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Additive Manufacturing and High Speed Machining -Cost comparison of short lead time manufacturing methods

Sebastian Hällgren[a,b], Lars Pejryd[b], Jens Ekengren[b]

[a]*Saab Dynamics, Development, 69180 Karlskoga, Sweden*
[b]*School of Science and Technology, Örebro Univeristy, Sweden*

* Corresponding author. Tel.: +46 734461231; *E-mail address:* sebastian.hallgren@saabgroup.com

Abstract

Additive Manufacturing (AM) using Powder Bed Fusion (PBF) allows part with abstract shapes, that otherwise would need costly tooling, to be manufactured with short lead time. In this study AM build time simulations are used to predict series part cost for eight parts that are possible to cut from rod blanks using High Speed Machining (HSM). Results indicate that when the part shape can be cut from rod blanks, AM is more expensive than HSM even for series of one. If post processing machining is added to the printed AM blank part, the cost difference increases further. Finally, the model is used to predict part-cost in series production if print speed increases, if machine cost is reduced or if part mass is reduced as a result of redesign for AM.

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Keywords: Additive manufacturing, Powder Bed Fusion, High speed machining, cost, series production, AISI MR,

1. Introduction

Additive Manufacturing or 3D-printing in metals makes it possible to manufacture shapes that previously were impossible to manufacture or could only be realised using long lead time tool based manufacturing methods. When series volume is low and Non-recurring cost (NRC) is large due to tooling, the per-part cost increases. Parts and products that have uncertain series volumes or high form requirements may be realised both during development and in series production using High Speed Machining. HSM is similar to AM as it manufactures parts with low tooling costs and short lead times. Low lead time manufacturing such as High Speed Machining or Additive Manufacturing is favourable for series production in lower volumes. During development, fewer parts are needed but sooner in order to reach the market quicker, and to reduce concurrent engineering team development cost. Geometrical changes, more common during development, are usually both faster and cheaper to accommodate when retooling is not needed.

High Speed Machining is a subtractive manufacturing method involving high feed rates and high spindle turning speeds that lowers torque and decreases tool temperature. Depending on part shape and machine, special or standardised fixtures are needed to hold the work piece steady in place. Today, most machines are numerically controlled (NC) and programmed using a 3D-model as input to plan toolpaths. In many cases, the first manufactured part may be delivered to the customer as the workflow is robust and well known. Blanks for machining may be standard rod blanks or cast or wrought parts in need of cutting to tolerances. The material removal rate (MRR) is determined by the material toughness in addition to part shape. A Machinability Rating (MR) has been established by AISI to relatively compare different materials cost to cut. The rating includes cost effects of MRR and tool wear. An AISI rating of 1.00 is assigned to a cold drawn steel B1112 with Brinell hardness of 160. Values lower than 1.00 indicates a more expensive to cut material and higher values means it is nominally a cheaper material to cut. Design guide lines for HSM inform a designer what shapes and features to avoid and which of them drives cost.

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3D printing or Additive Manufacturing has been around for about 30 years and was initially used to produce plastic prototype or mock-up parts during development. An energy source melts deposited powder layer by layer on a moving platform. Typical metal Powder Bed Fusion AM machine costs are close to 1M Euro. Major cost contributors are large part height that combined with small layer thicknesses causes long build times in an expensive machine. A trade-off scenario for lowest possible part cost exists between choosing build direction for low height, the resulting build volume utilisation and support structure build up and cost of removal. Most parts are post processed after print. Post processing often includes heat treatment and surface roughness adjustment. If the as-printed part dimensional requirements cannot be met by the printed surface, machine cutting is needed. Allowance material is needed to be added prior to building an AM blank similar to other near net shape manufacturing methods.

