Development of a Design Feature Database to Support Design for Additive Manufacturing

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Background: The use of Additive Manufacture (AM) in New Product Development (NPD) has increased over recent years. AM enables greater creativity in design, reduced tooling cost and faster product development time. However, there is a lack of available information to empower designers to take full advantage of AM. It is anticipated that the database will serve as a rich source of inspirational information for design practitioners and students.

Objective: This paper proposes the use of a 'design feature' database to aid practitioners and students when designing parts to be produced by AM.

Method: A taxonomy, comprising four categories was used as the framework for the design support tool. A database of design features was then created from a wide search of design for AM case studies. The value of the database was determined through w number of user trials.

Conclusion: The findings show positive feedback from the respondents where the database tool has enabled them to gain greater access to information when designing parts for AM.

Application: The subject of design for AM is relatively new and there is still a lack of information to assist users in the best approach when designing complex product features. The tool empowers design practitioners and students in the conceptual design process by serving as a collective source of information for design features produced by AM.

Keywords: Additive Manufacturing, Database, Taxonomy, Features

1. Introduction

Early additive manufacturing (AM) systems were unable to produce end-use products due to limitations in poor material properties, lack of Computer Aided Design (CAD) systems and unreliable system capabilities. As these deficiencies are overcome, it has beoame possible to make functional parts for final-use applications. Today, the use of AM has even greater potential to support the process of New Product Development (NPD). AM enables a creative design process with the advantage of faster product development time and consequential reduction in tooling cost. However, the lack of readily available design support tools results in parts that fail to take full advantage of the design freedom offered by AM. In addition, large amounts of design information generated during the design process such as the use of innovative features and novel geometry are not recorded, resulting in a potential loss of important design knowledge. This paper proposes a design support tool that will potentially aid design practitioners and students during the conceptual design of AM parts.

1.1 Previous Work

A range of tools to aid designers and practitioners when using AM systems have been proposed by previous research. The selection of the AM process was dependent on factors such as build envelope, accuracy, material, fabrication speed and other machine related parameters. Campbell and Bernie (1996) introduced a relational database system that focused on finding the most suitable combination of AM material and process. Jones and Campbell (1997) went on to utilise the use of Microsoft Access to develop a more systematic approach by employing the use of feedback to determine the performance and suitability of AM systems. Bibb et al. (1999) developed a computer-based design advice system that worked by using a knowledge base and an input inference engine. It also incorporated the use of CAD data as part of the AM selection process. The Industrial Research Institute Swinburne (IRIS) at Swinburne University in Australia also developed a system named the Intelligent RP System Selector (Masood and Soo, 2002), an rule-based expert system that assisted a user wanting to purchase an AM system. The main criteria for selection were based on price, dimensional accuracy, surface finish, maximum build volume, range of materials, range of layer thickness and speed of build. Lan et al. (2005) introduced a 'fuzzy' synthetic-evaluation method for ranking the use of AM processes based on quantitative data. It compared weighted factors such as technology, geometry, performance, economy and productivity. Similarly, Byun and Lee (2005) proposed an AM selection method by adopting a method of order preference, using attributes from the user to determine the suitability of AM technology for producing an end-use part. Going a step further, Rao and Padmanabhan (2007) employed AM process selection using a graph theory and matrix approach. Similar to other technology selectors, their system defined desirable attributes of an AM machine and used interrelations between the selection criteria and its relative importance, and then modelling the results in a graph and matrix. Munguia et al. (2008), depicted a more advanced computing-based system that utilised neural networks and fuzzy logic for the selection of AM systems according to two main specifications: general feasibility evaluation (fuzzy logic based) and cost estimation (neural network based). Their system was intended to support designers during the earlier design stage to assess the possibility of using

AM for production. Work by Kruf et al. (2006) centered on the design of AM parts that focused on material properties and reproducibility. Using 3D CAD software, an initial 3D model was created. Frozen elements and applied forces were defined and used as input for Computer Aided Optimisation (CAO) software. Within the CAO software, the soft kill option (removing non-efficient material) and finite element analysis analysis of the model were performed so as to obtain an optimal design. Other technical aids include those proposed by Ziemian and Crawn (2001) who developed a decision support tool for Fused Deposition Modelling systems to guide users for the most optimal build settings. Pandey et al. (2007) suggested that part deposition orientation is a major factor for AM as it effects build time, support structure, dimensional accuracy, surface finish and cost of the end product. From this, they proposed the automation of orientation selection to eliminate the operator's involvement and hence reduce possible errors.

