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ADDITIVE MANUFACTURING DESIGN FEATURE SELECTION FOR VARIABLE PRODUCT PLATFORMS

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Abstract

Additive manufacturing (AM) technologies enable new capabilities in producing innovative products with complex geometries, superior performance, and low material wastage. In this research, design for additive manufacturing (DFAM) freedoms and constraints are integrated with product platform design, aiming to help companies generate innovative platform-based product families by selecting appropriate AM design features to meet platform modules' design requirements in multiple market segments. In this paper, the concept a variable product platform is proposed to describe new characteristics of additive manufactured product platform modules. An object-oriented technique is used for representing design knowledge. A binary coding system is applied to code AM design features and platform variants' design requirements. Hierarchical agglomerative clustering is performed to create clusters that indicate appropriate AM design feature selection, and to group similar AM design features in terms of functionalities, materials, and key design parameters. The result provides a design proposal to explore AM-enabled design space at the conceptual design stage.

Keywords: Product families, Knowledge management, Early design phases, Design for Additive Manufacturing

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1 INTRODUCTION

Additive manufacturing (AM) represents a collection of manufacturing processes that produce parts by bonding raw materials in a layer-by-layer manner (Gibson et al. 2010b). Compared to conventional subtractive and formative manufacturing processes, AM processes have unique capabilities to create parts with complex geometries, multi-functionalities, and, in some cases, superior material properties (Gibson et al. 2010a). Other than prototypes, functional components can now be manufactured by AM, which have found applications in different industries such as aerospace, automotive, and bio-medical (Bourell et al. 2014). AM processes are expected to be used more extensively by companies of various sizes in the near future due to the maturation of technologies and the fall of machine/material prices (Bourell et al. 2014). Therefore new product design methodologies need to be developed for companies to explore the opportunities brought by these new manufacturing technologies (Seepersad 2014).

As a strategy to developing customized products while reducing cost and lead-time, the product platform concept (Simpson et al. 2006) is applied in this research to the design of additive manufactured products. Platform-based product family design aims to reduce cost by introducing commonality into product variants, and to satisfy diversified customer requirements in different market niches at the same time (Cameron and Crawley 2014). Platform strategies have been adopted by enterprises, from aircraft manufacturers to household appliance start-up companies (Shooter 2006, Willcox and Wakayama 2003), to improve the competitiveness of their product families. Due to the significant difference between AM and conventional production processes, platform concepts and strategies need to be re-defined in the context of AM. New design knowledge needs to be systematically explored in support of designing additive manufactured products; and new guidelines need to be proposed for efficient product design process management.

Design methodologies at the conceptual design stage are required to help designers define and explore design spaces enabled by AM (Bourell et al. 2014), in order to utilize AM benefits in innovative product development. The present research aims to integrate the knowledge of AM capabilities and constraints into product platform design process, by intelligently selecting AM design features to meet platform modules' design requirements in multiple market segments. In this paper, the concepts of a variable platform are first proposed for additive manufactured platform modules. Design knowledge is represented by an object-oriented technique. Attributes of AM design features and platform design requirements are coded in a binary coding system; and then hierarchical agglomerative clustering is performed to select appropriate AM design features for each platform. The proposed methodology provides a design proposal which guides designers in further detailed design.

2 LITERATURE REVIEW

Despite the variety of existing AM processes, all of them share the same general process chain consisting of CAD modeling, model slicing, tool path generation, machine setup, material deposition and fusion, and post-process (Gibson et al. 2010b). Components can be manufactured by AM in various types of materials including photoreactive resins, thermoplastics, metal alloys, composites, and graded multi-materials (Thijs et al. 2013, Gu et al. 2014, Liu et al. 2014). With advantages in fabricating products with superior performances that are difficult to be achieved by conventional manufacturing processes, AM technologies have greatly increased design freedom in product development (Gibson et al. 2010a). Design for additive manufacturing (DFAM) principles were summarized by Rosen (2014), who classified unique capabilities of AM into shape complexity, material complexity, hierarchical complexity, and functional complexity; while special AM design features such as cellular structures, topology optimized structures, and multi-material components were introduced as new design freedoms for products' performance enhancement. Maidin et al. (2012) constructed an AM design feature database which enabled users to gather and visualize information in the conceptual design stage. AM processes differ from each other in terms of stock material types, material bonding mechanism, and dimensional accuracies etc; and these characteristics need to be considered during product design (Nagel and Liou 2010). In the work of Vayre et al. (2012), a generic four-step AM feature design process was proposed, including initial shape generation, geometric parameters definition, parameter optimization, and manufacturability validation. Zimmer and Adam (2011) proposed a process independent method to define design rules using standard elements, specifying the elements' feasible attribute value ranges to ensure AM manufacturability.

