World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Research Article)

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Application of Optimized Advanced Generic Product Quality Technology Maturity Assessment Model, EbereDimMT005 by Professional Fuzzy Inference Rule on Metal Hybrid Manufacturing Processes

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World Journal of Advanced Engineering Technology and Sciences, 2025, 16(03), 451-469

Publication history: Received on 19 August 2025; revised on 25 September 2025; accepted on 27 September 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.16.3.1365

Abstract

With the design and development of a new technological maturity assessment model, an additive hybrid manufacturing technology that integrates metal additive manufacturing laser powder bed fusion and subtractive manufacturing computer and numerical control (CNC) Machining processes on a single manufacturing platform was opened for product quality (PQ) technological maturity assessment using the optimized advanced generic product quality technology maturity assessment model, EbereDimMT005 by professional fuzzy inference rule to ascertain the level of technology advancement. In doing so, a digital manufacturing and artificial intelligence, data analytics and software engineering based consolidated semi-direct technological maturity assessment methodology (SDTMAM) model, with fuzzy logic system, set theory and membership function models were progressively and systematically assembled and applied with an extension as optimized advanced generic scientific tools to source and process research data for assessment of the PQ technological maturity of individual additive and subtractive manufacturing technologies, as well as the hybrid manufacturing technology. A Capability Maturity Model Integration (CMMI) maturity profile of the Software Engineering Institute (SEI) of the Carnegie Mellon University, USA was adapted as a reference maturity profile framework for the technological maturity assessment (TMA) results and ranking. The metal HMT PQ after research and results simulation was consistently found at the quantitatively managed maturity level 4ML of 5-ML CMMI maturity profile, where the technological maturity level of metal HMT based on PQ is precisely at 3.18ML, which is 63.5% maturity, therefore justifies and validates the model.

Keywords: Hybrid Manufacturing; Subtractive Manufacturing; Additive Manufacturing; Machining Process; Product Quality; Maturity Profile; Metal Powder; Fuzzy Logic; Process Capability Area; Performance Indices

1. Introduction

A need for viable data-based status, the need to assure and reassure both the existing and prospective government agencies, academia, and private industry investors of the reality on the cutting-edge additive and hybrid manufacturing technologies has necessitated the need for continuous research into the product quality technological maturity assessment of the emerging technologies. Metal additive hybrid manufacturing technology as a new manufacturing technology in which subtractive and the base additive manufacturing processes are combined in a single manufacturing cell through a hybrid manufacturable means, process and product design, material selection, modelling and data filing, followed with a 3-D printing process, in a powder or wire feedstock materials form, in the additive hybrid manufacturable process design and implementation in layers, to produce higher quality products and engineering components of complex geometry for most currently in the high-risk fields of aerospace, medicine, automotive and

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defense industry sectors application taking advantage of the capabilities of the individual technology in a single machine platform. [1], [2] Hence, the need to ascertain a more detailed, reliable and confirmatory maturity model and level of technology advancement first in the subtractive, additive and hybrid manufacturing technology (in combination) resulted in the proposal to implement the designed and developed consolidated model, EbereDimMT005 by professional fuzzy inference rule on metal hybrid manufacturing technology that integrates additive laser PBF and the CNC Machining processes.