1.2 Problem Statement

None of the knowledge-based tools above guide designers in the creative part of designing AM parts or products. They assume that a design already exists and might need modification or optimization for AM. It is suggested by the authors that a database of AM design features would serve as a knowledge repository to inspire conceptual design for AM (DfAM). A similar approach was proposed by Burton (2005) who suggested a questionnaire approach based on five areas of concern (production volume, part or product form, function, construction and logistics) to validate whether a part or product was suitable for AM. Responses to the questions would result in design suggestions being made, e.g. parts consolidation, multiple feature sizes. However, this method was time consuming as it was a largely manual process and the examples of design ideas were limited. The aim of this research was to develop a computerized system that compiled existing knowledge in a format appropriate for recommending suitable DfAM features during the concept design process.

2. Design Features and the Development of a Taxonomy

According to Salomons et al. (1993), a feature is a set of information that refers to aspects of form or other attributes such as reasoning about the design, performance and manufacture or assembly issues of a part. For this research, the term "AM-enabled design feature" refers to aspects of a product's form or other attributes that would be uneconomical or very expensive to be produced with conventional methods and thus would be better suited for use with AM. There exist in the literature many examples of AM design features that have been created for different reasons and with different outcomes. Therefore, a decision was made to explore and categorise this range of features to gain a better understanding of the design thinking behind them. This was supported by the view that innovative AM-enabled design features can be seen as an embodiment of designers' tacit knowledge about designing for AM. Organising these features into a systematic taxonomy was then a first step to making this knowledge accessible to other designers. A thorough search of literature, websites and personal contacts was made so as to gather the necessary information towards the development of this taxonomy. A total of 113 AM-enabled design features were identified that were uneconomical or expensive to be produced using conventional methods.

The term taxonomy is derived from taxis (arrangement) and nomos (study) (Ostergaard 2009). Taxonomy is defined as a study of arrangements and considered as a way of ordering complex phenomena so as to enable comparison (Shneiderman 1992). In order to achieve a satisfactory classification and clarity in the taxonomy, several iterations were produced. The taxonomy was first peer-validated by the authors and a pilot study was conducted by reviewing the details with nine Industrial Design postgraduate students (Maidin S., 2009). In line with Gershenson (1999), the taxonomy was reviewed with the aim of ensuring orthogonality, spanning, precision and usability. Orthogonality ensures that there is no overlap between the taxons; spanning ensures that the taxonomy covers as much relevant elements as possible; precision ensures that the taxonomy goes into sufficient detail; and usability ensures that the taxonomy can be clearly understood and usable. Following this iterative process, a final version of the taxonomy was developed with its top-level taxons being the four key reasons for using AM. These were user fit requirements, improve functionality requirements, parts consolidation requirements, and aesthetics requirements. These are described below.

2.1 User Fit Requirements

User fit requirements are when parts or products need to be customised to accommodate specific user shapes. User fit requirements have application areas in sport, medical and consumer products.

2.2 Improve Functionality Requirements

Product functionality requirements are when part or product functionality need to be improved by using AM enabled geometry. Improvements came from using four approaches, i.e. weight reduction, increased surface friction, internal structure and multiple product versions.

2.3 Consolidation Requirements

Consolidation requirements are when AM is needed to reduce the number of parts in an assembly. The consolidation can come from four approaches, i.e. instant assembly features (building parts in already assembled locations), fasteners removal features, multiple functional parts and dual material features.

2.4 Aesthetics Requirements

The aesthetic (or form) requirements are when AM-enabled features are needed to improve product appearance. This includes approaches such as embossed features, surface features, visual features and personalisation.

The number of features represented within each category is shown in Table 1.

Reasons for using AM	Application	Number of Design Features
User fit requirement	User Shape Features	4 Sports features, 9 Medical features 7 Consumer Product features
Improve functionality	Weight Reduction Features	7 design features
	Increase surface friction features	3 design features
	Internal structural features	8 design features
	Multiple version features	2 design features
Parts consolidation	Instant assembly features	20 design features
	Fasteners removal features	7 design features
	Multiple functional parts	3 design features
	Dual material features	1 design features
Aesthetics	Embossed features	3 design features
	Surface features	13 design features
	Visual features	3 design features
	Personalisation features	13 design features
	Total	113 design features

Table 1: Number of Design Features within the Taxonomy categories

3. Design for Additive Manufacturing (DfAM) Feature Database

A decision was taken to adopt the use of “industry standard” software so as to provide greater access to potential users. Microsoft Access was used as a platform to develop a DfAM design feature database. A series of forms was first created that would enable the user to search or browse through the feature categories. The user is asked 11 questions to elicit information that best describes the AM requirements of the part or product.

