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Part Separation Technique for Assembly-Based Design in Additive Manufacturing Using Genetic Algorithm

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Abstract

Additive manufacturing (AM) has the potential to improve productivity especially processing time, cost and surface roughness. In similar lines, part separation for assembly-based design in additive manufacturing can help in improving productivity. This paper discusses an optimization technique for part separation in assembly based part design in additive manufacturing. The technique improves the productivity by decreasing the processing time of printed parts, which is the sum of the build time and the assembly time. The technique uses optimal cutting planes for part separation that has distinct advantages compared to random cutting planes. The work discusses a Genetic Algorithm (GA) technique for part separation using planar cuts. The optimization technique provides the optimal number of parts for assembly and their corresponding build orientations for the minimum processing time. Three examples have been provided to demonstrate the application of the proposed method. Finally, the results from two examples are compared to the already established hill climbing optimization method for part separation.

Keywords: part separation; assembly design; additive manufacturing; genetic algorithm

1. Introduction

Additive manufacturing (AM) has evolved over the years from rapid prototyping to manufacturing products that are ready to use with desired functionalities [1]. AM provides the ability to manufacture parts directly from a digital representation [2]. In addition, it provides the advantage of producing complex parts as a single product that may not be previously possible through traditional manufacturing processes. These advantages make it a useful alternative compared to traditional manufacturing processes.

Additive manufacturing can play an important role in coherence with a basic guideline of Design for Assembly, which is to minimize the number of parts for assembly in a product. In addition, assembly-based design can lead to product innovation [1]. In AM, assembly-based design can lead to an increase in productivity and produce complex parts with desired mechanical functionalities. In the literature, it has already been discussed that multi-part assembly manufactured using additive manufacturing can improve productivity compared to a single consolidated product [3].

The current work aims at improving productivity by minimizing the processing time for production, which is the

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sum of build time and assembly time. The work proposes an optimization technique for part separation in assembly-based design in additive manufacturing. In the design for additive manufacturing, most of the studies have been focused on designing products with multi-part that can be easily assembled or have the desired functionality [4]. However, very limited work has been done to explore the area of part separation with the goal of improving productivity.

This work uses a genetic algorithm-based optimization method to generate optimum cutting planes for part separation with the objective to minimize the processing time. For the optimum processing time, the technique provides (1) the optimal number of parts that a given object should be separated, and (2) their corresponding orientations. The processing time has two components: build time and assembly time. The processing time is the sum of both. Planar cuts have been used for part separation in this method. In the literature, the optimal cutting planes provide two distinct improvements compared to random cutting planes: (1) decreases the processing time, and (2) provides consistent results [4]. By using the information of the most recent cutting planes, optimal cutting planes are generated for part separation. Three examples have been provided to demonstrate the proposed technique.

The rest of the paper is organized as follows: Section 2 discusses the state of the art in part separation in additive manufacturing. Section 3 discusses the proposed technique for part separation. The examples and the results are provided in Section 4. Section 5 discusses the conclusion and provides the path for future research.

2. Literature review

The literature related to this paper can be discussed under two major categories: productivity improvement and part decomposition in additive manufacturing.

The area of improving productivity in AM has been discussed in the literature for a while. Productivity improvement can be achieved by minimizing the production cost or improving the quality of final products. The work of Huang et al. [5] is focused on minimizing cost in metal additive manufacturing. They integrated a process-based cost model with topology optimization to reduce the total processing cost. They also demonstrated that joint optimization would result into the reduction of build time in addition to cost. Wang et al. [6] focused on reducing material cost in 3D printing. An optimization technique was developed by reducing the material volume to design a physically stable, geometrically approximate and printable skin-frame structure. In another study, a computational model for determining optimal part orientation for minimizing surface roughness and energy consumption was developed by Strano et al. [7]. The output of their technique were pareto solutions which showed the compromise between the two conflicting objectives. Chen et al. [8] focused on improving the surface quality and manufacturing dimensional accuracy for binder jetting process. They conducted experiments to optimize four parameters of the binder jetting process for obtaining the goal. Productivity can also be improved by decreasing the processing time. This point has been the focus of literature in recent years. For example, Oh et al. [3] focused on improving processing time, cost and surface roughness for assembly based part design and quantitatively assessed their proposed method for Digital Light Processing AM technology. Deka et al. [4] developed an optimization algorithm called OAPS for part separation to minimize the processing time for selective laser sintering (SLS) process. It should be noted that the part separation process does not change the overall quality of the final part compared to the unseparated part when printed using the same printer. The surfaces generated by passing of the cutting plane are internal when all the separated parts are assembled together and thus the surface quality is maintained.