2. Methodology

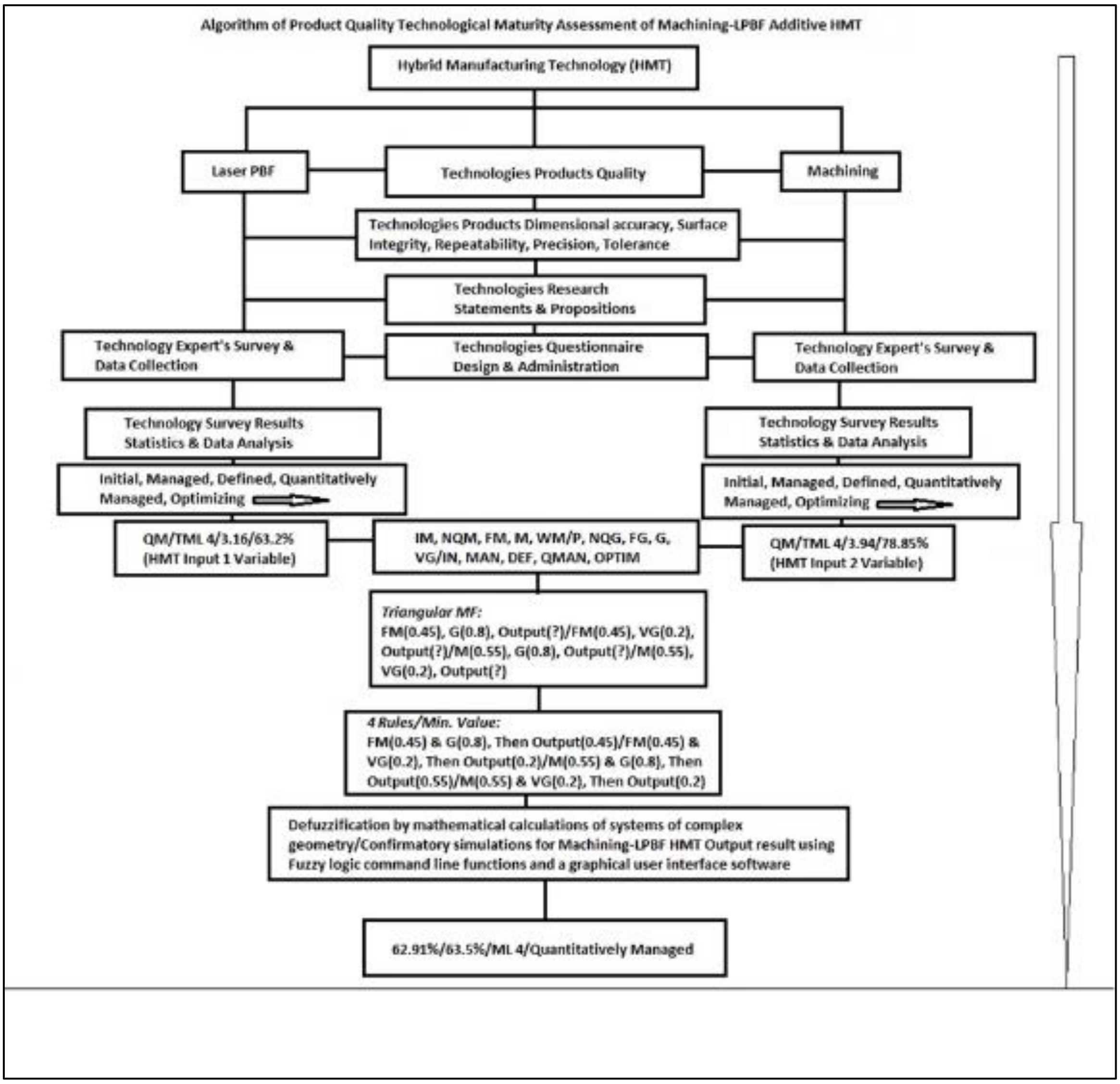

Figure 1 The algorithm of the product quality TMA of HMT by EbereDimMT005 model

EbereDimMT005 by professional fuzzy inference rule is the new model designed and developed, a nonlaboratory experimental research on the individual advanced subtractive and additive manufacturing technologies and in combination (hybrid), which involves applications of some knowledge of advanced digital manufacturing, artificial intelligence (AI), data analytics and software engineering to the optimized advanced generic product quality technological maturity assessment of hybrid manufacturing technology in progressive procedural steps. [1], [3], [4], [5], [6], [7], [8], [9]

Algorithm of Application of the Optimized Advanced Generic Product Quality TMA Model, EbereDimMT005 by Professional Fuzzy Inference Rule on Metal Hybrid Manufacturing Technology

The algorithm of implementation of optimized advanced generic semi-direct product quality TMA of a hybrid manufacturing technology that integrates metal additive laser powder bed fusion (LPBF) manufacturing and computer and numerical control (CNC) machining processes is shown in figure 1 below as also explained in the schematic illustration in table 1. [1], [3], [4], [5], [6], [7], [8], [9]

The Schematic Representation of the Optimized Advanced Generic TMA Model, EbereDimMT005 by Professional Fuzzy Inference Rule on Metal Hybrid Manufacturing Technology

Table 1 below shows progressive procedural steps for the optimized advanced generic TMA model, EbereDimMT005 by professional fuzzy inference rule for technology maturity assessment of metal hybrid manufacturing processes, drawn from the SDTMAM algorithm of figure 1 as implemented on the metal hybrid manufacturing technology that integrates LPBF and CNC machining processes with seamless flow and consistent result. [1], [3], [4], [5], [6], [7], [8], [9]

Table 1 Schematic representation of the optimized advanced generic TMA model, EbereDimMT005 implementation on metal HMT

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 survey was carried out, data collected and analysed with results
9.	Step9.	The Input/Output maturity results were independently fuzzified into five subsets each
10.	Step10.	Membership functions were created and assigned to the Inputs/Output fuzzy subsets with results.
11		Application and execution of Fuzzy graphical inference rules on process subsets with results
12	Step12.	Defuzzification of the result was carried out with engineering mathematical model for exact maturity level result by applying a centroid defuzzification method with results
13		Application and execution of Experts' inference rules on process subsets results with result
14	Step13.	Simulation of results 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 results
15	Step14.	Presentation and analyses of final results

3. Model charging and system harnessing

3.1. Determining the Product Quality Metal Hybrid Manufacturing Processes Capability Area

The capabilities of metal hybrid manufacturing technology are identified and classified under a single or a few variables or process capability areas, dependent on the expected research scope. Each of the process capability areas is defined based on the aim and objective of the research and with respect to the associated capability parameters which inversely transformed and served as the hybrid manufacturing process capability performance indices. In this case, the process product quality. [1], [10], [11], [12], [13], [14], [15], [16]

3.2. Determining the Metal Hybrid Manufacturing Processes Product Quality (PQ) Parameters

For the process product quality in this research covering the process achievable dimensional accuracy, surface roughness, tolerance, repeatability statuses of the metal hybrid manufacturing process, it is as the degree of how good or bad in terms of product physical appearance and related characteristics. Thus, if the capability of a manufacturing technology is determined by its manufacturable or achievable product characteristics and quality, they can be considered for some of the technology capability parameters. Also considering the commonness of these machined product characteristics with those of the additive manufacturing products, they also can be termed the interface parameters, which form the basis for measurement and comparison between the hybrid manufacturing processes. [1], [10], [11], [12], [13], [14], [15], [16]

3.3. Establishing Metal Subtractive (CNC machining) and Metal Additive Manufacturing Processes Expanded Parameters

18-number of expanded individual metal subtractive and additive manufacturing processes parameters each, covering the entire processes PQ capability area of the technologies as possible were identified and generated from the initial 5-number of manufacturing process product characteristics established from literature and related research publications. [1], [10], [11], [12], [13], [14], [15], [16]

3.4. Establishing the Metal Hybrid CNC Machining and LPBF Additive Manufacturing Product Quality Parametric Interface

These independent process parameters were unified by relationships and matchings to form a 19-number common manufacturing process product quality parametric interface for the metal hybrid manufacturing technologies under investigation and assessment. [1], [10], [11], [12], [13], [14], [15], [16]

3.5. Generating the Metal Hybrid Manufacturing Processes Product Quality Performance Indices

The parametric issues and concerns raised in the hybrid manufacturing technologies research literature and conference materials were used to identify and generate 28-number metal hybrid manufacturing process product quality performance indices, which serve as the common process performance indicators for the product quality technological maturity assessment of metal subtractive and metal additive hybrid manufacturing processes, also, from where the prepositional research statement for the experts' technological maturity surveys were coined. [1], [10], [11], [12], [13], [14], [15], [16]

4. Modeling and analysis

4.1. Experts' Fuzzy Survey Questionnaire Design for EbereDimMT005 Product Quality TMA of Metal HMT

As a result of the optimized advanced generic semi-direct technology maturity assessment methodology approach, EbereDimMT005 of the assessment, the challenging vague and irregular nature of the linguistic variables, maturity as a developmental process, product quality and parameters, the metal hybrid manufacturing processes parameters, the performance indices and the associated maturity profiling condition necessitated the introduction of artificial intelligence based fuzzy logic principle in the planning and design of a number set of questionnaires for experts' survey, and collation of research data. [1], [10], [11], [12], [13], [14], [15], [16]

