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Cost Sensitivity Analysis for Laser Powder Bed Fusion

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Abstract

Laser Powder Bed Fusion is the most widespread additive manufacturing process for metals. In literature, there are several analytical models for estimating the manufacturing cost. However, few papers present sensitivity analyses for evaluating the most relevant product and process parameters on the production cost. This paper presents a cost model elaborated from previous studies used in a sensitivity analysis. The most relevant process parameters observed in the sensitivity analysis are the 3D printer load factor, layer thickness, raw material price and laser speed.

Keywords: design costing, additive manufacturing, design to x (DtX), cost estimation, sensitivity analysis

1. Introduction and Literature Review

Manufacturing cost is one of the main drivers in product design. The advent of new technologies, such as additive manufacturing (AM), has increasingly pushed companies to consider new manufacturing options. Design engineers must quantify and evaluate the costs of their design solutions through appropriately developed cost models. Moreover, design teams should be aware of AM cost drivers (namely, factors that cause a change in the cost of a product) to develop competitive products. Sensitivity analysis is a technique that allows identifying such cost drivers.

Additive manufacturing, one of the nine enabling technologies of Industry 4.0, is getting increasing attention, especially for metal components. In this context, AM is seen as a technology able to produce high-performance and multi-functional products, which cannot be obtained with traditional techniques(Diegel et al., 2019; Leary 2020). Among the metal AM technologies (e.g., Directed Energy Deposition, Metal Bound Deposition, Binder Jetting - ISO/ASTM 52900), Laser Powder Bed Fusion (L-PBF) is the most widespread since its accuracy and maturity (ASM International. Handbook Committee, 2020; Wohlers et al., 2018).

In literature, it is possible to observe several cases of cost-effective solutions thanks to the adoption of AM techniques. Cost analysis is a mandatory activity during the design phase. A broad overview and potential means to reduce costs may help engineers in their tasks (Costabile et al., 2016). An extensive review of existing AM cost models is offered by (Kadir et al., 2020), who set out and classified most of the AM cost models developed in the last decade. More specific studies have been done on individual AM technologies. (Rickenbacher et al., 2013) developed a detailed analytical cost model for L-PBF by improving a previous version. This study analysed the L-PBF printing phases in detail, estimating the pre-print, post-print, and print phases analytically. An equation with linear regression coefficients calculates the fraction of time needed to produce each component within the printing job. Calculation of the printing time for L-PBF is also addressed in (Baumers et al., 2012). The authors presented an approach based on energy considerations, validated with data measured during the build experiments. Energy considerations were also made by (Gebbe et al., 2015) and (Kamps et al., 2018). Their papers presented a study on the energy consumption of an L-PBF process.

Interesting levels of detail are reached with (Roffredo, 2018), who developed a mathematical cost analysis model for the L-PBF process. The study proposes analytical expressions representing all operations related to the additive manufacturing process and all post-process operations necessary to obtain a complete estimate. A more general and less detailed cost model is proposed by (Lindemann et al., 2012), which offers a comprehensive overview of the different cost centres characterising the AM process. A general approach is also adopted by (Kopf et al., 2018), which presents a non-detailed cost model aimed at economic analysis and following optimisation of equipment for L-PBF. (Liu et al., 2019) developed a general cost model to make topological optimisation assessments.

From the literature analysis, developing detailed or general cost models has the production cost estimation as their primary objective. However, a well-established cost model finds application for estimating the production cost and further essential applications. One of these is sensitivity analysis, and a few studies have been carried out in this field. Di and Yang, 2021 performed a sensitivity analysis to assess the influence of process parameters (including machine investment, hourly labour rate, energy unit price, and material unit price) on the L-PBF process cost. The results show that material unit price and machine cost are the parameters that most influence the process cost. While energy cost and hourly labour rate have less impact. The sensitivity analysis does not consider process parameters such as layer thickness, laser speed, load factor and recoating time. Sensitivity analysis for the L-PBF process was also performed by (Schröder et al., 2015) and (Kretzschmar, 2015). The first study was done only on two components of different sizes and two production batches. The results obtained indicate that the investment cost of the machine is the most influential factor on the cost. This study misses presenting impacts of product features such as volume and height. The second study shows how mass and build height influence the cost of the process. The results show that mass (i.e., raw material) has a more substantial impact on the cost of the component than height. Process parameters have not been considered in the sensitivity analysis.

