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Evaluating the Design for Additive Manufacturing: A Process Planning Perspective

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Abstract

The emergence of Additive Manufacturing (AM) has greatly liberated the designers' hands, since the usual design constraints in machining or other traditional processing technologies partially or even totally disappeared in AM and it seems that AM can form any desired very complex geometries through a layer by layer construction manner. However, AM processes still have their own processing characteristics and limits. To help designers to benefit more from the unique characteristics of AM and avoid the processing limits or low down the later processing difficulty after design, this paper proposes a two-level evaluation framework to assess the design from a process planning perspective. The proposed evaluation framework is associated with a two-level process planning framework for AM, and within each level, several indicators for assessment are defined and used to convey the information from process planning for improving the design.

Key words: Design Evaluation, Process Planning, Evaluation Framework, Additive Manufacturing

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1. Introduction

Additive Manufacturing (AM) derived from Rapid Prototyping (RP) has been investigated and developed nearly 3 decades. Now, based on its maturity in some extent, it becomes a main role in some manufacturing contexts since it can be used in many application fields, especially in the customization production [1]. The main difference between AM and other conventional processing technologies is the ‘layer by layer’ additive construction manner, which makes the AM can manufacture designed parts with extremely complex geometries without the use of fixtures, tooling, mold or any other additional auxiliary. Therefore, this unique characteristic of AM would change the way of design in AM. At least, the usual constraints which should be taken into consideration when designing parts for traditional processing technologies could be reduced or even sweep up totally. Hague et al. already addressed the implication of AM on design in AM and drew a very optimistic picture for the design in AM [2]. But, is it true that the designer in AM owns the unlimited design freedom? This paper will present a preliminary answer and propose a two-level evaluation framework for design from a process planning perspective so as to help designers to improve their designs to get more benefits from AM. The left part of this paper is organized like this: the second section will discuss the necessary considerations and potential constraints when designing for AM; the third part will introduce the process planning for AM; based on that, the fourth part will propose a two-level evaluation framework for the design in AM as well as identify some common indicators for assessment; an illustration example will be presented in the fifth section; the last two sections will present some discussions and come to a conclusion with some further perspectives.

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2. Considerations & constraints for design in AM

Actually, the answer for the question posed in the first paragraph had already given by former researchers with a big 'NO' [3]. As the designers do for any other traditional processing technologies, the designers in AM still need to consider some factors and encounter some constraints of AM technologies. Though the topic of design for AM is relatively new and there is little research on it, some contributors still gave or hinted the considerations and constraints in the design for AM. For example, a lot of former researchers had investigated the selection of RP or AM processes for the design. These works mainly focused on the match of the design requirements or specifications with the available RP or AM process, where the characteristics and constraints of RP or AM processes were carefully studied. Zhang and Bernard made a good summary in their recent published work [4]. Apart from those, other works were done for developing specific methods or solutions to aid the design for AM [5-7]. The characteristics and constraints of AM were also investigated by them to establish some rules or AM knowledge to help design or initiate some structure optimization solutions to improve the design.

Therefore, to give a conclusion in general, the designer in AM should take three main aspects, where exist the potential constraints and characteristics, into consideration when designing for AM:

- Communication or Cooperation with user

The first step of design is to clarify or identify the exact needs or requirements of users. Hence, the communication or even cooperation with user should be taken into consideration. Usually, the users don't know well about the AM processes. Therefore, the communication may help users know more about AM and so as to make better or more reasonable production requirements or make their needs more precisely and understandable to the designers;

- Manufacturability

When the users' needs or requirements are made clear, the designers go into the conception design stage, where the manufacturability should be carefully investigated. AM processes' abilities, characteristics and limitations are the considered factors. For example, the volume of the build chamber, the available materials, the minimum feature size that can be built, the mechanical properties, the build time and cost and so on;

- Geometry and Topology

The last step is the detail design, where the part's geometry and topology should be constructed. At this stage, the designers should harness the advantages of AM processes which can realize extremely complicated shapes to improve their design. Topological optimization can be conducted and complicated concave, convex, saddle, valley or ridge type features can be adopted. However, the designer also should consider the part's geometry or topology's effects on the AM process planning, for example the orientation, slicing, support generation and tool-path planning.