To ensure sanity, remove bias to take care of various degrees of technology developmental stages, which the binary questionnaire response cannot capture, 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], [3], [4], [5], [6], [9] Next to enliven, is the set of 28 sub-parametric metal hybrid manufacturing processes performance indices carefully identified and established from various metal hybrid manufacturing technology literature and studies, experience and engineering practice. [1], [10], [17], [18], [19]

Thus, as contained are result oriented research propositional statements coined from the metal hybrid manufacturing processes and product quality key performance indices with appraisal expertise and experience to control and guide respondents directly to 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 hybrid manufacturing processes about the research statements. [1] 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], [3], [4], [5], [10], [11], [12], [13], [14], [15], [16] Similarly, to prevent a situation of bias in the questionnaire planning and administration, and the result too, sure was made that there is no information in the questionnaire system that can reveal or suggest to the expert respondents, the aim and beneficiaries of the project, neither the data nor the either statements. Hence, will eliminate sentiments and bias influences on the questionnaire system and research data collation. [1], [3], [4], [5], [6], [7], [9], [10], [11], [12], [13], [14], [15], [16]

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

Meanwhile, to ensure and improve the reliability and confidence of research, a total of 150 sets of the questionnaires were directly emailed to the targeted experts' respondents drawn from the field of metal additive and subtractive manufacturing. A situation where, based on the research variable of PQ, and importance of specialty in the project, the related quality and manufacturing engineers in the midst were marked and sub-grouped as main target. Then, applying the principal component analysis principle, the 63 questionnaires returned simultaneously for each process, and within the stipulated time frame were sorted independently and classified under three employers' groups within the first; academia, second; industry, and third; research institutes of the respondents also for each process. This was based on the employment data provided in the questionnaires, which includes current position of the respondents. [1], [3], [4], [5],[6], [7], [9], [10], [11], [12], [13], [14], [15], [16]

4.3. Maturity Profiling for the Product Quality TMA of the Metal Hybrid Manufacturing Processes

The capability maturity model adopted in this research as the maturity profile for the scientific technology maturity profiling 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. [9] 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], [3], [4], [5], [6], [7], [9], [10], [11], [12], [13], [14], [15], [16]

Technology maturity in metal hybrid manufacturing processes (MHMP) 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 MHMP 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], [3], [4], [5], [6], [7], [9]

Thus, the adapted maturity model for the EbereDimMT005 product quality technology maturity assessment of a metal hybrid manufacturing processes is the 5-step 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 hybrid manufacturing processes work areas, where achievement of a capability level in those MHMP work areas, as explained in the model, allots a particular maturity level to the processes. [1], [2], [3], [4], [5], [6], [7], [9]

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

5. Primary results and discussion

The integral TMA experts' survey data collected and results were processed and analyzed as presented simultaneously for both metal additive manufacturing process (MAMP) and the MSMT under hybrid manufacturing process.

5.1. Simultaneous Product Quality Metal Hybrid Manufacturing Processes Experts' Survey Maturity Data Profiling

Table 3 Product Quality Capability maturity ranking framework and experts survey results data profiling for MAMT LPBF

Level	Focus	Process Capability Area	Result
5 Process 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	
2Process Managed	Basic Process Management	-	-
1Process Initiated	Process is informal and Adhoc	No Process Area	

Table 4 Product Quality capability maturity ranking framework and experts survey results data profiling for MSMT CNC machining

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

The adapted capability maturity model integration (CMMI) was applied simultaneously as a reference maturity profile for both processes' scientific technology maturity assessment survey results data. The results in the table 3 and table 4 above, are the maturity assessment survey data collation and ranking for the product quality technological maturity assessment of the metal hybrid manufacturing processes in numbers.

Following the experts' survey statistical results for the MAMP LPBF 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 4th stratum of the CMMI maturity profile. While the remaining 19 MAMP concerns are heaped on the 3rd stratum. Whereas there is none on the 5th and 2nd strata. The 1st 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.

Similarly, the result in the table 4, is the maturity assessment survey outcome for the product quality technological maturity assessment of the MSMT CNC Machining. The representation shows that in the current performance capability maturity status as seen, 11 out of the 26 numbers of research survey statements of the questionnaire as coded with numbers, made it to the 5th stratum of the CMMI maturity profile. 10 made it to the 4th stratum, while the remaining 5 machining concerns are found on the 3rd stratum. Where there is none on the 2nd stratum. The 1st 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.

So, it shows in both table representations that for the current performance capability maturity status of the hybrid MAMP and MSMT manufacturing processes 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 up ranks of those on the 3rd stratum into the 4th stratum. The same thing will be expected of the few on the 4th stratum to move into the 5th stratum, while the 5ths continue to optimize.

Simultaneous Product Quality Experts' Survey Statistical Results and Graphical Representations, and Analyses for the Metal Hybrid Manufacturing Processes

The scientific statistical results and graphical analyses of the experts' survey primary data outcomes are as represented and explained in the tables 5, 6, 7 and 8, and figures 2, 3, 4, 5, 6, 7 and 8 below.

Table 5 Statistical results of Product Quality Technology Maturity Assessment of MAMP LPBF

Variable	**Total Count**	**Percent**	**Mean**	**StDev**	**Variance**	**Sum**	**Minimum**		**Q1**
LPBFPPQ Maturity	26	100	3.1546	0.4441	0.1972	82.0200	2.6700		3.0000
Variable	Median	Q3	Maximum	Range					
LPBFPPQ Maturity	3.0000	3.4150	4.0000	1.3300					

Table 6 Statistical results of Product Quality Technology Maturity Assessment of MSMT CNC Machining

Variable	**Total Count**	**Percent**	**Mean**	**StDev**	**Variance**	**Sum**	**Minimum**	**Q1**	**Median**
MPPQ Maturity	26	100	3.936	0.574	0.329	102.330	3.000	3.585	4.000
Variable	Q3	Maximum	Range						
MPPQ Maturity	4.330	4.670	1.670						

Table 5 and table 6 above presents the statistical results of the experts' survey showing the Minimum (mini) maturity level (ML) of the metal hybrid manufacturing processes. For MAMP, 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. Whereas for the MSMT, the 1st Quartile (Q1), the Median, 3rd Quartile (Q3), and the Maximum (max) ML of the MSMT, with a range of 1.670, and the interquartile range (IQR), 0.745 This means that the middle 50% of the maturity spread only has a variability of 0.745ML.

