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Design of Advanced Generic Model, EbereDimMT004 for Product Quality Technological Maturity Assessment of Metal Hybrid Manufacturing Technology by Membership Function

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ABSTRACT

The continued quest for management resources for technologymaturity assessment of the advanced metal subtractive, additive and hybrid manufacturing technologies has brought about the design and development of advanced generic product quality technological maturity assessment model, EbereDimMT004 by membership function. The new maturity model is based on the foundational single and hybrid manufacturing technology maturity assessment model, EbereDimMT002. Therefore, for viable and more secured future of metal hybrid manufacturing technologyin the worldhigh-risk operational and business fields of aerospace, medicine, automotive and defense in particular at present, metal subtractive and additive manufacturing technology product quality variables, in terms of the process capability areas, expanded parametric variables, maturity performance indices were determined and generated from literature, studies and experts' assemblies. Then, integrated to energize and drive the model.Achoice of fuzzy theory-based experts survey questionnaire model was opted, driven by a well coined and directed research statements and propositions sourced from the available process and product quality variables, interests and concerns.Questionnaires were administered strictly to the target industry audience, and responses received and profiled having adopted the recent Carnegia Mellon University Software Engineering Institute's (SEI) capability maturity model integration (CMMI) as the principal reference assessment and ranking model for hybrid manufacturing technology. With some knowledge of digital manufacturing, artificial intelligence (AI), data analytics and software engineering, robotics and automation, intelligent mechatronics systems and technology, research and data wascarefully processed all through the independent primary and secondary sections of the advanced generic product quality technological maturity assessment model, EbereDimMT004 by membership function in combination, with impressive and consistent research outcome as on the CMMI profile.

KEYWORDS: Advanced Manufacturing, Hybrid Manufacturing, Artificial Intelligence, Software Engineering, Product Quality, Fuzzy Logic, Set Theory, Membership Function, Digital Manufacturing

I. INTRODUCTION

Already, an advanced generic product quality technological maturity assessment (TMA) model, EbereDimMT003 by membership function has been designed and developed and seamlessly implemented, but on the independent advanced metal subtractive and additive manufacturing processes, each with impressive and consistent results. So, for obvious reasons but under different conditions, the zeal for continuous advancement and choking improvement demand in the standards from the high-risk technology fields of aerospace, automotive, medicine and defense industry sectors, necessitated and instigated the idea of extension of or from the novel generic product quality technological maturity assessment of metal hybrid manufacturing technology model EbereDimMT002 in Fuzzy logic system design to the more advanced generic and semi-direct product quality technological maturity assessment, EbereDimMT004 model design by the introduction of the existing semi-direct technology maturity assessment methodology model in design and for subsequent vast result oriented general industrial applications.[1], [2], [3], [4], [5], [6]

II. METHODOLOGY

EbereDimMT004 by membership function is the model to design and develop, a Non-Laboratory Experimental Research on the individual advanced subtractive and additive manufacturing technologies and in combination, which involves applications of some knowledge of advanced digital manufacturing, artificial intelligence (AI), machine learning, data analytics and software engineering to the advanced generic product quality technological maturity assessment of hybrid manufacturing technology in steps.[1], [2], [3], [4], [5], [6], [7], [8]

Algorithm of the Advanced Generic TMA Model, EbereDimMT004 by Membership Function Design

The EbereDimMT004 model design follows the algorithmic procedural steps in figure 1 below providing for implementation of the quantitative questionnaire based advanced generic product quality semi-direct technology maturity assessment model (SDTMAM) for metal hybrid manufacturing technology. [3], [4], [5], [6]

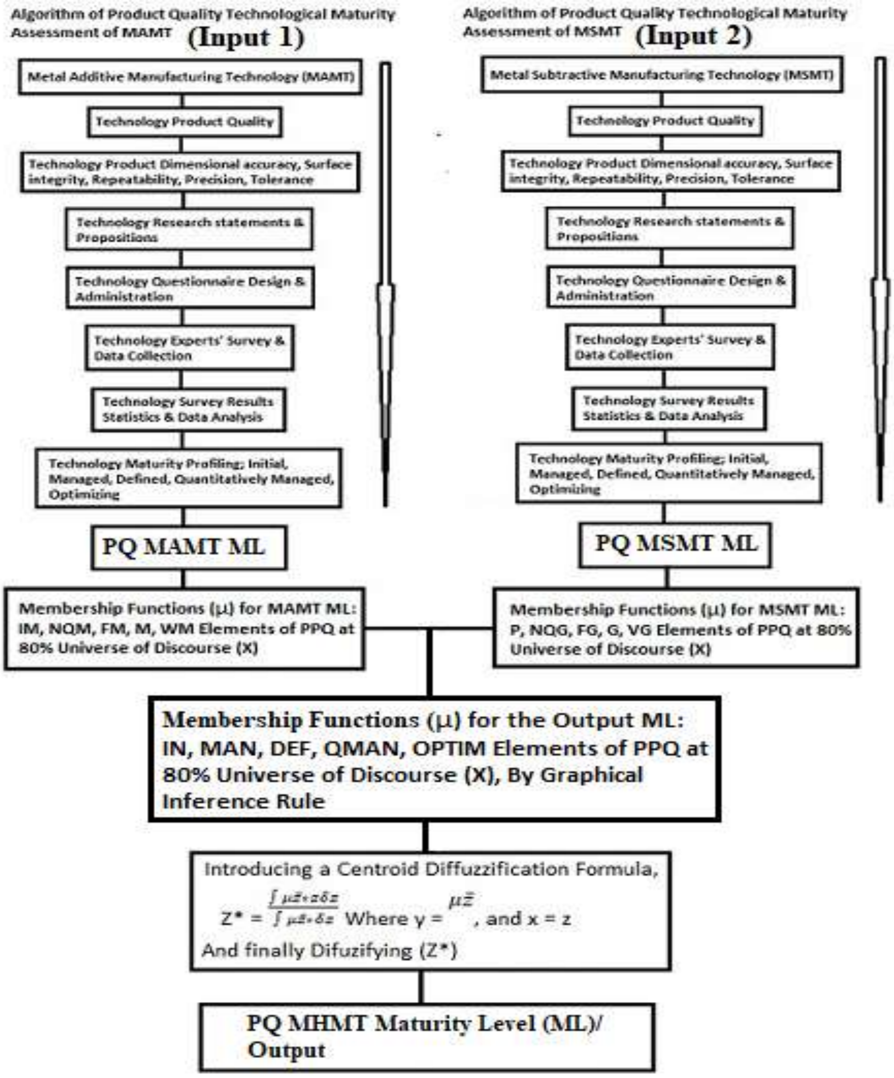


Figure 1 Algorithm of generic TMA of advanced MAHMT by membership function

The Schematic Representation of the Advanced Generic TMA Model, EbereDimMT004 by Membership Function Design for MHMT

