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A Novel Feature-Based Manufacturability Assessment System for Evaluating Selective Laser Melting and Subtractive Manufacturing Injection Moulding Tool Inserts

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Abstract: Challenges caused by design complexities during the design stages of a product must be coordinated and overcome by the selection of a suitable manufacturing approach. Additive manufacturing (AM) is capable of fabricating complex shapes, yet there are limiting aspects to surface integrity, dimensional accuracy, and, in some instances, design restrictions. Therefore, the goal is essentially to establish the complex areas of a tool during the design stage to achieve the desired quality levels for the corresponding injection moulding tool insert. When adopting a manufacturing approach, it is essential to acknowledge limitations and restrictions. This paper presents the development of a feature-based manufacturability assessment system (FBMAS) to demonstrate the feasibility of integrating selective laser melting (SLM), a metal-based AM technology, with subtractive manufacturing for any given part. The areas on the tool inserts that hold the most geometrical complexities to manufacture are focused on the FBMAS and the design features that are critical for the FBMAS are defined. Furthermore, the structural approach used for developing the FBMAS graphical user interface is defined while explaining how it can be operated effectively and in a user-friendly approach. The systematic approach established is successful in capturing the benefits of SLM and subtractive methods of manufacturing, whilst defining design limitations of each manufacturing method. Finally, the FBMAS developed was validated and verified against the criteria set by experts in the field, and the system's logic was proven to be accurate when tested. The decision recommendations proved to correlate with the determined recommendations of the field experts in evaluating the feature manufacturability of the tool inserts.

Keywords: feature selection; decision-based system; additive manufacturing; selective laser melting; injection moulding; tool inserts; automotive industry

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1. Introduction

Knowledge-based expert systems (KBES), or expert systems, as they are sometimes referred to, are interactive systems that require expert knowledge. KBES are computer systems that are capable of imitating intelligent human behaviour in problem solving [1]. The knowledge of an expert system is accumulated through the collective input of experience and expertise from numerous individual experts. Therefore, the collective experience of experts provides users with valued recommendations that can assist them in the decision making process. Expert systems are considered one type of KBES that denotes information in the form of 'IF-THEN' statements until a certain conclusion is reached [2]. Başak and Gülesin [3] stated that expert systems enhance quality and productivity and decrease costs. Furthermore, it is understandable that these types of systems are formulated in a step-by-step structure, where the user is led through the sequence of steps to reach a certain decision, whilst also comprehending how that decision has been made.

The purpose of the research presented here was to develop an expert system that contains expert data regarding the selection process that provides the user with decision making recommendations for manufacturing an injection moulding tool insert for the aftermarket automotive sector. SLM has shown promising potential in the fabrication of injection mould tooling inserts. Numerous researchers have directed their attention over recent years towards the development of decision-making systems or assessment methodologies to generally integrate the benefits of additive manufacturing (AM) technology in tooling processes with less focus on feature limitations. Therefore, more research must be oriented towards developing a systematic approach that evaluates the manufacturability feature limitations of SLM technology in comparison to conventional methods and presenting the challenging outcomes.

Pal et al. [4] discussed a methodology where quality function deployment (QFD) and analytic network process (ANP) are integrated to convert customer needs into product technical requirements. The second stage of the study was a decision-making tool used for prioritising the engineering requirements based on customer needs for selecting and evaluating an appropriate rapid prototyping (RP) approach for fabricating a rapid casting tool. Nagahanumaiah et al. [5] presented a systematic approach for manufacturability analysis of moulds produced by rapid tooling (RT) methods, the approach being founded in three phases: mould feature manufacturability, secondary elements compatibility, and cost effectiveness. The geometric features of the mould core and cavity were evaluated for manufacturability using a fuzzy analytic hierarchy process (Fuzzy-AHP) methodology, as geometric compatibility for manufacturing a feature is characterised by a 'pass' or 'fail' approach. Another study proposed an AM manufacturability assessment approach that incorporates the use of automated feature recognition from the original CAD model with established process knowledge to optimise process outputs for metal AM processes [6].

Additional work has been conducted by Nagahanumaiah et al. [7], where a computer-aided RT process selection and manufacturability evaluation methodology was presented for injection moulding. The process selection supports mould cost estimation models and process capability databases. The model is based on a QFD process capability mapping with a set of tooling requirements that are prioritised through a pairwise comparison using AHP. In the work of Nagahanumaiah and Ravi [8], a generic approach was investigated for using grey relational analysis to quantify the effect of different moulding process variables on selected quality parameters for parts produced from direct metal laser sintering (DMLS) moulds. Data for dimensional error and weight difference were normalised, often called grey relation generation, to define the relationship between the desired and actual experimental data.

Kerbrat et al. [9] developed a methodology that estimates the complexity of tools using manufacturability index calculations based on octree decomposition for machining and AM. In this approach, areas with the most complexity are focused on and the calculated indices indicate which areas are advantageous for machining or manufacturing via an AM process. In this case, tools are seen as separate single modules that are further assembled. Townsend and Urbanic [10] related AM with computer numerical control (CNC) machining in a holistic approach for design and manufacturing, which defines the strength and weaknesses of each process. Moreover, for any given criteria, one of the processes shows a distinct advantage over the other. The processes are mapped simultaneously to the geometry and function of the part with regard to process strength. In the referred study, modules were created to group part geometry, and process selection was determined to fabricate the modules. Functionality is associated with part geometry; hence, this systems approach proposed applying an AHP model that quantifies decision making for process selection.

Ponche et al. [11] proposed a numerical chain based on a new design for AM (DfAM) methodology detailing both design requirements and manufacturing specificities. The quality of the parts produced is significantly affected by the physical phenomena occurring during AM fabrication. Therefore, the methodology proposed in the work offers a new DfAM approach detailing design requirements and manufacturing specifications right from the part design stage, which allows for the optimisation of geometry for thin-walled metal parts. However, the work of the study conducted was restricted to extruded parts. Zhang et al. [12] proposed an evaluation framework in which quantitative indicators were defined according to the design needs of the specific AM process to convey information from the process planning for improving the design. Referring to the user's manufacturing requirements, the purpose of the framework is to check whether a designed part is suitable to be fabricated using AM processes.

Design and manufacturing are the key considerations for developing a product, and recently, combining additive and subtractive manufacturing technologies has gained much attention. In the design process, design rules are set and defined to take account of various manufacturing constraints. Different definitions have been recommended by previous research for machining features with different viewpoints. Başak and Gülesin [3] reviewed earlier studies concluding that a feature-based design involves defining all the necessary information in a database regarding part geometry, surface topology, dimensioning, and tolerances. Other studies considered a feature used in computer-aided design (CAD) as a geometric shape, and based on the type of application, it can be defined as geometric, manufacturing, or an assembly feature.