The possibility to manufacture abstract and complex shapes is perhaps the most obvious benefit of AM. Gibson et al. defines terms as shape complexity, material complexity, hierarchical complexity and functional complexity to describe areas where AM adds to existing manufacturing methods [1]. Klahn et al. defines four areas where additive manufacturing might be advantageous; integrated design, individualisation, lightweight design and efficient design [2]. Yau et al. compared dental prosthetics manufactured using AM and 5-axis milling and shortly states that AM is costlier [3]. Yoon et al. compared energy consumption of additive and subtractive methods. They found that injection moulding was 100 times more productive than AM, and the same applied for the Specific Energy Consumption (SEC) per part produced [4]. Faludi et al. did an environmental impact comparison between plastic Filament Depositon Modelling (FDM) parts versus milling and states that for FDM electricity had the largest environmental impact and for subtractive manufacturing material waste and cutting fluids were the largest, suggesting that FDM is better than milling from environmental impact [5]. Atzeni et al. shows result of a reengineering effort of an aircraft landing gear mechanism using both topology optimisation and part consolidation. They compare cost between AM and die casting finding that for less than 40 items AM was cheaper [6]. It is unclear if the time cost to reengineer the original design was included in the comparison.

Are parts that do not take advantage of the shape complexity that AM provides economically suitable for series production using AM? If not, how much faster or how much cheaper must metal PBF become to cost effectively produce simpler shapes using AM? What cost effect would a mass-reduction through topology optimisation have on a part produced in aluminium? Can print speeds derived from build simulation be used to predict print speeds for another material? To answer these questions, a cost comparison mathematical model has been created. It uses real part quotes and compares them to AM build time simulations.

Some differences between machining and AM are shown in table 1.

Table 1. High speed machining and additive manufacturing costs and strengths

	High Speed Machining, HSM	Metal Powder Bed Fusion
Cost drivers	Number of operations, Material Removal Rate MRR, volume removal	Part height, part volume, support/heat structures during build
Lead time drivers	Rod blank availability, machine setup and planning	Machine setup, post processing needs on printed AM blank
Accuracy	~0.01mm	~0.1mm
Surface roughness	Very fine	Medium/rough
Ultimate strength	Aluminium: A Titanium: T	Aluminium: 0.5*A (Cast like properties) Titanium: T (wrought like properties)
Data input	3D model, NURBS, drawings	3D model, tessellated
Strengths	Low NRC, fine tolerances, fine surfaces, robust workflow, good/stable material properties, many service providers, many materials	Low NRC, shape complexity for free, short lead time for cast like shapes, standardised shape (powder) on material
Weaknesses	Costly for many small features Long lead time for exclusive materials in rod Cost reduction due to large volume limited	Large surface roughness Moderate tolerance achievement Slow manufacturing speed Low material availability Limited part size.

2. Method

A mathematical model based on real HSM price quotes of designer drawn prismatic parts in aluminium has been created. HSM cost quotes were separated into recurring cost and non-recurring cost. Recurring HSM costs consist of material cost and machine cutting cost. NRC for HSM consisted of NC path planning and fixture cost. Non-recurring costs for AM consist of AM build preparation, machine preparation and recurring cost includes print time and material. Costs are compared between AM and HSM for the number of parts that fit within an AM build volume. The powder deposit cost is then shared for all parts built at the same time, creating a NRC per build chamber for the AM parts; see figure 1 and table 2. Cutting time effect for HSM due to change in material is modelled by the use of a ratio between the two materials' AISI Machinability Ratings (AISI MR), see figure 3 and table 4. The AM cost is estimated through build time simulations using an EOS SLM M290 printer. Parts were placed 10mm above the build platform. The build volume is filled with parts oriented with a build direction that trades-off support structure build up vs. build chamber packing. All parts share the powder deposit cost for the build. Build time is simulated for three different materials; steel, titanium and aluminium. AM blank cost is calculated by multiplying printing time to an experience based template cost per machine plus powder cost. The model aims to predict print times for a part in a new material by scaling a simulated print time for a given material with the max print speed ratio from table 4. Post process machine cutting of the AM blanks was estimated by offsetting part surfaces with stricter tolerances +0.5mm for allowance. After studying this effect on some of the parts, a 25% volume removal need of allowance was established, see figure 2. Support structures keep the part attached to the build plate during build and reduce part warping during cooling. This volume increases print time and adds post processing removal cost. In this model, a part volume increase of +15% was seen after correct build preparation of one part in *Magics* [7], and was assumed to be relevant for all parts. Post process machining time when material is changed is calculated by using the MRR of aluminium from quote divided by the AISI machinability rating ratio of the materials. A 3 minute handling time was added to account for coordinate measuring of the AM blank before post process cutting, see figure 3.