This paper confirms and extends the findings of previous sensitivity analyses (of other researchers) on L-PBF to define the most cost relevant product and process parameters. Indeed, a comprehensive study on this subject is not recognisable from the literature. The paper presents a sensitivity analysis more comprehensive than discussed above by analysing further product and process parameters (nine in total). This analysis considers eight parts and five materials on a cost model conceived to improve those available in the literature by adding details. Design and production engineers could benefit from these results. From this study, they will know the product and production parameters that can be adjusted for reducing the manufacturing cost of products. According to the component type, they can select the variable that maximises the cost reduction.

2. Laser-Powder Bed Fusion Cost Model

The cost model for L-PBF was obtained by merging and reviewing different studies in the literature. Further support was provided by a company that manufactures components through the L-PBF process. The literature review and comments from production technologists led authors to develop a cost model with further details than those presented in the literature (e.g. Rickenbacher et al., 2013; Baumers et al., 2012; Roffredo, 2018; Lindemann et al., 2012; Kopf et al., 2018). This step was required since cost models available in the literature give just equations without any process parameter. Such cost models, de facto, are useless. The cost model developed by the authors was, at last, implemented within an electronic spreadsheet (MS Excel) for the following sensitivity analyses.

This section gives a general overview of the developed model. The following sub-sections mainly focus on the novelties introduced in the model developed in this work. Previous works have been presented to give the background.

The calculation model was conceived considering the following cost items: material, machine, labour, consumable and energy.

2.1. Material Cost

The material cost (Equation 1) is one of the most critical factors which strongly influence the cost model. Its definition is highly dependent on the management of used powder (recovery and reuse) (Roffredo, 2018). The approach established in this study envisages powder recycling by defining a

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commercial value relative to the volume of reusable, recycled powder obtained from the printing job (Equation 2).

$$C_{material} = \frac{[V_{total\ powder} * \rho * C_{powder\ per\ kg}] - [V_{recycled\ powder} * \rho * (\alpha * C_{powder\ per\ kg})]}{n°_{batch\ quantity}} \quad (1)$$

$$V_{recycled\ powder} = (100\% - \beta) * (V_{total\ powder} - V_{component}) \quad (2)$$

$V_{total\ powder}$ (the total volume of powder fed into the print chamber) depends on the build plate dimensions and the height of the highest component (along the printing direction). The multiplication between $V_{total\ powder}$, the material density (ρ) and the unitary material cost ($C_{powder\ per\ kg}$) gives the cost incurred to fill the printing chamber.

The difference between the volume of powder fed into the chamber and the volume of the components and supports ($V_{total\ powder} - V_{component} - V_{supports}$) represents the volume of unsintered powder obtained from the build phase. The powder recovery process includes a recycling phase of the unsintered powder. That generates 5 - 10% (β) (Gebbe et al., 2015) of powder waste, so the $V_{recycled\ powder}$ represents the volume of reusable unsintered powder obtained through the recovery process. Therefore, its amount is given by providing a commercial value equal to a percentage of the unit cost per kg of the virgin powder. In this study, the economic value of the recycled powder is 75% of the price of the virgin powder (α). The lower price is due to considerations about the powder's degradation.

Finally, the product of these factors for the powder density ρ gives the economic value of the reusable unsintered powder. The difference between the cost to fill the chamber and the economic value of the reusable unsintered powder, divided by the number of components in the chamber $n°_{batch\ quantity}$, gives the material's cost.