The schematic representation of the implementation based EbereDimMT004 by membership function design algorithm, an advanced generic model for product quality technological maturity assessment of metal hybrid manufacturing technology as drawn from the SDTMAM algorithm illustrated in figure 1abovefollowing the procedural steps as shown in table 1.[3], [4], [5], [6], [7]

Table 1 Schematic Representation of the Advanced Generic Product Quality TMA Model, EbereDimMT004 by membership function design MHMT.[3], [4], [5], [6], [7]

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
9.	Step9.	The Inputs/Output maturity results were independently fuzzified into five subsets each
10.	Step10.	Membership functions were created and assigned to the Inputs/Output fuzzy subsets.
11	Step11.	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 results by applying a centroid defuzzification method with results
13	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
14	Step14.	Presentation and analyses of final results

III. SYSTEM MODELING AND ANALYSIS

EbereDimMT004 Model Design Requirements and considerations

The manufacturing technologies into consideration for the model design for product quality technology maturity assessment are the advanced metal subtractive and additive manufacturing technologies under hybrid manufacturing technology. The following factors and requirements for the implementation-based model design were determined and established.[3], [4], [5], [6], [7]

1. The design hybrid manufacturing technology

or process capability area, the product quality, which the attributes guide and direct the planning, development, design and parametric scope of the model.

2. The choice of the hybrid manufacturing technologies under study for model design and application was prompted by industry attention to the process and product challenges of the cutting-edge additive and hybrid manufacturing technologies.
3. The scope of the model under design covers the advanced metal subtractive and additive manufacturing technologies under hybrid manufacturing technology cell.
4. Determining the model's hybrid manufacturing technology or process capability variable, parameters, performance indices and the key performance indicators.
5. The membership make-up of the appraisal and respondents' team is specifically from the academia, industry and technology research institutions.
6. Target volume of the questionnaire interviewees and respondents among are experts and professionals, researchers, mostly quality and manufacturing engineers and technologists in the metal subtractive and additive manufacturing technologies domain.
7. The choice reference maturity profile to adopt or adapt as integral part of the model and design, the SEIs capability maturity model integration (CMMI) is opted.
8. The advantages of the advanced generic product quality technology maturity assessment model design, which include provision of benchmark quality ratingsfor advanced metal subtractive and additive manufacturing, and hybrid manufacturing processes in the areas of capability maturity levels, the outcomes that describe the strengths and weakness of metal subtractive and additive manufacturing, and hybrid manufacturing technologies, also in reaching consensus regarding the technologies key process issues and limitations, then provides appraisals database that can continue to serve to monitor the manufacturing processes improvement, progress and to support future assessment project.

Advanced Metal Subtractive and Additive Hybrid Manufacturing Processes Research Variables

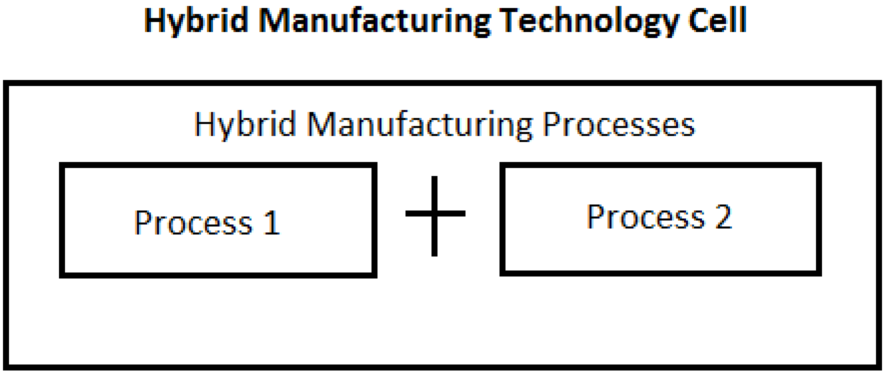


Figure 2 Hybrid manufacturing technology [3], [4], [5]

The Metal Hybrid Manufacturing Processes Capability Area

The capabilities of any of the metal hybrid manufacturing technologies or processes in figure 2 above, 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 processes product quality. [1], [2], [3], [4], [5], [6], [7], [8], [9]

The Metal Hybrid Manufacturing Processes Product Quality (PQ) Parameters

A metal hybrid manufacturing technology product quality as a measure of the process capability and maturity under consideration covers the achievable dimensional accuracy, surface roughness, tolerance, repeatability statuses of the manufacturing process. It is as the degree of whether good or bad in terms of physical appearance and related characteristics as limited to this design and research scope. Therefore, if the technology capability maturity of advanced metal subtractive and additive, and hybrid manufacturing technologies or processes depends on its manufacturable or achievable product characteristics and quality, then they are considered for the design the research technology capability maturity parameters, and can be expanded further as in the table 2 below as applicable to cover and serve more design need. [1], [2], [3], [4], [5], [6], [7], [8], [9]

Table 2. The metal hybrid manufacturing processes product quality parametric rough-in model

Serial No.	**Metal Hybrid Manufacturing Technology Capability Area of Product Quality**
	Technology Capability Parameters (TCP)
1	TCP1
2	TCP2
3	TCP3
4	TCP4
5	TCP5

Also, by statement or presentation, they serve as the industry process performance index or the process capability performance indicators. Hence, the process area and process performance indicators can be used in verifiable research investigative or propositional statements. The statements which are derived from the hybrid manufacturing process present state and militating conditions or recorded challenges and wins of the technology operations over time. They revolve around or cover all aspects of manufacturing engineering practices, concerns, goals, and results, as relate and affect the process capability performance indicators. To evaluate or put to test before the industry professionals and experts, these propositions are used to develop and design common sets of questionnaires across the hybrid manufacturing process capability area. This is purposely to conduct a survey for the primary research data collection. Fuzzy logic theory is applied in the design considering the methodology and the desired result. Hence, since the maturity is developmental, there is a need to capture those technology or process parameters at various intermediate stages of maturity to make accountable. Also, the CMMI maturity profile are all in human words, which are all linguistic variables, also there is a need to check the vagueness and imperfection of human bias decision and judgement in numbers as in table 3 below, where maturity and the CMMI profiles are simplified and fuzzified. [1], [2], [3], [4], [5], [6], [7], [8], [9]