Sormaz and Khoshnevis [13] defined a machining feature as a volumetric geometry that is machinable in a single operation, but expressed concerns due to restricting the definition to the removal of material volume. Wang [14] proposed a machining feature definition that entails surface features, geometrical features, and volumetric features. Givehchi et al. [15] added to the definition the state of the feature boundary representation. Le et al. [16] adopted a definition that describes a machining feature as a geometrical shape with a set of specifications that can be acknowledged by at least one machining process. Zhang et al. [17] proposed a definition for AM features in the same manner as machining features for which at least one AM process is known. The definition is based on the characterisation of AM processes that has an impact on build orientation and PBF in particular, which can manifest important effects on surface roughness and mechanical properties. Therefore, in this work, the manufacturing feature definition from the work of Le et al. [16] was adopted, which refers to both AM and machining features.

For the purposes of this research, design features with relevance to the scope of work for additive and subtractive manufacturing technologies were defined and are presented in Table 1 [18–20].

Table 1. Design Feature Illustrations and Definitions.

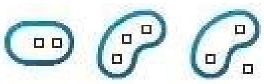
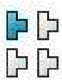
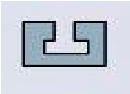
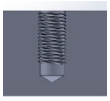
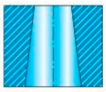
Design Feature	Illustration	Definition
Hole		A hole feature originates from a rounded profile. Hole types include 'through', 'blind', and 'tapered'.
Slot		A slot is a perimeter that has a constant centre line and width. Slot types include 'blind', which are contoured with two ends, and 'through', which pass completely through the part.
Pocket		A pocket is a feature with an open or a closed perimeter often called an open pocket or a closed pocket. Pocket types include 'through' and 'blind'.
Boss Extrude		A boss extrude feature adds to the area of the surface through extrudes above the planar surface.
Freeform Pattern		Any feature that has multiples that can be grouped together to create a pattern design. They can be machined as individual features or as a pattern.

Table 1. *Cont.*

Design Feature	Illustration	Definition
Fillet		Fillets are rounded corners. A curve created at the intersection of two or more faces.
Sharp Edge		A sharp edge on the external side of a body.
Undercut		An undercut refers to a feature that is described as a non-visible recessed surface that is inaccessible using a straight tool.
Tapping		Tapping is responsible for creating screw threads in a hole.
Negative draft		In a part viewed from a plan view, the side walls are tapered towards the bottom; the internal dimension at the bottom has a larger dimension compared to the top.

2. System Development

During the design stage, the designer is free to explore different "design for manufacturing" approaches, such as design for subtractive manufacturing (DfSM), DfAM, and design for hybrid manufacturing (DfHM), given that access to the manufacturing systems is available. Therefore, the first step after the CAD design of a tool insert is developed, is for the designer to analyse its manufacturability. When developing the FBMAS, the following specifications and limitations are considered for the GUI development.

2.1. Recognising System Specifications and Limitations

The following are the targeted system specifications:

- Applying the feature-based system to assist users in defining and evaluating manufacturability limitations of a given tool insert based on a set of predetermined features criteria;
- The system is feature-based, evaluating the tool insert as multiple features and providing recommendations according to rules in the "IF-THEN" format that are constructed in the knowledge base. The "IF" part includes the condition clauses and the "THEN" part includes the resulting sentences;
- Feature specifications of diameter to length ratios are derived from SECO [21,22];
- The separate feature recommendations are processed to provide the user with a generic part recommendation;
- The system is interactive in assisting the user to assess the feature-based manufacturability limitations and provide recommendations for which manufacturing technique to use.

The main limitations set for the developed feature-based system were:

- The only technologies that the FBMAS can be applied (i.e. will be limited) to are SLM for AM, CNC machining, die-sink electric discharge machining (EDM) and wire EDM for subtractive manufacturing;
- The rules set for the system were constructed on the basis of individualisation, with overlapping features being outside the scope of this research;
- The maximum part size allowed for this system is associated with the maximum volume of commercially acknowledged SLM machine systems (e.g., SLM Solutions [23]; 500 mm × 280 mm × 850 mm). The build platform wall allowance is understood based on technical user experience;

- The critical features identified for this study are limited to hole, slot, pocket, boss extrude, and freeform pattern (refer to Table 1);
- The maximum number of designs of a feature allowed for this system is five designs—this rule applies to each of the features individually;
- Economic cost factors were disregarded in this research.

2.2. Graphical User Interface

The FBMAS architecture is a fixed-inflexible system that can only provide the user with what the developer has predetermined for the system. The system was developed using Matlab (MathWorks, Matlab academic version R2017a). The logic of the system comprises fixed rules that define the design constraints provided by human experts. Those design rules was set for SLM and the subtractive manufacturing methods as focused by the FBMAS. Figure 1 provides a schematic illustration of the general FBMAS structure.

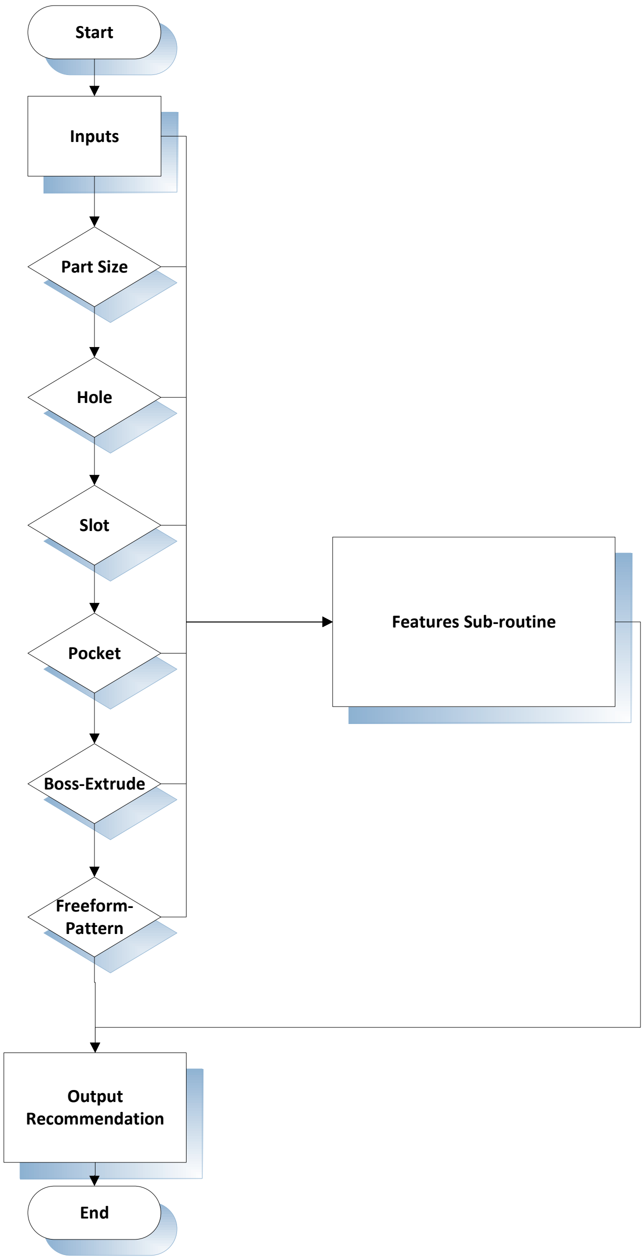


Figure 1. Schematic diagram of the FBMAS general structure.