Part consolidation is defined as reducing the total number of parts in an object. Part decomposition on the other hand is the separation of a given object into multiple parts. Part decomposition increases the number of parts which are finally assembled together after printing to form the original object. Schmelzle et al. [9] explored how Design for Additive manufacturing can help in part consolidation. They redesigned a multi part assembly and printed the part using Metal AM technology and showed the reduction in the product weight. Yang et al. [10] developed an innovative part consolidation method. They worked on achieving surface-level function integration and part-level function integration for meeting the functional requirements of the part and improving the performance. Yagnik [11] developed an assembled prototype that consists of more than 2500+ parts produced using FDM. The prototype was developed for a jet engine and helped them to understand the expected behavior of parts during actual manufacturing of the engine.

Although the literature mostly was focused on part consolidation, part decomposition or separation has gained attention in recent years. Luo et al. [12] developed a part decomposition method titled Chopper in which 3D models are decomposed in order to fit all the resulting parts in a predefined volume of an AM machine. They validated their work using FDM and Polyjet technology. Song et al. [13] developed a part separation method and validated it using multiple printing technologies including FDM, Selective Laser Sintering, and Stereolithography. They used the voxelization approach to produce 3D interlocking parts by decomposing a 3D model. Oh et al. [14] developed a part decomposition method that was focused on 2D batch placements of multiple parts in the limited workspace of the printer. Another algorithm named Dapper was developed by Chen et al. [15] for decompose-and-pack problems. The algorithm developed for powder and FDM based 3D printers decomposed an object into multiple parts and efficiently packed them. PackMerger, an optimization algorithm to print 3D objects was developed by Vanek et al. [16]. The optimization technique decomposed a 3D object into thin shells which are tightly packed using an optimization technique. The optimization technique minimizes the support material for printing and the bounding box volume for the minimum number of parts.

One of the important criterion that determines the processing time is the build orientation. Build orientation of parts is important in additive manufacturing as it plays a significant role in determining the quality and cost of a part [17]. A major challenge is to determine the feasible build orientation from the infinite possible orientations. The infinite orientations are generated by rotating a part at any angle in one of the three axes [18]. Different studies have addressed the problem of determining the build orientation in additive manufacturing. A multi-objective approach consisting of part accuracy and build time as the objectives for determining the optimal build orientation was proposed by Cheng et al. [19]. Another method was proposed by Lan et al. [20] for determining the build orientation for Stereolithography AM technique. They considered three criteria for determining the optimal orientation including surface quality, build time, and complexity of the support structures. Delfs et al. [21] developed an optimization method with two optimization objectives, surface roughness and build height. Their work discussed how build height is proportional to the build time and cost. Experiments were performed and experimental results were compared to the simulated results to validate their method.

In the current work, infinite build orientations are possible for the multiple parts. Thus, a criterion is needed for determining the build orientation of the parts. In this method, the height of the parts influences the layer preparation time as part of the build time. Once the part is separated by the cutting plane, the volume and surface area of the parts remain constant. Since it is assumed that any orientation can be printed, the next step is to find an optimal orientation to minimize the build time.

Part separation using optimal cutting plane shows lower processing time as well as consistent results, compared to separation done using random cutting planes. The current work introduces one more optimization technique for generating cutting planes using a genetic algorithm. Genetic algorithm has been used in the literature in several studies related to additive manufacturing. A system to determine the optimum build orientation using genetic algorithm was developed by Phatak et al. [22]. Byun et al. [23] developed another genetic algorithm to determine the optimal orientation of a part to decrease surface roughness and build time. An algorithm for efficiently packing the build volume for maximizing revenue and meeting delivery dates was developed by Dieder [24]. The work discussed GA and looked into the available literature on how GA has been utilized for optimizing part arrangement for a build. GA was used by Wodziak et al. [25] for reducing build time by optimizing the placement of parts in the workspace.

As mentioned before, productivity improvement has been widely discussed in the AM literature. In recent years, part decomposition or separation has gained some attention. The focus of the current work is on decreasing processing time with the aim of improving productivity by implementing part separation. In the current work, part separation is performed by using planar cut. The process is initialized with separating a given 3D model into two parts. The process is continued by further separating the part with larger surface area using the same technique until the minimum processing time and their corresponding number of parts are obtained. In addition, no use of genetic algorithm can be found in the literature for optimum part separation to minimize the total processing time. This study works in that area and demonstrates the proposed method using multiple examples.

