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Application of EbereDimMT001 with Fuzzy Logic in Product Quality Technology Maturity Assessment of Metal Additive Manufacturing Process

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Abstract

Additive manufacturing technology has for a long time been referred to as a new technology in all publications to date. A technology of over 20years of application since 1996, still being regarded and qualified as emerging technology to date. It was based on the fact and curiosity that the new generic Semi-Direct Technology Maturity Assessment Model (SDTMAM), EbereDimMT001 was designed. Hence, there is a need to assess to determine the level of technology advancement in the additive manufacturing technology (AMT). The research therefore aimed at adapting and implementing an already developed and designed model on a metal additive manufacturing technology (MAMP), first along the process capability variable of product quality (PQ). The manufactured product achievable characteristics such as (i) dimensional accuracy (ii) surface roughness (iii) precision or repeatability and (iv) tolerance, were considered for the technology capability parameters, where 18-number of metal additive manufacturing parameters were adopted to cover to achieve wide satisfactory technology applications, operational conditions and attributes. The digital technology and artificial intelligence driven model, EbereDimMT001 was applied with fuzzy logic and Set theory-based 26-number experts' survey questionnaires model was also adopted to source and collect the MAMP research data for maturity assessment. The 26-number experts' survey questionnaires are the research statements or proposition generated and coined from the 28 number of established metal additive manufacturing process capability performance indices, which are the subsets of the operational MAMP parameters A capability maturity model integration (CMMI) maturity profile of the Software Engineering Institute (SEI) of the Carnegia Mellon University, USA was adopted for maturity profiling of the scientific technology maturity assessment of metal additive manufacturing process. The models were coupled in series and was implemented progressively on a metal additive manufacturing process, and the product quality (PQ) technology maturity level was found at the quantitatively managed maturity level of 4 of 5 after research and results simulation. Thus, the product quality technology maturity level (ML) of a MAMP is at 3.18ML of the 5MLs, which means 63.5% maturity, therefore represents the product quality (PQ) technology maturity level of a metal additive manufacturing process. Meanwhile, this research is a sole effort and at student reach. Especially the questionnaire administration and sourcing of the research data. Hence, it is observed that the questionnaire did not get to the most desired experts' respondents at the upper echelon of the major or top-class metal additive manufacturing industries, research institutions, dealers and product users, for research data and probable difference or an improved result. So, there should be no limitation in the research respondents. data access and sourcing plan.

Keywords: Additive Manufacturing; Product Quality; Maturity Profile; Digital Manufacturing; Data Analytics; Process Parameters; Process Capability Area; Performance Indices; Fuzzy Logic

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1. Introduction

In the manufacturing industry, maturity assessment is very important due to advancement of new and evolving technologies, competitiveness, product life-cycle demand and consequent need for improved process capabilities in terms of product quality and industry best practice. [1, 2]

Also, the capability of a process to produce well successfully depends on its maturity which can be measured using the methods provided in a model as maturity levels. Each maturity level considers a given group of reference models or process work areas, where achievement of a capability level in those process work areas, as explained in the model, allots a particular maturity value or grade to the technology. [1, 2]

Thus, additive manufacturing technology is a new manufacturing technology in which products are produced as a whole and single unit part through an additive manufacturing means and process of product design, material selection, modelling and data filing, then comes 3-D Printing process, in a powder and wire feedstock material forms, and additive manufacturing process design and implementation in layers to produce components of a more complex geometry. [4] Additive manufacturing technology therefore, has for a long time been referred to as a new technology in all publications to date. A technology of over 20years since inception, still being qualified as emerging technology to date. [1, 2, 4]. Hence, there is a need to determine the level of technology advancement in the additive manufacturing technology (AMT), to assure both the existing and prospective researchers and investors in the high-risk field of aerospace, medicine and prosthetics, and automotive industry sectors, where the technology traverses of the reality. [1, 2, 3] Thus, has brought about the need to research on the technology maturity assessment of a metal additive manufacturing process. [1, 2]

2. Methodology

EbereDimMT001 is the Semi-Direct Technology Maturity Assessment model adopted, non-laboratory experimental research that involves applications of knowledge of advanced manufacturing, artificial intelligence, Fuzzy logic system, data analytics and software engineering to product quality technology maturity assessment of any advanced metal additive manufacturing technology, in the steps. [1, 2]

