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## Grouping parts for multiple parts production in Additive Manufacturing

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### Abstract

Rapid prototyping (RP) has evolved to Additive Manufacturing (AM) in recent years. It can produce functional or end-use parts with small or even medium quantities. And further, due to its unique layer-by-layer construction principle, it can produce different parts at the same time in a same AM machine. To improve the productivity and machine utilization of AM processes under multiple parts production context, this paper propose the conception of ‘Grouping parts’. Based on the Group Technology (GT) used in traditional processing technologies, a modified Group Technology for AM under multiple parts manufacturing context is presented. To group parts, a set of key attributes affecting the AM production time, cost, quality and work preparation are identified to represent the parts, and then a Grey Clustering method is adopted to conduct the similarity analysis. A simple case study is presented in the end to illustrate the proposed conception and its methodology.

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### 1. Introduction

Additive Manufacturing (AM), derived from Rapid Prototyping (RP), has been investigated and developed for more than 30 years. Now, it has become matured to some extent since it can not only manufacturing prototypes rapidly to support the rapid product development, but also can directly fabricate functional or end-use parts for some application areas. Therefore, AM begins to enhance its importance in the product development cycle with its manufacturing abilities. More even, due to its advantage of manufacturing more complex parts against traditional processing technologies, it has played an important role in customized production, especially with a potential in the mass customization production. AM is not just an enabling technology, but also an effective one for producing small batch or medium batch of customized parts. Since due to its special construction way, layer-by-layer, the AM technologies can realize manufacturing different parts in the same machine vat or chamber simultaneously. It is a real and ideal technology for the ‘concurrent manufacturing’. Based on this characteristic of AM, to improve the productivity or machine utilization of AM processing under the multiple parts

production context, several former researchers had investigated the packing strategy for AM technologies [1-4]. However, they only focused on how to pack more parts in one build process so as to increase the packing rate and reduce the average build time per part. That could be only based on the hypothesis that all of the parts to be packed have the same manufacturing requirements and can use the same machine parameter setup. But in real production case, this situation is rare. The fact is that, an AM service provider may receive different orders with different production requirements (ex, lead time) from different costumers (Figure 1). And the part or parts of one order would not possible fill up the entire AM machine work space. Therefore, to fully use the machine work space, different parts from different orders could be mixed and placed in a same AM machine when the lead time can be guaranteed. But a new problem comes out: how to optimally group a set of ordered parts which can be manufactured together to diminish the build time & cost and improve the machine utilization? For this question, to the knowledge of the authors, no related research in the past had been carried out to provide answers. Hence, the research presented in this paper mainly dedicates to answer this question for the first time by proposing the concept of

'Grouping parts'. To group parts under the multiple parts production context, two main tasks should be well accomplished, which is similar to the main steps of GT methods adopted in traditional processing or design technologies. One is the representation of parts, and the other is the analysis of parts' similarity. To solve the two sub-problems, at first several key attributes are identified from the perspective of AM production to form a vector and used to represent parts to be grouped, and then a Grey Clustering method is adopted for the similarity analysis.

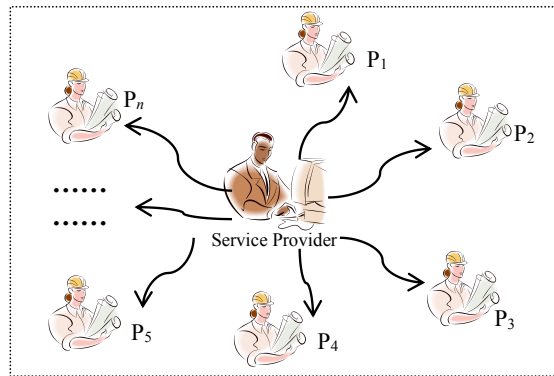


Fig. 1. Service providers under multiple parts production environment ( $P_i, i=1, 2, 3 \dots, n$ , denotes the  $i$ th part from customers)

The left of this paper is organized as: the second section will present the main steps of a modified GT approach deriving from the GT methods adopted in traditional design or manufacturing processes for AM; the third section will discuss the identification of a set of suitable attributes for the representation of parts; the fourth section will introduce the Grey Clustering method for similarity analysis; the fifth section will present a simple case study for illustration and the last section will come to a conclusion with some discussion.