Platform-based product family design is a strategy to provide product variety for satisfying customer needs in multiple niche markets, while at the same time limiting the cost by implementing commonality in design and manufacturing (Simpson et al. 2006). A product family consists of multiple product variants covering different markets, and a product platform is a common part shared by more than one product variant in the family (Pirmoradi et al. 2014). The concept of flexible platform was proposed in (Suh et al. 2007), where a platform was allowed to change over time in response to uncertainties of dynamic markets. In the work of Kashkoush and ElMaraghy (2014), three different hierarchical clusters were created to form three separate sets of product families, based on three similarity coefficients for assembly sequence, product commonality, and product demand.

Nanda et al. (2007) developed a knowledge management framework for product family design, which integrated the method of network bill of material, formal concept analysis, ontology, and an object-oriented database management system. Chen and Wei (1997) used object-oriented techniques in modeling fundamental geometric features and process knowledge, and created a framework to evaluate geometric features against process-specific design rules. In the work of Xue and Dong (1997), design and manufacturing features in injection molding were selected based on a coding system, followed by the fuzzy C-means (FCM) clustering method performed on the coded features. In the work of Liu and Rosen (2010), an old product's design features were modelled by ontology, and then a knowledge base composed of IF-THEN manufacturing rules was used to map new product design requirements to new AM process variables.

Methodologies in DFAM and product platform development have been extensively investigated respectively in literatures. However, few studies have been conducted to link these two research fields by applying AM capabilities in platform design to satisfy diversified customer needs and to achieve cost savings at the same time. This research aims to provide a design guideline in preliminary stages of additive manufactured product family development.

3 THE CONCEPT OF VARIABLE PRODUCT PLATFORMS

Conventionally a platform is considered identical across the product family. The same features and design variable values of a platform module are shared by all product variants. In conventional manufacturing processes, changes in product design will require changes in manufacturing processes such as fabricating a new mold or planning a new welding path, which result in an increase in production cost. This cost increase due to design changes, however, does not always occur in AM. The layer-by-layer manner of material fusion in AM makes it possible to fabricate components with different geometries or topologies by applying a similar manufacturing process strategy, i.e. sharing the same process platform. In addition, cost drivers in conventional manufacturing, such as mold fabrication, no longer exist in AM. Therefore the production cost may not be largely increased by changing the platform design. However, other cost increase due to platform design changes, such as manpower cost increase in product development stages, cannot be eliminated.

With AM technologies deployed for production, the product platform itself can be subject to design variations across different product variants in the family. In other words, product variants may share similar but not exactly the same platform modules. An additive manufactured platform module that is shared within a family but allows variations in different product variants is named a Variable Product Platform. An instance of a variable platform module on a particular product variant is defined correspondingly as a "platform variant". While achieving cost savings brought by design and process sharing, the application of variable platforms in product families may also in some extent compensate the product variant's performance lost compared with individually optimized design. Such a performance lost is one of the major disadvantages in conventional platform-based product family development (Moon et al. 2014).

With the implementation of AM techniques in production, a candidate variable platform module can be classified into two types: AM-platforms (to be fabricated by AM) and Non AM-platforms (to be fabricated by conventional processes). The above classification is based on three criteria:

1. Availability of AM design features.
   If the performance of a platform variant cannot be improved by implementing AM design features, the module is more reasonably fabricated using conventional manufacturing techniques which are usually cheaper.
2. Similarity between AM design features belonging to the platform's multiple variants.

If the AM design features applied to different platform variants are very dissimilar, the module may need to be re-evaluated to decide whether it should be treated as a unique module instead of a platform module, because each candidate platform variant needs to be designed and produced independently.