Figure 1 compares AM and HSM manufacturing steps where * describe steps that might not be needed depending on part requirements or AM process. Figure 2 shows how allowance and support volumes were estimated. Figure 3 visualises the cost model. Table 2 shows the parts with machining cost quotes separated in material, machining and non-recurring costs. Table 3 show the parts that were evaluated for cost in this study.

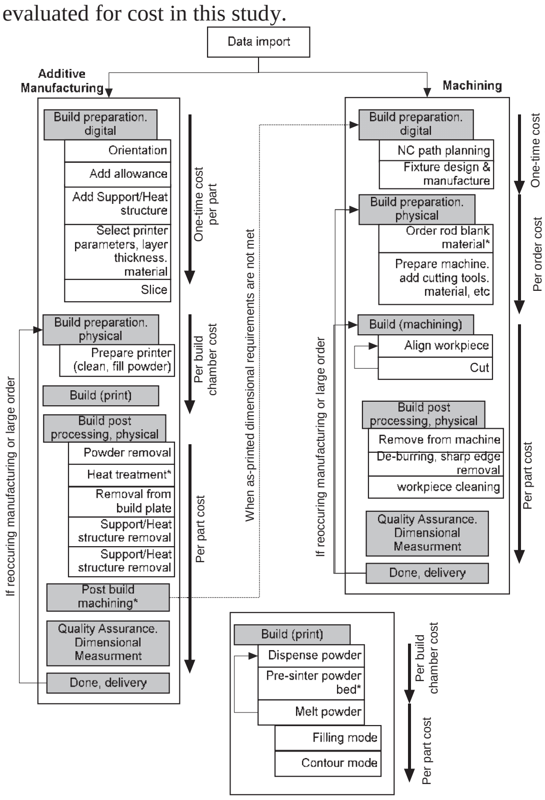

Figure 1. Manufacturing workflows with indications of recurring costs, one-time costs and per build/order cost.

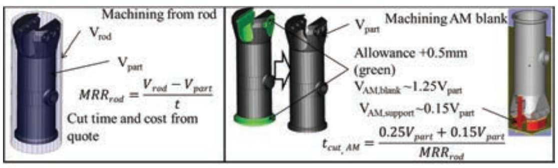

Figure 2. Allowance and support prediction "*Holder*".

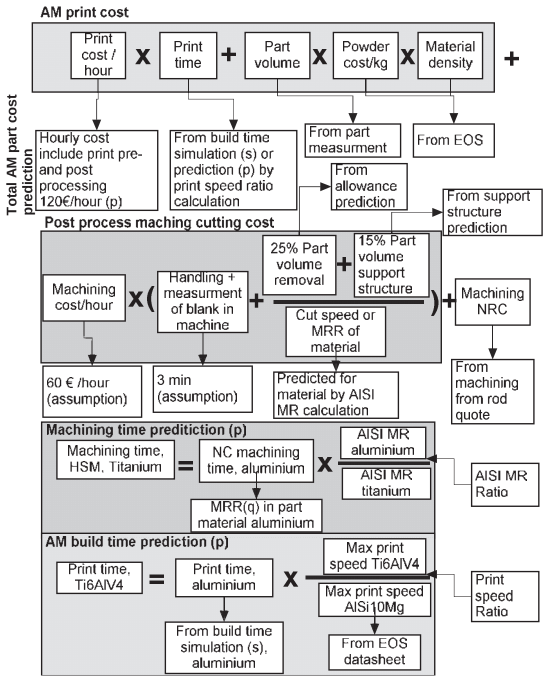

Figure 3. Cost prediction model.