## 2. Modified group technology for AM production

Actually, 'Grouping Parts' is an old concept and a very typical problem in traditional processing technologies as well as the coding of parts. Group Technology (GT), dedicated to group parts, is used to form part families by identifying and classing similar parts so as to take advantages of parts' similarity in manufacturing and design [5], since similar parts have similar process planning and design method according to the geometric shapes. Therefore, the similarity study in conventional processing technology is mainly based on the analysis of parts' similar geometric features. Features and their carried design or manufacturing information are usually extracted and used to represent the parts for similarity analysis [6]. However, due to the difference of processing principle between AM technology and traditional processing methods, the similarity study based on geometric feature would not work for AM, since there is no need to consider the selection of tools, fixtures and molds for related geometric feature shapes in AM. In addition, one AM machine can manufacturing different parts with different complex geometric shapes and further more it can realize the constructing of different parts within a same work space simultaneously. Therefore, to group parts in AM,

the conventional GT technologies should be modified so as to suite the production characteristics of AM technologies.

Though there exist large difference on processing principle between the traditional manufacturing technologies and AM processes, the main steps of GT approaches in AM and traditional processing are similar except some modifications. According to the special characteristics of AM technologies, the traditional GT methodology is mainly modified to meet the requirements of the multiple parts production context. The main steps of the modified GT approach for AM can be given in the following.

- *Determining the application objective*

Traditionally, GT is mainly used to provide information for two main steps in the development of product, design and process planning. Objective, design or process planning, should be determined so as to help identify related attributes to represent the parts. Herein, the objective of using GT is mainly to improve the productivity and utilization of an AM machine. Therefore, process planning or production is the main objective concerned.

- *Identifying the key attributes of parts*

In traditional processing technologies, usually related geometric features, design or manufacturing feature, should be identified as attributes to represent parts. However, geometric features are not very useful to design or manufacturing in AM as discussed above. Hence, the geometric features can't well or fully express a part's information for the production objective, and there is no need to construct and code parts to help form part groups or part families in AM since AM processing is not so sensitive to the geometric shapes of a part. Therefore, new different attributes should be identified and added to well express part's information which is useful to the production in AM.

- *Representing parts with attributes*

In conventional processing technologies, when the attributes are identified, they are usually organized in some structure to represent the parts with their related quantitative or qualitative values. There are three main structures for traditional GT method, hierarchical structure, chain structure and hybrid structure [5]. However, these structures are not suitable to AM, since there is no need to analyze the production flow or the similar geometric features to decide whether a part should use a tool or machine. And there is also no need to clarify the hierarchical relationships among the identified feature attributes so as to help form or select manufacturing cells. In AM production, the attributes to be identified may not have such chain or hierarchical relationships. The attributes to be identified in this paper are not only limited to the geometric factors, but also include other factors or implied information. The expanded range of attributes could well express the part's similar impact or effect on the AM production results from a multiple-point of view. Therefore, the GT in AM is mainly based on the similarity of part's general impact on the AM production preparation and results, such as process planning, the build time, cost, part's quality and so on. In other word, the modified GT methodology proposed in this paper is not to

really help construct the part families as defined and formed based on similar geometric shapes in traditional processing technologies, but just to form part groups which are more suitable or economic to be manufactured in an AM machine simultaneously. Therefore, a vector structure, proposed in [5], is adopted to organize the identified attributes which would not have clear chain and hierarchical relationships though they may be interrelated with each other. The next section will discuss the related attributes in detail.