According to the listed considerations and constraints, it is not difficult to find out that those factors are mostly related with the main content of process planning in AM. Ponche had recently proposed a design method which begins the conception design with build orientation selection and fulfilled the detailed design by integrating the tool-path planning and the processing simulation results [7]. His work has verified the importance and effectiveness of process planning to the design for AM. However, none of the former researchers dealt with the design from a comprehensive point of view from process planning in AM. Therefore, there is a need of an evaluation method to evaluate the part design in AM so as to give feedbacks to the designers for improving the conception and detail designs. To meet this need, this paper proposes an evaluation framework from a process planning perspective in a general level. The following section will introduce the main content of process planning for AM.

3. Process Planning content in AM

Though AM has been widely regarded as 'one button' processing technology due to its high automation, the preparation work before manufacturing should be also done by engineers or technicians using some tools and related experience or knowledge. The preparation work contains tasks from the selection of suitable manufacturing scenarios, which include AM machine, material, machine set-up parameters etc., to 3D data checking and detailed process planning, such as orientation, support design, slicing and tool-path generation. Many researchers had worked on the detailed process planning tasks [8], however none of them presented a full and systematic process planning content map. Herein, based on the comparison with traditional process planning, this paper gives a two-level process planning framework for the systematic process planning in AM, which is depicted in Figure 1.

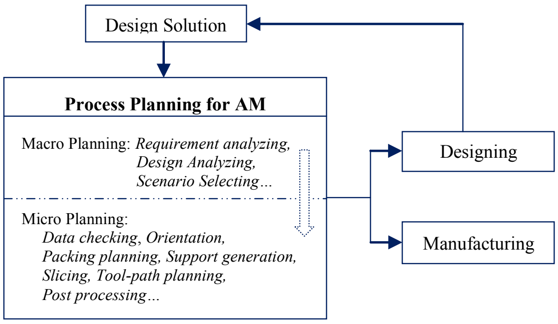


Fig. 1. Process Planning framework for AM.

3.1. Macro process planning

Macro process planning is the first level or stage of process planning in AM. The main contents contain the manufacturability analysis, selection of manufacturing scenarios and setting up the original processing parameters. These tasks can be finished only under full understanding of AM processes' characteristics and limitations as well as the design and production requirements. Hence, this process planning stage could be directly connected or associated with the conception design stage where manufacturability analysis based on analyzing the design requirements and selection of manufacturing scenarios based on functional and production requirements are both should be carried out.

3.2. Micro process planning

Micro process planning stage mainly focuses on the detailed technical aspects. The main contents include:

- 3D CAD data checking, repairing, scaling et al.;
- Determination of part's build orientation;
- Determination of the strategy for placing or packing parts in the build platform or chamber when under multi-parts production context;
- Support generation for some AM processes that need support structures;
- Determination of a slicing strategy;
- Determination of a tool-path or scanning strategy;
- Determination of post processing strategies.

Apparently, the main tasks in this micro planning stage have a very tight relationship with the detail design for AM since the results of these tasks directly determine a design's physical realization and mechanical properties. A well-understanding of the process planning and the processing characteristics can better benefit the AM technology when doing the design. The following section will present the proposed evaluation framework.

4. Evaluation Framework

4.1. Evaluation Framework

As discussed above, the main contents in the two stages or two levels of process planning for AM are tightly related with the design stages in AM. Hence, a corresponding two-level-evaluation framework derived from process planning can be generated to evaluate the design results during each design step. The main structure of the framework is depicted in Figure 2. As described in the framework, the evaluation has two levels which are directly connected with the two levels in process planning. The information or knowledge for evaluating a design is directly from the process planning results. And the two-level evaluation has an order, which is that a design can only pass the two evaluation levels one by one. To give feedbacks to designers, two separate indicator sets are provided to express the evaluation results of the two-level evaluation and related threshold indexes values are set for decision making. In the following section, two sets of indicators will be proposed for this two-level evaluation framework under a generic situation.