2.1. Algorithm of the Product Quality Technology Maturity Assessment of a Metal Additive Manufacturing Process (MAMP)

The algorithm of product quality technology maturity assessment (TMA) of metal additive manufacturing process (MAMP) is as in figure 1 below, and explained in the schematic illustration in table 1. [1, 2]

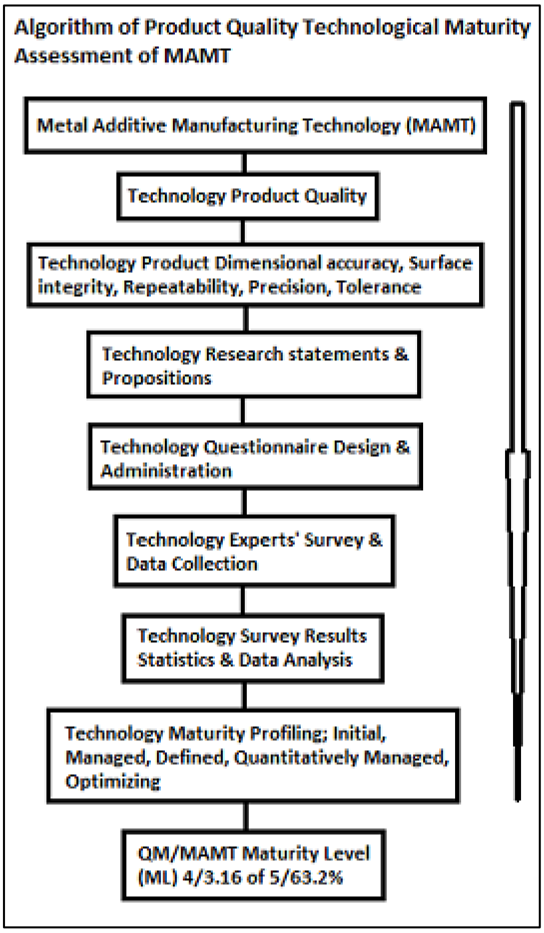

Figure 1 SDTMAM Model Algorithm of the Product Quality technology Maturity Assessment of Metal Additive Manufacturing Technology. [1, 2]

2.2. The Schematic Representation of the Semi-Direct Technological Maturity Assessment Methodology for MAMP

Table 1 shows steps for the generic EbereDimMT001 model for technological maturity assessment of the metal additive manufacturing process, which were drawn from the SDTMAM algorithm of figure 1. [1, 2, 4]

Table 1 Schematic Representation of the Semi-Direct Technological Maturity Assessment Methodology (SDTMAM) Model of MAMP

Serial No.	Steps	Description of activities
1.	Step1.	The strategic processes common capability areas of metal hybrid manufacturing technologies were determined
2.	Step2.	Processes performance indices were identified, and the performance indicators were established
3.	Step3.	The type of data, source and collection techniques was determined
4.	Step4.	Research propositions with respect to the processes were generated
5.	Step5.	A set of research questionnaire or survey interface tool was developed and designed
6.	Step6.	Technological maturity assessment maturity profile was determined
7.	Step7.	A digital technology and artificial intelligence (AI) Fuzzy logic and Fuzzy set theories were applied in the questionnaire design and administration programme.

8.	Step8.	Expert's technology maturity survey was carried out, data collected and analysed with results
9.	Step9.	Technology maturity assessed data was ranked on the CMMI profile according to the maturity levels with results
10	Step10.	Product Quality technology maturity level result established
11	Step11.	Simulation of result in fuzzy logic system in MATLAB Toolbox by artificial intelligence (AI) fuzzy command line functions, and by using a graphical user interface for the simulated result from AI to confirm or validate result.
12	Step12.	Presentation and analysis of result

2.3. Experts' Fuzzy Survey Questionnaire and design for MAMP Product Quality Technology Maturity Assessment

As a result of the Semi-Direct technological maturity assessment methodology approach of the assessment, the challenging vague and irregular nature of the linguistic variables, maturity as a developmental process, product quality and parameters, the metal additive manufacturing process parameters, the process performance indices and the associated maturity profiling reality necessitated the introduction of artificial intelligence based fuzzy logic principle in the design, planning and administration of a questionnaire for expert survey, and collation of research data as represents. [1, 2, 7]