2.2. Machine Cost

The machine cost consists of three cost items (Equation 3): (i) setup, (ii) idle and (iii) operation.

$$C_{machine} = \left[\left(\frac{T_{setup} + T_{idle} + T_{recoating}}{n°_{batch\ quantity}}\right) + T_{scan\_component}\right] * C_{machine\ unitary\ cost} \quad (3)$$

Machine cost is influenced by the hourly rate of the 3D printer and process time. According to (Ruffo et al., 2006), the hourly machine rate ($C_{machine\ unitary\ cost}$) depends on the hourly rate of depreciation, maintenance, and production overhead. These hourly rates further depend on more precise data such as investment cost, maintenance cost, load factor, annual machine time, depreciation time, building area, discount rate, and building yearly rent rate. In this paper, the cost of the printing platform was also included in the machine cost. The components manufactured using L-PBF technology are printed on a metal platform located in the printing chamber. At the end of each print job, the platform must be ground before being used again. The manufacturers of these platforms identify a maximum number of grinds that can be performed, so the platform has a useful life of 10 jobs (Roffredo, 2018). The platform and grinding costs have been obtained through LeanCOST (by Hyperlean Srl), a software tool for manufacturing cost estimation.

The setup time (T_{setup}) refers to the time needed to fill the printing chamber with powder, load the plate and manage the CAD file. The idle time (T_{idle}) is the amount of time the machine is not printing the part. It includes plate heating time, cool-down time at the end of printing, and plate and powder removal time.

More detail is required to analyse the operation cost during model building operations. As defined by (Roffredo, 2018), the build time is the sum of the recoating (Equation 4) and scanning times (Equation 5). The first accounts for the powder spreading by the recoater, layer by layer, to get the model.

$$T_{recoating} = \left({H_{max}}/{layer\ thickness}\right) * T_{machine\ recoating\ time} \quad (4)$$

Where H_{max} is the maximum height of the component in the printing direction, the layer thickness is the thickness of each layer, and $T_{machine\ recoating\ time}$ is the time recoater takes to distribute a layer of powder.

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The scanning time is the time spent by the laser to aggregate the powder and build the solid model. Printing a component with L-PBF technology can involve the construction of support volumes with a different structural matrix. The novelty compared to the literature is the possibility to manage the scanning of support structures. In fact, in this study, we separately computed the scanning time for the part and supporting structures. The scanning time of the component can be defined as follows:

$$T_{scan\_component} = \left({}^{P_{laser\_path}} \big/ {}_{V_{scan\_speed} * n^{\circ}{}_{machine\_laser} * F_{actor\_cont.}} \right) \tag{5}$$

The P_{laser_path} is the full path taken by the laser to build the component. It depends on the hatch distance, the number of layers, layer thickness, component volume, and perimeters passes. The V_{scan_speed} is the scanning speed of the laser and depends on the laser linear energy density and the laser power. $n^{\circ}{}_{machine\_laser}$ and $F_{actor\_cont.}$ are parameters that consider machines using several laser beams simultaneously.

The scanning time for the support volume is defined in the same way as for the component. In this case, however, printing parameters are introduced to obtain a structural matrix that may be less dense than the part. The parameters that differ between the part and its supports are:

- *Hatch distance*: The distance between two consecutive laser passes can be increased for support structures.
- *Scan speed*: It is possible to increase the laser scanning speed for support structures.
- *Number of layers*: It is possible to assume that not all layers will be printed to build the support structure.

The contribution of the two scanning times gives the total scanning time for the building job. Adding the recoating time and multiplying this amount by the hourly cost of the machine provides the operation cost.

2.3. Labour Cost

The labour cost related to the L-PBF process is the sum of three items: (i) machine setup, (ii) build platform loading and unloading and (iii) machine attendance. The first cost refers to the setup time (previously defined) spent by the operator to prepare the 3D printer. The second item accounts for the time required for loading and unloading the build platform. The last item accounts for the time spent by the operator attending the printing process. In this study, it was assumed that an operator could simultaneously control five machines. Finally, the ratio between the described times and the number of components in the chamber, multiplied by the unit labour cost, gives the labour cost.