The selected answers are linked to information taken from the taxonomy. For example if a user selects the first option (need custom fitting for individual user), the ‘user shape features’ and ‘personalisation features’ categories are highlighted and the other taxons are disabled. Table 2 shows the list of 11 questions and the associated categories of features linked to them. Clicking on each of the enabled elements brings up further information about each feature in that category (an example is shown in Figure 1). In addition to a question-based approach, a search function is also available to enable users to find specific keywords in the database.

Profile Options	**Enabled Categories**	**Reasons for Using AM**
Does the product need custom fitting that conforms to an individual user?	User shape features & personalisation features	User fit requirement
Does the product need to be lightweight?	Weight reduction features	Improve functionality
Does the product need to be hand held?	Increase surface friction features & dual material features	
Does the product have a need for internal structures?	Internal structural features & instant assembly features	
Does the product benefit from being made available in a range of sizes or shapes to fit different users?	Multiple version features	
Will the product benefit from parts reduction?	Instant assembly features & fasteners removal features & multiple functions parts	Parts consolidation
Does the product need to be attached to other components?	Fasteners removal features	
Will the product benefit from having combined functions?	Multiple functions parts	
Does the product require an “over moulding” characteristic?	Dual material features	
Does the product need to be aesthetically pleasing?	Embossed features & surface features & visual features	Aesthetics
Are personalised shapes or geometry an important factor for the product?	Personalisation features	

Table 2: Results of Concept Profile Selection

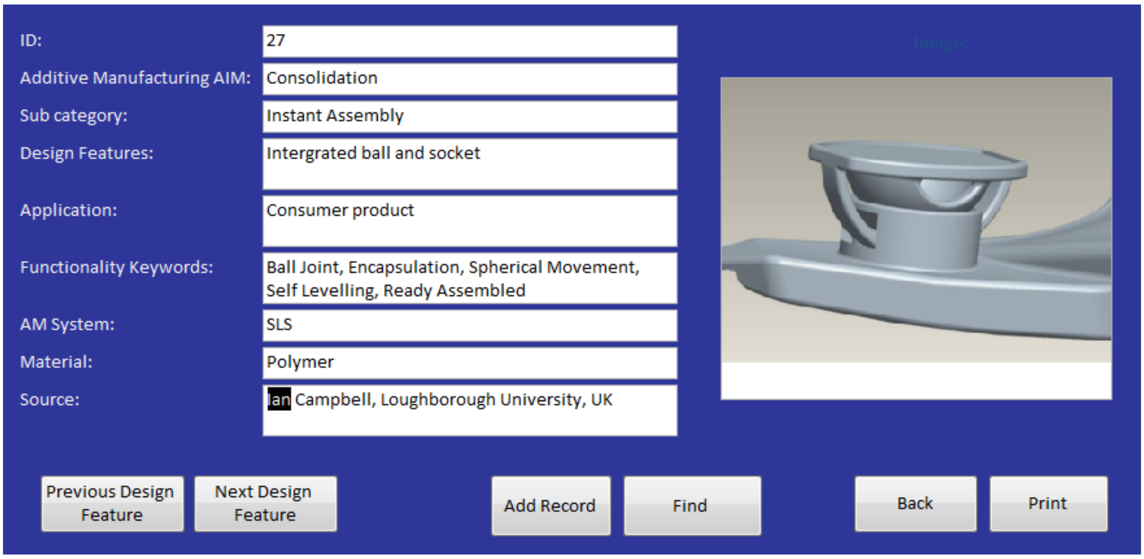


Figure 1: An example of a Parts Consolidation feature from the database

4. Student Designer Trial

The database was subjected to a series of trials in order to judge its effectiveness as a design tool and to gather feedback for further improvement. For the initial validation process, two groups of participants were involved, each comprising three final year undergraduates and one postgraduate. All eight students had sufficient exposure to product design and had previously used AM in their projects. Although the number of participants was small, the results of the trial still served to provide first-hand feedback on the tool's relevancy and effectiveness. The authors do not assign any statistical relevance to the results but maintain that they are a valuable qualitative guide to the feasibility of using the tool, particularly within an educational environment.