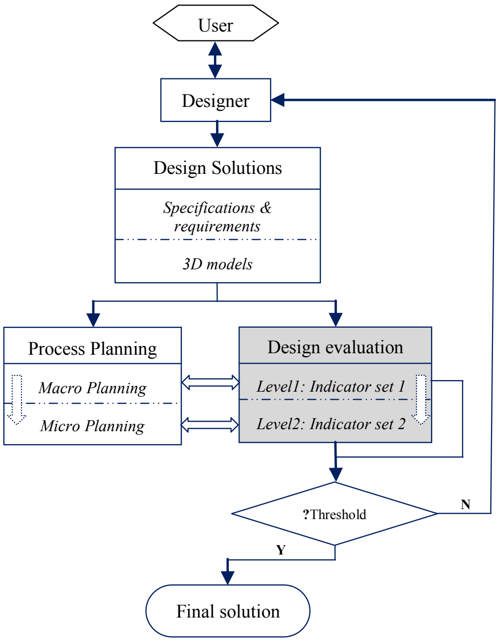


Fig. 2. Evaluation Framework for design in AM.

4.2. Indicators for evaluation

As discussed above, to evaluate a design, qualitative or quantitative evaluation indicators should be defined to convey the assessment feedbacks to the designers. Within the proposed evaluation framework, different indicators can be defined for the two evaluation levels or stages according to the specific AM process and the design needs. Herein, to be more generic, this paper proposes to define several common quantitative indicators for each evaluation level respectively to suite more AM process's characteristics and design needs.

For the first evaluation level, indicators should be appropriately set to indicate the extent of design's rationality referring to the design specifications and user's manufacturing requirements. The evaluation of rationality is to check that whether a designed part is suitable to be manufactured by AM processes. To give correct evaluation, analysis of design specifications or user's manufacturing requirements and AM processes' characteristics should be well conducted. Therefore, in this paper, two indicators, which are used to evaluate design's suitability of being manufactured by AM and the easiness of proposing a manufacturing scenario for a given design, are proposed for the first evaluation level:

- ***AI***: Adaptation indicator

Definition: *Adaptation indicator is an index to show the extent of a given design's suitability of being manufactured by AM processes.*

Before sending a designed part to the AM processing bureau, user or designer usually should compare the traditional processes with AM processes on the factors of production cost, time and quality. This indicator is used to show the user or designer whether the part is suitable to be processed by AM and how it is suitable when considering those factors. To give a quantitative evaluation, the matching extent between the design's specifications (or manufacturing requirements) with the available AM manufacturing scenarios is proposed as the adaptation indicator. For calculating the value, the design specifications (or manufacturing requirements) and AM manufacturing scenarios are represented by vectors with same dimensions, noted as design vector and process vector. The vectors are composited by selected sets of multi-attributes, which describe the design specifications (or manufacturing requirements) and the design manufacturing scenario's main characteristics. The matching extent is actually the similarity or deviation between the design vector and process vector. To calculate the value of similarity or deviation, the method proposed by Zhang and Bernard [4] is adopted. Based on that method, a modified expression for calculating the value of the indicator can be given as

$$AI=\frac{1}{e^{\frac{1}{n}\sum_{i=1}^{n}\omega_i|(x_i-p_i)/p_i|}} \tag{1}$$

, where x_i, p_i and ω_i denotes the attributes of the design vector, the attributes of process vector and related weights respectively, i=1, 2, 3…n. The value of AI is within (0, 1]. The exponential expression can well distinguish alternative designs. A high value index means that the design specifications or manufacturing requirements are reasonable and match the manufacturing scenario well. Otherwise, the design should be modified so as to suite the AM manufacturing scenarios;

- ***DI***: Discrimination indicator

Definition: *Discrimination indicator is an index to show the extent of easiness of identifying the optimal AM manufacturing scenarios from a set of alternatives for a given design.*

This indicator is used to assess the effect of the design specifications (or production requirements) on the decision making of identifying the optimal manufacturing scenarios from a set of alternatives. When a set of available AM manufacturing scenarios are available, a good design should be easy for the process planner to identify the optimal one. That means the AI index value of the optimal choice should have big difference with each other alternative AI index values. If a set of AI index values of available AM manufacturing scenarios for a design are very similar, the decision making of the selection would be difficult. And that also reflects the given design doesn't capture well the unique characteristics of any AM processes. Hence, from the point view of process planning, a good design should be convenient for the selection of AM scenarios and well suites the unique characteristics of AM processes. Otherwise, the design should be modified. The indicator can be calculated by

$$DI=e^{\sum_{i=1}^{n-1}|(AI_{\max}-AI_i)/AI_{\max}|} \tag{2}$$

, where AI_{max}, AI_i denotes the maximum AI index and the left ones respectively, i = 1, 2, 3… (n-1).