3. Part separation technique:

Section 3 describes the optimization function and the proposed technique for part separation. The objective function is to minimize the total processing time. In the previous work of the author [4], a hill climbing algorithm was used to generate the optimized cutting planes for part separation, while the current work introduces a GA technique, which has been discussed in section 3.4.

3.1 Optimization function for the total processing time

The separation technique described here is developed for selective laser sintering (SLS) additive manufacturing technology. The optimization function is to minimize the processing time, T_{total} of a part produced using SLS. The processing time consists of two components discussed in the subsequent sections, the build time and assembly time. The objective function for the optimization is expressed as:

$$Minimize\ total\ processing\ time\ , T_{total} = \\ Total\ build\ time\ (T_{build}) +\ assembly\ time\ (T_{assembly}) \quad (1)$$

3.2 Build time and assembly time calculation

3.2.1 Build time

The build time for SLS printing has been previously described in the literature as follow [26]:

$$T_{build} = Machine\ preparation\ time(T_{mp})\ + \\ Layer\ drawing\ time(T_{ld})\ + \\ Layer\ preparation\ time(T_{lp})\ + \\ Ending\ operation\ time(T_{eo}) \quad (2)$$

For a given SLS printer, the machine preparation time (T_{mp}) and ending operation time (T_{eo}) are printer dependent constant time and do not depend on the part to be printed. Thus, the total time for minimizing the build time can be considered as the sum of layer drawing time and the layer preparation time. Both the layer drawing time and layer preparation times have been described below.

$$Layer\ drawing\ time\ (T_{ld}) = \\ (V_p/t_{layer})\ /\ [N_{lh}(d_{laser} + h_{dis})v_l]\ +\ (A_p/t_{layer})/v_l \quad (3)$$

where V_p, t_{layer}, N_{lh}, d_{laser}, h_{dis}, v_l and A_p denote the total volume of the object, thickness of each layer, total number of laser heads, diameter of the laser, hatching distance, scanning speed of the laser and sum of surface area of all the parts in the object, respectively.

$$Layer\ preparation\ time\ (T_{lp}) \\ = Total\ layers\ of\ the\ object\ X\ printing\ time\ per\ layer \\ =\ (H_{max}/t_{layer})\ T_{layer} \quad (4)$$

where T_{layer}, H_{max} and t_{layer} denote the time for preparing a single layer, the part with the maximum height and the layer thickness, respectively.

The layer preparation time depends on the height of the object. During the part separation, the height in general decreases. This reduces the number of layers to be printed thereby decreases the layer preparation time. During the part separation process, the total surface area of the separated part increases compared to the unseparated part. This results into an increase in the layer drawing time. However, the decrease in the layer preparation time is more prominent compared to the increase in layer drawing time, thereby it decreases the total build time.

3.2.2 Assembly technique and assembly time

The current process considers assembling parts using adhesives. Sodhi et al. [27] described different techniques that can be used to perform part assembly. In this work, we assumed that adhesives are used for part assembly. For joining two parts of the assembly, a unit time per joint is estimated. Thus, the assembly time can be estimated as follows:

$$T_{assembly} = [Unit\ time\ per\ joint\ X\ Total\ number\ of\ joints] = [Unit\ time\ per\ joint\ X\ (Total\ number\ of\ parts\ - 1)] \quad (5)$$

Although considering a unit time per joint is not necessary an accurate estimation for calculating the assembly time, it is used here for simplicity purposes. The assembly time can be a function of different factors such as the type of fasteners and the shape of the parts. In practice, the unit time can have a statistical distribution. The unit time in this study is considered as a constant. Thus, the assembly time is a linear function of the total number of parts a given object is separated into.

3.3 Optimization technique

The build time for SLS printing depends on the layer drawing time and layer preparation time as discussed above. While calculating the layer drawing time in Equation 3, it can be observed that the time depends on two-part characteristics, the volume and the surface area of the parts which are represented by the variables V_p and A_p respectively. All the other variables in the equation are constant and do not depend on the part and instead are printer dependent. Similarly, the only variable which depends on the part for layer preparation time is the maximum height of the parts, H_{max}. Thus, the orientation of the parts is critical for calculation of the layer preparation time. Since it is assumed that all the orientations can be printed for the parts, H_{max} is calculated by comparing all the heights of the parts and considering the largest out of all of them. Thus, while calculating the build time to be minimized the above-mentioned Equations 3 and 4 can be simplified to:

$$T_{ls} = V_p / (K1) + A_p / (K2) \quad (6)$$

$$T_{ld} = (K3) * H_{max} \quad (7)$$

where the above-mentioned constants *K1, K2* and *K3* depend on the printer.