2.4. Consumable Cost

(Rickenbacher et al., 2013) presents a detailed cost model, but without considering the costs related to compressed air and gas consumption to inert the chamber. In this work, both elements have been evaluated considering the print time, unit consumption and unit cost (Equation 6).

$$C_{consumable} = \frac{(V_{compr.\ air} * C_{compr.air}) + (V_{inert\ gas.} * C_{inert\ gas})}{n^{\circ}{}_{batch\ quantity}} \tag{6}$$

Consumables are defined as the use of compressed air and inert gas. Both depend on the volume of compressed air and inert gas used during warm-up, component building, and cool-down phases and their respective unitary costs (Gebbe et al., 2015). The obtained cost is then divided by the number of components in the printing chamber.

2.5. Energy Cost

Energy cost (Equation 7) represents the machine's energy consumption during the warm-up, building, and cool-down phases (Gebbe et al., 2015). It is possible to define the relative power absorbed by the machine and the time phase for each of these phases. Their product gives the consumption of the respective stages. The multiplication for the unit price of energy offers the total energy cost.

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$$C_{energy} = [(T_{recoating} + T_{scan.time}) * P_{build} * C_{price\ energy}] + (T_{cool\ down} * P_{cool\ down} * C_{price\ energy}) + (T_{warm\ up} * P_{warm\ up} * C_{price\ energy})/n^{\circ}_{batch\ quantity} \quad (7)$$

The obtained cost is then divided by the number of components in the printing chamber.

3. Sensitivity Analysis

Sensitivity Analysis (SA) can be defined as a method to measure how the impact of uncertainties of one or more independent variables can lead to uncertainties on the dependent variables. The paper aims to identify the product and process parameters with the most significant impact on the 3D printing cost of L-PBF.

The SA was conducted considering the analytical cost model illustrated previously. The rules have been implemented in MS Excel to facilitate subsequent data processing. The SA was conducted from eight components with different shapes, materials (Aluminium AlSi10Mg, Nickel Superalloy Inconel 718, Stainless steel AISI 316L, Maraging steel, and Titanium TiGr1) and dimensions. These components (e.g. valve manifolds, brackets, cushions) are also used to validate the cost model (Figure 1). The parts belong to different machines for quality control and assembly to ensure results comparability.