The user is required to input the necessary information for each feature in the form of queries in the GUI for the different defined feature designs. The system then formulates the information and returns an output to the user with the decision recommendation for each feature design. After all identified features are assessed, the FBMAS displays a list of the individual feature decision recommendations and the overall recommendation for the part manufacturing. Figure 2 displays a graphical illustration of the FBMAS from the initialisation stage to displaying the recommendations.

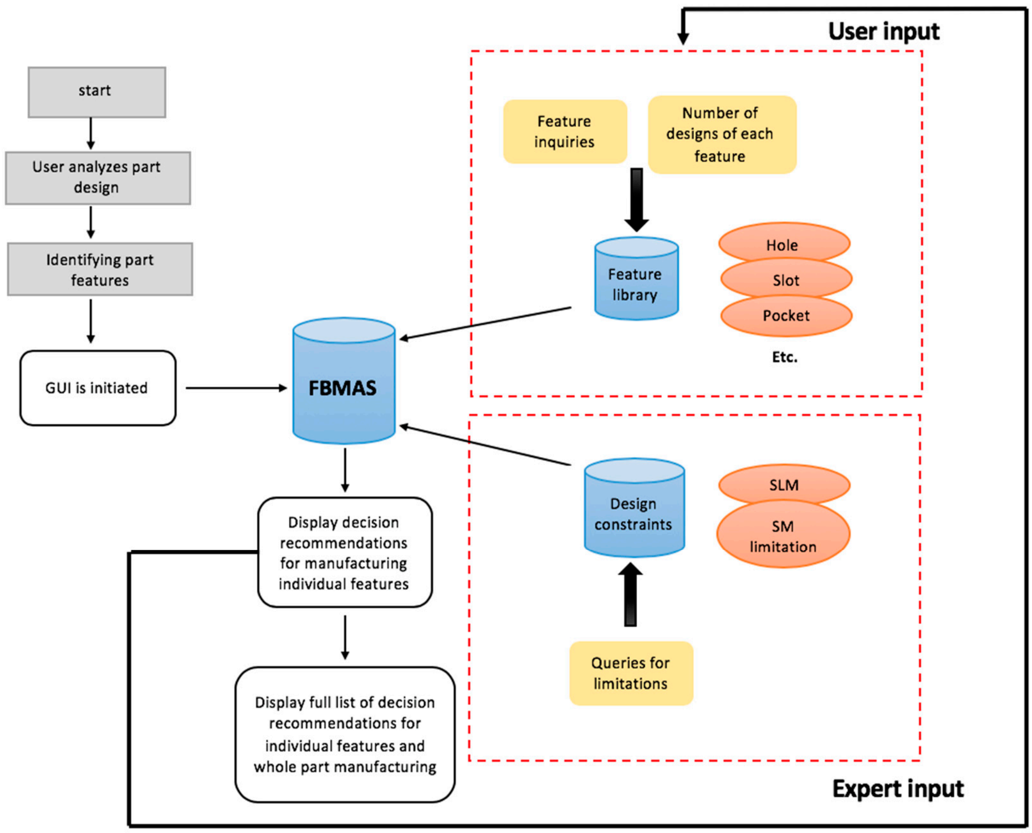


Figure 2. Graphical illustration of the FBMAS from initialisation stage to displaying recommendations.

2.2.1. FBMAS Main Initialisation

Figure 3 illustrates the primary screen that appears to the user when the FBMAS is initialised. In the first screen, there are two main panels, and the user is requested to input the necessary information for all fields in both panels.

The first panel comprises inquiries about the main part sizes. The maximum part length, width, and height were set to 500 mm, 280 mm, and 850 mm, respectively. The maximum part dimensions specified in this research were based on the maximum featured commercial SLM system on the market that is capable of efficiently producing large-volumetric-size metal components. The user must enter values for the three dimensions.

Depending on the rules and the constraints set for the maximum part size, the returned queries are checked with the design constraints as shown in the system logic in Figure 4. A decision recommendation is fed to the designer for the injection mould tool insert to be manufactured using subtractive technologies in the likelihood that the insert cannot be separated into smaller modules. If the insert design can be separated into individual modules, the user is recommended to separate the part before any further evaluation is conducted. After the recommendation message is displayed, the system terminates, and each module evaluated is treated as a separate entity.

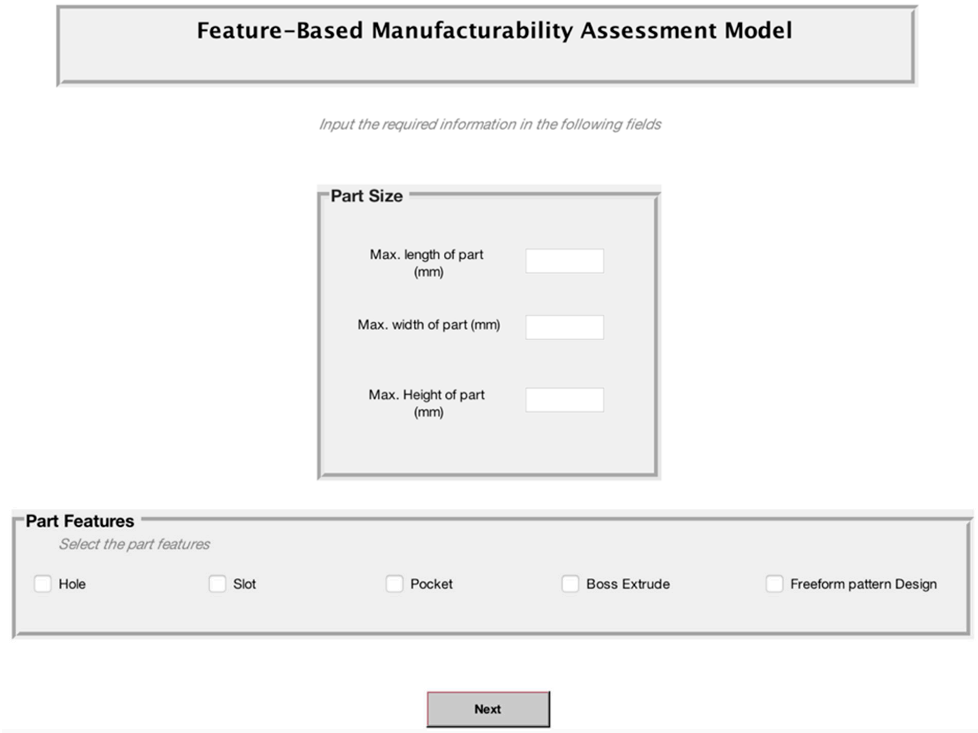


Figure 3. Initial screen of the FBMAS.