To unluck the bars, kill bias to take care of various degrees of technology developmental stages, which the binary questionnaire response cannot cover, the questionnaire was designed as a group based, such that the capability performance-based survey proposition has up to five-gravitating optional answers such as Not true, Not quite true, Fairly true, True, and Very true. [1, 2, 7]. Followed, is a set of 28 sub-parametric metal additive manufacturing process performance indices carefully identified and established from various metal additive manufacturing technology literature and studies, experience and engineering practice. [1, 2]

Thus, as indicated are result oriented research propositional statements coined from the process and metal product quality key performance indices with appraisal expertise and experience to control and guide respondents more strictly to an unbiased knowledge destinations and accurate decisions. A set of 26-number experts' survey questionnaires model was developed and designed ready for the product quality technological maturity assessment (TMA) of a metal additive manufacturing process with research statements. [1, 2] However, this is subject to continuous interrogation and review of the process capability performance areas, characteristics, propositional statements, and questionnaire design to suit maturity assessment of the target technology of the time. [1, 2]

Also, to prevent chances of bias in the questionnaire planning and administration method, and the result too, sure was made that there is no information in the questionnaire system that can suggest to the experts or professional respondents about the aim and end use of the project, neither the data nor their opted answers. This approach, will eliminate sentiments and bias influences on the questionnaire system and research data collation. [4]

2.4. Administration of Questionnaires to the Selected Experts' Respondents and Collation

A total of 150 sets questionnaires was directly emailed to the targeted professionals and experts' respondents drawn from the field of additive manufacturing, to ensure research reliability and confidence. [1, 2] A situation where, based on the research variable of PQ, and importance of specialty, the related quality and manufacturing engineers in the midst were marked and sub-grouped as the main target. Then, with the principal component analysis, the 63 questionnaires returned within the stipulated time frame were sorted and classified under three employers' groups within the first; academia, second; industry, and third; research institutes of the respondents. This was based on the employment data provided in the questionnaires, which includes current positions of the respondents. [1, 2]

2.5. Fuzzy Logic-Based EbereDimMT001 Model

Fuzzy logic utilized in the Ebere Dim MT001, Semi-Direct Technological Maturity Assessment Methodology (SDTMAM) model, [1, 2] is a multiple valued logic that is obtained from a fuzzy set to consider and utilize the intermediate or approximate values instead of the only actual binary or two truth precise values; True and False. [1, 2, 7]. Thus, it brings about infinite number of truth values between true and false, where the true can be represented as ''1'', and false by ''0'', and any truth value between the true and false lies in between ''0'', and ''1'', such as ''0.2, 0.3, 0.6, 0.9'' are the approximate values rather than the precise values. In comparison, looking at a Crisp logic, it uses binary sets and binary logic of 1 for true and 0 for false in handling precise or exact information, but in contrary to that, Fuzzy logic is not limited to the values, 0 and 1, rather it has the degree of truth proposition or statement that fall between 0 and 1. [7]

However, it has also been realized that the capability maturity model (CMM) is a linguistic variable, which means that knowledge of fuzzy theory will be needed to transform the variables into numerical variables. Fuzzy logic like other artificial or machine intelligence tools is a comprehensive or more valid way of collecting research data and information outside the conventional quantitative method. [1, 2, 7]

However, the inputs can be either crisp or fuzzy, and the outputs as well can be either crisp or fuzzy, depending on the system and operation under study. Hence, when the input is crisp, it is defuzzified. Then, when output is crisp, it is applied or used directly, but if the output is fuzzy, it is defuzzified. [1, 2, 7]

2.6. Metal Additive Manufacturing Process Product Quality (PQ) Parameters

Manufacturable product characteristics and quality which are considered for the technology capability parameters of the MAMP include (i) dimensional accuracy (ii) surface roughness (iii) precision or repeatability and (iv) tolerance. [1, 2, 4, 10]. The product quality technology capability parameters which were further expanded or extended up to 18 in number covering various possible aspects of the technology operational phenomenal conditions in a metal additive manufacturing process through relationship-based classification, grouping and matches. [1, 2, 10, 11]