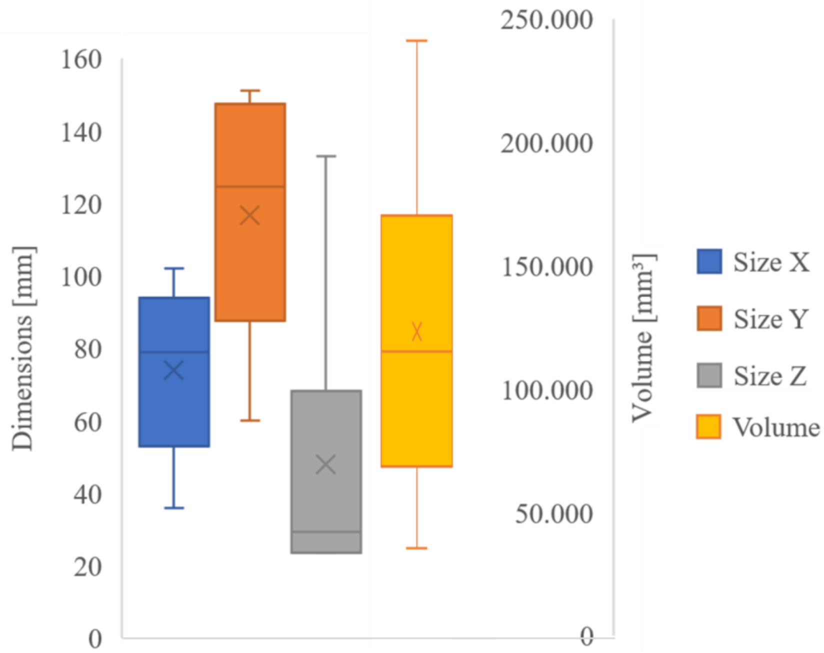

Figure 1. Dimensions of the components used for the Sensitivity Analysis

The variables considered for the sensitivity study are grouped into two types. Volume and print height of the part are the product parameters. On the other hand, seven variables were considered for the process: the load factor of the machine, the layer thickness, the print speed, the recoating time, and the unit costs of raw material, energy, and labour. The hourly cost of the machine was not considered because it depends on the load factor. The variables were chosen based on the authors' experience and other studies in the literature aiming at the economic study of the L-PBF process (Di and Yang, 2021; Schröder et al., 2015).

The variables were changed, concerning the starting condition, until reaching values equal to -80% and + 80% (with steps of 20%), thus determining nine observation values. The cost model developed in MS Excel automatically updates the other (dependant) process parameters when changing the observed variable. For example, when changing the material, the cost model automatically selects the suitable layer thickness and laser speed (among others). The starting condition refers to a printer with a printing plate size equal to 250x250mm, a height of 325mm, a single laser, recoating time of 6 seconds, and a load factor of 57% (Ruffo and Hague, 2007). The unit cost of raw material for the reference materials was recovered from the e-commerce website of a machine manufacturer (DMG

MORI, 2021). The reference values for the layer thickness and print speed have been defined considering several experimental studies available in the literature. Layer thickness depends on the material (e.g. 40µm for Inconel 718). Laser speed (e.g. 1300 mm/s for Inconel 718) depends on the Laser Linear Energy Density (e.g. 0.30 J/mm for Inconel 718), hatch distance (e.g. 80 µm for Inconel 718) and layer thickness (e.g. 40 µm for Inconel 718).
The unit costs of electricity and labour refer to an Italian production scenario and are 0.20 €/kWh and 35.00 €/hour respectively. All data were obtained considering printing only one component per build plate. The cost considered refers only to the component printing phase (i.e. from the machine setup to the removal of the part).
The database used for the sensitivity analysis of a specific parameter was constructed by simulating the cost as the component, material, and specific observed variable. The data were collected in tables with 72 rows (nine values of the experimental variable for eight parts) and five columns (5 materials). In total, 360 cost values were considered for each observed parameter. Considering different components made it possible to evaluate the average influence of the experimental parameter on the cost of production. All cost evaluations have been made for each material. A graph was then constructed for each observed parameter containing, for each material, the cost variation curves as a function of each variable. The curves have been averaged to study the global behaviour of the parameter and, therefore, to prioritise parameters.

4. Results and Discussion

4.1. Cost Model Validation

This section presents the cost model validation for evaluating its correctness. To do this, the authors considered eight components proposed by a manufacturing company that produce these parts internally.
Table 1 shows the manufacturing costs estimated using the proposed cost model (estimated cost) and collected from the manufacturing company (actual cost). For a correct comparison, the same information and parameter values used by the company were included in the model: same printing direction, batch quantity, material cost [€/kg], machine hourly rate [€/h] and scanning parameters (layer thickness, hatch distance, overlap rate). The comparison makes it possible to assess if the proposed model provides an estimate following the costs incurred by the company. This analysis allows concluding that the proposed model can be used for the sensitivity analysis.