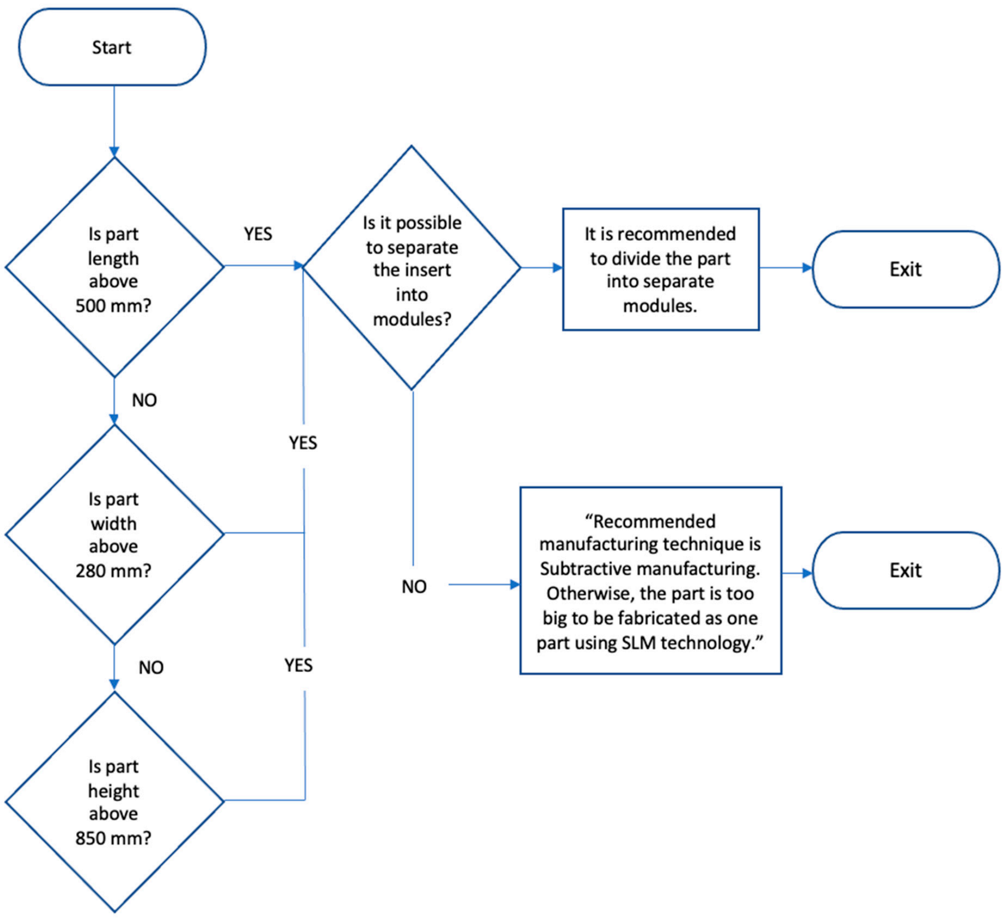


Figure 4. Size constraints.

As for the second panel, the user is obligated to specify the features that are identified for the given tool insert. For the purpose of clarification, each feature is accompanied with a sneak-peek descriptive 3D illustration providing affirmation of the user's feature selection. After the features are selected, the designated feature screens are activated for the user. At this stage, the next button activates the system to screen the constraints, and in case one of the constraints is met, the user is provided with a valid recommendation on how the insert should be manufactured. Otherwise, the next button activates the subsequent screens relying on the features selected from the third panel.

2.2.2. Design Features

In the likely event of a hole feature being selected, the user is approached with multiple inquiries. First, in a separate page, the user is prompted to input the number of different hole designs (as shown in Figure 5).

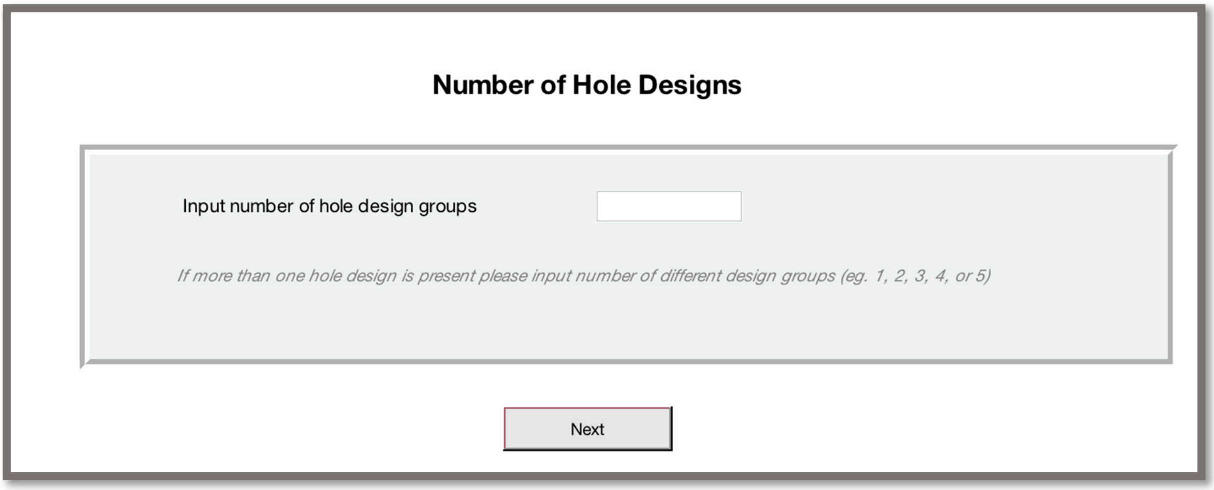


Figure 5. The user is prompted to enter the number of hole designs.

The maximum number of a given group of feature designs allowed for this system is five. For example, the maximum number of different designs for a hole feature is five—the same rule applies to all features of the FBMAS.

After the user inputs the number of hole designs, they are driven through a sequence of questions to identify the features' criteria and limitations. Those limitations are gauged through a set of logical rules that have an impact on the choice in manufacturing technology. The resulting recommendation decision for the hole feature page is saved, to be displayed in the recommendation list page. The recommendation list page is displayed at the end of the system after all the features of the insert are evaluated. If the user identified that there is more than one hole design, then the system is prompted to open the same number of design pages as specified by the user. Figure 6 displays the hole feature design page that appears to the user when a hole feature is selected in the initial page.