As discussed in Section 3.2, the machine preparation time and ending operation time are constant for a given printer. Thus, the total processing time can be calculated using the equation below which is based on the volume of the parts, the surface area of the parts and the total number of parts a given object is separated into:

$$T_{ls} + T_{ld} + T_{assembly} = [V_p / (K1) + A_p / (K2)] + [(K3) * H_{max}] + [Unit\ time\ per\ joint\ X\ (Total\ number\ of\ parts - 1)] \quad (8)$$

where the term $[V_p / (K1)]$ will be a constant for a given 3D object as the total volume would not change depending on the planar cut. Instead, the term which has the surface area $[A_p / (K2)]$, will change depending on the cutting plane used for separating the parts. As discussed in Section 3.2 the time for $T_{assembly}$ is a constant for a fixed number of parts.

For the optimization technique, the first step is to separate a given 3D object into two parts using planar cuts. The total processing time is calculated using the information of the two resulting parts. The fundamental way to describe a plane is using a point and a direction vector and thus the cutting planes in the problem are generated using the two features for the technique. The next step is generating an optimal cutting plane using the optimization process to update the plane to obtain an improved processing time compared to the time obtained in the first step. Out of the two parts obtained in the first step, the part with the bigger surface area is considered for further separation. The process is continued until the total processing time of separated parts does not exceed the processing time of the original unseparated part.

3.4 Optimized cutting plane using genetic algorithm:

Genetic algorithm (GA), an evolutionary search technique developed by John Holland has been used to generate the optimal cutting planes for this problem. GA can be a useful technique to search for an optimal cutting plane from infinite possible cutting planes. It starts with an initial set of the population called chromosomes which evolve in successive iterations of the optimization process. Two main operations, the crossover and mutation are used to generate the offspring from the initial chromosomes. The suitability of the chromosomes as a solution is determined using a fitness function.

In the current problem, the fitness function is the same as the objective function, whose goal is to minimize the processing time. The chromosomes are made up of genes and in this problem, the point and the normal of a plane form the genes that make up the chromosome, the plane. For the initial population, all the vertices of the triangles of the given 3D model are chosen to form the required vertices for the cutting plane. A normal for each vertex is randomly generated and associated with it to completely define a cutting plane. Thus, the initial chromosomes are formed using vertices of the object and randomly generated normal vectors. From the initial chromosomes, the fitness functions are evaluated for all the chromosomes. Elitism is used in this method, which means a particular portion of the fittest solution is retained as it is and carried over to the next generation for forming the population. The remainder of the chromosome then undergoes evolution to produce new chromosomes. This process is carried out until the process reaches the termination criteria.

Two type of crossover schemes were tried for this problem. A single point crossover and a heuristic crossover. It was found that the heuristic crossover method explored the search space efficiently compared to the single point method and thus was used. In the heuristic method, instead of directly swapping the genes between chromosomes during crossover, an average of both the genes representing the normal was calculated and was introduced in both the parents to generate the new chromosomes in subsequent generations. The crossover probability of 0.8 was set for this technique. Different mutation probabilities were tried, and it was observed that higher or lower mutation probabilities did not have any advantage and was fixed at 0.1.

4. Case study

Three different examples have been discussed to demonstrate the application of the above-discussed method. Results from two of the case studies are compared with the results from the already established hill climbing optimization technique. For every part separation in all the examples, the termination criterion was set to be 1 hour or 50 generations, whichever is earlier. The stl files used for testing the algorithm were low resolution files and thus the time or generation was sufficient to reach an optimum point. For all the examples, the unit time per joint was assumed to be 150 seconds. In the case studies, the material that is used to print the parts is assumed to be PA2200. Thus, it was appropriate to assume that adhesives can efficiently join the parts. The parameters considered for printing has been used from the available literature [26]. The parameters have been summarized in Table 1.