- *Calculating similarity and forming clusters*

When all the parts are represented by the identified attributes with their related values, the calculation of similarity can be conducted, and the clusters can be obtained according to the similarity values by setting a control coefficient. Here again, the calculated similarity is not used to express the geometric characteristics of parts but their implied production characteristics, since the attributes to be identified in this paper are different against traditional process technologies. There are many methods for similarity calculation and cluster formation, for example the ART1 and ART 2 method proposed by Carpenter et al had been applied by many other researchers in the past [7, 8]. However, many of the current methods are dedicated to binary and symbolic values, and mainly base on the rectilinear, Euclidean and Hamming distance metrics. And even some current methods need the attributes to be independent with each other, which is not realistic in AM production. To tackle of those inconvenience, this paper propose to use a relatively new similarity measure and clustering method, Grey Clustering. This method does not require the independency among part's attributes and can not only measure the similarity by using distance based sub-model as the former methods introduced above, but also can directly measure the similarity between two n-Dimensional vectors in a n-Dimensional space by investigating the shapes of the two vectors. The fourth section will present the proposed Grey Clustering in detail.

### 3. Key attributes for part representation

As discussed above, the key attributes to be identified for part representation in AM are different from those in traditional processing technologies. Attributes are not only limited to the geometric features of a part. Since the objective of the GT method proposed in this paper is process planning or production under multiple parts production context, key attributes should be selected under this context and used to convey the related information or impact of those parts to be grouped to the process planning or production. In this paper, key attributes are mainly identified from four facets: lead time, build time & cost, part quality and the impact on the work space planning.

#### 3.1. Lead time

One of the main advantages of Additive Manufacturing is that it can provide the customer with the expected part very rapidly. Therefore, lead time is the foremost thing that should be taken into consideration when grouping parts. For the users,

the lead time is the less the better, while for the manufacturing service provider, the productivity within the lead time should be the higher the better. However, when manufacturing multiple different parts from different orders, the lead time may be different. Hence, to meet the users' requirements on the lead time and get a higher productivity, those parts whose lead time can be all well guaranteed when they are produced simultaneously in one AM machine should be grouped together. Therefore, lead time is identified as the first key attribute for the grouping problem addressed in this paper.

#### 3.2. Build time & cost

Build time and cost are very important to the AM processing and also are the main facets attracting much attention in traditional processing technologies. Build time and cost compose of the main area where people want to find a good breakeven point between AM technologies and traditional processes. Many researchers had investigated the factors affecting the build time and cost for a part in AM [9-11]. Different parts may have different impacts on the build time, especially for the multiple parts production context [11]. A part's Z-height (a part's height in the build direction or orientation) has a direct impact to the part build time and further the part cost since it directly determines the number of slices [12]. Hence, an attribute which can well express the impact of part's Z-height to the build time should be identified. However, the part's height can be changed when placing on the bottom of the build platform or vat, since the parts may be rotated to get an optimal placing layout or an optimal packing solution to get a higher machine packing rate or productivity. Therefore, the range of a part's Z-height is identified as a key attribute to express a part's impact to the build time and cost. Theoretically, the range of a part's Z-height can be defined by its bounding box's parameters (Figure 2). The upper and lower boundary of the Z-height range is given as:

$$Z_{min} = \text{Min} \{l, w, h\}, \quad (1)$$

$$Z_{max} = \sqrt{l^2 + w^2 + h^2} \quad (2)$$

, where  $l$ ,  $w$  and  $h$  denote the length, width and height of a part's bounding box. The value of the Z-height range,  $[Z_{min}, Z_{max}]$ , depends on the orientation result. When a part's build orientation is fixed, the Z-height range would be a single numerical value, and if a part has several finite build orientation alternatives, the value would be a finite discrete set, but when a part can be rotated freely during the placing or packing, the value would be an infinite continuous interval. Therefore, those parts whose ranges of Z-height are similar should be grouped together.