3. AM manufacturability.
   A platform module is classified as a Non AM-platform if its design requirements are not achievable due to the manufacturing constraints of available AM processes or machines.

The approach to assess the above three criteria is described in Section 4.

4 AM DESIGN FEATURE SELECTION FOR VARIABLE PRODUCT PLATFORMS

To apply DFAM principles to the design of variable platform modules, candidate AM design features are to be mapped to each platform variant's design requirements in its corresponding market segment, in order to utilize the design freedom provided by AM technologies. While at the same time, AM constraints also need to be identified in the design process to ensure manufacturability.

4.1 Object-oriented representation of AM design features and platform design requirements

AM design knowledge needs to be organized for the ease of searching and extraction. In this research, the object-oriented technique is used for design knowledge representation and management. In the proposed approach, AM design features and platform variant design requirements can be modelled as two "subclasses" inherited from the AM design knowledge "superclass". The Unified Modeling Language (UML) graphical representation is presented in Figure 1, where inherited attributes are not shown in subclasses' diagrams.

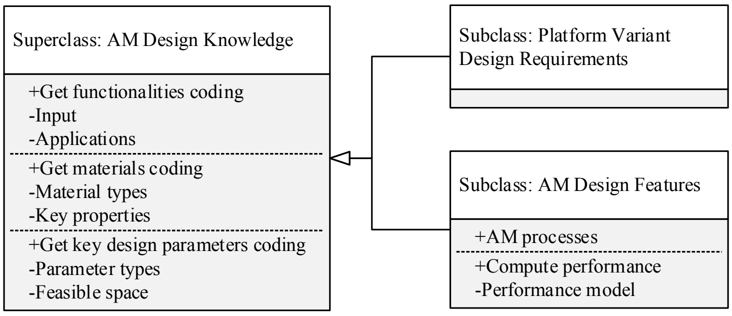


Figure 1. Object-oriented representation of AM design knowledge

All AM design features and platform variant design requirements consist of three categories or, defined in this research, three "dimensions" of knowledge:

1. The "Functionalities" dimension, including input types and applications of an AM design feature or a candidate platform variant module.
2. The "Materials" dimension, including material types and relevant key material properties most relevant to the application of an AM design feature or a platform variant module.
3. The "Key design parameters" dimension, including the types and feasible spaces of key design parameters in an AM design feature or a platform variant module.

4.2 Binary coding of AM design features and platform design requirements

Within the classes defined above, knowledge in all three dimensions is coded in binary vectors using a binary coding system, in which a "1" indicates "presence" while a "0" indicates "absence". The proposed approach allows different linguistic and parametric properties of design feature and design requirements to be unified in a dimensionless manner.

The proposed binary coding system is illustrated by coding a honeycomb structure, which is a AM design feature used for lightweight applications in automotive and aerospace (Rosen 2014). The coding in the "Functionalities" dimension is shown in Table 1. All applicable input types the intended applications of the AM design feature and the platform design requirements are coded by "1". For display purpose, this table is not complete, and the dots at the bottom indicate that more items are actually included in the coding system but omitted in Table 1 due to page limit.

Table 1. Binary coding in the "Functionalities" dimension

Functionalities			
Input	Code	Applications	Code
Electricity	0	Resist corrosion	0
Fluid flux	0	Damping	0
Surface traction	0	Cushioning	1
Impact load	1	Resist distortion	1
Static compression	1	Instant assembly	0
Static tension	0	Increase friction	0
Static torque	1	Fastener removal	0
Dynamic compression	1	Reduce weight	1
Dynamic tension . .	0 . .	Reduce compliance . .	1 . .

The coding of "material type" in the "Materials" dimension is linked to one or several available AM processes stored as an attribute in the "AM Design Features" class. For illustration, the binary coding of a honeycomb structure in the "Materials" dimension is shown in the Table 2. It is assumed that the available AM processes or machines owned by a particular manufacturer include selective laser melting (SLM), stereolithography (SLA), and fused deposition modeling (FDM). Again, Table 2 is not complete with items omitted due to page limit.

