

# Evaluating Design Complexity of CAD Models for FDM of Additive Manufacturing using Artificial Intelligence

Abhilasha Singh  
Department of Fashion Technology  
National Institute of Fashion  
Technology  
Patna, India  
abhilasha.abhilasha@nift.ac.in

Dr. Prabir Jana  
Department of Fashion Technology  
National Institute of Fashion  
Technology  
New Delhi, India  
prabir.jana@nift.ac.in

Dr. Deepak Panghal  
Department of Fashion Technology  
National Institute of Fashion  
Technology  
New Delhi, India  
deepak.panghal@nift.ac.in

**Abstract**—With the advantage of freedom of complexity in additive manufacturing come the limitations of fused deposition modeling. Conventional methods like machining do not handle complexity well. For creating parts with complicated or intricate features like undercuts, internal culling, or hollowed-out 3d surfaces, additional tools and setups are required which add to the production cost, and time and make the process complex. Additive manufacturing on the other hand works on the principle of slicing the objects into layers and hence no matter what the shape of the outline the nozzle or the machine head moves on the same plane. Hence the complexity of the object does not affect the complexity of production in additive manufacturing comprehensive research is required to objectively measure the complexity of an object. It can help in concluding whether the design is leveraging the benefit of “Complexity is free” of the fused deposition modeling technique of additive manufacturing technology. The objective of this research paper is to develop a framework for evaluating the complexity of CAD Models for FDM of Additive Manufacturing using AI. The objective is further broken down into two sub objectives: 1) To develop a framework for evaluating the design complexity of CAD Models for FDM of Additive Manufacturing using manual method. 2) To automate and validate the manual scoring system by rule based artificial intelligence approach. Framework has been developed for both manual and automated system. Finally, a comprehensive analysis and validation has been done to check the accuracy and robustness of the AI system.

**Keywords**—additive manufacturing, fused deposition modeling, CAD modeling, shape complexity

## I. INTRODUCTION

Additive manufacturing offers many advantages over conventional manufacturing methods. The authors of the book Fabricated, Hod Lipson and Melba Kurman have listed the advantages in an interesting way as the ten principles of 3D printing. These are: Manufacturing complexity is free, Variety is free, No assembly required, Zero lead time, Unlimited design space, Zero skill manufacturing, Compact, portable manufacturing, Less waste by-product, Infinite shades of materials, Precise physical replication. [1] The first point itself states that the complexity of the design does not impact the manufacturing cost when additive manufacturing is concerned. Although Additive manufacturing offers the freedom of design complexity, the technique of fused deposition modeling has its limitations. So there is a need to critically evaluate the complexity of the design as well as the feasibility of it. [2]

As product innovation increases with the increase in competition in the market, the level of complexity of the

products has reached new heights. Conventional methods like machining do not handle complexity well. For creating parts with complicated or intricate features like undercuts, internal culling, or hollowed-out 3d surfaces, additional tools and setups are required which add to the production cost, time and makes the process complex. Additive manufacturing on other hand workd on the principle of slicing the objects into layers and hence no matter what is the shape of the outline the nozzle or the machine head moves on the same plane. Hence the complexity of the object does not affect the complexity of production in additive manufacturing.

3D printing technology is emerging as a solution to the above-mentioned concerns. 3D printing is a form of additive manufacturing (AM) technology where the process of joining materials takes place to make objects from three-dimensional (3D) model data, usually layer by layer. Three-dimensional objects are created by laying down successive layers of material. It is a mechanized method whereby 3D objects are quickly made on a reasonably sized machine connected to a computer containing blueprints for the object. 3D printing can support customized product manufacturing in less time and cost and with a high precision rate.

There are several technologies under the umbrella of additive manufacturing, seven to be precise as per the classification by ASTM. Fused Deposition Modeling (FDM) is one of them. In this technology, any compatible plastic polymers such as Polylactic acid, Acrylonitrile butadiene styrene, Nylon, Onyx, etc are used as raw material in the form of the filament. The heating element in the printhead melts the filament and extrudes through the nozzle. The material is deposited on the build plate layer by layer to form the object as per the gcode of the CAD design fed into the machine.