Table 1. Estimated vs Actual costs

	Cod A	Cod B	Cod C	Cod D	Cod E	Cod F	Cod G	Cod H
Size [mm x mm x mm]	62 x 101 x 24	88 x 151 x 24	96 x 137 x 24	102 x 150 x 45	71 x 112 x 24	87 x 140 x 35	36 x 83 x 76	50 x 60 x 133
Volume [mm³]	63052	156206	112520	241057	84817	175000	35500	118000
Actual cost [€]	€ 320	€ 450	€ 565	€ 780	€ 1200	€ 475	€ 770	€ 950
Estimated cost [€]	€ 352	€ 409	€ 625	€ 815	€ 1000	€ 447	€ 712	€ 724
Deviation [%]	10.3%	-9.0%	10.7%	4.5%	-16.6%	-5.8%	-7.5%	-23.8%

4.2. Sensitivity Analysis

Before presenting the Sensitivity Analysis results, it is helpful to view the cost breakdown, as shown in the box plot of Figure 2. The total cost of the printing phase is divided into the items relating to material, machine, labour, consumables and energy. As can be seen from the graph, the cost of material and machine, in the production scenario considered in this work, are the two most important items, determining about 80% of the total cost. The remainder is due to labour and consumables. Electricity is almost negligible.

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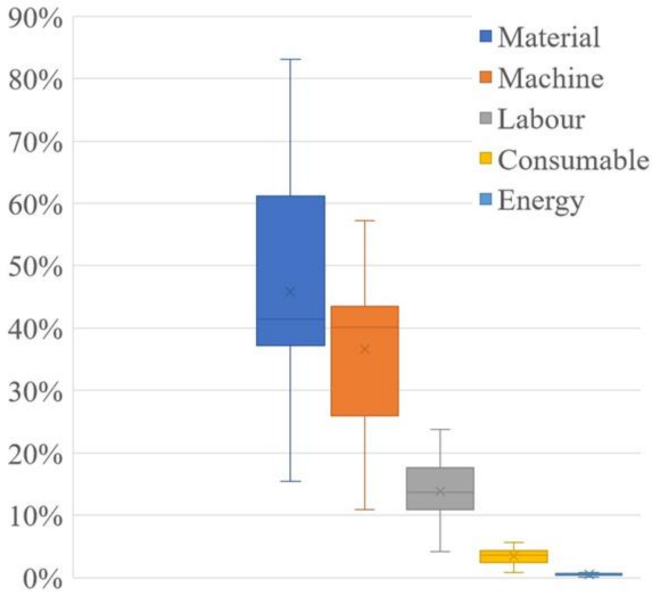

Figure 2. Cost breakdown

The sensitivity curves defined for each parameter and plotted for each material allowed authors to make careful considerations (Figure 3). For example, among the materials analysed, Titanium has the highest cost sensitivity for the part height, with a value approximately double that of Aluminum. This result is not only given by the higher cost of Titanium but also by the process parameters used for both materials. As for the volume, also in this case for Titanium, there is the most significant sensitivity. However, it should be noted that the minimum sensitivity is for Maraging Steel. Thickness and volume determine a direct relationship with cost.

In terms of process parameters, there is a need to differentiate the behaviour between load factor, layer thickness and print speed on the one hand, compared to the raw material price, recoating time, energy price and labour price on the other. The first group of parameters shows a hyperbolic sensitivity, while the second is linear. Subsequently, it is emphasised that recoating time and energy price do not vary with the material. Therefore, only one curve can be displayed from the graphs. In general, the limit curves are represented by Titanium and Aluminium.

From a global point of view, relative to the product parameters, the part height has a higher sensitivity than the volume (Figure 4). Among the process parameters, the load factor has the most significant impact on the printing cost, followed by the layer thickness. The results obtained in this study (Table 2) were compared with those obtained by other researchers.

For a 10% thickness variation, there is a cost difference of about 4% in the present work, while it is about 6% in (Schröder et al., 2015). It should be noted that the result presented in (Schröder et al., 2015) was obtained considering only two components and without indicating the material. The raw material is the third most sensitive parameter. In this case, the result completely overlaps with what is presented in (Di and Yang, 2021). Print speed is the fourth parameter in the order of importance. For this parameter, the results obtained in this study overlap with what is present in (Schröder et al., 2015). Against a 10% variation in print speed, a 4% variation in cost is observed. Labor Rate is the fifth most crucial process parameter, and the results overlap with what is present in (Di and Yang, 2021). Against a variation of 20% of the observed variable, the authors found a cost variation equal to 2.7% against 2.3% of (Di and Yang, 2021). The recoating time is the sixth parameter, but no references have been found in the literature. The last parameter in the order of importance among those analysed is the unit cost of electricity. The low priority of this cost item makes a change in the electricity cost practically irrelevant on the printing cost.