4.1 Method

The students were asked to sketch and redesign two familiar products, one when using the DfAM tool and the other without using it. Students 1 to 4 were given access to the database for their first sketching exercise and students 5 to 8 for their second sketching exercise. When not using the database, they were allowed to use the Internet to obtain ideas and to help them with the ideation process. Table 3 lists the products that were sketched during the validation process.

Student Participant	Product Sketched Using DfAM feature database	Product Sketched Without DfAM feature database (Website Access)
1	Table Lamp	Toy
2	Toy	Table Lamp
3	Chair	Computer mouse
4	Computer mouse	Chair
5	Salt Shaker	Kettle
6	USB Stick	Salt Shaker
7	Kettle	Ice-cream scoop
8	Ice-cream scoop	USB Stick

Table 3: Products that were sketched by the Student Designers

4.2 Sketch Results

Each student produced six sketches in total, as they had to develop three concept sketches using external sources such as websites and three concept sketches developed when using the database as an aid. The students were then asked to use peer review to select their best concepts (using the criteria of safety, usability, manufacturability, functionality, ergonomics, durability and aesthetics).

Figure 2 shows two examples of the selected concept sketches, without using the tool on the left and using the tool on the right. The salt shaker that was produced without the help of the DfAM feature database produced two AM-enabled features, i.e. an embossed feature for aesthetics and a snap fit feature that would open and close the lid. In contrast, the salt shaker that was developed with the aid of the DfAM feature database shows five AM-enabled features that were sourced from the database including a weave surface feature and a spiral element for enhanced aesthetics. A hand grip contour and over moulding feature for better ergonomics and a hook clip feature for improved functionality were also suggested. Figure 3 provides another typical example to show that more novel design features have been used by students when applying the DfAM tool. It shows the comparison of an ice-cream scoop sketched without and with using the DfAM feature database. The ice-cream scoop sketched without using the DfAM feature database shows fewer novel elements as compared to the one created when using the database, which generated a transparent feature to enhance its aesthetics, an over moulding feature for better ergonomics (both achieved through multi-material capability), a hollow structure to reduce weight, and an embossed pattern for brand imagery.

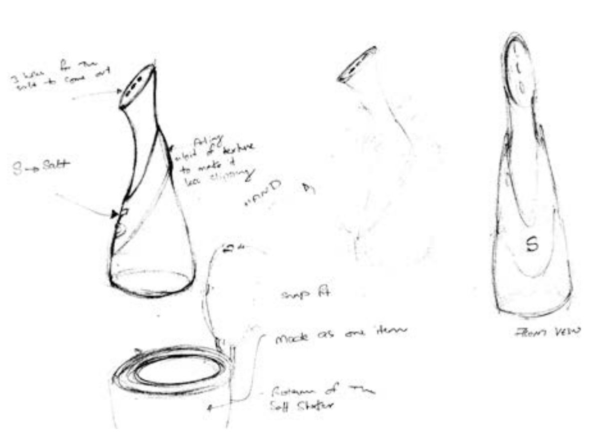
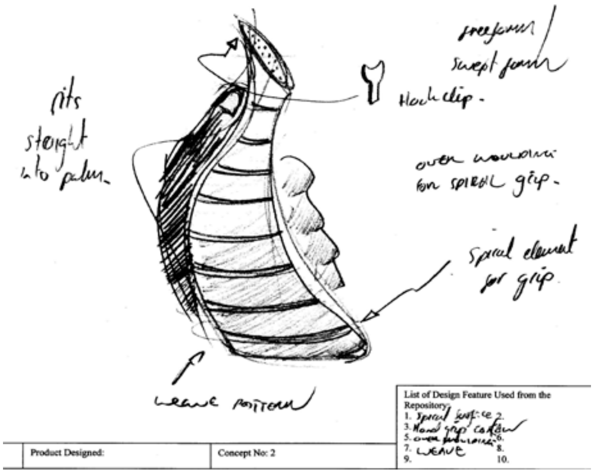
Without using DfAM feature database	Using DfAM feature database
	
Design features applied: 1. Embossed Feature 2. Snap fit feature	Design features applied: 1. Weave Surface Feature 2. Hock Clip Feature 3. Spiral Element 4. Over moulding feature 5. Hand grip contour