## II. LITERATURE REVIEW

Additive manufacturing is an industrial manufacturing ASTM technique in which a three-dimensional object is created by adding materials in layers in such a way that they are bound together by fusing or solidifying the material to achieve the desired design output. Additive manufacturing can refer to the umbrella term which includes 3D Printing technologies like VAT Photo polymerization, Material Jetting, Binder jetting, Material

Extrusion, Powder Bed Fusion, Sheet Lamination, Directed Energy Deposition. (ISO/ASTM, 2015)

The concept of 3d printing also referred to as additive manufacturing (AM), rapid prototyping (RP) was developed by Charles hull with a B.S in engineering physics from the university Colorado, hull started work on fabricating plastic device from photopolymers in early 1980s at ultraviolet products in California. Nearly 30 years have been elapsed since the 3d printing technology has emerged in to manufacturing industry. Initially, it was primarily used for prototyping purpose and hence, it was well known by its name rapid prototyping (RP). However, as the technology continued developing and gaining interests from many stakeholders, its application also started to cover a wide span of manufacturing process, including the actual component manufacturing. (3D Printing Industry, 2017)

Additive manufacturing (AM) has found its application in almost every field(Gibson et al., 2015). In an attempt to adopt and adapt to Industry 4.0, manufacturers seem very inclined towards switching to advanced manufacturing techniques like AM from conventional techniques. AM offers several benefits over conventional techniques. The authors of the bestseller book Fabricated, Hod Lipson and Melba Kurman summarises AM into ten principles: 1) Manufacturing complexity is free, 2) Variety is free, 3) No assembly required, 4) Zero lead time, 5) Unlimited design space, 6) Zero skill manufacturing 7) Compact, portable manufacturing, 8) Less waste by-product, 9) Infinite shades of materials and 10) Precise physical replication. These principles are the foundation of identifying AM potentials (Lipson and Kurman, 2018).

Noted authors in the field of AM, Prof. Ian Gibson, David Rosen and Brent Stucker list down several benefits of this technology, based on What You See Is What You Build (WYSIWYB). The approach according to them on the similar lines of What You See Is What You Get (WYSIWYG) approach of 3D CAD. Also known by other popular names such as Direct Digital Manufacturing, Rapid prototyping, 3D Printing, AM simplifies the multistage and multi-resource processes of the traditional method (Gibson et al., 2021).

This technique has been existing since a long time when rapid prototyping was the objective to visualise the design and functions beforehand. In recent times it is being used to fabricate end use products as well like aircraft parts, medical implants, fashion products and lot more. Additive manufacturing proves to be advantageous over subtractive manufacturing as it provides greater design flexibility, lower cost for making small volume of products, easy modifications etc.

The ASTM (F42 – additive manufacturing) has defined seven distinctive categories for 3D printing: (ASTMF2792, 2015)

1. Vat Photo-polymerisation
2. Material Jetting
3. Binder Jetting
4. Material Extrusion
5. Powder Bed Fusion
6. Sheet Lamination

## 7. Direct Energy Deposition

Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) falls under the category of Material Extrusion. FDM or FFF is the most cost effective and convenient technique of Additive Manufacturing. FDM offers a range of economic, low-powered desktop 3D printers for the users. More economic printers like Creality are used by the hobbyists to create décor items, collectibles, sculptures, games etc. Medium ranged printers like Ultimaker offer more accuracy and hence used for light industrial work while high end printers like Markforged offers more advance materials with enhanced properties and are used mainly for producing spare parts. Nonetheless, FDM has proven to be the most cost effective and convenient type of 3D Printing method and hence it is the most popular among the seven Additive Manufacturing techniques.

Author Ian Gibson and his fellow authors in their book Additive Manufacturing Technologies, lists down the steps of additive manufacturing : (Ian Gibson, 2010)

Step1: Conceptualization and CAD

Step 2: Conversion to STL

Step 3: Transfer to AM Machine and STL file

Manipulation

Step 4: Machine Setup

Step 5: Build

Step 6: Removal and Cleanup

Step 7: Post-process

Step 8: Application

Creating the CAD design is the most important in the entire 3D printing process that will heavily influence the printed result. A lot of thought process and engineering goes inside the creation of a CAD file. It is the outcome of the amalgamation of the idea of the designer, requirements of the consumer or the use of the product, availability of the raw material and limitations of the technology available as well as the cost and time. The functionality of the object should be achieved keeping in mind the technological limitation that might come during the manufacturing of the object. Additive manufacturing gives the freedom of complexity of geometry. Unlike machining or other traditional methods of manufacturing, no additional cost is incurred with increase in the complexity of geometry as the product is build layer by layer in additive manufacturing.