Table 2. Binary coding in the "Materials" dimension

Materials				
Material type - AM process		Code	Key properties	Code
Metal alloys	Ferrous – SLM	1	Oxidation rate	0
	Lightweight – SLM	1	Fatigue life	0
	Refractory – SLM	0	Bio-compatibility	0
	Superalloy – SLM	1	Impact toughness	1
	Biocompatible – SLM . .	0 . .	Wear rate	0
			Density	1
			Conductivity	0
			Hardness	1
Polymers	Elastic resin – SLA	0	Young's modulus	1
	Rigid resin – SLA	1	Tensile strength . .	1 . .
	ABS – FDM	1		
	PLA – FDM	1		
	Elastomeric – FDM/SLA . .	0 . .		

The coding of "feasible space" in the "Key design parameters" dimension is linked to the "material type" attribute in the "Materials" dimension. In other words, each set of binary codes in the "Materials" dimension has a corresponding set of binary codes in the "Key design parameters" dimension. As an illustration, Table 3 shows the binary coding a honeycomb structure in the "Key design parameters" dimension, corresponding to metal alloys processed by SLM machines. Again, Table 3 is not complete due to page limit.

Table 3. Binary coding in the "Key design parameters" dimension

Key design parameters			
Parameter type	Code	Feasible space (SI units)	Code
Clearance	0	<0.5 mm 0.5-1.0 mm . .	0 0 . .
Volume density	1	<10% 10-20% . .	1 1 . .
Cell size	1	<1.0 mm 1.0-5.0 mm . .	0 1 . .
Wall thickness . .	1 . .	<0.5 mm 0.5-1.0 mm . .	1 1 . .

It is noted that all AM design features and platform variants' design requirements share the same coding system; hence their binary vectors in the same dimension have the same length.

4.3 AM design feature selection using hierarchical agglomerative clustering

To satisfy customer needs in different market segments using additive manufactured variable platform modules, AM design features need to be mapped to each platform variant's design requirements. Such a mapping between design features to design requirements provides a design proposal at the early conceptual design stage. Designers can take the design proposal as a guide in the future detailed design stage.

Each AM design feature and platform variants' design requirements can be considered as a point located in a virtual three-dimensional space, defined in this paper as the Property Space: {[Functionalities], [Materials], [Key design parameters]}. Hierarchical agglomerative clustering is performed on points in the Property Space. In the proposed clustering process, Jaccard distance is used as the dissimilarity measure between any two binary vectors in each dimension. The Jaccard distance between binary vector A and B in the same dimension is calculated as

$$\mathrm{d_j(A,B)} = \frac{|\mathrm{A \cup B}| - |\mathrm{A \cap B}|}{|\mathrm{A \cup B}|} = \frac{\mathrm{J10+J01}}{\mathrm{J10+J01+J11}}, \quad \mathrm{d_j(A,B)} \in [0,1] \tag{1}$$

where J10 is the number of binary bits being 1 in A and 0 in B, J01 is the number of bits being 0 in A and 1 in B, and J11 is the number of bits being 1 in both A and B. When measuring the dissimilarity between two points P and Q in the virtual three-dimensional Property Space, the distance metric is the Euclidean distance calculated as

$$\mathrm{d(P,Q)} = \sqrt{\mathrm{d_j(F_P,F_Q)}^2 + \mathrm{d_j(M_P,M_Q)}^2 + \mathrm{d_j(D_P,D_Q)}^2}, \quad \mathrm{d(P,Q)} \in [0,\sqrt{3}] \tag{2}$$

where $\mathrm{d_j(F_P,F_Q)}$, $\mathrm{d_j(M_P,M_Q)}$, and $\mathrm{d_j(D_P,D_Q)}$ are the Jaccard distances between P and Q in the three dimensions [Functionality], [Materials], and [Key design parameters] respectively. In the proposed clustering process, the linkage criteria used to calculate inter-cluster distance is the Complete-Linkage, which is the distance between the most dissimilar members from two clusters. The Complete-Linkage S(C1, C2) between cluster C1 and C2 is formulated as

$$\mathrm{S(C1,C2)} = \max\{\mathrm{d(P^*,Q^*)}:\ \mathrm{P^*} \in \mathrm{C1},\ \mathrm{Q^*} \in \mathrm{C2}\} \tag{3}$$