Table 2. HSM and AM recurring and non-recurring costs.

	High Speed Machining, HSM	Metal Additive Manufacturing, AM
Initial investment, NRC	Fixtures +NC tool path planning Derived from cost quotes	AM build preparation Powder deposit time (NRC per build chamber)
Recurring cost	Cut time + material cost	Print time + powder cost + post process treatment

Table 3 Parts with material and machining costs from quotes.

Part name	Buy-to-fly ratio/ Volume/Area / rod blank dim.	BREP surfaces	Material	HSM cost NRC/ material +machining derived from quotes [€]
Guide	13.7 / 0.8 ø50x15	128	Aluminium A7075-T6	NRC: 380, Material: 0.5, Machining: 19
Cover	12.2/0.9 ø30x55	105	Aluminium A7075-T6	NRC: 490, Material: 0.6, Machining: 10
Lid	11.7/0.9 70x30x130	414	Aluminium A7075-T6	NRC: 380, Material: 2.2, Machining: 24
Housing	8.9/1.2 ø55x70	281	Aluminium A7075-T6	NRC: 690, Material: 3,0, Machining: 17
Bracket	10.4/0.2 ø90x30	233	Steel EN 10083-1-	NRC: 810, Material: 6.0, Machining: 50
Guard	7.9/0.9 ø25x15	31	Aluminium A7075-T6	NRC: 70, Material: 0.1 Machining: 3
Clamp	8.6/1.0 ø40x55	123	Aluminium A7075-T6	NRC: 530, Material: 1.4, Machining: 14
Holder	5.9/1.2 ø40x110	94	Aluminium A7075-T6	NRC: 320, Material: 1.4, Machining: 14

2.1. Assumptions

The number of parts that fit inside the build chamber is assumed to be the lot size. If lot size was to be larger, additional per-batch cost of AM machine preparation would add cost to subsequent parts. Part volumes used during build time simulations did not include the predicted +25% increase in volume due to allowance. This underestimates the AM blank cost. AISI Machinability Rating ratio is used to predict machining cost for HSM parts produced in other material than aluminium. The EOS SLM machine consumes inert gas during printing. This cost has been roughly estimated to 100€ per 100h build time. This adds less than 1% of cost and is not included in this cost prediction model. Redesign for AM is simulated by a reduction in 30% volume by the use of topology optimisation or lattices. 60µm titanium print cost is predicted by halving powder deposit time & doubling print speed from simulated 30µm. Table 4 shows print speed and material cost from EOS used in the model. Powder cost and print speeds vary largely between vendors. Table 5 shows AM hourly machine cost calculations.

Table 4. AM print speeds (max) and AISI Machinability Ratings with references.

Material	Build speed, max EOS M290 [cm3/h]	AISI Machinability Rating	Rod cost (€/kg)	Powder cost (€/kg)
Aluminium	26.6 (30µm) [8]	1.2 (A7075-T6) [11] 0.76 (die-cast) [12]	7	110
Titanium	13.5 (30µm) [9] 32.4 (60µm) [9]	0.22 [13]	28	440
Steel MS1	15.1 (40µm) [10]	0.36[14]	3.5	130

Table 5. Hourly AM machine cost calculation.