A set of questions are listed in the page, and the user has to provide an answer to each question. The questions generated are the result of the compiled design information obtained from inquiries and investigations conducted with experts in the automotive industry. First, the user is questioned to determine whether the hole has a negative draft. Therefore, if the user identifies that there is in fact a negative draft, a decision recommendation is displayed for the hole feature.

At this point, evaluating the rest of the feature criteria after a decision recommendation is made is unnecessary, because the outcome from the evaluation dominates any other outcome that may follow. If the user acknowledges this feature criterion, then a decision recommendation is displayed to indicate that a negative draft is not achievable using any subtractive method of manufacturing. Figure 7 is an example of the decision recommendation displayed.

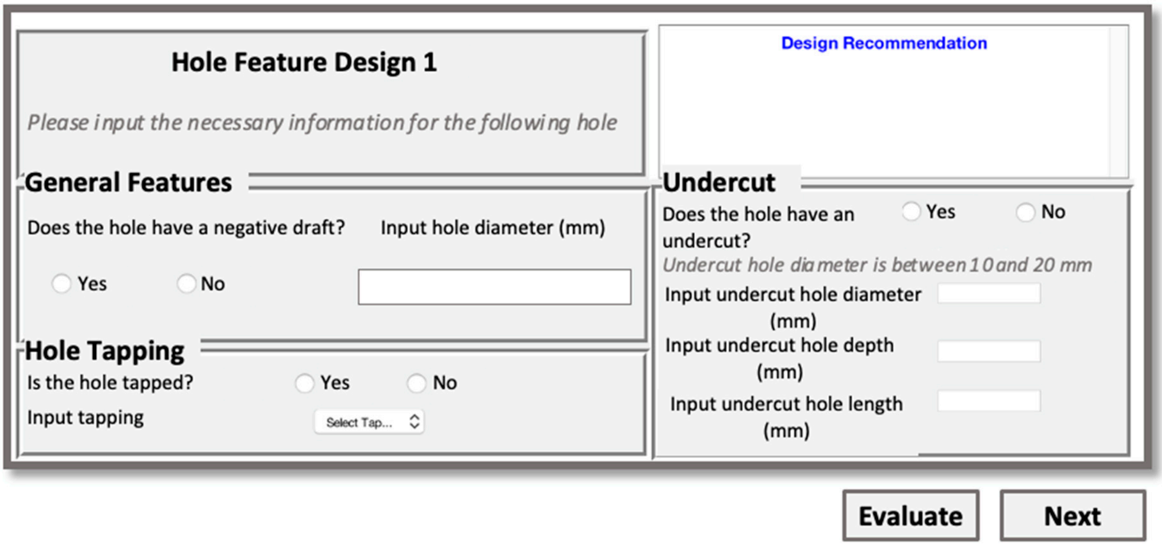


Figure 6. Hole feature main page displayed for the FBMAS.

Figure 7. Example of a displayed design feature recommendation.

However, if the abovementioned feature criterion is not present, then the logical flow of the system continues to evaluate the rest of the feature criteria. Further on, the user is required to answer a set of questions that inquire whether there is an undercut feature or not; if the user agrees that there is in fact an undercut feature, more questions have to be answered. First, the user is required to input the undercut hole diameter, followed by the undercut depth, and finally the length of the undercut feature.

Certain design limitations must be taken into account; for this, FBMAS design rules for SLM and subtractive technologies were the founding base for the selection system. It was found that the minimum diameter that SLM technology can accomplish for an open feature is 1 mm [24–26]. For subtractive technology, design guidelines were acquired and validated through experts in the automotive industry for the production of injection moulding tool inserts [27,28]. Creating an undercut feature requires the use of a T-slot cutting tool with specific diameters, as shown in Figure 8. The minimum hole diameter recommended is 10 mm, and the maximum is 20 mm; otherwise, it is considered a pocket. If the user inputs a value lower than 10 mm or greater than 20 mm, a message appears to direct them to input a valid undercut hole diameter. The length L of the undercut varies depending on the diameter that corresponds with the length of the T-slot cutting tool. The depth of the undercut is derived from the equation:

$$\text{Undercut depth} = \frac{(\text{Dc} - \text{Dm})}{2}$$

where Dc is the diameter of the cutter and Dm is the diameter of the tool shank.

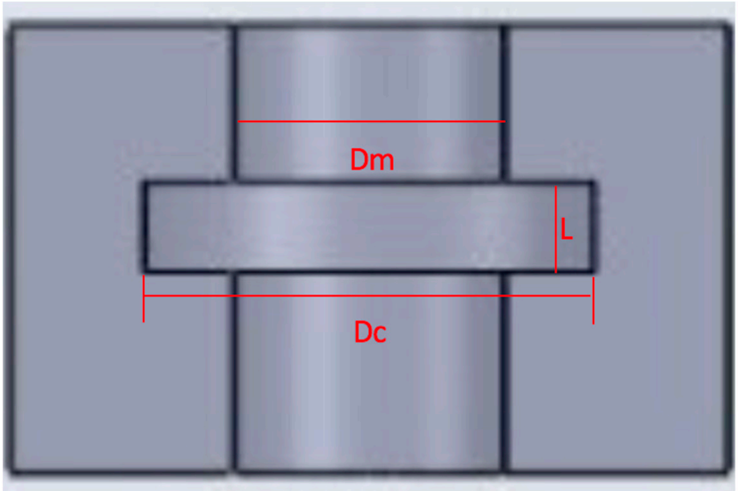


Figure 8. Illustrative undercut diagram.

Therefore, if the user assumes that there is an undercut feature and the required information is entered, then the system proceeds to analyse and assess the design rules that are defined for the undercut feature. Furthermore, a decision recommendation is displayed for the user identifying the proper manufacturing technology to seek. The system proceeds to enquire about other hole feature limitations. If no undercut is detected, the user is queried for the existence of hole tapping. If the user affirms, the following question examines the tapping size. According to the user's response, a decision recommendation is displayed if a limitation is detected; otherwise, the system resumes and enquires about additional limitations.

At this point, if none of the previous hole features presented a defined limitation, the decision system proceeds to enquire about the hole diameter. The minimum open feature diameter that can be accomplished by the SLM technology is 1 mm. However, for subtractive manufacturing, hole diameter and depth are associated with the cutting tool dimensions; therefore, it is important to signify the ratio of hole diameter to depth as a design limitation. The minimum permissible hole diameter is 1 mm, and the maximum is 20 mm. If the user enters a value outside the permissible range, a message appears, alerting the user to input a valid hole diameter. If the hole diameter exceeds 20 mm, a message is displayed for the user to refer to the pocket feature.