Integration of Fuzzy Logic in Model Design

The attention to Zadeh’s 1965 Fuzzy logic system proposed for EbereDimMT004 model, a semi-direct technological maturity assessment methodology (SDTMAM) model, is a multiple valued logic that is obtained from a fuzzy set to consider and include the intermediate or approximate technology maturity values for the questionnaire model instead of the only actual binary [10] or two truth precise values; True and False. 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. [11] 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. [3], [4], [5], [6]

However, it has also been realized that the capability maturity model (CMM) maturity profile, [3], [12] and the capability maturity model integration (CMMI) model maturity profile are linguistic variables, [3], [4] which means that knowledge of fuzzy logic theory is also vital to transform the linguistic variables into numerical variables and figures. Fuzzy logic like other artificial or machine intelligence tools is a comprehensive or more valid way of collecting maturity research data and information outside the conventional qualitative method. [1], [2], [3], [4], [5], [6], [7], [8], [9]

The Semi-Direct Technology Maturity Assessment Methodology (SDTMAM) Syntax Model Design

Syntax = A Set of the linguistic Terms and numerical figures adopted in the research as shown in the table 3 below.A set of Fuzzy logic theory based linguistic terms (human words) and numerical figures adopted in the research model design as shown in the table 3 below, is introduced for application as suitable considering the methodology and the desired result. Hence, the maturity is developmental, and at various stages. So, there is a need to capture some technology or process parameters at various intermediate stages of maturity to make all accountable. For instance, as provided in the response, A bit True (BT), Faily True (FT), Not very True (NVT), It is True (T), and Very True (VT). [1], [2], [3], [4], [5], [6]

Table 3. Illustration of the linguistic and numerical syntax in rough-in model. [3], [4], [5], [6], [11], [12]

Fuzzy Set Linguistic Variable (Maturity) Defuzzification					
CMMI Terms	Initial	Managed	Defined	Quantitatively Managed	Optimizing
CMMI Terms Synonyms	Credle	Developing	Developed	Mature	Improving
KPI Survey Data	A bit True	Fairly True	Not Very True	It is True	Very True
Semantic	BT	FT	NVT	T	VT
Number; (%) Maturity	20	40	60	80	100
Maturity Level	ML1	ML2	ML3	ML4	ML5
Membership Function; μ(x)					
Degree of Membership (DOM)					
Serial Number	1	2	3	4	5

Product Quality Technology Capability Performance Indices (PI) Model Design

The product quality technology capability maturity performance indices generated and established as provided in the rough-in model design table 4 below, each transformed to metal subtractive, additive and hybrid manufacturing processes capability performance indicator. Subsequently from the parent process capability area, product quality technology maturity parameters and process performance indicators, coined a good number of verifiable research investigative propositional research statements applicable to the research experts' survey questionnaire design. The statements are derived from the technology present state and militating conditions or recorded challenges and wins of metal manufacturing technology over time. They revolve around or cover all aspects of manufacturing engineering practices, concerns, goals, and results, as relate and affect the technology capability performance indices as concerns the product quality technology maturity. To evaluate or put to test before the industry professionals and experts, these propositions are used to develop and design common sets of questionnaires across the technology capability area of product quality, purposely for more direct and reliable sourcing of research data. [1], [2], [3], [4], [7], [8]

Table 4. Product Quality Technology Capability Performance Indices Rough-in Model. [3], [4], [5], [6], [11], [12]

S/No.	**Product Quality Technology Capability Performance Indices of Advanced Metal Subtractive and Additive Manufacturing Processes**
1	PI 1
2	PI 2
3	PI 3
4	PI 4
5	PI 5

The Fuzzy Expert's Survey Product Quality Hybrid Manufacturing Technology Capability Maturity Assessment Questionnaire Model

A set of questionnaire model providing for the research propositions and statements from the process capability area was designed. It is in relation to the advanced metal subtractive, additive and hybrid manufacturing processes product quality parameters and performance indices. The human and linguistic nature of the term maturity being developmental was strategically considered in the design based on the principles of Fuzzy logicas shown in table 5 below. Also, maturity being a vague linguistic variable and major influence in the model, fuzzy logic theory was employed and utilized very well in the definition of terms questionnaire modelling for direct and more reliable sourcing of research data. Hence, the fuzzification of the expert respondents' answer options in the rough-in model in table 5 below. [3]

Table 5Product Quality Technology Capability Maturity Fuzzy Expert's Survey Questionnaire Rough-in Model.[3], [4], [5], [6], [11], [12]

Experts' Survey Capability Maturity Questionnaire						
S/No	**Questionnaire Statements/Proposition**	**A Bit True**	**Fairly True**	**Not Very True**	**It is True**	**Very True**
1	P1					
2	P2					
3	P3					
4	P4					
5	P5					

However, survey was conducted for each of the hybrid manufacturing processes, the data collected was further processed on individual process basis. The maturity assessment results are processed with a Minitab statistical software and statistically analyzed, and presented with the mean, median, mode, range, difference, standard deviation (S), and the variance etc., for each of the processes (1) and (2) product quality capability areas experts' survey data.

Having determined each class capability maturity levels for the processes, then the expected capability maturity level of the hybrid manufacturing process (1) + (2), will imply that a set of each of the processes (1) and (2) capability maturity variables, becomes the inputs variables, while the output variables by default will be the product of the hybrid manufacturing process. For segregation and clarity therefore, the five subsets of each of the inputs (1) and (2), and the output maturity variables were substituted and mapped with five sets of related descriptors each accordingly as Immature (IM), Not Quite Mature (NQM), Fairly Mature (FM), Mature (M), Well Mature (WM) and Poor (P), Not Quite Good (NQG), Fairly Good (FG), Good (G), Very Good (VG), and the initial (IN), Managed (MAN), Defined (DEF), Quantitatively Managed (QMAN), Optimizing (OPTIM). [3], [4], [3], [4], [5], [6], [11], [12]

Maturity Modelling and Profiling for the Product Quality Technology Maturity

The maturity profile adapted in the design for the product quality technology maturity assessment model is the linguistic variables-based capability maturity model integration (CMMI) model by Carnegie Mellon University Software Engineering Institute (SEI), USA. Maturity levels of a CMMI maturity profile are well-defined evolutionary plateau towards achieving continuous advanced or developed metal subtractive and additive manufacturing processes.They are five maturity levels with continuous representation, marked by the numbers 1 to 5, and each maturity level provided a layer in the foundation for continuous manufacturing process improvement. The model also considers to run on a chosen reference manufacturing process capability area, where achievement of a capability maturity level in the manufacturing process capability area allots a particular maturity level to the manufacturing process technology as seen in the table 6 below. [3], [4], [5], [6], [11], [12]