Variable	Value	Note
machine cost (€)	860000	SLM M290 with support equipment
write-off # years	3	
machine cost/year (€/year)	286660	
operator annual cost (€/year)	67600	
# operators for AM preparation, print, post processing	2	Operators perform tasks denoted in figure 1, effectively sharing build preparation and post processing costs per machine hour
machine hours per year	3500	
Machine cost per hour (€/h)	120	Hourly machine cost includes operators, machine preparation (digital and physical)

3. Results and discussion

Results from AM build time simulations are shown in tables 6 to 9. (s) means that the cost is based on build time simulations (q) means quote and (p) is predicted costs from model described in figure 3. Adding predicted post process machine cutting costs increase part cost, see table 7. When material changes, costs from machining quote are multiplied by the AISI Machinability Rating ratio for the materials, see table 8. The potentially faster print of Titanium is lessened due to the thin layer thickness used for simulation. Increasing print speed 4x and 8x [15], keeping powder deposit time yields table 9. These parts in aluminium and steel require print times 4x-8x faster to be economically sound to print instead of machining, see table 9

Table 6. AM (blank) costs per material.

	AlSi10Mg	Ti6AlV4	MS1
Guide AM blank NRC	510	490	370
Print cost/part (s) [€/pcs]	22	32	36
Mtrl cost/part (s)[€/pcs]	0.6	4.2	2.2
Cover AM blank NRC (s)	560	540	410
Print cost/part (s)[€/pcs]	26	35	44
Mtrl cost/part (s)[€/pcs]	0.9	5.6	3.0
Lid AM blank NRC (s) [€]	760	750	550
Print cost/part (s) [€/pcs]	210	277	363
Mtrl cost/part (s)[€/pcs]	6.9	45.3	24.3
Housing AM blank RC (s)	600	590	440
Print cost/part (s) [€/pcs]	146	194	255
Mtrl cost/part (s)[€/pcs]	5.5	36.1	19.4
Bracket AM blank NRC (s)	690	680	500
Print cost/part (s) [€/pcs]	138	176	265
Mtrl cost/part (s)[€/pcs]	5.4	35.5	19.0
Guard AM blank NRC (s)	190	190	140
Print cost/part (s) [€/pcs]	7	14	14
Mtrl cost/part (s)[€/pcs]	0.3	1.8	1.0
Clamp AM blank NRC (s)	620	600	460
Print cost/part (s) [€/pcs]	66	94	132
Mtrl cost/part (s)[€/pcs]	2.4	15.6	8.3
Holder AM blank NRC (s)	1220	1210	920
Print cost/part (s) [€/pcs]	184	237	301
Mtrl cost/part (s)[€/pcs]	6.9	45.3	24.3

Table 7 AM + machined part cost, aluminium, cost/part per one lot.

	# pcs /lot	AM build cost (s) (€/pcs)	AM build (s)+ machining (p) (€/pcs)	Machining from rod (q) (€/pcs)
Guide	176	26	33	22
Cover	117	32	41	14
Lid	18	259	286	47
Housing	15	191	244	66
Bracket	18	182	232	101
Guard	132	10	15	4
Clamp	35	86	107	30
Holder	36	225	241	28

Table 8. Material change effect on part cost.

	# pcs / lot	Ti, AM blank (s) (€/pcs)	Ti, AM (s)+ HSM (p) (€/pcs)	Ti, HSM from rod (p) (€/pcs)
Guide	176	39	61	110
Cover	117	45	67	59
Lid	18	363	406	159
Housing	15	270	337	149
Bracket	18	250	306	264
Guard	132	17	35	17
Clamp	35	127	163	95
Holder	36	315	348	109

Table 9. Speed increase or printer cost reduction effect on per-part cost for aluminium parts in series production.

	# pcs / lot	AM blank (p), 4x faster print (€/pcs)	AM blank (p), 8x faster print (€/pcs	AM blank Ti (p), 60 µm (€/pcs)	AM blank (p), -30% volume (€/pcs)	HSM (q) (€/pcs)
Guide	176	9	6	22	18	22
Cover	117	12	9	25	23	14
Lid	18	102	75	204	188	47
Housing	15	82	64	153	141	66
Bracket	18	78	61	143	134	101
Guard	132	4	3	10	7	4
Clamp	35	37	28	71	64	30
Holder	36	87	64	180	162	28

Figure 4 shows a small and larger part in aluminium for series volumes of 1 to 10. Smaller parts show more economic promise to print instead of cut, as long as post process machining is not needed.