Many researchers have attempted to develop frameworks and methodologies to measure the complexity of models objectively. One such framework given by Globa et al, 2016 where the researchers have attempted to describe the step by step methodology of measuring the complexity of a model. Apart from using the shape grammar methodology they have also considered the metric complexity divided into categories geometric, combinatorial and spatial categories. The complexity of geometry has been categorised in 7 types which has further been broken into elements. Various elements like points, lines, shapes, transformation, arithmetic, colour etc were allotted points and the aggregate was used to find the overall complexity of the model. (Globa, 2016)

Jarek Rosignac has divided the complexity of a model into five categories- Algebraic, topological, morphological, combinatorial and representational complexity. Algebraic complexity depicts the degree of combination of primitive shapes through various Boolean operations by altering the dimensions, positions, orientation etc by the user. This representation is called Constructive Solid Geometry (CSG). More number of operations lead to more degrees of polynomial hence more complexity. Topological complexity describes the irregular, singular geometry on the surface which are often not a part of the outline or boundary or a part of the shape itself. This representation is called Selective Geometric Complex representation (SGC). Morphological complexity basically measures the smaller features and the size of the features. This type of complexity reduces when the smoothness is increased by increasing the maximum curvature at the edges. Combinatorial complexity is the measure of the vertices in the polygonal meshes of the model. Representational complexity refers to the ease of use of data representation of the model and making it simpler and compressed. (Rosignac, 2005)

While introducing the concept of feature shape complexity in their paper, Soonjo Kwon and his fellow researchers stated that it is a quantitative value representing the complexity of the shape of each feature comprising a model. The complexity is further categorised into volume and element complexity. The importance of features is determining the sum total of these two types of complexities. In the boundary volume complexity only additive features are considered while ignoring the subtractive features so that the original shape of the object can be preserved as much as possible. The relative volume complexity is the ratio of the relative volume of all the features comprising the original model and considers both subtractive and additive features. Elemental complexity can be broken down into surface complexity and curve complexity. Curve complexity was scored double than that of surface complexity. (Han, 2016). Sophia Psarra and her fellow researcher, have attempted to describe shape and shape complexity using local properties. They have described shape as perimeter configuration and also as a concept of stability and differentiation. (Psarra & Grajewski, 2001)

Pradel et al have used Shape Complexity Index (SCI) to determine the complexity of an object. They have considered design complexity with respect to fused deposition modeling technique. SCI is defined by the researchers as the ratio between the surface area of the component and the volume of the envelop space between the functional surfaces which in turn is the space between the two functional surfaces of the component. (Pradel, et al., 2017). In yet another attempt to measure the design complexity with respect to fused deposition modelling, researchers Nishkal George and Bopanna Chowdary has divided design features that might impact FDM into five factors- Wall thickness, number of ribs, external fillet, internal fillet and rib height. Each factor was measured based on three levels. (Chowdary, 2020)

Although many researches have been conducted to find out the shape complexity of an object, a comprehensive research is required to objectively measure the complexity of an object. It can help in coming to the conclusion whether the design is leveraging the benefit of “Complexity is free” of the fused deposition modeling technique of additive manufacturing technology. This paper proposes a framework to evaluate the design complexity keeping FDM in perview.

#### A. Objective

Objective of this research paper are:

1) To develop a framework for evaluating the design complexity of CAD Models for FDM of Additive Manufacturing using manual method.

2) To automate and validate the manual scoring system by rule based artificial intelligence approach.