2.7. Metal Additive Manufacturing Process Product Quality Performance Indices

28-number measurable performance indices with objective checks as evident, were sourced from various metal additive manufacturing parametric studies and literature, experience and engineering practice covering the process challenging goals and conditions of manufacture. [1, 2, 4, 12, 13] Thus, providing for a set of probable 28 well-articulated and purposefully coined propositional research statements meticulously generated for experts' survey. However, these metal additive manufacturing process product quality performance indices are subject to a continuous scrutiny and review of its capability areas, characteristics, propositional statements, including the questionnaire to suit maturity assessment of the target technology at a time. [1, 2, 14, 15, 16]

2.8. Maturity Profiling for the Product Quality TMA of the MAMP

Maturity model or Maturity profile used in this research is with evolutionary steps that tend towards achieving a continuous mature process. They are five steps with a continuous representation, marked by the numbers 1 to 5. Each maturity level provided a layer in the foundation for continuous process improvement. [1, 2] It is one of the software process appraisal or system assessment tools used as a benchmark for development, comparison, and as an aid to understanding for continuous improvement of advanced metal manufacturing technology. [1, 2, 3, 5, 6]

Technology maturity in metal additive manufacturing process (MAMP) is a measurement of the ability of the process or its product quality to achieve a continuous improvement in a particular capability area. Maturity levels of MAMP are well-defined evolutionary plateau towards achieving an advanced or developed manufacturing process. Each maturity level provides a layer in the foundation for continuous process improvement which presents a way to describe the performance of a system. The maturity levels are calculated by the accomplishment of the specific and generic goals related to all predefined set of process work areas. [1, 2, 3, 5, 11]

Thus, the adapted maturity model for the product quality technology maturity assessment of a metal additive manufacturing process is the 5 Steps linguistic variables-based Capability Maturity Model Integration (CMMI) model by Carnegie Mellon University, Software Engineering Institute (SEI) in the table 2 below. Moreover, each maturity level considers a given group of reference models or the metal additive manufacturing process work areas, where achievement of a capability level in those MAMP process work areas, as explained in the model, allots a particular maturity level to the process technology as in the table 2 below. [1, 2, 3, 5, 11]

Table 2 The Capability Maturity Model Integration (CMMI Maturity Levels) Model

S/No	Levels	Maturity Levels Term (Linguistic)	Maturity Levels Qualification and Description
1	Level 5	Optimizing	Industry continually improves the processes with respect to a good quantitative understanding of the common causes of variation
2	Level 4	Quantitatively Managed	Industry and the technologies establish quantitative objectives for process quality performance, and use them as bases in managing processes
3	Level 3	Defined	Technologies are well defined and understood, proactive, and are described in standards, procedures, tools, processes, and methods
4	Level 2	Managed	Technologies are planned and executed in accordance with the process discipline reflected by maturity level
5	Level 1	Initial	Technologies are normally ad hoc and chaotic, whereby success depends on the competence of the personnel

3. Results and discussion

Experts' survey was conducted for the technology maturity of a metal additive manufacturing process, the data collected and processed in the process class frequency distribution tables. The maturity assessment results are analyzed and presented with the mean, median, mode, range, standard deviation (S), and the variance, for the process capability areas experts' survey result.

3.1. Product Quality Metal Additive Manufacturing Process Experts' Survey Maturity Data Profiling

The adapted capability maturity model integration (CMMI) was applied as a reference maturity profile for a scientific technology maturity assessment survey results data. The result in the table 3 below, is the maturity assessment survey outcome for the product quality technological maturity assessment of a metal additive manufacturing process.