For the second evaluation level, indicators should be defined appropriately to indicate the extent of rationality of a design's details. Since different AM technologies have different process planning tasks, the defining of indicators depends on the specific application contexts. For example, some need supports or post processing, but others don't. Therefore, to be more generic, two common indicators, one is used to express the effect of a design's detail on the orientation task and the other is used to assess the extent of a design's utilization of characteristics of AM process, are identified for this evaluation stage:

- ***OI***: Orientation indicator

Definition: *Adaptation indicator is an index to show the effect of a given part's detail design on orientation task in AM process planning.*

This indicator is used to evaluate the design's effect on the orientation task in process planning. Orientation is a very important task since the build orientation affects the part's quality, build time and production cost. A large quantity of related researches had been placed on this topic [9]. A part's build orientation is selected mainly based on the study of the part's manufacturing requirements or specifications and the part's geometry as well as the characteristics of AM processing technologies. Geometric features are usually used to generate a set of available orientations to form a selection or solution space, and the key functional geometric features and their manufacturing requirements are very important to the decision making of selection an optimal orientation from the orientation spaces. Zhang and Bernard had proposed a new effective orientation method where AM features are defined and used to generate available orientations and aid the decision making [10]. Therefore, based on that method, the number of AM features and non-AM features can used to define this indicator, since they affect the difficulty of orientation task. Hence, the indicator can be expressed by

$$OI=(\frac{1}{N_p+N_n}+\frac{N_p}{N_p+N_n}) \tag{3}$$

, where N_p and N_n denote the number of AM features and the number of non-AM features (other geometric features that can be used for generating orientation) respectively. The first item in the left of expression (3) depicts the total geometric features' impact on orientation task, since the increase of geometric features would increase the work quantity of orientation. While the second one measures the rate of useful work in orientation task, since the proportion of functional AM features would indicate the proportion of useful work in orientation job. A higher value of this indicator means a design is easier to the orientation task;

- ***GI***: Geometry indicator

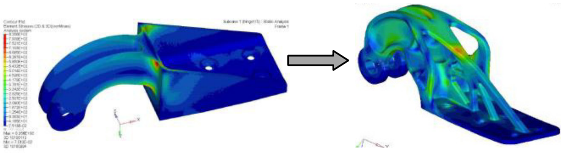
Definition: *Geometry indicator is an index to show the extent of a given design's utilization of AM process' characteristics.*

This indicator is used to show the design's utilization of the advantages AM processes against conventional processing technologies. Due to the unique layer by layer manufacturing principle, AM can generate any desired geometry shape theoretically. Hence, a good design should better benefit this feature. For example, lightweight design methods and topology optimization strategies could be used as much as possible without paying too much attention to the geometric complexity. To evaluate this aspect of a design, the bounding box which is the minimum cubic containing the part, used by former researchers as a component to describe the complexity of a part [11], and the volume of the designed part can be used to define the geometric indicator. The calculation of the proposed indicator can be given as

$$GI=V_b\,/\,V_p \tag{4}$$

, where V_b, and V_p denote the volume of part's bounding box and the part's volume respectively.

This indicator can not only reflect the complexity of a design, but also can convey the information of the topological optimization extent of a design. A larger value of this indicator means that a design may own a more complex geometry and get a better topological optimization enabling a considerable material reduction in manufacturing. A design example for Airbus published by Tomlin et al. from EADS is presented in Figure 3 can well demonstrate this point [6]. The part's mass has been reduced without damaging the desired mechanical properties though the geometry complexity is increased. In this example, the value of ***GI*** decreases, since the volume of part was reduced while the volume of its bounding box was unchanged.



