A METHODOLOGY TO DEVELOP TAXONOMY OF ADDITIVE MANUFACTURING USING FORMAL ATTRIBUTES SPECIFICATION TEMPLATE

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ABSTRACT: Additive Manufacturing (AM) is referring to technology that offers design creativity and freedom in developing the 3D product. AM generates and accumulates a large number of design information on geometrical part, materials, and processes. This is time-consuming for a designer in searching the right information about AM process. In this paper, the additive manufacturing processes have been classified according to their attributes information that is based on a systematic guideline, called Formal Attributes and Specification Template (FAST). FAST is used in the taxonomy generation for formal attribute identification which is later used in Formal Concept Analysis (FCA) to generate a lattice. The resulting lattice and formal attribute information obtained with FCA are later used to create taxonomy. The developed taxonomy was evaluated by homogeneous cluster analysis. The results of the evaluation show that the FAST method provides design rationale in developing AM taxonomy.

KEYWORDS: *Additive Manufacturing; Formal Attribute Specification Template; Formal Attributes; Formal Concept Analysis*

1.0 INTRODUCTION

There are two ways of manufacturing methods for creating a physical object, subtractive and additive manufacturing process. The subtractive process is the traditional process which involves a removal of material. While additive manufacturing (AM) is another method of the manufacturing process that involves the latest technologies in which part are produced by adding layer-by-layer of material deposition. AM offers a freedom on the geometrical such as design complexity, part consolidation, parts customization and material combination for each part production [1-5]. AM process cycle allows forming both virtual model and objects directly from computer-aided design (CAD) data without geometrical complexity limitations in hours. Therefore, it reduces the time to market and material wastage [6].

At present, technology and raw material are used to categorize the AM [7]. Recently, the American Society for Testing and Materials (ASTM) group "ASTM F42 agreed that the AM are categorized into seven categories, which are [8]: (i) VAT photopolymerization; (ii) powder bed fusion; (iii) material jetting; (iv) binder jetting; (v) material extrusion; (vi) directed energy deposition and (vii) sheet lamination.

Therefore, AM creates and requires understanding of the diversity of data that related to geometrical part design, materials, processes and part performance [9]. Moreover, the manufacturer is moving forward to achieve sustainable information in which the correspondent manufacturers are required to apply the end-to-end digital implementations of their logistics and supply chain, manufacturing processes, parts and service [4-5]. The manufacturers aim to improve the efficiency and innovation as well as increasing the tool life through the make use of product lifecycle data.

A critical drawback of the current method is the inappropriate combination of processes and there is no clear representation of data that hinder the elicitation of accurate process information. For example, Selective Laser Sintering is grouped with 3D printing or that some processes that may appear to produce similar result end up being separated.

Extensive research has been conducted in developing a common understanding of knowledge and information of manufacturing process using ontology [9-13]. Ontology is one approach to the formalize knowledge representation of the manufacturing processes, that captures the semantics of things represented in a specific domain which composes of classes representing a set of things that share the same attributes [13]. Several methods have been proposed ontology in AM domain [7, 14], but none is capable to provide a systematic method to develop the class taxonomy.

In previous studies such as [13, 15], formal concept analysis (FCA) is proposed to overcome the challenge of ontology in which the class hierarchy is developed in an ad-hoc manner. However, the approach lack of systematic guidelines to identify the formal attributes.

Therefore, in this paper, a methodology to develop AM taxonomy using a systematic guideline of formal attributes specification Template (FAST) to identify formal attributes was proposed. Subsequently, the class hierarchy in taxonomy is developed with the combination of formal concept analysis.

The paper framework is organized as follows. The methodology for AM taxonomy that is based on FAST is introduced in the following Section 2 while Sections 3 and 4 give several concluding remarks and also the future research.

2.0 METHODOLOGY

The proposed methodology used in this section is an extension of our previous work [13, 15-16]. The methodology consists of three major steps that focus on (i) categorization of attributes of AM processes using FAST, (ii) generation of concept lattice and (iii) the creation of taxonomy.