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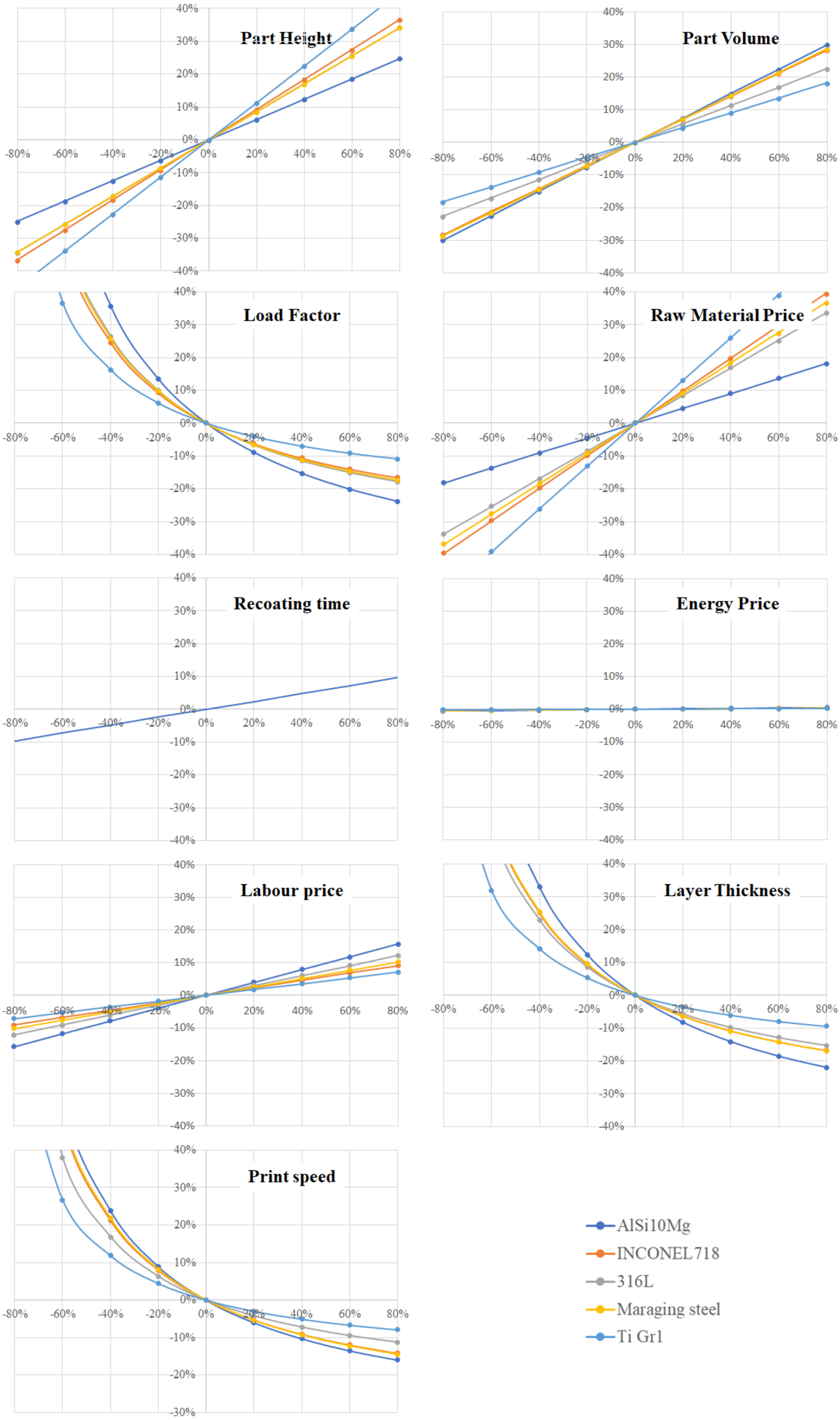