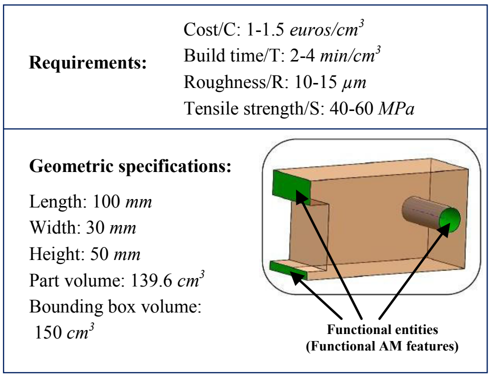
a. b.

Fig. 3. CAE analysis results comparison between original design (a) and optimized design (b).

With the evaluation framework and related indicators in hand, the evaluation of the design in AM can be conducted. The next section will present a simple design case study for illustration.

5. Case study

In this section, a modified design example from Ponche's work [7] is used for demonstrating of the effectiveness of this proposed evaluation framework on improving the design for AM. An assumption can be made as: a user mainly cares about the three main functional features as indicated in Figure 4. The relative positions among these entities should be well maintained with enough support from the part geometry to resist the deformation, and the surfaces of the three entities should have a good roughness so as to meet the assembly requirements. After communicating with the user, the designer determines the exact design specifications and manufacturing requirements. And an original design solution is conceived as depicted in Figure 4. However, is this design solution suitable for AM and can it well benefit the advantages of AM processing? To answer the question, the proposed two-level evaluation for the design is conducted. The following sections will present the details step by step.



Requirements:

Cost/C: 1-1.5 *euros/cm*^{3}
Build time/T: 2-4 *min/cm*^{3}
Roughness/R: 10-15 *μm*
Tensile strength/S: 40-60 *MPa*

Geometric specifications:

Length: 100 *mm*
Width: 30 *mm*
Height: 50 *mm*
Part volume: 139.6 *cm*^{3}
Bounding box volume:
150 *cm*^{3}

Fig. 4. Design specifications, requirements and the original design solution.

5.1. Level 1 Evaluation

The first step is to check the setting of design requirements or specifications whether is reasonable or not by using the Level 1 Evaluation. A supposing can be given that there are 5 available AM manufacturing scenarios (Table 1) derived from 5 different AM processes (scenarios extracted from KARMA knowledge base [12]) and the required values for ***AI*** (***AI$_{max}$***) and ***DI*** are set as 0.7 and 2.5 according to the process planning experience.

Table. 1. Manufacturing scenarios derived from 5 AM processes. (Note: C, cost; T, build time; R, roughness; S, tensile strengh)

Scenarios	C (*euro/cm*^{3})	T (*min/cm*^{3})	R (*μm*)	S (*MPa*)
SLA	1.04	5.36	2.47	61.38
SLS	1.63	2.24	17.67	47.60
SLM	4.12	9.07	10.95	475.00
Polyjet	1.11	3.16	8.43	21.42
EBM	5.53	6.21	24.92	936.60

Therefore, the design vector and the manufacturing scenario vectors can be given as

$$\begin{aligned}
&V_{design} = [(1,\ 1.5)\ (2,\ 4)\ (10,\ 15)\ (40,\ 60)];\\
&V_{SLA} = [1.04\ \ 5.3\ \ 62.47\ \ 61.38];\\
&V_{SLS} = [1.63\ \ 2.24\ \ 17.67\ \ 47.60];\\
&V_{SLM} = [4.12\ \ 9.07\ \ 10.95\ \ 475.00];\\
&V_{Polyjet} = [1.11\ \ 3.16\ \ 8.43\ \ 21.42];\\
&V_{EBM} = [5.53\ \ 6.21\ \ 24.92\ \ 936.60].
\end{aligned} \tag{5}$$