The user is required to enter the hole diameter, and the FBMAS system is responsible for assessing the information entered. Depending on the value submitted for the diameter, the system prompts the user to answer a question. For example, if the user enters a value of 1 mm for the hole diameter, the system proceeds to enquire whether the ratio of diameter to length is 2:1. If 'yes', a decision recommendation is displayed, but if 'no', another question appears to check if it is a blind hole. Figure 9 displays an example of the prompted question.

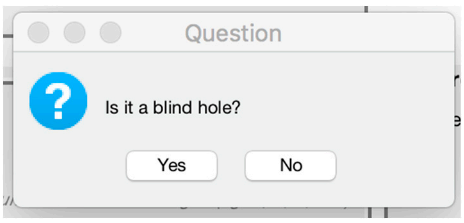


Figure 9. Example of question prompted by the system.

After the FBMAS enquires about all the defined hole feature limitations for each of the identified hole designs, the decision system proceeds to enquire about limitations that are detected in the subsequent design features in the same manner as the hole feature. The logical sequence in which the questions are arranged is dependent on the significance of each feature criteria to the decision making process. The slot feature is the next in the main logical flowchart.

During investigations for this research, it was shown that injection moulding tool inserts for automotive applications are most likely complex in design. In definition, the term complex means that multiple features are mutually integrated in one component, requiring the use of multiple manufacturing methods to achieve the desired design. Referring back to the slot feature design page, the user is asked whether the slot feature has sharp-edged corners. To create a sharp-edged corner, the user can either select the use of SLM technology or a subtractive manufacturing approach. To establish which subtractive manufacturing approach to use, the user has to determine whether the slot is through or blind. Then, EDM methods are attempted. Depending on the type of slot, for example if it is through, then wire EDM is recommended; otherwise, if the slot is blind, conventional die-sink EDM is recommended. Consequently, the system is guided to question the presence of an undercut in the slot feature. The slot feature follows the same design rules as the hole feature design. Moreover, the maximum undercut slot diameter is 25 mm; otherwise, the user is advised to refer to the pocket feature.

The pocket feature is the third feature in the system's logic and is assessed in the same manner as the previous design features discussed. The fourth feature in the FBMAS is the boss extrude. After the user selects the boss extrude feature from the main initialisation page, the feature design page is prompted. The FBMAS is executed to assess feature design limitations depending on the information entered by the user. First, the user is requested to enter the number of different boss extrude group features. According to the number of designs entered, design pages are opened subsequently. For each design page, the user is asked to fill out the enquiry fields. The user is asked whether there are any sharp-edged corners or corner fillets less than 1 mm in diameter.

If no constraints are identified, the FBMAS enquires about the spacing between the boss extrude feature and the nearest wall. Furthermore, the FBMAS checks if the height to width ratio of the boss extrude feature is more than 8:1; if the user confirms, then SLM technology is disqualified as a potential manufacturing technique.

A freeform pattern feature is simply multiple repetitions of an individual design feature. Significantly, the feature diameter is the key design criterion to query so as to assess design limitations for a freeform pattern feature. First, the user is asked about the number of freeform pattern designs. The same set of design rules for a feature diameter query was followed in the previous design features. The pattern diameter is directly associated with the feature's depth. Therefore, the design ratios were followed by the FBMAS to assess the adequate manufacturing technique for implementation. The minimum permissible diameter for CNC machining a freeform pattern design is 0.25 mm. The user is required to enter the diameter, and the system is responsible for assessing the input. Depending on the value submitted for the diameter, the system prompts the user to answer a question about the ratio, and according to the answer, a decision recommendation is displayed. If the user enters a value outside the permissible range, a message appears alerting the user to input a valid diameter.

2.2.3. Feature and Part Decision Recommendations

The decision recommendation page is the last stage of the FBMAS. At this point, the user has initiated all the necessary feature design pages that are of relevance to the part under consideration. In the recommendation page, each feature is displayed in the upper tab menu. When the user presses on one of the feature tabs, a display of the identified design groups of a given feature are displayed. For each design group specified by the user, a decision recommendation for the manufacturability of the given feature is presented, along with an explanation of limitations. Figure 10 shows the recommended decision for five hole feature design groups. These recommendations provide the user with an insight into the different capabilities and limitations of the defined manufacturing technologies in this system when it comes to design feature manufacturability.

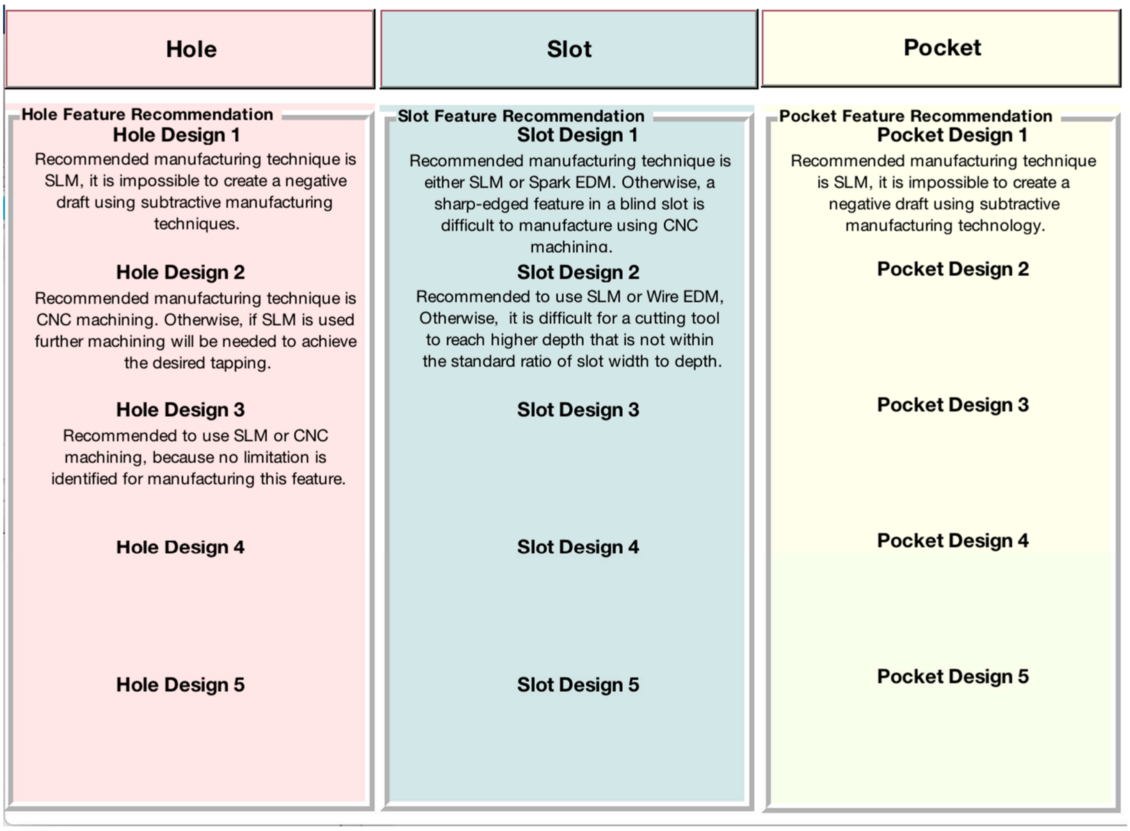


Figure 10. Design recommendation page of the FBMAS.