### III. METHODOLOGY – OBJECTIVE ONE

The methodology adopted for achieving the first objective ie “To develop a framework for evaluating the design complexity of CAD Models for FDM of Additive Manufacturing using manual method” is as follows:

Step 1: Identification of the parameters that contribute to the complexity of the object

Step 2: Identification of the sub factors in each factor identified in step 1

Step 3: Assigning the scores to the elements identified in step 2

Step 4: Identification of design features that pose limitation to FDM

Step 5: Assigning scores to the design features identified in step 4

Step 6: Calculating the final score by adding the score obtained in step 5 to the score obtained in step 3

Step 7: Categorising the complexity level based on the score ranges

*Step 1: Identification of the parameters that contribute to the complexity of the object*

The parameters that contribute to the complexity are identified based on various tools that used to create a CAD model. On studying the literature and various CAD modeling software (Solidworks, Fusion 360, Creo, Blender) the following parameters were identified: Geometric complexity, Dimensional complexity, Shape grammars, Transformations, Number of elements, Shape of elements, Colour and Symmetry

Geometric Complexity defines the the overall shape of the object and the elements used to create the shape. Dimensional complexity determines whether the spacial existance of the object. Shape grammar is the boolean operations done of the object to achieve the shape. Transformation is altering the dimension or the position of the object or the element with respect to the originally placed object or element. Number of elements states the number of components present in the object. Shape of the elements that are used to create the oobject. Colour of the

object or the component of the object is added by choosing the material or by rendering. Symmetry of the object can be achieved during CAD if the design permits.

*Step 2: Identification of the elements in each factor identified in step 1*

The identification of the parameters is followed by identification of sub factors in each factor. The factors identified are listed below:

- a) Geometric complexity- Points, Lines, Curves, Planes, Surfaces, Solids
- b) Dimensional complexity- 2D composition, 3D Composition
- c) Shape grammars – Addition, Subtraction, Cull
- d) Transformations – Scale, rotation, reflection, deformation, translation
- e) Number of elements – one element, 2-10 elements, multiple elements (one type), Multiple elements (“N” types)
- f) Shape of elements- standards and primitive, non-standard simple shapes, complex shapes
- g) Colour- No colour, one colour, multiple colours, colour gradient
- h) Symmetry – symmetrical, non-symmetrical

*Step 3: Assigning the scores to the elements identified in step 2*

Scores from 0-5 are assigned based on simplicity or the complexity of the sub-factors.

| Parameters                    | Sub parameters                  | Alloted     |
|-------------------------------|---------------------------------|-------------|
| Geometric Complexity          | Points                          | 0           |
|                               | Lines                           | 1           |
|                               | Curves                          | 2           |
|                               | Planes                          | 3           |
|                               | Surfaces                        | 4           |
|                               | Solids                          | 5           |
| Dimensional Complexity        | 2D Composition                  | 0           |
|                               | 3D Composition                  | 2           |
| Shape Grammars                | Addition                        | 0           |
|                               | Subtraction                     | 1           |
|                               | Cull                            | 2           |
| Transformations               | Scale                           | 1           |
|                               | Rotation                        | 1           |
|                               | Reflection                      | 1           |
|                               | Deformation                     | 1           |
|                               | Translation                     | 1           |
|                               | Number of Elements (Components) | One Element |
| 2-10 elements                 |                                 | 1           |
| Multiple elements (one type)  |                                 | 2           |
| Multiple elements (“N” Types) |                                 | N+1         |
| Shape of Element              | Standards and Primitives        | 0           |
|                               | Non-standard simple shapes      | 1           |

|          |                  |   |
|----------|------------------|---|
|          | Complex shapes   | 2 |
| Colour   | No colour        | 0 |
|          | One colour       | 1 |
|          | Multiple colours | 2 |
|          | Colour gradient  | 3 |
| Symmetry | Symmetric        | 1 |
|          | Non symmetric    | 2 |

*Step 4: Identification of design features that pose limitation to FDM*

There are certain limitations with additive manufacturing when it comes to the small features in the geometry. There are two types of small features: Positive small features – extruded features like horizontal and vertical walls, pins etc; Negative small features like holes, screw threads etc.

The actual CAD model and the printed product might vary in dimension hence we need to add tolerance. There is a minimum required dimension that should be taken while designing small features in the model. Lesser the number of small features, the design will be more accurate as the CAD model. (Diegel, 2020)

The features identified are: Vertical wall thickness, horizontal walls, support material overhang angle, horizontal holes, clearance between support and moving parts, Vertical circular holes, circular pins and screw threads.