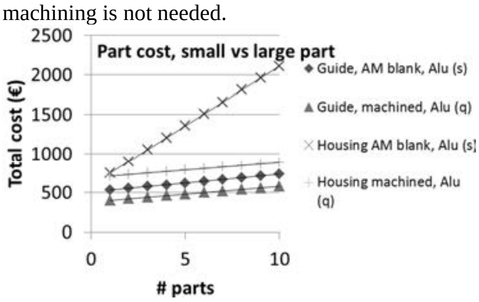

Figure 4. Large AM parts (*Housing*) print slowly and cut faster from rod than smaller parts (*Guide*). Machining from rod is cheaper from first part to last in both cases.

Printing in aluminium can be a very good alternative both cost and lead time wise during development when parts are to be cast during series production. Printed parts show many similar characteristics of cast parts; material properties, surface roughness and tolerance achievement are more similar to casting than they are for high speed machining. Testing part performance using printed parts during development to simulate performance of cast parts will yield comparable results and could save development time.

Lead time increases if the AM builder need to procure machining from outside. The machining quotes used in this study specify a lead-time of 5 days for material delivery and 30 days for part manufacturing. It is likely that a combination of AM + machining is chosen, the total lead time for part delivery would increase. If the AM builder has machining capabilities on standby for post-process machining cutting after print, the total lead time would get lower at probably higher cost due to lower machine utilisation during standby.

Figure 5 shows the print speeds per part. "Box" in the graph is print time for a 230x230x10mm^3 sized box, creating a maximum print speed. The relatively constant print speeds achieved for these parts of 7-12cm^3/h could mean that the movement of the laser beam is limiting the maximum print speeds. This makes predicting print speeds using a print speed ratio as described in figure 3 an inaccurate model. Simulating print times for one and two parts per material respectively is a better method to model AM cost per part. Powder deposit time as an AM NRC per build lot and the per-part print time can then be calculated and plotted as shown in figure 4 and figure 6.

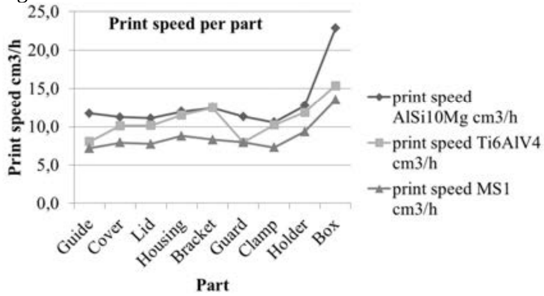

Figure 5. Print speed per part, excluding powder deposit time.

Large parts with large "buy-to-fly" ratios (part blank volume divided by final part volume) often result in a high MRR. Small parts tend to have small features that need lower MRR. If the cutting speed needed for high accuracy in aluminium is below the max cutting speed of titanium, this would provide both materials with the same MRR. An indication of machining part complexity is the parts MRR from the quote. If machining quotes are unavailable, other complexity estimators that could be used are the number of surfaces of the geometry or the ratio between volume and surface area of a part ("bulkiness") as stated in table 3. No studies of these relations on part cost have been conducted and the machining cost prediction model has not been validated for material changes. In order to predict machine cutting cost due to material change, further investigations with a machine operator is needed, possibly studying the MRR of individual tool paths and correcting them individually using the AISI machinability rating.

To assure safe builds and reduce part distortion due to thermal stresses, an experienced AM operator usually adds more or different support structures than the AM build preparation tool *Magics* provides per default. The increase in per part build time due to correct structures was approximately +15% which would increase AM cost further than our model shows.