3. System Verification and Validation

The verification of the system was established by inspecting the logic of the developed FBMAS. To validate the system for the purpose of supporting the fabrication of injection moulding tool inserts for the automotive industry, the process for the case studies was conducted in consultation with a stakeholder from the industry. The output decision recommendations of the FBMAS were compared with actual decisions made by the experts consulted to assess how well the system works. Considering how verification and validation are related to the development process of the FBMAS, Figure 11 displays the modelling paradigm. The paradigm is adopted from the simplified version illustrated by Sargent [29] for the verification and validation of simulation models.

The principal knowledge was captured to correspond with the need of this study. The real-life design evaluation process is the problem entity that needs to be modelled. The logical depiction of the system is the conceptual model, and the programming of the conceptual model is the computerised model. To develop the conceptual model, extensive analysis and flowchart modelling was carried out to validate compliance with the actual system. Verifying the computerised model ensures that the computer programming and implementation is conducted with no faults. Operational validation was carried out with sufficient experimentation to ensure that the model's outcome provides accurate results as intended in actual situations. Finally, in this work, data validity throughout all stages of the verification and validation process was performed to ensure that the design feature limitations are correctly defined and represented. The two main verification and validation techniques acquired in this work are event and extreme condition tests. In the "event" test, the model was run to depict similarities with the real-life system. As for the "extreme condition" test, the outcome should be perceived as acceptable regardless of the extreme inputs to the system [29].

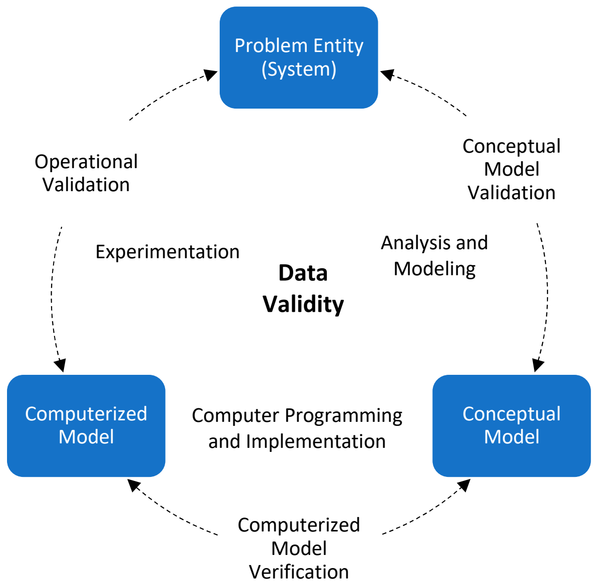


Figure 11. FBMAS verification and validation paradigm [29].

3.1. System Verification

Prior to utilising the developed FBMAS, the system had to be examined to verify that it operated accurately. The verification process was executed in several stages. Initially, the logic and interface of the system were verified through the different stages of system development. Furthermore, after completion of the system development, it was examined as a whole to ensure that it worked properly.

Different scenarios were established to examine the system's performance when subjected to different inputs and the effect of these variations on the system's outputs. Input variations were mainly set to the part size and presence of a given feature. To test the systems operation, variations in part size and feature existence were determined for the FBMAS to acquire the expected output. To verify the accuracy of the system's performance, the same criteria were tested manually to compare and ensure that the same results were acquired.

As an example for the verification process, the system was tested in various scenarios of entering different part size values. Firstly, the system was tested under extreme conditions where the input data provide plausible outputs for unlikely, extreme conditions. For example, if part size in any of the X, Y, and Z directions is zero, a message is displayed to state that a valid part size must be entered. Other event scenarios are were outwith part sizes above and below the SLM design limitations of 500 mm, 280 mm, and 850 mm, respectively. The results retrieved from the FBMAS were similar to those results determined from manually processing the system. Changing the inputs results in correspondingly altered outputs.

This system verification method was carried out multiple times to ensure the reliability of the FBMAS in accurately following the programmed logical design rules. Additionally, the same verification approach to test for feature manufacturability evaluation was used. Another event scenario was the system being fed with inputs that are known to provide a decision recommendation for manufacturability using SLM technology, and we checked that the output provided an accurate outcome. This method was followed to trace all the possible logical approaches of providing numerous inputs to the FBMAS and retrieve plausible outputs. We compared the outputs retrieved through the verification process of the FBMAS with the manual process at various stages through the development of the FBMAS. In continuously seeking to verify the system at all stages, errors were effortlessly detected and corrected instantaneously.

3.2. System Validation

The primary purpose for validating the FBMAS was to ensure that the system provides realistically feasible outcomes, assisting users in evaluating the manufacturability of the design features of injection moulding tool inserts for the aftermarket spare parts automotive industry. This approach ensures that the knowledge of experts for SLM technology and subtractive manufacturing techniques are accurately captured and constructed within the structure of the developed FBMAS. Design constraints were set to outline limitations that exist for the defined methods of manufacturing. Those constraints were defined by industrial experts and conform to the design constraints that do actually exist and cause manufacturing restrictions. Three industrial injection moulding core or cavity inserts were selected from the industry to validate the system. The case studies were selected by the experts to test the system's decision outcomes compared with the actual outcomes due to challenging limitations faced during manufacturing. The selection of the case studies was conducted under supervision and consultation of the industrial experts who have hands-on experience in the manufacturing of injection moulding tool inserts for the aftermarket automotive industry. El Kashouty [30] described the case studies comprehensively; nevertheless, in this work, the reflector study is discussed concisely.

4. Discussion

The study under review is for a headlamp reflector. The reflector is a standalone part that is not assembled to fit any other component. Figure 12 shows the product.

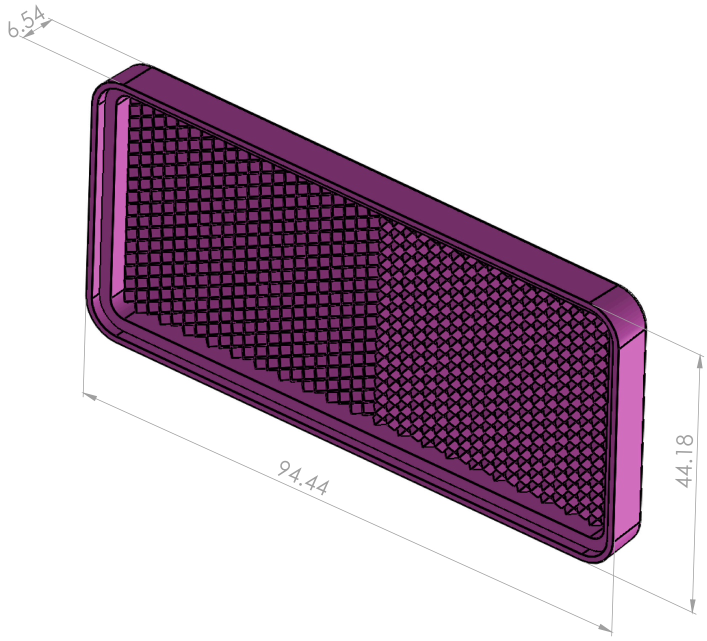


Figure 12. Reflector product, dimensions in (mm).