The first step is important as FAST systematically characterized formal attribute that can be used in FCA to generate the class taxonomy. The identification of formal attributes of a process was based on assumption that a process changes an object that exists before the execution of the process to produce another object. In a four-dimensional view, these objects correspond to the temporal parts of the object before and after the process. In addition, among the objects which participate in a process, this work can distinguish those entities that are not intended to be affected by the activity but that are used by the activity. Therefore, four types of objects that participate in a process can be identified: the objects that are transformed by the process (the inputs), the objects that are produced by the process (the outputs), the objects that are used for the execution of the process (the performers) and the objects that accommodate the process (the location of the process).

For example, the fuse deposition modeling (FDM) process always transforms a reel of plastic filament and produces a layer by layer object. A performer for this case is the heat that used to liquefy the reel of plastic filament and also a nozzle to deposit the material. However, in this example, the location of the process can be considered as absent since none of the AM processes always take place on the given machine.

3.0 RESULTS AND DISCUSSION

The aim of this paper is to develop a class of taxonomy of AM. The term of AM is commonly used for developing a prototype or an end used product. The first step is the identification of a list of potential classes in which it was extracted and analyzed through documentation review.

The next step is to obtain the formal attributes information using the FAST method. For example, Selective Laser Sintering (SLS) is a layer by layer process that produces physical object by using a laser beam. The object that is transformed by SLS process is metal powder. The object that is produced is a layer by layer object. Then, constraints on performers and location are further identified. Table 1 summarizes the potential classes and their formal attributes. Due to limited space, only a few processes are listed. Subsequently, all formal attribute information that is obtained using FAST can be further used to generate a class hierarchy. The important step in generating the class hierarchy is the use of FCA in which the information was organized in terms of a set of formal objects O, a set of formal attributes A and a set of binary relations between them. For our purpose, the objects represent the potential classes. In this step, a context table was created.

Then, a Concept Explorer that uses a Grail algorithm to generate the concept lattice is used to visualize the taxonomy [17]. The lattice was analyzed and corrected by tracing each path of the lattice. Two number of issues were identified the obsolete AM processes were included and the formal attributes were scattered. Therefore, the lattice was corrected and compared with the categorization proposed by [13]. The corrected lattice is shown in Figure 1. The white boxes refer to the object (in this paper object refers to AM process) and it has formal attributes that are represented in the grey box.

Table 1: List of potential classes and formal attributes for AM processes using FAST

	Object that is Changed by the activity	Object that is produced by the activity	Performer	Composition (participating object)
Stereolithography (SLA)	liquid photopolymer resin, 3D CAD model	a layer-by-layer object	involves a laser beam to solidify liquid resin	changed object is hardened
Fused Deposition Modelling (FDM)	a reel of plastic filament, 3D CAD model	a layer-by-layer object	involves nozzles to deposit materials, uses heat to liquefy the material, uses constant pressure and continuous stream	changed object is extruded through heated nozzles, use support materials
Objet Manufacturing Process (OMP)	photopolymers, 3D CAD model	a layer-by-layer object	involves inkjet head to deposit materials, uses ultraviolet light to liquefy the material	changed object is jetted through jet head, use support materials, involves piezoelectricity method to deposit material
Electron Beam Melting (EBM)	metals powder, 3D CAD model	a layer-by-layer object	involves electron beam to melt and fuse powder together, uses roller to spread powder over previous layer, uses powder bed	
Selective Laser Melting (SLM)	metal powder, 3D CAD model	a layer-by-layer object	involves laser or electron beam to melt and fuse powder together, uses roller to spread powder over previous layer, uses powder bed, uses inert gas	
Direct Metal Deposition (DMD)	metal powder, 3D CAD model	a layer-by-layer object, repaired object, added additional object	involves nozzles to deposit materials, uses multiple directions of nozzle axis	changed object is extruded through heated nozzles,

Laminated Object Manufacture (LOM)	sheet of paper, 3D CAD model	a layer-by-layer object	Involves build material applied to the part from a roll, involves a heated roller which activates heat sensitive adhesive, uses laser to cut the lines that form the edges of the desired shape	changed object is added with an adhesive material to glue the successive layers
3D Laser Cladding (3DLC)	metal powder, 3D CAD model	a layer-by-layer object, repaired object, added additional object	involves nozzles to deposit materials, uses multiple directions of nozzle axis	changed object is extruded through heated nozzles,