The largest uncertainty in the model is the amount and speed of post process machine cutting cost that these AM parts are in need of. Tolerance requirements are too strict for AM to fulfil with its as-printed surface for these parts. This model adds 40% (25% allowance, 15% support structures) of the finished printed part volume for machining cost predictions. The real values are part and geometry dependant and would be found during real re-engineering of parts and new NC tool path planning of AM blanks instead of rod. In this model the same 40% volume removal effect on cutting time cost is added to all parts. For some parts in this study that could be an overestimation. The machine operator that was interviewed in this study states that approximately half of the cutting time removes the majority of the material. The other half is spent on cutting the finer features. This could indicate that 50% of machining quotes to be added to the AM blank, assuming that the AM blank only needs fine machining. The operator also preferred cutting from rod instead of using blanks, stating it is often cheaper and faster.

For prototype production of cast like parts in low numbers during development, an AM operator would try to decrease the build height. Some parts with large build heights in this study would print faster by changing build direction when fewer parts are needed. An AM operator of parts in series production would compare effects of build volume packing, support structure build up and subsequent post-process machine cutting needs to select an optimal build direction. This task is manual and iterative and not easily predicted without multiple iterations.

Part placement in the build chamber relative other parts affects printing time. Tight packing lowers the total print time due to less time spent of the energy source moving between parts. When small parts were placed in each corner of the build chamber instead of packing them in a group close to the recoater, the build time increased +6%. This indicates that calculating total print time for *n* parts using a linear relation with powder deposit time being a constant and adding *n* parts * print time/part and disregard part position in the build plane adds a relatively small inaccuracy. The print time prediction model is visualized in figure 6.

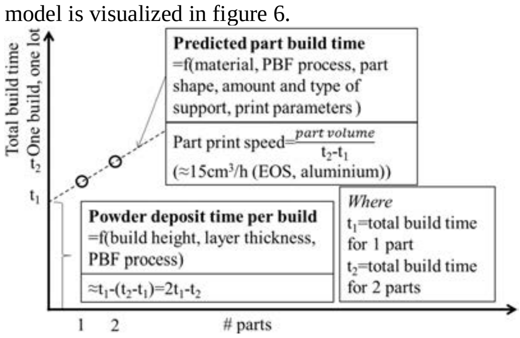

Figure 6. Simplified part cost prediction model for AM blank print time in series production for an EOS SLM machine.

4. Conclusions

A mathematical model to predict part cost for additive manufacturing for a number of existing prismatic parts, designed for machining from rod, has been created. The model predicts cost per part effect due to material change, print speed increase and mass reduction. Cost quotes for existing HSM-manufactured prismatic part geometries were cost estimated using AM build-time simulations to predict cost. Results show that:

- Parts that are possible to cut from rod blanks are more expensive to print mainly due to large print times. Larger parts in softer material that require long printing times but short machining times from rod blanks, create the largest cost differences.
- Predicting print time using print speed ratios between materials' maximum print speed produces inaccurate results. Instead, two print time simulations per part and material were used to calculate powder deposit time (NRC for the build) and per-part print time.
- Materials with a larger print-to-cut ratio (13.5/0.22 for titanium vs 26.6/1.2 for aluminium) show better promise for being economically feasible to print instead of machining from rod.
- The amount and speed of predicted post-process machining affects the total per-part cost to a large degree, suggesting more accurate cost predictions of post-processing of AM blanks is needed.
- Increasing print speed >8x at the same machine cost begins to shift the economy in favour of AM using aluminium for these parts, post process machining included. For titanium the shift occurs earlier.

An important guideline for designers for AM is to accept the as-printed properties and dimensional accuracy to remove post process machining in order to save cost and lead time. If post process machining is needed on many surfaces, it might be more economical to cut the entire part from a rod blank. Parts in easy-to-cut materials need to use AM advantages like shape complexity in order to make AM more economically suitable than HSM. Prismatic parts that "function through fit" rather than "function through shape" in aluminium are, according to this study, cheaper to manufacture using HSM than AM for series volumes of one an upwards.

Acknowledgements

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