After converting the design vector with interval numbers into vector with real numbers by using fuzzy method, each pair of design and scenario vectors can be processed by adopting equations (1) and (2) to obtain the related ***AI*** and ***DI*** values. Interval numbers in the design vector are approximated by the means of each attribute's boundary values, and it is given as

$$V_{design} \propto [1.25\ \ 3\ 12.5\ 50] \tag{6}.$$

The calculation of the ***AI*** value to SLA is given as

$$\begin{aligned}
AI_{SLA} &= \frac{1}{e^{\frac{1}{4}\sum_{i=1}^{4}\omega_i\left|(x_i-p_i)/p_i\right|}} \\
&= \frac{1}{e^{\frac{1}{4}[1\times\left|\frac{1.25-1.04}{1.04}\right|+1\times\left|\frac{3-5.3}{5.3}\right|+1\times\left|\frac{12.5-62.47}{62.47}\right|+1\times\left|\frac{50-61.38}{61.38}\right|]}} \\
&= 0.29
\end{aligned} \tag{7}$$

, where ***ω$_i$*** = 1, ***i***=1, 2, 3 and 4, since equal weights are assigned to the four attributes. Similarly, the left ***AI*** values can also be obtained. With all the ***AI*** values, the value of ***DI*** can be obtained by applying (2). The value is calculated as

$$\begin{aligned}
DI &= e^{\sum_{i=1}^{n-1}\left|(AI_{\max}-AI_i)/AI_{\max}\right|} \\
&= e^{[\sum_{i=1}^{5-1}\left|(AI_{\max}-AI_i)/AI_{\max}\right|]} = 4.67
\end{aligned} \tag{8}$$

, where ***AI$_{max}$***, ***AI$_i$*** denotes the maximum ***AI*** index and the left ones respectively, ***i*** = 1, 2, 3, 4 and 5. The evaluation results are presented in Figure 5. During the calculation of ***AI***, equal weights are assigned in this example. The evaluation results show that the design can pass the first evaluation level since both the ***AI*** and ***DI*** values to SLS process scenario meet the threshold requirement. That means the design requirements are reasonable and the part is suitable to be manufacturing by SLS process. Then the evaluation of detail design in the second evaluation level can be conducted.

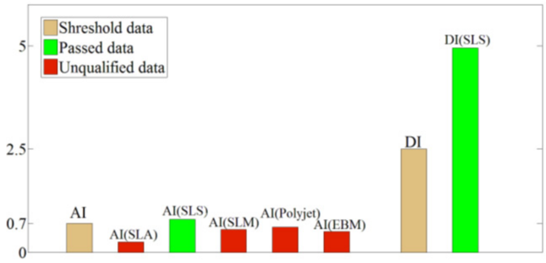


Fig. 5. Level 1 Evaluation results for the original design.

5.2. Level 2 Evaluation

This evaluation level mainly focuses on the geometric details of the design. An assumption can be made that the threshold values of ***OI*** and ***GI*** can be set as 0.7 and 2.5. The data set used to calculate the ***OI*** and ***GI*** values is provided in Figure 4. The number of AM features is 3 while the left surfaces on the part are identified as 8 non-AM features. By applying Equations (3) and (4), the indicators' values can be obtained.

$$OI = \left(\frac{1}{N_p + N_n} + \frac{N_p}{N_p + N_n}\right) = \left(\frac{1}{3+8} + \frac{3}{3+8}\right) = 0.36 \tag{9}$$

and

$$GI = V_p / V_b = 150/139.6 = 1.07 \tag{10}$$

The evaluation results are presented in Figure 6. According to the results, the design could not pass this evaluation level since the values can't pass the preset threshold values. Therefore, the design should be modified in the geometry so as to get some improvement.

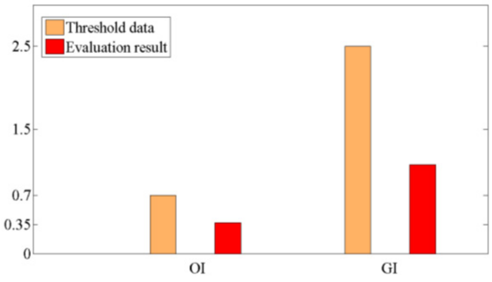


Fig. 6. Level 2 Evaluation results for the original design.