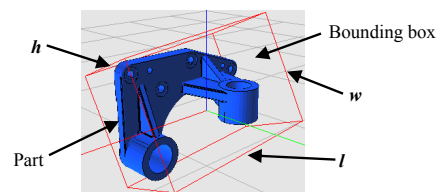


Fig.2. Bounding box of a part in AM production

3.3. Part quality

In AM processing, a same AM machine can usually form different manufacturing scenarios by selecting different setup parameters and materials, which would cause to different part qualities (<http://karma.aimme.es>). And different parts to be manufactured by a same AM machine may have different part quality requirements. If a group of parts with large difference on the part quality requirements are produced simultaneously, then the AM machine should adapt its setup to meet the needs of the part with the highest quality requirements, which would cause much waste of build time since other parts may do not have high requirements and they can be built up by using a low level setup, for example, higher scanning speed plus thicker layer plus larger hitching interval. Furthermore, different parts may require different scanning strategies, hatching vectors or layer thickness to obtain different part qualities. Therefore, those parts whose quality requirements are similar should be grouped together to lowdown the build time & cost and the production waste. For part quality, tensile strength and surface roughness are the most two common properties concerned. Hence, in this paper, these two mechanical parameters are identified as two key attributes from the factor of part quality.

3.4. Impact on work space planning

Under the multiple parts production contexts, different parts should be optimally placed on the bottom of the building vat or chamber to minimize the occupancy rate of the work space, the build vat or chamber or platform. For the searching of an optimal placing or packing solution, the shapes and their differences of the parts directly affect the computational efficiency [13]. Those parts whose shapes are similar would be easier to be optimally placed or packed within a shorter computing time. Since similar parts usually can be recognized and grouped into sub-groups, and the sub-groups can be regarded as one part during nesting or packing, which can greatly reduce the total number of parts to be nested and then reduce the length of sequence as well as the number of its permutations and combinations. Therefore, the parts with similar shapes should be grouped together to decrease the difficulty and computation time of work space planning. In AM, representative commercial software tools for work place planning use the parts' bounding box when doing the optimization (<http://www.materialise.com>). Therefore, those parts with similar bounding box would be more convenient for the work space planning. Hence, in this paper, the related parameters of a part's bounding box are used to define a key attribute as shown below to express that impact of part's shape.

$$B = (\text{Min } \{l, w, h\}) / (\text{Max } \{l, w, h\}) \tag{3}$$

, where  $l, w$  and  $h$  denote the length, width and height of a part's bounding box;  $B$  is the defined attribute.

When the key attributes are identified, then the parts to be grouped can be represented by vectors composing of those identified attributes. For example, a part,  $P$ , can be represented as:

$$P = \langle T, [Z_{min}, Z_{max}], S, R, B \rangle \tag{4}$$

, where  $T$  denotes the lead time (hour);  $[Z_{min}, Z_{max}]$ , Z-height range ( $[Z_{min}, Z_{max}], mm$ );  $S$ , tensile strength (MPa),  $R$ , surface roughness ( $um$ ) and  $B$ , the attribute on the similarity of part's bounding box.

When the values of those identified attributes are obtained, then the similarity analysis can be conducted by applying a suitable clustering method. The next section will introduce the Grey Clustering method to calculate the similarity and form suitable part groups or clusters.

4. Grey clustering

Grey Theory was proposed firstly by Deng in 1982 [14]. It is a relatively new type of mathematical method to deal with the uncertainty problems in control and system engineering. Grey Clustering is a part of this theory and is a method developed for classifying observation indices or observation objects into definable classes using grey incidence matrices or grey 'whitization' weight functions without target or prototype objects [15]. Compared with traditional GT method applied in conventional processing technologies, the modified GT in AM processing has no target or prototype parts to measure the similarity. And there is usually no binary attribute value, but some fuzzy or Grey values mixed with numerical values, for example, the range of Z-height. Even more, it does not need the attributes to be independent with each other. Therefore, this method is very suitable for the GT in AM under multiple parts production context. The clustering method is based on the Grey Incidence values between each pair of objects. The Grey Incidence can be calculated by

$$\epsilon_{ij} = \frac{1 + |s_i| + |s_j|}{1 + |s_i| + |s_j| + |s_i - s_j|} \tag{5}$$