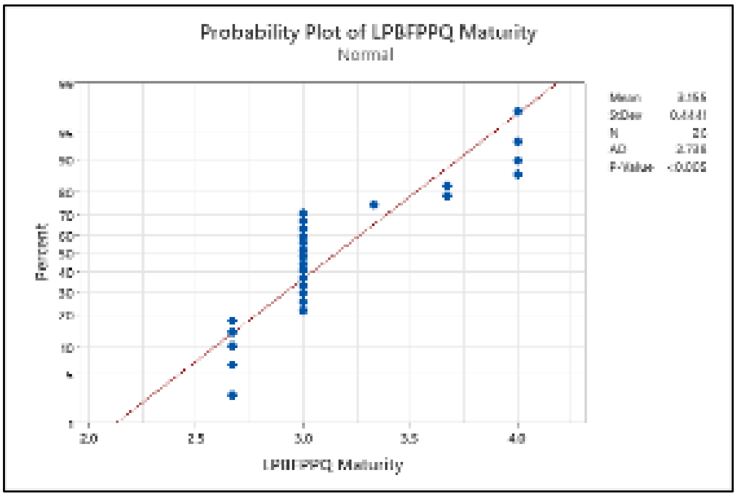

Figure 2 The normal probability test plot of LPBFPPQ maturity data on Minitab

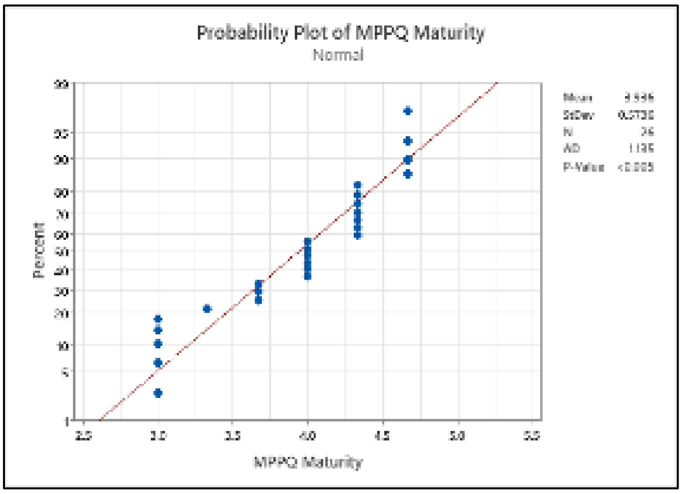

Figure 3 The normal probability test plot of CNC MPPQ maturity data on Minitab

Figure 2 and figure 3 show the both normal probability test results of the metal hybrid manufacturing processes. For the MAMP LPBFPPQ, Anderson-Darling (AD) is 2.738. The probability value; P-Value is 0.005 and less than the significant level of 0.05, and a standard deviation of 0.4441 was recorded. [1] Where for the MSMT CNC MPPQ, Anderson-Darling (AD) is 1.135. The probability value; P-Value is 0.005 and less than the significant level of 0.05, and a standard deviation of 0.5736 was recorded. Thus, the two results mean strong evidence against the null hypothesis (H_0). Also, both data do not follow a normal distribution and H_0 is rejected, and the test is statistically significant.

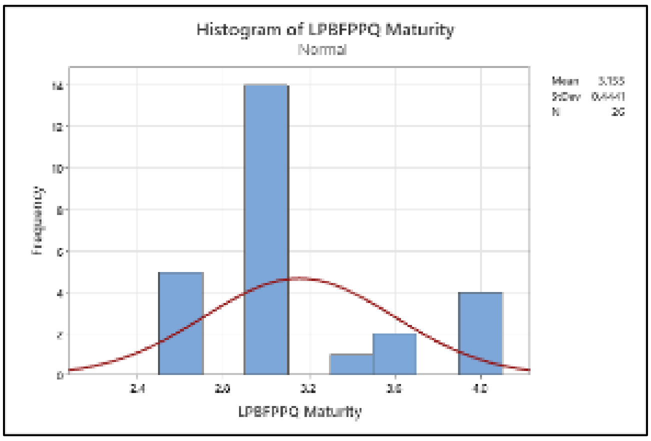

Figure 4 Histogram of LPBFPPQ maturity graph

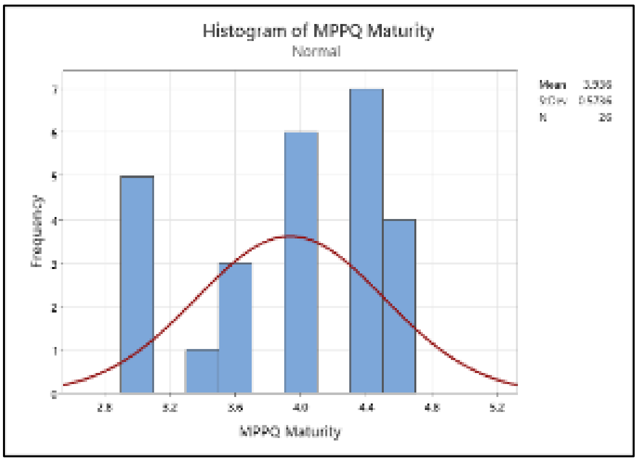

Figure 5 Histogram of CNC MPPQ maturity graph

Figure 4 and figure 5 are the histogram representations of the results of the 26-number sample size experts survey of the product quality technological maturity assessment of the metal hybrid manufacturing processes. Where for the MAMP LPBFPPQ, mode is 3.00, the mean maturity level 3.155, and the standard deviation (STD) 0.4441. Then, for the MSMT MPPQ, mode is 4.4, where the mean maturity level 3.936, and the standard deviation (STD) 0.5736.