Table 1. Printer parameters from Zhang et al. [26]

Printer	EOSINTP385
Material	PA2200
Layer thickness (t_{layer})	0.15 mm
Hatching distance(h_{dis})	0.33 mm
Diameter of laser head (d_{laser})	0.6 mm
Laser traveling velocity (v_l)	700 mm/sec
Number of laser heads (N_{lh})	1
Preparation time for each layer (T_{layer})	6 seconds

In this technique, the given 3D object is first separated into two parts, m1 and m2, using an optimized cutting plane. After the two parts have been generated the total processing time is calculated and compared to the processing time for the initial unseparated part. If the processing time for the unseparated part is more than the separated parts, the part with the higher surface area is further separated. The part separation will not be continued when the processing time of separated parts is more than the processing time of the unseparated part.

As mentioned previously, the solutions are formed by the combination of a vertex and a normal. Thus, the solution set depends on the resolution of the STL file that has been used. In the three examples, low-resolution files have been used. This reduces the number of initial population which further decreases as the parts are separated. High-resolution files were not used so that the algorithm can now iterate multiple generations before the termination criterion of 1 hour is met.

4.1 Angle bracket

An angle bracket shown in Figure 1 was used for the case study. The bracket was designed in SolidWorks and has dimensions 66.45 (mm) X 32.8 (mm) X 38.1 (mm). The processing time for the unseparated part in its optimal build orientation was calculated to be 1115 seconds.

For this case, the initial population was 95. Table 2 shows the processing time calculated during the part separation process. The minimum processing time for the bracket was calculated to be 708 seconds when separated into two parts. Figure 2 below shows the isometric view of the optimal orientation for the two parts for the minimum processing time.

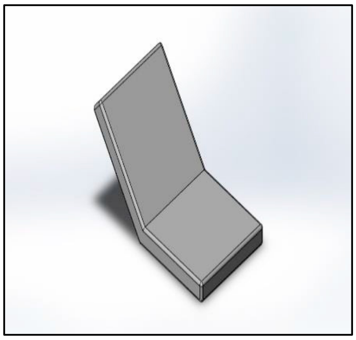

Fig. 1. Angle bracket

Table 2. Processing time for angled bracket

Total number of parts	2	3	4
Processing time	708	852	990

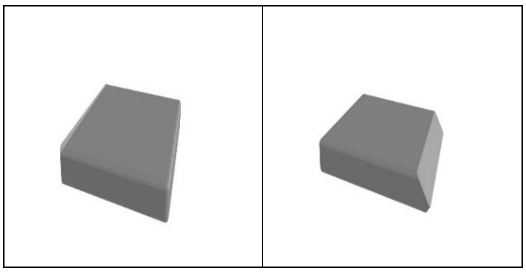

Fig. 2. Isometric view of parts for minimum processing time

4.2 Stanford Bunny

The second case study used to demonstrate the technique is the Stanford Bunny [28], which is part of the 'The Stanford 3D Scanning Repository'. An original ply file from the repository whose dimensions were reduced was used in this case. The final dimensions of the bunny shown in figure 3 [28] are

48.63(mm) X 36.75(mm) X 47.63 (mm). The processing time calculated of the unseparated bunny was 1550 seconds for optimal orientation.

The initial population for part separation for the bunny was 317. Table 3 shows the calculated processing time when the bunny was separated into multiple parts using the technique. For the bunny example, the number of parts for the minimum processing time was 2 and the minimum processing time was calculated to be 1258 seconds. Figure 4 shows the isometric view of the parts when separated into two parts in their optimal orientations.

Table 3. Processing time for Stanford Bunny

Total number of parts	2	3
Processing time	1258	1420

Fig. 3. Stanford Bunny [28]

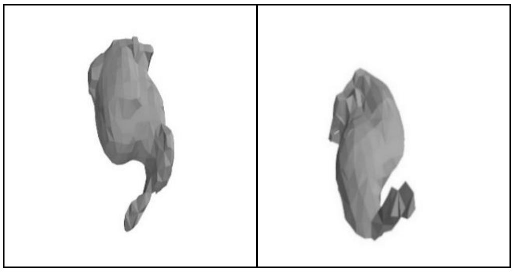

Fig. 4. Isometric view of Stanford bunny parts for minimum processing time

4.3 Axial flow fan blade

The third case study used in this paper is a low speed axial flow fan blade with support which was designed in SolidWorks. The dimensions of the part are 41.75 mm X 24.9mm X 21.15mm. For the optimal build orientation, the total processing time of the unseparated object is 1120 seconds. Figure 5 shows the unseparated object.