Using the above metrics and linkage criterion, a typical algorithm of hierarchical agglomerative clustering can be described as (Abbas 2008):

1. Initialize: total number of points = N; cluster level L = 0.

2. Compute $\mathrm{d}(\mathrm{P},\mathrm{Q})$ between all (P, Q) and construct the proximity matrix.
3. Merge the most similar clusters with $\mathrm{S}(\mathrm{C1},\mathrm{C2})_{\mathrm{L}} = \max \mathrm{d}(\mathrm{P}^*,\mathrm{Q}^*)_{\mathrm{L}}$
4. Update the proximity matrix using $\mathrm{S}(\mathrm{C1},\mathrm{C2})_{\mathrm{L}}$ values
5. Update L = L+1.
6. Go to Step 2 until all points are contained in one cluster (i.e. L = N - 1).

Not all AM design features in the database are included in the clustering process. A screening process is carried out by matching the “material type” attribute in the “Materials” dimension of both the design feature and design requirements. If there is a match, the corresponding binary codes in “Functionalities” and “Key design parameters” dimensions are extracted and later used in Jaccard distance calculation. If there is no match, the design feature is excluded from the clustering process. Figure 2 illustrates the procedure of screening AM design features to be included in the clustering process, based on the object-oriented representation of design features and design requirements.

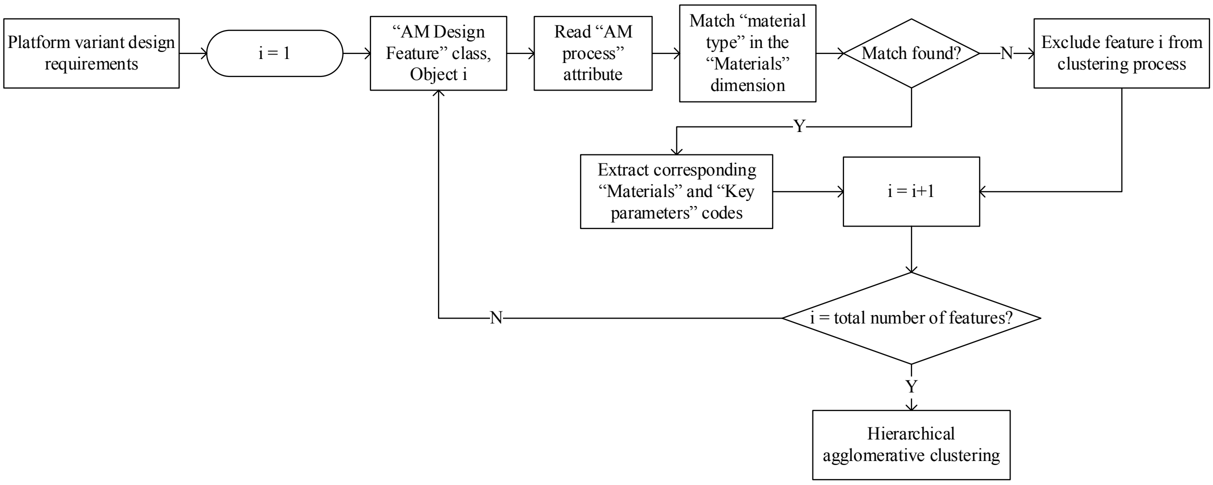


Figure 2. The procedure of screening design features to be clustered

The result of the hierarchical agglomerative clustering can be visualized in a cluster tree called dendrogram. An example is illustrated in Figure 3. The label “Rab” on the horizontal axis represents the design requirement of platform candidate a, variant b. The label “Fxx” represents an AM design feature in the database. Hierarchical clusters were linked by inverted “U” lines, whose heights indicate Complete-Linkage distance values. Clusters can be separated from the dendrogram by specifying a Complete-Linkage threshold or cut-off value. A dendrogram can be cut by designers based on their experience to form multiple clusters. For example, in Figure 3, the dendrogram is cut at 0.85, resulting in four distinct clusters {R11, R12, F05, F07, F06, F02}, {R21, R22, F04, F01}, {R31} and {R32}.