4.1. Manufacturability Assessment

The core tool insert for the reflector product was manufactured using two approaches, both subtractive and AM. Initially, the 3D CAD model (as shown in Figure 13) was prepared, and the core insert was CNC machined using a tapered-end mill with a 0.25 mm diameter and shank diameter of 3 mm to achieve the required sharp-edged freeform pattern design, although the required tip diameter was set to be sharp edged.

Figure 14a,b demonstrate a simplified design of the repetitive pattern of the core insert. Acquiring a tapered-end mill with a diameter of zero was impossible. Therefore, the CNC-machined insert did not deliver the stipulated results in accordance with part quality and accuracy. Furthermore, experts confirmed that if only subtractive methods are targeted, using die-sink EDM manufacturing techniques will deliver more satisfactory results.

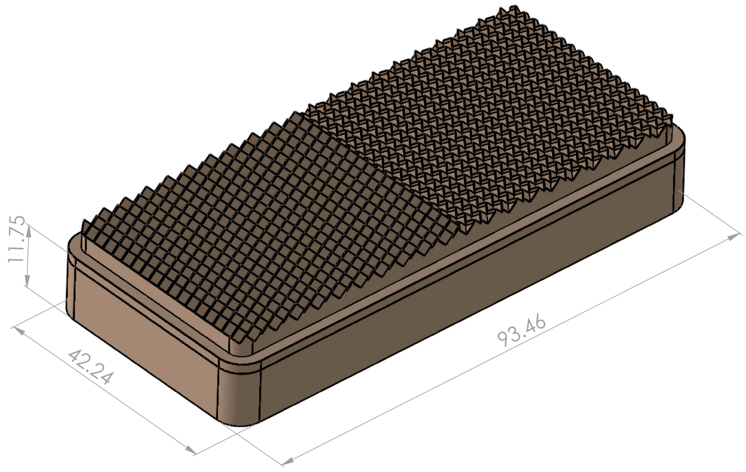


Figure 13. Reflector's core tool insert, dimensions in (mm).

(**a**) (**b**)

Figure 14. (**a**) A simplified view of the repetitive pattern of the core insert. (**b**) The reflector product with a simplified view of the repetitive pattern attached to the core.

The second approach for manufacturing was to use SLM technology. The core insert was successfully fabricated; moreover, minor postprocessing was required to achieve the desired surface finish. It was confirmed by experts that SLM offered positive results in fabricating the identified design features with no limitations.

4.2. Core Insert Features Evaluation Using FBMAS

The core's feature specifications were fed to the system and the possible decision recommendations were processed and displayed by the FBMAS. The acknowledged design features fed to the FBMAS were the minimum freeform pattern diameter. The identified pattern design requires that the base have a diameter of zero, as shown in Figure 15.

The user enters the identified features, and the freeform pattern design page is displayed. The user inputs the required information and presses the next button to display the decision recommendations, as shown in Figure 16. The FBMAS states that to manufacture the freeform pattern design of the core insert, it is recommended to use SLM technology as the ideal manufacturing technique, as opposed to subtractive manufacturing. The FBMAS recommendations conform to the recommendations indicated by the consulted experts, given the availability of the manufacturing systems.

Results obtained by Kashouty et al. [31] successfully demonstrate that employing SLM technology for producing tool inserts with complex surface topology proved to be an effective and efficient alternative to subtractive manufacturing. Significant benefits in terms of surface roughness, dimensional accuracy, and product functionality were achieved through the use of SLM technology for the fabricated tool inserts in comparison to their CNC counterparts.

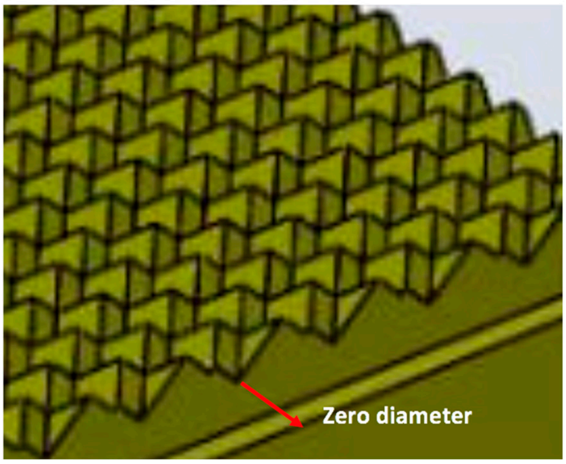


Figure 15. Detailed view of core insert.

Figure 16. Reflector's decision recommendation.

5. Conclusions

The work presented in this paper discussed the systematic approach for developing the feature-based manufacturability assessment system. The areas on the tool inserts that hold the most geometrical complexities to manufacture are focused on each manufacturing method, whilst defining their design limitations. The methodical description of the system's logical operations was clearly recognised through the presented segments of the flowchart and applied through the GUI. The main logic which the system follows is "IF-THEN" rules, used to define design limitations that assist users in determining the proper manufacturing method for the tool insert under consideration. The conditions of the "IF-THEN" are based on constraints set by the operations of SLM technology and the defined methods of subtractive manufacturing in the system. The system focuses on identifying the outcome through decision recommendations for the individual design features as well as the whole part in question. It was noted that the developed FBMAS decision recommendations proved to be in correspondence with the decision recommendations of the field experts in evaluating the feature manufacturability of the tool inserts. The developed FBMAS was self-verified against the criteria set by the field experts. The system's logic was proven to be accurate when tested. Selected tool inserts assisted in the validation process, exhibiting variability in the type of design feature validated for each study.

The developed FBMAS was verified, and the system's logic was proven to be accurate when tested. For the reflector's core insert, it was shown that the required base pattern must have a sharp-edge tip; therefore, the FBMAS recommended that the core insert be manufactured using SLM technology. Addressing the system's specifications and limitations provided the user with a focused insight into the positive outcomes of evaluating the tool insert's feature manufacturability, although there are other aspects to consider when selecting the adequate methods of manufacturing a tool insert. The FBMAS decision recommendations proved to correspond with the decision recommendations of the field experts in evaluating the feature manufacturability of the appointed tool inserts.

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