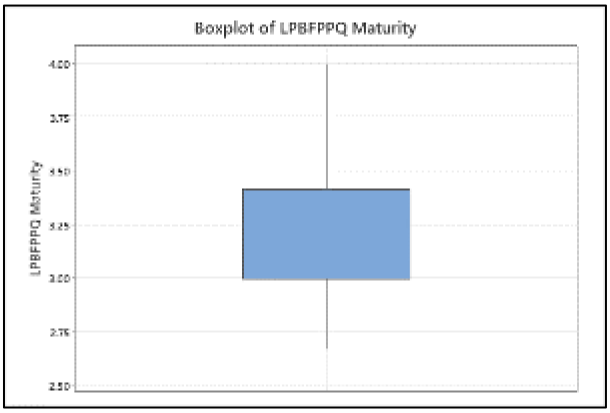

Figure 6 Boxplot of LPBFPPQ maturity

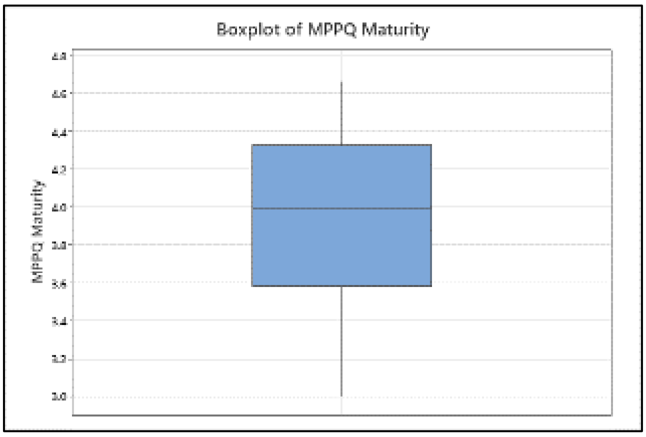

Figure 7 Boxplot of CNC MPPQ maturity

However, the boxplots figure 6 and figure 7, show the product quality metal hybrid manufacturing processes maturity data spreads. It shows that for the MAMP laser PBF Process PQ maturity, data is concentrated in the shaded area, which means the Variability (V) of the LPBFPPQ maturity, then the Range (R) 1.3300, shows the extent LPBFPPQ maturity data spread out, while the Interquartile Range (IQR) 0.4150 means that the middle 50% of LPBFPPQ maturity data spread has 0.4150ML variability, and the Median (M) 3.000ML, with a Mean (M) 3.155 ML.

Similarly, for the MSMT CNC Machining PPQ maturity, it shows data is concentrated in the shaded area, which means the Variability (V) of the CNC MPPQ maturity, where the Range (R) 1.670, shows the extent CNC MPPQ maturity data spread out, while the Interquartile Range (IQR) 0.745 means that the middle 50% of CNC MPPQ maturity data spread has 0.745ML variability. Where the Median (M) 4.000ML, with a Mean (M) 3.936 Maturity.

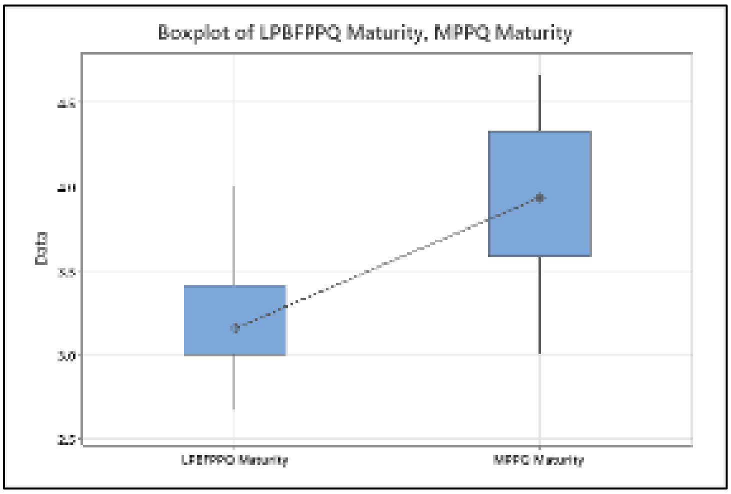

Figure 8 A double Boxplot for a set of LPBFPPQ maturity And CNC MPPQ maturity data

Finally, the double boxplot in figure 8 means that the LPBFPPQ maturity with the smaller box shows that data is more concentrated in the area and has less variability than the CNC MPPQ maturity. Thus, comparing their individual Range, it shows that the CNC MPPQ has more spread out. Also, their Interquartile Range (IQR), the CNC MPPQ data has more variability than the LPBFPPQ.

6. Method

μ_1: population mean of LPBFPPQ Maturity

μ_2: population mean of MPPQ Maturity

Difference: μ_1 - μ_2

Equal variances are not assumed for this analysis.

Table 7 Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
LPBFPPQ Maturity	26	3.155	0.444	0.087
MPPQ Maturity	26	3.936	0.574	0.11

Estimation for Difference

Difference	95% CI for Difference
-0.781	(-1.067, 0.495)

Test

Null hypothesis H_0: $\mu_1 - \mu_2 = 0$

Alternative hypothesis H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value

-5.49 47 0.000

Table 8 Product quality TMA of metal hybrid manufacturing processes results

Product Quality of Metal HMT (Subtractive and Additive) Maturity Level			
Laser PBF		CNC Machining	
ML	%tage	ML	%tage
3.16	63.2	3.94	78.8

Therefore, by the statistical analysis of the Fuzzy experts' survey results of the metal hybrid manufacturing technologies, the maturity levels and the percentage maturity of the processes are the cluster means as represent in the table 8 above being now the primary processes maturity levels.

6.1. Introducing Membership Function Model to the Maturity Levels

As the primary maturity level of the metal hybrid manufacturing technology that integrated the CNC machining and the laser powder bed fusion has been found, yet, there is a need to also find out how true or the degree of truth in the maturity level found. This leads to the introduction of membership functions model in addition, thereby advancing the generic product quality metal hybrid manufacturing TMA model, EbereDimMT002 [1], [5], [6], [12], [15], [16] further to determine the membership function of the primary maturity levels. Thus, a set of maturity subsets are established with some familiar descriptors, to determine the membership functions of the subsets as in the figures 9, 10, 11 and 12 below. Therefore, defining the membership functions for each set of the Input (1), Input (2) and the Output descriptors, a triangular membership function is applied in the three fuzzy subsets. Where the LPBF process subset descriptors; IM, NQM, FM, M, WM, the CNC Machining process subset descriptors; P, NQG, FG, G, VG, and the HMT Output subset descriptors: IN, MAN, DEF, QMAN, OPTIM, and equation of a straight line is used to determine the membership functions for all the different descriptors and their corresponding membership values as follows. [1], [5], [6], [12], [15], [16]

$\frac{y_2-y_1}{x_2-x_1} = \frac{y-y_1}{x-x_1}$ ---(i)

Where $y = \mu$ and $x = x_m$ (Input Variable or the element which must belong to the universe of discourse (X))

Input (1)