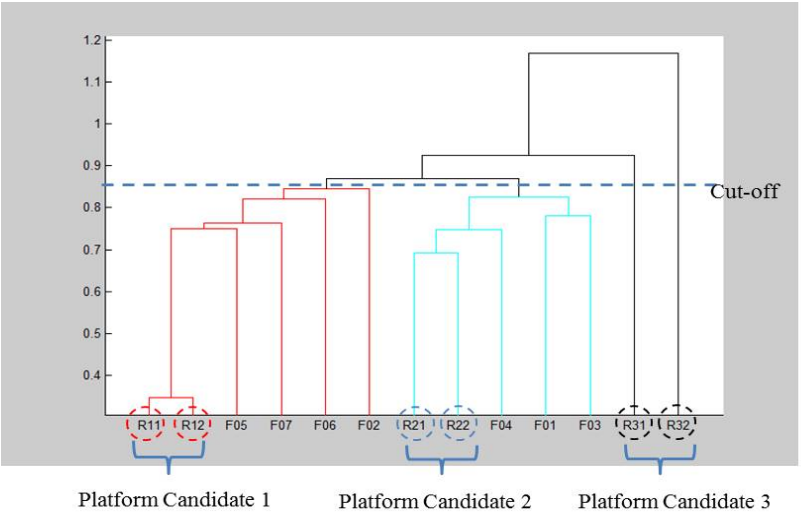


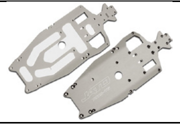
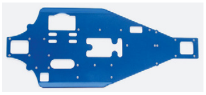
Figure 3. A dendrogram example showing hierarchical clustering result

The clustering result can be interpreted as: Platform Candidate 1 with variants R11 and R12 can be designed by implementing the same group of design features F05, F07, F06, and F02, which can be fabricated by AM techniques with expected performance improvement. Platform Candidate 2 with variant R21 and R22 can use the AM design features F04, F01, and F03. The platform variants R31 and R32 belonging to Platform Candidate 3 both have design requirements that are far apart from available AM design features; hence its performance improvement can hardly be achieved by re-designing using AM capabilities. The design requirements of R31 and R32 are significantly different; hence they may be also treated in the product design process as two unique modules instead of two variants of a candidate variable platform module. Other criteria, including cost-performance trade-off consideration and human designers' preferences, can be used to assist in deciding whether R31 and R32 should be platform or unique modules. These criteria are beyond the scope of the present study. Based on the above discussion, Platform Candidate 1 and 2 can now be classified as AM-platform modules. Jaccard distances between points can be accessed in each one of the [Functionalities], [Materials] and [Key design parameters] dimensions. As discussed in the previous section, a platform module is classified as a Non AM-platform due to three possible reasons: (1) there are no suitable AM design features, which can be indicated by a large distance in [Functionalities]; (2) AM design features of its platform variants are significantly different, also indicated by a large distance in the [Functionalities]; or (3) not manufacturable by AM, indicated by a large distance in [Materials] and/or [Key design parameters] dimensions.

5 CASE STUDY

To demonstrate the proposed approach, functional parts on nitro-powered R/C racing cars manufactured by Traxxas are to be re-designed using AM design features. Two market segments, i.e. "Stadium Truck" and "On-road Sedan" (Traxxas 2014), are identified with different design requirements. For simplicity, the present case study considers the re-design of individual components instead of multi-component modules. The chassis, bumper, and tire are chosen as candidate variable platforms, each of which consists of two platform variants in two market segments respectively. The current designs of the selected components are shown in Table 4 (Traxxas 2014).

Table 4. Current component designs of Traxxas nitro-powered R/C racing cars

	Chassis (R1x)	Bumper (R2x)	Tire (R3x)
Stadium Truck (Rx1)			
On-road Sedan (Rx2)			

Despite the fact that there are over hundreds of AM design features (Maidin et al. 2012), only sixteen features, as listed in Table 5, are included in this case study for demonstration purpose. They are represented by the proposed object-oriented modeling method, and stored in the database for retrieval.

Table 5. AM design feature list in the case study

F01	F02	F03	F04	F05	F06	F07	F08
Integrated living hinge	Threaded surface	Honeycomb	Hollow strut	Spiral structure	Weave structure	Curved tunnel	Integrated snap fit
F9	F10	F11	F12	F13	F14	F15	F16
Surface texture	Encapsulated bearing	Integrated socket	Topology optimized structure	Torus structure	Freeform surface	External rib	Internal rib

Hierarchical agglomerative clustering is performed on the design features and platform variant design requirements. The resultant dendrogram is illustrated in Figure 4.