However, technology maturity in manufacturing technology is a measurement of the ability of the process or its product quality to achieve a continuous improvement in a particular capability area. The maturity levels are calculated by the accomplishment of the specific and generic goals related to all predefined set of the associated process capability area, maturity parameters and performance indices research statements. [3], [4], [5], [6], [11], [12] It explains the maturity based CMMI model, and the truth-based survey response model. The data collected were further processed and put to statistical analysis, followed with ranking along the CMMI profile as the base model to represent each process maturity assessment result. Each of the hybrid manufacturing process performance indicators (PI) capability maturity is assessed and ranked individually, after which all the PI maturity are integrated under the maturity CMMI profile and ranked under the CMMI framework as illustrated in the Table 8.[3], [4], [5], [6], [11], [12]

Table 6. The Capability Maturity Model Integration (CMMI Maturity Levels) Model. [3], [4], [5], [6], [11], [12]

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

Summarized Fuzzification of the Linguistic Maturity and Questionnaire Response Profiles

The metal subtractive, additive and hybrid manufacturing processes capability maturity and the CMMI profiles are similarly simplified or fuzzified as in the table 7 below. Also, the CMMI maturity profile are all in human words, which are all linguistic variables, hence there is a need to check the vagueness and imperfection of human bias decision and judgement numerically or in numbers, most proficiently through percentage ratings. [1], [2], [3], [4]

Table 7. Fuzzification of Maturity and question response.[3], [4], [5], [6], [11], [12]

Serial No.	CMM Maturity Profile	Fuzzy Maturity Profile	Fuzzy Proposition Response Profile
1	Optimizing	Well mature	Very true
2	Quantitatively managed	Mature	True
3	Defined	Not well mature	Not very true
4	Managed	About mature	Fairly true
5	Initial	Not yet mature	A bit true

The model, EbereDimMT004 by membership function relies on the advanced metal subtractive and additive manufacturing technologies typical process products, and collaborative inputs of professionals and experts in the emerging technology. It is based on the appraisal reference models to determine the strengths and weaknesses of the process. Thus, the advanced generic product quality technological maturity assessment model for metal hybrid manufacturing processes is driven by the capability maturity model integration (CMMI) as the reference framework for the maturity profiling and ranking, Fuzzy system evaluation, and statistical data analysis components. [1], [2], [3], [4], [5]

Model Harnessing and Parametric Charging for Execution

The advanced metal hybrid manufacturing process technological maturity assessment model is made up of major components still in scalar rough-in states which form the tools utilized in the implementation of advanced metal subtractive, additive and hybrid manufacturing processes maturity appraisals, but these tools need to be fed with some number of inputs, with direction and energy to run. [1], [2], [3], [4], [5]

Metal Subtractive and Additive Manufacturing Processes Product Quality Parameters

Manufacturable product characteristics and quality which are considered for the technology capability parameters of the MSMT and the MAMT are the (i) dimensional accuracy (ii) surface roughness or integrity (iii) precision or repeatability and (iv) tolerance. [1], [2], [3], [4], [5]The product quality technology capability parameters which were further expanded and summarized to 18 in number as shown in table 8 below covering various possible aspects of the technology operational phenomenal conditions in the advanced metal subtractive and additive manufacturing processes through relationship-based classification, grouping and matches. [6], [7], [8], [9]

Determining the Subtractive and Additive Hybrid Manufacturing Processes Independent Parameters and their Interface Parameters

The subtractive and additive manufacturing process product quality as a measure of process capability and maturity under consideration covers the achievable dimensional accuracy, surface roughness, tolerance, repeatability statuses of the hybrid manufacturing process. It is as the degree how good or bad in terms of physical appearance and related characteristics.This implies that, if the capability of a manufacturing technology or process is determined by its manufacturable or achievable product characteristics and quality, they can be considered for some of the technology capability parameters as in table 8 and table 9 below. [1], [2], [3], [4], [5], [6], [7], [8], [9], [10],[13], [14], [15], [16]

Table 8. The Subtractive CNC Machining and Additive LBPF Manufacturing PQ Parameters.

The Subtractive (machining) and Metal Additive Manufacturing Processes Parameters		
S/No	**Part Machining Process Parameters**	**Part LPBF Additive Process Parameters**
1	Positional accuracy	Orientation
2	Surface roughness	Surface Roughness
3	Geometry	Geometry
4	Processing temperature (oC)	Processing Temperature (oC)
5	Processing speed	Processing Speed
6	Size (part to manufacture)	Build Size
7	Material (metal)	Material (metal)
8	Processing energy	Processing Energy
9	Dimensional accuracy	Dimensional Accuracy
10	Material removal rate	Material deposition velocity
11	Cost	Cost
12	Lead time	Lead time
13	Processing power	Processing power
14	Surface area	Surface area
15	Work holding technique	Work holding technique
16	Cutting depth	Layer thickness
17	Aspect ratio	Aspect ratio
18	Side wall angle	Side wall angle

Table 9. The Common or Hybrid Manufacturing Process Parametric Interface.

S/No	**The Subtractive – Additive Hybrid Manufacturing Parametric Interface**		
1	Part positional Accuracy	11	Cost of production
2	Part surface roughness	12	Lead time
3	Part geometry	13	Processing power
4	Processing temperature (oC)	14	Part surface area
5	Processing speed	15	Work holding technique
6	Part size	16	Feed thickness
7	Part material (metal)	17	Part aspect ratio
8	Processing energy	18	Part side wall angle
9	Part dimensional accuracy	19	Part wall thickness
10	Part processing rate		

Metal Subtractive and Additive Hybrid Manufacturing Product Quality Capability Performance Indices

Measurable performance indices of 28 in number were generated, with objective checks as evident from the metal subtractive and additive manufacturing processes literature and studies, experience and engineering practice covering the technology or process challenging goals and operational conditions of manufacture as shown in table 10 below. [3], [4] [5], [6], These performance indices are meant to yield some number of well-articulated and purposefully coined propositional research statements meticulously generated for the experts' survey questionnaires. However, these manufacturing processes 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 a target technology of study at a time. [1], [2], [7], [8], [9]

Table 10. The HM Process Product Quality Performance Indices. [1], [2], [3], [4], [3], [4], [5], [6], [7], [8], [9]