The initial population for this case study was 651. 710 seconds was the minimum processing time when the part was separated using the technique and was obtained when the object was separated into two parts. The processing time for different number of parts are shown in Table 4. The isometric view of the optimal orientation when separated into two parts is shown below in Figure 6.

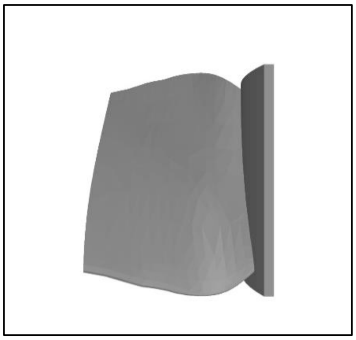

Fig. 5. Axial flow fan blade

Table 4. Processing time for axial flow fan blade

Total number of parts	2	3	4	5
Processing time	710	874	836	997

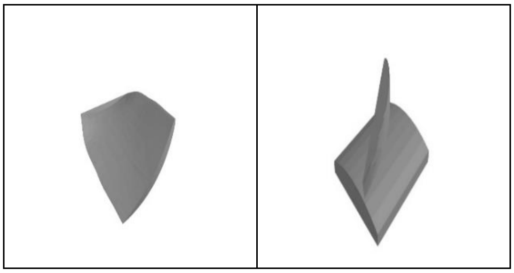

Fig. 6. Isometric view of two blade parts for minimum processing time

In all three case studies, it was observed that there is a limit to the number of parts a given object can be separated to using this technique. Anything more than four parts for the bracket, three parts for the Stanford Bunny and more than six parts for the blade was not favorable because it exceeds the processing time of the unseparated objects.

4.4 Comparison between hill climbing optimization used in OAPS and genetic algorithm technique

The hill climbing optimization technique used in the OAPS algorithm for part separation has been previously discussed in the literature as a technique that can be successfully implemented for part separation [4]. In order to compare the results of the GA technique to the hill climbing optimization technique, the later was implemented for part separation on the angle bracket and the Stanford Bunny. In the hill climbing technique, the optimization is performed by restarting the process multiple times from random starting points with the aim of reaching the local optimum every time. Within an hour, the algorithm restarted 34 times for the bracket and 12 times for the bunny respectively. The optimal results for both parts are reported in Table 5. In addition, optimum cutting planes give consistent results, and this was supported by the fact that the maximum and minimum processing times for all the iterations in OAPS lie within a very small range as reported in Table 5. This comparison between the techniques was done as a preliminary check which confirms that the GA technique can give comparable results as the hill climbing optimization technique.

Table 5. Comparison of processing time between GA and OAPS

	Angle bracket		Stanford Bunny	
	Optimum time (seconds)	Range of maximum and minimum time	Optimum time (seconds)	Range of maximum and minimum time
OAPS	676	6.12 %	1289	7.59%
GA	708	-	1258	-

From the multiple case studies, it can be seen that the GA technique can be used to improve productivity by part separation. The comparison of the GA with the results from hill climbing optimization technique demonstrates that the results are of comparable nature.

5. Conclusion and future work:

This current work provides a part separation technique to improve productivity for assembly based design in additive manufacturing. A consolidated part may not always result in better productivity compared to a multi-assembly part. This work explores the area and aims to improve the productivity by minimizing the processing time which is the sum of build time and assembly time. For the minimum processing time obtained using this technique, it provides the total number of parts a given object should be separated and their corresponding build orientation. In the current work, part separation is done using planar cuts. The technique minimizes the processing time by optimizing the cutting planes using genetic algorithm. Three examples have been discussed which demonstrate the application of this technique. The results from one of the case study is compared with the hill climbing optimization technique for part separation and the results obtained from both the techniques are comparable.

For future work, this method can be extended to different AM technologies including the technologies where support material is required. In addition, the method can be improved to discard parts that cannot be printed due to infeasible orientation. The current work also does not focus on eliminating sharp edges or vertices which can be another area of future research.

More case studies can be performed to improve the confidence in the algorithm. The work can be extended to include techniques where expert opinion can help for part separation instead of applying the algorithm. This can be applicable for simple objects. Experimental validation of the method can be performed and the results can be compared with the results from the algorithm. The experiments can be conducted to study if there is any change in mechanical strength due to part separation. In future, different assembly techniques can be considered for part assembly and complex functions for assembly time can be developed. Similarly, more comparisons can be done between the hill climbing optimization technique and the genetic algorithm method.

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