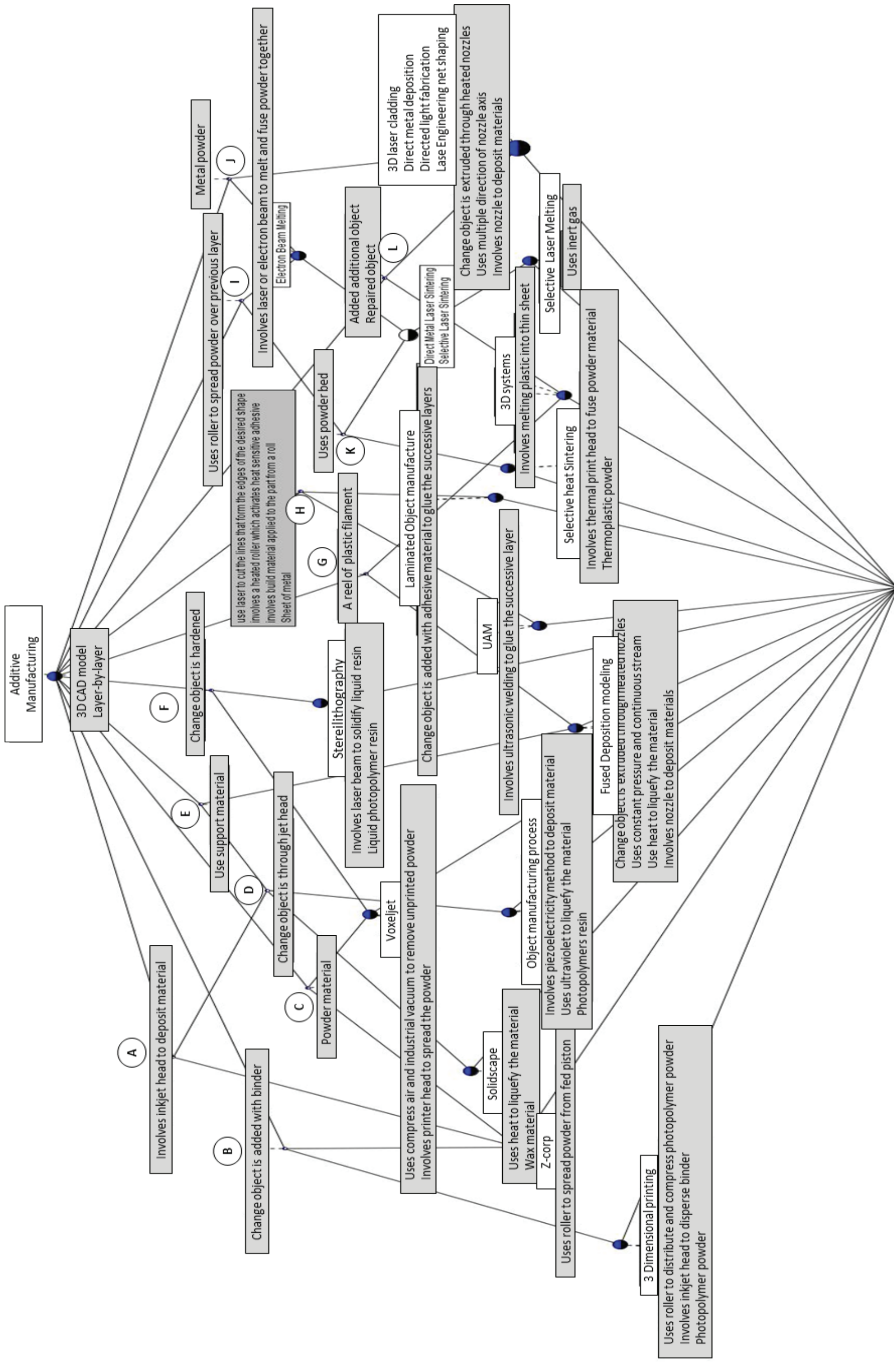

Figure 1: Screen dump of a partial AM lattice

It is interesting to note that there are twelve unnamed nodes (A, B, C, D, E, F, G, H, I, J, K, and L). These unnamed nodes can be considered as newly discovered classes that can be named or identified based on the name from the individual formal attributes and the parent nodes. For example, the node B is identified as "Binder Jetting". This information in corrected lattice was used to develop the AM taxonomy. The development of AM taxonomy is carried out using Protégé ontology editor. This software helps the specification of classes, relations, and axioms.