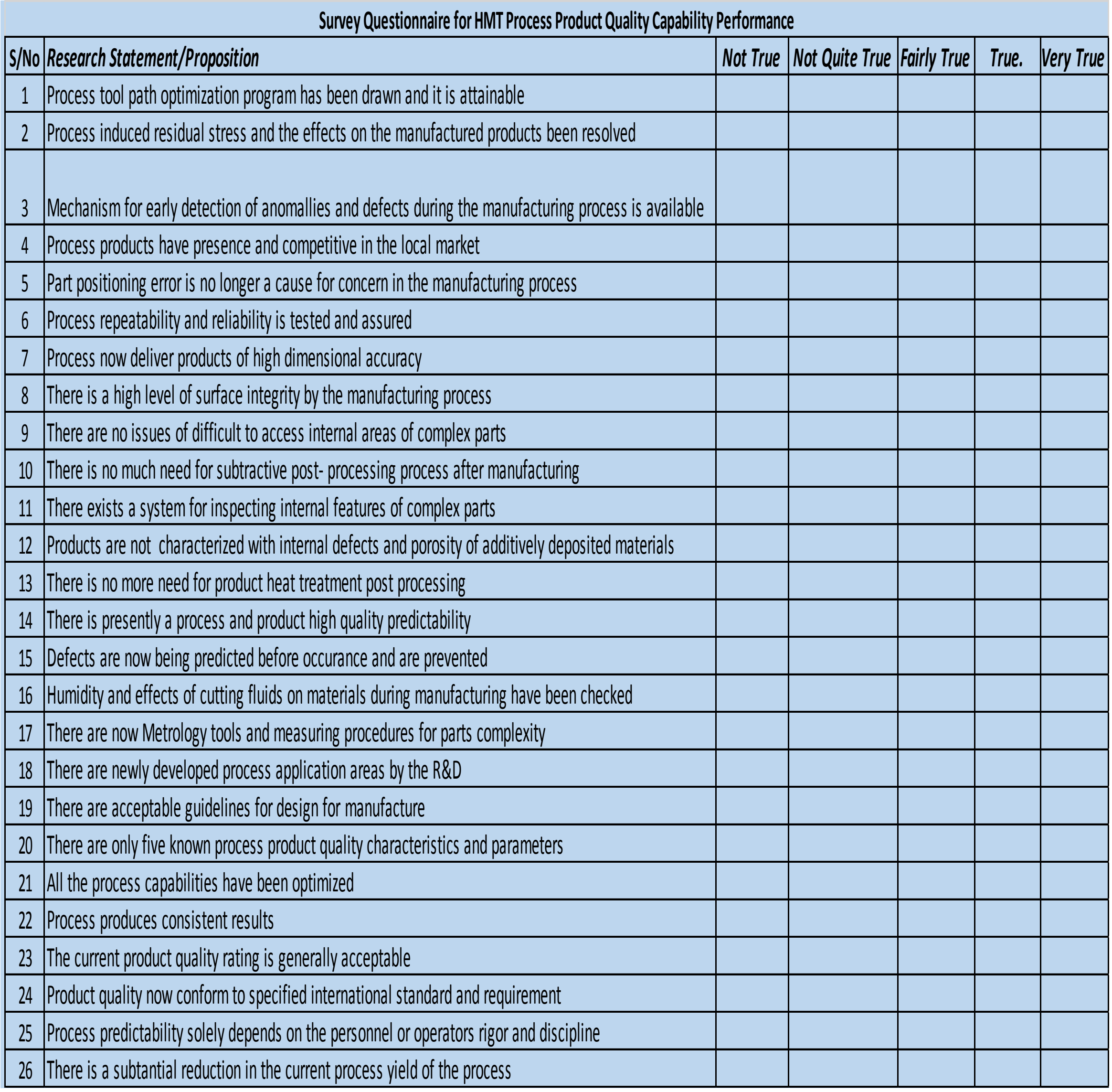
S/No.	Process Product Quality Performance Indices
1	Achievement of tool path optimization program
2	Existence of residual stress
3	Early detection of defects or anomalies
4	Products presence in both local and international market
5	Part positioning error
6	Process repeatability and reliability
7	High dimensional Accuracy
9	Level of surface integrity
10	Accessing difficult to reach areas inside complex part
11	Need for post-processing
12	Inspection of the internal features of a produced complex part
13	Internal defects and porosity of additively deposited material
14	Existence of post processing heat treatment
15	Process and high-quality product predictability
16	Predicting defects before they occur and acting accordingly in order to avoid their appearance
17	Analysis of the porosity, cracking, and microstructural effects of unequal reaction of different materials in the presence of cutting fluid remnant during deposition
18	Availability or development of a metrology tools and measuring procedures for the complexity of parts
19	R&D development of new application areas for the process
20	Acceptable guidelines for design for manufacture
21	Process product quality characteristics
22	Optimized process capabilities
23	Consistency of process results
24	Products quality acceptability and consistency
25	Product quality conformity to specified standard and requirement
26	Process product predictability due to personnel rigor and discipline
27	Improved process yields and capabilities
28	Process stability

Experts' Fuzzy Survey Questionnaires for the Product Quality Technology Maturity Assessment of MSMT and the MAMT.

Thus, a set of 26-number experts' survey fuzzy questionnaire was harnessed and developed as in the table 11 below, ready for application on the metal subtractive and additive hybrid manufacturing processes product quality technological maturity assessment (TMA). [1]It comprises of research statements jointly produced from various metal subtractive and additive manufacturing studies and literature, experience and engineering practice. Thus, meaning that they are subject to continuous scrutiny and review of the process capability performance areas, characteristics, propositional statements, and questionnaire design to suit maturity assessment of a target manufacturing technology at a time. [3], [4], [5], [6]

However, to checkmate situation of bias throughout the questionnaire planning and administration system, and results, it was ensured that there is no information in the questionnaire system that can suggest exactly to the participating experts and professionals or respondents, the intended use or purpose of the project, neither in the data nor their responses. With this approach, the possible sentiments and bias influences are eliminated from the questionnaire system.[3], [4], [5], [6]

Table 11. Experts' Survey Fuzzy Questionnaire for TMA of MSMT and the MAMT. [1], [2] [3], [4], [5], [6], [7], [8], [9]