5.3. Improved design

Since the design can't pass the Level 2 Evaluation, there is a need to make some modifications. In the original design, there are many non-AM features (8 non-AM features VS 3 AM features) which would increase a lot of quantity of labor to the orientation task, and the volume of the designed part is too large, which would cause much material consummation and miss the advantage of manufacturing complex geometry by using AM process. Therefore, modifications could be made on the original design to reduce the non-AM features as well as reducing the part volume by optimizing the topology of the part. After modifying, the improved design is presented in Figure 7.

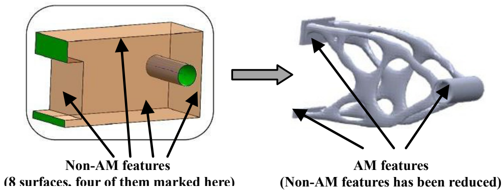


Fig. 7. Improved design.

The improved design shows that the number of non-AM features has been diminished to zero without changing the bounding box and the topology has been changed resulting a 4/5 mass reduction of the original design. Therefore, the ***OI*** and ***GI*** values, OI' and GI', for the improved design can be calculated as

$$OI' = \left(\frac{1}{N_p + N_n} + \frac{N_p}{N_p + N_n}\right) = \left(\frac{1}{3+0} + \frac{3}{3+0}\right) = 1.33 \tag{11}$$

and

$$GI' = V_p / V_b = 150/(139.6 \times 0.25) = 4.30 \tag{12}$$

The new evaluation results of the improved design within the Level 2 Evaluation are depicted in Figure 8. The new results show that the improved design meets the pre-set requirements and can pass the second evaluation level.

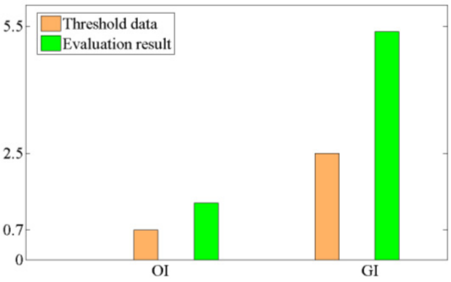


Fig. 8. Level 2 Evaluation results for the improved design.

6. Discussion

The results of this case study demonstrated the importance of the support information from process planning to the design in AM. The evaluating of the design from a perspective of process planning would help to improve the design and facilitate the later manufacturing. However, to use the proposed evaluation framework correctly and efficiently, three main facets should be considered carefully:

- Defining indicators and setting threshold values

To identify the suitable indicators for the evaluation framework is the foremost thing. The indicators are more sensitive or more representative, and the evaluation results would be more objective and practical. Additional specific indicators can be also defined apart from the four discussed in this paper when there is specific application needs. While for the pre-set threshold values of those indicators for evaluating, the setting procedure is not easy. Experience and knowledge of process planning for AM should be used and improved into a standard level so as to be more generic, except specific needs for specific design or application contexts;

- Value calculation methods for the indicators

To conduct an evaluation, quantitative or qualitative values should be given as well as some formulas or evaluating tools. Mathematical formulas derived from AM process planning models and knowledge could offer good quantitative values, while AM processing knowledge may offer more effective qualitative values. Hence, the selection of calculating method should also be paid enough attention;

- Accuracy of the behind AM knowledge

As discussed above, AM knowledge is very important for the determination of suitable indicators and the related calculation methods. Therefore, the accuracy of the AM knowledge would be the key points behind the evaluation process. At present, accurate AM processing prediction or simulation models are not accurate enough [7]. Hence, the experience of AM processing should be extracted, represented and reused to support the design evaluation and the design itself.

7. Conclusion

Compared with the design for traditional processing technologies, the design for AM has greatly increased the space of freedom for the designers. However, there still are a set of limitations or constraints existing in the AM processing technologies. When designing, they should be taken into consideration. However, the designers would probably don't own enough AM processing knowledge due to the fast development of AM technologies and the current knowledge gap between AM technologies and public. Therefore, to solve this problem, this paper proposed an evaluation framework from the perspective of process planning for AM. This framework can help designers better benefit the advantages of AM processing and at the same time to avoid some potential difficulties or problems derived from the constraints or limitations in AM to improve their designs. Future work should be placed on the defining of suitable evaluation indicators and extracting, representing and reusing the more accurate AM knowledge.

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