Evaluation of class hierarchy is necessary in order to get high accuracy and ontology that has greater reusability [13]. The evaluation of this class hierarchy is based on the work done by [8]. For this purpose, the equation was proposed by van der Weken is used to conduct the hierarchical cluster analysis. The equation is denoted by

$$sim_{\text{vanDerWeken}}\left(C_i, C_j\right) = \frac{\left|A'_i \cap A'_j\right|}{\min\left(\left|A'_i\right|, \left|A'_j\right|\right)} \tag{1}$$

Where $sim_{\text{vanDerWeken}}$ (C_i, C_j) is the semantic similarity between classes C_i and C_j. A_i and A_j are the set of attributes of classes C_i and C_j , respectively A_i and A_j are the complements of set A_i and A_j, $| A'_i \cap A'_j |$ represent the total number of complement of the set of attributes shared by C_i and C_j . $| A'_i |$ and $| A'_j |$ is the number of complement of the set of attributes of C_i and C_j. The more common attributes share by the process the more similar they are. The comparison is between stereolithography processes with other AM processes listed in Table 1.

Figure 2 shows the clustering of AM process according to FAST. The AM processes are categorized into only six clusters which are one cluster smaller than ASTM categorization. The clusters are directed energy deposition, material extrusion, binder jetting, vat photo-polymerization and sheet lamination. Surprisingly, selective laser melting (SLM) was not found in the group of selective heat sintering, direct metal laser sintering (DMLS) and selective laser sintering (SLS). ASTM categorized these processes into powder bed fusion. This inconsistency may be due to the missing of the formal attribute in which the attributes are manually identified.

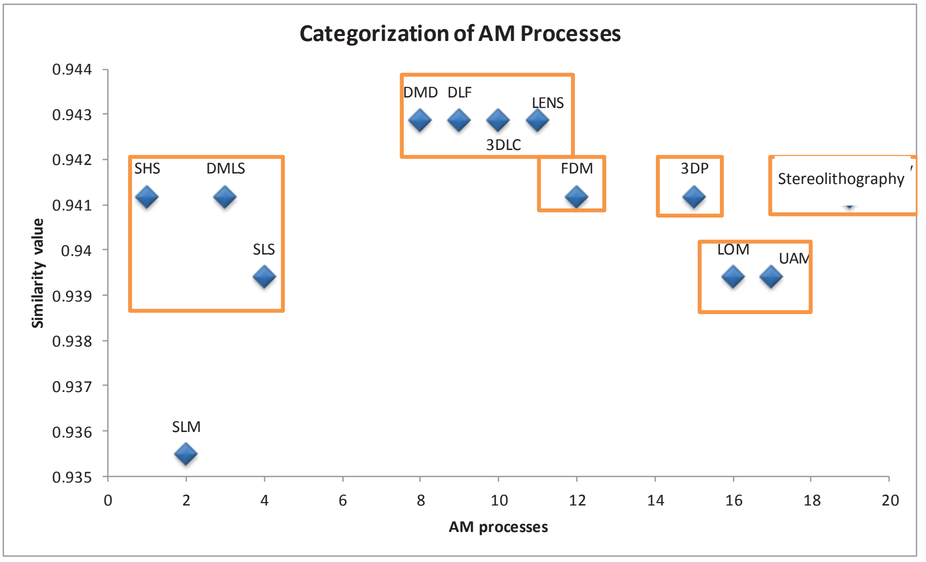

Figure 2: AM clustering

4.0 CONCLUSION

This paper highlights on the use of FAST for clustering the AM processes categorization. The foundation of the proposed approach is the use of FAST to determine the formal attribute that can later be used in the development of class hierarchy using FCA. The results of the clustering analysis demonstrated that the FAST can be used to classify the AM basic principle. The proposed approach needs more refining such as the mechanisms for the automatic identification of FAST potential classes and attributes in future work.

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