Figure 3. Sensitivity analysis for each observed parameter

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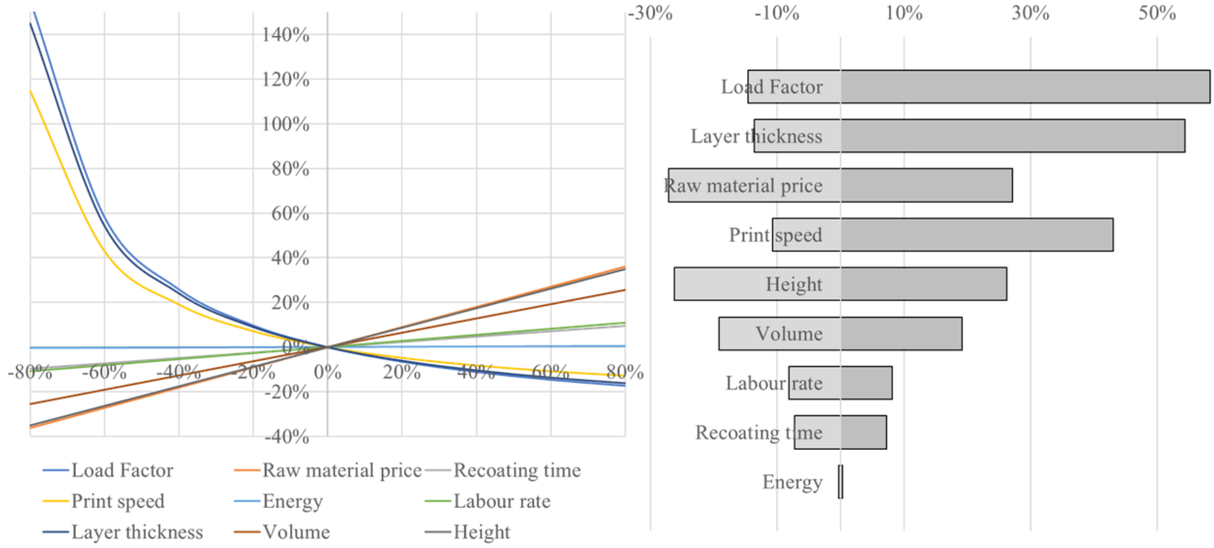

Figure 4. Overall sensitivity analysis (left) and main influencing factors (right) considering a -80% and +80% variation of the variable

Table 2. Sensitivity analysis comparison with literature results

	Variable deviation	Author's sensitivity	Reference sensitivity	Reference
Height	-	-	-	-
Volume	-	-	-	-
Load factor	-	-	-	-
Layer thickness	10%	4%	6%	(Schröder et al., 2015)
Raw material price	20%	9%	8%	(Di and Yang, 2021)
Print speed	10%	4%	4%	(Schröder et al., 2015)
Labour price	20%	2.7%	2.3%	(Di and Yang, 2021)
Recoating time	-	-	-	-

5. Conclusions and future work

The paper presented an analytical cost model for L-PBF that improves those already available in the scientific literature. The model has been used to carry out a sensitivity analysis to identify the most relevant product and process cost drivers. Obtained results highlight that the 3D printer load factor, the layer thickness and the raw material price are the three most cost-impacting process parameters. This achievement confirms and extends what was found by (Schröder et al., 2015) and (Di and Yang, 2021). Future work will improve the cost model (integration of post-process phases) and related sensitivity analysis. A broader set of components will be considered for increasing the robustness of the results achieved in this work.

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