Table 3 MAMP Product Quality Capability Maturity Framework and Survey Results Data Profiling

Levels	Focus	Process Capability Area	Result
5. Optimizing	Continuous Process Improvement	-	-
4. Process Quantitatively Managed	Process Quantitatively Managed	1, 5, 9, 17, 18, 19, 26	
3. Process Defined	Process Standardization	2, 3, 4, 6, 7, 8, 10, 11, 12, 13, 14, 15, 16, 20, 21, 22, 23, 24, 25	
2. Process Managed	Basic Process Management	-	-
1. Process Initiated	Process is Informal and Adhoc	No Process Area	

In addition to the experts' survey statistical results for the MAMP product quality capability maturity level ranking on the table 3, it is seen that 7 out of the 26 numbers of research survey statements of the questionnaire coded with their serial numbers, made it to the 4^{th} stratum of the CMMI maturity profile. While the remaining 19 MAMP concerns are heaped on the 3^{rd} stratum. Whereas there is none on the 5^{th} and 2^{nd} strata. The 1^{st} stratum of the CMMI maturity profile has no process area, which means that it did not come into assessment, hence overqualified for maturity level 1.

Thus, the representation shows that in the current performance capability maturity status of the MAMP manufacturing process and products, attention is needed with respect to each of the research statements to find out what is required to be done to ensure a continuous and sustainable movement of those on the 3^{rd} stratum into the 4^{th} stratum. The same thing will be expected of the few on the 4^{th} stratum to move into the 5^{th} stratum, and the 5^{th} optimizes.

Table 4 Statistical results of Product Quality Technology Maturity Assessment of MAMP

Variable	**Total Count**	**Percent**	**Mean**	**Sum**	**Minimum**	**Q1**
LPBFPPQ Maturity	26	100	3.1546	82.0200	2.6700	3.0000
Variable	Median	Q3	Maximum	Range		
LPBFPPQ Maturity	3.0000	3.4150	4.0000	1.3300		

Table 4 above presents the statistical results of the experts' survey showing the Minimum (mini) maturity level (ML) of the metal additive manufacturing process, the 1st Quartile (Q1), the Median, 3rd Quartile (Q3), and the Maximum (max) ML of the MAMP, with a range of 1.3300, and the interquartile range (IQR), 0.4150. This means that the middle 50% of the maturity spread only has a variability of 0.4150ML.

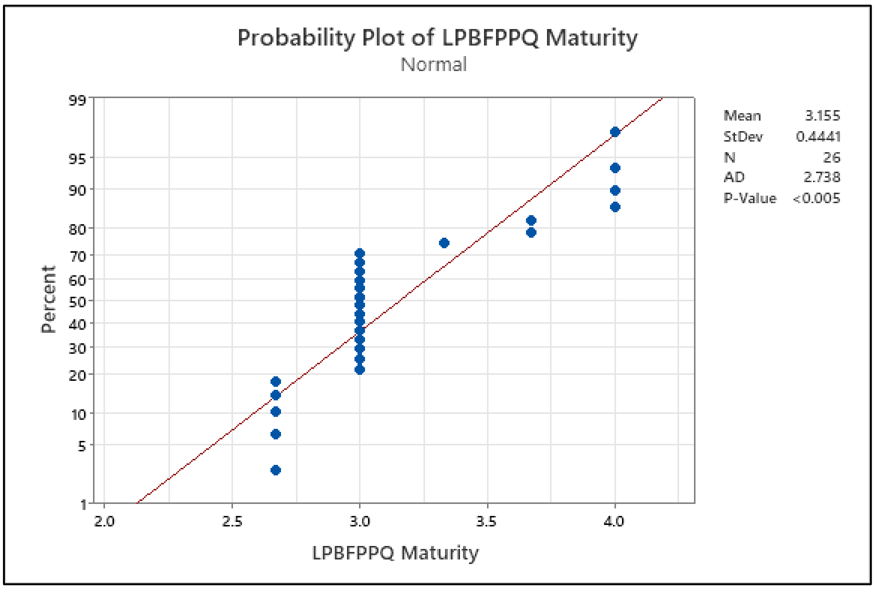

Figure 2 The normal probability test plot of LPBFPPQ maturity data on Minitab.

Figure 2 shows the normal probability test results for Anderson-Darling (AD). The probability value; P-Value is 0.005 and less than the significant level of 0.05. This means strong evidence against the null hypothesis (H_0). Also, the data do not follow a normal distribution and H_0 is rejected. Thus, the test is statistically significant. Standard deviation of 0.4441 was recorded.