*Step 5: Assigning scores to the design features identified in step 4*

The features identified which have a great impact on the modeled for FDM as they are limiting factors are assigned scores based on the Design for Additive Manufacturing guidelines given by ASTM and the researchers. The standards are as per the factors. Absence of limiting feature gains 1 point.

| Features                                   | Standard                   | Score( 1 or 0) |
|--|----------------------------|----------------|
| Vertical wall thickness                    | 1 mm min                   |                |
| Horizontal walls                           | 4 layers min (4 mm)        |                |
| Support material overhang angle            | 45 degree max              |                |
| Horizontal holes                           | should be teardrop         |                |
| Clearance between support and moving parts | 0.5 mm min                 |                |
| Vertical circular holes                    | undersize tolerance 0.2 mm |                |
| Circular pins                              | min diameter 2 mm          |                |
| Screw threads                              | min diameter 5 mm          |                |

*Step 6: Calculating the final score by adding the score obtained in step 5 to the score obtained in step 3*

It has been established that higher the complexity greater the advantage of additive manufacturing is leveraged as compared to manufacturing by conventional methods. At the same time the limitations in FDM printers can dilute that advantage. It can be safely said that there is no absolute

freedom of complexity in FDM. The freedom varies with the presence of small features which can be difficult to print by FDM technique. Hence the positive points earned due to advantages get mitigated by the limitations. In this step the effective score of the complexity of the model is determined by subtracting the score of the limiting factors from the score earned by the complex shape factors.

*Step 7: Categorising the complexity level based on the score ranges*

The final step categorises the complexity levels based on the score range matrix.

|              |         |              |
|--------------|---------|--------------|
| First Group  | 0-49    | Most simple  |
| Second Group | 50-149  | Simple       |
| Third Group  | 150-199 | Medium       |
| Fourth Group | 200-249 | Complex      |
| Fifth Group  | 250-500 | Most complex |

IV. METHODOLOGY – OBJECTIVE TWO

To achieve the second objective ie “To automate and validate the manual scoring system by rule based artificial intelligence approach” Rule- based AI- assisted complexity evaluation is used. The process involves the development of a python based scoring system engine. This scoring engine geometry parsing, symmetry analysis and feature detection of STL models to replicate the complexity evaluation of CAD models by manual process. This can be done in following steps:

- Step 1: CAD File Processing
- Step 2: Shape Element Identification
- Step 3: Symmetry Detection
- Step 4: Colour Analysis
- Step 5: Evaluation of Limiting Features
- Step 6: Rule Based Scoring
- Step 7: Validation

*Step1: CAD File Processing*

The CAD model is input by the user and are exported as STL or Standard Tessellation Language files. This file is analysed or parsed using the trimesh, numpy-stl and cadquery libraries in python to extract the following geometrical aspects of the model:

- a) Number of surfaces and meshes
- b) Geometric features (vertices, edges and faces)
- c) Dimensions and bounding box
- d) Surface area and volume

*Step 2: Shape Element Identification*

The shape primitives are identified using feature extraction logic. These shape primitives are as follows:

- a) Curves and straight lines – These are identified based on face curvature and normal vectors.
- b) Complex and simple surfaces- These are identified based on mesh density and variation of density

- c) Element count and diversity- These are identified based on grouping of connected faces

*Step 3: Symmetry Detection*

Detection of symmetry is done by reflecting of STL mesh along X, Y and Z axis. Symmetry is then compared with the original geometry using root mean square deviation (RMSD) or Euclidean point-cloud comparison.

*Step 4: Colour Analysis*

Colour analysis is performed incase the object is to be made of coloured material. Files like 3MF and OBJ contains the material colour attributes of the models. If these types of files are exported, colour parsing is done to classify the following:

- a) Monochrome
- b) Multicolour
- c) Gradient – this can be detected via HSV variation across regions.

*Step 5: Evaluation of Limiting Features*

Predefined heuristics are fed to the AI model for evaluating the limiting features of the CAD model. Based on Design for Additive Manufacturing (DfAM) guidelines, the rules are provided in the algorithm. The system checks the parameters like wall thickness, hole dimensions, and overhang angles against standard FDM printability guidelines using mesh slicing and geometric queries.

*Step 6: Rule- Based Scoring*

A predefined score is assigned to each extracted parameter based on the manual scoring system mentioned in methodology 1. Values will be aggregated using the logic conditions embedded in the script and final complexity score will automatically be calculated.