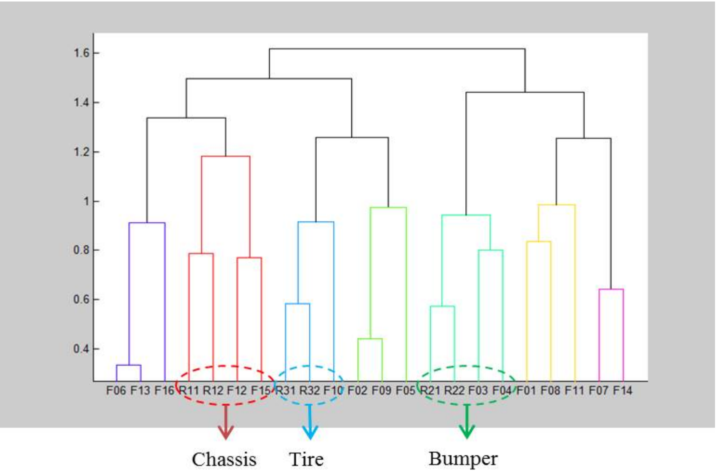


Figure 4. Hierarchical clustering result for nitro-power R/C racing platform variant design

The cut-off value is set at 1.2 to create seven clusters. The cluster {R11, R12, F12, F15} shows that the chassis of both stadium truck and on-road sedan can be re-designed by applying topology optimized structures and external ribs. Similarly, two other clusters {R21, R22, F03, F04} and {R31, R32, F10} indicate that the bumpers can be re-designed with honeycomb structures and hollow struts, and the tires can be re-designed with additive manufactured surface textures. In situations where databases of large numbers of coded AM design features (other than the sixteen feature examples in this case study) are given, the proposed methodology is capable of automatically suggesting applicable design features without the necessity for human designers to manually read and search the database. Therefore time and labor can be saved. Although the further detailed component design relies heavily on the designer's skill, experience, and design analysis in specialized engineering domains, the above clustering result provides a conceptual design proposal for additive manufactured platform modules. As an illustration, the bumper as a variable product platform re-designed with the above selected AM design features are shown in Figure 5, together with simulated deformation under impact.

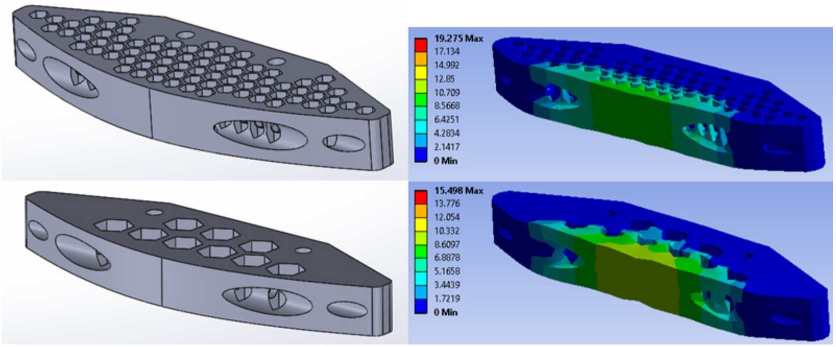


Figure 5. On-road sedan (upper) and stadium truck (lower) bumpers re-design with selected AM design features

6 CONCLUDING REMARKS

DFAM freedoms and constraints were incorporated into product platform design, aiming to meet diversified design requirements in multiple market segments. In this paper, we proposed the concept of a variable platform. An object-oriented technique is used for design knowledge representation. AM design features' attributes and platform variants' design requirements were coded. Hierarchical clusters were derived from the codes to provide a design proposal, which helps designers to explore AM-enabled design space at the conceptual design stage. However, the proposed AM feature selection process does not evaluate the effect of cost, which is an important factor in planning platform strategies. In future research, design and production cost of additive manufactured product families will be investigated. For each product platform in the design phase, a corresponding process platform also needs to be generated in the process planning phase.

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