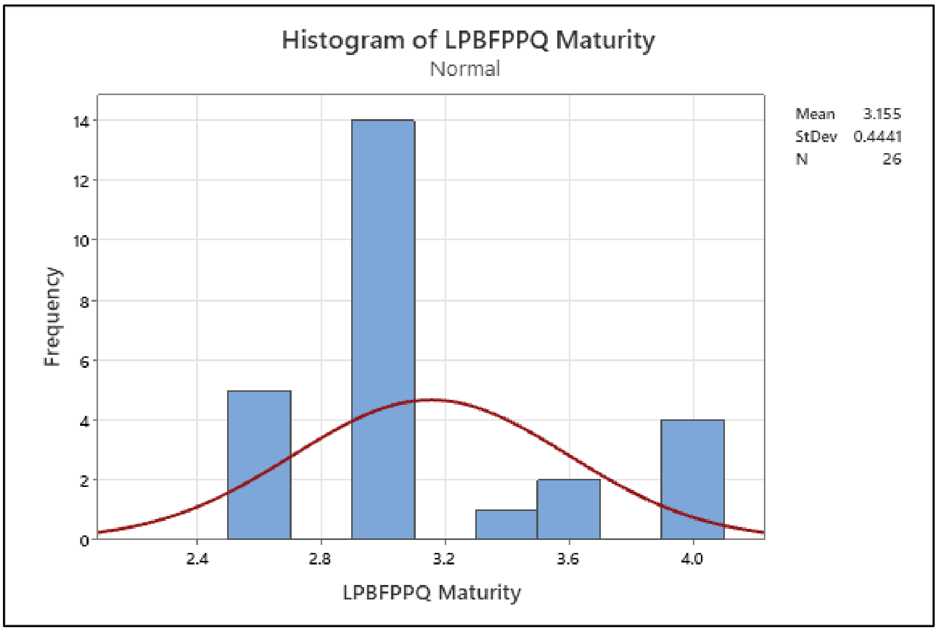

Figure 3 Histogram of LPBFPPQ maturity graph

Figure 3 is the histogram representation of the results of the 26-number sample size experts survey of the product quality technological maturity assessment of the metal additive manufacturing process. The mode is 3.00, where the mean maturity level 3.155, and the standard deviation (STD) 0.4441.

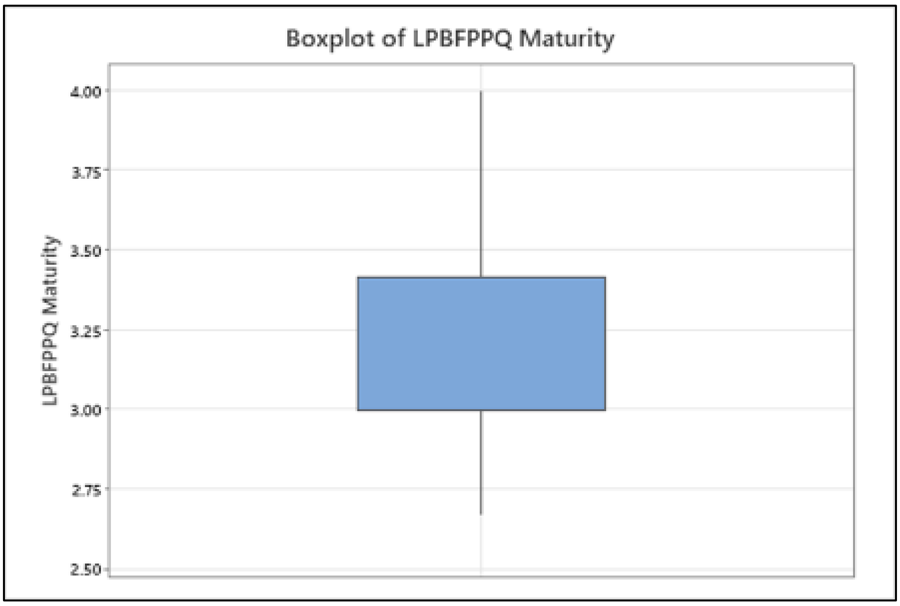

Figure 4 Boxplot of LPBFPPQ maturity

However, the boxplot figure 4, shows the product quality additive manufacturing process maturity data spread. It means that the laser PBF Process PQ maturity data is concentrated in the shaded area, which shows the Variability (V) of the LPBFPPQ maturity, where the Range (R) 1.3300, shows the extent LPBFPPQ maturity data spread out, while the Interquartile Range (IQR) 0.4150 meaning that the middle 50% of LPBFPPQ maturity data spread has 0.4150ML variability. Where the Median (M) 3.000ML, with a Mean (M) 3.155 ML.