, where  $\epsilon_{ij}$  denotes the grey incidence (similarity) between two vectors;  $s_i$  and  $s_j$  deriving from the two vector sets, here parts represented by vectors, are processed by a set of special Grey Operators [15]. After calculating each pair of studied objects, an 'Incidence Matrix',  $A$ , is obtained as:

$$A = \begin{pmatrix} \epsilon_{1,1} & \dots & \epsilon_{1,m} \\ & \epsilon_{3,3} & \vdots \\ & & \epsilon_{m,m} \end{pmatrix} \tag{6}$$

, where  $\epsilon_{ij}, i \neq j, i, j = 1, 2, \dots, m$ . is the absolute degree of incidence of a pair of objects, and  $\epsilon_{ii} = 1, i = 1, 2, \dots, m$ . For a chosen threshold value  $r, r \in [0, 1]$  and usually satisfies  $1 > r > 0.5$ , if  $\epsilon_{ij} > r$  and  $i \neq j$ , then the two objects can be grouped together. The threshold value determines the number of clusters as well as the fineness of the clustering result. The selection of the threshold value depends on the specific application requirements and context.

With the identified attributes and selected clustering method, the grouping of parts under multiple parts production context for AM can be realized. To illustrate the proposed modified method for AM part grouping, the following section will present a case study.

5. Case study

In this section, a set of 10 parts are assumed to be manufactured by a SLS printing machine. The proposed GT method will be used to group these parts. The parts and parts' specifications and its related manufacturing requirements are presented in Figure 3 and Table 1.

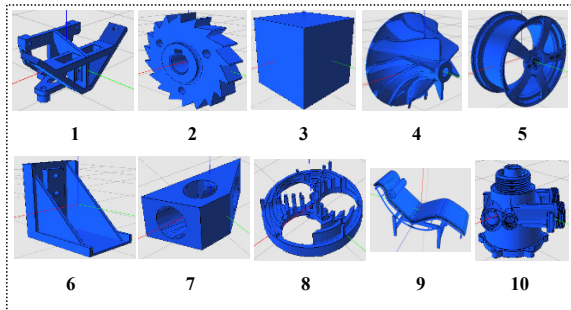


Fig.3. A set of 10 parts to be grouped

Table 1. Specifications of the parts

Part	Part specification			Production requirements		
	<i>l</i> (mm)	<i>w</i> (mm)	<i>h</i> (mm)	<i>T</i> (day)	<i>R</i> (um)	<i>S</i> (MPa)
1	34	74	34	5	15	50
2	119	28	120	10	25	45
3	50	50	50	3	20	45
4	8	14	14	7	16	40
5	21	41	41	6	18	50
6	31	21	43	5	22	50
7	30	75	20	8	18	45
8	61	61	15	14	22	50
9	72	31	25	6	16	55
10	131	134	97	14	18	40

As discussed above, the first step of grouping is to identify the key attributes for part representation. The attributes defined in Section 3 are adopted in this grouping case study. Therefore, the 10 parts can be represented by vectors as:

$$\begin{cases}
 P_1 = \langle T_1, [Z_{min}, Z_{max}]_1, S_1, R_1, B_1 \rangle; \\
 P_2 = \langle T_2, [Z_{min}, Z_{max}]_2, S_2, R_2, B_2 \rangle; \\
 P_3 = \langle T_3, [Z_{min}, Z_{max}]_3, S_3, R_3, B_3 \rangle; \\
 \dots \\
 P_{10} = \langle T_{10}, [Z_{min}, Z_{max}]_{10}, S_{10}, R_{10}, B_{10} \rangle.
 \end{cases}
 \tag{7}$$

The second step is to obtain the related attributes' values for each part. The proposed calculation method in Section 3 can be used for the calculation. In this example, an assumption is made that the parts can be rotated freely without fixed build orientation. Hence, the value of the identified Z-height range is a continuous interval. However, there is no need to process this value by using fuzzy methods, since the selected Grey Clustering can directly deal with continuous interval value for calculation. The interval values are treated as Grey numbers during computing. After calculation, the parts can be represented with two types of values, interval and numerical values.