Figure 2: Comparison of the salt shaker designs

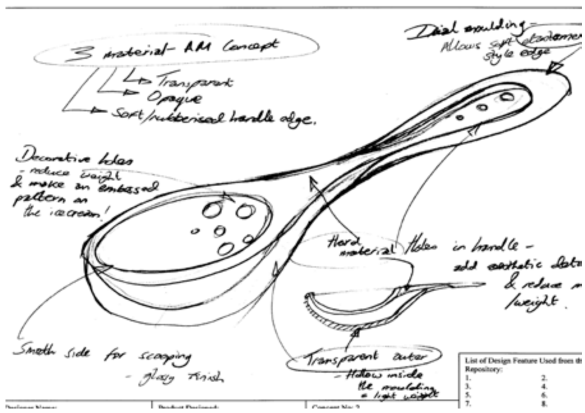
Without using DfAM feature database	Using DfAM feature database
	
Design features applied: Press in mechanism load and unload the ice cream	Design features applied: 1. Over moulding feature 2. Transparent feature 3. Hollow structure on the scoop 4. Embossed pattern on the scoop

Figure 3: Comparison of the ice cream scoop designs

By analysing and comparing all the sketches produced by the student designers when using the DfAM feature database, it was observed that the tool potentially provides ideas and suggests various features that can be incorporated into a product. The sketches show that students who used the DfAM tool were able to apply various design features from the database such as the variable wall thickness, living hinges, dual materials, internal structures and various surface features into their concept sketches. Table 4 shows the list of the features in the concept sketches that were generated with use of the DfAM feature database. This shows that all of the students were able to access the database and take inspiration from all of the thirteen feature categories, with the exception of multiple functional parts.

			Student Designers								
AM Reason	**Application**	**Design Features**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
User Fit Requirement	User Shape Features	Hand Grip Contour		x		x	x			x	4
Improve functionality requirement	Weight Reduction Features	Undercut Feature					x			x	2
		Thin Wall Feature		x		x					2
		Variable Wall Thickness	x	x			x			x	4
		Hollow Feature	x							x	2
		External Ribbing Feature		x							1
	Increase Surface Friction Features	Textured Surface Feature						x			1
		Circular Array Feature				x					1
		Honey Comb Feature					x				1
		Internal Shelving				x					1
	Internal structuring feature	Internal cable support	x								1
	Multiple Version Features	Customised Thread Feature			x						1
Consolidation Requirement	Instant Assemblies Features	Living Joint Feature			x					x	[illegible]
		Torus Feature			x						1
		Interconnected Feature			x						1
		Encapsulated Track & Ball		x							1
		Living Hinge Feature			x		x				2
		Integrated ball and socket			x						1
		Multiple link feature			x						1
		Encapsulated bearing		x	x						2
		Ball and socket feature								x	1
		Hook clip feature				x	x				2
		Slide opening & closing						x			1
		Snap fit hook	x								1
	Fasteners Removal Features	Hook clip				x	x				2
		Slide opening & closing						x			1
		Snap fit hook	x								1
	Dual materials	"Over Moulding"	x	x	x				x	x	7
Aesthetics or Form Requirement	Embossed Features	Embossed Alphabets	x			x	x		x	x	5
		Logo						x	x		2
	Surface Features	Weave Element					x				1
		Alphabet Element			x						1
		Spiral Element					x				1
		Overlapping Element	x						x		2
	Visual Features	Net Shadow Effect	x								1
		Transparent Feature				x	x	x	x	x	5
	Personalisation Features	Curve Feature					x				1
		Swept Feature					x			x	2
		Alphabet Feature						x			1
		Freeform geometry	x			x					2
		Floating Elements						x			1
		Replicated Element							x		1
		Bio- mimic feature			x						1

Table 4: Range of Features Used from the DfAM Feature Database

4.3 Student Questionnaire

After completing the design tasks, the eight student designers were given a questionnaire based on a 5-point Likert scale to gain further feedback concerning the usability, relevance, effectiveness and applicability of the feature database. The purpose was to find out their opinions about the tool's approach, overall functionality, the perceived benefits and whether it could be easily understood. The last question was open-ended that asked participants to leave suggestions for improvement. A summary of the responses is given below.