Survey Questionnaire for HMT Process Product Quality Capability Performance						
S/No	***Research Statement/Proposition***	***Not True***	***Not Quite True***	***Fairly True***	***True.***	***Very True***
1	Process tool path optimization program has been drawn and it is attainable					
2	Process induced residual stress and the effects on the manufactured products been resolved					
3	Mechanism for early detection of anomallies and defects during the manufacturing process is available					
4	Process products have presence and competitive in the local market					
5	Part positioning error is no longer a cause for concern in the manufacturing process					
6	Process repeatability and reliability is tested and assured					
7	Process now deliver products of high dimensional accuracy					
8	There is a high level of surface integrity by the manufacturing process					
9	There are no issues of difficult to access internal areas of complex parts					
10	There is no much need for subtractive post- processing process after manufacturing					
11	There exists a system for inspecting internal features of complex parts					
12	Products are not characterized with internal defects and porosity of additively deposited materials					
13	There is no more need for product heat treatment post processing					
14	There is presently a process and product high quality predictability					
15	Defects are now being predicted before occurance and are prevented					
16	Humidity and effects of cutting fluids on materials during manufacturing have been checked					
17	There are now Metrology tools and measuring procedures for parts complexity					
18	There are newly developed process application areas by the R&D					
19	There are acceptable guidelines for design for manufacture					
20	There are only five known process product quality characteristics and parameters					
21	All the process capabilities have been optimized					
22	Process produces consistent results					
23	The current product quality rating is generally acceptable					
24	Product quality now conform to specified international standard and requirement					
25	Process predictability solely depends on the personnel or operators rigor and discipline					
26	There is a subtantial reduction in the current process yield of the process					

Administration of Questionnaires to the Selected Experts' Respondents and Collation

Survey was conducted with questionnaires administered, the data collected and processed in the process class frequency distribution tables. Similarly, to further checkmate the chances of bias during questionnaire administration and data collation, sure was again made that the participating experts and professionals do not know the actual purpose of the project, neither the data nor their responses. With this approach as well, the possible remaining sentimental and bias influences are farther eliminated from the entire inputs and transformation systems. [1], [2], [3], [4],[5]

Also, for reliability and confidence of research data, the questionnaire was directly emailed to the targeted professionals and experts' respondents drawn from the field of advanced metal subtractive and additive manufacturing technologies. [3] A situation where, based on the research variable PQ, and importance of specialty in the system, the related quality and manufacturing engineers and technologists in the midst were marked and sub-grouped as main target. Then, applying principal component analysis, and to achieve a better manageable data size, the 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. [1], [2], [3], [4], [5]This was based on the employment data provided in the questionnaires, which includes current position and titles of the respondents.

Adoption and Integration of the CMMI Profile

The capability maturity model integration of the Software Engineering Institute of the Carnegie Mellon University, USA, was adopted for a reference maturity profile and ranking of the product quality capability maturity assessment data. It explains the maturity based CMMI model, hence the data collected with the truth-based survey response was further processed and put to statistical analysis, followed with ranking of data along the CMMI profile as the base model ranking for each of the manufacturing process maturity assessment result. Thus, each of the metal subtractive and additive manufacturing processes performance indicators (PI) capability maturity is assessed and ranked individually, after which all the (PI) maturity outcomes are integrated under the maturity CMMI profile and ranked under each CMMI frameworkas illustrated in the rough-in table 12 below. [1], [2], [7], [8], [9]

Table 12. Product quality capability maturity profile and data ranking rough-in model.[3], [4], [5], [6], [11], [12]

Level	Focus	Process Capability Area	Result
5 Optimizing	Continuous Process Improvement	X X X X …….	•
4 Quantitatively Managed	Quantitatively Managed	X X X ……	•
3 Defined	Process Standardization	X XXXXX ……	•
2 Managed	Basic Project Management	X ………	•
1 Initial	Process is informal and Adhoc	… (No Process Area)	•

IV. PRIMARY PRODUCT QUALITY TMA RESULTSOF METAL HYBRID MANUFACTURING TECHNOLOGY

Experts' survey was first conducted independently on the metal subtractive and additive (LPBF) hybrid manufacturing process, on test run, and data collected, processed with a Minitab statistical software tool, and presented in the process class frequency distribution table in Minitab. The data was then ranked on the capability maturity model integration (CMMI) maturity profile. The maturity assessment result was analyzed and presented with the product quality technology maturity mean value, the median, mode, range, standard deviation (S), and the variance in a statistical result table. Also, to be represented in graphical normal probability test plot, histogram and a boxplot in Minitab.Then, the metal hybrid manufacturing product quality technological maturity result will be presented as summarized in the table 13 below on simulation of the two inputs using the Fuzzy Logic System in MATLAB Toolbox. Thus, the primary product quality technology maturity of metal hybrid manufacturing technology is at the quantitatively managed (QM) maturity level (ML) on implementation.

Table 13. Presentation of Product Quality TMA of the Subtractive - Additive Hybrid Manufacturing Technology Results. [1], [2], [3], [4], [5], [6], [7], [8], [9]

Primary Hybrid Manufacturing Process Product Quality Maturity Level					
Laser PBF		**Machining**		**HM Technology**	
ML	**%tage**	**ML**	**%tage**	**ML**	**%tage**
Result	Result	Result	Result	QM	ML

V. ADVANCING THE GENERIC PRODUCT QUALITY METAL HYBRID MANUFACTURING TMA MODEL, EBEREDIMMT002

Membership Function of the Maturity Levels

Having shown the primary class capability maturity levels for the metal subtractive, additive and hybrid manufacturing technology with the generic product quality TMA model, EbereDimMT002. then the expected capability maturity level of the hybrid manufacturing technology with the advanced generic product quality TMA model, EbereDimMT004 will imply determining the membership function for the two primary maturity levels, where the two sets of the SMT and AMT capability maturity variables, become the input variables, while the output variables by default will be the outcome of the hybrid manufacturing processes. For segregation and clarity, the five subsets of each of the input and the output maturity variables were substituted and mapped with five sets of related descriptors accordingly.[1], [2], [3], [5]This means that now the primary maturity levels of the metalhybrid manufacturing technologies have been established, but there is yet a need to also find out how true or the degree of truth in the maturity levels found.Subsequently, and guided by the nature of each process set of numerical elements (x) of the defuzzified maturity assessment results, and the mean value (ẋ), which represents the process maturity level from the experts' survey, a common universe of discourse (X) is decided and applied for each of the processes, as shown in the figure 3 below.[1], [2], [3], [5]

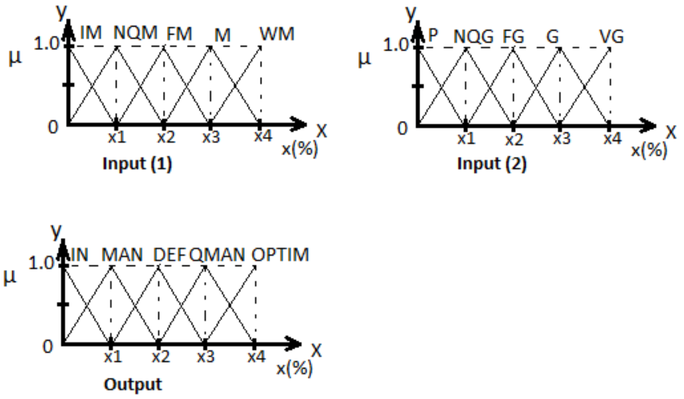


Figure 3 Triangular membership functions for the Inputs 1, 2, and Output above.