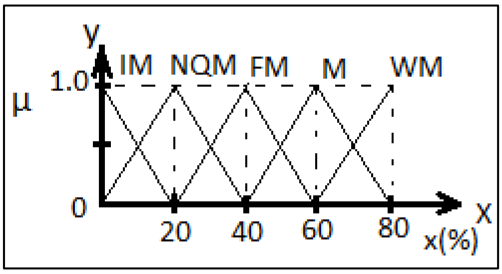

Figure 9 Element of the PPQ Input 1 universe of discuss

Membership functions summarily,

μIM = 20 –x/20 [0,20]

μNQM = x/20 [0,20], 40 – x/20 [20,40]

μFM = x - 20/20 [20,40], 60 – x/20 [40,60]

μM = x - 40/20 [40,60], 80 – x/20 [60,80]

μWM = x - 60/20 [60,80]

Input (2)

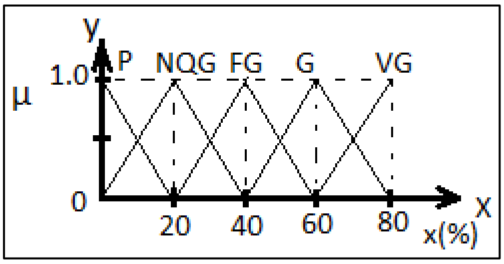

Figure 10 Elements of the PPQ Input 2 universe of discuss

Membership functions summarily,

μP = 20 –x/20 [0,20]

μNQG = x/20 [0,20], 40 – x/20 [20,40]

μFG = x - 20/20 [20,40], 60 – x/20 [40,60]

μG = x - 40/20 [40,60], 80 – x/20 [60,80]

μVG = x - 60/20 [60,80]

Then, applying the percentage of the crisp maturity values of the LPBF (Input 1) and the Machining (Input 2) against their respective current chosen universe of discourse (X), the elements of the subsets and membership functions (μ).

Therefore,

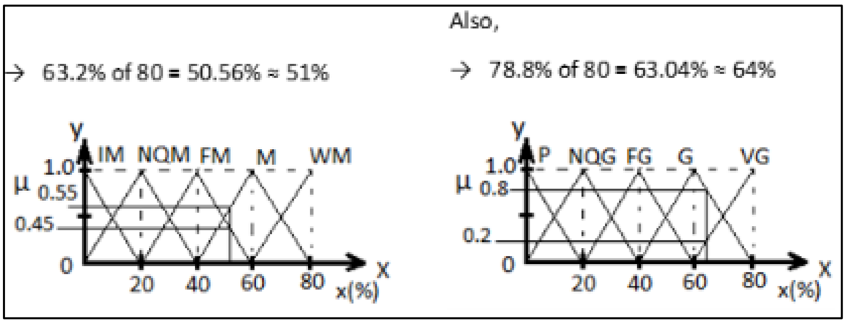

Figure 11 Membership values of the PPQ Inputs

Thus, forming the mapping between the different Inputs, their membership values are associated and matched. Each of them to each other, and a four-rule base is obtained as in table 9 below. [1]

Table 9 Four-Rule base of the PPQ TMA Inputs

Rule 1	**Input (1) FM (0.45)**	**Input (2) G (0.8)**
Rule 2	Input (1) FM (0.45)	Input (2) VG (0.2)
Rule 3	Input (1) M (0.55)	Input (2) G (0.8)
Rule 4	Input (1) M (0.55)	Input (2) VG (0.2)

Output

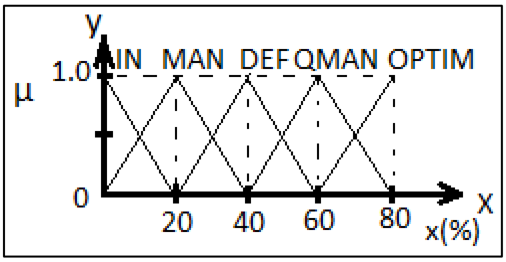

Figure 12 Membership functions of PPQ Output universe of discourse

Membership functions summarily,

μIN = 20 –x/20 [0,20]

μMAN = x/20 [0,20], 40 – x/20 [20,40]

μDEF = x - 20/20 [20,40], 60 – x/20 [40,60]

μQMAN = x - 40/20 [40,60], 80 – x/20 [60,80]

μOPTIM = x - 60/20 [60,80]

6.2. Introducing Process Product Quality (PPQ) Professional Fuzzy Inference Rule System Model

Here, on the basis of objective evidence and reasoning too as required, conclusions are to be reached to find what the Output will be for each of the mapping of the Input (1), Input (2) this time, where each subset is represented by its five individual assigned descriptors as follows.

The Input (1) subset descriptors: IM, NQM, FM, M, WM

The Input (2) subset descriptors: P, NQG, FG, G, VG

The Output subset descriptors: IN, MAN, DEF, QMAN, OPTIM

Thus, with the metal additive hybrid manufacturing professionals and experts' knowledge of the compatibility and complementarity of the two processes Inputs, a rule base system is developed and applied as in the Table 12 below. The system enables one of the entrusted mechanical engineers (quality and manufacturing engineers) engaged to run and determine through knowledge and experience, each Output by drawing inferences from each of the combination of Input (1) and Input (2) data each time from the beginning to the end. Hence a professional fuzzy inference rule.

Table 10 Professional Fuzzy Inference rules for the PPQ TMA Inputs and Output

Input 1/2	**IM**	**NQM**	**FM**	**M**	**WM**	**Output**
P	IN	MAN	DEF	QMAN	OPTIM	IN
NQG	IN	MAN	DEF	QMAN	OPTIM	MAN
FG	IN	MAN	DEF	QMAN	OPTIM	DEF
G	IN	MAN	DEF (1)	QMAN (2)	OPTIM	QMAN
VG	IN	MAN	DEF (3)	QMAN (4)	OPTIM	OPTIM

Hence, the membership functions of Input (1) are within the range of FM and M, while the membership functions of Input (2) are within the range of G and VG.

Then, fuzzification and evaluation of the rules imply.

Rule 1: If the Input (1) is fairly mature (FM), and the Input (2) is good (G), then, the Output, which is the hybrid Inputs (1) and (2) (Hybrid manufactured) maturity is defined (DEF).

Rule 2: If the Input (1) is fairly mature (FM), and the Input (2) is very good (VG), then, the Output, which is the hybrid Inputs (1) and (2) (Hybrid manufactured) maturity is defined (DEF).