- all the students felt that the DfAM feature database was effective
- they all felt that the information provided in the database was clear and the search function had helped them to save time in searching for innovative features.
- all participants felt that the feature database was simple and easy to use.
- 7 of the students agreed that the pictorial data and textual content were clear and easy to understand whilst 1 student suggested that at the conceptual stage of design some features were not very useful, such as the internal structuring features
- 5 of the students felt the tool provided useful examples of design features that could be incorporated into their own work
- 1 student suggested that brief explanations of the sub categories of the design features should be considered
- 4 of the students felt the DfAM system provided an aid to understanding the design potential for AM products or parts whilst the others gave neutral responses
- 4 of the students agreed that the DfAM system had helped to increase their design creativity whilst the others gave neutral responses
- 7 of the students felt that their concept design had been influenced by using the DfAM feature database. The remaining response was neutral

Further suggestions for improving the database included having additional suggestions of the features that could be added to a specific product; increasing the number of examples in the database; incorporating videos to show how each design feature functions; adding information on materials and manufacturing processes that might be suitable for each feature; putting the database on-line via the Internet; and further enhancing the interactive aspects of the tool.

5. Professional Designer Trial

In addition to the student participants, a second round of validation was conducted with seven professional designers. The professional designers were experienced practitioners in the industry with substantial knowledge about the use of AM. Each of them had at least three years of working experience and had been involved extensively in new product development.

5.1 Method

The aim of the trial was to test whether the DfAM feature database would be relevant, effective and applicable for the needs of professional designers. The designers had to create three conceptual designs for a product of their choice with potential for manufacture using AM. The products chosen by the designers were rather diverse, namely a computer mouse, a sensor, an ear thermometer, a watch bracket, an electric fan, a chair and a flashlight/mini fan.

5.2 Results

Once again, all of the designers were able to incorporate some of the feature ideas from the database into their design concepts (see figures 4 and 5 for two examples of this). The range of features applied are summarised in Table 5. The list shows that the designers applied features from all 13 feature categories from the DfAM database.