$$\begin{cases}
 P_1 = \langle 5, [34, 88.25]_1, 50, 15, 0.46 \rangle; \\
 P_2 = \langle 10, [28, 171.30]_2, 45, 25, 0.23 \rangle; \\
 P_3 = \langle 3, [50, 86.60]_3, 45, 20, 1 \rangle; \\
 \dots \\
 P_{10} = \langle 7, [97, 211.02]_{10}, 40, 18, 0.72 \rangle.
 \end{cases}
 \tag{8}$$

The third step is to calculate the grey incidence value between each pairs of parts and construct an 'Incidence Matrix', *A*, by applying the Grey Clustering method. The 'Incidence Matrix' of this example in this case study is presented below.

$$A = \begin{pmatrix} \varepsilon_{1,1} & \dots & \varepsilon_{1,10} \\ & \varepsilon_{3,3} & \vdots \\ & & \varepsilon_{10,10} \end{pmatrix}
 \tag{9}$$

$$A = \begin{bmatrix} 1.0 & 0.904 & 0.942 & 0.715 & 0.907 & 0.931 & 0.899 & 0.842 & 0.977 & 0.834 \\ & 1.0 & 0.958 & 0.674 & 0.829 & 0.848 & 0.822 & 0.777 & 0.886 & 0.913 \\ & & 1.0 & 0.690 & 0.860 & 0.881 & 0.852 & 0.803 & 0.921 & 0.878 \\ & & & 1.0 & 0.764 & 0.749 & 0.769 & 0.813 & 0.725 & 0.643 \\ & & & & 1.0 & 0.973 & 0.990 & 0.920 & 0.927 & 0.772 \\ & & & & & 1.0 & 0.963 & 0.897 & 0.952 & 0.788 \\ & & & & & & 1.0 & 0.929 & 0.918 & 0.766 \\ & & & & & & & 1.0 & 0.859 & 0.729 \\ & & & & & & & & 1.0 & 0.818 \\ & & & & & & & & & 1.0 \end{bmatrix}
 \tag{10}$$

The last step is to select a threshold value for *r*. In this case study, the threshold value is set as 0.92 to meet the requirement of separating the parts into at least three groups and it is just used for illustration. For real production context, the determination of suitable threshold values to generate suitable number of clusters for a group of parts should depend on real application needs and production knowledge. By comparing and checking the incidence values with the selected threshold value, a set of clusters of parts can be formed. The result is presented in Table 2.

Table 2. Grouping results

Groups	Cluster 1	Cluster 2	Cluster 3
Parts	{1, 2, 3, 5, 6, 7, 8, 9}	{4}	{10}

The results show that this set of parts can be grouped into three different clusters. Part 4 and part 10 are two separate clusters mainly due to their bigger difference of part size with the left 8 parts. Therefore, the two parts should not be produced together with other 8 parts and if there is only 10 parts for processing, the set of parts should be processed in three batches. However, the clustering result is only based on the preset clustering threshold value and equal weights for the attributes. Different clusters may be formed when adjusting the threshold value and assigning uneven weights for the part's representation attributes. Due to the limited pages of this paper, the number of parts in this case study is limited or even insufficient to fully testify the effectiveness of the proposed conception and its methodology. However, this case is just presented for demonstrating the main idea of the proposed grouping conception and modified GT method. When there are

more parts to be dealt with in the real production context, this proposed method could help manufacturing service providers to improve their productivity as well as make the manufacturing more reasonable under multiple parts production context.

## 6. Conclusion

Additive Manufacturing has become an enabling technology for customization production. Multiple different parts can be placed within one AM machine vat or chamber so as to improve the productivity. However, as proposed in this paper, before packing multiple parts in an AM machine, there is a real need to consider the different manufacturing requirements among the parts and their implied impact to the production so as to make the production more reasonable and economic. To help AM service providers to deal with this problem, this paper introduces a conception of ‘Grouping parts’ and its realizing methodology. A simple example is used to demonstrate the necessity of grouping parts before manufacturing. However, the work presented here is just a preliminary step. Future work would investigate further the identification of a set of more suitable key attributes and their values’ computation methods or models. And also more case studies under larger quantity of multiple parts context would be conducted.

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