Therefore, by the statistical analysis of the Fuzzy experts' survey results of the advanced metal additive manufacturing process, the maturity levels and the percentage maturity of the process is the cluster mean as in the table 5 below.

Table 5 Product Quality Technology Maturity Assessment Result of a Metal Additive Manufacturing Process

Process Product Quality Maturity Level	
MAMP	
ML	% Percentage
3.16	63.2

Thus, table 5 shows the result of the product quality technology maturity assessment of a metal additive manufacturing process (MAMP) at 3.16 of 5CMMI maturity profile, which is 78.8% maturity.

3.2. Contributions to Knowledge

The novel generic technology maturity assessment model, EbereDimMT001, designed was implemented successfully on the product quality technology maturity assessment of metal additive manufacturing process with impressive and consistent result, which validates the model. Therefore, the research has been able to make significant contribution to the field of advanced manufacturing engineering in general.

The generic technology maturity assessment model for advanced metal subtractive and additive manufacturing technology, EbereDimMT001, a semi-direct technology maturity assessment model was implemented on the metal additive manufacturing process, with an impressive and consistent result of 3.16 maturity level (ML) of 5CMMI maturity profile, which is 63.2% maturity, and within the Quantitatively Managed (QM) maturity level, which is a novel contribution to the field.

4. Conclusion

In conclusion therefore, the developed and designed novel generic model for maturity assessment of advanced manufacturing technology, EbereDimMT001 similarly was successfully adapted and implemented on metal additive manufacturing process (MAMP) with impressive and consistent outcome. Hence, the PQ technology maturity level of the MAMP is found at 3.16 of 5CMMl maturity profile, which is 63.2% maturity, with the application of the model. This model's result shows that the metal additive manufacturing technology is therefore at the quantitively managed (QM) maturity level. With the knowledge and experience in artificial intelligence fuzzy logic system and the SEI CMMI model, the novelty also opens doors for more research in the advanced manufacturing technologies, services, products and system development and improvement.

However, the results representation shows that in the current process product quality performance capability maturity profile of the MAMP, attention is needed with respect to each of the research survey statements to find out what should be done to ensure a continuous and sustainable movement of those on the 3rd stratum into the 4th stratum. The same goes to those on the 4th stratum to move into the 5th stratum.

Where in table 4, the outcome of the experts' survey shows the Minimum (mini) maturity level (ML) of the metal additive manufacturing technology, the 1st Quartile (Q1), the Median, 3rd Quartile (Q3), and the Maximum (max) ML of the MAMP, with a range of 1.3300, and the interquartile range (IQR), 0.4150, which means that the middle 50% of the maturity spread only has a variability of 0.4150ML.

Therefore, from the statistical analysis results of the MAMP, the maturity levels and the percentage maturity of the process is the cluster mean as in the table 4 above. Then, the metal additive manufacturing process (MAMP) product quality technological maturity is at 3.16ML, which means 63.2% maturity.

Limitations

- Could not get to the most desired experts and professional stakeholders questionnaire respondents.
- It was an individual research project
- Funding opportunity was limited
- The process capability area, parameters, maturity indicators (PMI), performance indices were solely identified and determined from studies and literature only.

Recommendations and Future Work

Experts' survey questionnaire should better target respondent quality and manufacturing engineers and technologists at the upper echelon of advanced manufacturing industries, institutions and societies such as the Mazak Corporation, DMG MORI, Manufacturing Technology Centre (MTC), UK, American Society of Mechanical Engineers (ASME), American Society for Testing and Materials (ASTM) for a more reliable, valid and dependable technology maturity research data.

Having gone through the rigours of the research, the product quality technology maturity assessment outcome for metal subtractive and additive manufacturing processes as reported, I suggest from observations, experience and knowledge that similar research be carried out on the advanced metal subtractive manufacturing processes.

Also, further study and research be carried out around the model to optimize the product quality technology maturity assessment and results of metal additive manufacturing technology.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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