The elements are further fuzzified by assigning each a membership function (μ(x)). Thus, fuzzy sets of maturity assessment results are got for the hybrid manufacturing processes as illustrated in figure 3 above. Then, a set of maturity subsets are established with some familiar descriptors, to determine the membership functions of the subsets as in the figure 3 above. Defining the membership functions for each set of the Inputs 1 and 2, and the Output descriptors, a triangular membership function is suggestedfor the three fuzzy subsets. The Input (1) subset descriptors; IM, NQM, FM, M, WM. The Input (2) subset descriptors; P, NQG, FG, G, VG. The Hybrid manufacturing process (Output) subset descriptors; IN, MAN, DEF, QMAN, OPTIM as in the figure 3, where 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], [2], [3], [5]

Thus, a triangular membership function is opted for and assigned to each of the Inputs and Output fuzzy set variables descriptors as shown in figure 3 above. Where equation of the straight line is used to determine the membership functions for all the Inputs and Output descriptors and their corresponding membership values as follow.[1], [2], [3], [5]

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

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

Therefore, the membership functions for each of the input (1) subsets becomes.

- μIM = $\frac{x_1 - x}{x_1}[0, x_1]$
- μNQM = $\frac{x}{x_1}[0, x_1], \frac{x_2 - x}{x_2 - x_1}[x_1, x_2]$
- μFM = $\frac{x - x_1}{x_2 - x_1}[x_1, x_2], \frac{-x + x_3}{x_3 - x_2}[x_2, x_3]$
- μM = $\frac{x - x_2}{x_3 - x_2}[x_2, x_3], \frac{x_4 - x}{x_4 - x_3}[x_3, x_4]$
- μWM = $\frac{x - x_3}{x_4 - x_3}[x_3, x_4]$

Then, the membership functions for each of the input (2) subsets becomes.

- μP = $\frac{x_1 - x}{x_1}[0, x_1]$
- μNQG = $\frac{x}{x_1}[0, x_1], \frac{x_2 - x}{x_2 - x_1}[x_1, x_2]$
- μFG = $\frac{x - x_1}{x_2 - x_1}[x_1, x_2], \frac{-x + x_3}{x_3 - x_2}[x_2, x_3]$
- μG = $\frac{x - x_2}{x_3 - x_2}[x_2, x_3], \frac{x_4 - x}{x_4 - x_3}[x_3, x_4]$
- μVG = $\frac{x - x_3}{x_4 - x_3}[x_3, x_4]$

Whereas the membership functions for each of the Output subsets becomes.

- μIN = $\frac{x_1 - x}{x_1}[0, x_1]$
- μMAN = $\frac{x}{x_1}[0, x_1], \frac{x_2 - x}{x_2 - x_1}[x_1, x_2]$
- μDEF = $\frac{x - x_1}{x_2 - x_1}[x_1, x_2], \frac{-x + x_3}{x_3 - x_2}[x_2, x_3]$
- μQMAN = $\frac{x - x_2}{x_3 - x_2}[x_2, x_3], \frac{x_4 - x}{x_4 - x_3}[x_3, x_4]$
- μOPTIM = $\frac{x - x_3}{x_4 - x_3}[x_3, x_4]$

However, applying the crisp or classical mean maturity value of the processes A and B; $\dot{X}_1$ and $\dot{X}_2$, and taken their percentages each of the maximum element in the universe of discourse (X). This is to determine the ranges they fall within their individual universe of discourse.

$\dot{X}_1$ % of $x_4 = \dot{x}_1$
and
$\dot{X}_2$ % of $x_4 = \dot{x}_2$

Therefore, the membership functions of Process A; FM and M, as well the membership functions of Process B; FG and G, will become
μFM = $[x_3 - x/x_3 - x_2 = x_3 - \dot{x}_1/x_3 - x_2]$ and μM = $[x - x_2/x_3 - x_2 = \dot{x}_1 - x_2/x_3 - x_2]$ ------ Process A
μFG = $[x_3 - x/x_3 - x_2 = x_3 - \dot{x}_2/x_3 - x_2]$ and μG = $[x - x_2/x_3 - x_2 = \dot{x}_2 - x_2/x_3 - x_2]$ --------Process B

Four-Rule Base Membership Functions of TMA Inputs

Then, by forming the mapping between the different inputs, the membership values are associated and matched to each other, thus a four-rule base is established as in table 14 Below

Table 14. Four-Rule base membership functions of TMA Inputs.

Rule 1	Input (1) μFM	Input (2) μFG
Rule 2	Input (1) μFM	Input (2) μG
Rule 3	Input (1) μM	Input (2) μFG
Rule 4	Input (1) μM	Input (2) μG

Graphical Technique Inference for the Inputs and Output

Therefore, a graphical technique of inference is applied as in figure 4 below to obtain the require maturity level of the output finally by a centroid defuzzification method.

