material}}$$

Based on material type, and if it is new, or used powder.

M_{material} : Mass of used material (Kg)

C_{material} : The commercial price of the used powder (€/kg)

$$M_{\text{material}} = (V_{\text{build}} * P_{\text{melted density}}) + ((V_{\text{waste}} + V_{\text{powder loss (inside the build part)}}) * P_{\text{density}})$$

$$P_{\text{melted density}} = (P_{\text{density}} / 0.6)$$

The volume of the powder loss that accumulated inside the build part, (e.g. if the part has internal channel)

The volume of the powder loss within the build process (proportional to the build time)

V_{build} : The total build volume (mm^3)

V_{waste} : The volume powder waste due to AM build process (mm^3)

P_{density} : The powder density (Kg/mm^3)

$P_{\text{melted density}}$: The Melted powder density (Kg/mm^3)

The total build volume, is the entire build inside the machine, including the product volume, and the support structure, also if the project requires test part for some control analysis, the volume of the required test part is included.

The proposed cost model

For the sake of example, let's assume that the product will have one activity (build job), and the final cost will be as follows:

Build job

Final product cost = Material cost + Build platform cost + Build job cost

This value can vary, based on material type of the platform (which is mainly similar to the powder material type), and size of the build platform.

$$C_{\text{build-machine}} = T_{\text{build}} * C_{\text{AmMach}}$$

T_{build} : The time for building the entire job (h)

C_{AmMach} : AM machine's hourly rate (€/h)

The Build time is out of our scope, however, several software are able to estimate this value, in which we based our model.

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Competence Unit Training CU 34 – Process Selection

Course: AM Cost Evaluation and management based on process oriented approach (Part 2)

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