*Step 7: Validation*

The system is validated by comparing the AI-generated scores with manually derived scores for a few models. The AI-generated scores are compared with manually derived scores for a set of models. Error rates, correlation coefficients, and discrepancies are recorded to assess the performance of the AI model.



AI-Assisted Design Complexity Scoring Pipeline

V. CASE STUDY: EVALUATION OF SHAPE COMPLEXITY OF TEA CUPS DESIGNED IN CAD MODELING SOFTWARE

Four models of tea cup were developed in a commercial 3D CAD modeling software. Different elements and tools were used to create the geometry.



| Parameters                      | Sub parameters    | Alloted | Shape A | Shape B | Shape C  | Shape D  |
|---------------------------------|-------------------|---------|---------|---------|----------|----------|
| Geometric Complexity            | Points            | 0       | 0       | 0       | 0        | 0        |
|                                 | Lines             | 1       | 0       | 0       | 0        | 0        |
|                                 | Curves            | 2       | 4x2=8   | 4x2=8   | 34x2=68  | 36x2=72  |
|                                 | Planes            | 3       | 3x3=9   | 3x3=9   | 3x3=9    | 3x3=9    |
|                                 | Surfaces          | 4       | 2x4=8   | 2x4=8   | 32x4=128 | 22x4=132 |
| Dimensional Complexity          | Solids            | 5       | 1x5=5   | 1x5=5   | 1x5=5    | 1x5=5    |
|                                 | 2D Composition    | 0       | 0       | 0       | 0        | 0        |
| Shape Grammars                  | 3D Composition    | 2       | 1x2=2   | 1x2=2   | 1x2=2    | 1x2=2    |
|                                 | Addition          | 0       | 0       | 0       | 0        | 0        |
|                                 | Subtraction       | 1       | 0       | 0       | 1        | 1        |
|                                 | Cull              | 2       | 0       | 0       | 0        | 2        |
| Transformations                 | Scale             | 1       | 0       | 0       | 0        | 1        |
|                                 | Rotation          | 1       | 0       | 1       | 1        | 1        |
|                                 | Reflection        | 1       | 0       | 0       | 1        | 1        |
|                                 | Deformation       | 1       | 0       | 1       | 1        | 1        |
|                                 | Translation       | 1       | 0       | 0       | 0        | 0        |
| Number of Elements (Components) | One Element       | 0       | 0       | 0       | 0        | 0        |
|                                 | 2-10 elements     | 1       | 0       | 0       | 0        | 0        |
|                                 | Multiple elements | 2       | 0       | 0       | 2        | 0        |

|                  | (one type)                    |     |    |    |     |     |
|------------------|-------------------------------|-----|----|----|-----|-----|
|                  | Multiple elements ("N" Types) | N+1 | 0  | 0  | 0   | 3   |
| Shape of Element | Standards and Primitives      | 0   | 0  | 0  | 0   | 0   |
|                  | Non-standard simple shapes    | 1   | 1  | 1  | 0   | 0   |
|                  | Complex shapes                | 2   | 0  | 0  | 2   | 2   |
| Colour           | No colour                     | 0   | 0  | 0  | 0   | 0   |
|                  | One colour                    | 1   | 1  | 1  | 0   | 0   |
|                  | Multiple colours              | 2   | 0  | 0  | 2   | 0   |
|                  | Colour gradient               | 3   | 0  | 0  | 0   | 3   |
| Symmetry         | Symmetric                     | 1   | 1  | 1  | 0   | 0   |
|                  | Non symmetric                 | 2   | 0  | 0  | 2   | 2   |
| Total            |                               |     | 35 | 37 | 224 | 237 |

| Features                                   | Standard                   | Score(1 or 0) | Shape A | Shape B | Shape C | Shape D |
|--|----------------------------|---------------|---------|---------|---------|---------|
| Vertical wall thickness                    | 1 mm min                   |               | 1       | 1       | 1       | 1       |
| Horizontal walls                           | 4 layers min (4 mm)        |               | 1       | 1       | 1       | 1       |
| Support material overhang angle            | 45 degree max              |               | 1       | 1       | 0       | 0       |
| Horizontal holes                           | Should be teardrop         |               | 1       | 1       | 1       | 1       |
| Clearance between support and moving parts | 0.5 mm min                 |               | 1       | 1       | 1       | 0       |
| Vertical circular holes                    | Undersize tolerance 0.2 mm |               | 1       | 1       | 0       | 0       |
| Circular pins                              | min diameter 2 mm          |               | 1       | 1       | 1       | 1       |
| Screw threads                              | min diameter 5 mm          |               | 1       | 1       | 1       | 1       |
| Total                                      |                            |               | 8       | 8       | 6       | 5       |