Rule 3: If the Input (1) is mature (M), and the Input (2) is good (G), then, the Output, which is the hybrid Inputs (1) and (2) (Hybrid manufactured) maturity is quantitatively managed (QMAN).

Rule 4: If the Input (1) is mature (M), and the Input (2) is very good (VG), then, the Output, which is the hybrid Inputs (1) and (2) (Hybrid manufactured) maturity is quantitatively managed (QMAN).

Therefore, a graphical technique of inference is applied as in the figure 13 below, to obtain the required maturity level of the Output.

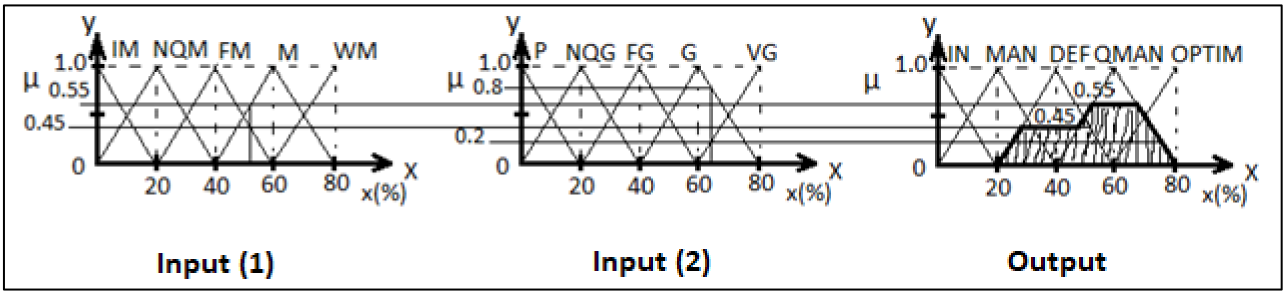

Figure 13 Manual graphical technique of inference of PPQ TMA

However, the Output above is an aggregated Output graph. It is still a vague value. Hence, it covers the entire shaded region. So, to determine the crisp or classical Output that gives the exact, a clear-cut or precise maturity value of the processes pair Inputs and Output value, and engineering mathematical model being a centroid method is applied as in the figure 14 below, and finally defuzzifying the value (Z*).

Therefore, applying the Centroid Defuzzification method;

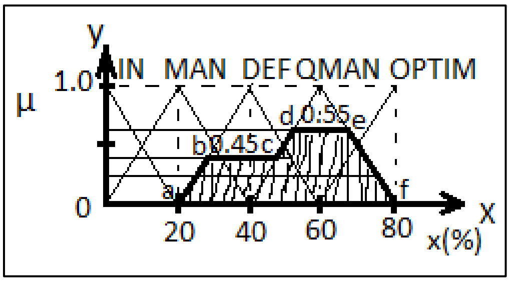

Figure 14 Fuzzy process PQ TMA Output

Applying the equation of a straight line; Eqn. (i)

$\frac{y_2 - y_1}{x_2 - x_1} = \frac{y - y_1}{x - x_1}$, Where y = μz, and x = z

Process Product Quality Defuzzification of the fuzzy Set Inference Output Result

Finally, defuzzifying value (Z*) implies introducing a Centroid Defuzzification formula; Eqn. (ii) [53].

$Z^* = \frac{\int \mu\bar{z} * z\delta z}{\int \mu\bar{z} * \delta z}$ Where $y = \mu\bar{z}$, and $x = z$ .... (ii)

Thus, the product quality technology maturity assessment of the metal hybrid manufacturing technology is the result of the defuzzification of the shaded portion of the graphical figure 14, by engineering mathematical model calculations and result for the complex system geometries. [1]

Confirmatory Product Quality Metal Hybrid Manufacturing Technology Maturity Assessment Results Simulations in Fuzzy Logic System in MATLAB Toolbox

The assenting result of the simulation is as represents in the graphical figure 15 below following the fuzzy logic command line functions for the AM (LPBF), SM (Machining), and HM Processes Product Quality Maturity. [1], [5], [6], [12], [15], [16]

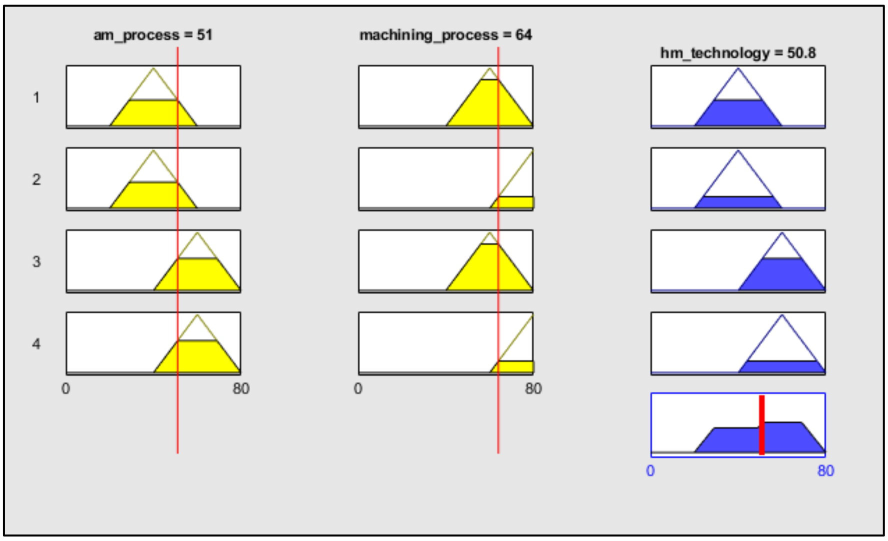

Figure 15 The Rule Viewer Output format in a fuzzy logic system toolbox in MATLAB.

7. Discussion

In summary, figure 15 above shows a dynamic inference process for the fuzzy product quality metal hybrid manufacturing technology maturity assessment process, where the values of the Inputs 1 and 2, can be varied accordingly to yield a corresponding Output of each fuzzy rule. Also shown last are the aggregated or integral Output fuzzy set, and its defuzzified or precise maturity level or value within the universe of discourse, hence to further be converted to percentage maturity level.