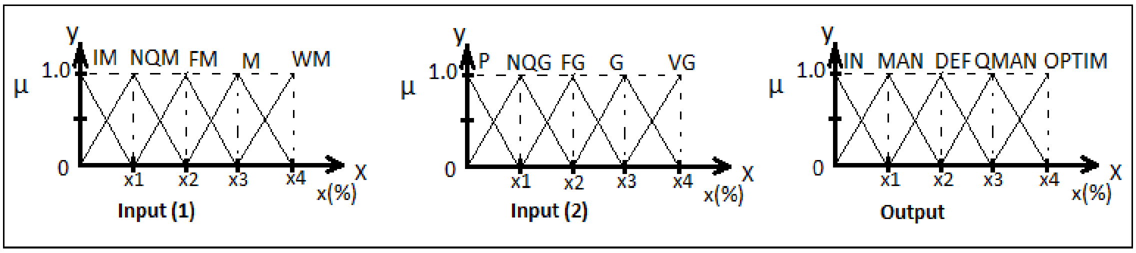


Figure 4 Graphical technique inference for the Inputs and Output

However, the Output above is an aggregated Output graph. It is still a vague value or fuzzy. Therefore, to determine the crisp or classical Output that gives the exact maturity value of the processes pair Inputs and Output value, a centroid method is applied as below. Finally, defuzzifying the value (Z*), by applying the equation of a straight line; Eqn. (i) along the fuzzy output boundaries.[1], [2], [3], [5]

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

and defuzzifying value (Z*) implies introducing the centroid defuzzification method formula;

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

which resolves the center of gravity of the fuzzy set elements x(%) along the x-axis of the universe of discourse (X), to arrive at a precise technological maturity level.

VI. SUMMARY

Guided by the aim and methodology of the research, the planned, designed and developed generic model for technological maturity assessment of a metal hybrid manufacturing technology commenced with the proper definition of the subject and process capability areas. Then, determination of process variable and parameters, and the capability performance indices, which formed the source of target research data. Also, guided by the objectives of the researchwhich looked and determined the maturity of the hybrid manufacturing processes first from the proposed process capability area (PCA) of the products quality, for more research information and data required for process and product improvement. The CMMI model maturity profile only was adopted and characterized for the PCA. Research interface model (tool), a fuzzy logic-based questionnaire was developed and designed for product quality technological maturity assessment of the manufacturing technologies.

Experts' technological maturity assessment survey for the PCA of the manufacturing technologies was planned for administration among the target and reachable respondent audience of quality and manufacturing engineers and technologists. The resource persons were targeted within the scope of three industry areas of academia, industrial and technology research institutes. Engineering statistical model was introduced for processing and analysing the results of the survey area. All the survey propositions which also represent the process performance indicators and invariably, the present state process or technology state or maturity were ranked on the referenced CMMI maturity profile. However, since the mean values maturity results were still in fuzzy form, hence each fuzzy process technological maturity value was defuzzified by the assigning of a membership functions to each to obtain crisp mean values. Having determined the maturity levels of the two manufacturing processes in hybrid cell solution, the Inference System and graphing model was introduced and used to determine the maturity of hybrid manufacturing technology.

Results were simulated after defuzzification using graphical user interfaces model. Finally, the models above were logically combined, and followed the exact procedure to successfully assess the product quality maturity level of hybrid manufacturing technology that integrates metal subtractive (CNC machining) and additive (LPBF) manufacturing technologies with very impressive results as shown in the table 15. Thus, considering the procedure, the consistency of results, and reality, technological maturity of any manufacturing technology, process and management system can be assessed with either adoption or adaption of the advanced generic semi-direct technological maturity assessment methodology (SDTMAM), EbereDimMT004 model.

Presentation of Results

Therefore, by the model implementation results and simulation, the percentage (%) process product quality technological maturity assessment by membership function of the metal hybrid manufacturing technology, will imply as to be represented in table15 below.

Table 15. The Advanced MAHM Process Product Quality ML Result

Process Product Quality Maturity Level					
PBF		**Machining**		**HMT**	
ML	%tage ML	ML	%tage ML	ML	%tage ML
QM	QM	QM	QM	QM	QM

Precautionary Measures

To further avoid situation of bias in the questionnaire planning and administration system, and results, sure was made that the participating experts and professionals did not know the intended use or the actual purpose of the questionnaire exercise, neither from the data nor responses. Hence, with the approach, sentimental influence was eliminated from the entire process.

Contributions to Knowledge

Based on the design, development and seamlesstest-run of the advanced generic product quality TMA model, EbereDimMT004 by membership function on metal hybrid manufacturing technology, the research has been able to make significant contributions to the field of metal hybrid manufacturing technology and manufacturing engineering in general.

The model has been used to determine the maturity level of metal additive HMT in terms of PQ, at quantitatively managed ML which is a novel contribution to the field.

Generation of the process capability area performance indices for the HMT, in the areas of PQ, which further researchers could utilise.

Demonstration that artificial intelligence (AI) is a veritable tool that can be used to assess the technological maturity of hybrid manufacturing technology with optimum precision and unlimited advantages.

Substantiation and quantification of technological maturity in terms of process product quality, which is the first of its kind.

Design, development and generation of a set of fluidic fuzzy questionnaires for process product quality maturity assessment of metal subtractive and additive hybrid manufacturing technologies.

Generation of questionnaire statements bank for technological manufacturing assessment in the area of PQ.

Introduction and application of membership function, which has extended the generic model, EbereDimMT002 and enabled a more precise maturity assessment and monitoring, which further researchers embarking on similar study will find as a useful tool.

VII. CONCLUSION

In conclusion therefore, the advanced generic model for product quality technological maturity assessment of metal hybrid manufacturing technology, EbereDimMT004 was designed. The model was successfully illustrated and test-runwith impressive and consistent result at the quantitatively managed (QM) maturity level (ML).

EbereDimMT004 is an advanced generic model in the sense that it takes only provisions and definition of any choice maturity data, the variables, parameters of the capability area and the performance indices, a raw maturity survey results to run a product qualitytechnological maturity assessment model on any metal hybrid manufacturing technology.

It is observed that the generic technological model application on any process area, variable, parameter depends on how knowledgeable the researcher is in or about the area irrespective of his level of experience or knowledge in or about the model. Thus, applicability of the model depends on the knowledgeability in the proposed area of and for the application. For example, as the questionnaire survey model certainly continues to change and differ with the project areas. You may know the model but and still unable to apply it in every other domain. Hence, you will always need corroboration or collaboration with the experts in that field of study.

The current study is therefore a smart pioneer or foundational research which will open doors for further research in the manufacturing technologies with more additional variables, systems, technologies and process areas.

VIII. RECOMMENDATIONS AND FUTURE WORK

Having gone through the rigours of the research subject, the process and the outcome as reported, I suggest from observations, experience and knowledge that further study and research be carried out for more contribution to knowledge.

Proof by EbereDimMT004 in numbers and figures that the maturity of the metal hybrid manufacturing technology is at quantitatively managed maturity level.

There should be continuous adoption or adaption and implementation of model on varieties of hybrid manufacturing technologies

Further research is needed for possible optimization of EbereDimMT004 model and maturity outcome.

A computer programme to run the advanced generic technological maturity assessment model on hybrid manufacturing technologies be written.

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