**Final Score**

|         |           |
|---------|-----------|
| Shape A | 35+8=43   |
| Shape B | 37+8=45   |
| Shape C | 224+6=230 |
| Shape D | 237+5=242 |

Shape A and B falls under the category of simplest design while Shape C and D falls under the category of Complex design.

### VI. AI- BASED RESULTS AND VALIDATIONS

The effectiveness of the proposed AI- based scoring system is evaluated by comparing it with the manual scoring system. For this a set of CAD models is subjected to both manual scoring system and AI based automated scoring system. This is done to find out the closeness of the scoring done by automated system in comparison to the scoring done by the manual scoring system.

#### Experimental Setup:

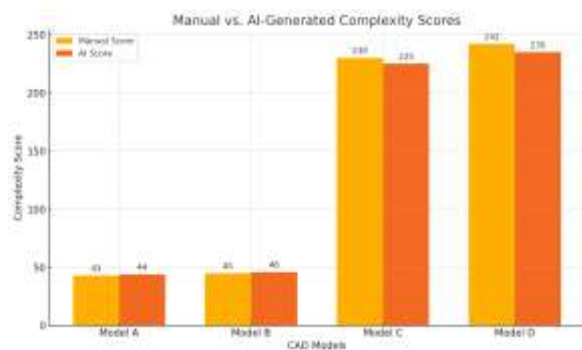
Four models of tea cup developed in a commercial 3D CAD modeling software (Model A, Model B, Model C and Model D) that were subjected to manual scoring were exported in STL format and input into the Python script created for the research. The custom python script uses trimesh, numpy-stl and cadquery libraries to extract the geometrical features. It will also detect symmetry and identify limiting features for FDM example overhang angles, thin walls, post diameter etc. the scoring system will follow the same rule as of the manual scoring system.

#### Results:

| Model | Manual Score | AI-Generated Score | Absolute Error | % Deviation |
|-------|--------------|--------------------|----------------|-------------|
| A     | 43           | 44                 | 1              | 2.33%       |
| B     | 45           | 46                 | 1              | 2.22%       |
| C     | 230          | 225                | 5              | 2.17%       |
| D     | 242          | 235                | 7              | 2.89%       |

#### Analysis:

Mean absolute error across all four models was 3.5 points. The average deviation percentage was less than 3%. This shows a high correlation between manual scoring and AI rule based automated scoring systems. The said deviation attributes to the limitations in mesh resolution and primitive detection in highly detailed areas such as surface textures or curved handles. The detailed detection method can be implemented in the future scope of this research.



Manual vs AI-generated Shape Complexity Score

The results show the validation of accuracy and robustness of the AI based shape complexity evaluation method. There

is a minimum deviation in the results of both the systems demonstrating the reliable replication.

### VII. CONCLUSION

The paper illustrates that even if it is well established that additive manufacturing offers the advantage of freedom of complexity, it does not offer complete freedom in fused deposition modeling. Hence both advantages and limitations are to be considered to find effective freedom in terms of design complexity. Manual process is automated using AI for increased accuracy and efficiency of analysis of design complexity of the object. Based on the complexity score of design the suitability of object to be manufactured using additive manufacturing technology is decided. It may be concluded based on the results and analysis that the system is capable of becoming scalable and implementable in the real word Additive Manufacturing workflows.

### VIII. FUTURE SCOPE

The rule-based AI system developed in this research can be made more effective and accurate by implementing machine learning models which are trained on larger datasets of CAD models. The CAD Models can have the complexity label for accurate recognition and association of shape with complexity. Other components and parameters of DfAM, like topology optimization, part time estimation, material consumption and multi material support can provide a comprehensive model. The model can further be extended to other domains of additive manufacturing.

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