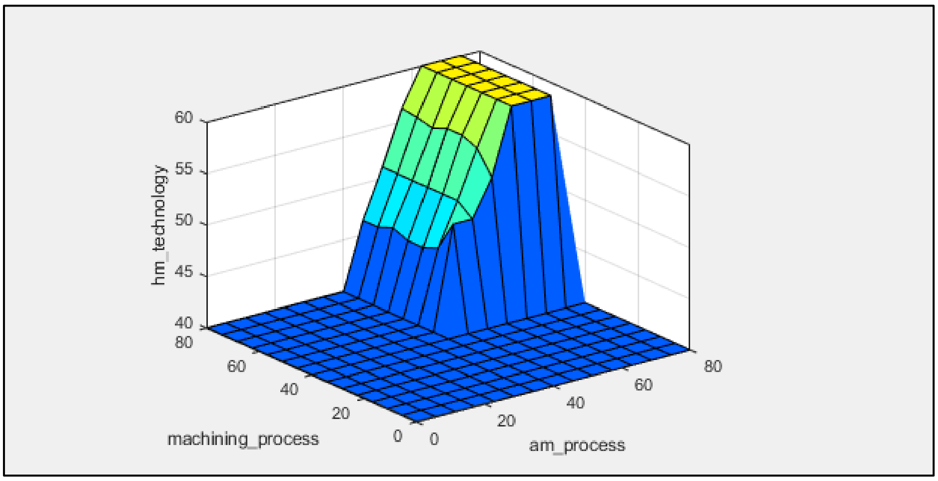

Figure 161 The Surface Viewer Output format in fuzzy logic system toolbox in MATLAB.

Whereas figure 16 that follows shows a static three-dimensional graphical mapping of combination of the Inputs 1 and 2, and the Output process product quality metal hybrid manufacturing technology maturity level. The developed inference system in this case now has three Inputs, where the surface view shows any of the two sets combination of Inputs and Outputs maturity level or value within the universe of discourse, to further be converted to percentage maturity level.

Therefore, by the engineering mathematical model implementation results, the percentage (%) product quality technology maturity of CNC Machining-Additive LPBF hybrid manufacturing technology, implies

$$\frac{\mathbf{50.33}}{\mathbf{80}} \times \mathbf{100} = \mathbf{62.91}\%$$

Thus, the hybrid manufacturing technology product quality is at maturity level 4 (Quantitatively managed)

Whereas, by the simulation of the model implementation results, the percentage (%) product quality maturity of CNC Machining-Additive LPBF hybrid manufacturing technology, implies

$$\frac{\mathbf{50.8}}{\mathbf{80}} \times \mathbf{100} = \mathbf{63.5}\%$$

Also, the metal hybrid manufacturing technology product quality by simulation is at maturity level 4 (Quantitatively managed)

7.1. Optimized advanced generic product quality TMA model result and discussion

The table 11 below presents result of the optimized advanced generic technology maturity assessment model, EbereDimMT005 by Professional fuzzy Inference Rule on metal hybrid manufacturing Technology.

Table 11 Metal Additive Hybrid Manufacturing Processes Product Quality MLs

Process Product Quality Maturity Level					
LPBF		Machining		HMT	
ML	%	ML	%	ML	%
3.19/5	63.75	4.0/5	80	3.18/5	63.5

Therefore, the product quality technology maturity of metal hybrid manufacturing technology is at maturity level 4 (Quantitatively managed) of the 5CMMI maturity profile.

Analysis of Processes Product Quality ML

The technological maturity level of the metal additive hybrid manufacturing technology (MAHMT) with respect to the process product quality (PPQ) is as follows and in the table 11 above.

LPBF: the maturity level is 3.19/5 representing 63.75%

Machining: the maturity level is 4.0/5 representing 80%

MAHMT: the maturity level is 3.18/5 representing 63.5%

The MAHMT maturity for PPQ is therefore at 63.5%

7.2. Contributions to Knowledge

The optimized advanced generic technology maturity assessment model, EbereDimMT005, was implemented successfully on the product quality technology maturity assessment of metal hybrid manufacturing technology that integrated LPBF and CNC Machining processes with impressive and consistent result, which validates the model. Thus, the research has been able to make significant contribution to the field of advanced manufacturing engineering.

The optimized advanced generic technology maturity assessment model for metal hybrid manufacturing technology, EbereDimMT005 by Professional fuzzy Inference Rule, a semi-direct technology maturity assessment model was implemented on the metal hybrid manufacturing process, with an impressive and consistent result of 3.18 maturity level (ML) of 5CMMI maturity profile, which is 63.5% maturity. and within the Quantitatively Managed (QM) maturity level, which is a novel contribution to the field.

8. Conclusion

In conclusion however, the optimized advanced generic model for product quality technology maturity assessment of metal hybrid manufacturing technology, EbereDimMT005 by Professional Inference Rule was successfully adapted and implemented on MHMT that integrates additive Laser Powder Bed Fusion and the subtractive CNC Machining processes with impressive and consistent result. Hence, the PQ technology maturity level of MHMT is found at 3.18ML of 5CMMl maturity profile, which is 63.5% maturity, with the application of the model. The result shows that the metal hybrid manufacturing technology is therefore within the quantitively managed (QM) maturity level. Therefore, with the knowledge and experience in artificial intelligence fuzzy logic system, data and software engineering, and the SEI CMMI, the novelty also opens doors for more research in the advanced manufacturing technologies, services, products and system development and improvement.

Limitations

Could not easily get to the most desired experts and professional stakeholders questionnaire respondents at the academia and industry top echelon.

It was a private research project

Funding was much limited

The process capability area, parameters, maturity indicators (PMI), performance indices were solely identified and determined from literature, studies and assembly materials only.

Recommendations and Future Work

Experts' survey questionnaire should better target respondent quality and manufacturing engineers and technologists at the upper echelon of advanced subtractive, additive and hybrid 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). Also, Metal Additive Manufacturing (METAL AM), Wohlers Associates, VoxelMatters, Formnext and others for a more involved, reliable, valid and dependable technology maturity research data.

Having gone through the rigors of the research, the product quality technology maturity assessment result for metal hybrid manufacturing technology as reported, I suggest from observations, experience and knowledge that further study and research be carried out in other technology or process capability areas like process efficiency, process effectiveness identifiable as maturity is not limited to process product quality capability area.

Similarly, there is also a need to delve into plastic and ceramics products technology maturity assessment using the existing models as applicable, hence not limited to metals, even in tripartite or multitasking manufacturing technology too.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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