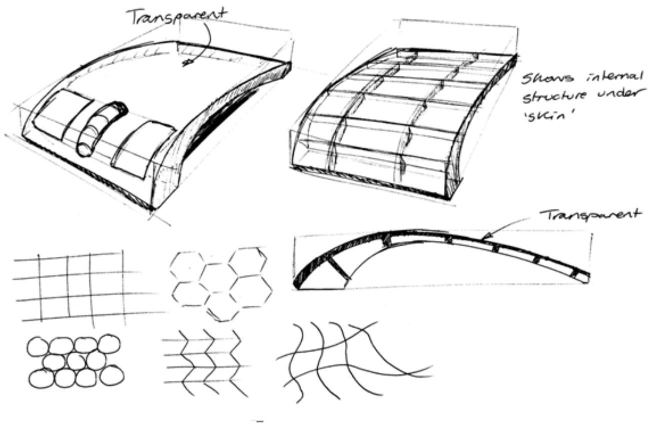


Figure 4: Concept of Computer Mouse Sketched by Designer 1

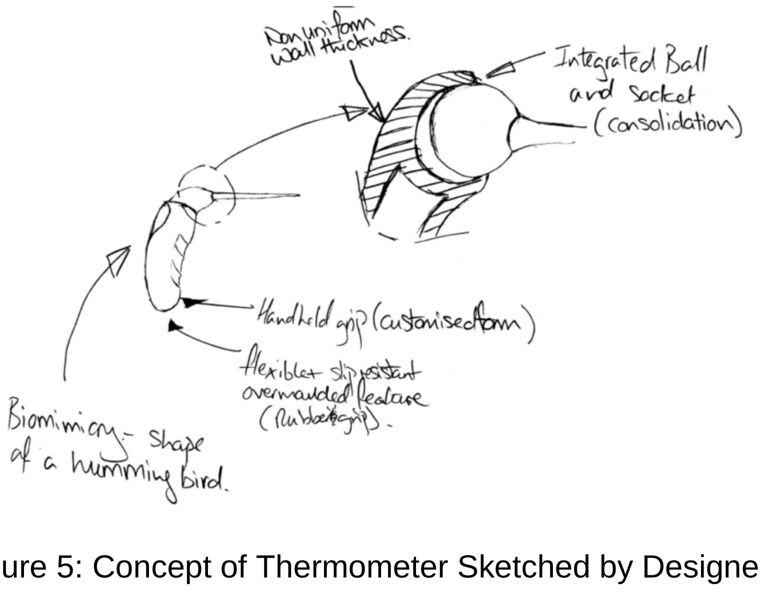


Figure 5: Concept of Thermometer Sketched by Designer 3

			Professional Designers							
AM Reason	**Application**	**Design Features**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**Total**
User Fit Requirement	User Shape Features	Hand Grip Contour			**x**				**x**	**2**
Improve functionality requirement	Weight Reduction Features	Thin Wall Feature							**x**	**1**
		Variable Wall Thickness Feature	**x**		**x**					**2**
		Internal selective reinforce feature	**x**				**x**	**x**		**3**
		Hollow Feature				**x**				**1**
	Increase Surface Friction Features	Textured Surface Feature				**x**				**1**
		Circular Array Feature	**x**					**x**		**2**
		Honey Comb Feature	**x**							**1**
	Internal structuring feature	Internal cable support		**x**						**1**
		Internal shelving		**x**			**x**			**2**
	Multiple version feature	Size variations				**x**				**1**
Consolidation Requirement	Instant Assemblies Features	Living Hinge Feature				**x**	**x**			**2**
		Integrated ball and socket feature			**x**					**1**
		Internal Hinge Button Feature	**x**		**x**					**2**
		Enclosed Volume Feature	**x**							**1**
	Fasteners Removal Features	Internal cable support			**x**		**x**			**2**
		Mounting Boss Feature	**x**	**x**	**x**					**3**
		Snap fit cap		**x**						**1**
	Multiple Functional Part	Multiple Elements							**x**	**1**
	Dual materials	Over Moulding	**x**		**x**					**2**
Aesthetics or Form Requirement	Embossed Features	Embossed Alphabets				**x**	**x**			**2**
	Surface feature	Double Mesh Feature			**x**					**1**
		Fingerprint Feature							**x**	**1**
		Perforated Feature			**x**		**x**			**2**
	Visual Features	Transparent Feature	**x**					**x**	**x**	**3**
	Personalised feature	Replicated Element					**x**			**1**
		Bio- mimic feature			**x**					**1**

Table 5: Range of Features Used by the Professional Designers

5.3.2 Professional Designers Questionnaire Feedback

The professional designers were asked to complete the same questionnaire as before and the responses are summarized below.

- 3 of the designers felt that the DfAM feature database was generally effective whilst the other 4 gave neutral responses
- 3 designers agreed that the pictorial data and textual content of the DfAM system database was clear and easy to understand, 1 designer felt that there should be a larger library of images, and the other 3 gave neutral responses.
- 4 designers felt that providing examples of design features that could be incorporated into their design work was a good approach whilst the other 3 gave neutral responses.
- 5 designers felt that the DfAM feature database was helpful for them to incorporate novel design features into their design whilst 1 designer found that the feature database was not helpful as he felt that he already had sufficient experience and knowledge in designing for AM but commented that the tool would be more useful to a less-experienced designer
- 5 designers felt that the database provided an aid towards greater understanding for use of AM for products or parts whilst 1 designer found that the database did not provide this benefit due to his level of experience and knowledge.
- 6 designers agreed that the tool helped to enhance their design creativity
- 4 four designers felt that their concept design was influenced when using the DfAM feature database

These responses, although not as positive as from the students, still indicate that the database was generally felt to be easy to use and influential during the design process. Other suggestions that were noted included adding information concerning dimensions to the geometry features in the library; improving the interface of the database; further investigating how different features are described or identified by different users; allowing designers access to all the features at once; providing information on cost or economic justification; and providing information on materials and surface finish.

6. Conclusions and Future Work

Through analysing and comparing the sketches produced by the student designers when using the DfAM feature database, it can be identified that the DfAM tool provided ideas and suggested features that they incorporated into their product design. Together with the questionnaire feedback, the results provide evidence that the AM feature database has been inspirational, useful, relevant and helpful to support the conceptual design of parts and products. The database was of particular benefit to student designers with no recorded negative comments. However, its usefulness to experienced professional designers is less evident, although an overall positive response was still received. From the user trial results, it can be concluded that the proposed tool would be more effective at an educational level or for less experienced graduate designers.

As AM becomes more widely used, it is anticipated that new design features will emerge and these should be included in future versions of the database. Several suggestions to aid towards greater functionality of the database include the ability to view the features in 3D, and to publish the database on the Internet for greater accessibility. In addition, further work would include allowing users to upload their own design features into the relevant categories of the database. This too would be best achieved through an Internet version of the database.

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